Measurement of Photoneutron Spectrum at Pohang Neutron Facility

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Pohang Neutron Facility, which is the pulsed neutron facility based on the 100-MeV electron linear accelerator, was constructed for nuclear data production in Korea. The Pohang Neutron Facility consists of an electron linear accelerator, a water-cooled Ta target with a water moderator and a time-of-flight path with an 11 m length. The neutron energy spectra are measured for different water levels inside the moderator and compared with the MCNP calculation. The optimum size of the water moderator is determined on the base of this result. The time dependent spectra of neutrons in the water moderator are investigated with the MCNP calculation.

1. Introduction

Among the various kinds of neutron sources (reactors, accelerator-based neutrons, and radioisotopic neutron emitters), the accelerator-based neutron source is the most efficient one for high-resolution measurements of microscopic neutron cross sections. It produces short bursts of neutrons with a broad continuous energy spectrum by nuclear reactions of energetic photons or charged particles. Especially, an electron linear accelerator (linac) is a powerful tool to produce intense pulsed neutrons. Pulsed neutrons based on an electron linac are suited for measuring energy dependent cross sections with high resolution by the time-of-flight (TOF) technique covering the energy range from thermal neutrons to a few tens of MeV. The measurement of neutron cross sections gives basic information for the study of neutron interaction with nuclei. Precise measurements of neutron cross sections are of great importance for the safety design of nuclear reactors and for the evaluation of the neutron flux density and energy spectrum around a reactor.

The nuclear data project was initiated to construct the infrastructure for the nuclear data production by the Korea Atomic Energy Research Institute (KAERI) [1]. There was no activity for nuclear data production experiment until this project was launched. Since then, the collaboration group for nuclear data production was organized from several universities in Korea. The pulsed neutron facility using a 100-MeV electron linac was proposed in 1997 at the Pohang Accelerator Laboratory (PAL) [2]. The 100-MeV electron linac was designed and constructed based on experiences obtained from construction and operation of the 2-GeV electron linac at PAL [3].

The neutron energy spectra are measured for different water levels inside the moderator and compared with the results of the MCNP calculation. The optimum size of the water moderator is determined on the base of this result. Furthermore, the time dependent spectra of neutrons in the water moderator are investigated with the MCNP calculation.

2. Pohang Neutron Facility

The Pohang Neutron Facility (PNF) consists of a 100-MeV electron linac, a water-cooled Ta target, and an 11-m long TOF path. The 100-MeV electron linac consists of a thermionic RF-gun, an alpha magnet, four quadrupole magnets, two SLAC-type accelerating sections, a quadrupole triplet, and a beam-analyzing magnet. After the RF-conditioning of the accelerating structures and the wave-guide network, we tested the beam acceleration [3]. The maximum RF power from a SLAC 5045 klystron was up to 45 MW. The RF power fed to the RF-gun was 3 MW. The maximum energy is 75 MeV, and the measured beam currents at

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the entrance of the first accelerating structure and at the end of linac are 100 mA and 40 mA, respectively. The length of electron beam pulses is 1.8 μs, and the pulse repetition rate is 12 Hz. The measured energy spread is ± 1% at its minimum. The energy spread was reduced by adjustment of the RF phase for the RF-gun and by optimization of the magnetic field for the alpha magnet.

As a photoneutron target, it is necessary to use a heavy mass material in order to produce an intense neutron source by way of Bremsstrahlung under the high beam power of electrons. We have chosen a tantalum as the target material, which has the advantage of high density (16.6 g/cm^3), high melting point (3,017^{o}C) and high resistant against the corrosion by cooling water. The design of a water-cooled Ta target was done using the Monte Carlo simulation codes, EGS4 and MCNP version 4B. The Ta target as shown in Fig. 1 was composed of ten sheets of Ta plate, 4.9 cm in diameter and 7.4 cm in total length. There was 0.15-cm water gap between them in order to cool the target effectively [4]. The housing of the target was made of titanium. The conversion ratio obtained from MCNP code from a 100-MeV electron to neutrons was 0.032. The neutron yield per kW beam power at the target was 2.0×10^{12} n/sec, which was about 2.5% lower than the calculated value based on the Swanson's formula [5].

