Design of Neutron Monitor for Wide Energy Range from Thermal to 100MeV

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I. INTRODUCTION

Intense and spallation neutron sources using high-power proton accelerators have been developed for basic scientific research, such as neutron structural biology and material science, and for the development of transmutation technology for long-lived transuranic nuclides[1-3]. At these facilities, neutrons with wide energy distribution are produced as secondary particles and become a major source of external exposure outside the radiation shield. Radiation monitoring of the neutrons is very important for radiation safety management for workers and the members of public. BF_3 and ^3He proportional counters equipped with a moderator, so called “rem counters”, are commonly used in neutron monitoring for radiation protection. However, the rem counter is not sensitive for the neutrons above several tens MeV and it overestimates the dose in energy range from several eV to keV. It is therefore essential to develop a neutron monitor that has a much better energy response for the neutron in wider energy region.

The purpose of the present study is to develop a neutron monitor that has an energy response corresponding to the effective dose and ambient dose in energy range from thermal neutron to 100 MeV. We apply the spectrum weight function (SWF) method [4,5] to organic liquid scintillators that have been used for the spectrum measurement of high-energy neutrons. This paper presents the principle of application of the SWF method for neutron dose monitoring and calculations of response functions of the organic liquid scintillators, and discusses the applicability of the SWF method using the liquid organic scintillator to the neutron dose monitoring.

II. METHODS

II.1 PRINCIPLE OF SPECTRUM WEIGHT FUNCTION METHOD AND ITS APPLICATION TO NEUTRON DOSE MONITOR

The SWF method is to evaluate radiation dose by applying an operator to the energy response function of a detector. If $R(E,E_R)$ is the energy response of the neutron detector and $D(E)$ is the dose conversion factor corresponding to it, the $G(E_R)$ function connecting these two functions must meet the following condition.

$$D(E) = \int R(E, E_R) \cdot G(E_R) dE_R. \qquad (1)$$

This $G(E_R)$ function is called as the spectrum weight function, which is the operator correlating $R(E,E_R)$ and $D(E)$.

If there is $G(E_R)$ function for neutron detector, we can evaluate neutron dose directly by applying $G(E_R)$ from Eq.(1) to a measured pulse height spectrum of the neutron detector. The measured pulse height spectrum $P(E_R)$ as a function of recoiled particle energy E_R is expressed using the detector response matrix $R(E,E_R)$ by

$$P(E_R) = \int R(E, E_R) \cdot \phi(E) dE, \qquad (2)$$

where $P(E_R)$ is the measured pulse height spectrum, and $\phi(E)$ is neutron fluence with energy E.

The integral dose D for neutrons is given by

$$D = \int \phi(E) \cdot D(E) dE. \qquad (3)$$

Using Eqs. (1) and (2), the integral dose can be written as

$$\begin{aligned} D &= \int \phi(E)\cdot D(E)dE \\ &= \int \phi(E)\cdot (\int R(E,E_R)\cdot G(E_R)dE_R)dE \\ &= \int (\int R(E,E_R)\cdot \phi(E)dE)\cdot G(E_R)dE_R \\ &= \int P(E_R)\cdot G(E_R)dE_R \qquad (4) \end{aligned}$$

As described above, the integral dose *D* is estimated from the pulse height spectrum by multiplying the spectrum weight function $G(E_R)$ which can be determined by solving the above Eq.(1).

II.2 CALCULATION OF RESPONSE FUNCTIONS AND THE G(ER) FUNCTIONS OF ORGANIC LIQUID SCINTILLATOR

In the present study, we focused on the organic liquid scintillator BC501A as a neutron detector. BC501A, which is compatible with the NE213 organic liquid scintillator, is used for the measurement of high-energy neutron spectra and can separate the gamma-neutron signals by the pulse shape distribution (PSD) techniques. To calculate the $G(E_R)$ function of Eq.(1), it is necessary to obtain the response function of BC501A. Monte Carlo codes SCINFUL[6] and CECIL[7] were used for calculating the response functions of BC501A for various mono-energetic neutrons. SCINFUL, developed by Dickens, calculates the response functions of the cylindrical NE213 detector for the incident neutron energies up to 80MeV and considers the following 11 reaction channels, i.e., H(n, p), C(n, n), C(n, n'),C(n, 2n), C(n, p), C(n, np), C(n, d), C(n, ^{3}He), C(n, α), C(n, n'3α) and C(n, xγ). CECIL, originally developed by Stanton[8] and then modified by Cecil et al., calculates the response functions of hydrocarbon scintillator for the incident neutron energies up to several GeV and considers the following 7 reaction channels, i.e., H(n, p), C(n, n), C(n, 2n), C(n, np), C(n, α), C(n, n'3α) and C(n, xγ). Both SCINFUL and CECIL calculate the response function of BC501A, but they employ different cross section of C(n, np) and C(n, α) and light output of deuteron.

