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ARTICLE

Measurement of neutron yields from a water phantom bombarded by 290 MeV/u carbon ions

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Double differential thick target neutron yields down to 0.6 MeV of neutron energy from 290 MeV/u carbon ion incidence on a water phantom were measured in the wide angular range at HIMAC facility. The water phantom size was 20 cm thick, 32 cm wide and 45 cm high. NE213 organic scintillators 12.7 cm thick and 12.7 cm long for high energy neutron measurement and 5.08 cm thick and 5.08 cm long for low energy one were adopted. Measurement angles were 15˚, 30˚, 45˚, 60˚, 75˚ and 90˚. Neutron energy was determined by the time-of-flight technique between the phantom and the detector. Neutron flight paths were 1.5 to 4.0 m. In order to measure neutrons scattered from the floor or other items in the experimental area, a 110 cm long iron shadow bar was placed between the phantom and each neutron detector. The measured neutron energy spectra were compared with calculation results by the PHITS code.

Keywords: carbon ion; water phantom; double differential thick target neutron yield; energy spectrum; NE213; TOF; SCINFUL-QMD; PHITS

1. Introduction

Heavy ion cancer therapy has been increased by reason of its clinical advantages. During the treatment, the secondary particles such as neutron and gamma-ray are produced by nuclear reactions of a heavy ion incidence on a nucleus in a patient body. It has become essential to estimate the risk of secondary cancer from recent survey[1,2]. In particular, it is important to know contribution of secondary neutrons for the estimation because the secondary neutron has a strong penetrability and gives undesired dose to normal tissues in a wide area. Estimation of the secondary neutrons yield data is critical for assessment of radiation safety on both of workers and public in treatment facilities.

The experimental data of neutron yields are required to be simulated with high accuracy. Especially, the accurate data around neutron energy of 1 MeV is required because the 1 MeV neutron has a large relative biological effectiveness (RBE).

The exposure dose from secondary neutrons is predicted by simulation codes. 290 MeV/u carbon ion incident neutron double differential cross sections for bio elements have been measured down to 0.6 MeV of neutron energy using NE213 liquid organic scintillators[3,4]. Monte-Carlo simulation code, PHITS[5] reproduced the measured neutron spectra well in both the magnitude and shape[1].

On the other hand, thick target neutron energy spectra from a water phantom bombarded by 200 MeV/u carbon beam obtained at GSI for 0˚ to 30˚ using BaF_2 scintillators[6]. The experimental data showed discrepancies with simulation data by PHITS.

In this study, we measured double differential thick target neutron yields down to 0.6 MeV of neutron energy from carbon ion incidence on a water phantom in wide angular range from 15˚ to 90˚ with the therapeutic ion energy using NE213 scintillators. The experimental data are compared with calculated results by the PHITS code.

2. Experiment

The measurement of neutron energy spectra was performed at PH2 course of Heavy Ion Medical Accelerator in Chiba (HIMAC), National Institute for Radiological Sciences. The experimental setup is illustrated in **Figure 1**.

Incident ^{12}C beam energy was 290 MeV/u. The beam spot size was less than 10 mm in diameter at the target position. Since the synchrotron was operated in a pulse mode (0.3 Hz repetition cycle) and incident carbon beam intensity was very weak in level of 5×10^5 particles / 3.3

