Measurements of Neutron Spectra Produced from a Thick Iron Target Bombarded with 1.5 GeV Protons

Shin-ichiro Meigo*,†, Hiroshi Takada*, Nobuhiro Shigyo**, Kiminori Iga**, Yousuke Iwamoto**, Hirohiko Kitsuki**, Kenji Ishibashi**, Keisuke Maehata**, Hidehiko Arima**, Tatsushi Nakamoto*** and Masaharu Numajiri***
**Center for Neutron Science, Japan Atomic Energy Research Institute*
Tokai-mura, Naka-gun, Ibaraki-ken 319-1195
***Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University*
Hakozaki, Higashi-ku, Fukuoka 812-8581
****High Energy Accelerator Research Organization (KEK)*
Oho, Tsukuba, Ibaraki 305-0801 Japan
e-mail: †meigo@linac.tokai.jaeri.go.jp

For validation of calculation codes which are employed in the design of accelerator facilities, spectra of neutrons produced from a thick iron target bombarded with 1.5-GeV protons were measured. The calculated results with NMTC/JAM was compared with the present experimental results. It is found the NMTC/JAM generally shows in good agreement with experiment. Furthermore, the calculation gives good agreement with the experiment for the energy region 20 $\sim$ 80 MeV, whereas the NMTC/JAM gives 50 % of the experimental data for the heavy nuclide target such as lead and tungsten target.

1. Introduction

Applications of high energy particle accelerators are rapidly growing in many fields such as spallation neutron source and accelerator driven system. For the design of the target and shielding of the accelerator facilities, it is necessary to estimate the reaction rate and the neutron production in a thick medium in the energy region up to several GeV.

Nucleon-Meson Transport codes such as NMTC/JAM[1] NMTC/JAERI[2, 3], and LAHET[4] have been widely employed for the neutronics calculation. It is generally known that the codes can describe the particle productions and the transport in a thick medium. The accuracy of the codes, however, has not been completely satisfactory yet. In order to comprehend and improve the accuracy of the code, studies[5, 6] have been performed from both the theoretical and the experimental points of view. A series of the measurements of neutron production double differential cross sections were carried out at LANL and High Energy Accelerator Organization (KEK)[7]. For the spectrum of the thick target, the spectrum of neutrons produced from a thick lead[8] and tungsten targets[9] were measured. The experiment data of the spectrum are, however, very scarce for incident energies higher than 256 MeV.

For the validation of the calculation code employed in the design of the accelerator facilities, it is required the spectrum of neutrons produced from a thick target which is longer than the mean free path of the outgoing particles. In the accelerator facilities, iron takes important roles, because the yoke of magnet was made of iron steel. By the interaction between protons and irons, the neutron are produced in the beam line and accelerator, which is a source of the neutrons for the shielding of accelerator. For the shielding for the accelerator facilities, it should be confirmed the spectrum of neutrons produced from a iron target between the calculation and experiment. However, these experimental data were scarce for the projectiles above 0.8 GeV. In this study, the spectrum produced from the iron target bombarded with 1.5-GeV protons, which was the same energy of the previous experiment, was measured. These experimental data were compared with the calculation of NMTC/JAM.

2. Experimental procedure

2.1 Incident particles and target

The experiment was carried out at the $\pi2$ beam line of the 12-GeV Proton Synchrotron. Schematic view of the experimental arrangement is shown in Fig. 1. The incident particles were supplied as the secondary particle generated by an internal target which was placed in the primary 12-GeV proton beam. After passing the bending magnet, the secondary beam having a unique momentum was introduced to the thick target. The interval between and duration of the primary proton pulses were 4 and 2.5 s, respectively. The intensity of the incident particles was so weak ($\leq 10^5$ particles/pulse) that incident particles were counted one by one with beam scintillators. As incident projectiles, 2.3 GeV/c protons were employed, whose energies are 1.5- GeV for protons. The incident particles were identified 1.5-GeV protons from other particles by the time-of-flight (TOF) technique with a pair of scintillators (Pilot U) located at a separation distance of 4 m. The size of the incident beams was 2.0 and 1.6 cm in FWHM on the perpendicular and horizontal plains, respectively. Each Pilot U scintillator was connected with two photo-multipliers on opposite sides to obtain good time resolution. In order to subtract the neutrons produced from the beam scintillator, background measurements were performed without target.