Figure 1 shows geometry for calculating the response function of BC501A. Mono-energetic neutrons are assumed to be incident to the center of the front surface of the scintillator. The calculations were carried out for a scintillator of 12.7cm in diameter and 12.7cm in length. The size of scintillator was chosen by the following reasons. First, 1) this size of scintillator is equivalent to the recoiled proton range, Ep=117MeV, and has enough sensitivity for high energy neuron of several hundred MeV, and the light attenuation in the scintillator doesn't become a problem, 2) the response functions have been measured for mono-energetic neutrons up to 135MeV by Nakao[9] and up to 65MeV by Meigo[10], and therefore the calculated response functions can be verified by referring these data.

The $G(E_R)$ function was calculated by unfolding method which used a successive approximation method of response function and dose conversion factor[11]. The successive approximation method was chosen by modifying the SAND-II code[12], because this method has an advantage to get a solution with good stability, no oscillation and non-negative. On calculating the $G(E_R)$ function, the iteration frequency was settled by 10-20 % because of a tendency of oscillation by many iteration frequencies.

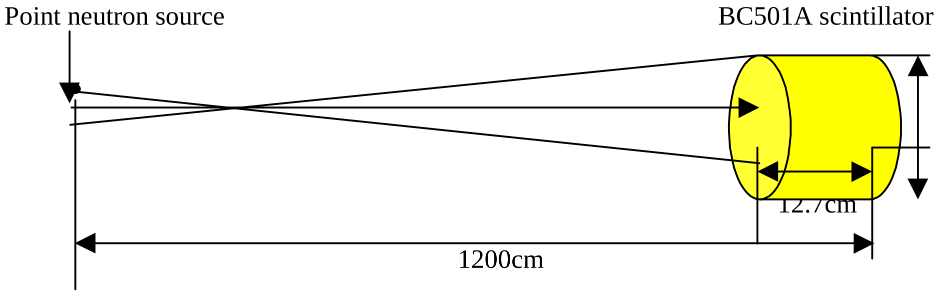

Fig.1 Geometry for calculating the response function of BC501A

III. RESULTS AND DISCUSSION

Figure 2 shows response functions of BC501A calculated by SCINFUL and CECIL for the incident neutron energies E_n = 10, 20, 30, 40, 50, 60, 70 and 78MeV. It was found that the response functions calculated by two different codes agree with each other for the incident neutron energies below 20MeV. This is because light output in the energy region is mainly due to recoiled protons and no significant difference exists in the cross section data for the reaction in the two codes. However, the difference in the shape of response function and the position of recoiled proton edge is becoming obvious with increasing the incident neutron energy. This is caused by the difference in the cross section of C(n, np) and C(n, α) and light output of deuteron in SCINFUL and CECIL.

The $G(E_R)$ functions were calculated by unfolding method using the response functions shown in Fig. 2 and the dose conversion factors compiled in ICRP74. Figures 3 and 4 show the $G(E_R)$ functions calculated for effective dose and ambient dose conversion factors and the response functions by SCINFUL and CECIL codes, respectively. As seen in Figs. 3 and 4, the $G(E_R)$ functions are reflected by the conversion factors used. Difference in the $G(E_R)$ functions becomes markedly from the light output about 10MeVee by the difference in the values of effective dose and ambient dose conversion factors, as shown in Fig. 5.

Figure 6 shows the $G(E_R)$ functions calculated by the response functions by SCINFUL and CECIL codes using the effective dose conversion factors. To see a variation of evaluated dose by the difference of the response functions used, the effective doses were evaluated by supposing one of the simplest pulse height spectrum of neutron shown in Fig. 7. It was found that the effective dose calculated by the $G(E_R)$ function from SCINFUL gives higher values, about 2 times, than that from CECIL. The results suggest that it is very important to determine an appropriate response function of the scintillator in order to reduce uncertainty of the evaluated dose. The appropriate response function will be determined by calculations with both SCINFUL and CECIL and the experimental data [9,10].

