Measurement of the angular distribution of γ-rays emitted from the compound state after neutron capture by ^{81}Br for a search of T-violation

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Abstract. It is known that parity violation can be enhanced in compound nuclei due to mixing of s- and p-waves, and it is suggested that time reversal invariance (T) violation is enhanced by the same mechanism. We are planing a T-violation search using compound nuclei produced in neutron capture reactions. Although ^{81}Br is one of the candidate target nuclei, its sensitivity to T-violation has not yet been determined. For an estimate of the latter, a measurement of the angular distribution of γ-rays emitted in the ^{81}Br(n,γ) reaction was carried out in November 2017, of which we report first results.

1. Introduction

It has been suggested by Gudkov [1] that fundamental CP-violation (and hence also T-violation due to the CPT theorem) is enhanced in compound nuclei by the same mechanism as for P-violation, i.e., due to mixing of opposite-parity states in the vicinity of a p-wave resonance. Both symmetry violations can be investigated using transmission experiments of polarized neutrons and are related by

$$\Delta\sigma_\mathrm{T} = \kappa(J)\frac{W_\mathrm{T}}{W_\mathrm{P}}\Delta\sigma_\mathrm{P}\,, \qquad (1)$$

where $\Delta\sigma_\mathrm{T}$ and $\Delta\sigma_\mathrm{P}$ are T and P violating differences of total cross sections observed for two states of opposite neutron polarization, respectively. W_T and W_P are corresponding matrix elements. The factor $\kappa(J)$ depends on the total channel spin J and includes amplitudes of partial neutron widths at the resonance (see Ref. [2] for a more detailed presentation of our research strategy and the formalism). Different models of CP (T) violation predict different ranges of values for the ratio $W_\mathrm{T}/W_\mathrm{P}$ [1]. The sensitivity to T-violation is also impacted by the experimentally accessible $\kappa(J)$, which has a value specific for each nuclear resonance. So far it has only been determined for the 0.734 eV p-wave resonance in the system ^{139}La + n by Okudaira et al. [3]. It is of interest to measure it for other nuclei as well since this would yield alternative candidates for a T-violation search.

The parameter $\kappa(J)$ can be determined by a measurement of the angular distribution of γ-rays following (n,γ) reactions using unpolarized neutrons. According to Flambaum [4] the corresponding cross section can be written as

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

where θ_γ represents the angle of γ-ray emission with respect to the incident neutron direction. The neutron energy dependent parameter a_1 is related to $\kappa(J)$ and is therefore of interest (Ref. [2] presents these dependences explicitly). Since a_1 is asymmetric with respect to the p-wave resonance energy and occurs in Eq. (2) with a $\cos\theta_\gamma$ dependence, the shape of the resonance depends on θ_γ as well. Besides the ^{139}La already investigated, ^{81}Br is considered as a potential candidate target nucleus to search for T-violation. Here we report the result of a first measurement of the angular dependence of γ-ray emission in the reaction ^{81}Br(n,γ) near the p-wave resonance at 0.88 eV neutron energy.

2. ^{81}Br(n,γ) measurement

2.1. Resonance parameters and γ-ray energies

In Table 1 we show the resonance parameters in the system ^{81}Br + n, while Table 2 summarizes the relevant γ-transitions after neutron capture.

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Table 1. Resonance parameters in the system ^{81}Br + n, 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]
0.88	1		9.28×10^{-5}	
101	0	2	156	224
135	0	1	264	292

Table 2. Overview of the γ-rays emitted after neutron capture by ^{81}Br, E_γ denotes the γ-ray energy, E_{level} is the energy of the populated nuclear state and F is its total angular momentum [5]. The parentheses indicate that the corresponding F-values are not yet confirmed.

E_γ [keV]	E_{level}[keV]	F
6745	846.7	$(1 +, 2, 3 +)$
7172	420.1	(2)
7229	362.8	$(2) +$
7302	290.8	$(3) -$
7547	45.9	$2 -$

Figure 1. Exploded view of the components of the target frame.

Figure 2. Photograph of the readily assembled target.

Figure 3. A typical neutron capture spectrum, obtained by summing up all γ ray-events from the target, with the neutron energy derived from the neutron TOF. The acquisition time was about 3 hours.

Figure 4. A typical γ-ray energy spectrum, obtained by summing up events from all detectors and without restriction on the neutron TOF. The acquisition time was about half an hour.

2.2. Experiment

The experiment was carried out at the Accurate Neutron-Nucleus Reaction measurement Instrument (ANNRI), installed at Beam Line 4 at the Material and Life Science Experimental Facility (MLF) at J-PARC. Its main component is a germanium detector array consisting of 22 germanium crystals surrounding a nuclear target, which is hit by a pulsed beam of epithermal neutrons from the spallation source of MLF. This setup enables us to measure the γ-ray energy and also the neutron time of flight (TOF), from which the neutron energy can be calculated. More details about the apparatus and the technique can be found in Ref. [3].

