Simplified Neutron Detector for Angular Distribution Measurement of p-Li Neutron Source*)

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Boron Neutron Capture Therapy (BNCT) is one of the most promising cancer therapies using ^{10}B(n, α)^{7}Li nuclear reaction. Because nuclear reactor is currently used for BNCT, the therapy is much restricted. Many kinds of accelerator based neutron sources for BNCT are being investigated worldwide and p-Li reaction is one of the most promising candidates because the emitted neutron energy is comparatively low and no gamma-ray is produced. To use p-Li neutron source for BNCT, measurement of the angular distribution is important. However, the energy of neutrons changes depending on the angle with respect to the proton beam, e.g., the energy of forward emitted neutrons are about 700 keV and it is 100 keV for backward direction. So a neutron detector, the efficiency of which is not dependent on energy, is needed. Though so-called "Long Counter" is known to be available, its structure is complicated and moreover it is expensive. Thus we have designed and developed a simplified neutron detector using Monte Carlo simulation. We verified the developed detector experimentally and measured the angular distribution in detail for p-Li reaction by using it. The obtained results were compared with analytical calculations.

Keywords: neutron detector, neutron source, Boron Neutron Capture Therapy, accelerator, p-Li

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1. Introduction

The number of patients of cancer is increasing every year and the efficient treatment method is expected. And the aging of population needs less invasive therapy method. Boron Neutron Capture Therapy (BNCT) is one of the least invasive cancer therapies using ^{10}B(n, α)^{7}Li nuclear reaction [1]. BNCT utilizes high flux thermal or epithermal neutron. Because nuclear reactor is currently used for BNCT, the therapy is much restricted [2]. Many kinds of accelerator based neutron sources for BNCT are being developed worldwide and p-Li reaction is one of the most promising candidates because the emitted neutron energy is comparatively low and no gamma-ray is produced from p-Li reaction [3].

To use a p-Li reaction for BNCT, measurement of the angular distribution and energy distribution is important. In this study, we tried to measure the angular distribution. The reason is in the following: At present, there are no simple spectrometers especially for neutrons having energies less than 1 MeV. In addition, the p-Li reaction is a two-body process, which means that the neutron energy can be calculated theoretically, if the emission angle is fixed. For the BNCT study, it is thus more crucial to measure the angular distribution than the energy distribution. And for the angular distribution measurement, not only the flux intensity of generated neutrons, the energy also depends on the neutron emission angle with respect to the proton beam [4]. The values of forward emitted neutrons and backward ones are about 700 keV and 100 keV, respectively. So a neutron detector, the efficiency of which is not dependent on energy, is needed to measure the angular distribution. Though so-called "Long Counter" is also known to be available for that purpose, its structure is complicated and moreover it is expensive.

Thus we have developed a simple neutron detector with constant efficiency for 100 - 700 keV neutron using Monte-Calro simulation results. The developed detector was inexpensive, small-size and easy-to-use than the conventional detector especially to measure p-Li neutrons utilized for BNCT. The developed detector was tested by using D-T and Am-Be neutron sources to confirm the accuracy of calculation. Then we measured the angular distribution from the p-Li neutron source using a Dynamitron accelerator of Tohoku University, Japan.

2. Design of the Detector

Figure 1 shows a conceptual arrangement before the design calculations. To make a constant-efficiency neutron detector, we employed a ^{3}He proportional counter, which has 2 inch in diameter and the pressure was 1 MPa, covered with a polyethylene moderator, because ^{3}He has high sensitivity to thermal neutrons. Neutrons produced in a target lithium are incident to the front side of our detector. They are counted by the ^{3}He counter after moderated in

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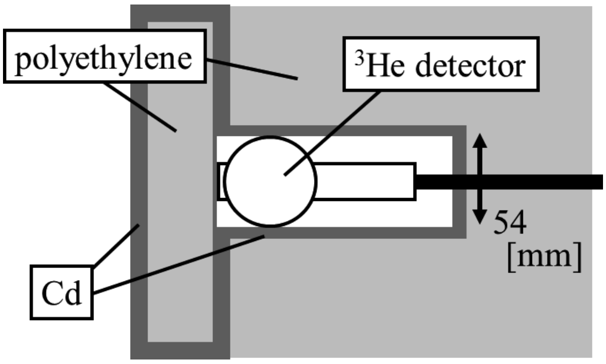

Fig. 1 Conceptual arrangement before the design calculations. p-Li neutrons are moderated in the front polyethylene. And the scattering neutrons from wall are shielded with side and back polyethylene and cadmium layers.

the front side polyethylene. A front surface cadmium was used to shield thermal neutrons scattered from the wall of the experimental room. When the thickness is adequate, the count rate becomes constant for various neutron energies.