Since we have to utilize the space and the infrastructures of the PAL, an 11-m long TOF path and a detector room were constructed perpendicular to the electron linac. The TOF tubes were made by stainless steel with two different diameters of 15 and 20 cm.

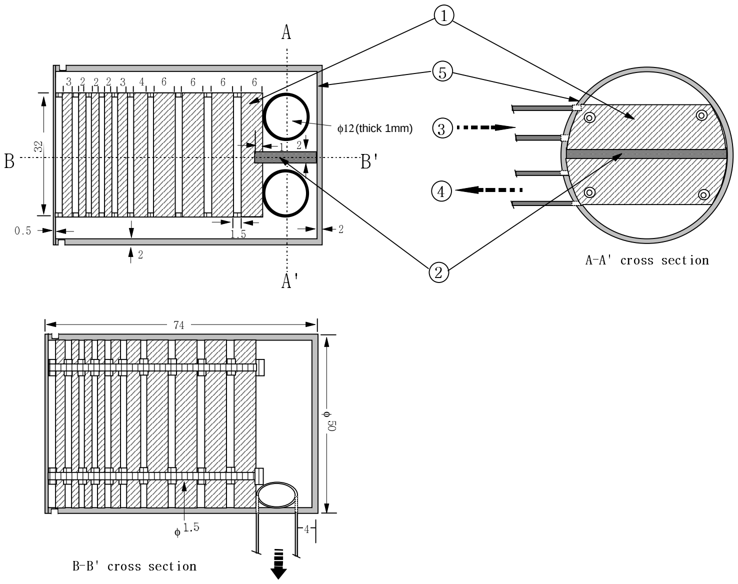

Fig. 1. Schematics of the water-cooled Ta target: Ã Ta plate, Ẽ Parting strip, Ĩ Cooling water (inlet), Ñ Colling water (outlet), Õ Ti housing. The numbers refer to dimensions in mm.

3. Experimental Arrangement

The experimental setup for the neutron TOF spectrum measurement is shown in Fig. 2. The Ta target is located in the position where the electron beam hits the center of the target. The target system consists of a Ta target and a water moderator. The water moderator is of a cylindrical shape with a diameter of 50 cm and a height of 30 cm, whose housing was made of aluminum with a thickness of 0.5 cm. The water moderator was mounted on an aluminum plate with a thickness of 2.5 cm and an iron table with a thickness of 2 cm as shown in Fig. 3. The rear part of the water moderator is covered by a 10 cm lead.

In order to reduce the gamma flash generated by the electron burst from the target and scattered high energy neutrons from the beam, a Pb block with a size of 20 x 20 x10 cm^3 was placed at the entrance of TOF tube with a diameter of 15 cm. Lead was chosen because of its low energy cross section which is about 3 barns at 0.007 eV and 11 barns above 0.2 eV; therefore the lead can serve as an effective low band filter removing more high energy neutrons than sub-thermal neutrons. There is 1.8 m thick concrete between the target room and the detector hall. The sample was placed at the midpoint of the TOF path.

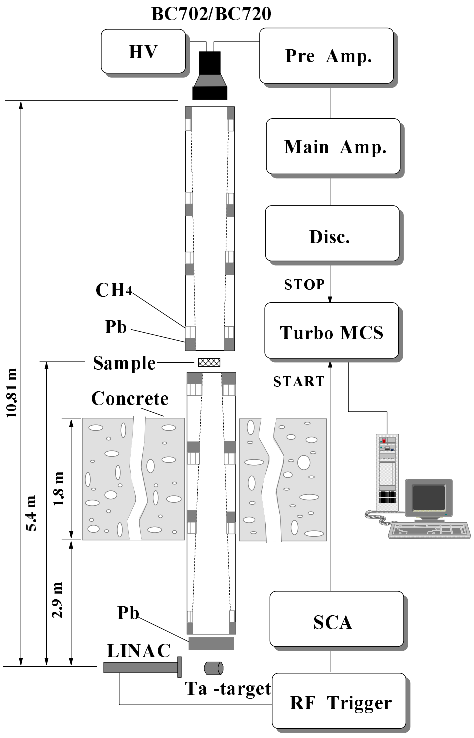

Fig. 2. Experimental setup and a block

As a neutron detector, a ^{6}Li-ZnS(Ag) scintillator BC702 with a diameter of 12.5 cm and a thickness of 1.5 cm mounted on an EMI-93090 photomultiplier was used. It was located at a distance of 10.8 m from the photoneutron target. The neutron detector was shielded by lead bricks and borated polyethylene plates.