A iron target was bombarded with the proton beams. The target was a rectangular parallelepiped $15 \times 15 \times 20$ cm^3, which was the same size as the target used in the previous experiments[8, 9]. In the iron target, protons caused the partially energy loss which is 0.23 GeV in the average. A beam dump consisted of a carbon block pile of 0.5×0.5 m^2 in the area and 1 m in thickness was located at a 8.5 m distance from the target. The carbon was surrounded by sufficiently thick iron blocks except on the beam-incident surface.

2.2 Neutron detector

As neutron detectors, NE213 scintillators(12.7 cm in diam. and 12.7 cm in thick.) were used. The detectors were placed at angles between 30° and 90° to the beam axis and at a common distance of 1.5 m from the center of the target. At the angle 15°, the distance was chosen 2.0 m so that the higher energy resolution was achieved. In order to reject the detection of the charged particles (i.e. π, p, d), NE102A scintillators of $17 \times 17 \times 1$ cm^3 were used as veto counters. They were placed at a distance of 2 cm from the surface of the NE213 scintillators. The pulse height of the neutron detectors was calibrated using gamma-rays from ^{137}Cs, ^{60}Co and ^{241}Am-Be.

As the neutron detection efficiency, the calculation results of SCINFUL-R[10] were used. Hence, the results of SCINFUL-R were utilized for detection efficiencies below 80 MeV. Above 80 MeV, the calculated efficiency of CECIL[11] adjusted to connect smoothly with that of SCINFUL-R at 80 MeV was employed. The detection efficiencies for ^{60}Co and ^{137}Cs biases were employed for the analysis of the neutron spectrum above and below 20 MeV, respectively.

2.3 Electronic Circuit

The diagram of the electronic circuit is shown in Fig. 2. A personal computer (PC-AT) was utilized for controlling CAMAC ADCs and TDCs. The events arising from μ^+ projectiles were eliminated by the unti-coincidence of all beam scintillators. The number of incident particles was accumulated by the scaler. A good discrimination for the incident proton against the π^+ was achieved so that the uncertainty of the incident proton counts could be less than 1 %.

Anode signals of the photomultipliers coupled with NE213 scintillators were branched out to three pulses. One pulse was put into a CFD to produce the start signal of TOF measurement. Other two pulses were put into three ADCs (Fast, Total) which collected the charge of pulse during each gate signal duration. In order to eliminate gamma-ray counting, the two-gate integration method After the elimination of the photons, the TOF spectrum of the neutrons was obtained.

3. Calculation

The neutron spectrum calculation was carried out with NMTC/JAM[1] and MCNP-4A[12]. NMTC/JAM calculated the nuclear reactions and the particle transport above 20 MeV. MCNP-4A calculated the neutron transport below 20 MeV using a continuous energy cross section library FSXLIB-J3R2[13] processed from the nuclear data file JENDL-3.2[14]. In NMTC/JAM, the Niita's systematics[1] was implemented to estimate total, elastic and non-elastic nucleon-nucleus cross sections in the transport calculation part. The level density parameter derived by Ignatyuk[15] was also employed in the statistical decay calculation in NMTC/JAM.

Furthermore, additional calculations were performed by substituting the in-medium nucleon-nucleon cross sections (NNCS) for the free NNCS in the nuclear reaction calculation part of NMTC/JAM. The in-medium NNCS parameterized[16] similarly to those of Cugnon[17] were employed in this calculation.

