PROCEEDINGS OF SCIENCE

Measurement of angular correlations in the (n, γ) reaction for T Violation Search

T. Okudaira*, **H.M.Shimizu, M.Kitaguchi**[2], **K.Hirota, S.Takada**[3], **T.Yamamoto, A Okada, T.Yoshioka**[4], **T.Ino**[5], **K.Sakai**[6], **K.Asahi**[7], **T.Momose**[8], **T.Iwata**[9], **M.Hino**[10], **T.Shima**[11], **Y.Yamagata**[12]
Nagoya University
[2]*Nagoya University KMI*
[3]*Kyusyu University*
[4]*Kyusyu University RCAPP*
[5]*KEK*
[6]*JAEA*
[7]*Tokyo Institute of Technology*
[8]*University of British Columbia*
[9]*Yamagata University*
[10]*KURRI*
[11]*Osaka University RCNP*
[12]*RIKEN*

E-mail: okudaira@phi.phys.nagoya-u.ac.jp

Large enhanced P-violations was discovered in several compound nuclei. A mechanism of P-violation can be applied to enhancement of T-violation in compound nucleus. We plan the experiment for sensitive T-violation search, however, the mechanism of P-violation(s-p mixing) has not been verified in detail yet and the spin factor $\kappa(J)$ has not been measured in candidate nuclei for T-violation search. We need to measure angular distributions in the (n,γ) reaction for verification of s-p mixing and determination of $\kappa(J)$ as a feasibility study for the T-violation search. The (n,γ) reaction of ^{139}La which is one of the candidate nuclei was measured with 4π germanium spectrometer in J-PARC/MLF/ANNRI. A neutron spectrum and a γ-ray spectrum for ^{139}La was obtained.

The 26th International Nuclear Physics Conference
11-16 September, 2016
Adelaide, Australia

*Speaker.

PoS(INPC2016)188

1. T-violation search in compound nucleus

The parity violations enhanced by 10^6 times larger than that in nucleon-nucleon reaction have been observed in compound nucleus reactions. The mechanism of the P-violating effect has been proposed theoretically to be applicable to enhance the experimental sensitivity to the breaking of the time-reversal invariance (T) by searching for the non- zero T-odd correlation terms in the p-wave resonances[1]. The advantage to apply the enhancement mechanism is that takes T-odd effects due to the final-state interaction is expected to be negligibly small as long as the neutron propagation through the target material can be described by the neutron optics.
The enhancement of T-violation is given as

$$\Delta\sigma_{\mathrm{CP}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\Delta\sigma_{\mathrm{p}} \tag{1.1}$$

where $\Delta\sigma_{\mathrm{CP}}$ and $\Delta\sigma_{\mathrm{P}}$ are the CP-violating and P-violating cross section, W_{T} and W denote the CP- and P-violating matrix elements.The $\kappa(J)$ is the spin factor given as

$$\kappa(J=I+1/2) = \frac{3}{2\sqrt{2}}\frac{2I+1}{2I+3}\frac{(\sqrt{2I+1})(2\sqrt{I}x-\sqrt{2I+3}y)}{(2I-3)\sqrt{2I+3}x-(2I+9)\sqrt{I}y} \tag{1.2}$$

$$\kappa(J=I-1/2) = -\frac{3}{2\sqrt{2}}\frac{(2I+1)\sqrt{I}}{\sqrt{(I+1)(2I-1)}}\frac{2\sqrt{I+1}x+\sqrt{2I-1}y}{(I+3)\sqrt{2I-1}x-(5I-3)\sqrt{I+1}y} \tag{1.3}$$

where I is the target nuclear spin and J the spin of the compound state and x and y are given as x^2 $=\Gamma^n_{p,1/2}/\Gamma^n_p$ and y^2 $=\Gamma^n_{p,3/2}/\Gamma^n_p$ respectively. $\Gamma^n_{p,1/2}$ and $\Gamma^n_{p,3/2}$are the partial neutron width. x and y can be defined by using only one parameter ϕ as $x = \cos\phi$ and $y = \sin\phi$. Equations (1.2) and (1.3) visualize that the enhancement of the T-violation strongly depends on the parameter x.
When we assume s-p mixing [2], the partial neutron width can be estimated by the angular distribution of individual γ-rays from the compound resonance as long as both the spin of the compound state (J) and the spin of the final state of the γ-ray transition are known. The differential cross section of the γ-rays to unpolarized neutron can be written as