In order to monitor the neutron intensity during the experiment, a BF_3 proportional counter with a diameter of 1.6 cm and a length of 5.8 cm was placed inside the target room at a distance of about 6 meters from the target as shown in Fig. 4. The polyethylene sphere with a diameter of 30.5 cm was used as a neutron moderator for the BF_3 counter. The neutron detector with polyethylene sphere has the maximal response for fast neutrons [6]. The lead shield with a thickness of 10 cm was used to protect gamma flash generated by the electron burst from the target. Additionally, a borated polyethylene plate with a thickness of 5 cm was used to cut the thermal neutrons generated from the moderator and walls inside the target room.

In order to investigate the neutron energy spectra for the different water levels in the moderator, we used four water levels as shown in Fig. 5. G1 represents the geometry without water inside the moderator. G2 corresponds to the half of water in the moderator in which water is around the target but no water above the target. G3 is the geometry with a water level of 5 cm above the target surface. Geometry G4 is a full of water in the moderator, which corresponds to 11 cm water level from the target surface. The cooling water inside the Ta target could not change significantly the spectral distribution of original photoneutrons.

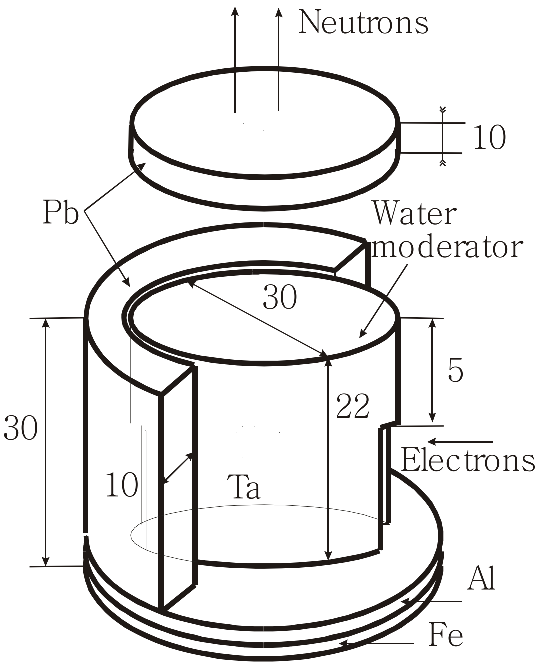

Fig. 3.Geometry for the target system used in the experiment and the MCNP calculation. The numbers in this figure refer to dimensions in cm.

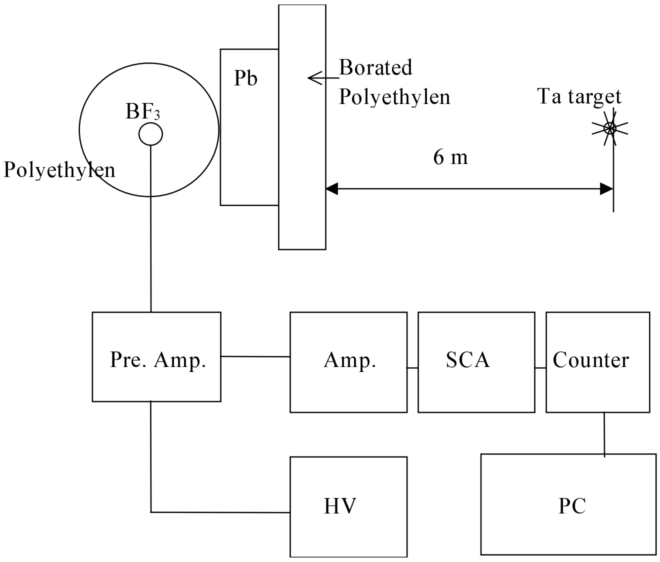

Fig. 4. Experimental arrangement for a BF_3 neutron monitor in the target room and block diagram for the data taking.