Figure 8 shows the dose conversion factors obtained by folding the $G(E_R)$ functions and the response functions for various iteration frequencies ITMAX. In the case of ITMAX=15, the dose conversion factors folded by the $G(E_R)$ function have a little oscillation. However, it should be improved with increasing the number of ITMAX, and the dose conversion factor calculated using the $G(E_R)$ function is in agreement with those of ICRP 74[11]. It is concluded from the above results that the neutron dose can be evaluated using the response functions of the BC501A and the $G(E_R)$ functions for mono-energetic neutrons of the energy from 750keV and 80MeV.

IV. FUTURE WORK

The present study showed that the SWF method using the BC501A organic liquid scintillator can be used for neutron dose monitoring for mono-energetic neutrons from 750keV and 80MeV. In the next step, we will study applicability of the method to neutron fields of continuous energy spectrum. In addition, the response function of ^{10}B loaded liquid organic scintillator, BC523A, will be calculated by SCINFUL and MCNP[13]. BC523A is efficient for the detection of thermal neutrons as well as high-energy neutrons. It is expected that the SWF method using BC523A provides a neutron monitor for the energy range from thermal to 100MeV

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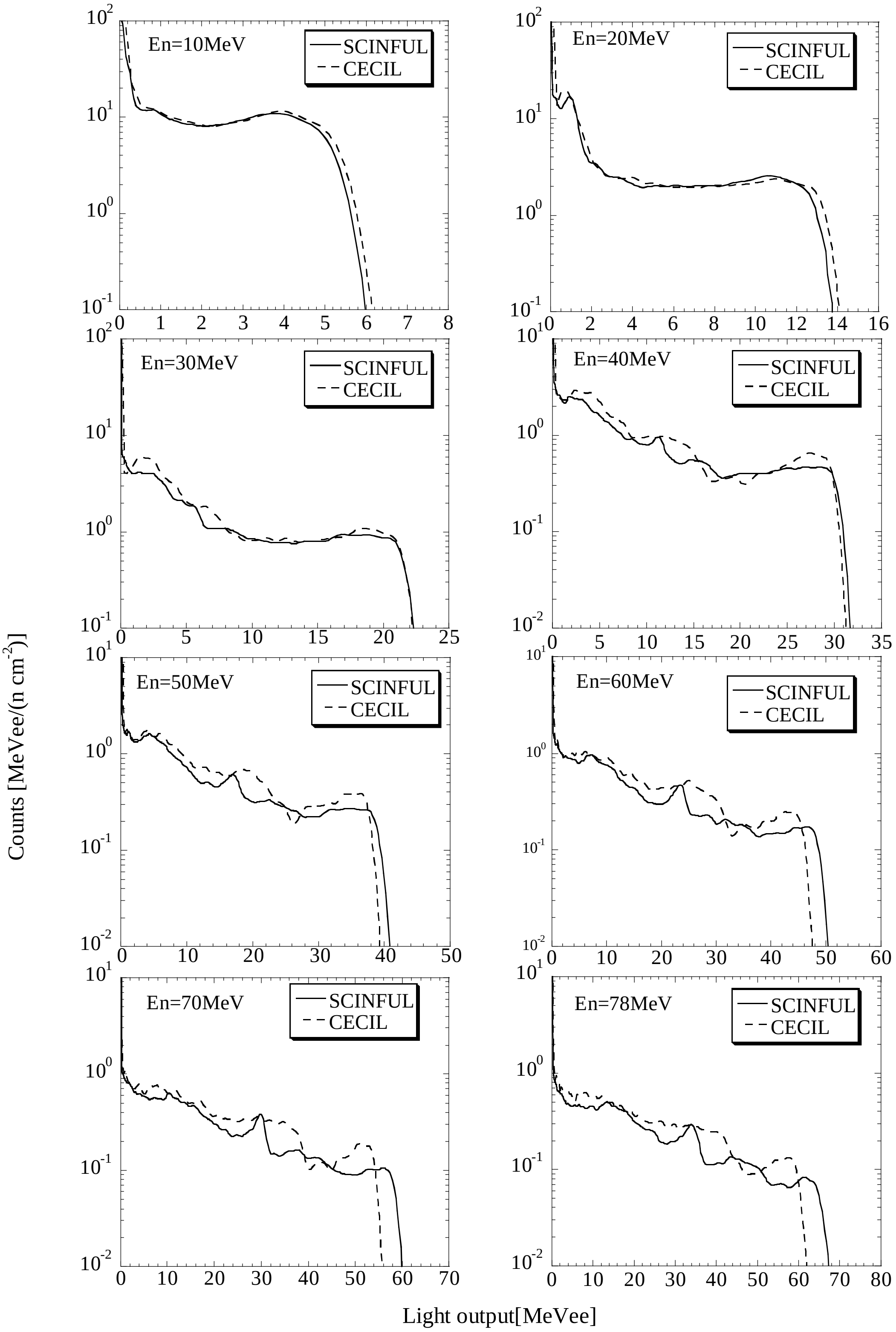

