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Reproduction of neutron fluence by unfolding method with an NE213 scintillator

Tsuyoshi Kajimoto [a,*], Toshiya Sanami [b], Noriaki Nakao [c], Robert Froeschl [d], Stefan Roesler [d], Elpida Iliopoulou [d,e], Angelo Infantino [d], Markus Brugger [d], Kenichi Tanaka [a], Satoru Endo [a]

[a] Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan
[b] High Energy Accelerator Research Organization, Oho, Tsukuba, Ibaraki 305-0801, Japan
[c] Shimizu Corporation, 3-4-17 Etchujima, Koto-ku, Tokyo 135-8530, Japan
[d] CERN, 1211 Geneva 23, Switzerland
[e] Medical Physics Laboratory, School of Medicine, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece

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ABSTRACT

The reproduction of neutron fluence derived by the unfolding method was confirmed by simulating an experiment at Cern High energy AcceleRator Mixed field facility (CHARM). Fluences on an NE213 scintillator located at positions surrounded with shields were calculated using PHITS. A neutron light output spectrum and response matrix were calculated according to the calculated fluence. Furthermore, response matrices with simple distributions of neutron incident position and direction on the scintillator were also prepared because a response matrix with guessed distributions is used in measurements. In spite of using response matrices with different distributions, the unfolded fluence agreed with each other, unless the distribution was focused on a position. The agreement of the fluences enables us to measure the fluence at various positions even though the distributions are experimentally unknown. Finally, experimental fluences were obtained under the same conditions, and were compared with the simulation results.

1. Introduction

The estimation of neutron energy spectra is needed to design the radiation shielding in high-energy accelerators because many neutrons produced in not only a target but also accelerator components by impact of beam, deeply transmit through shield due to high penetration capability. Experimental spectra are needed to validate the estimation. These spectra should be flux on a surface or fluence into a volume [1]. The flux is limited only when the surface can be defined uniquely. At positions behind or surrounded by the shielding and in the maze, the fluence can be obtained.

The fluence can be obtained by dividing the energy spectrum by the effective area, which is obtained from the track length estimation [2,3]. The track length depends on the detector shape and irradiation field: incident position and direction on the detector. Thus, the track length is measured or calculated according to incident position and direction distributions on the detector. Since neutrons are uncharged particles, it is difficult to experimentally grasp the distributions. The use of particle transport Monte Carlo code is effective to calculate the track length.

A method has been proposed to measure neutron fluences [4]. The method by the unfolding procedure with an cylindrical NE213 scintillator, which has widely been used to measure neutron fluxes [5–12], has been adopted for the neutron fluence measurement. The NE213 scintillator was located on the top of the roof shielding of Cern High energy AcceleRator Mixed field facility (CHARM) [13,14]. The method has been validated by the agreement between two fluences measured by changing the detector orientation; measurements were taken with different incident position and direction distributions on the scintillator. However, the response matrix and effective area have been calculated with simple distributions, and the accuracy of method has not been estimated.

By simulating an experiment at CHARM, we confirmed the accuracy and reproduction of neutron fluence derived by this method. Fluences at two positions surrounded with the shielding were calculated by constructing the geometry with PHITS [15]. A neutron light output spectrum and a response matrix were calculated according to the calculated fluence. The fluence was derived by unfolding the light output spectrum with the response matrix. The difference of unfolded to

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* Corresponding author.
E-mail address: kajimoto@hiroshima-u.ac.jp (T. Kajimoto).

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calculated fluences was less than 19% below 100 MeV, and 42% above 100 MeV. Finally, experimental fluences under the same conditions as the simulation were compared with the calculated fluences.

2. Fluence derivation by unfolding

To derive experimental and simulated neutron fluences, we used the method reported in Ref. [4]. The neutron fluence, $d\phi(E)/dE$ (n/MeV/cm^2/proton) with an energy, E, was derived from

$$\frac{d\phi(E)}{dE} = \frac{N(E)}{B\,A(E)\,\Delta E}, \tag{1}$$

where B is the number of beam protons, $N(E)$ is the neutron energy spectrum, and $A(E)$ is the effective area calculated using the track length estimation.

The neutron energy spectrum was derived by the unfolding method using the iterative Bayesian algorithm [16] in the RooUnfold package [17]. The neutron energy spectrum at the ith energy bin, $N(E_i)$, is

$$N(E_i) = \sum_j O(L_j)\,P(E_i|L_j), \tag{2}$$

where $O(L)$ is the neutron light output spectrum and subscript j shows the bin number of the spectrum. $P(E|L)$ is the conditional probability, which is expressed from the response matrix and a probability distribution consisting of the ratio of each bin value to the sum of the neutron energy spectrum. The neutron energy spectrum was obtained by giving an initial guess of the probability distribution.

The unfolding was performed by using experimental and simulated neutron light output spectra. Furthermore, the output of the simulation was used for calculating the neutron fluence, response matrix, and effective area. The calculated neutron fluence was as a true to the unfolded fluence by the simulation, and was used to confirm the fluence reproduction.

