The measurements of neutron energy spectrum at 180 degrees with the mercury target at J-PARC

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Abstract. Spallation neutron production at 180 degrees is of importance for an evaluation of radiation protection for ADS (Accelerator-Driven System) and nuclear physics. It was, however, quite difficult to measure this. We measured the energy spectrum of spallation neutron at 180 degrees at the proton transport beam line (3NBT) to MLF (Materials and Life Science Experimental Facility) on J-PARC using a NE213 liquid scintillator. The irradiated proton energy was 3 GeV, and the intensity was \(1 \times 10^{10}\) protons. The neutron energy was determined by a Time-Of-Flight method with n-gamma discrimination. We also simulated the energy spectrum by using the PHITS code and compared this with measured spectrum. In this paper, the overview of the experiment and the results are described.

1. Introduction
In the Japan Proton Accelerator Research Complex (J-PARC) [1], a MW-class pulsed neutron source, the Japan Spallation Neutron Source [2], and the Muon Science facility (MUSE) [3] are installed in the Materials and Life Science Experimental Facility (MLF). Since 2008, this source has produced a high-power proton beam of 300 kW. In 2015, we successfully ramped up the beam power to 500 kW and delivered a 1 MW beam to the targets. To produce a neutron source, a 3 GeV proton beam collides with a mercury target, and to produce a muon source, the 3 GeV proton beam collides with a 2 cm thick carbon graphite target. To efficiently use the proton beam for particle production, both targets are aligned in a cascade scheme, with the graphite target placed 33 m upstream of the neutron target. For both sources, the 3 GeV proton beam is delivered from a rapid cycling synchrotron (RCS) to the targets by the 3NBT (3 GeV RCS to Neutron facility Beam Transport) [4, 5]. Before injection into the RCS, the proton beam is accelerated up to 0.4 GeV by a LINAC. The beam is accumulated in two short bunches and accelerated up to 3 GeV in the RCS.

To evaluate the ADS system parameters, data for fast neutrons measured with low uncertainty is mandatory since ADS is a fast reactor system. However, uncertainties mostly affect ADS parameters [6]. Thus we tried to develop an irradiation field of the neutron at 3NBT. As a first step, the actual neutron spectrum of the spallation target was measured. On the entrance of a magnet at the most downstream side, significant radioactivation was observed. It is also our motivation of this measurement to make establish that whether this activation was caused by beam loss or spallation neutrons.
2. Experiment

2.1. Setup

NE213 liquid scintillator ($\phi 8 \text{mm} \times 20 \text{mm}$) was employed, whose response and characterisation can be found in [7]. The scintillator was directly connected onto a photomultiplier (Hamamatsu H3164-10) surface. A magnetic shield made of FINEMET® surrounded it to avoid magnetic field leakage from bending magnets. To concentrate on the low energy range, a high voltage of $-1400 \text{V}$ was applied. The photomultiplier was fixed on the beam pipe directly to minimise neutron attenuation. A low-attenuation signal cable (SUCOFEED) whose length was about 100 m was used to achieve n-\(\gamma\) discrimination. At full power operation there are unavoidable pile-up events. Thus the beam power is kept lower than 150 W to 200 W. The proton intensity was monitored by the current transformer shot by shot with 1% uncertainty. The typical intensity was $1 \times 10^{10}$ protons per shot. The nominal repetition rate was 25 Hz. A VME digitiser SIS3316-125-16 [8] was employed in this measurement. The start signal for the Time-Of-Flight (TOF) was the beam-synchronised pulse. The time resolution was 4 ns per channel.

We measured the accumulated neutron flux by using the irradiation foil method [9]. $^{115}\text{In}(n, n')^{115m}\text{In}$ reaction was employed to evaluate the fast neutron flux. The threshold neutron energy is 0.34 MeV for this reaction. The shape of indium sheet was 25 mm square, and the weight was 8.7 g. The sheet was placed onto the beam pipe flange near the upstream side of the scintillator. The sheet was irradiated for one week, which is a typical run cycle of the MLF.

2.2. Analysis

NE213 Scintillator 

The distribution of PSD is shown in figure 1. In figure 2, signals for neutron and gamma are clearly discriminated at low energy. Below channel 1000 which is equivalent to $^{241}\text{Am} 60\text{keV}$ total absorption peak, the signals are clearly separated.

