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ARTICLE

A method of neutron-energy evaluation based on the position distribution of recoil protons

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A method of neutron-energy evaluation, which was recently proposed by the author's group, has been applied to the investigation of an ^{241}Am-Be source in order to confirm the validity of this novel approach; the method is based on the position distribution measurement of recoil protons by an imaging plate (IP) combined with a cone-like converter. The observed position distribution of recoil protons apparently involved neutron-energy information. An unfolding of the position distribution was plainly attempted with the response functions calculated by a simplified Monte Carlo method; the evaluated neutron spectra indicated the energy characteristics of an ^{241}Am-Be source. When a full Monte Carlo Code, PHITS, was used to calculate the position distributions of recoil protons in order to obtain more correct response functions, the result of neutron-spectra evaluation has been much improved. The evaluation of neutron-energy spectrum by the present method will be further improved by the more accurate calculation of response functions with taking account of the complicated response of IP to low energy protons carefully, as well as by the application of more reliable unfolding algorithms and more appropriate position sensitive detectors.

Keywords: neutron-energy spectrum; imaging plate; cone-like polyethylene converter; recoil proton; position distribution; response function; PHITS

1. Introduction

In conventional radiological applications, photon radiations (X-rays, gamma-rays) have been mainly used for therapy and diagnosis purposes and accompanied neutron generations have been almost negligible. On the other hand, in advanced radiation therapy techniques such as the intensity modulated radiation therapy (IMRT with high energy X-rays) and the charged particle therapy (high energy proton or carbon beams), plenty amount of neutrons can be generated through nuclear reactions.

The biological effectiveness of neutrons per unit physical dose (absorbed dose [Gy]) significantly depends on the neutron energy [1]. Especially, in the energy region from 100 keV to 10 MeV, the value of radiation-weighting factor exceeds 10. Therefore, careful attentions should be paid to such fast neutrons.

There are some neutron-energy measurement techniques such as the time-of-flight method, the Bonner sphere spectrometer, and the proton recoil telescope, but these techniques are generally a rather difficult and time-consuming task. Hence, it is not common to apply these techniques at medical facilities.

Recently, a novel method of energy evaluation of fast neutrons has been proposed [2]. This method is easy to carry out because it is based on the measurement of the position distribution of recoil protons by an imaging plate (IP) combined with a cone-like acrylic converter. In this study, using cone-like polyethylene converter and response functions calculated by Particle and Heavy Ion Transport code System (PHITS), we have applied this method to the evaluation of neutron-energy for an ^{241}Am-Be source in order to confirm the validity of this novel approach.

2. Methods and materials

2.1. Principle of neutron-energy evaluation

Figure 1 shows schematic representation of the principle of neutron-energy evaluation by an IP combined with a cone-like converter made of hydrogenous materials. Here, suppose that an IP without the protective layer such as BAS-TR 2025 (Fuji Film Co. Ltd.) is used. The sensitivity of such an IP to fast neutrons is very low or almost negligible. When fast neutrons enter the hydrogenous converter, recoil protons may be emitted by H(n, p) reaction. By placing a converter only on the phosphor layer of the IP, emitted

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recoil protons are recorded on an IP. When the thickness of converter increases, a relatively high probability of the H(n, p) reaction is achieved and the total number of recoil protons increases. Therefore, the proton-induced signals on the IP also become relatively large with an increase in the converter thickness. On the other hand, when the thickness of converter increases considerably, some low energy protons do not reach the IP due to their short ranges. Hence, the increase in IP signals mentioned above may saturate at a certain value and, after that, begin to decrease with a further increase in the converter thickness.

The position distributions of recoil protons are closely related to the macroscopic cross-sections of H(n, p) reaction, the emission angular distribution of recoil protons, and the ranges of recoil protons in a converter through the energy of incident neutrons. Therefore, as shown in Figure 1, those position distributions of recoil protons that appear on the IP may be affected by the energy of incident neutrons. If response functions are known for some monoenergetic neutrons, in principle, unfolding calculations may be available to determine the actual neutron-energy spectrum.