On the other hand, scattered neutrons from the wall of the experimental room are incident to side polyethylene. They cannot reach the ^{3}He detector because they are moderated in the side polyethylene and absorbed by the cadmium. So our detector seldom counts the scattered neutrons from the wall.

Simulation calculations were performed to investigate the optimum amounts of moderator and shielding materials to shield scattered neutrons and to estimate the detector efficiency for 100 - 700 keV source neutron using MCNP-5 (a general Monte Carlo N-Particle Transport Code, version 5) [5]. JENDL 4.0 was used as a neutron cross section library [6]. The number of history was selected appropriately so that the standard deviation is less than 3%.

3. Calculation and Design Results

Calculated relative increase due to scattered neutrons in the wall is shown in Fig. 2 as a function of surrounding polyethylene thickness. The increase effect of scattered neutrons decreases with the thickness of polyethylene. Because the effect becomes saturated for thickness more than 7 cm, 7.3 cm thick polyethylene shield was adopted. The effect of thermal neutron scattering from wall is reduced to less than 10%. Relative detector efficiencies for various thicknesses of the front polyethylene moderator are shown in Fig. 3 as a function of the source neutron energy of 100 - 700 keV. The calculation indicates 3.4 cm thickness of polyethylene is the best and the difference of efficiency is suppressed to be within 9%. Thus we made a neutron detector with 3.4 cm thick front polyethylene moderator and 7.3 cm thick shielding polyethylene (Fig. 4). Figure 5 expresses the relative efficiency of the developed de-

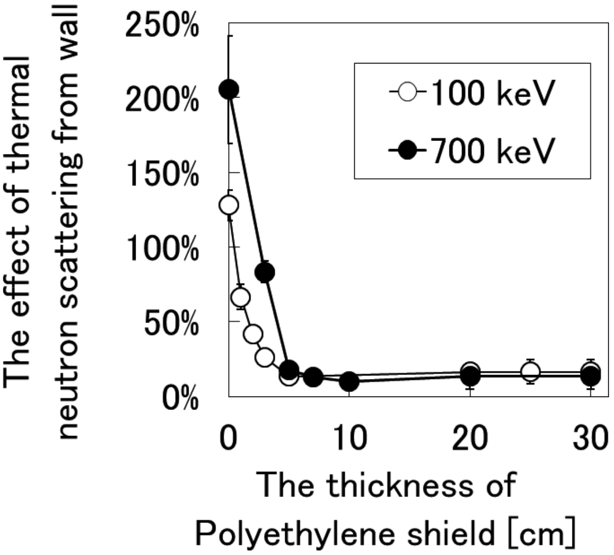

Fig. 2 Calculated relative increase due to thermal neutrons scattered in the wall as a function of the thickness of the shielding polyethylene. The symbol indicates the source neutron energy: ●; 100 keV and ○; 700 keV.

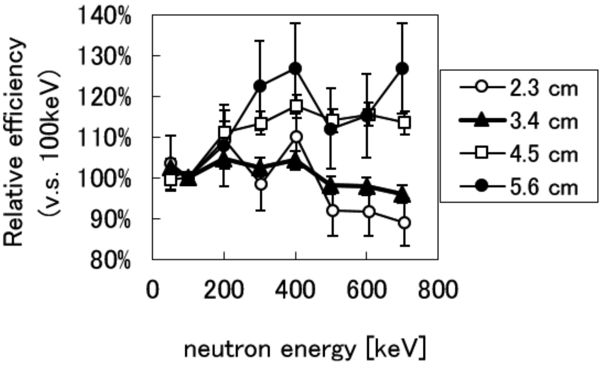

Fig. 3 Relative efficiency as a function of source neutron energy. The symbol indicates the front polyethylene thickness: ○; 2.3 cm, ▲; 3.4 cm, □; 4.5 cm and ●; 5.6 cm.

