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A feasibility design study on a neutron spectrometer for BNCT with liquid moderator

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HIGHLIGHTS

- It is necessary to measure neutron spectrum for BNCT to evaluate the radiation exposure dose.
- We designed a new spectrometer using an unfolding technique and a liquid moderator.
- Performance of our assembly was evaluated by simulation for ABNS neutron spectra.
- Finally, its capability of measuring neutron spectrum was confirmed.

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ABSTRACT

Neutrons generated by accelerators have various energy spectra. However, only limited methods are available to measure the whole neutron energy spectrum, especially when including the epithermal region that is normally used in BNCT. In the present study, we carried out the design study on a new neutron spectrometer that can measure such a neutron spectrum more accurately, precisely and with higher energy resolution, using an unfolding technique and a liquid moderator.

1. Introduction

Boron neutron capture therapy (BNCT), based on the $^{10}B(n,\alpha)^{7}Li$ reaction, is a promising radiotherapy for cancers. Cases have been reported only using nuclear reactors as a neutron source; recently, instead of nuclear reactors, accelerator-based neutron sources (ABNSs) are being developed for BNCT (for the latest review about the current status of BNCT see Moss (2014)). However, there are several limitations on ABNSs, e.g., with a low source neutron intensity or a high neutron energy, so that the neutron field of ABNSs generally has a complex neutron spectrum. In addition, the spectrum shape would easily be changed depending on elemental designs of the ABNSs, e.g., the kinds of incident particles, target nuclei and neutron moderators.

To determine the neutron absorbed dose or equivalent dose to patients, we must correctly evaluate each neutron energy spectrum for each ABNS, especially around the epithermal region, which is mainly used in BNCT, as well as additionally in the high energy region to estimate unwanted neutron dose to normal tissues. At present, such spectra are evaluated by a multi-foil-activation method or the Bonner sphere spectrometer (Bramblett et al., 1960) combined with numerical simulations. These methods normally require an unfolding process with a special adjustment code like SAND-II (Griffin et al., 1994). Generally, these methods do not have a very precise energy resolution, or they require an "intelligent" initial guess to obtain reliable results (Thomas, 2010). This is because the number of measured data values is small. In other words, the unfolding process used on these methods is normally underdetermined problem, due to the difficulty to prepare many kinds of activation foils or to prepare a lot of spherical shells to be used as a moderator. Many researchers have made special efforts to tackle this issue. For example, the neutron energy spectra of the Heavy Water Thermal Neutron Irradiation Facility at the Kyoto University Research Reactor (KUR-HWNIF) was evaluated by a multi-foil-activation method using 15 nuclear reactions

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(Sakurai and Kobayashi, 2004). Liu et al. (2013) made 36 kinds of experimental conditions by using "activation-detector-complexes", based on both activation foils and the Bonner sphere. In spite of these efforts, the number of measured data values is not enough and the unfolding process is still underdetermined to measure the high energy resolution neutron spectra for the range covering ten orders of magnitude from thermal neutron energy to the source neutron energy of ABNS.

To resolve this issue and improve the energy resolution, we have carried out a design study of a new neutron spectrometer, using an unfolding technique and a liquid material as a moderator to get a large number of detector response functions for neutron energies in thermal (< 0.5 eV), epithermal (0.5 eV–10 keV) and fast (> 10 keV) regions. In the present paper, we numerically confirm the feasibility of this spectrometer to measure neutron spectra in a wide dynamic range with sufficient energy resolution. And we propose an appropriate material for the liquid moderator.

2. Theory

In this study, a method to detect neutrons after moderating them was employed for neutron spectrometry, based on the following principle. Generally, a neutron detector has its own response for each neutron energy, called the response function. It can be easily changed by modifying the combination of the neutron detection device, neutron moderator and so on, and the function itself is determined depending on the material, thickness, density and so on of the moderator. The detector output signal using i^{th} moderator, $\boldsymbol{M_i}$, is given as eq. (1),

$$\boldsymbol{M_i} = \int \boldsymbol{R_i(E)}\cdot\boldsymbol{\Phi(E)dE} \tag{1}$$

where $\boldsymbol{E}$ is neutron energy, $\boldsymbol{R_i(E)}$ is the response function for the i^{th} moderator and $\boldsymbol{\Phi(E)}$ is the incident neutron energy spectrum. We can obtain the neutron spectrum information by unfolding a set of measured values, $\boldsymbol{M_i}$.

