Distributions of neutron yields and doses around a water phantom bombarded with 290-MeV/nucleon and 430-MeV/nucleon carbon ions


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ABSTRACT
Double-differential neutron yields from a water phantom bombarded with 290-MeV/nucleon and 430-MeV/nucleon carbon ions were measured at emission angles of 15°, 30°, 45°, 60°, 75°, and 90°, and angular distributions of neutron yields and doses around the phantom were obtained. The experimental data were compared with results of the Monte-Carlo simulation code PHITS. The PHITS results showed good agreement with the measured data. On the basis of the PHITS simulation, we estimated the angular distributions of neutron yields and doses from 0° to 180° including thermal neutrons.

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1. Introduction

Hadrontherapy, i.e., the medical use of charged particle beams supplied by a particle accelerator, is known to be an effective treatment for cancers that are difficult to remove by surgery. When compared with photons and fast neutrons, charged particle beams demonstrate a good depth-dose profile (Bragg curve) inside the body of a patient, which enables the dose to be concentrated on a tumor located at a fixed depth inside tissue without unnecessary exposure of normal tissue. In addition, the charged particles such as heavy ions have a high relative biological effectiveness (RBE) owing to their high linear energy transfer (LET) characteristics [1,2]. The Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) in Japan is one of the leading facilities for hadrontherapy. As of December 2014, 8841 patients have been treated there [3]. Although HIMAC can provide various charged particles with different energies, carbon ions with primary energies between 140 MeV/nucleon and 430 MeV/nucleon are used for treatment owing to their penetration lengths in the patient’s body [4], good dose concentrations [1,2], and relatively high LETs [1,2]. On the basis of the results accumulated with HIMAC and the prior researches [5–7], treatment facilities employing carbon-ion beams have been constructed and planned worldwide [3].

For designing new facilities, proper shielding is indispensable not only to ensure radiation safety but also to reduce the overall cost of the facility. The yields of secondary particles from interactions with accelerated carbon ions and materials on or around the beamline should be well understood as source terms in dose estimation to establish reasonable shielding requirements. Secondary neutrons are especially important because they have a high penetrability through shielding materials and dominate the radiation dose outside the shield. Experimental data on neutron production from materials consisting of heavier elements such as copper and lead, which are used for constructing accelerator apparatuses and beam dumps, are available [8,9]. These data have been used to improve Monte-Carlo simulation codes for predicting the dose map throughout a facility based on calculations of nuclear reactions and particle transport in 3-dimensional space [9,10].
However, the situation is different for a medical treatment room, where the body of a patient becomes a source of the secondary neutrons because the carbon ions are stopped inside the body. Experimental data on neutron production from tissue-substitute materials that consist of lighter elements are strongly required for optimization of the design of access mazes, walls, and shields in treatment rooms [11,12].

At the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany, Gunzert-Marx et al. [13] experimentally studied neutron production from 200-MeV/nucleon carbon ions stopped in a thick water target. Their results are the only data available on double-differential neutron yields for a combination of primary carbon ions and a thick water target. The data have been utilized for investigating mechanisms of nuclear reactions, validating Monte-Carlo simulation codes, and estimating dose contributions of neutrons during carbon-ion therapy. The accuracy of Particle and Heavy Ion Transport Code System (PHITS) [14] was found to be good through a comparison of simulated data with experimental data. However, the experimental data were restricted to forward angles below 30° with respect to the beam axis and high-energy neutrons above 20 MeV. In addition, new treatment facilities such as HIMAC have planned to use carbon-ion beams with higher primary energies than that used by the GSI [3]. To optimize shielding design in the nuclear engineering field, the demand for the acquisition of new experimental data and validation of Monte-Carlo simulation codes for neutron production still remains.

