BNCT Facility Development in HANARO

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Abstract

An irradiation facility for boron neutron capture therapy (BNCT) was developed using one of the typical tangential beam tubes in HANARO. Thermal neutron was chosen because of the impossibility of sufficient epithermal neutrons for BNCT at the exit of the beam tube. The facility is designed not only for BNCT study but also for dynamic neutron radiography (DNR) and other experiments requiring pure thermal neutrons. Silicon and bismuth single crystals cooled by liquid nitrogen are selected to filter out fast neutrons and γ-rays and to penetrate the thermal neutrons as much as possible. A water shutter is installed in front of the radiation filter to keep the radiation level low in the irradiation room while it is filled with water. A prompt gamma neutron activation analysis (PGNAA) system was also developed to measure the boron concentration quickly from patient's blood samples. A spare neutron beam from a dedicated beam instrument was diffracted upward using pyrolytic graphite to obtain almost pure thermal neutrons at the target position.

1. Introduction

BNCT is one of the promising treatment methods for a malignant brain tumor. Thermal or epithermal neutrons are used as a neutron source. While a thermal neutron beam can only be applied to focused irradiation for which the opening of the scull is needed, an epithermal neutron beam can be applied to full brain irradiation without the opening of the scull. The thermal neutron beam can be used directly for cell culture study or small animal irradiation as well. If the efficacy of the BNCT is sufficiently proven through current worldwide research, a dedicated neutron source that can be installed in a hospital will be demanded[1]. On the other hand, we cannot expect the continuous research on BNCT for a very long time if no good results come forth. Therefore, we are supposing that the role of HANARO for BNCT cannot last for a long time whether the worldwide BNCT is successful or not, but that it should contribute to BNCT research in Korea. At the same time, we do not expect many experiments for BNCT in HANARO. So, an applicability of the facility for other purposes is desired, if possible.

One typical tangential beam port whose nose is located in the thermal neutron peak area in the heavy water reflector, is the only facility available for the BNCT. Its long and narrow tube does not allow sufficient epithermal neutrons for BNCT at the beam exit, but thermal neutron BNCT would be possible. There is no extra beam tube for the PGNAA. Since the beam cross-section required for the PGNAA is small, however, the possibility to utilize the spare beam of a dedicated neutron beam instrument exists. Finally, we decided to develop a thermal neutron BNCT facility for a wide range of studies for BNCT from cell culture and animal irradiation to clinical trials and a PGNAA system for boron concentration measurement. Since HANARO did not have a pure thermal neutron field such as thermal column, we expected the BNCT facility to provide it.

In this paper, design consideration and method for the BNCT facility and the PGNAA system are described. Also, design of the irradiation room is explained.

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2. BNCT Facility Development

2.1 Design Considerations

For the thermal BNCT to be possible, thermal neutron flux should be maximized at the exit of the beam tube while fast neutron and γ-ray fluxes should be minimized. Considering the beam tube length of over 400cm, however, extraction of enough thermal neutrons outside may result in a large leakage of fast neutrons and γ-rays. Thus, a radiation filtering technology is adopted to get an almost pure thermal neutron beam.

The reactor should not be shut down due to the activities related with the BNCT because many experiments for different research purposes are normally conducted simultaneously. Temporal surgical operations before and after irradiation of a patient should be possible in the irradiation room while the reactor is in full power operation. The irradiation room should be spacious for the operation and DNR, also it should be prepared with equipment for the patient's safety during the irradiation and be shielded to keep the radiation level outside within the prescribed limit.

To measure the boron concentration in the patient's blood or biological samples on site, a PGNAA system should be developed.

2.2 Radiation Filter

A good material for the neutron filter in thermal BNCT should have characteristics of low thermal neutron absorption and a high fast neutron cross section in order to extract thermal neutrons as much as possible. However, there are few materials having such characteristics. Among them, Al and Si are strong candidates. For the γ-ray filter, Bi is the best candidate because of its low neutron absorption and secondary γ-ray production.

