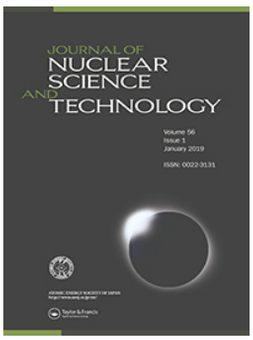

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ARTICLE

Preliminary design study of a simple neutron energy spectrometer using a CsI self-activation method for daily QA of accelerator-based BNCT

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ABSTRACT

For recent boron neutron capture therapy (BNCT), accelerator-based neutron sources have been actively developed in place of reactor-based neutron sources. In this study, a novel neutron energy spectrometer for the daily quality assurance (QA) of BNCT was designed on the basis of a CsI self-activation method for accelerator-based neutron sources. The spectrometer design was optimized in terms of its energy resolution. To verify its applicability to high-intensity BNCT neutron fields, some practical simulations were performed. It was shown that the designed spectrometer was able to evaluate a neutron energy spectrum in approximately 900 s after an instantaneous neutron irradiation. In addition, its energy resolution was sufficient for detecting an unexpected distortion in the spectrum. The results confirm that the designed spectrometer can be employed for the daily QA of BNCT to check that the expected spectrum remains unchanged.

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CsI self-activation method; activation method; accelerator-based BNCT; daily QA; neutron spectrum

1. Introduction

Boron neutron capture therapy (BNCT) is one of the radiation treatments that utilizes an α particle and a Li nucleus emitted during the nuclear reaction between a ^{10}B and a neutron. Large energy of 2.31 or 2.79 MeV, *Q*-value of ^{10}B(n, α) ^{7}Li reaction, is locally deposited to a tumor cell. As the range of these high linear energy transfer (LET) particles (about 9 x 10^{-3} mm and 5 x 10^{-3} mm in tumor cells for an α particle and a Li nucleus, respectively) is approximately equal to size of tumor cells (typically ~ 10^{-2} mm), the BNCT has been used to selectively kill tumor cells. This treatment requires intensive neutron sources of which the typical neutron fluence rate is over 10^{9} cm^{-2} s^{-1}. Recently, instead of conventional nuclear reactor-based neutron sources, accelerator-based neutron sources that can be installed inside hospitals have been developed [1,2].

One of the important quality assurance (QA) procedures for BNCT involves confirming the actual neutron energy spectrum. Because the cross-section of ^{10}B capture reaction depends on neutron energy by the 1/v law, the dose given to tumors and normal tissues are sensitive to small deviations in the incident neutron energy. Generally, the Bonner sphere spectrometer (BSS) has been used to precisely evaluate such neutron energy spectra [3,4]. However, the BSS is unsuitable for quick daily assessments because it involves performing repeated measurements using spherical moderators of different sizes. Therefore, several other approaches have been developed to avoid such complicated procedures. For example, Murata and Miyamura [5] and Tanimura et al. [6] used a position sensitive ^{3}He proportional counter to determine the neutron absorption position along the neutron beam axis for the evaluation of neutron energy spectra. Harano et al. [7] used two proportional counters inside a single cylindrical neutron moderator to evaluate the averaged energy of neutrons. Gómez-Ros et al. [8] proposed a cylindrical neutron spectrometer by embedding seven semiconductor-based thermal neutron detectors in a single moderator.

Unfortunately, global standards or requirements for a neutron spectrometer for the BNCT daily QA have not been commonly established yet. So, we here propose the following criteria practically for the present study. Such a spectrometer can evaluate neutrons from thermal energy to 1 MeV in about a few 10 min within the relative error of 20% in each energy bin.

In our previous studies [9,10], the self-activation method of iodine-containing scintillators, such as NaI and CsI, had been successfully employed for largely weak photo-neutron detection around a high-energy X-ray linear accelerator (LINAC) of which the typical neutron fluence rate is around 10^{4} cm^{-2} s^{-1}. Among iodine-containing scintillators, a CsI scintillator is slightly hygroscopic, and the light output can be easily readout using a photodiode, which, unlike

