Benchmark Experiments for Cyclotron-based Neutron Source for BNCT

IV. 4. Benchmark Experiments for Cyclotron-based Neutron Source for BNCT

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Introduction

Boron Neutron Capture Therapy (BNCT) is promising treatment for brain tumors such as glioblastoma multiforme, which are at present considered to be inoperable. BNCT relies on two components, ^{10}B-doped pharmaceuticals and neutrons for irradiation. The ^{10}B component, which is delivered preferentially to the tumor cells, is administered to the patient, who is subsequently irradiated with an external neutron beam. The ^{10}B (n,α) ^{7}Li reaction, on which BNCT is based, has a large cross section of ~3800 barn for thermal neutrons and produces two particles, α and ^{7}Li, with high linear energy transfer (LET) and relative biological effectiveness (RBE). The mean free path of the particles in cells is about 10 μm and 5 μm for α particles and for ^{7}Li, respectively. Considering that the mean cellular diameter is of the order of 10 μm, it is possible that BNCT may act selectively in killing cells.

The use of epithermal neutrons in BNCT has recently been of increasing interest, taking into account that incident neutrons are moderated in the human body. The accelerator-based neutron sources are also required for the ease of use and the establishment with hospitals. Many groups have been investigating the accelerator-based neutron sources. However they have not been realized yet in practical applications, mainly because of a very high beam current required for accelerators which introduces a serious difficulty in target cooling. In the previous study[1)], we found the feasibility of a cyclotron-based BNCT using the Ta(p, n) neutrons at 90° bombarded by 50 MeV protons, and the iron, AlF_3, Al and ^{6}LiF moderators through measurements of angular distributions of neutron energy spectra from Ta(p, n) reaction and simulations using the MCNPX code[2)]. This

cyclotron-based BNCT which requires comparatively low beam power gives similar dose distribution with the other accelerator-based BNCT, and provides a realistic solution to the realization of the accelerator-based BNCT.

In order to realize the cyclotron-based BNCT, it is required to validate the accuracy of the simulations by the measurements. Here in this study, we measured the neutron energy spectra behind the moderator and the distribution of thermal neutrons in an acrylic phantom by using the gold activation foils through the $^{197}Au(n,\gamma)^{198}Au$ reaction at the Cyclotron and Radioisotope Center (CYRIC) of Tohoku University. The method for measuring the intensity of neutrons irradiated to the patient has not been established yet in the BNCT treatment using the epithermal neutrons, and most facilities use the computer code for the treatment planning. Because the neutron energy spectrum behind the moderator is the neutron source in the code, the validation is essential for accelerator-based BNCT. The measurement of distribution of thermal neutrons in a phantom is also very important, because the thermal neutrons directly interact with ^{10}B and dominate the tumor dose.

Experimental method

The experimental arrangement is shown in Fig. 1. The measurements of the epithermal neutron energy spectrum and the thermal neutron distribution in an acrylic phantom were performed at the TOF (Time-Of-Flight) room at CYRIC, which is connected to the 5th target room and has very low background. The experimental arrangements for neutron spectrometry and thermal neutron distribution in a phantom are both shown in Fig. 1. The neutrons were produced from the 3mm thick (stopping-length) Ta target bombarded at an angle of 90° by 50 MeV protons, and extracted to the TOF room through the first and second collimators. The first collimator made of 150 cm thick concrete has a hole shown in Fig. 1. The moderators were set in the second collimator with a hole of 100 cm wide by 50 cm high in a concrete wall of 283 cm thickness between the 5th target room and the TOF room. The front surface of the moderator is 1048 cm distant from the neutron production target. Since this geometrical arrangement is a little different from that in our previous feasibility study[1)] due to a space limitation, the shape of the neutron energy spectrum behind the moderator may be slightly different from simulations. However, its difference is not very serious for validation of simulation. The number of beam particles incident on the target was measured from the current of the target itself which was surrounded by a biased-copper mesh to suppress secondary electrons escaping from the target.

The measurement of the epithermal neutron spectrum was performed with our new multi-moderator spectrometer[3)] and a bare ^{3}He counter with/without the Cd absorber and a conventional Bonner Sphere of 11.6 cm radius moderator developed by Uwamino et al.[4]). The neutron energy spectrum was obtained by unfolding the measured counts with the SAND-II code[5)]. Two initial guesses of the neutron energy spectrum were used in the unfolding procedure. One is calculated spectrum under this experimental geometry with the MCNPX code, the other is the 1/E spectrum.

The measurement of the thermal neutron flux distribution was performed in an acrylic phantom of 30 cm × 30 cm × 30 cm (density: 0.944 g/cm^{3}) by the gold activation technique. The phantom was set at 15 cm behind the moderators. The gold foils of 1 cm diameter by 100 μm thickness were set at 0, 1, 3, 5, 8, 10 and 12 cm depth in a phantom on the beam line. The ^{198}Au gamma ray activities through the ^{197}Au(n,γ) reaction were measured with a HP-Ge detector, whose efficiency was calculated with the EGS4 code[6)].

