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Neutron spectral fluence measurements using a Bonner sphere spectrometer in the development of the iBNCT accelerator-based neutron source

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ABSTRACT

The neutron spectral fluence of an accelerator-based neutron source facility for boron neutron capture therapy (BNCT) based on a proton linac and a beryllium target was evaluated by the unfolding method using a Bonner sphere spectrometer (BSS). A ^{3}He-proportional-counter-based BSS was used with weak beam during the development of the facility. The measured epithermal neutron spectra were consistent with calculations. The epithermal neutron intensity at the beam port was estimated and the results gave a numerical target for the enhancement of the proton beam intensity and will be used as reference data for measurements performed after the completion of the facility.

1. Introduction

Boron neutron capture therapy (BNCT) was developed using reactor-based neutron sources, and considerable work has been done on characterizing reactor-generated neutrons in clinical studies of BNCT (Auterinen et al., 2004; Sakurai and Kobayashi, 2000). Recently, accelerator-based neutron sources as an alternative to reactor-based neutron sources for BNCT have been developed (Tanaka et al., 2009; Kreiner et al., 2014). Each facility chose their best combination of neutron-source components. The specifications of accelerator-based neutron sources, namely, the kind of beam particle, beam energy, neutron production reaction, and moderator and filter materials, vary depending on concepts of the facility, such as the facility size, neutron yield efficiency, and level of activation. Characteristics of generated neutron beam, especially neutron energy distribution, are different for each facility. Therefore, it is important to experimentally determine the spectral neutron fluence, as well as to perform a prior evaluation using Monte Carlo calculations.

A project team headed by the University of Tsukuba, called the iBNCT, is developing an accelerator-based BNCT facility at the Ibaraki Neutron Medical Research Center under the framework of the Ibaraki International Strategic Zone (Kumada et al., 2014). The iBNCT employs a ^{9}Be(p,n) reaction using an 8-MeV proton beam to generate neutrons. The 8-MeV proton beam is generated using a radio-frequency quadrupole (RFQ) linac and a drift tube linac (DTL) (Yoshioka et al., 2014). The RFQ + DTL type proton linac has a good track record as a front-end linac in the Japan Proton Accelerator Research Complex (J-PARC) facility. The iBNCT team plans to generate 10-mA and 8-MeV proton beams using the RFQ + DTL accelerator, and send them to a 0.5-mm-thick beryllium target (Kumada et al., 2015). This combination was adopted to maintain a low level of activation while also generating a clinical level intensity neutron yield. The expected epithermal neutron flux at a beam port after the moderator and filter assembly is 10^{9} cm^{-2} s^{-1} (Kumada et al., 2014). As of 2015, the iBNCT facility has achieved the acceleration and transporting of an 8-MeV proton beam to the target assembly and has successfully generated neutrons. Current work at the facility is focused on enhancing the beam intensity.

The unfolding method using a Bonner sphere spectrometer (BSS) is widely used technique for measuring neutron spectral fluence (Bramblett et al., 1960; Knoll, 2010). The unfolding method using BSS have been applied to measurements of BNCT neutrons (Marek and Viererbl, 2011; Mirzajani et al., 2014). In this study, BSS based on a ^{3}He proportional counter was used for the gamma-ray mixed pulsed neutron field. However, the high event rate of a typical Bonner sphere detector based on the ^{3}He proportional counter for a treatment level intensity neutron beam would disrupt accurate pulse counting. Once an accelerator facility is built and the treatment level intensity is achieved, it is not easy to decrease the intensity by orders of magnitude to allow the

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effective use of a BSS. Under such conditions, measurements are made using activation foil detectors. However, the activation method using activation foil detectors needs complicated techniques and devices to measure the induced activity. In addition, the uncertainty of the on-site induced activity measurements at the BNCT facility might be larger than that for simple pulse counting measurements using a Bonner sphere detector based on a ^{3}He proportional counter because of the traceability chain of radioactive standards. In this study, precise measurements using a BSS based on a ^{3}He proportional counter were performed after installation of the beryllium-target neutron-generation system with a tentative ion source and before a planned upgrade to enhance the beam intensity.

2. Experiment

2.1. Selection of measurement point

The actual treatment will be carried out at the collimator exit, the "beam port." However, if the measurement position is too close to the beam port, neutron scattering between the collimator structure and moderators of the Bonner sphere detectors will affect the Bonner sphere measurements. This effect is specific to the geometrical relationship between the collimator and each Bonner sphere detector, and is difficult to correct. Since this study is concerned with evaluating the neutron source, the measurement position is located far enough from the collimator to avoid any interactions. However, positioning the measurement point too far from the beam port can also be problematic. If the measurement position is too close to the back wall of the treatment room, the ratio of room-scattered neutrons to direct neutrons from the beam port increases and the uncertainty due to the geometrical modeling of the room construction in the Monte Carlo calculations increases. Multiple locations were selected as measurement positions that were not too close to the collimator structure or the back wall and were expected to experience different neutron energy distributions.