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photomultiplier tubes, does not require a high-voltage power supply. In this method, the information of the incident neutron intensity is derived from the activity of ^{128}I generated in the CsI scintillator. Owing to the relatively short half-life of ^{128}I (1500 s), a highly precise neutron detection is possible even for short-time irradiations. Unlike conventional activation methods, after a neutron irradiation, a series of simultaneous readouts from several CsI crystals are made in the CsI scintillator itself without requiring external radiation detectors such as a high-purity germanium detector. Hence, we investigated the applicability of the CsI self-activation method for the daily assessment of BNCT neutron energy spectra. Although it is apparent that this method is too sensitive for highly intensive neutron fields of BNCT, an adequate amount of activity can be generated from just the instantaneous neutron irradiation of the accelerator-based neutron beam by appropriately adjusting the irradiation time. By simultaneously arranging several CsI detectors in a measurement site, we evaluated the neutron energy spectra from a single instantaneous neutron irradiation. Besides, unlike previous studies which employ active neutron detectors such as the proportional counters, the CsI self-activation method is not sensitive to γ-rays. Generally, accelerator-based neutron sources contain more γ-rays compared with reactor-based neutron sources. This feature is useful to detect neutrons selectively under the existence of γ-rays.

In the present work, a design study of our novel neutron energy spectrometer for the daily QA of BNCT was carried out based on the CsI self-activation method. To verify its applicability for daily QA procedures, some practical simulations with the spectrometer were performed at a BNCT field.

2. Material and method

2.1. CsI self-activation method

When a CsI crystal is irradiated by neutrons, ^{127}I in the crystal is activated through the capture reaction of ^{127}I(n, γ)^{128}I, generating radioactive ^{128}I, which disintegrates to ^{128}Xe by emitting β-rays with a half-life of 1500 s. The cross-section of this reaction increases with a decrease of neutron energy by the 1/v law and becomes 6.2 barn for 0.025 eV. The emitted β-rays of which the maximum energy is 2.2 MeV are efficiently detected by the CsI scintillator itself. Average wave length of scintillating photons emitted by the CsI is 5.5 x 10^{-4} mm. The number of scintillating photons emitted by the absorption of one average energy β-ray (0.733 MeV) is calculated to be about 48,000. Consequently, we can precisely evaluate the amount of ^{128}I by fitting the decay curve of the β-ray counts with a half-life of 1500 s. The neutron intensity information is derived from the saturated activities obtained using the fitting procedure of the decay curve mentioned above, similar to that in a conventional neutron activation method.

2.2. Principle of spectrum unfolding

In the present study, the saturated activity of ^{128}I in the i^{th} CsI scintillator, $(A_\infty)_i$, can be expressed as follows:

$$(A_\infty)_i = \sum_{j=1} R_{ij}\phi_j \tag{1}$$

where Φ_j is the neutron fluence rate in the energy group j, and R_{ij} is the response function of the ith CsI scintillator for the jth energy group of neutrons. In the self-activation method with iodine-containing scintillators, the response (cm^2) is defined as the saturated activity of ^{128}I per unit neutron fluence rate. To evaluate the incident neutron energy spectrum from the information of ^{128}I activity generated in the CsI scintillators, an unfolding procedure is necessary. In this study, we employed the Bayesian estimation method proposed by Nauchi and Iwasaki [11]. In this method, the Bayes' theorem is iteratively applied. There are some advantages of using this method. For example, the unfolded spectrum is guaranteed to be non-negative. In addition, the calculation algorithm can be coded in a very simple manner. When an appropriate initial guess is available from some experimental measurements or simulation calculations, such an initial guess is used for the unfolding procedure.

2.3. Design procedure and its optimization

Figures 1 and 2 show the schematics of the designed neutron energy spectrometer with the CsI self-activation method. The spectrometer consists of four CsI crystals, several energy filters, and neutron shield materials. The four CsI crystals are placed on the same plane, which is perpendicular to the neutron beam axis. We employed a commercially available CsI detector Radi PA1100 (Horiba, Japan) for the neutron detection; this detector was originally developed for a γ-ray dosimeter [12]. Hence, the CsI crystal size and the container outer dimension are set to approximately 12 mm × 12 mm × 19 mm and 68 mm × 28 mm × 121 mm (width × depth × height), respectively.