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(a_0 + a_1\cos\theta_\gamma + a_3(\cos^2\theta_\gamma - \frac{1}{3})\right) \tag{1.4}$$

where θ_γ is the polar angle of the outgoing γ-ray momentum for the case that the incident neutron is unpolarized and only s- and p-wave amplitudes are present. The parameters a_1 and a_3 for γ-ray are given as $\cos\phi$, $\sin\phi$ and other resonance parameters [2].

We plan experiments for the sensitive T-violation search in J-PARC. Candidate nuclei for the experiment are ^{139}La, ^{131}Xe, ^{81}Br ,^{115}In, ^{117}Sn and so on, which have the large enhanced P violation. The enhancement of T-violation is based on the s-p mixing, however, the s-p mixing of these nuclei has not been verified in detail yet. Therefore the s-p mixing needs to be verified and $\kappa(J)$ of these candidate nuclei need to determine with measurement of $a_0, a_1 ....$ term for feasibility study of T-violation search.
These terms can be measured with precise angular distribution measurements of γ-rays emitted from compound nucleus directly. Therefore γ-ray detectors which have high energy resolution and angular resolution are needed to select γ-rays from each transitions.

2. Experimental setup

The experiments were carried out at ANNRI beam line of Materials and Life Science Experimental Facility (MLF) in the Japan Proton Accelerator Research Complex (J-PARC). In this experiment, the proton beam power was 206 kW pulsed neutrons were provided with the repetition rate of 25 Hz. The pulsed neutron beam was collimated to a 22 mm diameter at the target position. The total measurement time with ANNRI was about 30 h (2.6×10^6 shot).

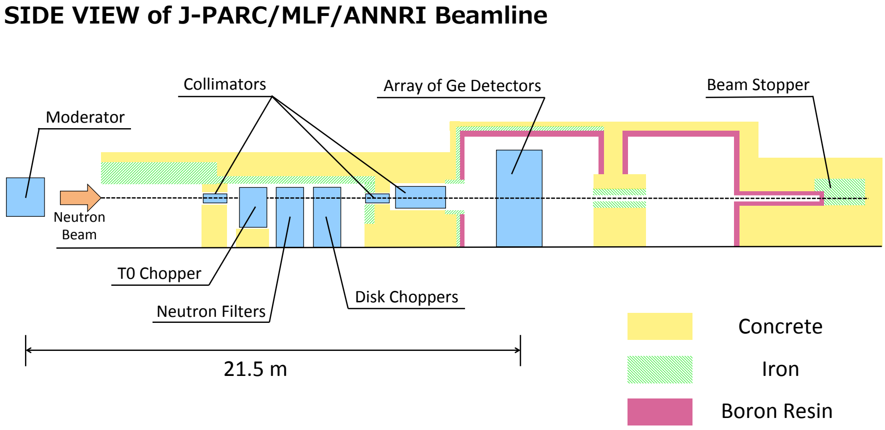

Figure 1: Schematic of ANNRI

2.1 γ-ray detectors at ANNRI

The (n,γ) reaction was measured with 4π germanium spectrometer in ANNRI. The spectrometer was located at 21.5 m flight length and consists of two cluster germanium detectors(14 channels) and eight coaxial-shaped germanium detectors(8 channels) as shown in figure2. Each crystal was installed at 36, 71, 72, 90, 108, 109,144 degree with respect to the neutron beam line.
The deposit energy of γ-ray in germanium crystal and detection time of γ-ray ware acquired as two-dimensional data of neutron time-of-filght versus γ-ray energy.