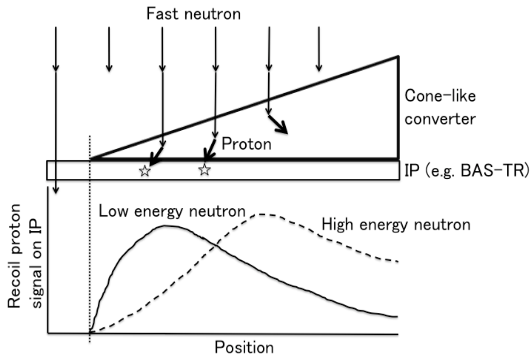

Figure 1. Schematic representation of the principle of neutron-energy evaluation by an IP combined with a cone-like converter. Only half of the converter is drawn.

2.2. Verification of principle

In order to verify the principle of neutron-energy evaluation, we used a simplified Monte Carlo method. This computer program merely calculates the position distribution of recoil protons that reach the IP surface instead of a photo-stimulated luminescence (PSL) intensity distribution related to their energy deposition in the phosphor layer of the IP. In the calculation, (1) H(n, p) reaction cross-sections were obtained from JENDL-3.3 [3], (2) the scattering process was assumed to be isotropic in the center-of-mass coordinate system for low-energy neutrons (< 10 MeV), (3) residual ranges of recoil protons in acryl were evaluated on the basis of Janni's table [4], (4) the contribution of secondary neutrons was ignored, and (5) the direction of neutron incidence was set to be perpendicular to the IP surface.

Figure 2 shows the calculated results for an acrylic converter having a triangular cross-section (base length: 50 mm; height: 40 mm) for different neutron energies from 0.5 to 10 MeV. In Figure 2, the center of a converter corresponds to 0 mm. The shape of results for each neutron energy were different each other, so we verified neutron-energy evaluation is possible by using the method based on the measurement of the position distribution of recoil protons.

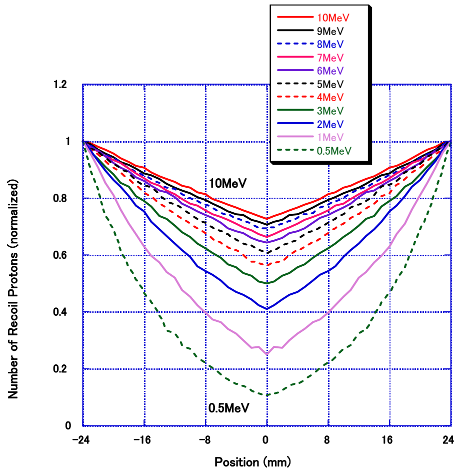

Figure 2. Calculated responses of a triangle-shaped converter for monoenergetic neutrons.

2.3. Materials

In the present experiment, we used a polyethylene triangular prism with a base square of 50 × 50 mm^2 and height of 40 mm as the converter. The position distribution of recoil protons was recorded on an IP as the PSL intensity for the neutron irradiation by an ^{241}Am-Be source. The IP used were a soft beta-ray type IP (BAS-TR 2025, Fuji Film Co. Ltd.) and an X-ray type IP (BAS-MS 2025, Fuji Film Co. Ltd.).

The converter was directly placed on the surface of BAS-TR, so both signals of recoil protons and gamma rays were recorded on the resultant image because the BAS-TR dose not have a protective layer of polyethylene terephthalate (PET) film on its surface and even low energy protons reach the phosphor material. Another X-ray type IP, BAS-MS, was arranged under the BAS-TR in order to measure gamma-rays that penetrated the BAS-TR. The polyethylene converter and two imaging plates were installed in a rectangular box made of steel for the shielding of ambient light. In order to reduce the intensity of gamma-ray from the neutron source, a 50mm-thick lead plate was inserted between the source and the IP. These imaging plates were scanned by a BAS-2500 (Fuji Film Co. Ltd.) with the fixed scanning parameters of "latitude"=5, "sensitivity"=4000, and "resolution"=50 μm. Scanned images were analyzed by using the "Multi Gauge" software (Fuji Film Co. Ltd.) to evaluate the position distributions of PSL intensity on IP.

