The Measurements of Total Cross Section for Thermal Neutrons at PNS *

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Abstract: A system of measuring total cross section for thermal neutrons, the photoneutron source (PNS, phase 1), has been developed for the acquisition of nuclear data from the Thorium Molten Salt Reactor (TMSR) at the Shanghai Institute of Applied Physics (SINAP). It is an electron LINAC accelerator pulsed neutron facility that uses the time-of-flight (TOF) technique. It is recording the neutron TOF and identifying neutrons and γ-rays by using a digital-signal-processing technique. The background was obtained by employing 12.8 cm boron loaded polyethylene (PEB) (5% w.t.) to block in flight path. The neutron total cross-sections of natural beryllium were measured in the neutron energy region from 0.007 to 0.1 eV. The present measurement result was compared with the existed experimental and the evaluated data of ENDF/B-VII.1. The system errors were determined by using Geant4 Monte Carlo simulation method.

Key words: Neutron total cross-section, Natural beryllium, Digital-signal-processing, Pulse-shape discrimination (PSD), Time-of-flight method, Geant4

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1 Introduction

Neutron total cross sections have been under investigation for over 70 years by using transmission method. With the development of scientific technology, the method of measurement is improving and the energy range of neutrons is expanding all the time.

At 1941, the resonance filter method was used to define the energy of the neutron beam from the paraffin block which served to slow down the fast neutrons produced by the proton-beryllium reaction in the cyclotron by Henry B. Hanstein. Its measuring system consisted of an uranium oxide ionization chamber connected to an Edelman string electrometer 1]. The disadvantage of the resonance filter method was only a few points of neutron energy which could be measured. At 1947, T. Brill used the rotating shutter mechanism for velocity selection of slow neutrons from the thermal column of the Argonne heavy-water pile 2]. It is the prototype of the neutron energy measurement using the time of flight method, and the energy range of neutrons was expanded very large. There was a similar experimental device at the heavy water thermal neutron facility of the Kyoto University Research Reactor (KUR). He-counter was used to detect the chopped neutrons from 0.001 to 0.025 eV 3].

Pulsed-beam time-of-flight technique was developed at the Weapons Neutron Research facility at Los Alamos National Laboratory. Neutrons were produced by spallation of the 800 MeV proton beam incident on a tungsten target, and detected by BC404 detector 4]. It determined neutron total cross sections with a continuous spectrum of neutrons up to 600 MeV. Another neutron time-of-flight facility (n_TOF) at CERN allowed high-resolution measurements of neutron induced cross-sections with the 20 GeV/c proton beam, a pure lead target, and a 185 m neutron flight length 5]. The Pohang Neutron Facility consisted of an 60 MeV electron linear accelerator, a water-cooled tantalum target with a water moderator, a 12-m-long time-of-flight path, and a Li-ZnS(Ag) scintillator as a neutron detector. It measured neutron total cross sections in the neutron energy region from 0.2 to 120 eV 6]. The Gaerttner Laboratory 55 MeV electron linear accelerator at Rensselaer Polytechnic Institute was used in the measurement of the neutron total cross sections in the energy range of 0.4 to 20 MeV with a 100 m flight path, fast detector response...
and electronics, and a narrow pulse width to provide good energy resolution. It used a method to determine the time-dependent background component using a combination of experimental data and Monte Carlo methods \[7\]. At 2010, a digital-signal-processing method which allowed to be obtained with high statistical accuracy was introduced to measure the total neutron cross sections \[8\].

In the present work, the system of measuring neutron total cross sections consists of a 16 MeV electron accelerator, water-cooled tungsten (W) target (diameter = 60 mm and length = 48 mm) with a 10-cm-long polyethylene moderator, and a 6.2-m-long flight path \[9\]. As a result of the limitation of experimental space, the tungsten target chamber and the neutron detector were shielded to reduce the background. A method of using 12.8 cm boron polyethylene(PEB) to block the neutron flight path was used to determine the time-dependent background component, which was proved to be reliable by Geant4 simulation. A digital-signal-processing technique was used in the data acquisition of the system.

2 Experimental Setup

The PNS is a compact type system of measuring neutron total cross sections, and all devices of it are in the experimental hall in $11m \times 8m$ space, as shown in Fig. 1. It has the advantage of small space, but the disadvantage of high background. In order to reduce the background, the tungsten target chamber is shield by 5 cm Al, 25 cm Pb, 15 cm polyethylene(PE), and 5 cm Al in sequence. At the entrance of electron beam, it is shield by 10 cm Al, 10 cm Pb, and 10 cm PEB. There is a L type wall in the vicinity of neutron detector, which consists of 30 cm concrete, and 30 cm PEB. The TOF detector is shield by 5 cm Fe and 30 cm PEB, and the monitor detector by 20 cm PEB.