It is assumed that the neutron beams come from one direction which is parallel to the z-axis shown in Figures 1 and 2. In front of the CsI crystals, a carefully selected energy filter was installed to modify the response function shape of each CsI scintillator. The designed energy filter consists of two layers: a neutron moderator layer and a neutron absorber layer. A polyethylene plate was used as the neutron

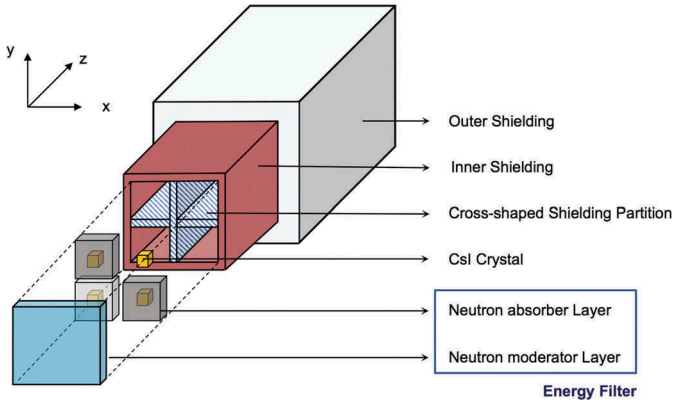

Figure 1. Schematic of the designed neutron energy spectrometer with the CsI self-activation method.

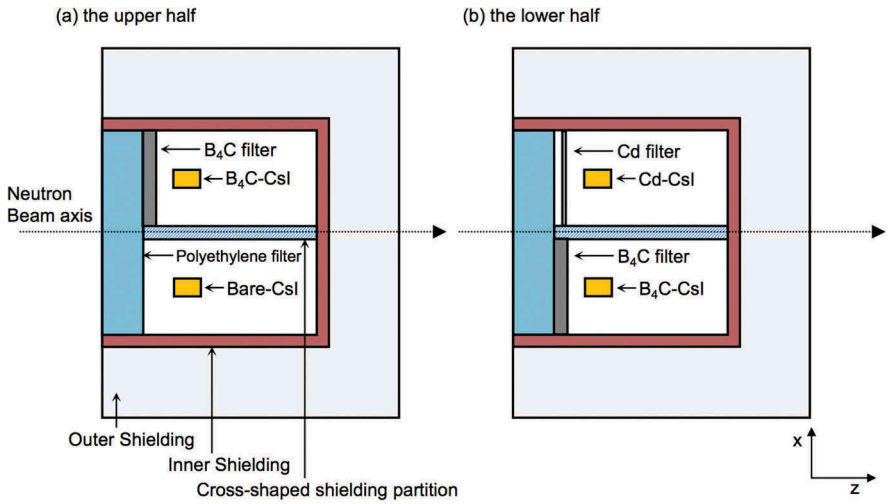

Figure 2. Cross-sectional views of the designed spectrometer in the *x*–*z* plane through the center of the CsI crystals placed on (a) the upper half and (b) the lower half in Figure 1. The neutron beam axis is along the *z*-axis.

moderator. The neutron absorber layer was divided into four regions: bare (no neutron absorbing filter), Cd, and B_4C 50 wt% silicone rubber (B_4C). Because of the high neutron absorption ability of B_4C, the activities inside the CsI scintillators placed behind the B_4C filter may be lower than those of other CsI crystals. To compensate for the poor statistical uncertainty, B_4C filters of the same thickness were placed in front of two different CsI crystals. Consequently, the spectrometer has three different filtering conditions. In this paper, we denote the CsI scintillators placed behind the Cd filter and B_4C filters as Cd–CsI and B_4C–CsI, respectively, whereas the CsI scintillator with no filter in front is denoted as bare-CsI, as shown in Figure 2.

Although neutrons are principally assumed to enter from one direction, i.e., perpendicular to the energy filter in the present design, an interference may occur between the different filter regions to some extent. To avoid the interference, a cross-shaped shielding partition with 10-mm-thick B_4C plates is made between the CsI crystals along the beam axis, as shown in Figure 1. In addition to the components mentioned above, to remove the outer scattering neutrons, the entire spectrometer is shielded via 50-mm-thick polyethylene plates (outer shielding) and 10-mm-thick B_4C plates (inner shielding).

Next, the geometry of the energy filter was adjusted and optimized to obtain appropriate response functions for each CsI. To appropriately select the thickness of the energy filter, an optimization procedure was carried out in terms of the energy resolution. To this end, a series of possible response function candidates were obtained in advance using the Monte Carlo simulation code PHITS (ver. 2.88) [13] by varying the thickness of the energy filters. The thicknesses of the polyethylene and B_4C filters were varied in the ranges of 10–50 mm and 5–20 mm, respectively. On the other hand, the thickness of the Cd filter was fixed at 1 mm, because Cd has a very large capture cross-section only for thermal neutrons (approximately 2700 barn), and the 1-mm-thick Cd filter is practically thick enough to absorb almost all the thermal neutrons. The neutron energy group structure comprises 18 groups for energies ranging from 0.01 eV to 10 MeV for the same width on a logarithmic axis.