3. Results

3.1. Position distribution of recoil protons

The obtained position distribution of recoil protons for an ^{241}Am-Be source is shown in **Figure 3** as a solid line. Gamma-ray components were subtracted from the signals appeared on BAS-TR with assuming that relative gamma-ray profiles were common to BAS-TR and BAS-MS. The position distribution measured by a ^{252}Cf source and a cone-like acrylic converter in the previous paper is also presented in Figure 3 by a dashed line for comparison [2].

Observed position distribution of recoil protons apparently involved the difference of two neutron-energy spectra. In Figure 3, a dip of center part (~ 0 mm) relative to the both-side edge (~ ± 25mm) is about 50 % and 60 % for ^{241}Am-Be and ^{252}Cf respectively. By looking at the response functions calculated by a simplified Monte Carlo method (Figure 2), we can easily expect that the mean neutron energy for an ^{241}Am-Be source may be higher than that for a ^{252}Cf source.

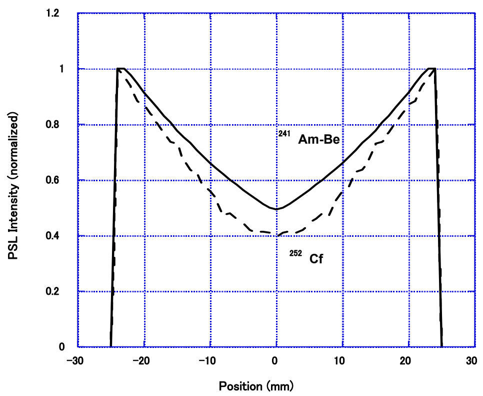

Figure 3. Obtained position distributions of recoil protons for an ^{241}Am-Be source (solid line) and for a ^{252}Cf source (dashed line).

3.2. Response function

3.2.1 PHITS

In order to obtain more correct response functions, we calculated the position distributions of recoil protons by using a full Monte Carlo Code, PHITS [5]. PHITS takes all interaction of neutrons and secondary neutrons into consideration, while a simplified Monte Carlo method does not consider. In the same way as a simplified Monte Carlo method, we calculated the position distribution of recoil protons that reach the IP surface instead of the PSL intensity distribution related to their energy deposition in the phosphor layer of the IP.

3.2.2 Elastic scattering cross-section of neutron

We used a polyethylene as the converter, which is composed of hydrogen and carbon. **Figure 4** shows elastic scattering cross-sections of neutrons with hydrogen (dashed line) and carbon (solid line) [6]. In Figure 4, elastic scattering cross-sections with carbon increases suddenly at particular energies of incident neutrons. Therefore, such “resonance” in cross-sections may affect the calculation of response functions. In order to reduce local effects by resonance in cross-sections at particular neutron-energies, we calculated response functions for each incident neutron as the average of response functions for certain energy region. For example, the calculated result for 5 MeV is the average from 4.5 to 5.5 MeV.

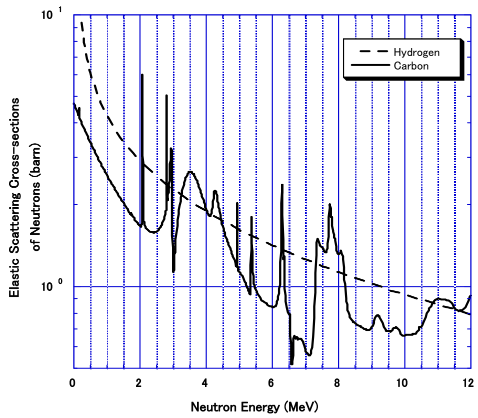

Figure 4. Elastic scattering cross-sections of neutrons with hydrogen (dashed line) and carbon (solid line) (JENDL-4.0).

3.2.3 Calculation result

Figure 5 shows calculation results of the position distributions of recoil protons by using PHITS. The shape of results for each neutron energy is distinguishable each other, so the position distribution of recoil protons apparently involves the neutron-energy information. In comparison with results calculated by a simplified Monte Carlo method in Figure 2, those are different especially for low energy incident neutrons. As mentioned above, calculation results by using PHITS may be more correct than those calculated by a simplified Monte Carlo method. These differences will affect the neutron energy evaluation.