With this background in mind, our study aimed to obtain experimental data on double-differential neutron yields at emission angles of 15°, 30°, 45°, 60°, 75°, and 90° in the energy range above a few MeV from a water phantom bombarded with carbon ions with therapeutic energies of 290 MeV/nucleon and 430 MeV/nucleon. We derived distributions of neutron yields and effective doses around the water phantom. All the experimental data were compared with calculation results of PHITS to examine the accuracy of the Monte-Carlo simulation code. Furthermore, on the basis of the PHITS simulation, we estimated angular distributions of neutron yields and doses in the range from 0° to 180° including thermal neutrons, which are not obtainable from experiments.

2. Materials and methods

2.1. Experimental procedure

The experiment was performed at the PH2 beamline of HIMAC. The experimental procedure was similar to the one described in detail in our previous paper [15]. Fig. 1 illustrates the setup of the target and detectors in the present experiment. A pulsed beam of 12C ions accelerated up to 290 MeV/nucleon or 430 MeV/nucleon was extracted from the synchrotron at a repetition cycle of 0.3 Hz with a pulse width of approximately 1 s and guided to the experimental room through a vacuum tube. The diameter of the beam spot was tuned to approximately 0.5 cm at the exit window of the tube by measuring the position as well as horizontal and vertical profiles with a fluorescent plate that was temporarily inserted on the beam axis for beam tuning. The beam intensities were maintained at $1 \times 10^8 - 3 \times 10^9$ particles per pulse with a flat top distribution during the measurement by monitoring with a beam pick-up detector, which consisted of a 0.5-mm-thick NE102A plastic scintillator.

A water phantom representing a human torso was mounted on a stage 10 cm downstream from the beam exit window. Fig. 2 illustrates the size and shape of the phantom, which consisted of purified water filled in an acrylic resin container with 1-cm-thick walls. The density of the acrylic resin was 1.19 g/cm³. The height of the phantom was 45 cm, and the lengths of minor and major axes were 20 cm and 32 cm, respectively. The phantom orientation was adjusted depending on the beam energy in order to completely stop the beams in the phantom: for the 290 MeV/nucleon beam, the minor axis of the phantom was along the beam axis; for the 430 MeV/nucleon beam, the phantom was rotated by 90° relative to the beam direction such that the minor axis of the phantom was perpendicular to the beam. The ranges of 290-MeV/nucleon and 430-MeV/nucleon carbon ions in water were estimated to be approximately 15 cm and 30 cm, respectively, by the Stopping and Range of Ions in Matter (SRIM) software [16].

Neutrons emitted from the water phantom were detected by neutron detectors consisting of NE213 liquid organic scintillators and photomultiplier tubes placed at horizontal angles of 15°, 30°, 45°, 60°, 75°, and 90° with respect to the beam axis. The angles were referenced to a spherical polar coordinate system with its origin centered on the surface upstream of the water phantom. The flight-path lengths from the phantom to the neutron detectors were also measured from this origin to adopt the same coordinate system. A veto detector consisting of a 2.0-mm-thick NE102A plastic scintillator and a photomultiplier tube was also mounted in front of each neutron detector to tag the charged particle events and to eliminate them from the neutron events for the off-line data analysis. To measure neutrons with a wide energy range from a few MeV to several hundred MeV, we employed two independent detection systems (systems A and B) using NE213 scintillators in two different sizes. System A consisted of three NE213 scintillators with both diameter and thickness of 12.7 cm and was used to

![Fig. 1. Schematic of experimental setup at the PH2 beamline.](image-url)
detect neutrons above approximately 10 MeV. System B was used for the detection of low-energy neutrons below 10 MeV with three NE213 scintillators with both diameter and thickness of 5.08 cm. We employed the smaller scintillators in system B for low-energy neutron detection because they have a better performance regarding pulse shape discrimination between neutrons and photons compared with the larger ones. Each system measured neutrons at three angles simultaneously, and data were obtained at six angles using both systems A and B by changing their positions. The kinetic energy of the neutrons was determined by measuring the time-of-flight (TOF). The flight-path lengths for systems A and B for 290-MeV/nucleon and 430-MeV/nucleon carbon-ion beams summarized in Table 1 are the distances between the origin of the present coordinate system and the mid-position of the neutron detectors. A longer flight-path length provides better energy resolution, while the geometric efficiency of neutron detection decreases with increasing flight-path length, obeying an inverse square law.