3. Method

3.1. Response function evaluation

The response functions of the detector were evaluated by A General Monte Carlo N-Particle Transport Code, Version 5 (MCNP-5) (X-5 Monte Carlo Team, 2003). The detector model is shown in Fig. 1. For simplicity, the contribution of room-return neutrons was ignored, and therefore the detector shield and incident neutron collimator were not modeled in the calculation to evaluate the response function. As the neutron counter, a ^3He proportional counter was assumed. Candidate materials for liquid moderator were water, heavy water, boric acid solution and trimethyl borate, which are in the liquid state at room temperature. Calculations were carried out according to the following procedures. At first, mono-energetic neutrons were incident to the counter from the liquid moderator side. To simplify the test condition, a broad parallel neutron beam was employed for the incident neutrons, because the target of the detector being developed was neutrons that move toward a specified direction. After that, the detector response was evaluated as the $^3He(n,p)^3H$ reaction rate for each incident neutron energy, between 0.01 eV and 20 MeV for a certain moderator arrangement. This response data set for energy was calculated repeatedly to get the every response function by changing the moderator thickness from 0 mm to 200 mm in 1 mm increments. Examples of the evaluated response function are shown in Fig. 2.

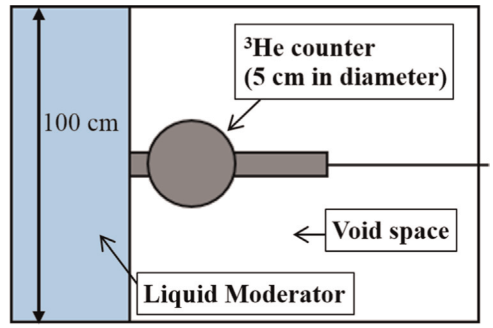

Fig. 1. Detector model. A ^3He proportional counter was assumed as a neutron counter, and the liquid moderator was placed in front of the counter.

3.2. Numerical simulation

Numerical simulation was performed to examine the performance of this spectrometer to measure the neutron energy spectrum. At first, a TRUE neutron spectrum was assumed as shown in Fig. 3. Count rates to be measured by the detector were calculated by a folding process (Eq. (1)) with the evaluated response functions. After that, statistical errors were added to the count rates to simulate the measurement. In this study, we assumed that the numbers of measured counts were large enough to assure that they were following a normal distribution, and a simulation was performed for 0, 1, 2, 5, 10 and 15% additional relative error cases. Finally the neutron energy spectra were estimated by unfolding the count rates. For unfolding process, we used the Bayesian estimation method which has the feature that physically meaningless negative spectral values can be avoided (Iwasaki, 1997).

From the simulation, we considered how the statistical errors should be suppressed to obtain meaningful results and which moderator material should be used in the measurement. At first, the estimated neutron spectrum for each candidate moderator material was examined from the neutron flux deviation ratio, $\boldsymbol{R_{dev}}$ defined as Eq. (2).

$$\boldsymbol{R_{dev}} = \frac{\sqrt{\int_{E_{min}}^{E_{max}} (\boldsymbol{\Phi_e(E)} - \boldsymbol{\Phi_t(E)})^2 \mathrm{d}\boldsymbol{E}}}{\int_{E_{min}}^{E_{max}} \boldsymbol{\Phi_t(E)}\mathrm{d}\boldsymbol{E}} \tag{2}$$

$\boldsymbol{R_{dev}}$ indicates the difference between the TRUE spectrum and the evaluated neutron spectrum. The smaller $\boldsymbol{R_{dev}}$ is, the better the estimated spectrum agrees with the TRUE spectrum. $\boldsymbol{E_{max}}$ and $\boldsymbol{E_{min}}$ are maximum and minimum energy for each energy region, namely, thermal (0 eV < $\boldsymbol{E}$ < 0.5 eV), epithermal (0.5 eV < $\boldsymbol{E}$ < 10 keV) and fast neutron (10 keV < $\boldsymbol{E}$ < 10 MeV) regions. $\boldsymbol{\Phi_t}$ is the TRUE neutron spectrum and $\boldsymbol{\Phi_e}$ is the evaluated neutron spectrum. $\boldsymbol{R_{dev}}$ was obtained for each candidate moderator and examined error cases.

4. Results and discussion

Fig. 3 shows the numerical simulation results. Without statistical errors, each estimated spectrum agreed with the TRUE spectrum for all candidate materials (Fig. 3(a)). For the results with statistical errors, acceptable agreement was seen for some candidates. Example results with an additional error (the case with 2% error of detector response) are illustrated in Fig. 3(b). Fig. 4 indicates the neutron flux deviation ratio and we found that trimethyl borate gave the best results among the candidates, especially in the small error cases.

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