EPJ Web of Conferences **219**, 09004 (2019) https://doi.org/10.1051/epjconf/201921909004
PPNS 2018

Measurement of the angular distribution of prompt gamma-rays emitted in the ^{117}Sn(n, γ) reaction for a T-violation search

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Abstract. It is theoretically suggested that the violation of charge conjugation and parity symmetry (CP-violation) could be enhanced in several compound nuclear reactions. According to the CPT theorem the violation of time-reversal symmetry (T-violation) would be enhanced too. The experimental sensitivity to find a T-violating effect in neutron-induced compound nuclear reactions depends on the value of a spin factor $\kappa(J)$, which is a parameter specific for each nuclide. It can be determined from the angular dependence of γ-ray emission in (n, γ) reactions induced near a p-wave resonance. In this paper, the measurement result and the analysis status of experiments using the target nucleus ^{117}Sn are reported.

1. Introduction

Violation of charge conjugation and parity symmetry (CP-violation) stronger than expected within the Standard Model of particle physics is necessary to explain the dominance of matter over anti-matter in the current universe. It is theoretically suggested that CP-violation is enhanced in several nuclear compound reactions [1]. According to the CPT theorem the violation of time-reversal symmetry (T-violation) must also be enhanced. By measuring the spin-dependent neutron transmission asymmetry through polarized nuclear targets one can measure enhanced T-violating terms in the neutron-nucleus forward scattering amplitude, thus providing a sensitive probe for T-violation beyond the Standard Model. The experimental sensitivity depends on the nuclear species studied. One of the key parameters allowing to identify good candidate nuclei is the spin factor $\kappa(J)$. It is related to neutron resonance partial widths via a mixing angle ϕ describing the superposition of different spin components. A more detailed explanation of theoretical background as well as the involved measurement methodology of this T-violation search is described in Ref. [2].

So far only ^{139}La has been used as a target nucleus for neutron capture to measure the value of $\kappa(J)$, which was recently determined by Okudaira et al. [3]. To identify further candidates for a T-violation search, other nuclei must be measured. The parameter ϕ can be determined by measuring the angular distribution of prompt γ-rays emitted from excited states of the compound nucleus. The differential cross section for unpolarized neutrons is described by Flambaum as follows [4]:

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

where θ_γ is the angle between the flight directions of the emitted gamma-ray and the incident neutron. The a_0 term corresponds to the ordinary Breit-Wigner formula, whereas the a_1 term and the a_3 term include the parameter ϕ and hence are sensitive to $\kappa(J)$. Equation (1) indicates that, due to these terms, the shape of the p-wave resonance depends on the direction of emitted γ-rays with respect to the incident neutron beam.

The isotope ^{117}Sn is one of the target nuclei candidates for T-violation search. Table 1 shows the resonance parameters of the system ^{117}Sn + n. In this paper, the results of a measurement of the angular dependence of γ-ray emission near the p-wave resonance at 1.33 eV is reported.

2. Experiment

Our experiments were performed using the Accurate Neutron-Nucleus Reaction measurement Instrument (ANNRI) at the MLF beamline 04 at J-PARC. The instrument (see Ref. [2] for a detailed description) employs epithermal neutrons projected onto a nuclear target which is surrounded by an array of germanium detectors for investigation of the prompt γ-rays emitted in (n, γ) reactions [6].

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Table 1. Resonance parameters of the system ^{117}Sn + n [5]. E_0 denotes the resonance energy, l is the orbital angular momentum of the neutron, J is the total angular momentum, Γ_n is the neutron width, and Γ_γ is the γ width.

E_0 [eV]	l	J	Γ^n[meV]	Γ^γ[meV]
-81.02	0	1	118.51	91
1.327 ± 0.001	1	1	$(1.84 \pm 0.1) \times 10^{-4}$	148 ± 10
15.385 ± 0.016	1		$(1.23 \pm 0.6) \times 10^{-4}$	136 ± 18
21.390 ± 0.025	1		$(2.75 \pm 0.1) \times 10^{-4}$	125 ± 12
26.215 ± 0.025	1		$(27.6 \pm 0.1) \times 10^{-4}$	129 ± 8
34.044 ± 0.017	1		$(249 \pm 12) \times 10^{-4}$	
38.80 ± 0.05	0	1	4.1 ± 0.2	119 ± 9