Result and Discussion

Figure 2 shows the comparison of measured and calculated neutron energy spectra behind the moderator. Good agreement between the calculation and the measurements could be obtained. The energy spectrum gives two peaks at thermal energy of ~0.1 eV and at epithermal energy of ~10 keV. The former peak component mainly comes from the neutrons scattered down to thermal energy by the surrounding bulky concrete and the latter peak component is the neutrons moderated through the moderator assembly which can be used for BNCT.

Figure 3 shows the comparison of the depth distribution of measured and calculated reaction rates of ^{197}Au(n,γ)^{198}Au in an acrylic phantom. The calculations agree with the measurements within ~20 % over the depth of 16 cm. The calculations at the depth shallower than 8 cm underestimate the measurements, which is the similar as the result for measuring the neutron energy spectrum. We consider that these underestimations may come from underestimation of the neutron-production yield from the Ta(p,n) reaction. The calculation using the LA150 cross-section data[7]] underestimates the measurement in the energy range lower than ~5 MeV[1]]. This underestimation may give a strong influence on the results in this study. While at the deeper position, the calculations of the reaction rates overestimate the measurements. This may be because the measurements of gamma rays emitted from ^{198}Au have the large uncertainties due to the insufficient radioactivities. We

could not get the higher neutron flux at the irradiation points in this experimental arrangement.

Because the discrepancy between the measurement and calculation was found for the thermal neutron flux distribution in the phantom as the above, we performed the measurement using the mono-energetic neutrons at Fast Neutron Laboratory (FNL) of Tohoku University. Figure 4 shows the comparison of measured and calculated reaction rates of $^{197}Au(n,\gamma)^{198}Au$ in an acrylic phantom by 8 keV neutrons. As shown in the figure, the result is the same as those using the continuous energy neutrons at CYRIC. From these the results, the above mentioned discrepancy may be arising from the problem in the MCNPX code or the cross section data. We will need to investigate further the cause.

Reference

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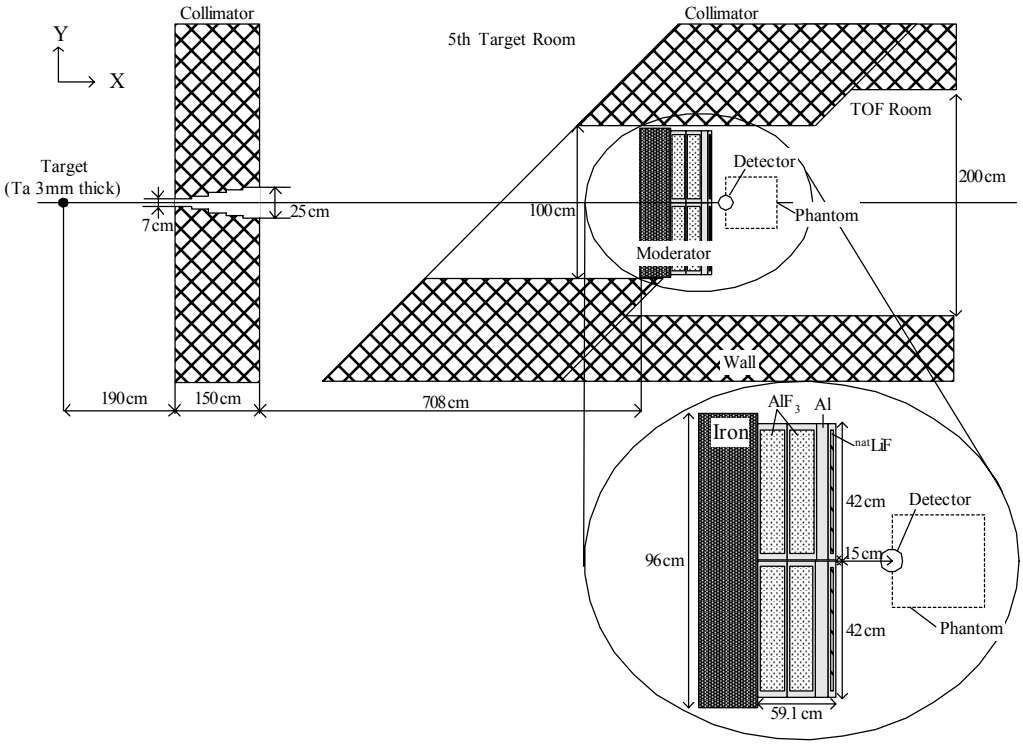

Fig. 1 Cross-sectional view of the experimental setup.