In order to compare the experimental results, the calculation results should be smeared with the energy resolution. The calculated result with and without smearing of the resolution are shown in Fig 3. By the comparison of both results with and without smearing, it is found that the effect of the energy resolution on the spectra is smaller than 25 % for the energy lower than 150 MeV.

4. Results and Discussion

4.1 Neutron spectra produced from the iron target

The calculated results with the NMTC/JAM-MCNP-4A code system are compared with the present experimental results shown in Fig. 4. It is observed that the calculations using both free(shown by solid lines in the figure) and in-medium(shown by dot lines in the figure) NNCS give good agreement with the experiment within 50 %. For the angle at 90 °, the calculation with the in-medium NNCS shows better agreement with the experiment than calculation with free NNCS.

4.2 Dependence on the target nuclei

In order to comprehend the dependence of the target nuclei, the comparisons between calculation and experiment [8, 9] for the heavy metal target are shown in Figs 5 and 6. It is found that the difference of calculation results between Free and in-medium NNCS for iron target is much smaller than those for heavy metal targets. For the heavy metal target, the calculation with the in-medium NNCS gives much better agreement with the experiment in the energy region above 20 MeV. By using in-medium NNCS in NMTC/JAM, *n*-*p* cross sections becomes smaller than free NNCS. This improvement is ascribed to the fact that the high energy nucleon emission is enhanced in the calculation because the mean free path of nucleon in a target nucleus is estimated longer by in-medium NNCS than the free one. Iron nuclei has almost same neutron and proton numbers. Therefore, difference is relatively smaller than difference for heavy metals. On the other hand, lead and tungsten are neutron rich nuclei. As a result, the dependence of NNCS on the neutron spectrum is stronger than the iron case.

5. Conclusion

For the validation of the nucleon meson transport code, the neutron spectra from a thick iron target bombarded with 1.5 GeV protons were measured at 4 angles between 15° and 90°. The accurate neutron spectra were obtained in the energy region between 4 and 1-GeV by the time-of-flight technique.

The calculation results with the NMTC/JAM-MCNP-4A code system are compared with the present experiment data. The calculation was made by using free and in-medium nucleon-nucleon cross sections (NNCS). It is found that calculation with both free and in-medium NNCS show good agreement with the experiment within 50 %. Even the calculation with free NNCS gives good agreement in the energy range between 20 and 80 MeV, whereas calculation gave about 50 % lower neutron flux for heavy metal target. For the result at 90 °, the calculation with in-medium NNCS shows better agreement than the calculation with free NNCS. It can be concluded that NMTC/JAM code system can be predicted the neutron spectrum from iron magnet and collimator with 50 % uncertainties.

By the comparison of heavy metal target, it is recognized the NNCS dependence on iron target is not stronger than heavy metal cases. It can be thought this dependence will become an clue to improve the calculation for the heavy metal targets.

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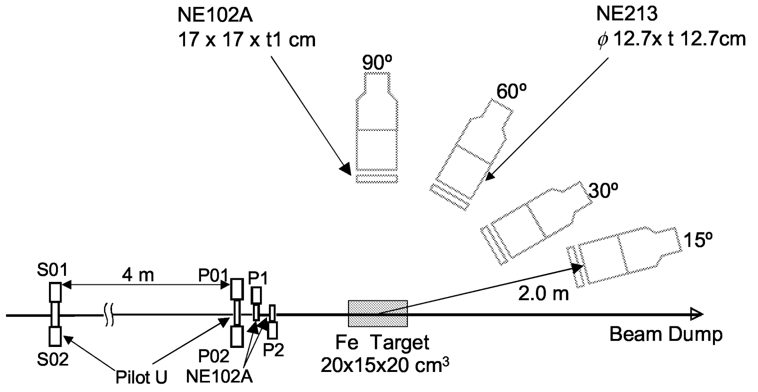

Fig. 1: Illustration of the experimental arrangement.