Through a preliminary study for Al, we could not obtain high thermal neutron flux with a small contamination of fast neutron and γ-ray fluxes from the beam tube. Thus, Si was chosen as a neutron filter. Its thermal neutron cross section becomes lower when it is crystallized. Moreover, it becomes much lower as the temperature goes down. Fig. 1 shows the neutron cross sections of a Si single crystal at room and liquid nitrogen temperatures. The cross section variation for Bi has similar trend as that for Si. Thus, single crystals of Si and Bi cooled by liquid nitrogen are the best radiation filters to get high purity thermal neutrons. After sensitivity studies, the radiation filter selected was a Si single crystal of 40cm in length and 20cm in diameter plus a Bi single crystal of 15cm in length and 10cm in diameter. The filter can provide a high portion of un-collided thermal neutrons coming from the nose of the beam tube and an almost parallel beam is obtained if it is more than 1m distant from the beam exit.

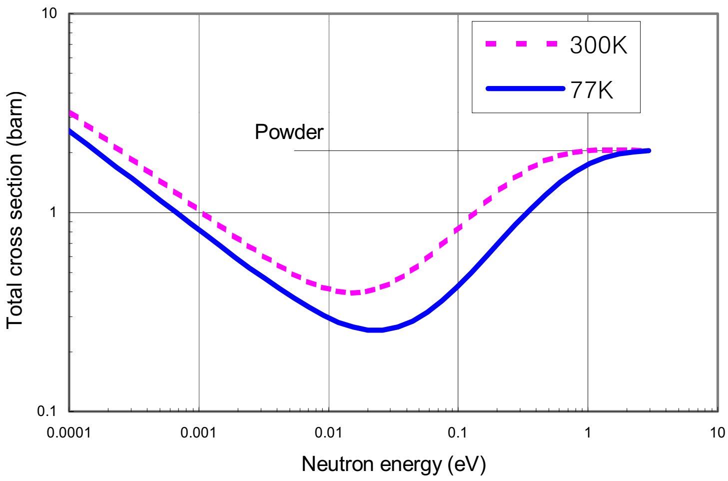

Fig. 1 Neutron cross sections of Si single crystal at room and liquid nitrogen temperatures.

The radiation filter is positioned at the exit part of the beam tube to minimize the neutron loss due to scattering. Scattered radiation at the filter could cause a high radiation level around the filter. For the shield outside the filter, shielding materials such as polyethylene, lead, plastics containing boron or lithium, etc., surround the filter.

The thermal neutron beam coming out from the filter should be collimated for the focused irradiation. A collimator having a cone shape is prepared. It is fixed to the outside of the filter. Two different collimators are prepared to configure different beam sizes.

A water shutter of 135cm in length is placed in front of the radiation filter. It allows for a sufficiently low radiation level in the irradiation room while it is filled with water. The water will be drained when a patient or sample is irradiated. Thus, it is possible to operate the reactor continuously regardless of BNCT irradiation. Fig. 2 shows the radiation filter, water shutter and auxiliary shields of the BNCT facility in HANARO.

