New Methods to Reduce Systematic Uncertainties of Capture Cross Section Measurement Using a Sample Rotation System

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Abstract

New methods to reduce systematic uncertainties of capture cross section measurement using a sample rotation system have been developed. Theoretical and experimental tests of these methods have were conducted. Theoretical study using a Monte Carlo simulation code was performed. The calculated results were compared with test experimental results. The test experiment was carried out in Japan Proton Accelerator Research Complex.

I. INTRODUCTION

Accurate nuclear data for neutron-induced reactions are necessary for the design of nuclear transmutation system to reduce minor actinides (MA) and long lived fission products (LLFP) contained in nuclear waste. However current uncertainties of nuclear data such as MA and LLFP do not fulfill requirement for the design of transmutation facilities. Measurement of the neutron capture cross sections of MAs is ongoing at the Accurate Neutron Nucleus Reaction Measurement Instrument (ANNRI) in the Materials and Life Science Experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC).

Neutron capture cross section σ [cm^2] is determined in experiments based on the following equation:

$$\sigma = \frac{1}{nt}\frac{\epsilon_\gamma}{\epsilon_n}\frac{N_\gamma}{N_n}, \tag{1}$$

where n [atoms/cm^3] is the atomic density of the sample, t [cm] is the sample thickness, ϵ_γ and ϵ_n are the efficiencies of γ-ray and neutron detectors, and N_γ (N_n) is the number of detected γ-rays (neutrons) with the γ-ray detector (neutron detector). The capture cross section can be determined from remeasured N_γ and N_n. In the determination of capture cross section, the systematic uncertainty of final cross section is governed by two factors: the incident neutron energy spectrum and normalization to a standard value at a certain neutron energy.

In ANNRI experiments, the incident neutron energy spectrum is determined by measuring 478 keV γ-rays from the ^{10}B(n,$\alpha\gamma$)^{7}Li reaction. Detected γ-ray counts are converted to the numbers of neutrons using the reaction rate of ^{10}B(n,$\alpha\gamma$)^{7}Li reaction calculated from the cross section of the ^{10}B(n,$\alpha\gamma$)^{7}Li reaction. The energy dependence of the reaction rate depends on the atomic area density of ^{10}B in the boron sample because the neutron self-shielding factor increases with the ^{10}B area density and also changes with the neutron energy. Thus, boron sample thickness (^{10}B atomic area density) is very important to determine the incident neutron energy spectrum.

The saturated resonance method is a commonly-used technique to obtain the absolute cross section [1]. This technique is based on the fact that neutron capture yield becomes equal to the number of the incident neutrons at a strong resonance when the sample is very thick and the resonance is fully saturated. Although this technique allows for determining the absolute cross section value without any nuclear data as standard, it requires a thick sample that is sometimes not available.

In the present work, we suggest two new methods to reduce systematic uncertainties related to the two factors above using a sample rotation system.

II. Methodology

1. Principle

Two methods employ change of the self-shielding effect with sample rotation angle. When a sample is tilted with respect to the beam axis, effective thickness of the sample becomes larger than the actual thickness. The reaction yield at the tilted angle θ including the self-shielding effect is expressed as follows:

$$Y_\theta = c\frac{\sigma_{cap}}{\sigma_{tot}}\phi\left(1 - e^{Nt\sigma_{tot}\frac{1}{\cos\theta}}\right), \tag{2}$$

where c is correction factor of multiple-scattering effect and, σ_{cap} and σ_{tot} are the capture and total cross sections. The two new methods suggested below are based on the yield change with sample rotation.

2. Method 1: Boron sample thickness determination

The first method is for thickness determination of ^{10}B sample which is used for measurement of the incident neutron spectrum in ANNRI experiments. The ratio of the reaction yield at a rotation angle of $0°$, $Y_{0°}$ to yield at θ, $Y_{\theta°}$ is written as:

$$R(T) = \frac{Y_{0°}}{Y_{\theta°}} = \frac{1 - e^{Nt\sigma_{tot}\frac{1}{\cos\theta}}}{1 - e^{Nt\sigma_{tot}}} \tag{3}$$

The energy dependence of the yield is measured by the neutron time-of-flight (TOF) method. Thus, the yield ratio $R(T)$ is explicitly written as a function of TOF T.

The reaction yields of ^{10}B(n,$\alpha\gamma$)^{7}Li for different boron thicknesses were calculated using a Monte Carlo simulation code. A typical calculated result of the yield ratio $R(t)$ of 0° to 45° is shown in Fig. 1. The yield ratio $R(t)$ is equal to 1 at low energies (slow TOF) and increases with neutron energy until $1/\cos\theta$ that is 1.41 for 45°. The transient TOF region between the two constant values 1 and 1.41 changes with the sample thickness. We define T_{half} as the TOF value where $R(t)$ becomes the half of the maximum. T_{half} changes with the sample thickness. In other words, the sample thickness can be determined from T_{half}. Figure 2 shows a plot of T_{half} vs sample thickness.