The signal charges integrated over specific gate widths and TOFs were recorded event by event and independently for systems A and B via electronic circuits, which consisted of NIM and CAMAC modules, connected to personal computers. Details

<table>
<thead>
<tr>
<th>Angle (deg.)</th>
<th>290 MeV/nucleon beam</th>
<th>430 MeV/nucleon beam</th>
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<tbody>
<tr>
<td></td>
<td>System A</td>
<td>System B</td>
</tr>
<tr>
<td>15</td>
<td>353.95</td>
<td>245.74</td>
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<tr>
<td>30</td>
<td>361.55</td>
<td>229.64</td>
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<td>45</td>
<td>373.95</td>
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<td>60</td>
<td>275.95</td>
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<td>75</td>
<td>246.45</td>
<td>188.24</td>
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<tr>
<td>90</td>
<td>259.05</td>
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of the measurement circuitry including information on the gate widths and the delays are described elsewhere [15].

The carbon ions were completely stopped in the phantom. Projectile-like fragments passing through the phantom were led to a beam dump made of a 100 cm × 100 cm × 155 cm iron block placed on the beam axis about 700 cm downstream from the beam exit window. To avoid detecting neutrons generated by nuclear reactions of the projectile-like fragments and originated from the beam dump, a shield constructed from an iron block (100 cm × 100 cm × 63 cm) and a concrete block (100 cm × 100 cm × 50 cm) was put in the path from the beam dump to the neutron detectors.

Measurements with iron bars inserted in the flight path from the phantom to the neutron detector were performed to evaluate the contribution of background neutrons scattered from floor, ceiling, and walls of the experimental room. Those iron bars, referred to as shadow bars, blocked neutrons that directly flew from the phantom to the detectors and thus made it possible to measure the background neutrons. The dimensions of the shadow bars were 15 cm × 15 cm × 110 cm and 10 cm × 10 cm × 60 cm for systems A and B, respectively. The background measurement was performed in a single run for all detectors using six shadow bars.

2.2. Data analysis

To derive the neutron yields, we evaluated the number of ions incident on the water phantom, extracted the neutron events from the total events acquired in the experiment, and determined the kinetic energy of those neutrons based on the TOF data. The carbon-ion beam was monitored by the beam pick-up detector ion by ion. Under high beam intensity, two or more signals from the beam pick-up detector accidentally arrived at a constant-fraction discriminator (CFD) of the electronic circuit in a short time range below 40 ns, which corresponds to the resolving time of the CFD, and those multiple incident events were counted as a single event by the present measurement system. Fig. 3 shows an example of a light-output spectrum measured with the beam pick-up detector by turning off the coincidence measurements of the neutron detectors. Because the light output of the multiple incident events was larger than that of the single incident events, the peaks of the multiple incident events were observed at the region of higher channels in the light-output distribution. Using these light-output distributions, we experimentally estimated the fraction of single incident events in all incident events for current beam intensities. During the neutron-yield measurements, the coincidence measurements between the beam pick-up detector and neutron detectors were restored and the beam intensity was controlled to keep the number of multiple incident events one order of magnitude below that of single incident events. In the off-line data analysis, multiple incident events were discarded and the number of incident carbon ions was estimated by multiplying the fraction of single incident events with the number of total events counted with the beam pick-up detector.

