Measurement of Neutron Production Spectra at the Forward Direction from Thick Graphite, Aluminum, Iron and Lead Targets Bombarded by 250 MeV Protons

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Neutron energy spectra at the forward direction produced from stopping-length thick graphite, aluminum, iron and lead targets bombarded by 250 MeV protons were measured at the neutron TOF course at RCNP of Osaka University. The experiments were performed by the time-of-flight technique with the flight path length of 11.4m and 67.8m, and neutron energy spectra were obtained in the energy range from 10 MeV to 250 MeV. To compare the experimental data, Monte Carlo calculations by PHITS, MCNPX, and JQMD+INC codes were performed. It was found that these calculation results at 0-degree generally underestimated the experimental data for all targets in the energy range above 20 MeV.

1. Introduction

Various Monte Carlo transport calculation codes have been widely employed for the shielding designs of proton accelerator facilities. In such designs, it is important to estimate the energy spectra of the secondary particles, especially neutrons, produced by beam losses in thick materials of beam line modules and the beam dump as source terms. The accuracy of calculated results has been verified by the benchmark experimental data. The double differential neutron energy spectra at 0-degree by bombarding 210 MeV protons on a thick iron target were measured at RIKEN [1]. No other experimental data are available from other thick targets. We have measured neutron energy spectra from thick graphite, aluminum, iron and lead targets at the forward direction bombarded by 250 and 350 MeV protons at the TOF course of the RCNP (Research Center of Nuclear Physics) ring cyclotron of Osaka University. We already reported results of the 350 MeV measurement [2]. In this work, the 250 MeV measurements and the calculation results of the PHITS [3], MCNPX [4] and JQMD+INC [5] codes are reported.

2. Experiment

The experiments were carried out at the neutron TOF course of the RCNP ring cyclotron of Osaka University. A schematic view of the experimental arrangement is illustrated in **Figs. 1**. The characteristics of the targets used in this work are summarized in **Table 1**. The targets were covered with aluminum foil to absorb secondary electrons emitting from the targets. The neutrons produced at 0-degree direction were transported to the TOF course through the 150-cm-thick iron collimator of a 12-cm high and 10-cm wide opening, while charged particles were rejected by a vertical bending magnet equipped in the collimator. The neutron TOF measurements were performed using an NE213 organic liquid scintillator (12.7-cm-diameter by 12.7-cm-long) placed at either 11.4 m (short path) or 67.8 m (long path) from the beam-incident surface of the target. The long path measurement was carried out to get good time resolution in higher energy region. In the measurements, the currents of the proton beam were kept in the range of 0.2 nA for the short path and 5 nA for the long path.

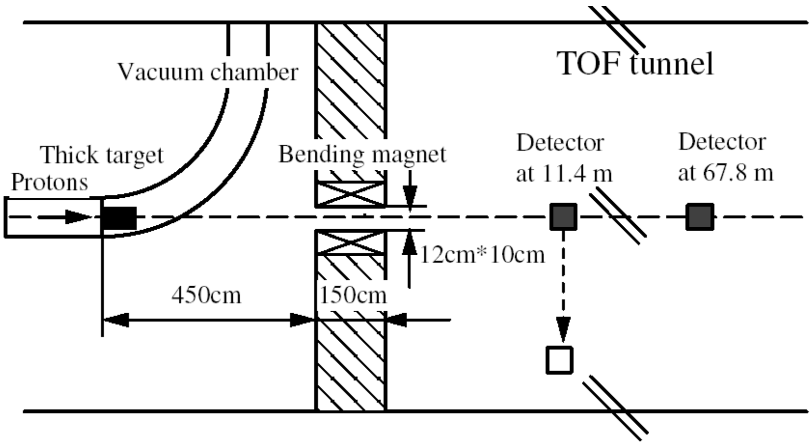

Fig. 1 Illustration of experimental setup at RCNP.

Table 1 Target characteristics and stopping range of 250 MeV protons in the target

Material	Density (g/cm^3)	Size (cm)	Stopping range (cm)
Graphite	1.76	6.0×6.0×27.5	25.0
Al	2.72	ϕ6.0×20.0	18.0
Fe	9.12	ϕ6.5×7.5	6.93
Pb	11.3	6.0×6.0×7.5	6.76

3. Analysis

The TOF distributions of neutrons were converted to the neutron energy spectra. In the TOF distribution analysis, neutron events above the Am-Be (4.2 MeVee) bias were summed up and neutron TOF distributions in wide energy range above 10 MeV were obtained.