Fig.2 Calculated response functions of BC501A by SCINFUL and CECIL codes.

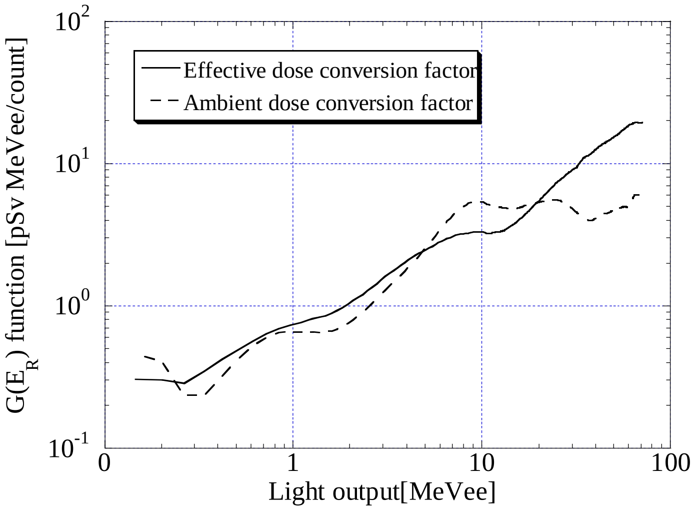

Fig. 3 Spectrum weight function, $G(E_R)$ calculated by SCINFUL response function and dose conversion factor

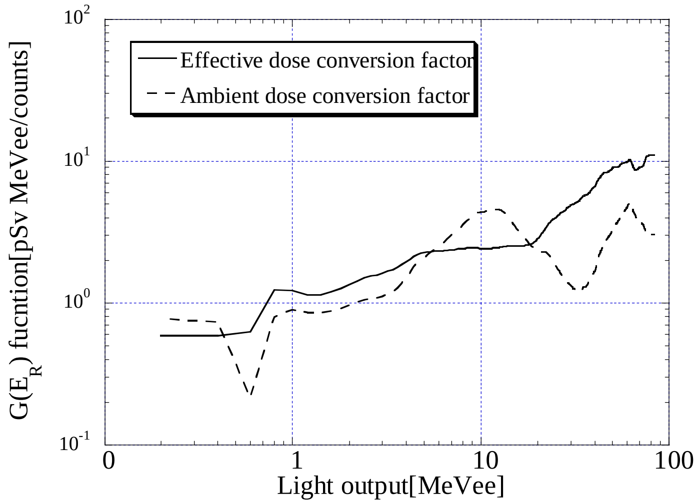

Fig. 4 Spectrum weight function, $G(E_R)$ calculated by CECIL response function and dose conversion factor