The charged particle events were separated from the non-charged particle (neutron and photon) events for the off-line analysis using light-output spectra of the veto detectors as demonstrated in Fig. 4. While the charged particles caused large light outputs in the veto detectors, the non-charged particles gave a light output corresponding to an offset and caused a sharp peak in the low light-output region of the spectrum. Fig. 5 depicts the two-dimensional scatter plot of a pulse shape discrimination (PSD) for neutrons and photons on the basis of a two-gate integration method. The width of the total gate was 200 ns. The slow gate was opened for 155 ns with a 45-ns delay from the total one in the present measurement. The neutron events were successfully discriminated from the photon ones using the scatter plots of the PSD. For those neutron events, we determined their kinetic energies based on the TOF data. The range of the TOF measurement was set to 250 ns and 300 ns on the measurement circuitry of the system A and B, respectively, for the 430 MeV/nucleon carbon-ion beam. The neutrons arriving outside of those ranges were rejected online by the electronic circuits. In addition, the events of multiple incidences inside the TOF ranges were discarded in the off-line data analysis. Fig. 6 shows the relationship between the TOF and the light output with the total gate for neutrons and photons obtained at 15° by system A for the 430-MeV/nucleon carbon-ion beam. The events with larger values on the abscissa are the ones with shorter TOF in the present measurement. Hence, events of prompt gamma rays appear in the right part of the figure. With increasing light output, events of prompt gamma rays are shifted to the faster region owing to an effect called time walk in the measurement circuitry. We corrected this time walk in the off-line analysis by shifting an event’s TOF value relative to an arbitrarily determined standard according to its corresponding light-output value [17]. Then, the determined standard for the prompt gamma-ray events was used as a time standard to deduce the neutron energy from the TOF data. The neutron energy, $E_n$, is obtained from the following equation:

$$E_n = m_n \left( \frac{1}{\sqrt{1 - \left( \frac{1}{\gamma} \right)^2}} - 1 \right),$$

Fig. 3. Light-output spectrum of the beam pick-up detector for the 430 MeV/nucleon carbon-ion beam.

Fig. 4. Example of a light-output spectrum of a veto detector.
where $m_n$ is the rest mass of the neutron, $L$ is the flight-path length, $c$ is the velocity of light in vacuum, and $T$ is the difference of the TOFs between prompt gamma rays and the neutron.

Events whose light output did not exceed a threshold level were rejected in the off-line analysis. The threshold levels of the present data analysis were set at 1.072 MeVee and 0.213 MeVee for systems A and B, respectively, which correspond to the positions at half height with respect to Compton edges in measured light-output spectra of photons of the radioisotope sources of $^{60}$Co and $^{137}$Ba [15]. Neutron-detection efficiencies of the NE213 scintillators at those threshold levels were calculated using the Monte-Carlo simulation code SCINFUL-QMD [18,19] to determine the absolute yield of neutrons entering to the detector placed at each angle.

Fig. 7 exhibits typical results of energy resolutions of systems A and B for the 430-MeV/nucleon carbon-ion beam. The energy resolution of a TOF measurement depends on geometric and time components, and is expressed as follows:

$$\frac{\Delta E_n}{E_n} = \gamma(\gamma + 1)\sqrt{\left(\frac{\Delta t}{T}\right)^2 + \left(\frac{\Delta L}{L}\right)^2},$$

where $\Delta E_n/E_n$ denotes the energy resolution, $\gamma$ denotes the Lorentz factor, $\Delta L$ represents the uncertainty of the flight path length and is estimated to be half of the thickness of the scintillator, $L$ is the flight-path length, $\Delta t$ is the time resolution of the measurement system, and $t$ is the TOF. The time resolution $\Delta t$ was estimated from the measured full width at half maximum (FWHM) of the prompt gamma-ray peak corrected for the time-walk effect. It was 1.72 ns and 1.81 ns for systems A and B, respectively. As the present measurement used a thick target, the positions of neutron production were distributed inside the water phantom along the beam trajectory. The time fluctuation caused by this uncertainty of the production points is also included in the time resolution $\Delta t$. The energy resolution of system B became worse for high-energy neutrons above 10 MeV compared with that of system A since system B has a shorter flight-path length than system A.