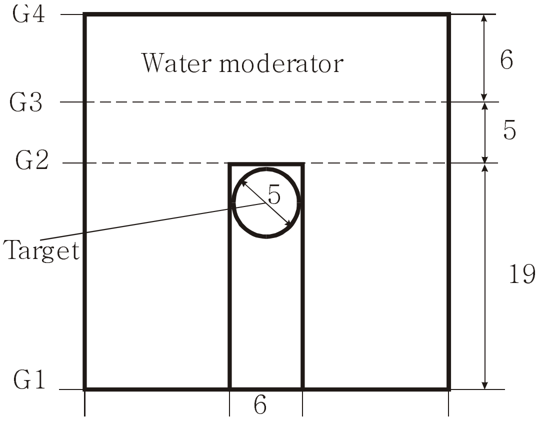

Fig. 5. The geometry used in MCNP for optimizing the water level: G1, G2, G3, and G4 indicate the water level in the moderator vessel. The numbers refer to dimensions in cm.

4. Data Taking

The neutron energy spectra produced from a tantalum target with a water moderator were measured by the TOF method. As shown in Fig. 2, the signal from the ^{6}Li_ZnS(Ag) scintillator was connected through an ORTEC-113 pre-amplifier (Pre. Amp.) to an ORTEC-571 amplifier (Main Amp.). The amplifier output was then fed a discriminator (Disc.) input, whose output was used as a stop signal of the 150 MHz time-digitizer (Turbo MCS). The lower threshold level of the discriminator was set to 30 mV. The Turbo MCS was operated as a 16384-channel time analyzer. The channel width of the time analyzer was set to 0.5 μs. The 12 Hz trigger signal (RF Trigger) for the modulator of the electron linac was connected to an ORTEC-550 single channel analyzer (SCA), the output signal was used as the start signal for the Turbo MCS. The Turbo MCS is connected to a personal computer. The data were collected, stored and analyzed on this computer.

The block diagram of the data acquisition system for the BF_3 neutron monitor is shown in Fig. 4. The signal from a BF_3 counter was connected through an ORTEC-142PC preamplifier (Pre. Amp.) to an ORTEC-590A spectrometric amplifier (Amp.). The amplifier output was fed to an ORTEC-SCA550 single channel analyzer (SCA), where the distance from the preamplifier to the amplifier is about 30 m. The single channel analyzer was used to create the standard signal and to cut noises originating from gamma rays and low-energy neutrons. The output signal from the single channel analyzer was fed into an ORTEC-996 timer and counter. The counter was connected with a personal computer. During the experiment, the electron linac was operated with a repetition rate of 12 Hz, a pulse width of 1.8 μs, a peak current of 30 mA, and electron energy of 60 MeV.

5. Data Analysis

The neutron energy spectra generated by the Ta target with a water moderator with different water levels of G1-G4 were measured with the TOF method at PNF. Fig. 6 shows a typical neutron TOF spectrum for the G3 geometry. The neutron energy spectrum mainly consists of fast neutrons with the mean energy of 0.92 MeV and thermal neutrons produced in the water moderator and scattered from the wall and other materials around the target. The TOF spectrum was only measured in the direction perpendicular to the incident electron beam. In order to estimate the background level, we took neutron TOF spectra for a Sm sample with a Cd filter of 0.5 mm in thickness and a run without any samples (blank run). The background level was estimated from the fitting function $F(I) = a + b \times I + c \times I^2$, where a, b, and c are constants and I is the channel number of the time digitizer, as shown in Fig. 7. The resonances in the neutron TOF spectrum for the blank run are related to Sb and W impurities inside the Pb block. The signal-to-background ratio defined as the neutron counts minus background counts divided by the background counts at a particular energy was about 10 to 1.