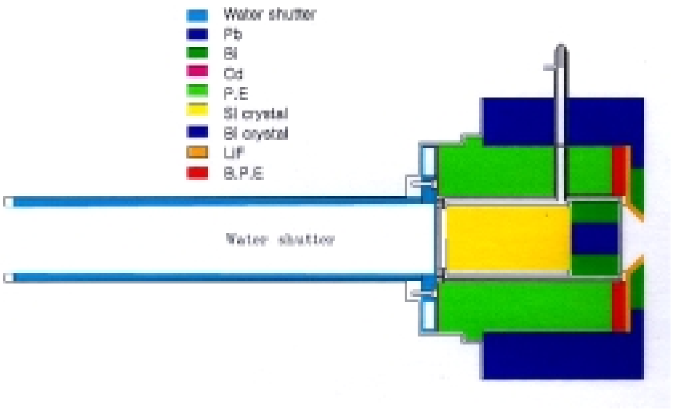

Fig. 2 The radiation filter for BNCT at HANARO

2.3 Neutron Flux at the Collimator Exit

The radiation streaming phenomena inside the beam tube is analyzed using the Monte Carlo code, MCNP. The flux and dose at the exit of the collimator of 15cm in diameter are calculated. The computational geometry is too large and complicated to get a reliable result with a small statistical error. Thus, the calculations are divided into two steps. First, the neutron source at the beam tube nose and its angular distribution are calculated using the model of the core and the front part of the beam tube. Second, the flux and dose distributions through the beam tube are calculated using the neutron source at the nose.

The cross sections of Si and Bi single crystals are not provided for in the MCNP code. Thus, these are specially prepared using a semi-empirical equation[2]. In the second calculation for the long beam tube, a method of geometry splitting with Russian roulette is used to direct more particles toward the detector for a small statistical error in the results. The importance of each cell increased as the cell approached the detector. It is assumed that the angular distribution of the neutron source at the nose is isotropic.

For the free beam condition, the thermal neutron flux at the collimator exit for the reactor power of 30MW is calculated to be 9.4×10^8 and 2.6×10^9 n/cm^2-sec at room and liquid nitrogen temperatures in the filter, respectively. Thermal-to-fast flux ratio is expected to be over 60 and the γ-ray dose is small.

The thermal neutron flux is measured at the collimator exit using Au wire and/or foil. At the reactor power of 24MW, it is 8.34×10^8 and 1.2×10^9 n/cm^2-sec at room temperature and liquid nitrogen temperature at the filter, respectively. When the measured flux is compared with the calculated one, the former is about 10% higher than the latter at room temperature for the filter. At the beam tube nose, the component of neutron source towards the exit is calculated to be 10% higher compared with that for an isotropic source distribution. Thus, the difference is thought to be from the assumption of an isotropic source distribution in the calculation. At liquid nitrogen temperature for the filter, however, the flux is measured to be 43% lower than the calculation. This is deduced mainly due to the difference between the cross sections used in the MCNP calculation and the actual one of the Bi single crystal. The measured cross section of a Bi single crystal at room temperature is compared with the calculated one in Fig. 3. There is a large difference between the two.

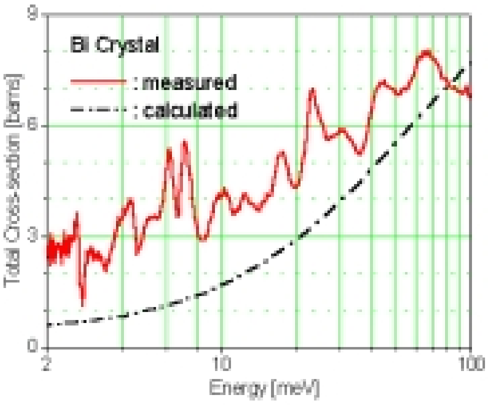

Fig. 3 The total neutron cross section of Bi single crystal at room temperature

2.4 Irradiation Room

Since the irradiation room is the only convenient space in the reactor hall available for the temporal surgical operation before and after the patient's irradiation, the room is designed to be spacious. The large space is necessary for other experiments such as DNR. It also provides a 180° arc with at least a 2m radius centered at the irradiation position for various alignments of a patient's bed.

The beam direction and the patients position relative to the beam direction should be accurately known because focusing the neutron beam is very important. Two grooves are prepared in the floor, which are parallel to the beam line.

A neutron shield composed of borated plastic sheets and boron glass surrounds the patient during the irradiation. A neutron shield tent prevents activation of materials inside the room and allows quick access for the medical team into the room after irradiation. A boron glass above the patients head allows for monitoring of the patient by a video camera.