2.3. Derivation of neutron yields and effective doses

The double-differential neutron yield (neutrons/MeV/sr/ion), $d^2\gamma/\rho_\Omega$, with respect to the neutron energy $E$ and the emission angle $\theta$ in the spherical polar coordinate system employed in the present study was derived from the following relation:

$$\frac{d^2\gamma}{dE d\Omega}(E, \theta) = \frac{N_n}{N_{ion} \cdot \varepsilon(E) \cdot \Delta E \cdot \Delta \Omega},$$

where $N_n$ and $N_{ion}$ are the numbers of detected neutrons and incident carbon ions, respectively, $\varepsilon(E)$ is the energy-dependent neutron detection efficiency calculated with SCINFUL-QMD [18,19], $\Delta E$ is the energy bin width, and $\Delta \Omega$ is the solid angle subtended by the front face of the neutron detectors. Note that the origin of the solid angle is set to the origin of the spherical polar coordinate system describing the detector position in the present study. The final result for the double-differential neutron yield was obtained by subtracting the result of the background measurement with the shadow bars from that of the foreground measurement without the shadow bars, both of which were derived from Eq. (3) on the basis of the neutron energies determined by the TOF method. Note that the energies of the background neutrons scattered from floor, ceiling, and walls of the experimental room were estimated by Eq. (1) as well as the neutrons that directly flew from the phantom to the detector using the same flight-path length listed in Table 1 in both foreground and background measurements.

The neutron yield (neutrons/sr/ion), $d\gamma/d\Omega$, at angle $\theta$ was obtained by energy integration of the double-differential neutron yields expressed as follows:

$$\frac{d\gamma}{d\Omega}(\theta) = \int_{E_1}^{E_2} \frac{d^2\gamma}{dE d\Omega}(E, \theta) dE,$$

where $E_1$ and $E_2$ are the energy limits.
where $E_1$ and $E_2$ are the lower and upper limits of integration, respectively. We mention here that we assumed a point source of secondary neutrons at the origin of the present coordinate system in deduction of the neutron yields and effective doses to apply those results to conventional analytical models for neutron shielding on the basis of an inverse square law and exponential attenuation in a shield. The uncertainty of the mean solid angle come from this assumption is discussed in Section 2.4.

The effective dose per ion 1 cm away from the source ($pSv\,cm^{-2}/ion$), $dH/d\Omega$, along the emission angle $\theta$ was also derived from the double-differential neutron yields by the following equation:

$$dH(d\Omega) = \int_{E_1}^{E_2} C(E) \cdot \frac{d^2\gamma}{dE \, d\Omega}(E, \theta) \, dE.$$  

(5)

where $C(E)$ is the conversion coefficient to convert neutron fluence to effective dose. We employed a dataset of the conversion coefficients for antero-posterior (AP) geometry established by the International Commission on Radiological Protection (ICRP) in Publication 116 [20] because a radiation dose in a shielding calculation is usually assessed with an effective dose for AP geometry. Eq. (5) was solved by summing up the double-differential neutron yields at each energy bin between the integration period multiplied by the bin width and the conversion coefficient corresponding to the energy at the midpoint of the bin.

2.4. Uncertainty

The uncertainties included in the present data mainly consist of statistical errors, the uncertainty of the neutron detection efficiency calculated by SCINFUL-QMD, and uncertainty in the mean solid angle. The statistical errors were derived from a statistical model of a Gaussian distribution by considering the propagation of errors in a subtraction process of the background neutrons. The uncertainty of the neutron detection efficiencies was estimated to be 15% in the present analysis on the basis of the discussion in our previous work [15]. The uncertainty in the mean solid angle stemmed from the uncertainties of the flight-path lengths between the positions of neutron production in the water phantom and detection in the detector. The estimated uncertainty in the solid angle due to the thick target was less than 10% for the detector of system A at 90° for the 430-MeV/nucleon beam, which has the maximum uncertainty regarding the solid angle in the present study. Error bars presented in this paper represent one standard deviation.