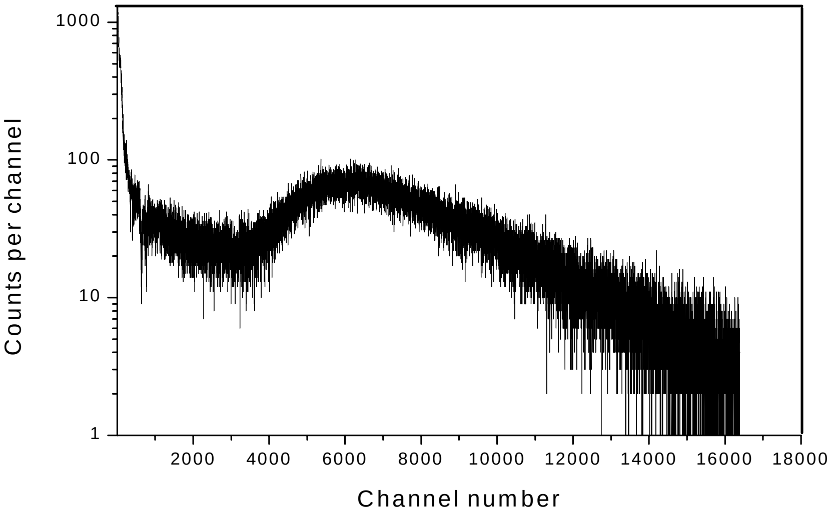

Fig. 6. Typical neutron spectrum for the G3 geometry measured at 11 m TOF path

5. 1 Neutron Monitor Counts

The BF_3 proportional counter was operated in the count mode as a neutron monitor. The neutron monitor was tested by using a neutron source ^{252}Cf with a mean neutron energy of 2.13 MeV and an activity of 5.4×10^4 n/sec. The pulse shape of the neutron monitor was checked with an oscilloscope and no saturation was observed during the linac pulse duration. The typical behavior of neutron counts during the one period of experiment is shown in Fig. 8. Neutron counts during the experiment were changed due to the unstable modulator system for the electron linac. The background count rates for the BF_3 neutron monitor were less than 0.01 counts per second. The background count rates were measured before and immediately after operating the accelerator. The average count rates for the neutron monitor were about 300 counts per second. The neutron monitor counts were used to normalize the neutron intensity between the runs.

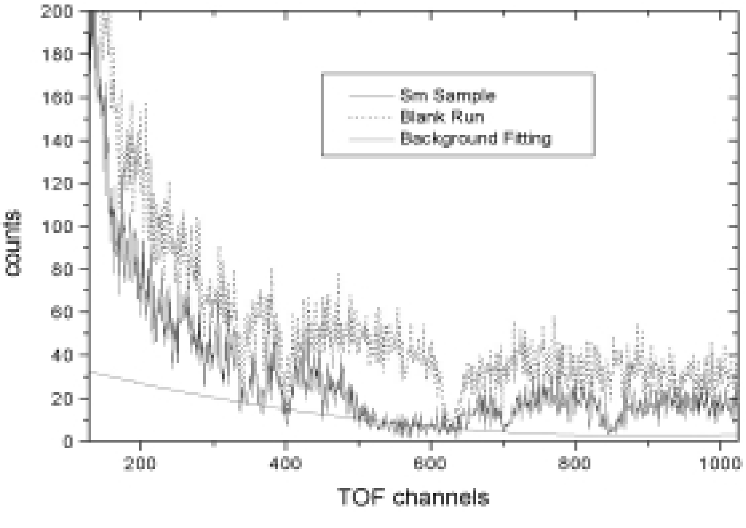

Fig. 7. Typical background level measured at 11 m TOF path length. Solid line and dot line represent the TOF spectrum for Sm sample and without any sample in the beam line, respectively.

5.2 Neutron Energy Spectrum

The measured TOF spectra as a function of channel number were normalized using the neutron counts from the neutron monitor and converted as a function of neutron energy. Each channel I in the time analyzer is converted to the neutron energy E_i via:

$$E_i = \left\{ \frac{72.3 \times L}{(I - I_0) \times \Delta\tau} \right\}^2 \tag{1}$$

Where, L is the neutron flight path in meter, $\Delta\tau$ is the channel width in µs and set to 0.5 µs, and I_0 is the number of channel at the time of flight equals to zero when the neutron burst was produced. The relation between a channel number of the neutron TOF spectrum and its energy was calibrated with resonance energies of Ta, Sm, and other samples with a black resonance. Good linearity was found between the neutron TOF and the channel number. We found the flight path length L equal to 10.81±0.02 m.

