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Development of a new multi-moderator spectrometer for epithermal neutrons

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Measurement of the neutron energy spectrum in the epithermal energy region is very important for accelerator-based Boron Neutron Capture Therapy (BNCT), but the measuring technique is not well established. We developed a new multi-moderator spectrometer using boron-loaded silicon rubber and polyethylene for epithermal neutrons.

In this paper, the response functions of the new multi-moderator neutron spectrometer were calculated with the MCNPX code, and were compared with the measured results in a neutron calibration field using a ^{252}Cf neutron source.

This spectrometer can be applied to measure the neutron spectrum to be used in accelerator-based Boron Neutron Capture Therapy.

Key Word: epithermal neutron, neutron spectrometer, BNCT, response function

I. Introduction

Boron Neutron Capture Therapy (BNCT) is a promising treatment for brain tumors such as Glioblastoma Multiforme, which are at present considered to be inoperable. At present, the beams used in BNCT are thermal neutrons from a nuclear reactor. However, Gliobastoma Multiforme often locates near the center of the brain surrounding normal tissues, while thermal neutrons which have feeble penetration stop in the skin or in other normal tissues. The use of epithermal neutrons in BNCT, especially in accelerator-based BNCT, has recently met increasing interest, taking into account that incident neutrons are moderated in the human body. For example, Yanch et al.[1)] showed that epithermal neutrons in the energy range from 4 eV to 40 keV are most effective in the treatment of a brain tumor at a depth of 7 cm. From such a reason, the measurement of epithermal neutron spectrum to be used for the treatment planning is very important for accelerator-based BNCT. However, the spectrometry of neutrons in epithermal energy region of a few eV to several tens keV is very difficult and the measuring technique is not well established.

This paper describes the development and performance test of a new multi-moderator spectrometer for epithermal neutrons.

This new spectrometer is considered to be applied to validate the cyclotron-based epithermal neutron field for BNCT at CYRIC under designing[2)] at the Cyclotron and Radioisotope Center (CYRIC).

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II. Concept of a new multi-moderator spectrometer for epithermal neutrons

A new multi-moderator spectrometer is similar to the boron-shell spectrometer by Wang et al.[3)] The boron-shell spectrometer was developed for measuring the neutron energy spectra which have peaks in the energy range between 1 eV and 10 keV, in order to overcome the problems of the conventional Bonner Sphere whose response functions have no peaks for neutron energies below 10 keV. The boron-shell spectrometer, which consists of a ^{3}He-filled spherical proportional counter surrounded with a hemispherical boron-shell jacket and a spherical paraffin jacket, has a set of response functions which peak at various positions on the logarithmic energy scale between 1 eV and 10 keV by varying ^{10}B loading in boron-shell jacket and the thickness of paraffin jacket. The neutron spectrum can be obtained through unfolding a set of count rates with different jackets.

Our new spectrometer can obtain a similar set of response functions by varying the thickness of spherical inner and

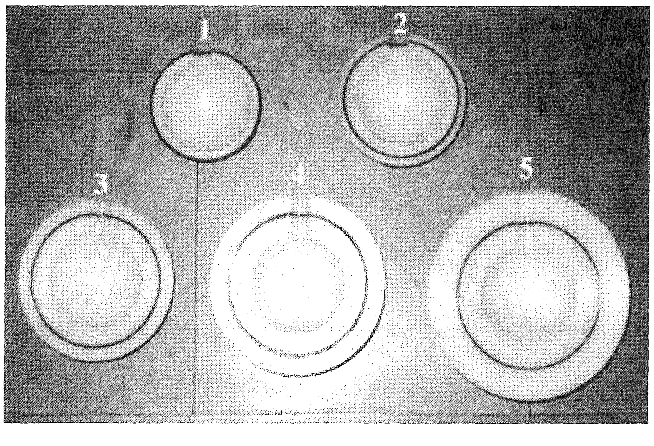

Fig.1: Photograph of new multi-moderators.

outer polyethylene moderators inserting a 1 mm thick silicon rubber loaded with ^{nat}B (50 wt. %) between the polyethylene moderators. The response functions of boron-shell spectrometer have uncertainties due to different boron loadings as described by the authors, while this new spectrometer may have less uncertainty than the boron-shell spectrometer owing to employment of a single ^{10}B loaded rubber. We used a spherical ^3He counter, 5.08 cm in diameter and filled with 10 atm (at 22 °C) ^3He gas (LND Inc.) for neutron counting.

