# Circular polarization measurement of $\gamma$-rays emitted from $^{32}S(n,\gamma)^{33}S$ reaction with polarized neutrons


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**Abstract**

We aim to measure a circular polarization of $\gamma$-rays emitted from neutron capture reactions with the pulsed neutron source for nuclear data and nuclear physics studies. A $\gamma$-ray polarimeter was developed to measure the circular polarization. One of the performance indicators for polarimeter is an analyzing power which is something like so-called efficiency in the polarization measurement. Therefore, the analyzing power was evaluated using the neutron capture reactions of sulfur-32 at ANNRI in J-PARC•MLF, and obtained to be 1.92±0.23%.


## 1. Introduction

### ◎ Motivation

Circular polarization measurements of $\gamma$-rays from neutron capture reactions give important information;

・Spin of excited states and multipolarity of $\gamma$-transitions [1].

Circular polarization of $\gamma$-rays, $P_\gamma$, is described as

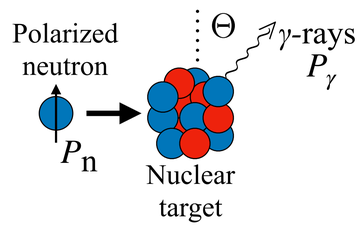
$$P_\gamma = P_n R \cos\Theta \quad \bullet\bullet\bullet \textbf{(1)}$$

$P_n$ : neutron polarization

$R$ is a function of the spin and multipolarity

$$R = \frac{2(J_c - I)}{2I+1} \frac{L(L+1) + J_c(J_c+1) - J_f(J_f+1)}{L(L+1)}$$

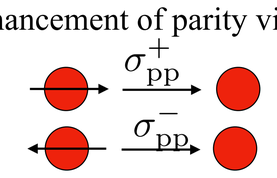
Some measurements have been conducted with polarized thermal neutrons in nuclear reactors [4-6].
This is applicable to determining the spin of the resonance by measuring it against the resonance.



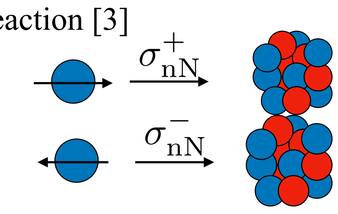

$I$ : spin of target nuclei
$J_c$ : spin of compound state
$J_f$ : spin of final state
$L$ : multipolarity

・Angular correlation terms of neutron capture reaction [2].

Enhancement of parity violation in compound reaction [3]




$$\frac{\sigma^+_{pp} - \sigma^-_{pp}}{\sigma^+_{pp} + \sigma^-_{pp}} \sim 10^{-7}$$




$$\frac{\sigma^+_{nN} - \sigma^-_{nN}}{\sigma^+_{nN} + \sigma^-_{nN}} \sim 10^{-1}$$

The mixing of the s-wave and p-wave amplitudes (s-p mixing model) was proposed to explain the enhancement. The s-p mixing model predicts the circular polarization-dependent cross section. The verification of the s-p mixing model is also important in the study of the search for time-reversal symmetry breaking [7].

These circular polarization measurements with the pulsed neutron source in MLF shall be performed.

➡ A measurement apparatus of circular polarization, called $\gamma$-ray polarimeter, has been made as shown in **Fig. 1**.

### ◎ Purpose of this study

One of the performance indicators for polarimeter is an analyzing power, $P_a$, which is something like so-called efficiency in the polarization measurement.

The circular polarization of $\gamma$-rays is experimentally derived from $P_\gamma = A/P_a, \quad \bullet\bullet\bullet \textbf{(2)}$

where $A$ is the asymmetry of the $\gamma$-ray transmission when the current in the polarimeter has forward and reverse directions.

Therefore, the analyzing power is required to convert the measurement result, asymmetry, to the circular polarization.

➡ The analyzing power was evaluated from measurement of polarized-neutron capture reactions of sulfur(S)-32 in J-PARC•MLF•ANNRI.

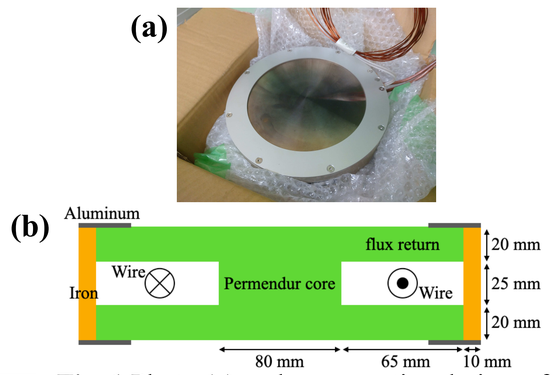



**Fig. 1** Photo **(a)** and cross sectional view of the polarimeter **(b)**.

## 2. Principle of $\gamma$-ray Polarimeter

The circular polarization of $\gamma$-ray, $P_\gamma$, can be determined by measuring $\gamma$-rays transmitted through a magnetized material.