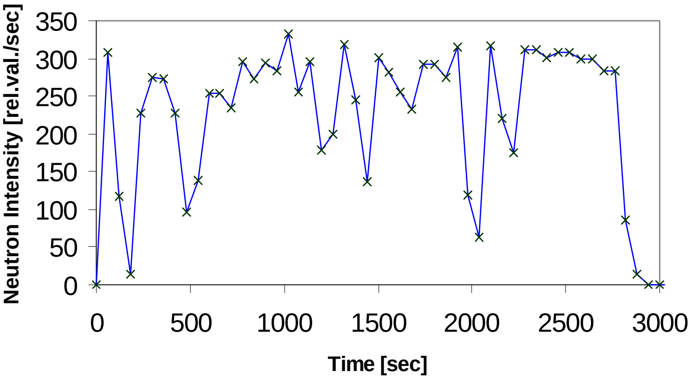

Fig. 8. Typical neutron intensity measured by a BF_3 monitor for an hour operation.

The measured neutron flux was corrected for the detector efficiency, $\varepsilon(E_i)$ which is energy dependent and is given by:

$$\varepsilon(E_i) = 1 - \exp\left(-\frac{t}{C\sqrt{E_i}} \right) \tag{2}$$

where t is the thickness of scintillator in centimeters and C is constant for each scintillator and is given by the manufacturer [7]. In this experiment we used 1.5 cm thick BC702 ^{6}Li-ZnS(Ag) scintillator and for this C= 12.5 cm/eV$^{0.5}$.

Fig. 9 shows the neutron flux (number of neutrons per energy group) in the energy range of 0.01 to 1 eV for different water levels. The neutron flux in each channel was summed up over every 0.23 lethargy width. The G3 geometry with a water level of 5 cm gives more thermal neutrons compared to other geometry. Too high water level in the moderator decreases thermal neutrons due to the absorption of thermal neutrons.

5.3 Compare with the MCNP calculation

The continuous energy Monte Carlo code MCNP version 4B [8] has been used to calculate the neutron spectra for various geometries. The MCNP code has its own nuclear data library generated from the evaluated nuclear data files of ENDF/B-VI [9]. Using the MCNP statistical sampling technique, the neutron distributions of moderated neutrons were calculated as a function of time and energy. The purpose of this calculation is to compare with measurements for the thermal neutron flux leaving the water moderator and to optimize the photoneutron target system.

The neutron source term for the tantalum plates in the target was chosen to be an “evaporation” energy spectrum [10, 11] given by:

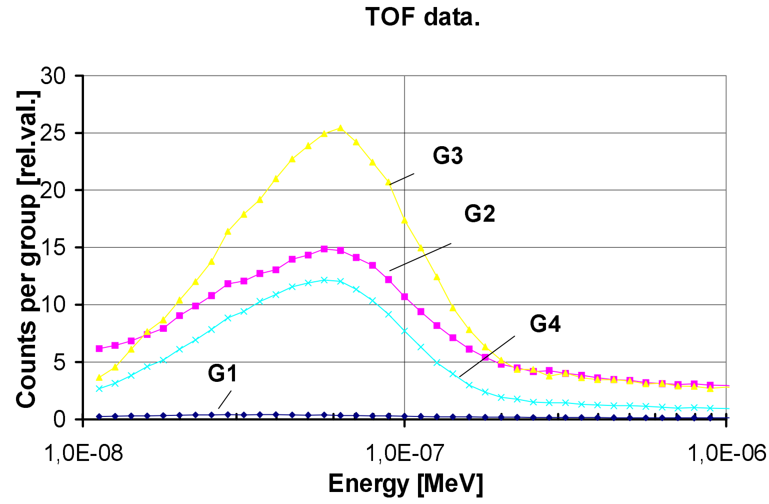

Fig. 9. Measured neutron flux for different geometry in the neutron energy from 0.01 to 1 eV.

$$\phi(E) = cE\exp(-E/T) \qquad (3)$$

where E is the neutron energy in MeV, T is the effective temperature of the tantalum target in MeV and c=4.7259 is a normalization constant. Using an effective temperature of 0.46 MeV [12], Eq. (3) gives neutron energy about 0.92 MeV in average. The source parameters were chosen such that the neutrons at "birth" are distributed uniformly throughout a homogenized mixture of tantalum and cooling water with isotropic angular distribution [13].

