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1 Nagoya University Accelerator-based Neutron Source (NUANS)

1.1 Introduction

Boron neutron capture therapy (BNCT) is the most attention radiotherapy that can individually destroy cancer cells based on the ^{10}B(n, a)^{7}Li reaction between boron and neutrons. Research reactors were previously used as a neutron source for BNCT, but most research reactors have already closed or are in the process of shutting down. Accordingly, in lieu of research reactors, several accelerator-driven neutron sources have been constructed or are under construction worldwide.

An accelerator-based neutron source that combines a high-power accelerator and a lithium (Li) target is very advantageous for BNCT from a neutronic point of view. At Nagoya University, we have been developing a sealed Li target with a unique structure and have conducted an accelerator-based neutron BNCT project.

1.2 Nagoya University Accelerator-based Neutron Source (NUANS)

1.2.1 Accelerator

In 2015, an electrostatic DC accelerator (Proton-Dynamitron, Ion Beam Applications SA) with proton energy of 2.8 MeV and a maximum current of 15 mA was installed at Nagoya University. Figure 1 shows the appearance of the accelerator. We assembled the beamline, started beam conditioning, and completed the HV conditioning (3.1MV) in 2017.

The proton beam trajectory is controlled by three quadrupole magnets and a set of steering magnets. To estimate the spatial variation of the beam size over the beamline, beam transport analysis was performed by a linear optics model (the 6 by 6 thick lens quadrupole model). In addition, as a beam scanning system was introduced to reduce the heat load on the target, we succeeded in expanding the beam irradiation area. We were able to transport a high-current beam of 8 mA by using beam analysis and beam scanning in 2020.

1.2.2 Sealed lithium target

A unique developed sealed lithium (Li) target shown in Fig. 2 has a structure where Li metal settles on a cooling plate covered with titanium (Ti) foil. High heat removal efficiency could be achieved by inducing turbulent flow by developing a ribbed cooling water channel [1]. The basic design and production of the sealed Li target structure have been completed, and an endurance test by proton beam irradiation is currently being conducted. No damage was observed on the Ti foil after proton beam irradiation with a beam power density of 5.7 MW/m^2 for a total of 50 h.

1.2.3 Beam shaping assembly

The beam shaping assembly (BSA) of NUANS has a unique system with a nozzle for a compact gantry system. Previous designs and preliminary experiments have shown that the neutron field emitted from the nozzle conforms to International Atomic Energy Agency Technical Documents (IAEA-TECDOC-1223) [2, 3]. Improvement in the BSA and nozzle led to more therapeutically suitable neutron generation.

1.2.4 Neutron characteristics

The spatial distribution of thermal neutron in the water phantom was measured by the gold foil activation method. The current of the proton beam used in the experiment was 4mA. The thermal neutron flux was evaluated to be 2.5 × 10^8 n/cm^2/s at a distance of about 20 mm from the beam incident surface of the water phantom.

1.3 In Vitro experiments

As the first step to evaluate the performance of NUANS, "in vitro" tests had been performed by using human squamous cancer (SAS) cells. SAS cells were soaked in a

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Fig. 1 Proton-Dynamitron

medium of 200 ppm boron-phenylalanine (BPA) for over 24 h before the neutron irradiation. The neutron flux had a comparatively flat distribution in the radial direction of the BSA extraction port (12 cm in diameter) and nine 0.6-mL tubes could be set in the irradiation area. Each tube contained a cell suspension of 5×10^4 cells/0.5 mL and was set in an acrylic case dipped on a water phantom for neutron irradiation.

The neutron flux was almost constant during irradiation. The thermal neutron flux was measured in all batches to be about 2.6×10^7 n/s/cm^2 at the phantom current of 0.5 mA. The total dose was controlled by changing the neutron irradiation time from 10 to 70 min. The gamma-ray dose measured by ionization was 0.3 Gy/h. Figure 3 shows the comparison between the control group without BPA and the BPA group. The BPA group showed neutron fluence-dependent cancer cell damage, while the survival rate of the control group was approximately 1.0 without regard to increase neutron fluence. This suggests that NUANS is a device suitable for BNCT that has a known gamma-ray contamination rate.

1.4 Conclusion

We are working on adjusting the proton beam current to 15 mA and improving the sealed Li target to obtain

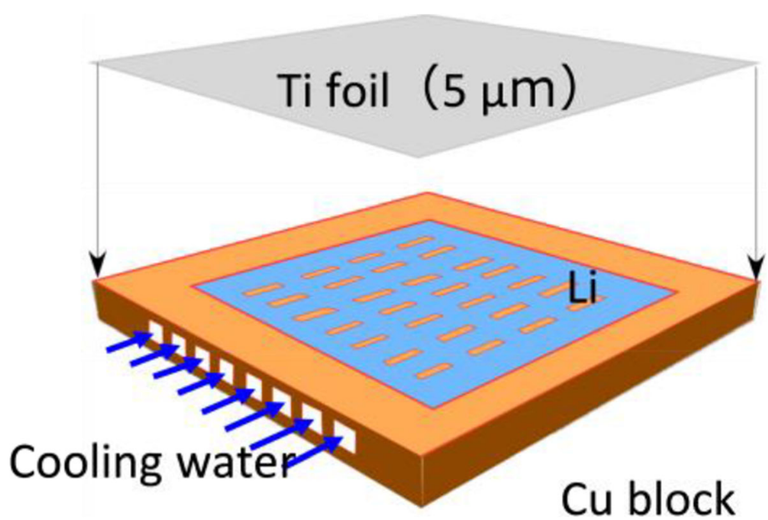

Fig. 2 Sealed Li target

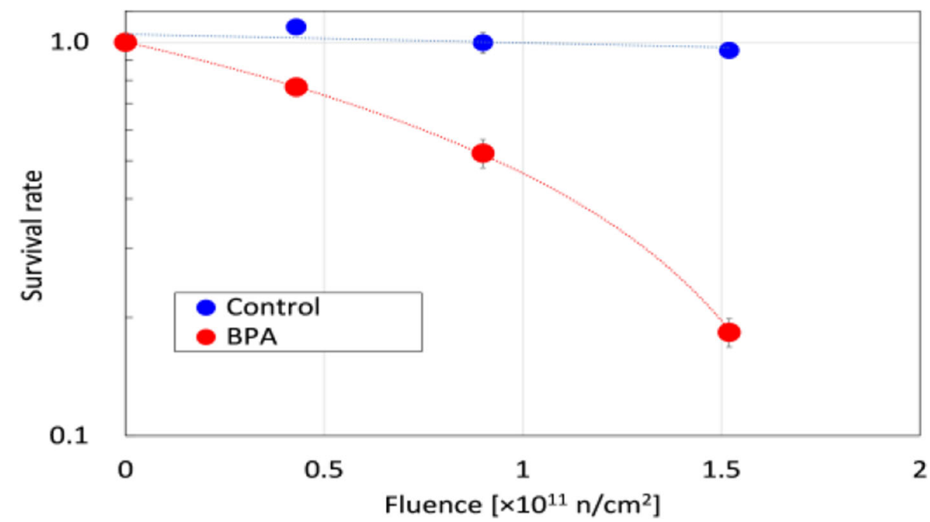

Fig. 3 Comparison between the control group and the BPA group

an epi-thermal neutron flux of 1×10^9 n/cm^2/s. We are also preparing to conduct in vivo experiments in the near future.