The Measurement of Neutron Flux and Spectrum at the Irradiation facility for BNCT of HANARO

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ABSTRACT

An irradiation facility for Boron Neutron Capture Therapy (BNCT) using thermal neutron was designed and installed at the IR port, which is one of the horizontal beam ports in HANARO. The target of the design was to extract more thermal neutrons but less fast neutrons and gammas. It allows a shorter irradiation time for the patients and minimizes their exposure to fast neutron or gamma radiation. According this design aim, a special filter composed with silicon and bismuth single crystals was contrived. In order to confirm the expectations at the design stage, the neutron flux and spectrum were measured using the activation detectors. The results of measurement were sufficiently satisfied. At the room temperature on the filter, the measured thermal neutron flux at the center of the beam exit is 8.344×10^8 n/cm^{2}s, which is 14% higher than expected value. And the Cd ratio was measured as 104. And the fast neutron flux is approximately 6×10^8 n/cm^{2}s, it is only 1/1000 of the thermal neutron. When the filter is cooled down to liquid nitrogen temperature and the reactor is operated at 30 MW, then the thermal neutron flux over 2×10^8 n/cm^{2}s is convinced for various purposes as well as BNCT.

1. INTRODUCTION

The BNCT is one of the radiation therapies using the thermal or epithermal neutrons for the malignant brain tumour treatment. An irradiation facility for the BNCT was developed at HANARO. Because there was no thermal neutron traps such as thermal column and any modification of the biological concrete shield was not possible in HANARO, the neutron beam tube was the only option for the BNCT. Since all beam tubes are optimized in the D_2O reflector region to extract high thermal neutrons, it was found that the enough epithermal neutron flux with low fast neutron and gamma fluxes could not obtained. Therefore it was decide to use the thermal neutron and to minimize the fast neutron and gammas using a filter.
A dose received by the patients should be controlled as accurate as possible. This can be achieved when the radiation level at the beam exit is known precisely. Thus it is very

important to know the accurate neutron environment at the BNCT facility.
The absolute neutron flux, distribution and spectrum were measured at the surfaces of beam exit and the lead shield added in the next of filter assembly. The measurements were performed using the activation detectors and compared with the expected values by the calculation. This paper describes the general description for the BNCT irradiation facility and measured results of the neutron flux and spectrum.

2. IRRADIATION FACILTY FOR THE BNCT

The radiation filter should not only maximize the penetration of thermal neutrons but also minimize fast neutrons and gammas. Feasibility study for the neutron and gamma penetration was performed for candidate materials of aluminum, silicon and bismuth [1]. Upon investigation into the attenuation effects of each material using MCNP4B [2], it was found that the single crystals of silicon and bismuth make their cross sections lower at thermal neutron energy range. Thus, silicon and bismuth single crystals were selected as a filtering materials for fast neurons and gammas, respectively. Also it was found that if the crystals are cooled down to the liquid nitrogen temperature, these effects would be increased.
The facility is composed of a water shutter, a filter assembly, and surrounding shields. The water shutter prevents the high radiation from coming out to the irradiation room by filling it up with the water in case of unemployed condition. The filter assembly is consist of the silicon and bismuth single crystals. It is maintained at the liquid nitrogen temperature during the BNCT irradiation. Two layers were designed around the silicon crystal to contain the liquid nitrogen and sustain a vacuum condition for suppressing the heat conduction. The shields around the filter were constructed using polyethylene, borated polyethylene, lead, LiF, etc.. They will accommodate the scattered neutrons and gammas from the filter, and keep a low level of radiation around the filter. Finally, a thick lead shield was added to block the gammas coming into the irradiation room and a collimator made of $^{6}Li_2CO_3$ and polyethylene is installed at the center of the shield. Various collimator with different diameters can be inserted in the lead shield. Figure 1 and Figure 2 show the conceptional view of the BNCT facility at HANARO and the filter assembly.