Further, to obtain the energy resolution for optimizing the spectrometer design, a series of simulations were performed using mono-energy neutron sources $\Phi(E_J, E)$, which have a single peak at energy $E = E_J$. In this simulation, at first, the generated activity of ^{128}I was calculated from the mono-energy neutron incidence on each CsI scintillator. Then, the incident neutron energy spectrum was unfolded on the basis of the activity information with a uniform spectrum as an initial guess. These calculations were performed with trying all the candidates of the prepared response functions. The unfolded spectrum $\Phi_{\mathrm{unf}}(E_J, E)$ exhibited a certain broadening from $\Phi(E_J, E)$ depending on the energy resolution, which is characterized by the response functions [14]. Figure 3 shows an example of such a single-peak broadening.

When the response function is appropriately selected, $\Phi_{unf}(E_J, E)$ may be concentrated at approximately E_J. Therefore, to express the degree of degradation in terms of the energy resolution, the quantity $\Delta L(E_J)$ is defined as follows:

$$\Delta L(E_J) = \sum_{j}^{n} \left[\left\{ \mathrm{Log}_{10}(E_J) - \mathrm{Log}_{10}(E_j) \right\}^2 \left\{ \Phi(E_J, E_j) - \Phi_{unf}(E_J, E_j) \right\}^2 \right] \quad (2)$$

where the term $\{\mathrm{Log}_{10}(E_J) - \mathrm{Log}_{10}(E_j)\}$ indicates the distance between E_J and E_j on the energy logarithmic axis. After $\Delta L(E_J)$ is calculated for all the energy groups J = 1–n, the average value of $\Delta L(E_J)$, i.e., $\overline{\Delta L}$, can be obtained as follows:

$$\overline{\Delta L} = \frac{1}{n} \sum_{j=1}^{n} \Delta L(E_j) \quad (3)$$

We use $\overline{\Delta L}$ as an index of the total energy resolution of the spectrometer. Consequently, the combination of energy filters that minimizes $\overline{\Delta L}$ will yield the optimum response functions.

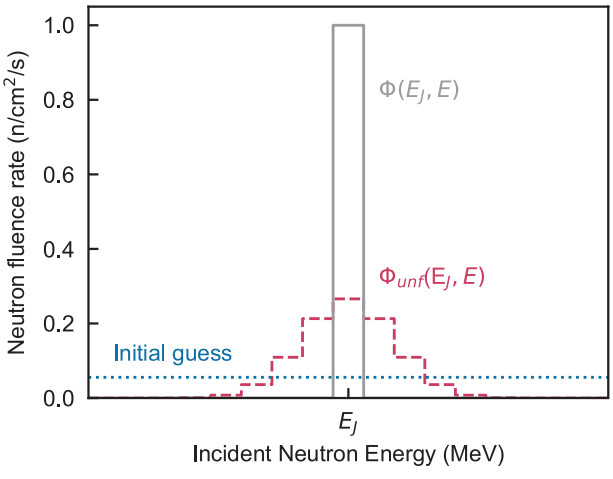

Figure 3. Example of single-peak broadening of Φ_{unf}.

2.4. Practical simulation of application to BNCT fields

To verify the applicability of the designed spectrometer for the daily QA of BNCT, practical simulations with the spectrometer were performed at a BNCT field. An actual BNCT spectrum was quoted from literature; an accelerator-based neutron source (provided by the Kyoto University Research Reactor Institute) with a proton beam current of 1 mA [1] was employed as the true spectrum for the simulations.

First, an appropriate neutron irradiation time was estimated. As mentioned before, the CsI self-activation method can be used for sensitive neutron detection. With this characteristic, a sufficient amount of activity can be obtained from just the instantaneous neutron irradiation and is preferable for daily QA procedures. On the other hand, to avoid excessive generation of ^{128}I from excess neutron incidence, the irradiation time should be appropriately selected. The irradiation time t_{irr} was calculated as follows:

$$t_{irr} = \frac{1}{\lambda} \left(\ln \frac{A_\infty}{A_\infty - A_0} \right) \quad (4)$$

where λ is the decay constant of ^{128}I, A_∞ is the saturated activity of ^{128}I, and A_0 is the initial activity of ^{128}I, which is the value when the neutron irradiation is terminated. The theoretical value of A_∞ for each CsI scintillator was calculated by convoluting the response functions with the true spectrum. To obtain an acceptable count rate of the β-rays emitted from ^{128}I, A_0 should be appropriately adjusted. Based on our previous experience of using Radi PA1100, the practical upper limit of A_0 is set as 1000 Bq. Because the bare-CsI has the highest sensitivity among the three filtering conditions, t_{irr} was evaluated using A_∞ of the bare-CsI. A_0 generated inside the other scintillators were then calculated using t_{irr}.