In the calculation, we ignore the effect of aluminum wall of the water moderator because of its small contribution to the total flux of scattered neutrons. The minimum and maximum neutron cutoff energies were 0.0001 eV and 10 MeV, respectively. The neutron time cutoff was 10^7 Shakes (1 Shake = 10^{-8} sec).

We considered the neutron energy regions from 0.001 eV to 10 MeV for the calculation. The energy region was divided into 200 groups with an equal lethargy width. The neutron current within 15 degrees

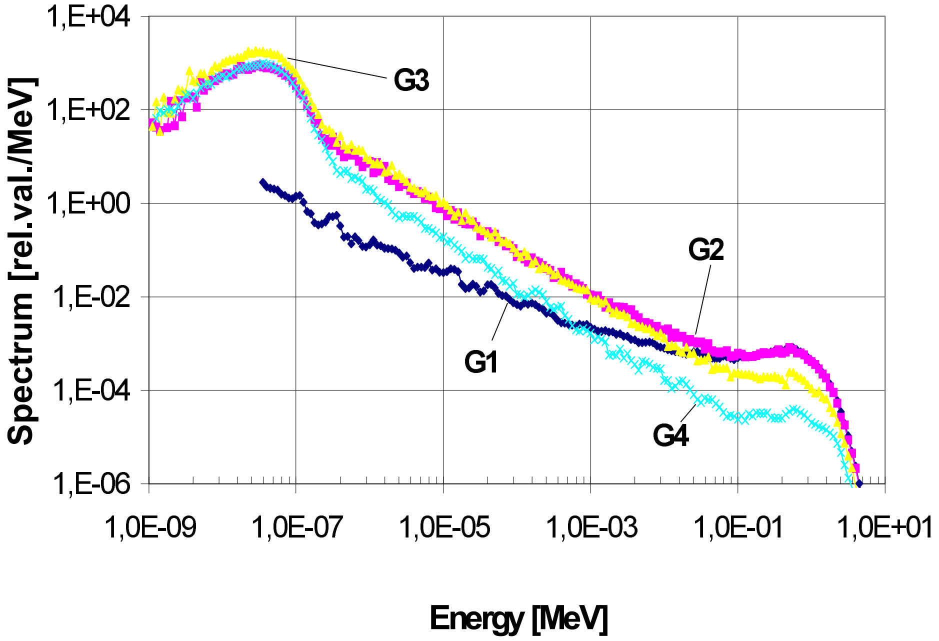

Fig. 10. Neutron energy spectra in the water moderator calculated by the MCNP code for different geometry as shown in Fig. 5.

with respect to the direction of detector from the lead surface was calculated for different water levels inside the moderator. For good statistics in the calculation, the number of particle history calculated for different geometry was more than 50,000,000 counts.

Fig. 10 shows neutron spectra calculated by MCNP code for different geometry described above. For fast neutrons in the energy regions of 0.1 to 10 MeV, the neutron flux for geometry G1 and G2 is almost same and higher than other geometry because there is no water above the target surface. The neutron flux in the energy region from 0.01 eV to 0.1 eV is maximum around at 5 cm of water level, which corresponds to geometry G3, as shown in Fig. 11. The points correspond to MCNP calculation and the line is a polynomial spline interpolation.

The measured differential neutron spectra for three geometries were shown in Fig. 12 compared with those of the MCNP calculations. In this figure, the spectrum for G3 (G4) geometry was multiplied with a factor 10(0.1) for the better visualization. The points (triangles, quadrates, and circles are for G3, G2, and G4 geometry, respectively) represent the result of the MCNP calculation. The measured differential energy spectra were normalized using the neutron monitor counts. The calculated spectra have relative normalization (normalization coefficients are C1= 3540 for G2, C2=35400 for G3, and C3=354 for G4).