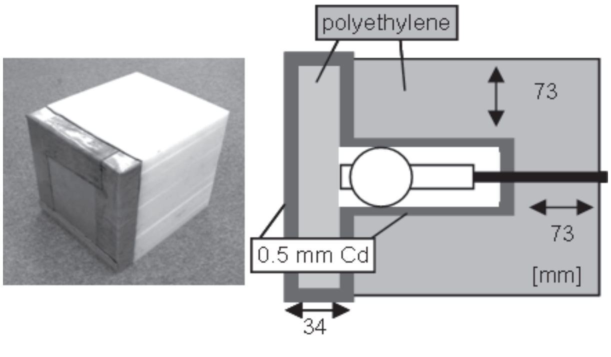

Fig. 4 Photo of produced detector (left) and the design details (right).

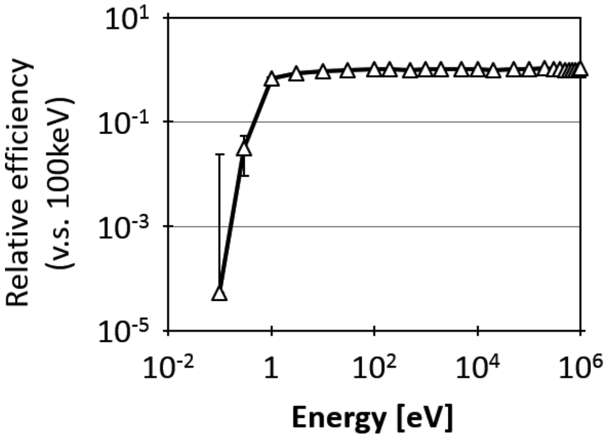

Fig. 5 Relative efficiency of developed detector as a function of source neutron energy.

tector. The efficiency of the detector is almost constant in the range of 100 ~ 700 kev and the efficiency for thermal neutron is less than 1/1000 of that of epi-thermal neutron.

4. Comparison between Test Measurements and Simulation Calculations

To compare the simulation calculation with the experimental result using the developed detector, D-T (without any moderator) and Am-Be neutron sources (with a stainless steel moderator) were used.

The D-T neutron experiment was carried out at the Intense 14 MeV Neutron Source Facility, OKTAVIAN, of Osaka University, Japan. The OKTAVIAN facility is a Cockcroft Walton type accelerator and generates 14 MeV neutrons. The stably produced maximum neutron source intensity is $\sim 1 \times 10^{11}$ n/sec at present. And the character of D-T neutrons of OKTAVIAN was measured very well [7]. In our experiment we put the developed detector in front of the tritium target of OKTAVIAN and the distance was 30 cm. The neutron flux intensity was measured with niobium foils. Niobium is activated with fast neutrons via (^{93}Nb(n, 2n)^{92m}Nb) reaction, which has an energy threshold of 9.1 MeV. Several foils of 1×1 cm^2 by 100 μm in thickness were put in front of the tritium target.

The Am-Be neutron source generates 2.4×10^6 n/s (4.6×10^{10} Bq) in a double-sealed stainless steel casing and the size was 3.5 cm $\phi \times 7$ cm. The distance from the Am-Be neutron source and the developed detector was 30 cm and a 30 cm thick stainless steel block was put into the interspace to moderate and make neutron energy spectrum with a peak at 300 keV. The energy spectrum passing through the stainless steel moderator was calculated using MCNP-5 (Fig. 6).

The efficiency (count per source neutron) of ^{3}He detector was measured and compared with the calculation value estimated with MCNP-5 in Fig. 7. The measured count rates were in good agreement with the calculation results. The calculation to experiment (C/E) ratios were 1.01 and 0.97 for D-T and Am-Be sources, respectively.