We measured the ^{81}Br(n,γ) reaction for 33 hours in November 2017. The target was made from MgBr$_2$ powder with natural isotopic abundance, enclosed in a frame of Aluminum as shown in Fig. 1. The assembled target can be seen in Fig. 2.

3. Results and analysis

3.1. Neutron and γ-ray energy spectrum

The summed intensities of γ-rays plotted as a function of neutron energy yield a so-called "neutron capture spectrum". As visible in Fig. 3, it displays the resonances
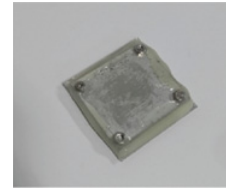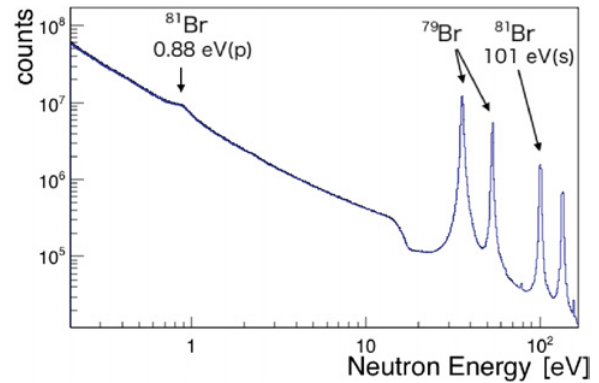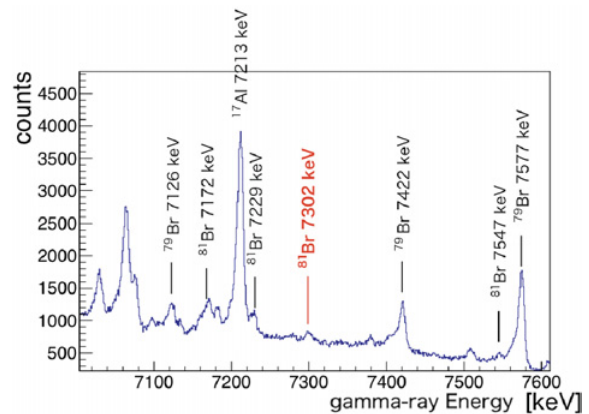
characteristic for the nuclides exposed to the beam. Figure 4 shows a typical γ-ray spectrum in the region of interest obtained by integrating over all neutron energies. Most useful for the determination of $\kappa(J)$ is the γ line at 7302 keV, because the other transitions either have lower branching intensities or are contaminated by energetically close γ-rays from other isotopes. Using a well isolated line facilitates a clear background subtraction.

In order to determine $\kappa(J)$, the γ-ray events detected at 7302 keV were analyzed. It can be clearly seen that the corresponding nuclear transition is well isolated, while the majority of other transitions is suffering from background contamination due to other γ-rays. This is particularly important for a clear background subtraction.
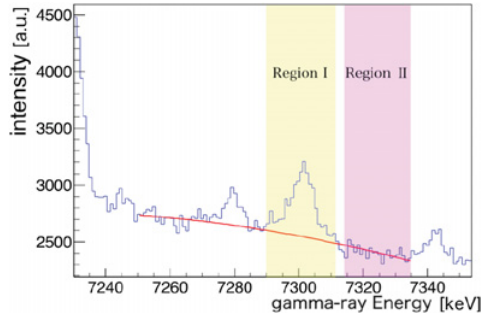
Figure 5. Regions of the signal around 7302 keV (region I) and for background estimation (region II). The red line shows the result of a polynomial fit to the events in region II.

3.2. Various corrections

3.2.1. Beam flux correction

For further analysis of the neutron capture spectrum it was necessary to normalize the γ-counts to the incident spectral neutron flux, for which we employed the ^{10}B(n,γ) reaction using a dedicated target. This isotope was chosen due to its high neutron capture cross section and the absence of resonances at the relevant neutron energies. The γ-ray with 477.6 keV thus provides a suitable normalization signal. The neutron beam flux, as a function of neutron energy E_n, can be represented as

$$I(E_n) = \frac{N(E_n)}{\sigma(E_n)\epsilon T},\qquad(3)$$

where $\sigma(E_n)$ is the neutron capture cross section of ^{10}B taken from Ref. [6], $N(E_n)$ is the number of 477.6 keV events measured during the time T, and ϵ is the detector efficiency at this γ-ray energy. The latter was determined using the ^{14}N(n,γ) reaction induced in a melamine target, more details can be found in [3].