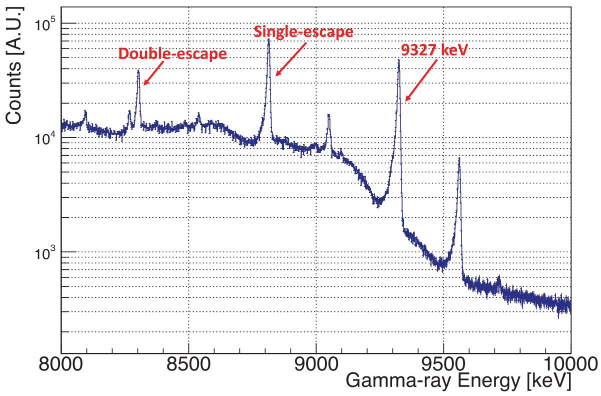

Figure 1. Gamma-ray spectrum due to neutron capture in the target, shown for the range 8 – 10 MeV. The peak with an energy of 9327 keV and its single- and double-escape peaks due to ^{117}Sn in the target can be observed clearly.

We conducted a neutron-irradiation experiment in May, 2017. The target consisted of a tin plate with dimensions of $40 \times 40 \times 4\,\mathrm{mm}^3$ and natural isotopic abundance, hence 7.68% of ^{117}Sn. The chemical purity was 99.9%. In this experiment, the time averaged power of the proton beam was 150 kW. The beam was collimated to be 22 mm in diameter. The total measurement time was about 65 hours.

Figure 1 shows the spectrum of the energy deposit of γ-rays in all detectors. The γ-transition in the nucleus ^{118}Sn with an energy of 9327 keV and its single- and double-escape peaks can be seen clearly. The γ-rays with energy of 9563 keV stem from the ^{115}Sn(n,γ) reaction. It is known that the compound state in the p-wave resonance decays to the ground state of ^{118}Sn directly. Therefore, we focused our analysis of the peak with 9327 keV and its single- and double-escape peaks.

Figure 2 shows the neutron-energy dependence of neutron absorption by the target, which was measured by detecting emitted γ-rays as a function of the time of flight (TOF) of the neutrons. The neutron energies were calculated from the TOF using the kinetic energy formula of classical mechanics. Close to the 1.33 eV p-wave resonance in ^{118}Sn of interest to us one can see at 1.45 eV an s-wave resonance of ^{116}In, and at 6.22 eV a p-wave resonance of ^{120}Sn. According to the JENDL database [7], the cross section of the resonance in ^{118}Sn is 1.8 barn, while that in ^{116}In is about 2.9×10^4 barn. Thus, their count rates become comparable if the target is contaminated by 0.01% of ^{116}In.

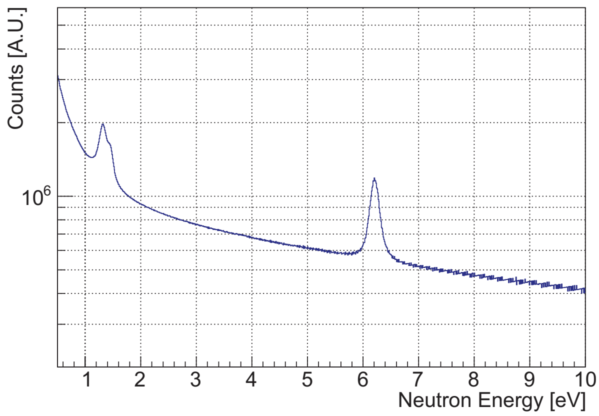

Figure 2. The energy spectrum of neutrons absorbed by the target. The peak on the left includes the p-wave resonance at 1.33 eV.

3. Analysis

3.1. Corrections

3.1.1. Subtraction of background events

The neutron energy spectrum gated with events from the 9327 keV photo, single and double escape peaks includes events from other sources than the resonance of interest in ^{118}Sn. There are two main kinds of background events. One is the Compton scattering of the 9563 keV γ-rays emitted in the ^{115}Sn(n, γ) reaction. The other stems from pileup due to simultaneous detection of γ-rays. These background events must be subtracted. First, the number of such events in the signal region was estimated using a GEANT4 simulation [8] applied to a monoenergetic γ-ray spectrum. Spectra gated with events from the background regions (in the 9563 keV peak and for energies larger than 9600 keV) were scaled such that the number of events matched that of GEANT4 calculated background events. After that, they were subtracted from spectra gated with events from the signal region.