A TOF spectrum is shown in figure 3. The first peak around channel 475 is the flash-gamma signal in the carbon target for the muon source $^1$. By fitting with a Gaussian to the second peak, it is found that the time resolution is 5.3 ns. The distance from the mercury target to the scintillator is 126.4 m. Thus the solid angle is $3.15 \times 10^{-9}$ sr. The response function for NE213 in the energy range from 0.1 MeV to 80 MeV was calculated by SCINFUL-R [10].

The obtained spectrum for 180 degrees spallation neutrons is shown in figure 4 in blue. The peak around 580 ns was caused by ringing.

\footnote{The peak around 580 ns was caused by ringing.}
statistical uncertainty is less than 1%. The systematic uncertainty, however, still needs to be estimated: it is expected to less than 10%. The energy resolutions, which are determined by the TOF resolution, are 0.15% at 0.1 MeV, 0.5% at 1 MeV, and 1.5% at 10 MeV.

When proton beam loss occurs, beam loss monitors would detect it and immediately the proton beam is stopped within the next proton bunch. If there is loss, TOF signals would be observed before the flash-gamma signal in figure 3. Thus it is concluded that almost no neutrons from beam loss were observed.

*Indium sheet* 
During one week of irradiation, the beam condition was quite stable. The actual operating rate was 98.8%, and the beam power was 150.4 kW on average. From equation 1 in Ref. [9], the reaction rate was evaluated as $8.29 \times 10^{-34}$/proton with 10% uncertainty.

3. Discussion

3.1. Comparison of measured data with calculations
Simulations were performed by using PHITS code [11]. The structures of the mercury target, the muon target, the beam pipe line, and the beam tunnel are described in detail in the code. We simulated the TOF spectrum to be the same as the real measurement. The calculated TOF spectrum is converted to an energy scale.

The measured and calculated spectra are shown in figure 4. The one from the bare mercury target is also superposed. The shape of the measured spectrum is consistent with the calculated one. The resonance peaks for the total inelastic scattering from the structure materials (Al, Ti, and C) appears in the same neutron energy channel. In the energy range below 1 MeV, the measured flux is lower than the calculated one. Above 10 MeV range, it seems that the bare, the measured, and the calculated spectra converge.

3.2. Comparison of absolute flux measurement
To calculate the reaction rate from the measured spectrum, the total cross section used in [9] was employed, obtaining $8.85 \times 10^{-34}$/proton. Thus the reaction rate from the indium irradiation method showed a good agreement with the one from the measured flux within the uncertainties.

3.3. Comparison of the total inelastic scattering of carbon with the evaluated data
The 2 cm thick carbon graphite target is used as a muon source at MUSE. To confirm the validity of this measurement, the neutron spectrum with and without the muon target was measured to
Neutron yield 1/sr/lethargy/p

Neutron MeV

The calculation w/o structures
The calculation w structures
The measurement

Figure 4. Neutron spectra (Red: the calculated spectrum of the bare target, Green: the calculated one, Blue: the measured one).

Figure 5. Comparison of the total inelastic scatterings of carbon. The red line for JENDL-4.0/HE. The blue filled square with line for the measured results.

evaluate the total inelastic scattering of carbon, which is defined as \( N = N_0 \exp (-N_{\text{carbon}} \sigma t) \) where \( N \) (\( N_0 \)) is the number of neutrons with (without) the carbon target, \( N_{\text{carbon}} \) is the number of carbon atoms in the muon target, \( \sigma \) is the cross section of \( C(n,n') \), and the \( t \) is the target thickness. The obtained spectrum is seen in figure 5 with JENDL-4.0/HE data [12]. It is obviously seen that the obtained spectrum shape follows the evaluated data and a sharp peak around 2.1 MeV is observed above the statistical uncertainty. Thus it is indicated that our measurement is certainly valid.

4. Conclusion
We measured the energy spectrum of spallation neutrons at 180 degrees in J-PARC for the first time. NE213 liquid scintillator was employed to discriminate neutron signals from photons. We also used the indium irradiation method to measure the absolute flux above 0.34 MeV neutron energy range. The neutron spectrum was successfully obtained with a low power beam of about 150 W. The calculated spectrum using the PHITS code is consistent with the measured one. Resonance “dips” appeared in same energy channel. The absolute flux measured by the irradiation method is also consistent with the measured flux within the uncertainties. By comparing the total inelastic scattering of carbon using the graphite target used for the muon source, it showed that this measurement is valid. To measure neutron flux at higher energy, the irradiation method using Bismuth should be employed.

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