Figure 1 shows the photograph of the cross sections of newly-developed moderators, which are half of spherical moderators. The density of the polyethylene moderators is 0.928 [g/cm^2]. **Table 1** shows the dimension of the new spectrometer, which was optimized by calculations using the MCNPX code[4] as mentioned in the next section.

Table 1: Dimension of a new multi-moderator spectrometer.

Detector Number	Inner polyethylene thickness [cm]	Outer polyethylene thickness [cm]
1	0.64	-
2	0.95	0.64
3	1.43	1.11
4	1.75	1.59
5	1.91	2.54

III. Calculation of response functions

The response functions of the multi-moderator spectrometer were calculated and optimized using the MCNPX code with the ENDF/B-VI cross section library[5]. We worked out the reaction rates of the $^3He(n, p)T$ reaction and the elastic scattering for neutrons of energies higher than 1.02 MeV[8] using incident parallel neutron beams.

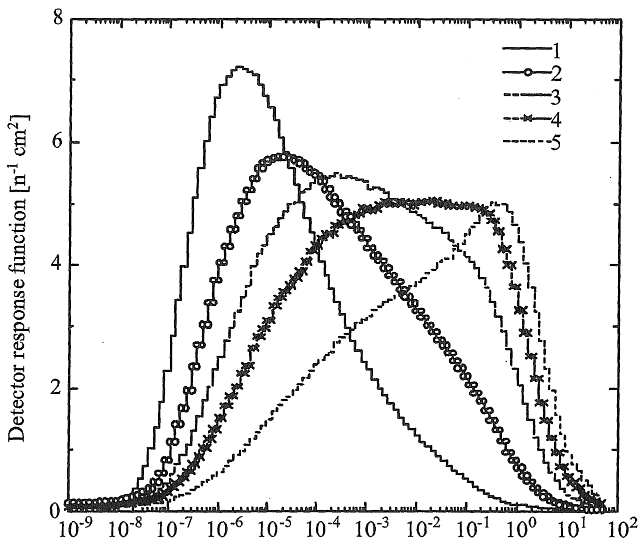

Fig.2 Calculated response functions of a new multi-moderator spectrometer.

First, we calculated the responses of conventional Bonner Sphere in order to validate our calculation by comparisons with the results calculated by Uwamino et al. They used the ANISN[6] adjoint calculation with the ENDF/B-IV[7] cross section library[7] for the calculations of response functions of conventional Bonner Sphere[8].

Table 2 shows the ratio of the responses calculated in this work to those by Uwamino et al. Our calculation agrees with their results within 14 % difference.

Figure 2 shows the calculated response functions of the new multi-moderator spectrometer. Their response functions peak at various positions on the logarithmic energy scale in the energy range from 1 eV to 1 MeV as shown in the figure, and therefore, the neutron energy spectra can be obtained by using an unfolding method with good energy resolution especially in epithermal energy region.

Table2: Ratio of the responses calculated in this work to those calculated by Uwamino et al[8].

Energy of incident neutrons [MeV]	moderator radius [cm]			
	11.6	7.6	5.6	4.1
0.144	1.14	1.02	0.98	1.09
0.565	1.08	1.02	1.03	1.06
5	1.11	1.06	1.13	1.14

IV. Performance test

In order to test the detector performance of the new spectrometer, it is required to perform the measurements in the epithermal neutron calibration filed. However, no epithermal neutron calibration filed is available, because the measuring technique of the spectrometry in the epithermal neutron region is not well established. In this study, therefore, we measured the neutrons from a polyethylene sphere of 35 cm diameter in which a ^{252}Cf neutron source of 7.6×10^5 [n/sec] (on 3 June, 2003) was centered, by using the new spectrometer at the neutron calibration room of the Hot Laboratory at CYRIC, Tohoku University. This neutron spectrum was investigated by Takada[9] with a conventional Bonner Sphere. The present results were compared with the measured data by Takada. Since Takada's data are given both with and without background subtraction, we can compare the neutron energy spectrum which includes room-scattered neutrons using his data without background subtraction.