Neutron detection efficiencies were obtained from calculation results of the CECIL code [6]. The results of CECIL agree with the measurements within 15 % in the energy region between 10 and 206.8 MeV for 4.2 MeVee bias [7]. To get better energy resolution results, the long path measurements were used for the energy range above 100 MeV.

The statistical uncertainties at the neutron spectra determination varied from 0.5 to 5 %. The systematic error comes mainly from neutron detection efficiency, which was determined to 15 %. The energy resolution depends on the time and the geometrical component. The time component estimated from FWHM of the flash gamma-ray peak was 1.2 ns. The geometrical component comes from the target thickness and from the size of the sensitive area of the detector. The typical neutron energy resolutions of 200 MeV with the graphite target are 12.7 MeV at 11.4 m and 2.1 MeV at 67.8 m, respectively.

4. Monte Carlo Calculation

The Monte Carlo particle transport code, the PHITS, MCNPX and JQMD+INC codes with the Bertini model [8] based on intranuclear cascade model were used. In the PHITS and MCNPX calculations, the JENDL/HE2004 [9] and the LA150 [10] evaluated neutron data libraries were employed for energies up to 150 MeV. In the JQMD+INC calculation, QMD model was employed above 50 MeV and the Bertini model under 50 MeV. In all calculations, neutrons produced within an angle of 3-degrees were collected.

5. Results

(1) Intercomparison with each calculation result

Figure 2 shows the calculated neutron energy spectra from the graphite target. The difference of calculation results using between JENDL/HE2004 and LA150 is very small. A discrepancy of the results with Bertini model between PHITS and MCNPX above 200 MeV may come from the difference of the using parameter in Bertini model.

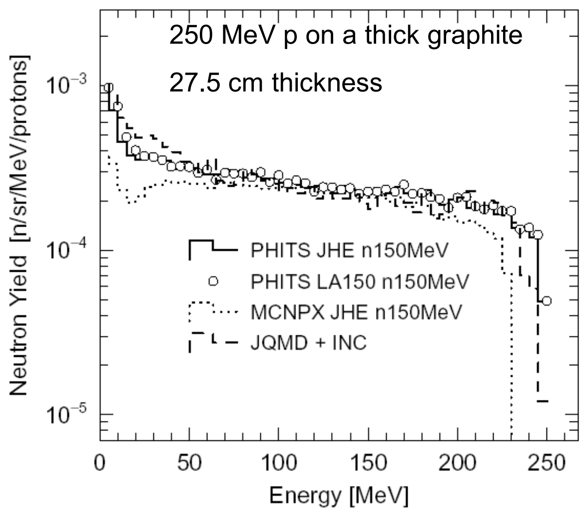

Fig. 2 Calculated results for graphite target. JHE shows JENDL/HE2004. n 150 MeV indicates the use of neutron data library below 150 MeV.

(2) Experimental results and the comparison with the calculation

Figure 3 shows the measured and the calculated neutron energy spectra from thick targets. All calculation results underestimate the experimental ones in the neutron energy range from 30 MeV to 200 MeV. The underestimations of the calculations are also found in 210 MeV proton incident experiment at RIKEN [1] and 350 MeV experiment at RCNP [2]. Those may result from the underestimation of neutron-production cross sections at small angles and the strong self-shielding in target nucleus.

Figure 4 shows that The results of neutron yields integrated at the forward direction of 250 MeV proton incidence as a function of the target mass. 10 – 50 MeV neutrons and 50 – 250 MeV neutrons are corresponding roughly to evaporation-preequilibrium and cascade neutrons, respectively.