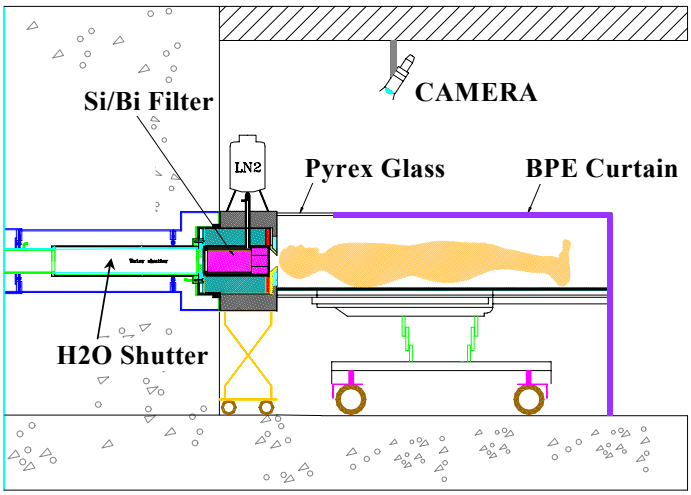

Figure 1. BNCT irradiation facility

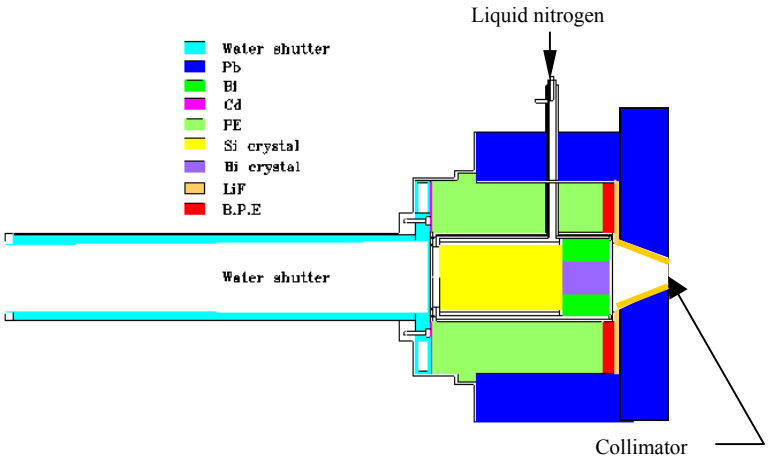

Figure 2. Filter for the BNCT

3. NEUTON MEASUREMENTS

3.1. Neutron flux and distribution

The absolute neutron flux, distribution, and Cd ratio were measured at the beam exit of the BNCT irradiation facility using Au foils and wires as the activation detectors. Thin Au foils were placed horizontally with intervals from the center of the collimator, and Au foil covered with 0.02 inches thick of Cd plates was placed at near the center position. The thickness and diameter of the Au foils are 0.001 inches and 0.5 inches, respective. These activation detectors were irradiated for 3 hours at a reactor power of 24 MW without cooling by liquid nitrogen.

Due to the relatively short irradiation times, effects of nuclear burn up and transmutation correction for both target and product isotopes can be neglected. Self absorption corrections for the thermal neutrons were considered by the simple attenuation formulas for the parallel beam incident on a plan or wire as follows. The reaction rate for a foil of thickness t and radius r will be

$$R = N\sigma\phi_0\pi r^2 \int_0^t \exp\left(-\Sigma_t t'\right)\, dt' = N\sigma\phi_0\pi r^2 \frac{1}{\Sigma_t}\left[1-\exp\left(-\Sigma_t t\right)\right] \qquad (1)$$

and for a wire of length l and radius r will be

$$R = N\sigma\phi_0\pi \iint_{x,y} \exp\left[-\Sigma_t\left(y+\sqrt{r^2-x^2}\right)\right]dydx \qquad (2)$$

where, Σ_t is total macroscopic cross section, N is atom density, σ is microscopic activation cross section, and ϕ_0 is incident neutron flux.