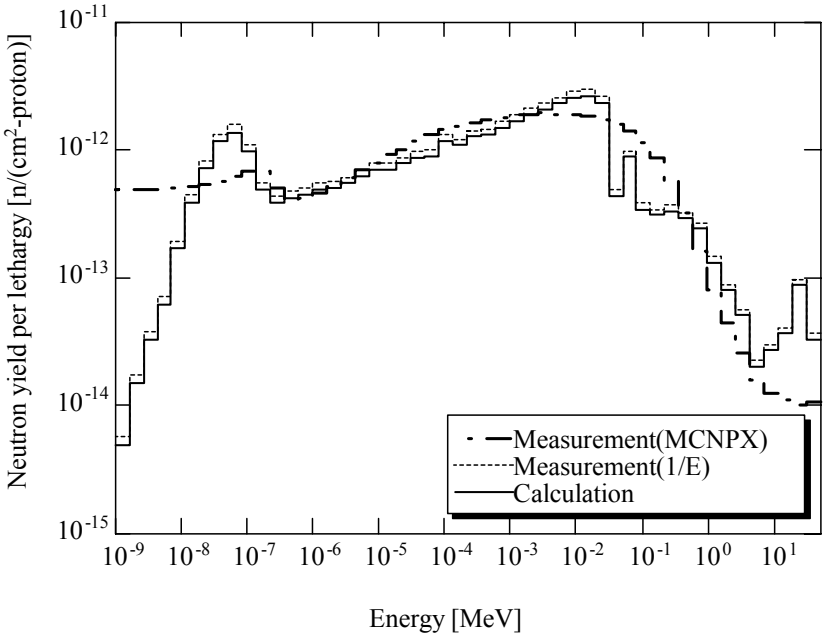

Fig. 2 Comparison of measured and calculated neutron energy spectra behind the moderator.

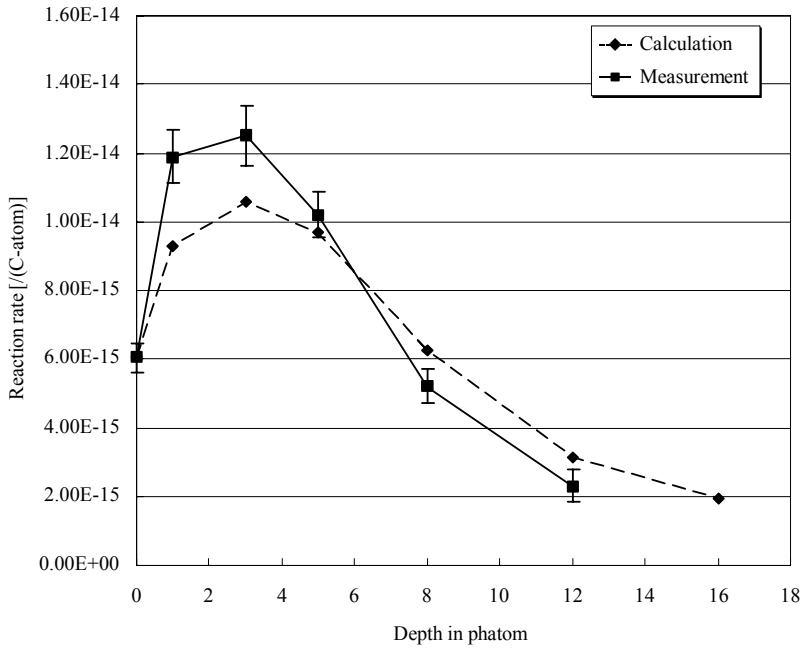

Fig. 3. Comparison of measured and calculated reaction rates of $^{197}Au(n,\gamma)^{198}Au$ in an acrylic phantom put behind the moderator at CYRIC.

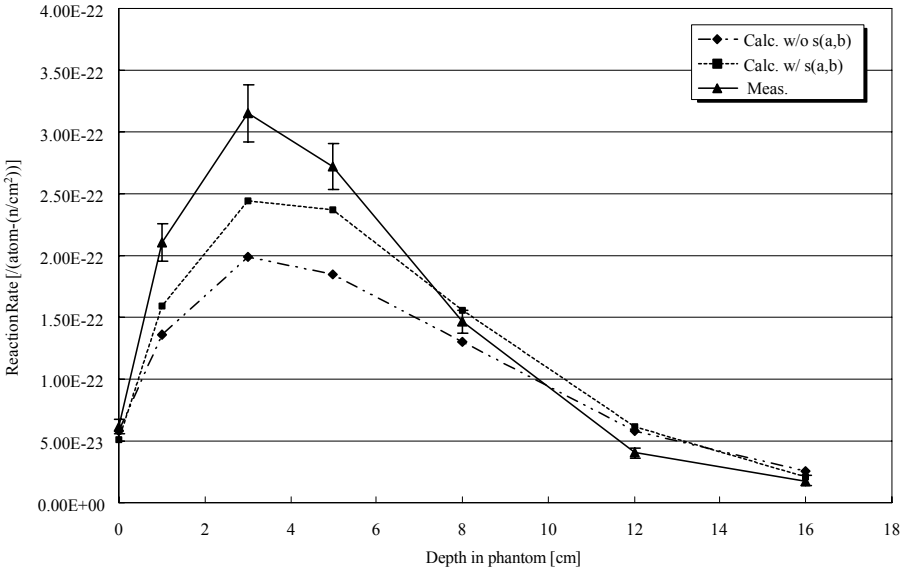

Fig. 4. Comparison of measured and calculated reaction rates of $^{197}Au(n,\gamma)^{198}Au$ in an acrylic phantom by 8 keV neutrons at FNL.