日本語標題　試料回転法を用いた中性子捕獲断面積の高精度化のための新たな手法

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

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Abstract

A new method to reduce systematic uncertainties of capture cross section measurement using a sample rotation system has been developed. Theoretical and experimental tests on the method have been conducted. Calculations using Monte Carlo simulation code were performed. Experiments using a sample rotation system at the Accurate Neutron Nucleus Reaction Measurement Instrument in Materials and Life Science Facility of the Japan Proton Accelerator Research Complex were also conducted.

I. Introduction

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

The neutron capture cross section σ $[cm^2]$ is determined in the 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 density of sample, t [cm] is thickness of sample, ϵ_γ and ϵ_n are efficiencies of γ-rays and neutrons detectors, and $N_{\gamma,n}$ is the number of detected γ-rays or neutrons. $N_{\gamma,n}$ is measured using a γ-rays detector or a neutron flux monitor. The neutron capture cross section can be determined by measuring N_γ and N_n. In the determination of capture cross section, the systematic uncertainty of final cross section is governed by the incident neutron energy spectrum.

In ANNRI experiments, the neutron energy spectrum can be 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 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 increase with the ^{10}B area density and also changes with the neutron energy. Thus, ^{10}B atomic area dinsity is very important to determine the incident neutron energy spectrum.

In the present work, we suggest a new method to reduce systematic uncertainties related to the incident neutron using a sample rotation system. Theoretical and experimental studies were also performed.

II. Methodology

1. Principle

The new method employs the change of the self-shielding effect with the sample rotation angle. When a sample is tilted with respect to the beam axis, the effective thickness of the sample becomes larger than the actual thickness. The reaction yield at the tilted angle θ in consideration of the self-shielding effect can be expressed as follows:

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

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

2. Sample Area Density Determination

The new method is for atomic area density 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 the yield at θ, Y_{θ° is written as:

$$R = \frac{Y_{\theta^\circ}}{Y_{0^\circ}} = \frac{1 - e^{Nt\sigma_{tot}\frac{1}{cos\theta}}}{1 - e^{Nt\sigma_{tot}}}. \tag{3}$$

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 reaciton yields of $^{10}B(n,\alpha\gamma)^{7}Li$ for different area density were calculated using a Monte Carlo simulation code. A typical calculated results of the yield ratio $R(t)$ is of 0° to 60° is shown in Fig. 1. The yield ration $R(t)$ is equal to unity at low energies (slow TOF) and increases up to $1/\cos\theta$ that is 2.0 for 60° at high energy area. The transient TOF region between the two constant values 1.0 and 2.0 changes with the sample atomic area density. We define T_{half} as the TOF value where $R(t)$ becomes the half of the maximum. T_{half} changes with the sample atomic area density. In other words, the sample area density can be determined from T_{half}. Figure 2 shows a plot of T_{half} vs the sample atomic area density.