3.2.2. Background subtraction

The neutron capture spectrum of ^{81}Br+n, gated at 7302 keV, also includes events from Compton scattering of more energetic γ-rays. They constitute a continuum background and it is necessary to remove these events. For this purpose we defined two regions in the spectrum as indicated in Fig. 5. Region I was centered around the peak of the 7302 keV transition, and a region II, not containing an isolated γ-line, was chosen at slightly higher energy. For background subtraction we used events from gating on region II allowing us to fit a third order polynomial and thus obtaining the necessary normalization constants.

3.3. Angular distribution

In order to evaluate the distortion of the p-wave resonance, we use the quantity A_{LH} described in detail in [2] which is defined as

$$A_{LH} = \frac{I_L - I_H}{I_L + I_H}.\qquad(4)$$

Here I_L and I_H are count rate integrals in energy ranges lower and higher than the central energy $E_0 = 0.88$ eV of the p-wave resonance, respectively. This is illustrated in Fig. 6 showing the data with the regions of integration for different detectors of the array. The result of integration
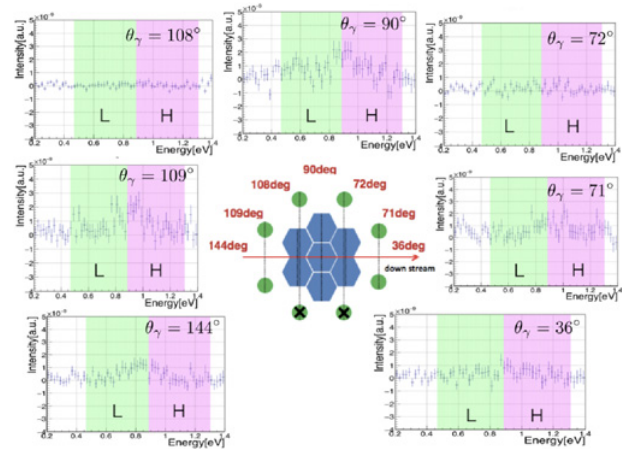

Figure 6. Spectra of the p-wave resonance measured for the different angles accessible at ANNRI, gated via the 7302 keV transition in ^{82}Br. The energy regions L and H are highlighted in green and magenta. The detectors marked by crosses were not available for our experiment.
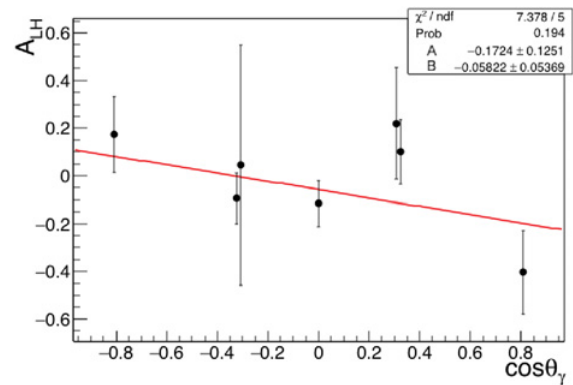

Figure 7. Measured dependence of A_{LH} as a function of $\cos\theta_\gamma$. The red line is the fit discussed in the text.

and the extraction of A_{LH} is shown in Fig. 7. The error bars include the uncertainty of the background subtraction.

The dependence of A_{LH} on the angle θ_γ can be parameterized as

$$A_{LH} = A\cos\theta_\gamma + B.\qquad(5)$$

The values of A and B can be extracted by fitting Eq. (5) to the experimental data for the individual detectors of ANNRI. The best fit is also shown in Fig. 7, with the resulting fit parameters given by

$$A = -0.17 \pm 0.13\qquad(6)$$
$$B = -0.058 \pm 0.054.$$

As indicated by the error bars the distortion of the p-wave resonance was not yet clearly measurable, mainly due to insufficient statistics.

According to the Flambaum formalism the quantity $\kappa(J)$ can be determined from the values of A and B but also requires the branching ratio

$$B_f = \frac{\Gamma_{r,f}^{\gamma}}{\Gamma_r^{\gamma}}\qquad(7)$$

to be known. Here the quantity Γ_r^{γ} is the γ width of the resonance r, and $\Gamma_{r,f}^{\gamma}$ denotes the partial γ width for

transition to the specific final state (f). A measurement to determine this branching ratio was carried out in February and May 2018 for a total of 300 hours. The data are currently being analyzed.

4. Summary and future plan

We are planning to continue our search for T-violation using compound nuclei. Identification of best candidate nuclei requires determination of the parameter $\kappa(J)$, for which we have started an experiment using ^{81}Br at BL04 (ANNRI) at J-PARC MLF. Further we took data to measure the branching ratio, which are currently under evaluation. Both measurements shall allow us to extract $\kappa(J)$. However, as the statistic significance of the reported first results on the parameters A and B of the distortion of the p-wave at 0.88 eV in the system ^{81}Br + n does not yet allow us to draw definite conclusions, further experiments will be necessary.

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