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Measurements and Monte Carlo calculations of forward-angle secondary-neutron-production cross-sections for 137 and 200 MeV proton-induced reactions in carbon

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ABSTRACT

Secondary neutron-production double-differential cross-sections (DDXs) have been measured from interactions of 137 MeV and 200 MeV protons in a natural carbon target. The data were measured between 0° and 25° in the laboratory. DDXs were obtained with high energy resolution in the energy region from 3 MeV up to the maximum energy. The experimental data of 137 MeV protons at 10° and 25° were in good agreement with that of 113 MeV protons at 7.5° and 30° at LANSCE/WNR in the energy region below 80 MeV. Benchmark calculations were carried out with the PHITS code using the evaluated nuclear data files of JENDL/HE-2007 and ENDF/B-VII, and the theoretical models of Bertini-GEM and ISOBAR-GEM. For the 137 MeV proton incidence, calculations using JENDL/HE-2007 generally reproduced the shape and the intensity of experimental spectra well including the ground state of the ^{12}N state produced by the ^{12}C(p,n)^{12}N reaction. For the 200 MeV proton incidence, all calculated results underestimated the experimental data by the factor of two except for the calculated result using ISOBAR model. ISOBAR predicts the nucleon emission to the forward angles qualitatively better than the Bertini model. These experimental data will be useful to evaluate the carbon data and as benchmark data for investigating the validity of the Monte Carlo simulation for the shielding design of accelerator facilities.

1. Introduction

Recently, neutrons emitted by intermediate-energy (100–200 MeV) proton-induced reactions have become important for proton therapy and for the design of shielding in intermediate-energy proton-accelerator facilities. In accelerator facilities, graphite is often selected as the principal energy-absorbing material in the beam dump because of its favorable physical properties [1]. For proton therapy, neutron production in a body mainly composed of hydrogen, carbon, and oxygen, must be correctly estimated to understand the secondary neutron effect on a cell because these neutrons can increase the risk of a second cancer if they reach a normal tissue. To generate neutrons with the characteristics desired for such applications, it is important to estimate the double-differential cross-sections (DDXs) for neutron emission induced by the interaction of protons with carbon.

A system that generates neutrons with the desired characteristics can be designed via Monte Carlo transport calculation codes (e.g., PHITS [2], FLUKA [3], MARS [4], MCNP [5]), which describe the interaction and transport of all particles created in nuclear reactions. An open problem in the theoretical description of this transport and the associated neutron spectra involves reproducing the location and intensity of the so-called "quasifree-scattering (QF-scattering) peaks" at very forward angles (below 30°) [6]. The QF peak, which is centered near the beam energy, has been attributed to the quasielastic charge exchange nucleon–nucleon collisions inside the target nucleus [6]. However, the various versions of the intranuclear cascade models cannot predict the entire neutron spectra [6]. In particular, the amplitudes of the quasielastic peaks are usually underestimated because "in-medium" and/or "mean-field" effects are neglected [6].

Over the last 20 years, the DDX for neutron emission induced by reactions with 200 MeV–2 GeV protons has been measured

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at forward angles [7–12]. The neutron production DDXs for 100–200 MeV C(*p*,*xn*) reactions at forward angles [13–15] have been measured. Two previous experiments [13,14] have focused on the physics of the giant Gamow–Teller resonances (GTR), QF scattering, etc. However, so far, only one measurement has been conducted for neutron-production DDXs in the intermediate-energy region, which covers a wide range of neutron energies from several megaelectronvolts to the maximum energy [15]. Thus, systematic studies of neutron-production DDXs for carbon at forward angles between 0° and 30° are scarce.

The evaluated nuclear data libraries such as JENDL/HE files [16] and ENDF/B-VII [17] provide the most widely used evaluated nuclear data for high-energy proton- and neutron-induced reactions. For proton-incident energies in the 100–200 MeV range, these libraries are available for Monte Carlo particle transport calculations. For energies less than 150 MeV, the JENDL-HE evaluation for carbon applied the GNASH code [18], whereas, above 150 MeV, the Japan Atomic Energy Research Institute (JAERI) quantum molecular dynamics model (JQMD) [19] was used. In an international code comparison, the GNASH code was found to be one of the most reliable codes for calculations below 150 MeV [20] and was extensively used in the ENDF/B-VII evaluation. ENDF/B-VII provides proton and neutron cross sections for proton-incident energies less than 150 MeV, whereas JENDL/HE files extend the results up to 3 GeV.

In the intermediate-energy region, however, Monte Carlo calculations using those evaluated nuclear data and the intranuclear cascade models have not been thoroughly checked against the experimental neutron-production DDXs at forward angles.

