Study on Neutron Spectrum Unfolding Using Boron and Cadmium Cover to Acquire Additional Activation Reactions

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1. Introduction

Particle accelerator is equipment that uses a high energy particle beam to produce radioisotopes such as ^{18}F, ^{99m}Tc and ^{60}Co. It has been widely used in the field of medicine, engineering, and other electro-scientific industries. For the efficient use of the particle beam, characteristics of the particle beam should be analyzed. The characteristics of the beam can be estimated by the neutrons produced during the accelerator operation. In order to understand the physical properties of neutrons including the energy spectrum, spreading directions, and the amount of the neutrons produced while the particle accelerators run, an unfolding process [1] has been employed.

An unfolding method combines the neutron activation analysis with the computer simulation [2]. This combined method is accurate than measuring neutrons directly in that the initial estimation is obtained by the computer simulation and further corrected by the measurement data. This simulation-activation measurement combined unfolding technique, however, is highly dependent on simulation without sufficient number of the activation samples. Available materials for activation foil are limited. Therefore, in this study, a method to acquire additional activation reactions introducing cover materials was studied.

2. Methods and Results

2.1 Unfolding Process with Cover Materials

Multiplying the cross-section matrix to neutron flux matrix represents the activity of the foil as shown in Eq. (1).

$$\mathbf{S}\cdot\mathbf{\Phi} = \begin{bmatrix}\sigma_1 & \sigma_2 & \sigma_3 & \sigma_4 & \cdots & \sigma_g\end{bmatrix}\begin{bmatrix}\Phi_1\\ \Phi_2\\ \Phi_3\\ \vdots\\ \Phi_g\end{bmatrix} = A \quad (1)$$

where

S: Group Activation Cross-section
Φ: Group Flux
A: Measured Activity
g: Number of Energy Groups
σ_i: i-th energy group activation cross-section
Φ_i: i-th energy group flux

In case that uses two or more activation foils, matrix of the group activation cross section is expressed as (n×g) matrix that each row represents the activation cross section of each reaction and the matrix of the measured activity is expressed as (n×1) matrix. Then, the Eq. (1) is replaced with the Eq. (2).

$$\begin{bmatrix}\sigma_{1,1} & \cdots & \sigma_{1,g}\\ \sigma_{2,1} & \cdots & \sigma_{2,g}\\ \sigma_{3,1} & \cdots & \sigma_{3,g}\\ \vdots & \ddots & \vdots\\ \sigma_{n,1} & \cdots & \sigma_{n,g}\end{bmatrix}\begin{bmatrix}\Phi_1\\ \Phi_2\\ \Phi_3\\ \vdots\\ \Phi_g\end{bmatrix} = \begin{bmatrix}A_1\\ A_2\\ A_3\\ \vdots\\ A_n\end{bmatrix} \quad (2)$$

where

n: Number of Reactions

The neutron flux can be simply derived through matrix inversion if the number of measurement activities is equal to the number of the neutron energy groups. However, to obtain the reactions as many as neutron energy groups is difficult because available foil materials are limited. Unless the number of neutron energy groups is enough, the spectrum estimation will be inaccurate. Therefore, neutron spectrum obtained by simulation is used as an initial guess and iterative procedure is carried out until the acceptable solution is obtained. However, the unfolding result is dependent on the simulation in case that few samples are used. In order to reduce dependency on simulation, cover materials that can make additional reactions with same number of activation foils are used in this study. The matrix operation of moderated flux can be expressed as shown in Eq. (3).

$$\mathbf{S}\cdot\mathbf{\Phi}' = \begin{bmatrix}\sigma_1 & \sigma_2 & \sigma_3 & \sigma_4 & \cdots & \sigma_g\end{bmatrix}\begin{bmatrix}\Phi'_1\\ \Phi'_2\\ \Phi'_3\\ \vdots\\ \Phi'_g\end{bmatrix} = \mathbf{A}' \quad (3)$$