The absolute flux values calculated based on measured activities at each points are listed in

Table 1, and shown as a function of distance from the center in Figure 3. All activities are measured using a high purity GeLi detectors and analyzed using MCA with the uncertainties less than 3 %. The neutron flux at the center of the collimator is 8.344×10^{8} n/cm^{2}s, which is 14 % higher than expected value of 7.33×10^{8} n/cm^{2}s by MCNP4B [2] under the same conditions. The Cd ratio at the same position is 104, which is smaller than the expected value of 121. As shown in the figure, the change of the neutron flux is not clear within the 5.5 cm radius of the collimator, but it decrease rapidly down to 1/1000 of the inner values in outer region. Since the radius of the collimator is 7.5 cm, it is confirmed that the neutron beam is well collimated. When a human phantom is positioned at the beam exit, the neutron flux is measured as 1.625×10^{9} n/cm^{2}s, which is about 2 times higher than without a phantom.

Table 1. Neutron flux at the measured points in the horizontal direction

Distance from the center (cm)	Neutron flux (n/cm^{2}s)
0	8.3440×10^{8}
2.5	7.9937×10^{8}
5.5	7.0252×10^{8}
8	1.4312×10^{7}
10.1	1.2764×10^{6}
19	6.0647×10^{5}
20	3.6327×10^{8}
39	2.3829×10^{8}

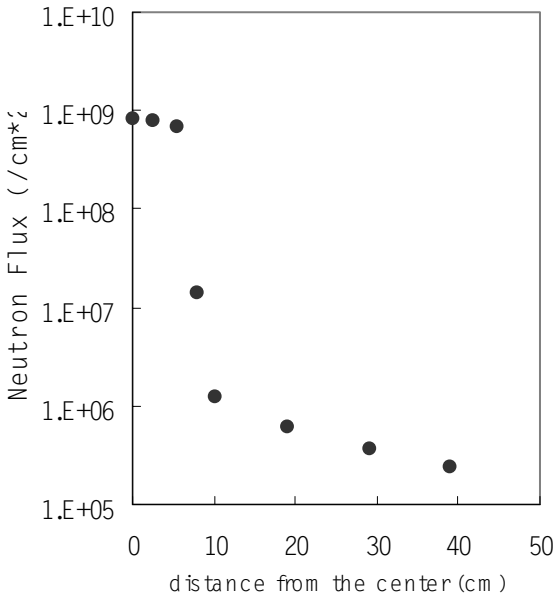

Figure 3. Neutron flux distribution in horizontal direction

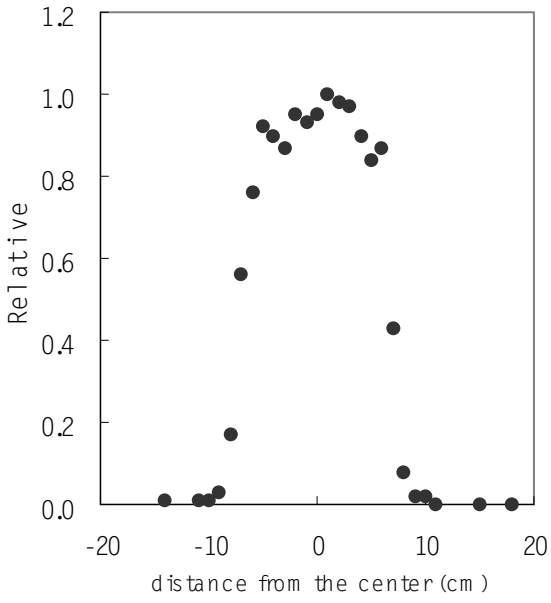

Figure 4. Neutron flux distribution in vertical direction

To measure the neutron flux distribution in vertical direction, 0.004 inches diameter of Au wires were used. Au wires was placed across the lead shield and the collimator from the top to the bottom in vertical direction, and another Au wire enveloped in the Cd tube was placed crossing the bare wire from the center of the collimator to the end of left side of the lead shield in horizontal direction. The inner diameter and thickness of the Cd tube are 0.05 inches and 0.02 inches, respectively. They were irradiated under the similar condition when Au foils are irradiated. Figure 4 shows the vertical distribution of the measured neutron flux. As shown in the figure, vertical distribution is similar to the horizontal distribution, and the neutron fluxes in the region out of the collimator are turned out to be negligible. The epithermal neutrons measured from the Cd covered wire have the similarly distribution.
The neutron fluxes were measured also at the various perpendicular distances from the beam exit using the Au foils. The measured results are listed in Table 2. The differences between the calculated and measured values are around 10 %.