Magnetic Compton scattering cross section [8]

$$\sigma_{Comp} = (\sigma_0 + S P_\gamma \sigma_c \cos\theta)$$

$\sigma_0$ : Klein-Nishina cross section
$\sigma_c$ : Polarization dependent cross section
$S$ : Electron polarization
$\theta$ : Angle between $\gamma$-ray momentum and electron polarization

➡ Transmission, $T$, depends on the circular polarization

$$T = \exp\{-\rho d(\sigma_{PE} + \sigma_{Comp} + \sigma_{PP})\}$$

$\sigma_{PE}$ : Photoelectric effect cross section
$\sigma_{PP}$ : Pair production cross section
$d$ : thickness of polarimeter
$\rho$ : electron density

The analyzing power is theoretically calculated by

$$P_a = \frac{T^{left} - T^{right}}{T^{left} + T^{right}}$$

$T^{left}$ : Transmission for left-handed circularly polarized $\gamma$-rays.

The average magnetic field in the core was estimated to be 1.38 T by a magnetic field simulation. **Fig. 2** shows the calculated analyzing power from the transmission.

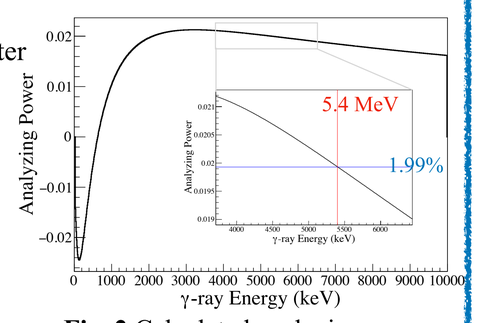



**Fig. 2** Calculated analyzing power.

The analyzing power was estimated to be about 2% at 5.4 MeV.

## 3. Experiment

### ◎ Method

$\gamma$-rays from polarized-neutron capture are circularly polarized as shown in **Eq. (1)**.
The R-value of 5.4-MeV $\gamma$-rays emitted from the capture reaction of $^{32}S$ is estimated as 0.5 with the accurately examined spins and transitions. This is why the $^{32}S(n,\gamma)^{33}S$ reaction was adopted in this study to determine the analyzing power.

➡ The analyzing power can be evaluated from **Eqs. (1) and (2)** as $P_a = \frac{A}{P_n R \cos\Theta}, \quad \bullet\bullet\bullet \textbf{(3)}$

where asymmetry, $A$, was measured by changing the polarization direction of neutrons instead of changing the current direction in the polarimeter.

### ◎ Experimental setup

The experiment was conducted at the ANNRI of MLF in J-PARC, which has the pulsed neutron source. The target was prepared by pressing natural sulfur in powder form.

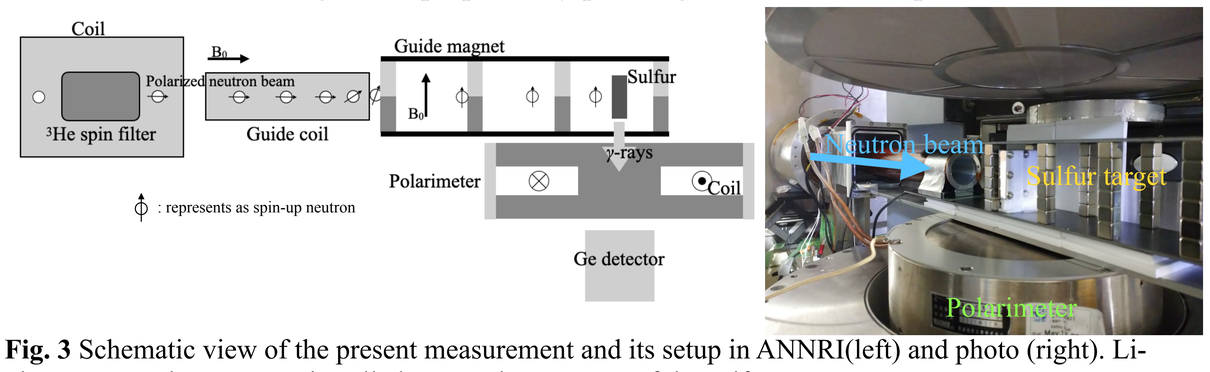



**Fig. 3** Schematic view of the present measurement and its setup in ANNRI(left) and photo (right). Li-glass neutron detector was installed at 7-m downstream of the sulfur target.

Polarized neutrons were produced by a $^3$He spin filter [9]. The spin direction was turned up (down) by both the guide coil and magnet in neutron-transporting. The polarimeter was installed between the sulfur target and the Ge detector. The neutron polarization was simultaneously monitored by the neutron transmission measured by a Li-glass detector.