2.5. Monte-Carlo simulation

Fig. 8 depicts a three-dimensional view of the computational geometry constructed in PHITS [14]. The water phantom used in the simulation was modeled with acrylic resin and water to represent the actual phantom and rotated by 90° for each incident beam to align its minor and major axis with the beam axis of the 290-MeV/nucleon and 430-MeV/nucleon carbon ions, respectively. Parallel beams of the carbon ions were generated 10 cm upstream from the front surface of the phantom, and the diameter of the beam was set to 0.5 cm.

Neutrons produced in the phantom by bombardments with carbon ions were scored in the angular range from 0° to 180° with 15° steps by 13 scorers arranged 350 cm away from the phantom on the horizontal plane crossing the center of the phantom. The size of those scorers was defined to be 12.7 cm in both diameter and thickness. Note that the modeling of the detector housings and veto detectors was omitted in the simulation, because the neutron production from those materials is negligible. The space outside the water phantom and the scorers were filled with dry air.

Nuclear reactions of a carbon-ion incident on the water phantom were treated with the JAFERI Quantum Molecular Dynamics-2.0 (JQMD-2.0) model [21] incorporated with the Generalized Evaporation Model (GEM) [22] installed in PHITS version 2.760. The macroscopic cross sections of carbon ions inside the phantom were determined on the basis of the Hybrid Kurotama model [23,24]. The energy loss of all transport particles was calculated with the SPAR model [25], which is the default one for energy loss calculations in the PHITS version 2.760. The cutoff energy of the neutrons was set to $10^{-10}\,MeV$. The Evaluated Nuclear Data File library (ENDF/B-VII.1) [26] was utilized in the macroscopic transport simulation of neutrons in the energy region from $10^{-10}\,MeV$ to 20 MeV where the theoretical models fail to reproduce the cross sections having resonance peaks. Charged particles, that is, protons, deuterons, tritons, helium nucleus, and heavy ions, were transported down to $10^{-3}\,MeV$, which is the minimum energy recommended in PHITS for charged particle transport. The uncertainty due to statistics in the Monte-Carlo simulation was set below 5% for an energy bin.

3. Results and discussion

3.1. Double-differential neutron yields

The double-differential yields of neutrons detected at 75° are shown in Figs. 9 and 10 for the 290-MeV/nucleon and 430-MeV/nucleon carbon-ion beams, respectively. Note that the spectra contain neutrons produced in the water phantom by nuclear reactions of the primary carbon ions as well as of secondary particles and imply the presence of multiple-scattering and attenuation effects inside the phantom. The closed circles are experimental results measured by system A. The plus and cross marks represent results of the foreground and background measurements, respectively, with system A. The figures show that the neutron yields in the background measurement are satisfactorily low compared with those in the foreground. This means that the contribution of background neutrons was small, and the present experiment was performed with a good signal-to-noise ratio. We also plotted experimental results obtained with system B as open circles. System B successfully measured neutrons down to a few MeV. The data from systems A and B showed good agreement in the overlapped region around 10 MeV. We employed data of system B below 10 MeV and 7 MeV, respectively, for the 290-MeV/nucleon and 430-MeV/nucleon carbon-ion beams.