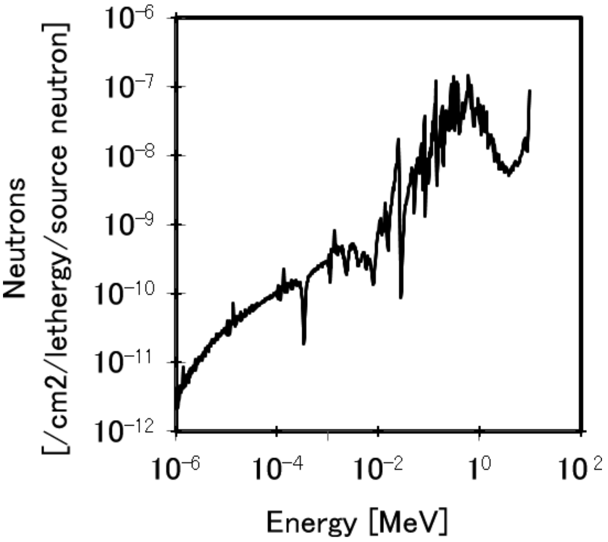

Fig. 6 Calculated energy spectra of the neutron to confirm the accuracy of our simulation calculation to develop the neutron detector. An AmBe neutron source was used and the neutrons were moderated by stainless steel.

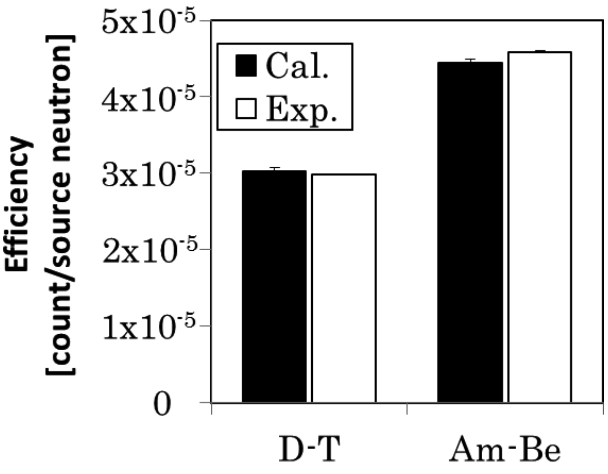

Fig. 7 Comparison between measured and calculated efficiency. The black bars indicate the calculation and the white bars indicate the experimental result.

5. Measurement of p-Li Angular Distribution

We measured the angular distribution of p-Li neutron source with the developed detector using a Dynamitron accelerator in Tohoku university [8, 9]. The proton energy was 2.5 MeV and the beam current was 1 μA. The proton energy was calibrated by measuring the excitation function of the threshold reaction of ^{7}Li(p, n)^{7}Be, which has the threshold energy of 1.88 MeV [10]. The shape of the lithium target was coin-type and the dimensions were $30\,\mathrm{mm}\,\phi \times 2\,\mathrm{mm}$. The number of generated neutrons was relatively monitored by a BF$_3$ counter fixed near the lithium target. The number of signal counts from our developed detector was normalized by the BF$_3$ counts.

The whole number of generated neutrons for 1 μA beam of 2.5 MeV protons was also measured with another new target assembly. The number was estimated by the radioactivity of the ^{7}Be in lithium target, which was produced from ^{7}Li(p, n)^{7}Be reaction. The radioactivity was measured by an HPGe detector.

The detector was rotated around the lithium target and placed at various angles from the beam line. The front side of the detector faces to the lithium target at all times. The distance from the lithium target to the detector was 1 meter or 2 meters fixed based on the results from the simulation calculations carried out beforehand. If it is nearer, the angular resolution becomes worse. If it is farther, the count rate decreases and the influence of scattered neutrons becomes larger.

We calculated the neutron flux per μA per steradian from the count of the developed detector and a BF$_3$ counter. As a result of measurement, the obtained angular distribution increases with scattering-angle cosine (μ) similar to the previous results. To compare and discuss the result of our experiment, we carried out an analytical calculation using the neutron source reaction code, DROSG-2000 [11]. Figure 8 shows the C/E ratio between the obtained result and the thick target yield calculation result by DROSG-2000. It is found that there is a valley in the C/E curves. We expected this was due to the structure of the lithium target assembly. Thus we corrected the distribution for the influence of it using MCNP-5 and the absolute number of neutrons per 1 μA for the proton energy of 2.5 MeV was obtained by integrating the obtained angular distribution.