3. Experiment and simulation

To obtain the experimental and simulated neutron light output spectra, an experiment was performed at CHARM, and was simulated by reconstructing the experimental geometry. Fig. 1 shows sectional views of CHARM, which consisted of an irradiation room, paths to the irradiation room, a beam dump, and shields. The CERN Shielding Benchmark Facility (CSBF) is integrated into the roof shielding of CHARM. The irradiation room is enclosed with marble, normal concrete, and iron, and contains a target and movable shields consisting of two normal concrete and two iron plates with dimensions of $4.8 \times 0.2 \times 2.2$ m^3 ($L \times W \times H$). The beam dump is made of 8-m-thick iron.

The experiment and simulation were performed by changing the target and the neutron detector position. The target and the position are summarized in Table 1. The neutron detector was an NE213 scintillator with 12.7 cm in diameter and length, and was placed either above the target or in the maze surrounded with shields. In run #1, two veto scintillators with dimensions of 15 × 15 × 0.6 cm^3 and 15 × 15 × 0.3 cm^3 were set in front of the NE213 scintillator toward the target and upstream toward the beam, respectively. The vertical shielding structure between the target and the NE213 scintillator consisted of 10-cm-thick marble, 80-cm-thick iron, and 240-cm-thick concrete (80-cm-thick barite concrete and 160-cm-thick normal concrete). Part of shields above the target was removed only in run #1. In run #2, the veto scintillators with 0.6 and 0.3 cm in thicknesses were installed in front of the NE213 scintillator downstream toward the beam and toward the target, respectively. The horizontal shielding structure between the target and the NE213 scintillator consisted of 120-cm-thick normal concrete and 160-cm-thick iron.

A 24 GeV/c proton beam bombarded a $\Phi 8.0 \times 50$ cm^3 target. The characteristics of the target are summarized in Table 2. The slit aluminum target has many longitudinal slits to reduce the effective density.

Table 1
Experimental and simulation conditions. An NE213 scintillator was set positioned above the target or in the maze. The distance was from the target center to the center of the NE213 scintillator.

	Target	Position	Distance [m]
Run #1	Copper	Above target	5.75 (5.74, vertical)
Run #2	Slit aluminum	In maze	9.25 (9.05, horizontal)

Table 2
Target, effective density of the target, energy loss of protons penetrating the target, and transmission rate for the target.

Target	Density [g/cm^3]	Energy loss [MeV]	Transmission rate
Copper	8.9	786	0.00011
Slit aluminum	0.9	86	0.64

The energy loss of protons penetrating the target was calculated with SPAR [18]. Because the energy loss was too small to the beam energy, beam protons penetrated the target unless beam proton interacted with the target nucleus. The transmission rate was calculated from hadronic total cross sections by using systematics reported by Niita et al. [19]. For the copper target, the beam protons mostly reacted in the target. Since over half of the beam protons transmitted the slit aluminum target, the target and beam dump became the source of secondary particles.

3.1. Experimental neutron light output spectrum

The detectors, electronic circuit, and data analysis were the same as in Ref. [4]. These were described below, simply.

The target was irradiated with beam protons with an intensity of 3×10^{11} protons/spill during the measurement. The intensity was recorded spill-by-spill using a secondary emission chamber (SEC) [20]. The conversion factor from the SEC count into the number of beam protons was 1.87×10^7 (protons/count) [21].

Event-by-event data was acquired by the NIM and VME modules. The data consisted of four values from analog-to-digital converters (ADCs), and the time difference between the time of the signal from accelerator and the time the NE213 detector fired. The signal from accelerator was reached prior to the irradiation to the target. The ADC values were acquired from the total and slow components of the signal from the NE213 detector, and each signal from the veto detectors.

Neutron events were extracted from event-by-event data. Events originating in the beam were selected from the increase of event rate in the time difference spectrum. The averaged event rate was 36 and 1 events/ms for beam on and off for run #1, respectively, and 25 and 2 events/ms for beam on and off for run #2, respectively. Charged particle events were removed from the plots of ADC values for each veto detector. Neutron events were distinguished from γ-ray events by pulse shape discrimination (PSD), which was performed from the scatter plot of ADC values of total and slow components for the NE213 detector.

Fig. 2 shows neutron light output spectra drawn from the neutron events. The ADC value of the total components for the NE213 detector was converted into the light output value (MeVee: MeV electron equivalent) by using a calibration curve, which was obtained by measuring γ-rays from checking sources, cosmic-ray muons [22], and the maximum energy deposition of protons for the NE213 scintillator. The lowest bin edge of the light output spectrum was limited by the PSD to be 3.0 MeVee for run #1 and 4.2 MeVee for run #2.

3.2. Simulated neutron light output spectrum

PHITS version 2.82 was used for the simulation. The simulation space had dimensions of $24 \times 23 \times 10$ m^3 ($L \times W \times H$) as shown in Fig. 1. For the slit aluminum target in run #2, the effective density was used by ignoring the slit. The density and elemental components reported by Iliopoulou et al. [21] were used for shielding materials: normal