The measured neutron spectra were agreed with those of the MCNP calculation within the experimental uncertainty. The statistical uncertainty of MCNP calculation was ranged from 3 to 9 %

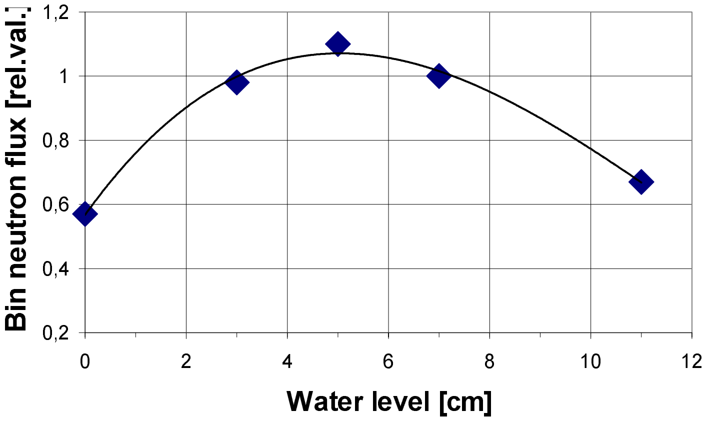

Fig. 11. Calculated neutron flux as a function of the water level in the moderator in the neutron energy from 0.01 eV to 0.1 eV. The measured points are connected by a spline fit.

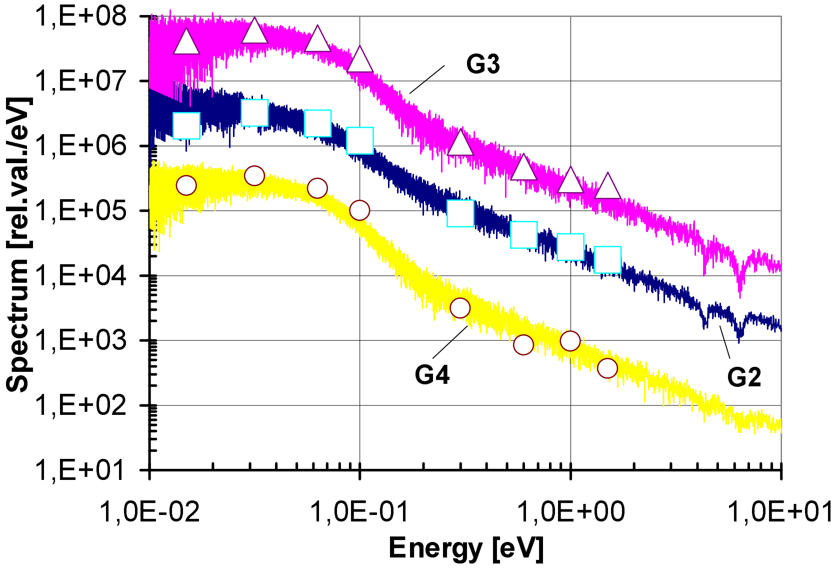

Fig. 12. Measured and calculated differential neutron spectrum for three different geometries. The points correspond to MCNP calculation. The spectrum for G3 (G4) geometry is multiplied by a factor 10 (0.1) for the better view.

depending on the energy bin.

6. Conclusion

The neutron energy spectra produced by the photoneutron target with a water moderator were measured with a ^{6}Li-ZnS(Ag) glass scintillator as a neutron detector with the neutron TOF method at 11 m flight path of Pohang Neutron Facility. As a neutron monitor, a BF_3 proportional counter was used. The neutron TOF spectra were normalized with the neutron monitor counts. We measured the neutron TOF spectra for different water levels inside the moderator and compared with the MCNP calculation in order to maximize the thermal neutron flux.

The measured neutron energy spectra for different water levels in the moderator were verified by the MCNP calculations. The experimental and calculated data were agreed within the experimental uncertainty. According to the results of the measurement and the calculation, the 5 cm water level in the moderator gives the maximal thermal neutron flux for the present geometry of the photoneutron target system.

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