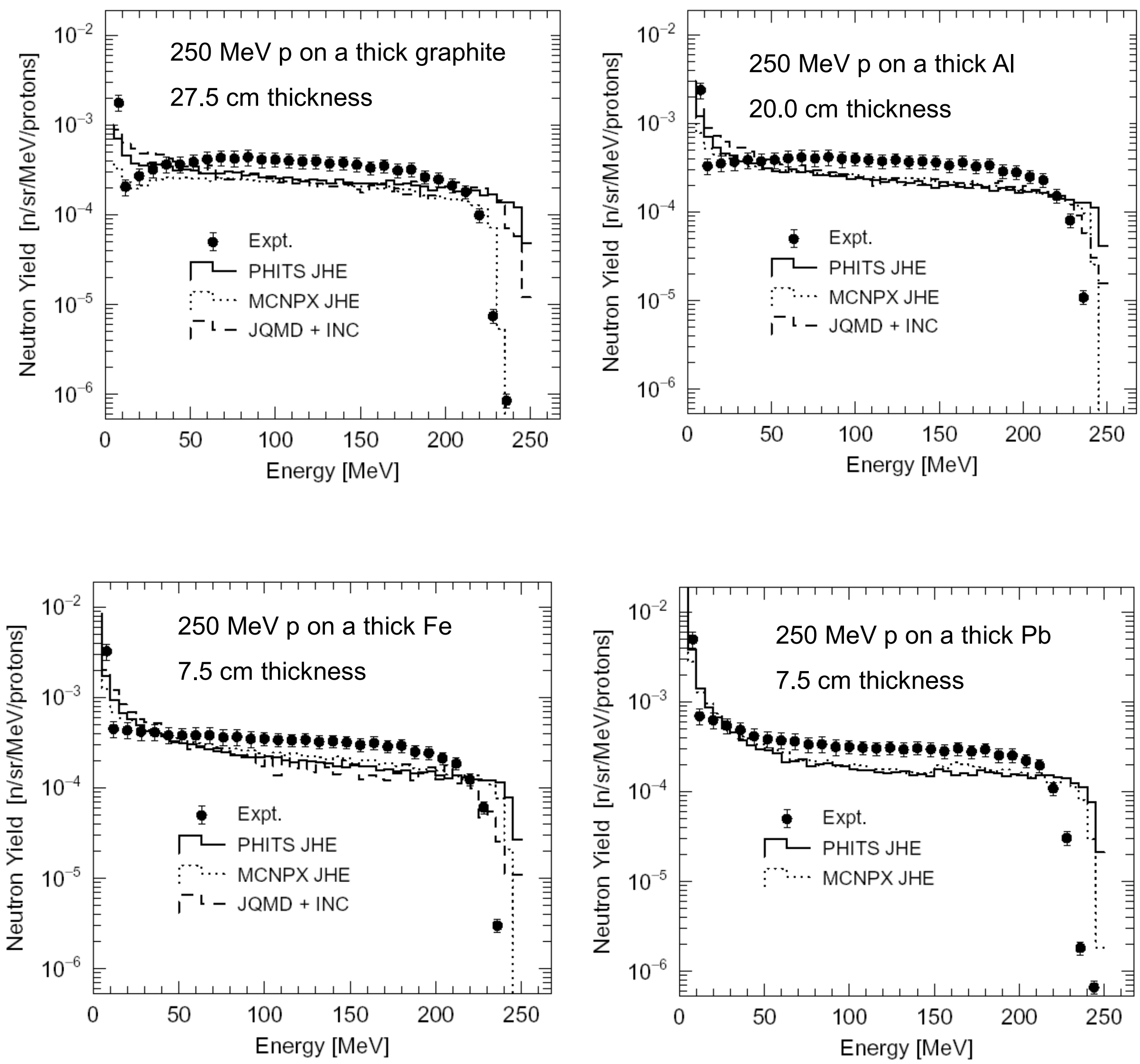

Fig. 3 Measured and calculated neutron energy spectra at 0-degree.

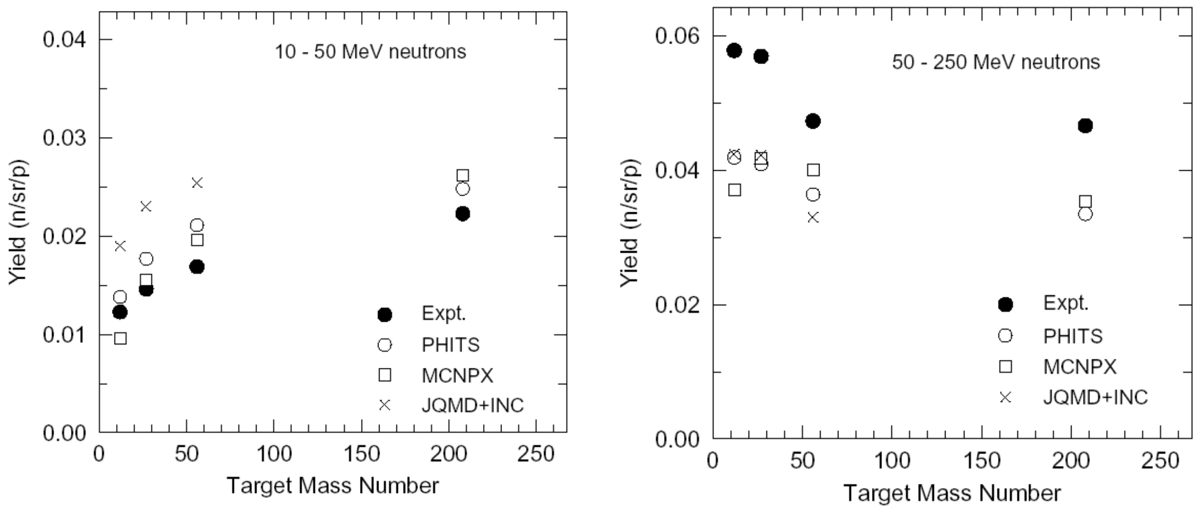

Fig. 4 Neutron yields integrated at the forward direction of 250 MeV proton incidence as a function of the mass of the thick targets. Left: 10 – 50 MeV neutron yield; right: 50 – 250 MeV neutron yield.