Table 2. Neutron flux along the perpendicular distances from the beam exit

Distance (cm)	Calculated (A)	Measured (B)	Ratio (B/A)	Cd ratio (measured)
0	7.33×10^{8}	8.344×10^{8}	1.14	104
105	3.41×10^{8}	3.340×10^{8}	0.98	160
200	2.28×10^{8}	2.580×10^{8}	1.13	-
357	1.21×10^{8}	1.300×10^{8}	1.07	-

3.2. Neutron spectrum

Nine neutron activation foils including Au, Au with Cd, Ag, Ag with Cd, Sc, Cu, Mn, Ti, and Ni are prepared to measure neutron spectrum at the center surface of the collimator. Ti and Ni foils were selected for fast neutrons and the other for thermal and epithermal neutrons. All detectors were arranged in a circle of 5 cm in diameter and irradiated at the same time so as to represent the average flux within the collimator. The irradiation time was 3 hours and the power level was 24 MW. The measured activities after irradiation were converted into saturated reaction rates to be used to unfold the neutron energy spectrum. In the calculation of the saturated reaction rate, only self-absorption corrections for the thermal neutron detectors were taken into account as mentioned previous section.
The corrected saturated reaction rates were used as an input data for unfolding the neutron spectrum with the SNL-SAND-II computer code [3], which does an iterative calculation with the measured activities and initially given spectrum. SNL-SNAD-II has the interval averaged cross section data library for the 640 energy intervals between 10^{-10} MeV and 20 MeV, which is based on the ENDF-VI dosimetry file. Since the fast neutron flux at the beam exit is very low and consequently the measured activities from the Ti and Ni were also very low and exhibited large errors, two detectors are discarded in this unfolding process. Accordingly neutron spectrum unfolding is performed only in the energy range of thermal and epithermal

neutrons. The calculated spectrum by MCNP4B was used as an initial spectrum.
The final result was obtained after 10 iterations. The measured and calculated saturated reaction rates are listed in Table 3. The deviation of the measured values from the calculated are less than 3 %, and the final standard deviation of the measure activities is 2.697 %. The errors of the measured values are also less than 3 % without considering the uncertainties coming from the nuclear data. Figure 5 shows a final spectrum with a calculated spectrum by MCNP4B. Thermal neutron flux below 0.5 eV, an approximate cadmium cut-off energy, is calculated as 7.85×10^{8} n/cm^{2}s. This is 6 % lower than measured value at the center position.
On the other hand, the fast neutron flux were estimated roughly from the measured activities of Ti and Ni activation detectors. It was done using the approximated average reaction cross sections calculated with the interval averaged cross sections of the SNL-SAND-II library and the theoretical fission spectrum of the U-235.

$$\overline{\sigma} = \frac{\int_E \phi(E)\sigma(E)dE}{\int_E \phi(E)dE} \approx \frac{\sum_g \phi_g \sigma_g}{\sum_d \phi_g} \tag{3}$$

The summation in the equation was carried out over 184 energy intervals from 1.7 MeV for Ti, and over 206 energy intervals from 0.5 MeV for Ni. The integral neutron flux above the threshold can be approximated as

$$\int_E \phi(E)dE = R/\overline{\sigma} \quad (\mathrm{E} \geq \mathrm{E}_{\mathrm{theshorld}}) \tag{4}$$

where R is reaction rate per atom.
The reaction rates per atom were measured as 1.125×10^{-20} and 5.261×10^{-20} for Ti and Ni, respectively and their uncertainties were ± 20%. The calculated fast neutron fluxes above their threshold energy are 5.682×10^{5} n/cm^{2}s and 6.455×10^{5} n/cm^{2}s, respectively. They are comparable with the calculated value of 6.55×10^{5} n/cm^{2}s for the energy above 1.0 MeV.