Fig. 1. Experimental geometry (plan view) of the PNS.

The electrons are stopped in a heavy target by the bremsstrahlung mechanism, and the radiation pulse produced in the detector is called the $\gamma$ flash. At the same time, neutrons are produced by the ($\gamma,n$) reaction with the target element. The neutrons and $\gamma$ from the target go through a Pb plate with 5 cm thickness, 10 cm diameter to reduce the $\gamma$ flash at first. To maximize the thermal in this facility, we utilize a PE plate with 10 cm thickness, 20 cm diameter. Pulsed neutron beam was collimated to 5 cm diameter by a 10 cm PEB tube, a 15 cm Pb tube, a 10 cm PEB tube, and a 5 cm Pb tube in sequence, as shown in Fig. 2.

The sample changer was located at 331 cm from the target. Five samples (including a open target) were held in the sample changer which cycled at set intervals, typically waiting 300 s on each sample. The first sample was a natural beryllium (Be) plate with 10-mm-thickness, $10 \times 10cm^2$ in cross-sectional area. The second one was a high-purity (99.995%) indium (In) with 0.1-mm-thickness (the data of this one was not discussed in this paper). The third one was a set of notch filters of Cd (purity 99.99%) with 0.125-mm-thickness, Co (purity 99.9%) with 0.05-mm-thickness, Ag (purity 99.95%) with 0.1-mm-thickness, In (purity 99.99%) with 0.05-mm-thickness plates. It was used for the energy calibration. The fourth one was a PEB plate with 12.8-cm-thickness to be used for the
background measurement. The last one was a blank sample. They all had the same size as that of Be sample in cross-sectional area. In the present experiment, the data were collected for 40 min for each sample.

As a neutron detector, we used a $^6\text{LiF(ZnS)}$ scintillator, product code EJ426HD2 from Eljen company, with a diameter of 50 mm and thickness of 0.5 mm, mounted on an EMI9813 photomultiplier produced by ET enterprise Ltd [10–13]. There were two identical neutron detectors, one called TOF detector and the other called monitor detector. Transmitted neutrons were detected 620 cm downstream of the production target in the TOF detector. The monitor one was placed at the bottom to the right of the neutron beam pipe and data from this monitor were used to correct for any variations in the beam intensity.

3 Data acquisition

The neutron energy spectra produced from the W(tungsten) target with a 10-cm-long polyethylene moderator were obtained by using the TOF technique. We used a CAEN DT5720 digitizer, four channel 12 bit 250 MS/s waveform digitizer (WFD) with a bandwidth of 125 MHz, and 2 Vpp dynamic ranges on single-ended coax MCX input connectors in this work. The acquisition continued into a new buffer, without dead time [14]. Therefore, there is no need to take dead time correction when no signal overlapping has happened. In this work, waveform traces with 512 samples were stored for off-line analysis, and the post-trigger phase waveform comprised 80% of the entire acquisition window.

The signal obtained by the TOF detector was connected to channel 1 of the digitizer, and the signal for monitoring the beam intensity was connected to channel 2. The trigger signal (the electron GUN start signal) was connected to channel 3, used as the start signal for TOF calculation. The digitizer was connected to a personal computer with a Linux operating system via an optical cable. Because of different baselines, the thresholds of the three channels were set as -14.65 mV, -4.88 mV, and -4.88 mV respectively. The self-trigger mode was used, which means that any channel signal going above the threshold will trigger the DAQ. The trigger occurs on the falling edge of the signal. The data acquisition software known as TMSR-Digitizer-DAQ was developed based on ROOT [15] and Gnuplot [16]. The digitizer houses optical link interface which supports a transfer rate of 80 MBytes/s. It is a very high efficiency DAQ system for millisecond or second level neutron TOF spectroscopy, which incorporates data compression, automatic change of target, automatic alarm of beam loss, and automatic file opening functions [17].

During the experiment, the electron accelerator was operated with a repetition rate of 40 Hz, a pulse width of 1 $\mu$s, a peak current of 10 $\mu$A, and an electron energy of 16 MeV.

4 Simulation Method

![Fig. 2. The geometry (plan view) of tungsten target chamber in the simulation. Position 1 is the left surface of Pb plate with 10-cm-diameter; Position 2 is the left surface of the neutron tube with 5-cm-diameter.]
In order to obtain the system and statistical errors of this system, a Monte Carlo simulation code based on Geant4 was implemented. The version of Geant4 was Geant4.10.3 with G4NDL4.5, neutron data files with thermal cross-sections.