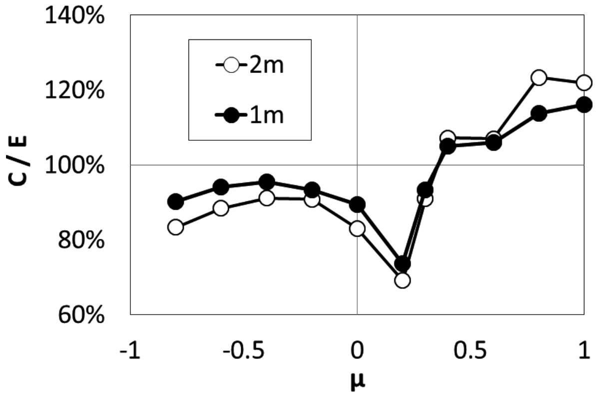

Fig. 8 C/E of angler distribution (DROSG-2000 calculation/ examination result). The symbol indicates the distance from the lithium target to the detector: ○; 2 m and ●; 1 m.

6. Discussion

As a result of comparison of the corrected results with analytical calculation by DROSG-2000 in Fig. 8, the distribution is in fairly good agreement with the analytical calculation within 20% except around $\mu = 0.2$. However, the gradient of angulr-distribution was a little weak than the analytical calculation (C/E > 1 with $\mu \simeq 1$, and C/E < 1 with $\mu \simeq -1$). The difference was larger than the statistical error. There are two reasons to be able to possibly explain this difference. The first is the effect of the scattering neutron from the wall of the experimental room. However, as described in Chap. 3, the developed detector is well shielded from the scattered neutrons with cadmium and polyethylene. Hence, there is little sensitivity for that neutron. The other is the scattering of proton in the target lithium. Accelerated protons are not only absorbed by lithium but also scattered in it before aborption. As a result, in some cases when absorption occurs, the flying direction of proton is not the same as that of the incident proton. The DROSG-2000 calculation does not take into account the changing of the direction of the proton beam caused by scattering in the lithium target. This might be the main reason of the difference. In reality, the gradient calculated by DROSG-2000 is also a little higher than other research results [4, 12, 13]. Though the measurement points were few in those researches and it is thus difficult to calculate the gradients, the results of other researches support our result rather than DROSG-2000 calculation.

The angular distribution may change depending on the precise position of p-Li reaction on the lithium target because neutrons produced in the lithium target have to go through the structural materials in the lithium target before reaching the developed detector. The transmitting length of neutron is changed according to the precise nuclear reaction position in the target. It may consequently lead to the substantial difference at $\mu = 0.2$ in Fig. 8. Though the Li

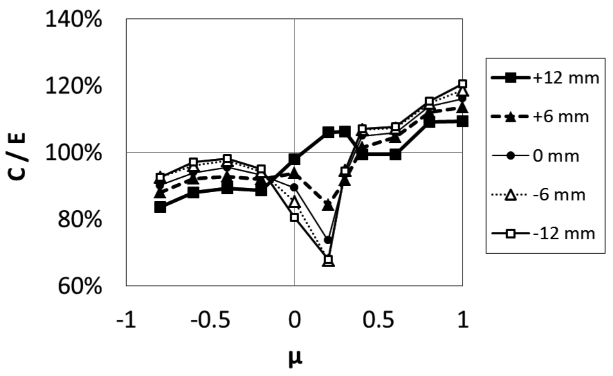

Fig. 9 C/E of angler distribution (DROSG-2000 calculation/ examination result) changing with the precise position. The symbol indicates the distance of the p-Li reaction point from the center of the lithium target: ■; +12 mm, ▲; +6 mm, ●; 0 mm (center), △; −6 mm and □; 12 mm.

target assembly has a quite complicated structure, we estimated the effect roughly. As a result the estimated effects varies from 87% to 153% if changing the position of the p-Li reaction on the surface as in Fig. 9. Since it is difficult to determine the real position experimentally, estimation of the precise correction factor around $\mu = 0.2$ would be a new challenge in the future.

7. Conclusion

p-Li reaction is a promising candidate as a neutron source for BNCT. To use it, measurement of angular distribution is important. We designed and made a simplified neutron detector having constant efficiency in energy range of 100 - 700 keV and measured the angular distribution with a Dynamitron accelerator. The result was in fairly good agreement with analytical calculation by DROSG-2000 except around $\mu = 0.2$. And it was found that the gradient of the angular distribution was a little weaker than the analytical calculation. For the valley of the yield around $\mu = 0.2$, it is thought that it depends on the position of incidence of protons on the lithium target. However, it was difficult to fix the position. To estimate the precise correction factor around $\mu = 0.2$, further studies should be performed in the future.

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