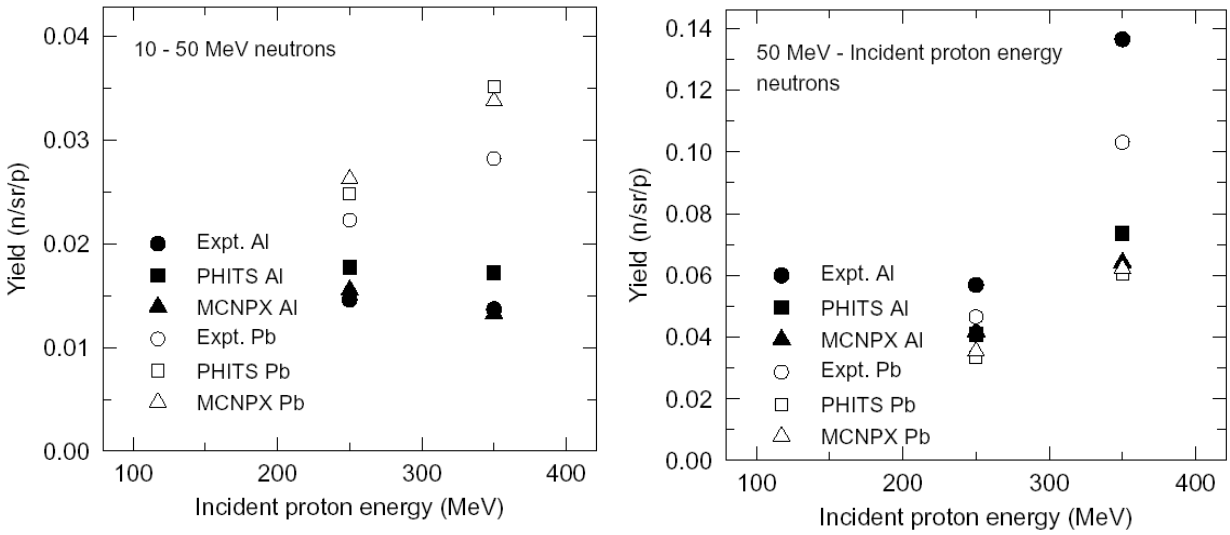

Fig. 5 Neutron yields integrated at the forward direction for the aluminum and lead thick targets as a function of incident energy. Left: 10 – 50 MeV neutron yield; right: 50 – incident energy neutron yield.

For 10 – 50 MeV neutrons in the figure, all results increase with mass number, gradually. On the other hand, the dependency to the mass is less for 50 – 250 MeV neutrons. For the comparison of the experimental and calculated yields in the figure, the calculated 50 – 250 MeV neutrons tend to be less emitted than the experimental ones, and the calculated 10 – 50 MeV neutrons are more emitted These may indicate that the calculated energy of residual nucleus is higher than the experimental one.

The results of neutron yields integrated at the forward direction as a function of incident proton energy are shown in **Figs. 5** for the aluminum and lead targets. The results of 350 MeV proton incidence have been reported [2].

10 – 50 MeV neutrons increase with incident proton energy for the lead, on the other hand, those for the aluminum is not depend on incident energy. For 50 – 350 MeV neutrons at 350 MeV proton incidence, the discrepancy between the experimental results and calculated ones are larger than that of 250 MeV proton incidence.

6. Summary

Neutron energy spectra produced at the forward direction from thick graphite, aluminum, iron and lead targets bombarded by 250 MeV protons were measured by the TOF method at RCNP of Osaka University. The experimental data were compared with the calculated results of the PHITS, MCNPX and JQMD+INC codes. All calculations give lower neutron energy spectra than the experimental ones for all targets above 20 MeV and must be improved for neutron production at 0-degree. These experimental data will be useful as benchmark data for investigating the accuracy of the Monte Carlo simulation and for the shielding design of accelerator facilities.

Acknowledgment

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