Second, the required measurement time of the β-rays emitted from ^{128}I after terminating the irradiation was estimated, with an acceptable statistical accuracy for determining the generated activity. After the termination of the neutron irradiation, the time variation in the count rate of a CsI scintillator was analyzed to quantify the generated ^{128}I activities using the decay-fitting approach [15]. The quantification accuracy of ^{128}I activities depends on the measurement time. If it takes too long to accurately obtain the measurements, it is not practical for daily use. To estimate the appropriate measurement time, some fitting procedures were

applied using numerically simulated decay curves. The initial count rate C_0 is calculated as follows:

$$C_0 = \alpha\varepsilon A_0 \tag{5}$$

where α is the fraction of β-ray emission per decay (0.931 for ^{128}I), and ε is the detection efficiency of β-rays. ε is found to be 0.93 from the actual energy discrimination setting (150 keV) of the measured spectrum and CsI crystal dimension. The time variation in the count rate $C(t)$ can be expressed as follows:

$$C(t) = C_0 \exp(-\lambda t) + C_B \tag{6}$$

where t is the elapsed time after the termination of the neutron irradiation, and C_B is the background count rate. C_B is fixed at 3 cps, which is observed as a typical background value of Radi. The total count for the kth sampling N_k is given as follows:

$$N_k = \int_{T_{k-1}}^{T_k} C_0 \exp(-\lambda t)dt + \int_{T_{k-1}}^{T_k} C_B\, dt \tag{7}$$

where T_{k-1} is the measurement start time, and T_k is the measurement finish time of the k^{th} sampling. The simulated sampling data N_k were obtained at 60 s intervals using Equation (7). In addition, to consider the uncertainty in the counting statistics of each sampling, the normal distributed random errors with a standard deviation $\sigma_k = \sqrt{N_k}$ were considered when determining N_k using 500 sets of random number seeds. By fitting a series of data using the least square method, the value of C_0^{fit} was obtained along with its uncertainty, and the value of A_∞^{fit} was derived along with its uncertainty $\sigma_{A_\infty}^{fit}$. This procedure was repeated several times by varying the number of fitting data points via increasing the measurement time from 180 s up to 1200 s. The relative error of A_∞^{fit}, which was defined as the ratio of $\sigma_{A_\infty}^{fit}$ to A_∞^{fit}, was then calculated at each measurement time and plotted as a function of the measurement time.

Finally, the unfolding calculations were performed. As the first approach, the true spectrum was used as the incident spectrum as well as the initial guess with the assumption that the expected spectrum was correctly irradiated. To examine the effect of the quantification accuracy of ^{128}I on the unfolded spectrum, the unfolding calculations were performed by varying the measurement time. As the second approach, to check the detectability of an unexpected incidence, another accelerator-based neutron source, from a previous study [2], was used as the unexpected incident spectrum, and the true spectrum was only used as an initial guess. The saturated activities generated by the incident spectrum were obtained using the same approach as that used for the true spectrum mentioned above. As the last approach, a uniform spectrum was assumed as the initial guess under the condition that no information was available beforehand.

3. Results

Figure 4 shows the calculation results of $\overline{\Delta L}$ for various energy filtering combinations. The value of $\overline{\Delta L}$ is minimum when a combination of a 35-mm-thick polyethylene filter and a 20-mm-thick B_4C filter is employed. When the polyethylene filter thickness is much smaller than 35 mm, the neutron moderation is not enough for proper absorption of high energy neutrons by both Cd and B_4C. On the other hand, for the polyethylene filter thickness is far larger than 35 mm, neutrons are excessively moderated and the response functions for Cd and B_4C filters become almost indistinguishable. Therefore, from the balance mentioned above, the value of $\overline{\Delta L}$ becomes minimum for a 35-mm-thick polyethylene filter. When the thickness of the B_4C filter is greater than 20 mm, the outer scattering component may not become negligible. From this result, the aforementioned combination is selected as the optimum set of energy filters in terms of the energy resolution. Figure 5 shows the response functions corresponding to this geometry. The shapes of the response functions differ depending on the neutron absorbing materials used in the energy filters. Among the three filtering conditions, only bare-CsI has a sensitivity below approximately 10^{-5} MeV for low energy neutrons. The discontinuous tendency of response functions observed at 10^{-5} MeV is originated from a sudden change of the absorption cross-section of ^{127}I around 10^{-5} MeV.