2.2 Target

The $^{\mathrm{nat}}$La target whose size were $10 \times 10 \times 0.8$ mm was used in this experiment. The purity of $^{\mathrm{nat}}$La target were 99.9 %. $^{\mathrm{nat}}$La consists of 0.09% of ^{138}La and 99.91 % of ^{139}La.

3. Experimental results and analysis

Figure4, 5 are γ-ray spectrum and TOF spectrum for La target.
^{139}La has 3 neutron resonances in lower energy region as shown in Table.1 [3]. The γ-ray transition in $^{139}\mathrm{La} + \mathrm{n} \rightarrow ^{140}$ La are shown in figure3[4].

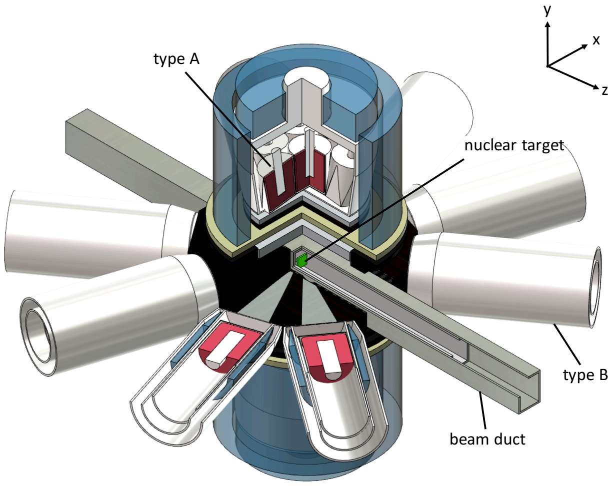

Figure 2: 4π germanium spectrometer in ANNRI

E_0 [eV]	J	1	$2g\Gamma_n$ [meV]	Γ_γ [meV]
-48.63	4	0		62.2
0.734±0.100		1	0.00073	45 ± 5
72.3±0.1		0	30.30±0.85	52.6±5.4

Table 1: Resonance parameters of ^{139} La

In γ-ray spectrum, almost all the intense photo peaks for ^{139}La(n,γ) reaction were observed with high energy resolution.
TOF spectrum was corrected by the beam spectrum measured with ^{10}B target. 0.734 eV p-wave peak and 72.3 eV s-wave peak of ^{139}La were observed in TOF spectrum.
The angular distribution of 5161 keV γ-ray from 0.734 eV p-wave resonance to ^{139}La ground state were measured. Therefore $\kappa(J)$ can be estimated from this date in principle. The analysis for $\kappa(J)$ is now in progress.

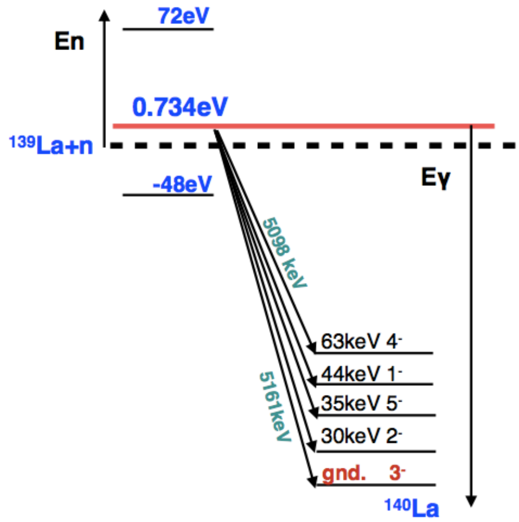

Figure 3: Transitions from ^{139}La+n to ^{140}La

4. Conclusion

The T-violation in compound nucleus can be enhanced with the same mechanism of enhancement of the P-violation. We plan experiments for the sensitive T-violation search in J-PARC. The T-violation in compound nucleus are proportional to the P-violation in compound nucleus and spin