Figs. 11 and 12 show double-differential neutron yields at 15°, 30°, 45°, 60°, 75°, and 90° for 290-MeV/nucleon and 430-MeV/nucleon carbon-ion bombardments of the water phantom, respectively. The results calculated by the PHITS code are also shown with solid lines in the figures. The statistical error of low-energy neutron spectra measured by system B, whose lower energy limits for neutron detection were 1.0 MeV at 15°, 30°, and 45° for the 290-MeV/nucleon beam and 2.0 MeV otherwise, was larger than that of system A used above approximately 10 MeV. This is because of the lower neutron-detection efficiency of system B using the short scintillators compared with that of system A, and the low measurement efficiency for small solid angles subtended by system B in the present detector arrangement. In both spectra for the 290-MeV/nucleon and 430-MeV/nucleon carbon-ion beams, one can see broad peaks around approximately half of the projectile energy per nucleon at small angles. The peaks are formed by neutrons resulting from direct interactions of nucleons in an overlapping region of colliding projectile and target nuclei. Those neutrons are emitted in forward directions with almost the same kinetic energy as the striking nucleons in the projectile nucleus. The high-energy tail of this peak extends beyond the projectile
energy per nucleon owing to the high-momentum components of the Fermi distribution of the projectile nucleus with Lorentz contraction [10] and momentum broadening by multiple nucleon scattering events in a region where projectile and target nuclei overlap [10,15]. With increasing emission angles, the peak energy is shifted downward and no pronounced peak is observed at backward angles.

The PHITS simulation successfully reproduced the characteristics of the neutron spectra mentioned above. In particular, the dropping curves at the high-energy tail were properly simulated by PHITS for both 290 MeV/nucleon and 430 MeV/nucleon beams. This fact proves the usefulness of PHITS for simulations of heavy-ion interactions with tissue-substitute materials and therapeutic carbon-ion beams.

Some deviations from the experimental results were observed in the neutron spectra calculated by PHITS for both incident energies. For the spectra of the 290-MeV/nucleon system, PHITS gave approximately two times larger values than those of the experiment below the neutron energy of several tens of MeV. The spectra in that energy region include neutrons from nuclear reactions of carbon ions that lost part of the primary energy of 290 MeV/nucleon in the phantom and were affected by scattering and attenuation inside the phantom. The PHITS simulation of neutron production from nuclear reactions of low-energy ion incidence and secondary neutron transport inside the phantom would be responsible for this discrepancy, because cross sections of the 290-MeV/nucleon carbon-ion beam calculated by PHITS agreed well with the experimental data obtained in our previous work [15]. At small angles of the 430-MeV/nucleon carbon-ion system, PHITS underestimates the neutron yields around 100 MeV. Systematic measurements of neutron-production double-differential cross sections and yields using thin and thick targets would help to clarify the reason for these discrepancies.
3.2. Angular distributions of neutron yields

Figs. 13 and 14 show angular distributions of neutron yields around the water phantom bombarded with 290-MeV/nucleon and 430-MeV/nucleon carbon ions, respectively. The circles were obtained from the experimental data using Eq. (4) with $E_1$ set to 2.0 MeV. The squares and triangles are results of the PHITS simulation with $E_1$ set to 2.0 MeV, which is equivalent to the value adopted for the experimental data, and $1.0 \times 10^{-9}$ MeV, which corresponds to thermal neutron energy. The value of $E_2$ was set to 1000 MeV for all data. The PHITS results were obtained beyond the angular range of the experiments to estimate the overall angular distributions of neutron yields from 0° to 180°. One can see a rapid rise of the neutron yields toward zero degrees in the PHITS results for both incident energies. These neutrons are coming from the direct process of nucleus-nucleus reactions, and the tendency is also observed in the experimental data of neutron-production cross sections [27].

In case of the 290-MeV/nucleon beam, the measured neutron yields decreased with increasing emission angle. The PHITS simulation results with the $E_1$ value of 2.0 MeV showed a tendency similar to the experimental one but the values were slightly larger than the experimental values. The deviation from the experimental data is within a factor of 1.5 at maximum and is caused by the differences of the double-differential neutron yields discussed above. Considering neutrons whose energy was as low as thermal energy, the angular distribution of neutron yields at backward angles greater than 90° became flat. This indicates that the fraction of low-energy neutrons below 2.0 MeV increases in the backward angular region whereas the high-energy neutrons are dominant at forward angles, and those low-energy neutrons lose information.
regarding the incident direction of primary ions by undergoing multiple scattering events in the water phantom.