Table 1 lists the estimated appropriate irradiation time and the generated ^{128}I activities of each CsI detector. The appropriate irradiation time is estimated to be 0.04 s for an accelerator-based BNCT source with a proton beam current of 1 mA so as to

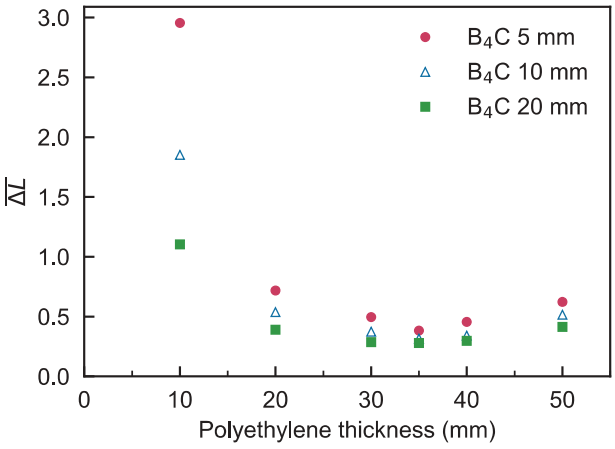

Figure 4. Calculation results of $\overline{\Delta L}$ for various energy filtering combinations.

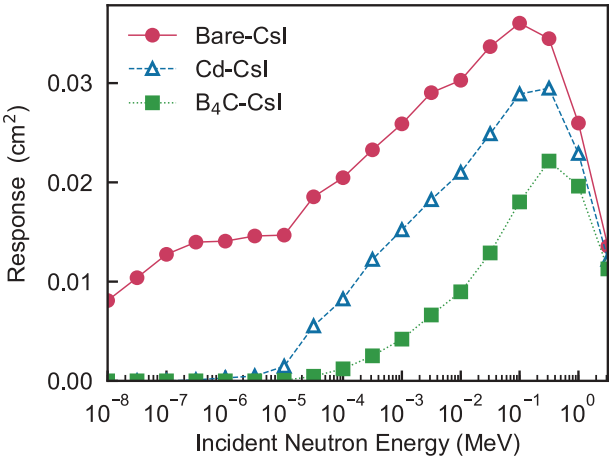

Figure 5. Response functions of the three CsI detectors with the optimum filtering condition.

Table 1. Estimated appropriate irradiation time and generated ^{128}I activities of each CsI crystal.

Irradiation time (s)	A_0 of ^{128}I (Bq)		
	Bare-CsI	Cd–CsI	B_4C–CsI
0.04	1000	566	215

adjust the A_0 of bare-CsI to the practical upper limit of 1000 Bq. Such an instantaneous neutron irradiation is feasible for an actual accelerator-based BNCT source, with adequate initial activity generation.

Figure 6 shows the time variations in the relative error associated with ^{128}I estimation. The relative error depends on the measurement time and initial count rates and improves with an increase in the measurement time. In particular, for measurement times less than 300 s, a slight increase in the measurement time corresponds to a significant improvement in the quantification accuracy of ^{128}I. For example, when the measurement time increases from 180 s to 240 s, the relative error decreases by 2.15%. However, when the measurement time increases from 300 s to 360 s, the relative error decreases by only 0.64%. Even

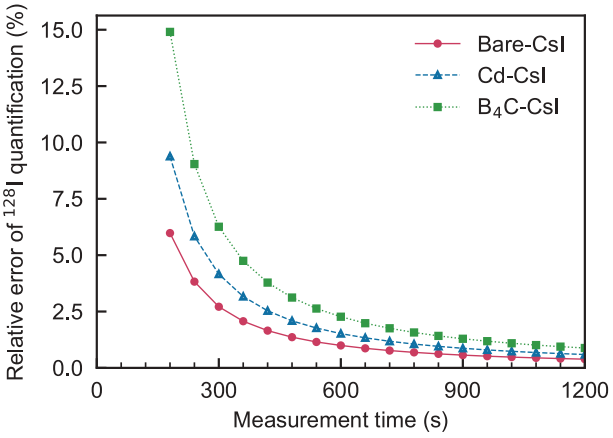

Figure 6. Time variations in the relative error associated with ^{128}I estimation for different filtering conditions.

when measurement time becomes longer than 900 s, apparent improvement of the relative error is not expected due to the subtle increase of total counts.