To address this issue, we report herein the measurements of neutron-production DDXs at six angles (0°, 5°, 10°, 15°, 20°, and 25°) for energies greater than 3 MeV and for a carbon target bombarded with 137 and 200 MeV protons at the time-of-flight (TOF) course in the Research Center of Nuclear Physics (RCNP) ring cyclotron of Osaka University. In addition, we compare the measured data with the JENDL/HE file, the ENDF/B-VII library, and physics models implemented using the PHITS code.

2. Measurement

The experiments were performed in the 100 m tunnel of the RCNP ring cyclotron of Osaka University at frequencies of 11.6 and 13.4 MHz with 137 and 200 MeV protons, respectively; the beam current was 10–60 nA. A schematic of the experimental arrangement is shown in Fig. 1. The experimental setup was almost the same as that for our previous measurement [21,22].

The proton beam extracted from the ring cyclotron at 137 and 200 MeV was transported to the neutron experimental hall and hit a 1.5-mm-thick (342.5 mg/cm^2) natural carbon target placed in the swinger, which was placed in a vacuum chamber. For neutron measurements at 0°, the target was set at the entrance of the swinger as shown in Fig. 1. Measurements at angles between 5° and 25° were performed by moving the target forward along the curve trajectory of the proton beam in the swinger. The energy loss of protons in carbon was 1.87 and 1.47 MeV for 137 and 200 MeV protons, respectively. In calculating the energy loss, we assumed that the neutrons were produced at the target midpoint [23]. The *Q* value and threshold energy of the natural carbon used in this study are summarized in Table 1.

To measure the proton beam intensity, we used a swinger magnet to deviate the protons into a Faraday cup after they passed through the target. The proton beam intensity was also monitored with plastic scintillators by counting the protons scattered from a 100-μm-thick plastic film set in front of the carbon target. Neutrons produced at the target entered the 100 m tunnel through a 10 × 12 cm^2 aperture in a 150-cm-thick movable iron collimator embedded in a 150-cm-thick concrete wall located 4.5 m from the target. At 20 m from the target, the radius of the neutron beam was about 22 cm. The clearing magnet in the movable collimator reduced the number of charged particles contaminating the neutron beam. The movable collimator and the swinger magnet allowed neutron emission to be measured for angles between 0° and 25°.

This facility is perfectly suited for a TOF study because the available flight path is about 100 m long. The neutron TOF measurements were performed at 0°, 5°, 10°, 15°, 20°, and 25° using three different-sized NE213 organic liquid scintillators (25.4 × 25.4 cm^2, 12.7 × 12.7 cm^2, and 5.08 × 5.08 cm^2, in diameter and length), each performing measurements at a different target–detector-surface distance. Table 2 summarizes the detector settings, such as neutron energy ranges, detector sizes, flight paths, and solid angles.

For the 7 m measurements, a 5-mm-thick plastic scintillator (NE102A) placed in front of the detector tagged events induced by charged particles. To obtain good energy resolution in the high-energy region, we performed long-path measurements using the 25.4 × 25.4 cm^2 NE213. To avoid contamination with lower-energy neutrons, the time intervals between the successive proton-beam pulses were enlarged to 500 ns using a beam chopper. These time intervals correspond to frame-overlap neutron energies of about 90 MeV at 95 m, about 10 MeV at 20 m, and about 1 MeV at 7 m.

Data were recorded using a conventional computer-automated measurement and control system in the event-by-event mode.

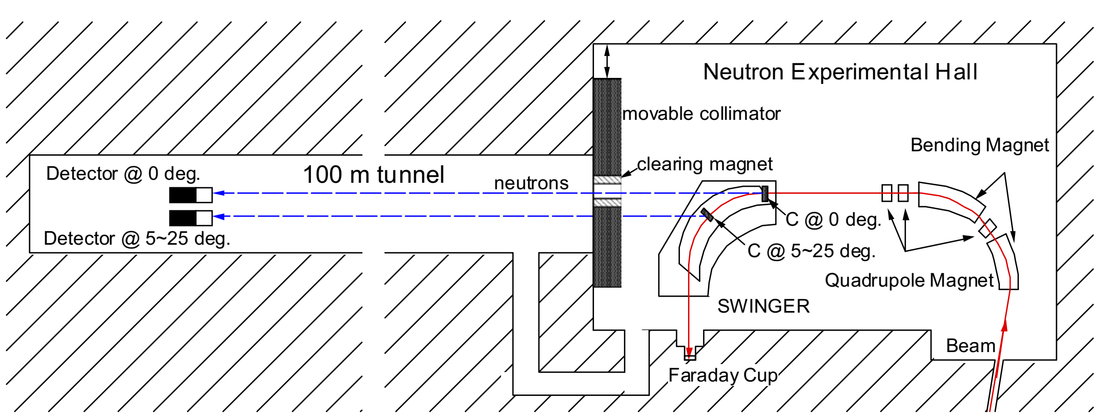

Fig. 1. Schematic of experimental setup in the neutron experimental hall and the 100 m tunnel.