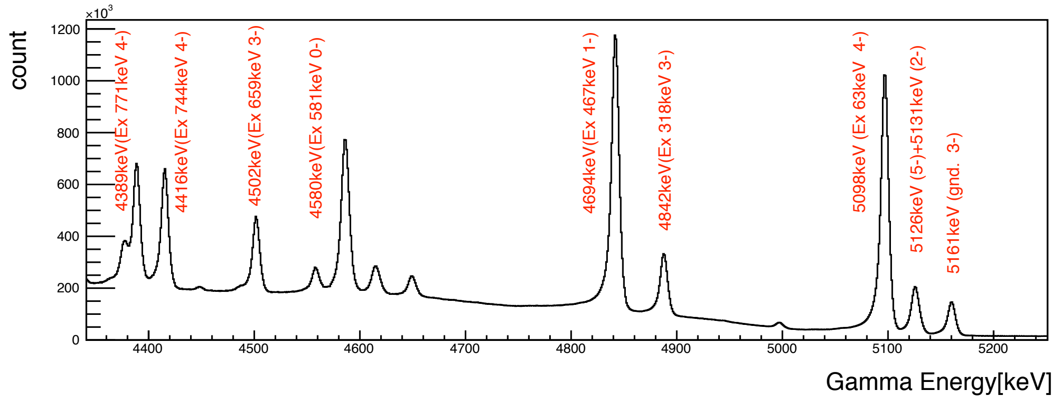

Figure 4: γ-ray spectrum

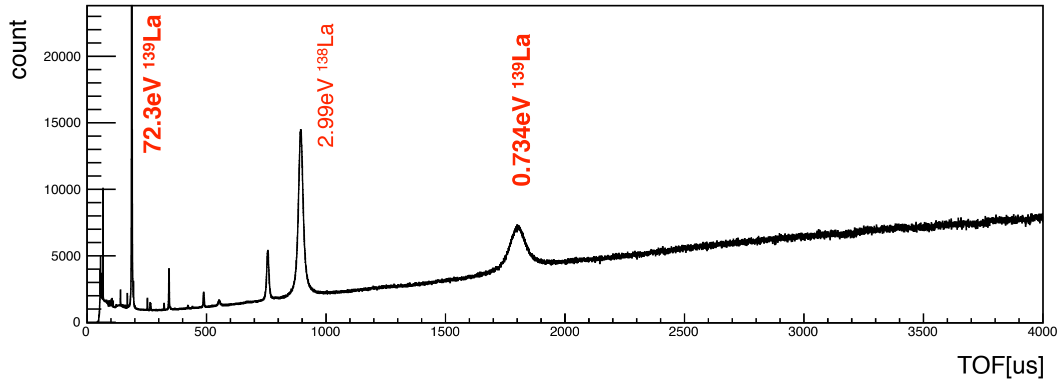

Figure 5: TOF spectrum

factor $\kappa(J)$. The candidate nuclei are ^{139}La, ^{131}Xe, ^{81}Br ,^{115}In, ^{117}Sn and so on, which have the large enhanced P-violation, however, $\kappa(J)$ of these nuclei have not been measured yet.
We measured angular distribution in ^{139}La(n, γ) reaction from 0.734 eV p-wave resonance to ^{139}La ground state to determine $\kappa(J)$ with 4π germanium spectrometer in J-PARC/MLF/ANRRI. γ-ray spectrum and neutron spectrum for ^{139}La was obtained. Therefore $\kappa(J)$ can be estimated from this date in principle. The analysis for $\kappa(J)$ is now in progress.

5. Acknowledgments

The authors would like to thank the staffs of ANNRI for their maintenance of 4π germanium detectors and MLF for their operations of the accelerators and the neutron production target.

References

[1] V.P.Gudkov, Phys. Rep. 212 (1992) 77

[2] V.V. Flambaum, O.P. Sushkov, Nucl. Phys. A 412 (1984) 13.

[3] S.F. Mughabghab, ”Atlas of Neutron Resonances - Resonance Parameters and Thermal Cross Sections Z = 1 — 100 ”, Elsevier (2006).

[4] J. K. Tuli ed. "Thermal Neutron Capture ’s (CapGam)", National Nuclear Data Center, Brookhaven National Laboratory, http://www.nndc.bnl.gov/capgam/, 2012.