3.1.2. Beam intensity correction

In the epithermal energy region, the beam intensity increases for lower neutron energies. To account for this variation, the energy spectrum of neutrons absorbed by the target must be corrected. For normalization we use gating to the 477.6 keV γ-quanta emitted in the reaction $^{10}\mathrm{B}(n, \alpha\gamma)^7\mathrm{Li}$ from a dedicated target, because the cross section has no resonance at epithermal energies [7]. The neutron beam flux, as a function of neutron energy E_n, can be represented as

$$I(E_\mathrm{n}) = \frac{N(E_\mathrm{n})}{\sigma(E_\mathrm{n})\epsilon T}, \qquad (2)$$

where $\sigma(E_\mathrm{n})$ is the cross section of the reaction, $N(E_\mathrm{n})$ is the number of 477.6 keV γ-rays detected during the measurement time T, and ϵ is the detection efficiency at this energy.

3.2. Asymmetry

Figure 3 shows spectra of the neutron-energy dependent neutron absorption by the ^{117}Sn target, for the different

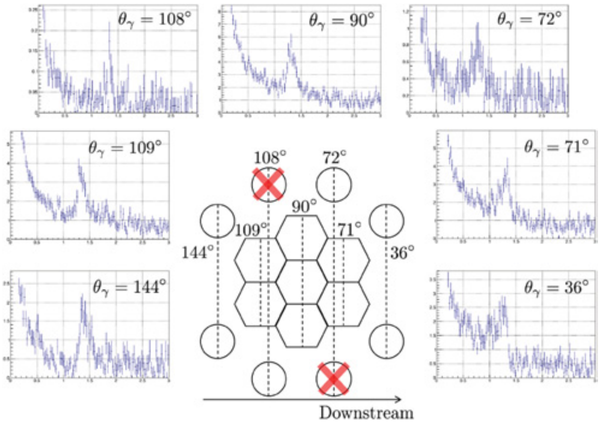

Figure 3. The neutron energy spectrum around the 1.33 eV p-wave resonance in ^{118}Sn, for the various angles accessible at ANNRI. The central figure shows the placement and the shape of each crystal. The detectors marked by red crosses were not available for our experiment.

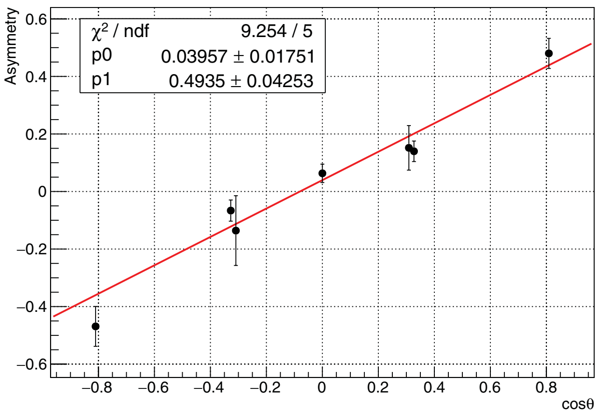

Figure 4. The angular dependence of A_{LH}. The solid line shows the linear fit using the function of Eq. (4).

angles accessible at ANNRI. An angular dependence of the shape of the p-wave resonance has clearly been observed. For a quantitative evaluation we define an asymmetry A_{LH} as

$$A_{\mathrm{LH}} = \frac{N_{\mathrm{L}} - N_{\mathrm{H}}}{N_{\mathrm{L}} + N_{\mathrm{H}}}, \tag{3}$$

where N_{L} and N_{H} are the integrated counts in a lower (L) and a higher (H) energy region, respectively. The regions for integration 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 values of A_{LH} calculated for different angles θ_γ are plotted in Fig. 4. The observed angular dependence can be parameterized as

$$A_{\mathrm{LH}} = A\cos\theta_\gamma + B. \tag{4}$$

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

$$A = 0.494 \pm 0.043, \quad B = 0.040 \pm 0.018. \tag{5}$$

The errors include the fitting error as well as the errors propagated from background subtraction and neutron beam intensity normalization.

The ϕ parameter will be determined from comparing these results of A and B with theoretical values calculated from the Flambaum formalism. This however also requires the knowledge of a branching ratio, which by the time of writing this article was not yet determined.

4. Summary

CP-violation (T-violation) is one of the necessary conditions to explain the dominance of matter over antimatter in the current universe. In preparation of a T-violation search using compound nuclei created by neutron capture, one has to determine the spin factor $\kappa(J)$ which enters the experimental sensitivity. The angular distribution of prompt γ-rays emitted from ^{117}Sn(n, γ) reactions was measured for 65 hours using the instrument ANNRI at beamline 04 at MLF, J-PARC, and the angular dependence of the shape of p-wave resonance has been observed clearly. The parameter ϕ, and hence the value of $\kappa(J)$, will be determined after the branching ratio from the compound state to the ground state in each resonance will be determined.

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