As shown in Eq. (4) and Eq. (5),

$$\mathbf{S}\cdot\mathbf{M}\cdot\mathbf{\Phi} = \begin{bmatrix}\sigma_1 & \sigma_2 & \cdots & \sigma_g\end{bmatrix}\begin{bmatrix}s_{1\to1} & \cdots & s_{g\to1}\\ s_{1\to2} & \cdots & s_{g\to2}\\ s_{1\to3} & \cdots & s_{g\to3}\\ \vdots & \ddots & \vdots\\ s_{1\to4} & \cdots & s_{g\to g}\end{bmatrix}\begin{bmatrix}\Phi_1\\ \Phi_2\\ \Phi_3\\ \vdots\\ \Phi_g\end{bmatrix} = \mathbf{A}' \quad (4)$$

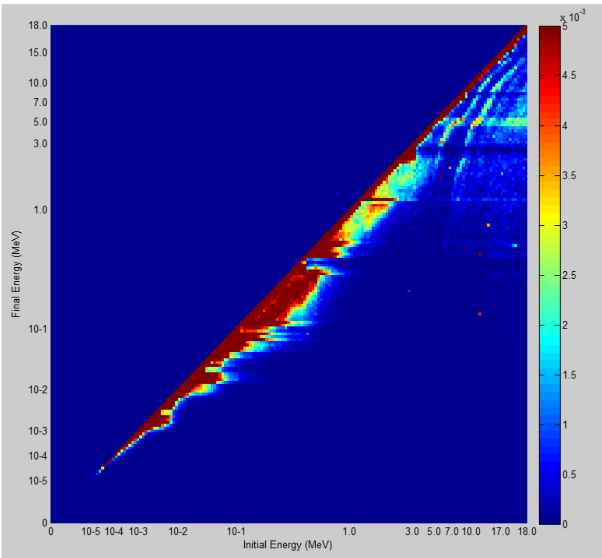
$$\mathbf{S}' \cdot \mathbf{\Phi} = [\sigma'_1 \quad \sigma'_2 \quad \sigma'_3 \quad \sigma'_4 \quad \cdots \quad \sigma'_g] \begin{bmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \\ \vdots \\ \Phi_g \end{bmatrix} = \mathbf{A}' \qquad (5)$$

where

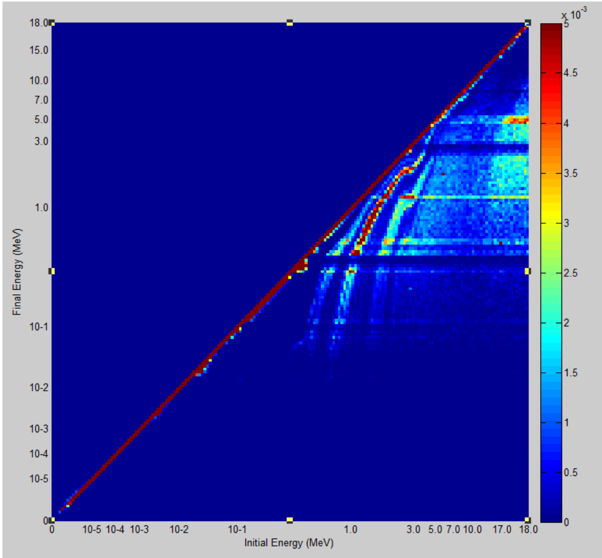
A': Measured Activity of Moderated Flux
M: Flux Moderation Function
S': Modified Group Activation Cross-section

additional reactions can be obtained if we know how the flux change for each energy group.

Boron and cadmium are used as cover materials, which actively capture the thermal neutrons. Boron and cadmium can make significant change in the activation result because the activation reaction cross section is usually high in thermal region. 2 cm thick boron and cadmium plate is located between source point and activation foils. Moderating matrices of the boron and cadmium were acquired using SCX card of MCNPX 2.7 [3] code in the energy from 0 to 18 MeV. Energy bins of the matrices are set corresponding to energy groups of EAF 2010 cross section library [4]. Fig. 1 shows that the moderated neutrons came from which initial energy group. Passing through without energy reduction is most often. Neutrons between 1 keV and 1 MeV are commonly losing their energy in boron, on the other hand, neutrons of above 1 MeV are commonly moderated passing through cadmium.



(a) Boron



(b) Cadmium

Fig. 1 Neutron Flux Moderation Function.