Considering the calculation time, the local weighted method was used in the simulation. At the first step, the particles with information on time, position, direction, energy, type at position 1 (as shown in Fig. 2) were recorded in the simulation of the electrons from electron tube with 16 MeV energy bombarding the tungsten target. At the second step, the particles recorded at position 1 were increased the weight to continue the simulation. The number of neutron detected by TOF detector was about 14 in the simulation of electrons with 16 MeV, \(10^{13}\). It was about 39 with the same number of electrons in the experiment. From the comparison of these results, it was the conclusion that the physical list used in the simulation was reliable despite the error of simulation was large cause of low statistic.

In order to further reduce the computation time, the neutrons with information on time, energy at position 2 (as shown in Fig. 2) were recorded from the second step of simulation. Then, the positions of neutron source were chosen randomly at position 2, and the directions were all set to parallel to TOF tube at the third step of simulation. The five different samples were all simulated as the experimental process, and the results of that were compared with the ones of experiment which would be discussed in the next section.

In the simulation, it took almost all influencing factors of system error into consideration, such as the pulse width (1 \(\mu\)s), the slowing down time of PE with 10-cm-thickness, the time precision of electronics, and geometrical factors. The system and statistical errors of simulation were also displayed in the next section.

5 Data Analysis and Results

The TOF spectrum was only measured in the direction perpendicular to the incident electron beam. The method applied for n/\(\gamma\) identification for TOF spectrum calculations was the pulse-shape discrimination (PSD, calculated by using integral lengths) method \[12, 17\]. The falling edge of the electron GUN RF signal was used as the start signal and the neutron peak position of TOF detector was used as the stop signal for neutron TOF measurement.

The neutron total cross section is determined by measuring the transmitted neutron beam through a known amount of sample and comparing this with the transmitted beam without sample. The transmission rate of neutrons at the \(i\)th group energy \(E_i\) is defined as the fraction of incident neutrons passing through the sample compared to that in the open beam, which is related to the neutron total cross section \(\sigma_T(E_i)\) as follows:

\[
T(E_i) = \frac{S(E_i)/M_S - B(E_i)/M_B}{O(E_i)/M_O - B(E_i)/M_B},
\]

\[
\sigma_T(E_i) = -\frac{1}{N}\ln T(E_i),
\]

where \(S(E_i)\) is the counts of the sample with a thickness of \(N\) atoms per barn, \(O(E_i)\) is the blank sample counts, and \(B(E_i)\) is the background sample counts. \(M_S, M_O,\) and \(M_B\) are the normalized constants according to the monitor counts of three kinds of samples. \(S(E_i),\) \(O(E_i),\) and \(B(E_i)\) are all normalized to the counts of \(O(E_i)\) through the three normalized constants.

![Fig. 3. Experimental TOF spectra for open target, notch filter, and background.](image)

The background level was estimated by using the background sample with 12.8-cm-thickness PEB. No neutrons at the energy region of 0.001~200 eV transmitted through the PEB with 12.8-cm-thickness in the simulation. That
proved the background level in Fig. 3 to be reliable. It was also proved to be accurate by the neutron TOF spectrum for the notch filter of 0.05 mm Co, 0.1 mm Ag, 0.05 mm In, and 0.125 mm Cd samples in Fig. 3. The dip of Co was not enough deep caused of transmission rate and width of TOF bin. The transmission rate of Co was about $3 \times 10^{-7}$, In about $8 \times 10^{-6}$.

In Fig. 3 the TOF spectra for open target, notch filter of experiment had subtracted background. The TOF spectra for open target, and notch filter of experiment were conform to the ones of simulation on time and shape, except some differences on counts in short time region.

![TOF spectra](image)

Fig. 4. TOF spectra for open target, and notch filter subtracting background of experiment compared with simulation.

The resonance times of Co, Ag, and In were determined by fitting the absorption peak as a function of time of flight by using the following fitting function,

$$y = C_0 + C_1 t - (2A / \pi) w / [4(t - t_c)^2 + w^2],$$

where $C_0$ is the starting neutron count, $C_1$ is the slope, $A$ is the area of the absorption peak, $w$ is the width of the peak, and $t_c$ is the position of the peak, i.e. the resonance time. All the results were shown in Table 1.

| Isotope | Neutron energy/eV | Experiment/µs | Simulation/µs |
|---------|-------------------|---------------|---------------|
| $^{59}$Co | 132               | 39.50         | 37.22         |
| $^{109}$Ag | 5.19               | 189.72        | 188.14        |
| $^{115}$In | 1.457               | 355.23        | 353.29        |