For the neutron distribution of the 430 MeV/nucleon system, the PHITS results gave about 25% smaller values than the experimental values for forward angles of 15°, 30°, and 45° while the data for larger angles agreed well with the experimental ones within 10%. This is explained by the underestimation of double-differential neutron yields around 100 MeV at forward angles observed in Fig. 12. The distribution of neutrons, whose energy ranges from thermal to hundreds of MeV, is not flat even at backward angles greater than 90° because energy reduction by multiple scattering is suppressed owing to a relatively short distance from an average interaction point of the primary ions on their trajectory inside the water phantom to the surface at the transverse side of the phantom compared with the case of the 290-MeV carbon-ion beam.

### 3.3. Angular distributions of neutron doses

Figs. 15 and 16 exhibit angular distributions of effective doses of neutrons produced from the water phantom bombarded with 290-MeV/nucleon and 430-MeV/nucleon carbon ions, respectively. The relationship between results of the present experiment and the PHITS simulation was similar to that of the neutron-yield distributions discussed in Section 3.2. The difference in the effective doses due to the difference in the lower periods of integration, that is, 2.0 MeV or $1.0 \times 10^{-9}$ MeV, was small compared with that observed in neutron yields because the influence of low-energy neutrons on the effective dose was small. For example, the conversion coefficient from fluence to effective dose at the neutron energy of 100 MeV is approximately two orders greater than that at $1.0 \times 10^{-9}$ MeV under the AP geometry [20]. This fact emphasizes the importance of PHITS being able to correctly reproduce the high-energy neutron yields. The neutron dose was higher in the forward directions and decreased exponentially with increasing emission angle. The present results confirmed that proper shielding that attenuates neutrons produced in forward directions is important to reduce neutron doses outside treatment rooms of carbon-ion therapy facilities.

### 4. Conclusions

The double-differential neutron yields from a water phantom were measured for 290-MeV/nucleon and 430-MeV/nucleon carbon ions at the emission angles of 15°, 30°, 45°, 60°, 75°, and 90° in the neutron-energy region from 2 MeV to several hundred MeV. From those measured data, angular distributions of neutron yields and effective doses around the water phantom were also derived. The results of the present work complemented experimental data on neutron production from tissue-substitute materials bombarded with carbon ions with therapeutic energies and will be utilized as a source term in neutron-dose estimation inside and outside of shields used in treatment rooms where patients are irradiated with carbon-ion beams. From comparisons with simulation results of the Monte-Carlo particle transport code PHITS, it was found that PHITS can reproduce the angular distributions of neutrons above 2 MeV from the water phantom within 50% and 25% for 290-MeV/nucleon and 430-MeV/nucleon carbon-ion bombardments, respectively. In addition, we also estimated the angular distributions considering the neutron energies down to thermal energy and emission angles from 0° to 180° using the results of PHITS simulations. The effective dose around a source point of the water phantom showed a rapid rise when approaching 0° and an exponential attenuation for backward angles. From the results of the present study, we concluded that PHITS is a useful tool to establish a reliable dose map throughout a facility including treatment rooms. Meanwhile, some discrepancies were observed between the results of experiments and PHITS. PHITS overestimated the neutron yields in the energy region below several tens of MeV for the 290-MeV/nucleon beam and underestimated the absolute values of the broad peaks observed in the spectra for forward angles for the 430-MeV/nucleon beam. This could come from an inaccurate simulation of the elementary process of nuclear reactions in the reaction model of PHITS. To clarify the reason for the discrepancies and improve the accuracy of PHITS, we plan to perform measurements of neutron-production double-differential cross sections and yields for 100-MeV/nucleon and 430-MeV/nucleon carbon-ion beams with thin and thick targets consisting of the light nuclei that make up human-body tissues. In addition, we also plan to measure charged-particle-production double-differential cross sections to understand the nucleus-nucleus interactions comprehensively.

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