Figure 3 shows the experimental geometry at the Hot Laboratory. The room is 9.3 m × 6.0 m × 4.6 m height. The centers of the spectrometer and the neutron source were set at 120 cm high from the grating hatch, which is 5 cm thick aluminum and is set at 50 cm high from the floor. The distance of the centers between the spectrometer and the neutron source was 100 cm. The spectrometer and the neutron source were put on the stainless steel supports. All

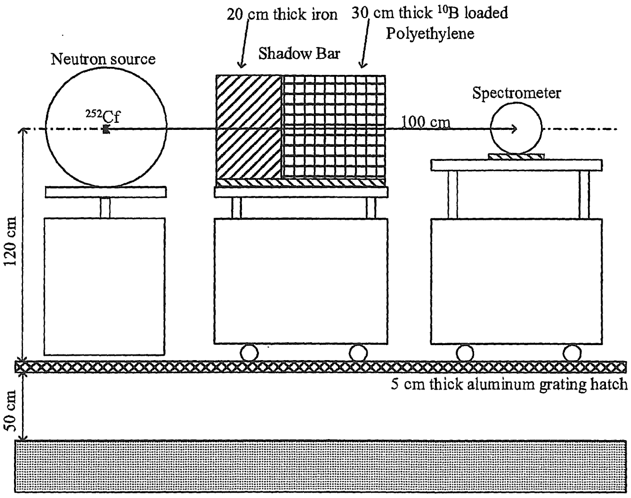

Fig. 3: Experimental geometry at the Hot Laboratory.

the experimental geometry was the same as that of Takada's experiment.

We also performed the measurement with background subtraction. In this case, we did two measurements. One was the geometry using stainless steel supports and the other was that using the polystyrene foam supports in order to decrease the neutrons scattered by the supports. The contribution of the room-scattered neutrons was estimated with a shadow bar, which consisted of 20 cm thick iron and 30 cm thick ^{10}B loaded polyethylene.

In these measurements, we used a bare ^{3}He counter in addition to the new spectrometer with five moderators.

The neutron energy spectra were obtained by unfolding the measured counts with the SAND-II code[10]. An initial guess of the neutron energy spectra used in unfolding was

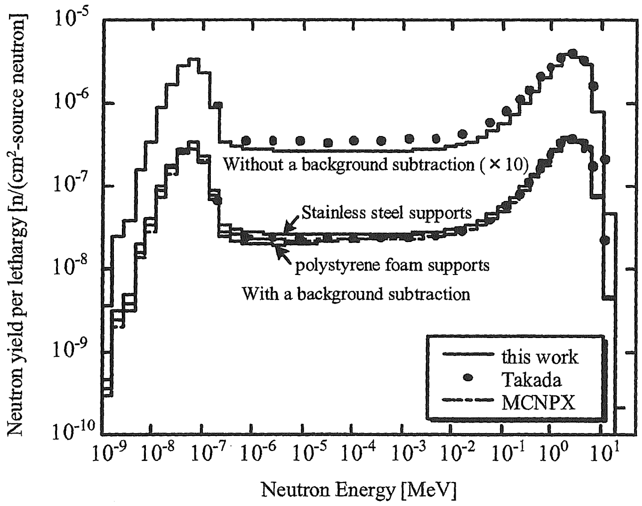

Fig. 4: Measured neutron energy spectra of polyethylene-moderated ^{252}Cf neutron source compared with the MCNPX calculations and Takada's data with and without background subtraction.

calculated with the MCNPX code, for only the data with background subtraction. In this unfolding, we used the response functions calculated with the MCNPX code.

Figure 4 shows the measured neutron energy spectra compared with Takada's data and the MCNPX calculation. In this figure, our measured spectrum without background subtraction agrees with Takada's data within ~20 %. Our two measured spectra with background subtraction using polystyrene foam supports and stainless steel supports also agree well with Takada's data within ~15 %. From these results, we can conclude that the calculated responses have accuracy with ~20 %, and this new spectrometer can measure the neutron energy spectrum in the energy range between thermal to a few MeV. However, we must be careful to the scattered low-energy neutrons as shown in some differences of the results using the stainless steel supports and the polystyrene foam supports, in order to get the results with good accuracy.

VI. Conclusion

We developed a new multi-moderator neutron spectrometer to measure the neutron spectrum in the energy range between thermal and a few MeV, and tested the detector performance. The results agree well with the measured data using a conventional Bonner Sphere. This spectrometer will be efficiently applicable to evaluate the epithermal neutron field for the accelerator-based Boron Neutron Capture Therapy. We have a plan to measure the epithermal neutron field fabricated at the CYRIC for the cyclotron-based BNCT.

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