Figure 7 shows the unfolding results for various measurement times when the true spectrum is irradiated on the spectrometer as expected. When the measurement time is short, the unfolding results show significant uncertainties around the true spectrum because of the poor quantification accuracy, as shown in Figure 6. On the other hand, for longer measurement times, the unfolding results and the true spectrum are in good agreement. A measurement time of at least 900 s is required to reasonably evaluate the neutron energy spectrum.

Figure 8 shows the unfolding result when an unexpected spectrum is incident and the ^{128}I initial activities generated in each CsI crystal for this spectrum are tabulated in Table 2. The unfolded spectrum is not in good agreement with the initial guess and approaches the actual incident spectrum. Although the unfolded spectrum does not accurately match with the incident spectrum, a shape similar to that of the incident spectrum is observed except for the energy region below 10^{-6} MeV. In this energy region, the hump structure appears although the energy spectrum of the incident neutrons does not have this. This structure causes the influence on the initial guess because the response function for bare-CsI only has sensitivity for this region. Figure 9 shows the unfolding result with a uniform spectrum as the initial guess for a measurement time t = 900 s. When the information is not available beforehand, the unfolded spectrum is not in good agreement with the true spectrum.

4. Discussion

The neutron irradiation time required for an adequate generation of ^{128}I is found to be 0.04 s, as listed in Table 1. The required measurement time to obtain a valid unfolding result is approximately 900 s, as shown in Figure 7. The actual time for unfolding calculations of course depends on the calculation environment to some extent. For example, this is less than few seconds with the CPU 1.2 GHz intel Core m5. Therefore, the total required time to estimate a neutron energy spectrum is found to be approximately 900 s by summing up these periods. This time is reasonable for daily measurement. When incident neutrons have unexpected energy spectrum, the unfolded spectrum exhibits a certain deviation from the initial guess, which were originally expected to be an energy spectrum of incident neutrons, as shown in Figure 8. This result indicates that the designed spectrometer has sufficient energy resolution to detect unusual neutron incidences due to a miss operation or a mechanical trouble. Therefore, the proposed spectrometer can be applied

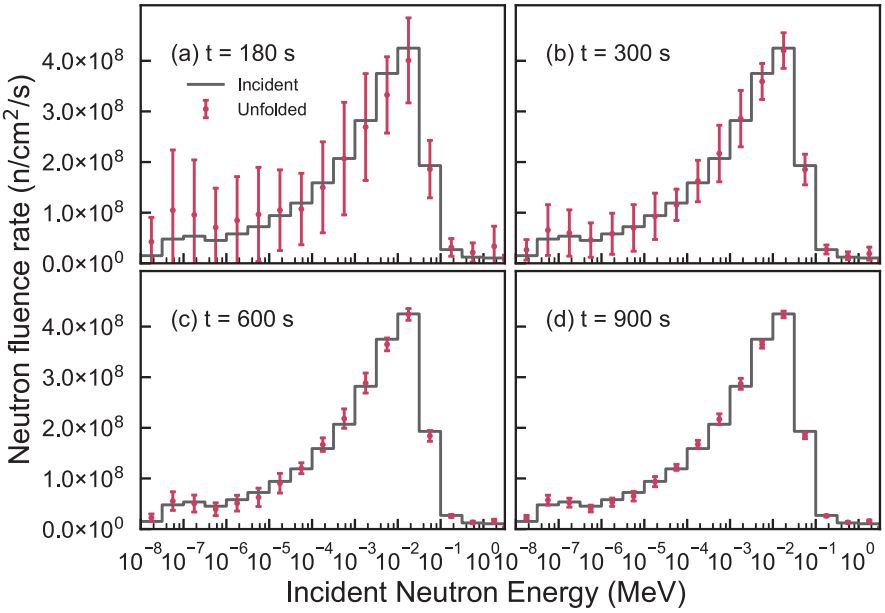

Figure 7. Unfolding results for various measurement times, *t*. The true spectrum is used as the incident spectrum as well as the initial guess.