Table 3. Measured and calculated saturated activity rates

Reactions	Measured saturated activity rate/atom	Calculated saturated activity rate/atom	Deviation of A from B (%)
Au197(n,γ)Au198	6.884×10^{-14}	6.748×10^{-14}	2.015
Au197(n,γ)Au198 Cd	6.289×10^{-16}	6.115×10^{-16}	2.846
Sc45(n,γ)Sc46	1.802×10^{-14}	1.846×10^{-14}	-2.384
Sc45(n,γ)Sc46 Cd	4.704×10^{-17}	4.850×10^{-17}	-3.015
Ag109(n, γ)Ag110	3.217×10^{-15}	3.290×10^{-15}	-2.219
Cu63(n, γ)Cu64	3.145×10^{-15}	3.059×10^{-15}	2.811
Ti-nat(n,x)Sc46 *	1.125×10^{-20}	not used	-
Ni-58(n,p)Co58	5.261×10^{-20}	not used	-
Standard deviation of measured activities (%)			2.697

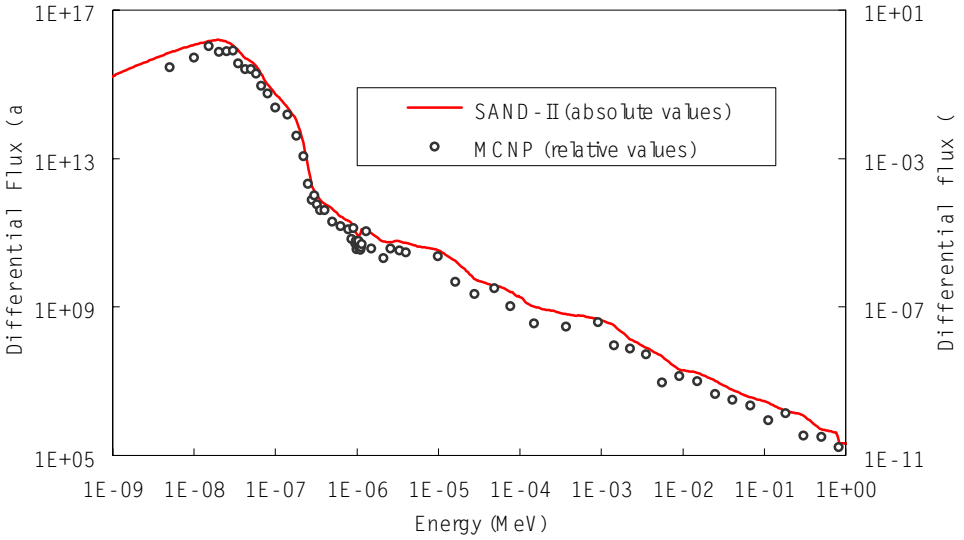

Figure 5. The final spectrum obtained from the SAND-II

CONCLUSIONS

The absolute neutron flux, Cd ratio, and flux distribution were measure around the neutron beam collimator and the lead shield of the BNCT irradiation facility in HANARO. The neutron spectrum at the center of the collimator was also measured. Activation detectors were used for the measurements and SNL-SAND-II computer code was used for the spectrum unfolding. The filter will be maintained at the liquid nitrogen temperature during actual irradiation for the BNCT, but these measurements were performed at room temperature, and the results were compared with the expected values under the same circumstances.

The maximum thermal neutron flux at the center of the collimator are 8.344×10^{8} n/cm^{2}s, which is 14% higher than expected values at the design stage. The Cd ratio is 104, and the fast neutron flux is approximately 6×10^{5} n/cm^{2}s. From the measurements it was confirmed that the filtering performance of the BNCT irradiation facility is well agree with the design target. When the filter is cooled down to liquid nitrogen temperature and reactor is operated at 30 MW, then more than 2×10^{8} n/cm^{2}s of thermal neutron flux is convinced.

It is concluded that thermal neutrons high enough for the actual BNCT irradiation but less fast neutrons and gammas can be obtained owing to the silicon and bismuth filter. Furthermore it is expected that this facility can be utilized for other purposes besides BNCT considering the high quality and high intensity thermal neutron flux.

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ACKNOWLEDGEMENTS

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