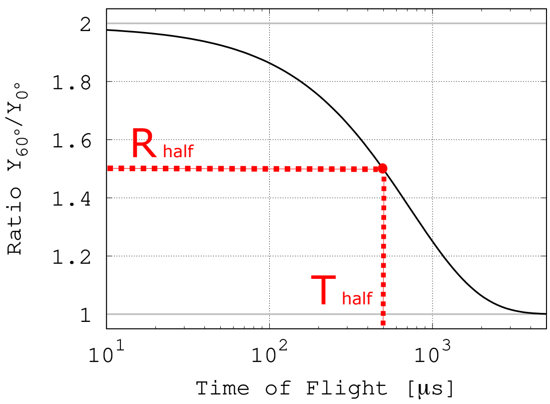

Figure 1: *Reaction ratio TOF spectrum*

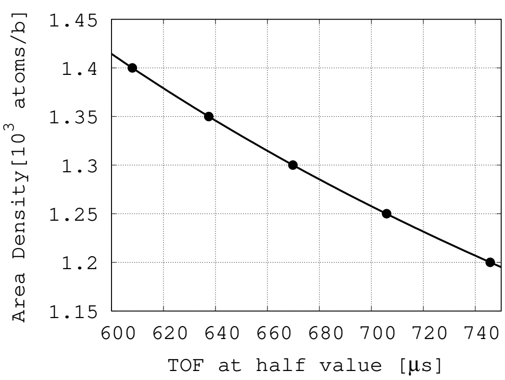

Figure 2: *Sample atomic area density calibration curve*

III. Analysis

1. Simulation

We performed simulations of the sample rotation measurement by using the Monte Carlo simulation code PHITS[2]. A ^{10}B 90% enriched B_4C sample calculated $^{10}B(n,\alpha)Li^{7}$ reaction counts. The ratio at each a tilted angle and at each thickness was derived from the calculated reaction counts. The calibration curve was obtained at a tilted angle of 45°.

2. Experiment

The sample rotation measurement was performed at ANNRI beam line in MLF of J-PARC. The sample rotation system installed at the beam line was used to rotate samples. A ^{10}B 90% enriched B^4C sample with an area density of 1.259×10^{-3}atoms/b, a diameter of 10 cm and a thickness of 0.5 mm was used for the test of the rotation system. A ^{nat}C sample with a diameter of 10 mm and a thickness of 0.5 mm was used to derive the background events due to scattered neutrons. Neutrons were produced from the spallation reactions coused by a 3-GeV proton beam shot to a mercury target of the MLF [3]. The neutron beam was collimated to a diameter of 13 mm at the sample position. A TOF method was employed in this experiment with a neutron flight path of 27.9 m from the spallation source to the sample position. γ-rays emitted from the sample were detected by a NaI(Tl) detector.