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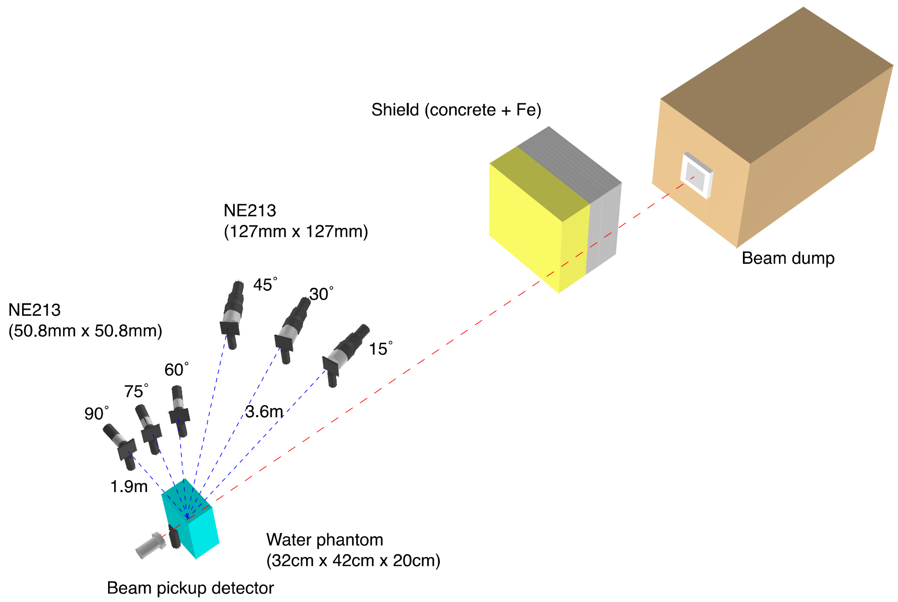

Figure 1. Experimental setup of double differential thick target neutron yields for 290 MeV/u ^{12}C incidence on a water phantom at HIMAC.

sec, the number of incident carbons can be individually counted. The carbon ions came from a vacuum duct through a 100 μm thick aluminum window. Before bombardment on a water phantom target, the beam passed a beam pickup detector which was a 2 mm thick NE102A plastic scintillator. The detector provided the signal for the time-of-flight (TOF) measurement and the number of incident ions.

The water phantom was composed of 1 cm thick acrylic case and filled with purified water. Dimension of the water phantom was 32 cm x 40 cm x 20 cm. The thickness of the phantom was enough for 290 MeV/u carbon ion to stop completely in the medium.

Emitted neutrons were detected with NE213 liquid organic scintillators. Two size of scintillators were used to cover wide neutron energy range. Large and small detector sizes were 127 mm in diameter and 127 mm long and 50.8 mm in diameter and 50.8 mm long, respectively. The scintillators were placed at 15˚, 30˚, 45˚, 60˚, 75˚ and 90˚. Scintillation lights from the NE213 liquid organic scintillators are originated from as well as gamma-rays and charged particles. Distance between the phantom and NE213 scintillators were varied from 2.4 m to 3.7 m for large scintillators and from 1.8 m to 2.4 m for small ones, respectively. The light outputs of the neutron detectors were calibrated by using photons from gamma-ray sources of ^{241}Am (Eγ = 0.060 MeV), ^{137}Cs (Eγ = 0.661 MeV), ^{60}Co (Eγ = 1.22 MeV), and ^{241}Am-Be (Eγ = 4.33 MeV) to determine the threshold level. The kinetic energies of neutrons were determined by TOF technique using the time difference between the beam pickup scintillator and the neutron detector.

A veto detector, 2 mm thick NE102A plastic scintillator, was put in front of each NE213 scintillator to separate charged particle events.

In order to reduce neutrons from the beam dump, a couple of an iron of 63 cm thick and a concrete of 50 cm thick shields was placed between the detectors and beam dump as shown in Figure 1. For measurement of background neutrons, the measurement with an iron shadow bar of 110 cm thick set between a target and detector were also carried out.

Data on the signal charge integrated with a specific gate width, and flight time triggered by the beam pick up scintillator and the neutron detectors were recorded event by event via an electronic circuit connected to a personal computer.