### ◎ Measurement conditions

- The spin direction was flipped every 30 minutes.
- Total measurement time was 28.9 hours for spin-up, and 30.1 hours for spin-down.
- Neutron polarization was 99.5% on average.

## 4. Analysis and Results

**Figs. 4 and 5** show the TOF and $\gamma$-ray spectra. To obtain the net-count of the $\gamma$-rays, the background was estimated by fitting the spectra with a third-order polynomial function.

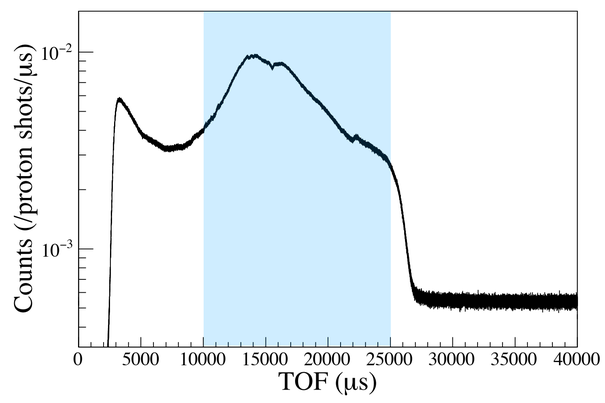



**Fig. 4** Time of flight (TOF) spectrum. The blue region indicates the gate region.

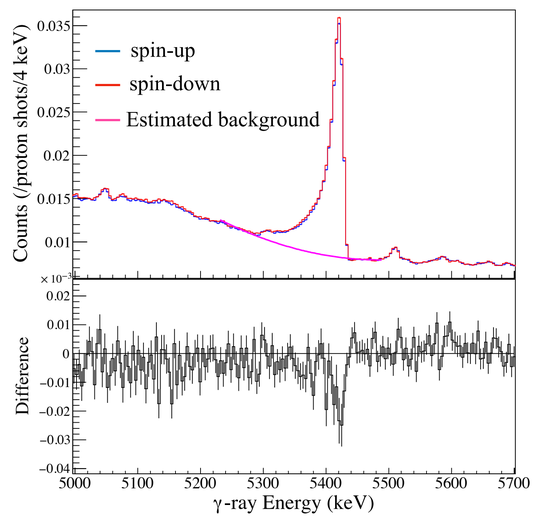



**Fig. 5** The $\gamma$-rays spectra for spin-up and spin-down neutrons gated at 3 meV to 25 meV (top) and difference between those (bottom). The backgrounds were estimated with a third-order polynomial function.

The asymmetry corrected by the neutron polarization and the transmission of $^3$He spin filter was defined as

$$A' = \frac{(T^{up} + T^{down})A - (T^{up} - T^{down})}{(P_n^{up}T_n^{up} + P_n^{down}T_n^{down}) - A(P_n^{up}T_n^{up} - P_n^{down}T_n^{down})}$$

where $A = \frac{N^{up} - N^{down}}{N^{up} + N^{down}}$

$T_n^{up}$ : Neutron transmission of the spin filter
$P_n^{up}$ : Neutron polarization
$N^{up}$ : Net-counts of the 5.4-MeV $\gamma$-rays for spin-up neutron.

The asymmetry was obtained as follows for full-absorption, single-, and double-escape peaks of 5.4-MeV $\gamma$-rays.

| Peak | Asymmetry |
|---|---|
| Full absorption | -0.0091±0.0014 |
| Single escape | -0.0093±0.0022 |
| Double escape | -0.0133±0.0034 |

➡ Weighted average $A' = -0.0096 \pm 0.0011$

The analyzing power can be determined from **Eq. (3)** as

Analyzing Power : $P_a = 1.92 \pm 0.23\%$

This value is consistent with that expected from the magnetic simulation.

**Circular polarization experiments are possible at ANNRI !**

## 5. Summary

- We developed a $\gamma$-ray circular polarization measurement apparatus, $\gamma$-ray polarimeter, which is expected to provide promising results in use at ANNRI in J-PARC•MLF with Ge detectors.
- The circular polarization of $\gamma$-rays from $^{32}S(n,\gamma)^{33}S$ reactions was measured to evaluate the analyzing power of the polarimeter.
- The analyzing power was obtained to be $P_a = 1.92 \pm 0.23\,\%$, and it was confirmed that the circular polarization measurement can be performed wth the pulsed neutron source.
- Although several measurements have been made at reactor neutron sources, this study succeeded the measurement of the circular polarization of $\gamma$-rays in neutron capture reactions with the pulsed neutron source for the first time.
- $\gamma$-ray circular polarization measurements from (n,$\gamma$) reactions provide for new study method in nuclear data and nuclear physics, and these experiments shall be conducted using this technique in the near future.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