The flight-path length $L$ was obtained from the resonance energy $E_n$ in eV corresponding to the resonance time as indicated in Table 1 by using the following fitting function,

$$E_n [eV] = (72.3 \times L [m] / (TOF - \tau_0) [µs])^2,$$

where $\tau_0$ is the time difference between the start time from the RF trigger and the real time zero when the neutron burst was produced. The $L$ and $\tau_0$ of both experiment and simulation were all shown in Table 2. The simulation was conform to experiment on the $L$, and there was little difference between them. The electron source in the simulation was set at 8 cm from the front surface of target, so the $\tau_0$ of simulation was very close to zero. The RF trigger of experiment was delayed.

| Length/m | $\tau_0$ /µs |
|----------|--------------|
| Experiment | 5.903        | 2.35         |
| Simulation | 5.929        | -0.09        |

The total cross sections of beryllium were obtained in the neutron energy range from 0.007 to 0.1 eV by using Eqs. 1 and 2, as shown in Fig. 5(a). The statistical error can be determined from Eq. 2 if we assumed the monitor counters are equal during the measurements as follows:

$$\Delta \sigma_{stat.} = \frac{1}{N} \sqrt{\frac{S(E_n) / M_S + B(E_n) / M_B}{[S(E_n) / M_S - B(E_n) / M_B]^2} + \frac{O(E_n) / M_O + B(E_n) / M_B}{[O(E_n) / M_O - B(E_n) / M_B]^2}},$$

where $N$ is the number of counts, $S$ is the signal counts, $B$ is the background counts, and $O$ is the overall counts.
where subscript $i$ correspond to each energy group, as the reference \[6\]. The overall statistical errors for the measured total cross sections are varied from 2\% to 6\%, depending on the neutron energy as shown in Fig. 5(b). The uncertainties in the measured energy are all 1.39\% in Fig. 5(c).

![Graph showing the neutron total cross section of beryllium compared with previous experiment data and evaluation data from ENDF/B-VII.1 in the energy range from 0.007 to 0.1 eV. (b) Statistical errors for present data. (c) Fractional uncertainty in the measured energy.](image)

Fig. 5. (a) The neutron total cross section of beryllium compared with previous experiment data and evaluation data from ENDF/B-VII.1 in the energy range from 0.007 to 0.1 eV. (b) Statistical errors for present data. (c) Fractional uncertainty in the measured energy.

The present measurement is shown to be in excellent agreement with the high-accuracy measurement done by J.A.Harvey et al. \[18\] in the energy range from 0.007 to 0.1 eV, and shows some deviation with the measurement done by K.Kanda et al. from 0.03 to 0.1 eV, and by V.F.Gerasimov et al. \[19\] from 0.007 to 0.04 eV. There are big differences between the present measurement and the one done by V.P.Duggal et al. \[20\].

Fig. 6(a) is shown the total cross section of beryllium calculated by simulation and the initial value used in Geant4, and the energy range is the same as the experiment. Real error is the difference between the simulation value and the initial value divided by the initial value in Fig. 6(b). The system and Statistical errors for simulation data could be estimated to be below 10\% from Fig. 6(b). This result could be used to estimated the system and statistical errors of this experiment because the statistical errors are closely between experiment and simulation. The uncertainties in the calculated energy are all 1.39\% in Fig. 6(c).

![Graph showing the neutron total cross section of beryllium compared initial data used in Geant4 with simulation data in the energy range from 0.007 to 0.1 eV. (b) Real errors and Statistical errors for simulation data. (c) Fractional uncertainty in the calculated energy.](image)

Fig. 6. (a) The neutron total cross section of beryllium compared initial data used in Geant4 with simulation data in the energy range from 0.007 to 0.1 eV. (b) Real errors and Statistical errors for simulation data. (c) Fractional uncertainty in the calculated energy.
The system errors of simulation were obtained by a function as $\Delta \sigma_{sys} = \sqrt{\Delta \sigma_{real}^2 - \Delta \sigma_{stat}^2}$ when the real errors $\Delta \sigma_{real}$ were greater than the statistical errors $\Delta \sigma_{stat}$. The result is shown in Fig. 7. The system errors of experiment can be deduced to be less than 7% from the ones of simulation in the energy range from 0.007 to 0.1 eV.

![Fig. 7. The system errors of simulation in the energy range from 0.007 to 0.1 eV.](image)

6 Conclusion

A system of measuring neutron total cross section for thermal neutrons was described in detail in this paper. The neutron total cross section for beryllium were measured by this system in the range from 0.007 to 0.1 eV, and compared with previous experiment data and evaluation data from ENDF/B-VII.1. The statistical errors are varied from 2% to 6% depending on the neutron energy. The digital-signal-processing technique and a measuring background method were used in the system. The system and statistical errors were obtained by using Geant4 simulation. In order to decrease the calculation time, the local weighted method was used in the simulation. The system errors were estimated to be less than 7% in the range from 0.007 to 0.1 eV by simulation.

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