3. Data analysis

Figure 2 shows the light-output distribution of the beam pickup detector. To determine the number of

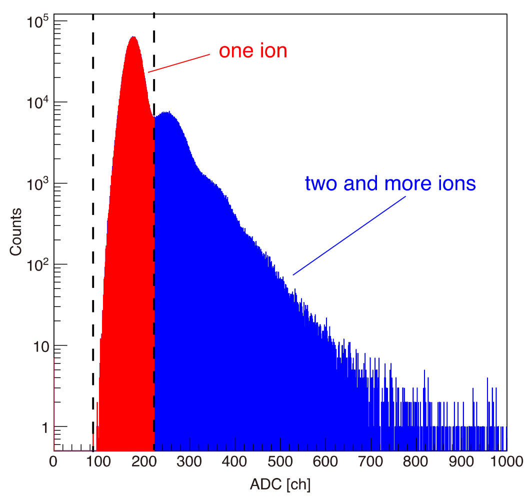

Figure 2. Light output spectrum of beam pickup detector.

heavy ions bombarding the target, the incident beam was monitored ion by ion. Events that two or more heavy ions were incident simultaneously which is blue region above 220 ch in the figure were designated as multiple incident events, give larger light outputs compared with the single incident events. The beam intensity was controlled to keep the condition that the number of the multiple incident events is 10 % or less than that of the single ones.

A typical result of separation of neutron and gamma-ray events using light output data with total and slow gates for the small NE213 scintillator is demonstrated in **Figure 3**. One can see that neutron events were clearly separated from photon events in low light output region.

Neutron detection efficiencies of the NE213 scintillators were obtained using a computer simulation code named SCINFUL-QMD[7]. The threshold levels were set at the position of half height with respect to a Compton edge in light-output spectra with photons from the gamma-ray sources mentioned above. The neutron detection efficiencies of both size of scintillators calculated by SCINFUL-QMD with various threshold levels were shown in **Figure 4**.

Figure 5 indicates an example of the TOF spectra of without and with a shadow bar, where the charged particle events were excluded. The horizontal axis of the TOF spectra is reversed, because the stop signal of the TOF measurement is taken from the beam pickup detector. The peak of prompt gamma ray appears at 3120 ch of the spectrum. The neutron energy was deduced from the TOF data. The results of the double differential thick target neutron yields were obtained by subtracting the background data measured with the shadow bars from the data of foreground measurement.

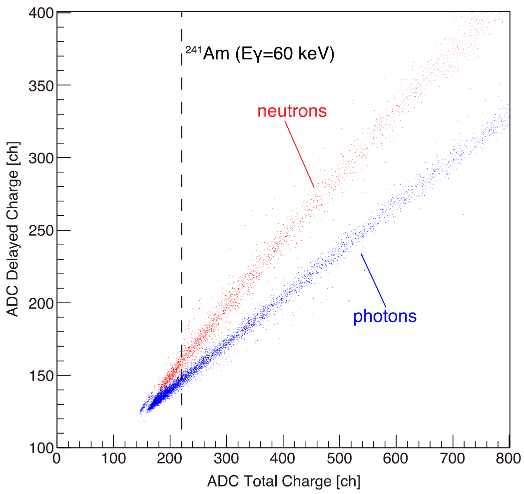

Figure 3. Separation of neutron and gamma ray events for the small NE213 scintillator using light output spectra with different integration time.

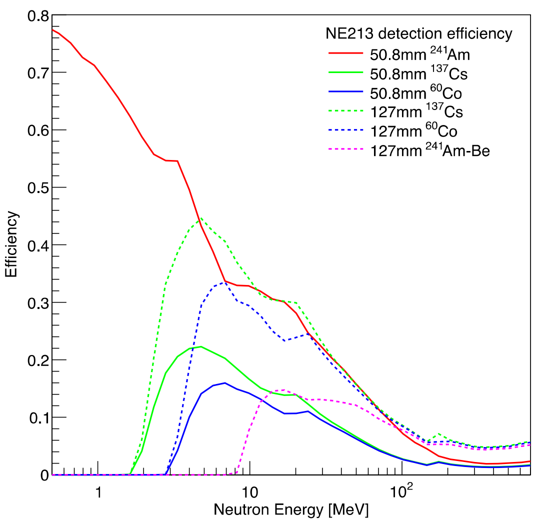

Figure 4. Detection efficiencies of two sizes of NE213 scintillators using SCINFUL-QMD code.