The radiation level in the room is kept sufficiently low during the preparation and post actions of irradiation due to a water shutter. The dose outside the room is also low from the viewpoint of radiation protection. The distance from the collimator exit to the inner surface of the wall is 180～550cm and the dose rates at those distances are calculated to be 4～40 mSv/hr. Considering the available room space, the concrete shield thickness is decided to be 50cm. Doses in some areas are measured above the prescribed limit and those areas are reinforced with an additional shield.

3. PGNAA System

Boron concentration in the biological samples or patient's blood should be measured at the BNCT site. To measure the boron concentration, a PGNAA system is developed using neutron diffraction technology. It is installed above the shield of a beam tube adjacent to the BNCT facility. A spare neutron beam from a dedicated beam instrument is diffracted upward using pyrolytic graphite to obtain almost pure thermal neutrons at the target position. The measured thermal neutron beam flux is about $1\text{x}10^8$ n/cm^2-sec at the sample position with an Au Cd ratio of 266. It's sensitivity for boron concentration measurement is less than 1ppm. The PGNAA system can be used for other multi-element analysis and has a Compton suppressor for its better performance. Its gamma spectrum for a standard sample is almost comparable with a case using guided cold neutrons. Fig. 4 shows the PGNAA facility.

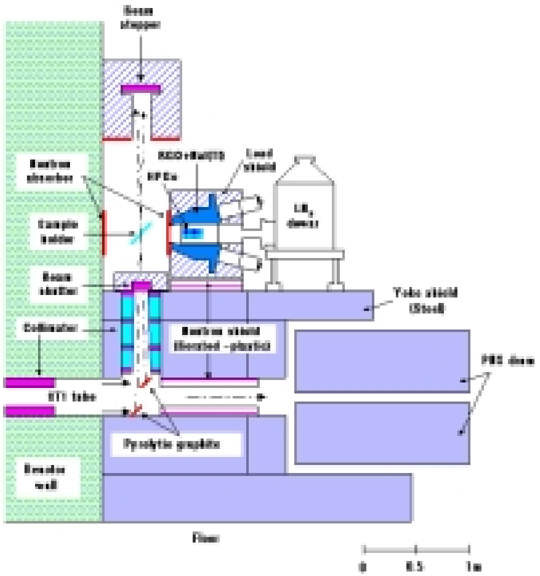

Fig. 4 Schematic Drawing of the PGNAA System

4. Other Application

The prepared BNCT facility can provide a high thermal neutron flux with low fast neutron flux and γ radiation. The angular distribution of the thermal neutron flux at the collimator exit is highly forward. The beam is almost parallel if it is more than 1m distant from the collimator exit. The intensity of the parallel beam is about 5×10^8 n/cm^2-sec. The high beam intensity and the wide space in the irradiation room provide an excellent condition for not only the DNR but also other experiments requiring a pure thermal beam. Some tests showed its good performance for the DNR.

5. Conclusion

The thermal BNCT facility was developed in HANARO. High pure thermal neutrons of which the free beam intensity is more than 1×10^9 n/cm^2-sec is possible using single crystals of Si and Bi. The facility is very good for DNR as well. The spacious irradiation room was prepared for a temporal surgical operation and for DNR. A water shutter makes the reactor operate continuously regardless of the BNCT activities. The PGNAA system was also developed using pyrolytic graphite to measure the boron concentration in the biological samples and patient's blood. The commissioning results of the BNCT facility and PGNAA system confirm that they can be used for BNCT.

It is not expected that the role of HANARO for BNCT will continue for a long time whether the worldwide BNCT research results are a success or not. However, the BNCT research will continue in Korea and the HANARO BNCT facility should have an important role in this research. Since the use of this facility for BNCT would not be frequent, it is desired that the application of the facility will be used for other purposes, if possible. High thermal neutron flux and a spacious room are believed to be good conditions for various applications.

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References

1. Current Status of Neutron Capture Therapy, pp.89-95, IAEA-TECDOC-1223. IAEA, May 2001.
2. A.K. Freund, Cross-sections of Materials Used as Neutron Monochromators and Filters, *Nucl. Inst. Methods*, Vol. 213, pp. 49-501, 1983.