2.2 Initial Spectrum Estimation

The neutron spectrum unfolding process was carried out to validate that using cover materials is effective. An initial neutron energy spectrum was arbitrarily set 175 group flux from 0 to 18 MeV. The activation foils were gold and cobalt foils. There are three dominant reactions: ^{197}Au (n, γ) ^{198}Au, ^{197}Au (n,2n) ^{196}Au, and ^{59}Co (n, p) ^{59}Fe. A threshold energy of those reactions is 0, 8.5 and 1.5 MeV, respectively. Three activities without the foil cover materials - bare condition, and several numbers of activities with the cover materials and their combinations were obtained by the MCNPX 2.7 and the FISPACT [5] code, as shown in Table I.

Table I: Calculated Foil Activity Using Cover Materials

Cover Materials	Activated Nuclide [Unit: Bq]		
	^{198}Au	^{196}Au	^{59}Fe
Bare	6.947E+07	6.468E+04	5.342E+02
Boron	6.208E+05	5.367E+04	4.428E+02
Cadmium	4.290E+07	5.362E+04	4.386E+02
B-Cd	4.115E+05	4.383E+04	3.575E+02
Cd-B	4.145E+05	4.390E+04	3.586E+02

SAND-II [6] code was used for neutron energy spectrum unfolding. Uniform distribution from 0 to 18 MeV was inputted as an initial guess of the neutron spectrum. The unfolding results of bare condition and cases of using the cover materials were compared. Fig. 2 shows the unfolded neutron spectrums according to used number of reactions. Unfolded spectrum of bare condition has three branches coincident with the threshold energy of the reactions. From 0 to 1.5 MeV, the unfolded spectrum of bare condition indicates flat lines which are equal to initial guess. In the range of 1.5 MeV to 8.5 MeV, the unfolded spectrum has similar trend although it is not completely matched with the original spectrum and highly underestimated above 8.5 MeV. It shows that three reactions of two foils are not sufficient to accurately estimate the neutron spectrum. Unfolding result with nine reactions, using boron and cadmium, shows more analogous to real spectrum than bare condition. Flat line is still indicated below 1 eV, however, unfolded spectrum follows the actual spectrum from 1 eV to 8.5 MeV. In case that 15 reactions are used, working with boron, cadmium, and their combinations, the estimated spectrum is more comparable to real spectrum. In all cases, the unfolding spectrums are not changed below 1 eV. The neutrons of this low energy region are almost absorbed by the cover material; therefore, an effect of the cover materials is not appeared. Also, unfolding results are too low above 8.5 MeV. It is because the activity of ^{196}Au is underestimated compared to ^{198}Au or ^{59}Fe in the process of unfolding spectrum. In this high energy region, unfolded spectrums are rarely adjusted. The reason why the effect of moderation is not appeared is that high energy neutron passes through the cover material as its own energy, in other words, high energy neutrons are not moderated.

The results show that additional reactions obtained by the cover materials help in unfolding spectrum accurately. However, boron and cadmium are not effective in the energy range of less than 1 eV and above 10 MeV. Proper materials, therefore, are needed which are effective in very low and high energy regions.

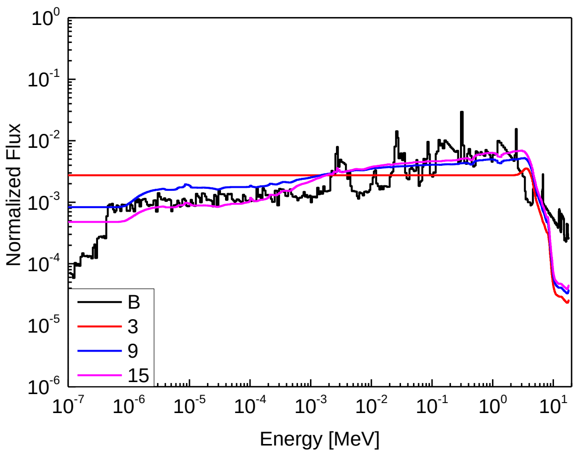


Fig. 2 Unfolding Results According to Number of Reactions.

3. Conclusions

The uses of the particle accelerators are rapidly increasing in these days. The produced neutrons should be identified for effective utilization of the facility. The purpose of this study was to suggest foil cover materials to acquire additional activation reactions. Unfolding neutron spectrum was performed with gold and cobalt as activation foils and boron and cadmium as foil cover materials. The unfolded spectrum became similar to actual spectrum according to increasing the number of reactions that were obtained by cover materials with same foils. This study is expected to improve efficiency of neutron spectrum unfolding using limited number of activation foils.

Acknowledgement

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