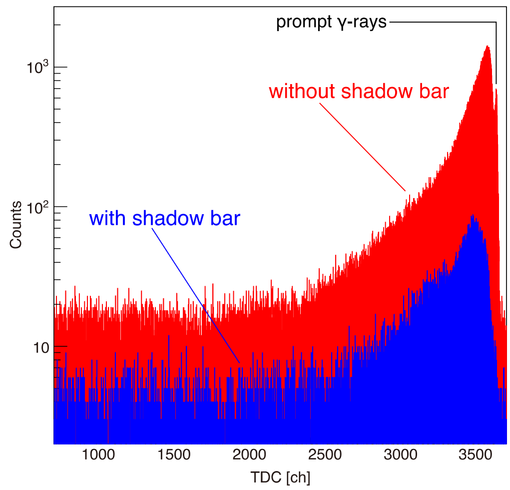

Figure 5. Examples of TOF spectra with and without a shadow bar for large NE213 scintillator.

4. Results

Experimental data of double differential neutron thick target yields are shown in **Figure 6**. Calculation results by the PHITS code are also indicated in the same figure. quantum molecular dynamics (QMD)[8] and generalized evaporation model (GEM)[9] are used as nuclear reaction models. The NASA systematics[10] is adopted as nucleus-nucleus cross sections. PHITS reproduce neutron yields above 30 - 40 MeV, however, overestimates them below 30 MeV.

Figure 7 stands for energy integrated neutron yields above 2 MeV of neutron energy. PHITS overestimates experimental data about 30 % because the code overestimates neutron energy spectra below 30 MeV.

5. Conclusion

Double differential thick target neutron yields from a water phantom bombarded by 290 MeV/u carbon beam were measured at the six laboratory angles from 15˚ to 90˚ by the TOF method using two sizes of NE213 liquid

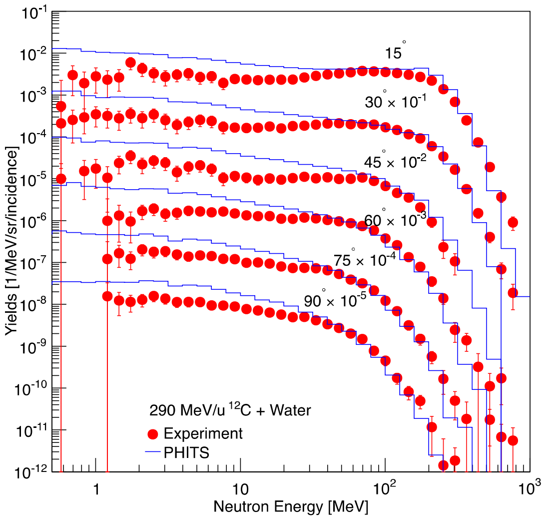

Figure 6. Experimental data of double differential thick target neutron yields for 290 MeV/u carbon incidence on a water phantom with the PHITS calculation.

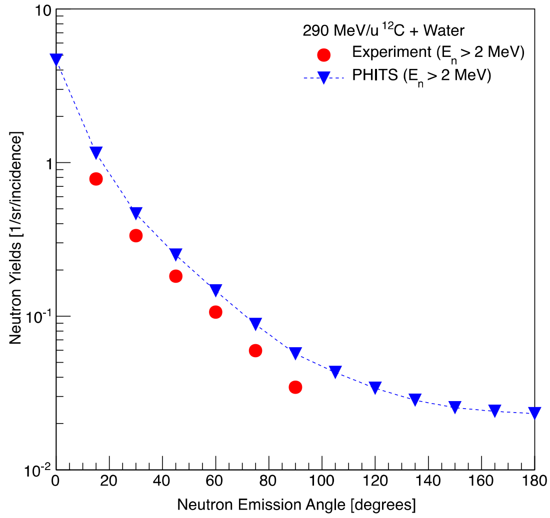

Figure 7. Angular distribution of neutron yields for experimental and PHITS data integrated by neutron energy above 2 MeV.

organic scintillators down to 0.6 MeV. PHITS reproduce energy spectra of experimental data above 30 MeV well and overestimate that energy. The PHITS code overestimates angular distribution of neutron yields above 2 MeV because of overestimation of neutron energy spectra below 30 MeV.

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