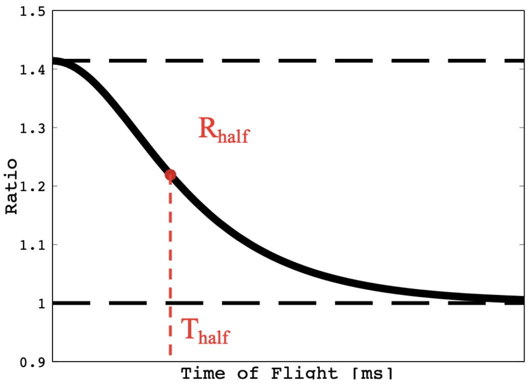

Figure 1: *Reaction ratio TOF spectrum*

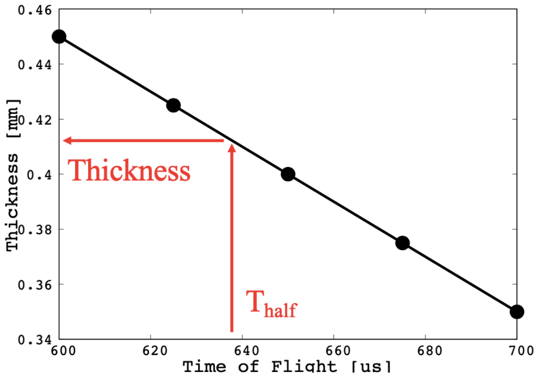

Figure 2: *Plot of T_{half} vs TOF*

3. Method 2: Capture reaction rate determination

The second method suggested in this work is to enable absolute normalization for capture cross section measurement even when a sample is not thick enough for the saturated resonance method. According to Eq. 3, the absolute reaction rate that is the ratio of capture yield to the number of the incident neutrons can be determined from a change of resonance peak height when the sample is tilted with respect to the neutron beam axis. Rotational change of the peak height of the first resonance of ^{237}Np of the sample used in test experiments described in the next section was calculated. A plot of calculated resonance peak height vs $1/\cos\theta$ is shown in Fig. 3. The resonance peak height is normalized to one at an angle of 0°. The self-shielding factor can be determined from this curve.

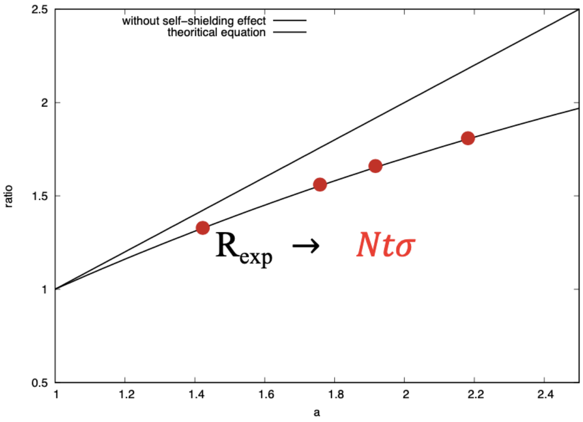

Figure 3: *Ratio at resonance peak*

III. SIMULATION AND EXPERIMENTS

We performed simulation studies using the Monte Carlo simulation code PHITS [2]. In simulation to test Method 1, the reaction rates of ^{10}B(n,α)^{7}Li in ^{10}B 90% enriched B_4C sample irradiated with neutron beam was calculated. Calculations were made for different sample thicknesses and T_{half} defined in the previous section were derived from the calculations. The obtained results are shown in Fig. 4. The simulation results are plotted as points. The curve is a fitting to the simulation results. This plot gives relation between T_{half} and the sample thickness that can be used to determine the sample thickness from T_{half} measured in experiments.

In simulation for Method 2, neutron capture reaction rates of ^{237}Np were calculated. The total mass and dimensions of the ^{237}Np sample was the same as the test experiments. Calculations were done for different tilted angles and the height of the first resonance peak was obtained. The peak height normalized to an angle of 0° is plotted as a function of $1/\cos\theta$ shown as Fig. 5.

The sample rotation measurement was carried out at ANNRI in MLF of J-PARC. The ^{237}Np sample was tilted with a sample rotation system. A ^{237}Np sample (5.2 MBq) was irradiated with a neutron beam from a spallation neutron source of MLF. A TOF method was employed in this experiment with a neutron flight path of 27.9 m. Neutron capture γ-rays emitted from the sample were detected with a NaI(Tl) detector. After background subtraction, the peak heights of the first resonance of ^{237}Np (E_n = 0.49 eV) were derived for different tilted angles. The experimental results are plotted in Fig. 5. The simulation and experimental results do not agree well.

IV. SUMMARY

In order to reduce systematic uncertainties of neutron capture cross section measurement, two new methods using a sample rotation system were proposed. In the first method, the thickness of a boron

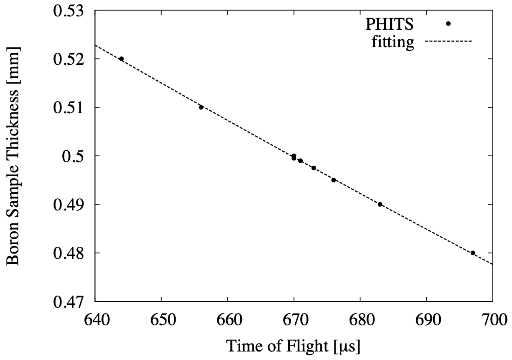

Figure 4: *Calibration curve for the boron sample thickness*

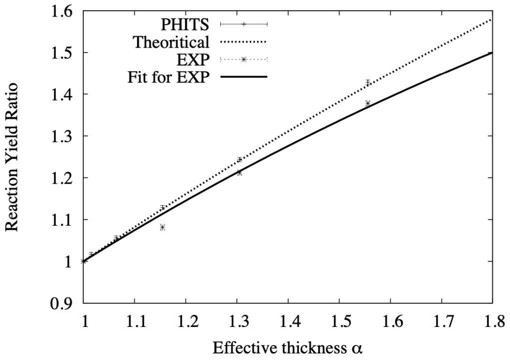

Figure 5: *Reaction yield ratio at each tilted angle*

sample used to measure the incident neutron energy spectrum can be determined precisely. In the second method, the absolute capture reaction rate can be determined even when the sample is not thick enough for the saturated resonance method. Monte Carlo simulations were carried out and, for the second method, compared with results of a test experiment. Results showed that the calculation and the experimental results do not agree well. The cause of the disagreement is not yet clear. More investigation and study are necessary to improve agreement.

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