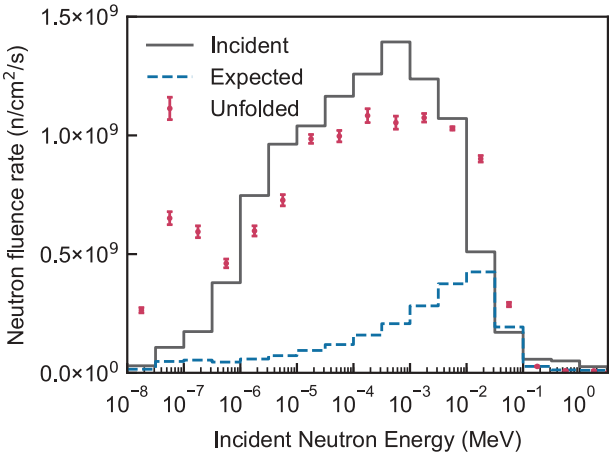

Figure 8. Unfolding result with the assumption that incident neutrons have unexpected energy spectrum. Expected spectrum is used as the initial guess. The measurement time is 900 s.

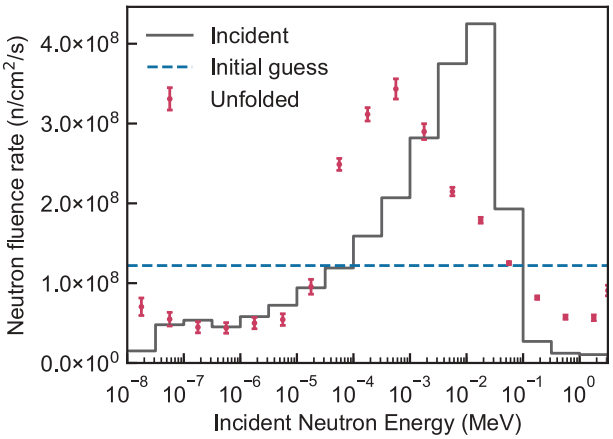

Figure 9. Unfolding result with a uniform spectrum as the initial guess for a measurement time t = 900 s.

Table 2. The ^{128}I initial activities generated in each CsI crystal for the unexpected spectrum.

Irradiation time (s)	A_0 of ^{128}I (Bq)		
	Bare-CsI	Cd–CsI	B_4C–CsI
0.04	3972	1704	501

to the daily QA of BNCT whether the expected spectrum is correctly irradiated or not. In summary, from Figure 7, it can be concluded that the present spectrometer can evaluate neutrons from 10^{-8} MeV to 1 MeV in 15 min (900 s) within the relative error of 17% in each energy bin. These satisfy the proposed criteria in Introduction part.

The quantification accuracy of ^{128}I depends not only on the measurement time but also on the initial activities, as shown in Figure 6. In this study, we fixed the identical dimensions of the four CsI crystals with the tentative assumption of employing Radi PA1100. Therefore, the A_0 values of the CsI scintillators differ depending on the corresponding energy filtering conditions, as listed in Table 1. To reduce the measurement time while maintaining the quantification accuracy, it is effective to increase the crystal sizes of Cd–CsI and B_4C–CsI so that the initial activities of Cd–CsI and B_4C–CsI increase nearly equal to that of bare-CsI.

When a uniform spectrum is used as the initial guess, the unfolded spectrum does not match with the true spectrum, as shown in Figure 9. This result indicates that the energy resolution of the spectrometer is insufficient for reproducing an incident spectrum without prior information. To confirm that the spectrum remains unchanged for daily measurements, an appropriate initial guess should be determined using the Monte Carlo simulations and measurements via more precise methods such as BSS.

Some limitations should be noted in this study. First, in the design of this spectrometer, it is assumed that the neutron beams come from one direction uniformly. This is, to some extent, realistic for accelerator-based neutron sources, but not actually guaranteed. Such unreasonable situations probably affect the unfolding results. Second, this spectrometer is unsuitable for the repetitive measurement at short intervals because the residual activities of ^{128}I remain inside CsI crystals for a while, although the overlap of previous decay curves can be subtracted by calculations. Finally, only one example spectrum is examined to check the detectability of unexpected incidence. So, the detectability should be investigated for various different neutron spectra in the future work.

5. Conclusions

A neutron energy spectrometer for the daily QA of BNCT was designed using the CsI self-activation method. The response functions were optimized in terms of their energy resolutions. A practical simulation was performed with a BNCT neutron beam to demonstrate the performance of the designed spectrometer. The neutron irradiation time and the measurement time post neutron irradiation were estimated to be 0.04 s and 900 s, respectively. As these times are acceptable, the spectrometer can be employed for daily measurements.

Disclosure statement

No potential conflict of interest was reported by the authors.

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