IV. Results and Discussion

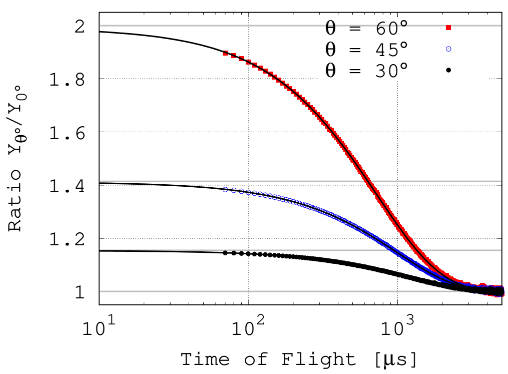

Figure 3: *Reaction ratio at each a tilted angle*

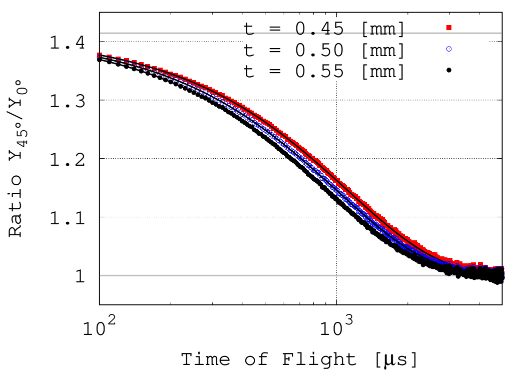

Figure 4: *Reaction ratio at each a thickness*

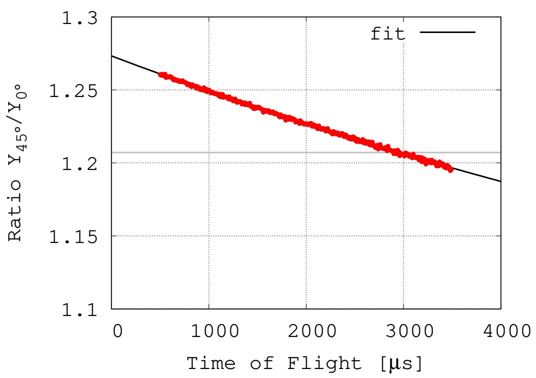

Figure 5: *Reaction ratio TOF spectrum*

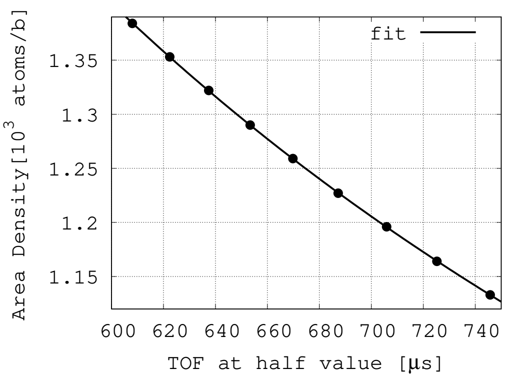

Figure 6: *Sample atomic area density calibration curve*

1. Simulation of Boron Sample Rotation

The ratio at each a tilted angle with different thicknesses were plotted in Fig. 3 and Fig. 4 respectively. These results were fitted to the following equation.

$$R(t) = \frac{1 - e^{(c_1 + c_2 t)/cos\theta}}{1 - e^{(c_1 + c_2 t)}} \tag{4}$$

The energy dependence of the ratio changes with thickness and the tilted angle. The ratio at a thickness of 0.45 and a tilted angle of 45° was shown in Fig. 5. The boron calibration curve to determine the boron sample thickness (Fig. 6) was derived from the result calculated at each thickness. In this simulation, the area density value of the boron sample of 1.259 $\pm$ 0.025 [10^{-3}atoms / b] was obtained. The calculation results of the first method to determine the boron sample area density is reasonable agreement.

2. Rotation experiment of a Boron sample

The TOF spectrum of ^{10}B(n,$\alpha\gamma$)^{7}Li reaction shown in Fig. 5 was obtained by using a sample rotation system. In this analysis, blank background, the background events induced due to scattered neutrons at the sample were subtracted. Correction for smaller sample size than the neutron beam was employed made. The ratio Y_{45°/Y_{0° was obtained as shown in Fig.8. The experimental results differs from the calculated one. The applied correction seems insufficient. This disagreement is possibly caused by system asymmetry or system axis misalignment. A larger boron sample than the neutron beam is necessary in the future work.

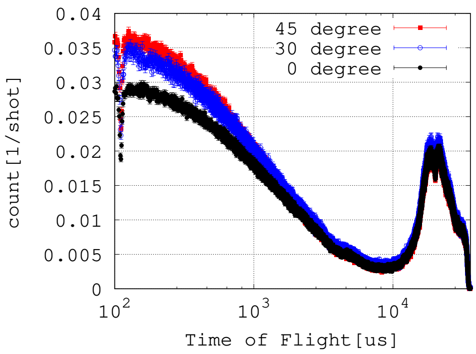

Figure 7: *TOF spectrum of the ^{10}B(n,$\alpha\gamma$)^{7}Li reaction*

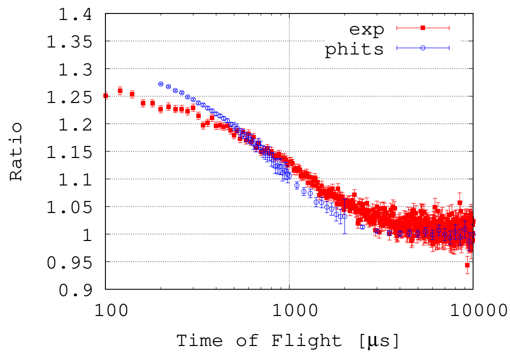

Figure 8: *Reaction yield ratio*

V. Summary

In order to reduce systematic uncertainties of neutron capture cross section measurement, a new method using a sample rotation system were proposed to determine a sample atomic area density for a neutron energy spectrum. The calibration curve for the area density of the boron sample can be obtained by using Monte Carlo calculation code. A test measurement to determine the boron area density were conducted. The experimental result were different from the calculated result. We plan to use a larger boron sample than the neutron beam to test the sample rotation system in the future.

References

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