The spatial trend of the neutron energy distribution was estimated by Monte Carlo calculations using the PHITS code (Sato et al., 2013). Fig. 1 shows the calculation geometry and positions on the neutron beam axis in the treatment room where the spectra were evaluated. The simulation geometry includes the beryllium target, target mount system, target cooling system, fast neutron filter, neutron moderator, thermal neutron filter, gamma-ray filter, collimator, and internal structures of the treatment room. Polyethylene panels for suppressing thermal neutrons and a rail for installing heavy equipment and

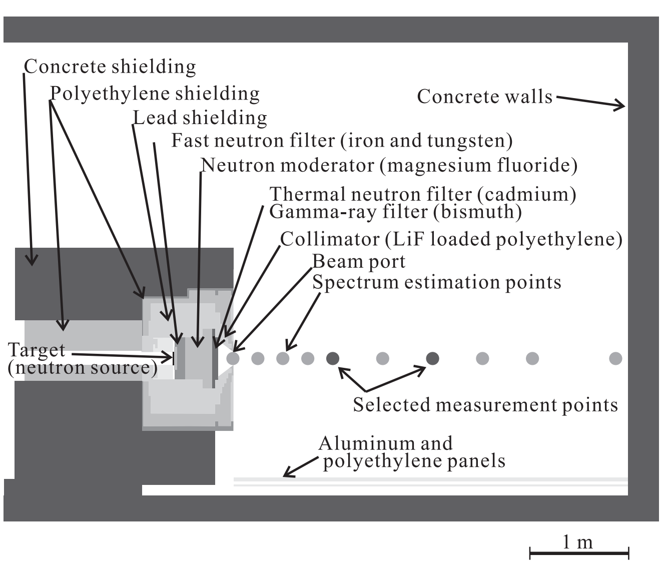

Fig. 1. Schematic of the PHITS calculation geometry. The spectrum estimation points were located on the neutron beam axis.

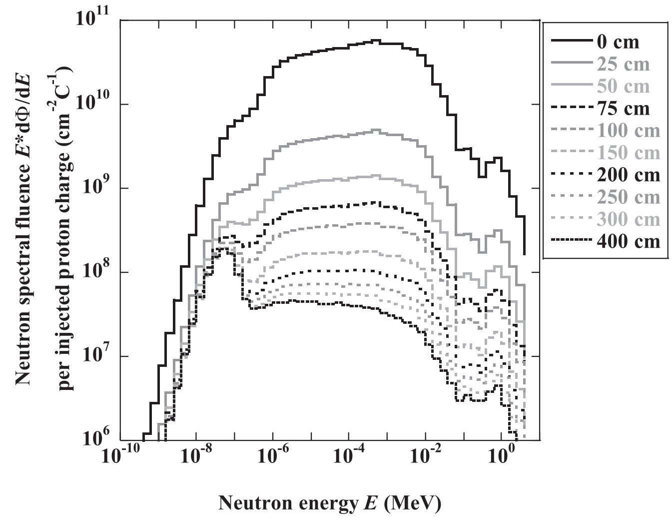

Fig. 2. Neutron energy distributions along the neutron beam axis calculated using the PHITS code.

associated hollow spaces on the floor were re-created accurately in the simulation. In this way, the contributions from scattered neutrons were reproduced in the calculation. Fig. 2 shows calculated neutron energy distributions along the neutron beam axis. It shows that epithermal neutrons from 0.5 eV to 10 keV are dominant and that a peak of thermal neutrons below 0.5 eV hides in a shoulder of the epithermal neutrons near the beam port. The contribution from thermal neutrons increases with distance from the beam port. The epithermal neutron distributions mainly consists of direct neutrons from the beam port whose fluence decreases with distance from the beam port. The thermal neutrons can be mainly attributed to scattered neutrons whose fluence was more dependent on the surrounding structures, such as the walls and the floor, than on the distance from the beam port. Finally, two measurement positions of 1 m and 2 m from the beam port were selected.

2.2. Equipment and methods

The neutron spectral fluence in the treatment room of the iBNCT facility was measured by the unfolding method using a ^{3}He-proportional-counter-based BSS. In the unfolding method using the BSS, the neutron spectral fluence is evaluated from multiple Bonner sphere detector measurements with different response functions as an inverse problem (Wiegel and Alevra, 2002; Knoll, 2010). The neutron spectral fluence at the measurement positions was calculated beforehand by the PHITS code. The calculated neutron spectral fluence is used as a default spectrum in the unfolding procedure. Fig. 3 shows response functions for Bonner sphere detectors using a ^{3}He proportional counter (SP9/15.5/Kr 0823-202; Centronic Ltd). The effective ^{3}He gas pressure in the ^{3}He proportional counter was 0.056 atm. The moderator material was high-density polyethylene and their density was evaluated to be 0.95 g/cm^{3} by measurement of its weight and volume. The diameter of the candidate moderators ranged from zero (bare, i.e., no moderator) to 10 in. The energy of neutrons generated by the iBNCT system distributes below 6.1 MeV (Yoshioka, 2016), and epithermal neutrons from 0.5 eV to 10 keV are most important in this study. An objective of these measurements was to confirm that the moderator and filter assembly of the neutron source worked effectively and that the expected neutron energy distribution was achieved at the measurement point. An effective combination of Bonner sphere detectors (see Table 1) was carefully selected to realize good diversity of response functions in the epithermal energy region, as shown in Fig. 3.

The beam current was reduced as much as possible within the stable operation range. While the average intensity of the generated neutrons