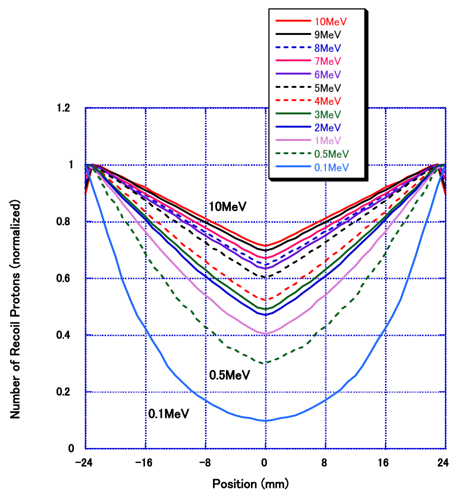

Figure 5. Calculation results of position distributions of recoil protons by using PHITS.

3.3. Evaluation of neutron-energy spectra

An unfolding of the resultant position spectra was simply executed in the same way as reference [2]. The evaluated solutions of neutron-energy for an ^{241}Am-Be source are shown in **Figure 6** by the two sets of bar graph. The line is just a guide to the eye. When comparing with known reference spectra in **Figure 7**, the evaluated spectrum by using PHITS indicated the energy characteristics of an ^{241}Am-Be source [7]. Moreover, when PHITS was used to calculate response functions, the result of neutron-spectra evaluation has been much improved in comparison with evaluation by using a simplified Monte Carlo Method. For the further improvement, accurate response functions should be calculated with taking account of the complicated response of IP to low energy protons carefully. The development of an imaging detector suitable for the proton distribution measurement under intense gamma-ray backgrounds is also needed.

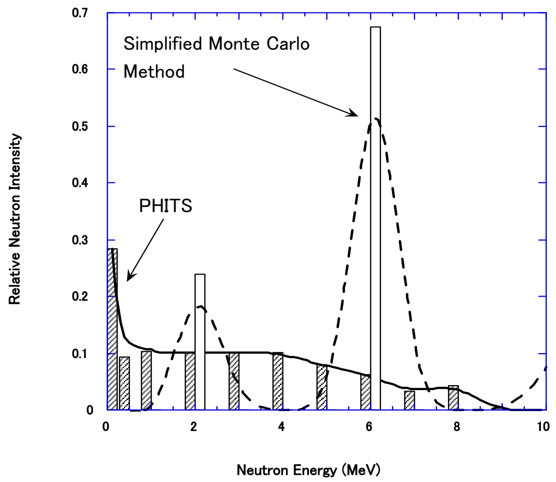

Figure 6. Evaluated neutron-energy spectra for an ^{241}Am-Be source. The line is just a guide to the eye.

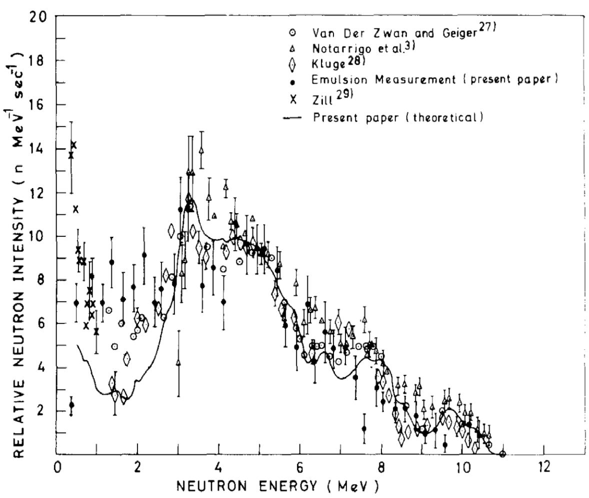

Figure 7. Reference neutron-energy spectra for an ^{241}Am-Be source [7].

4. Conclusion

A Neutron-energy spectrum of an ^{241}Am-Be source has been evaluated on the basis of the position distribution measurement of recoil protons emitted from a cone-like polyethylene converter. The evaluated spectrum properly indicated the energy characteristics of an ^{241}Am-Be source. The neutron-energy evaluation by the present method will be further improved by the more accurate calculation of response functions with taking account of the complicated response of IP to low energy protons carefully, as well as by the application of more reliable unfolding algorithms and more appropriate position sensitive detectors.

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