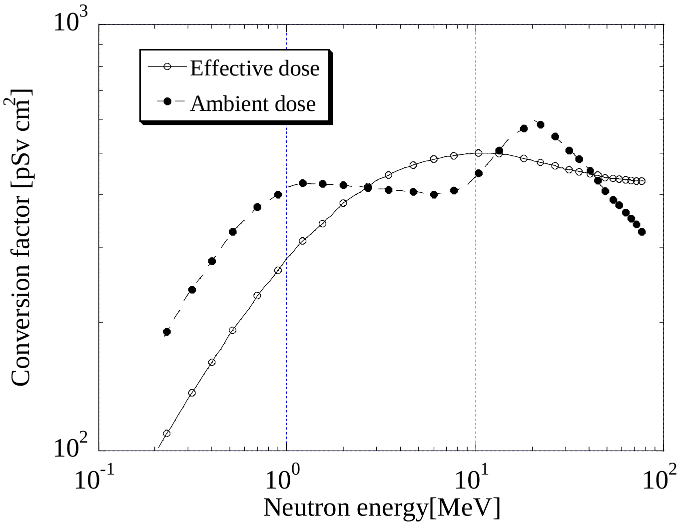

Fig. 5 Neutron dose conversion factors in ICRP 74

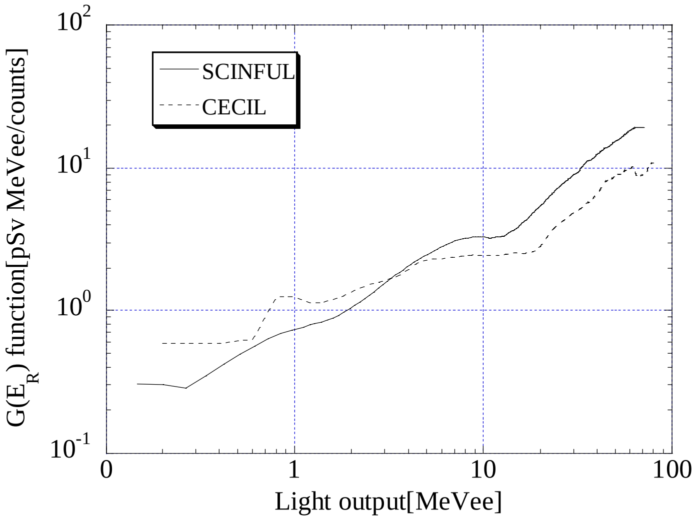

Fig. 6 Spectrum weight functions, $G(E_R)$ by effective dose conversion factor of response functions of SCINFUL and CECIL

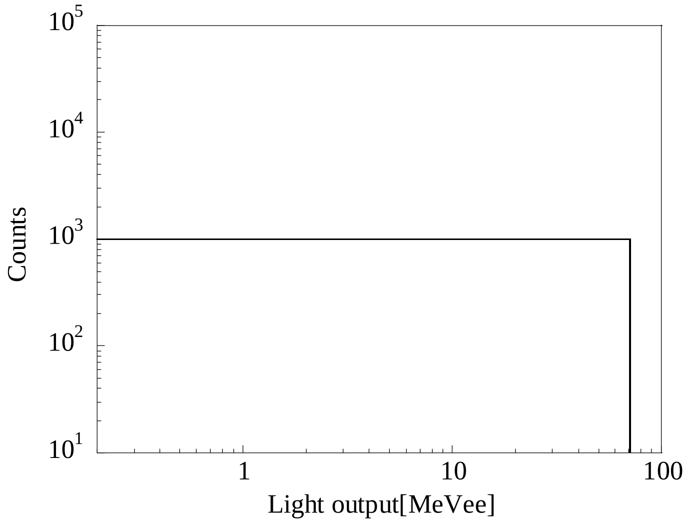

Fig.7 Supposed pulse height distribution for dose evaluation

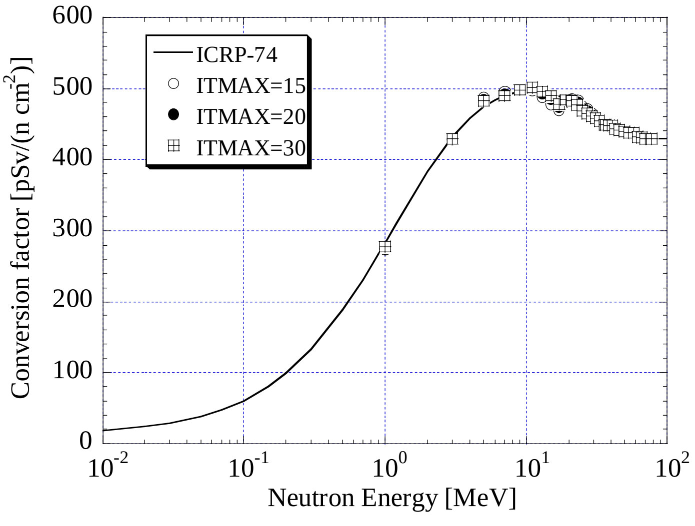

Fig. 8 Comparison the folded effective conversion factors by $G(E_R)$ function and effective dose conversion factors by ICRP74