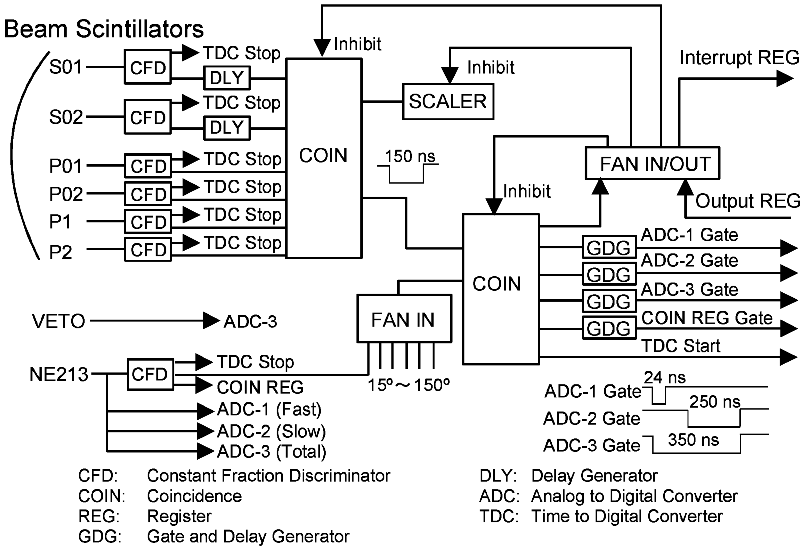

Fig. 2: Diagram of the electronic circuit used in the present experiment.

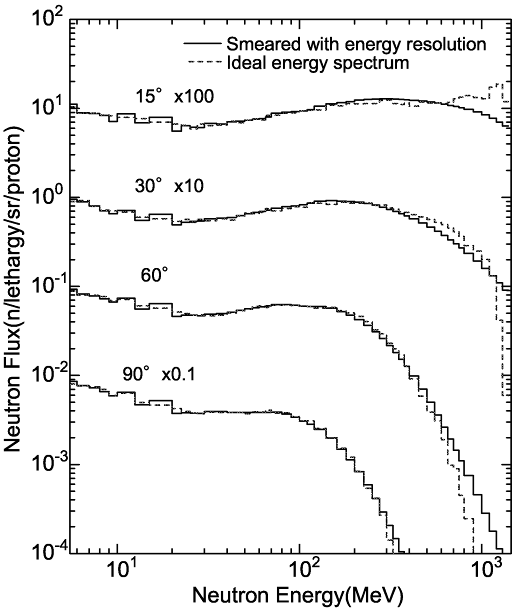

Fig. 3: Comparison of neutron spectrum between with and without energy resolution.

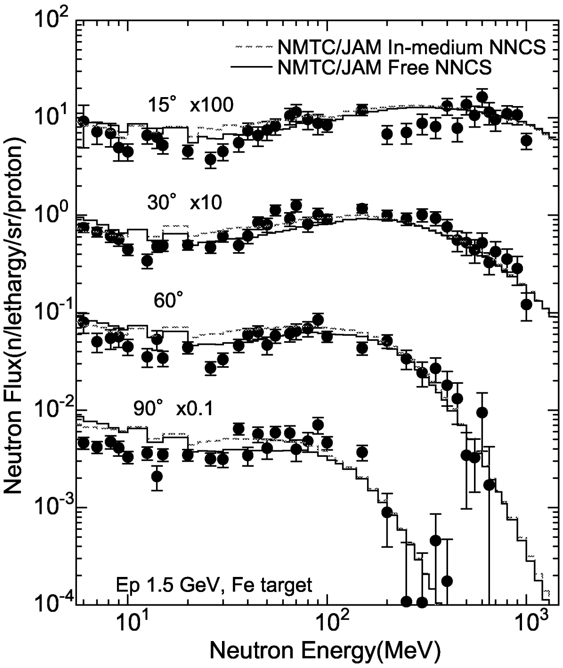

Fig. 4: Comparison of neutron spectra for 1.5-GeV protons between NMTC/JAM and present experiment.

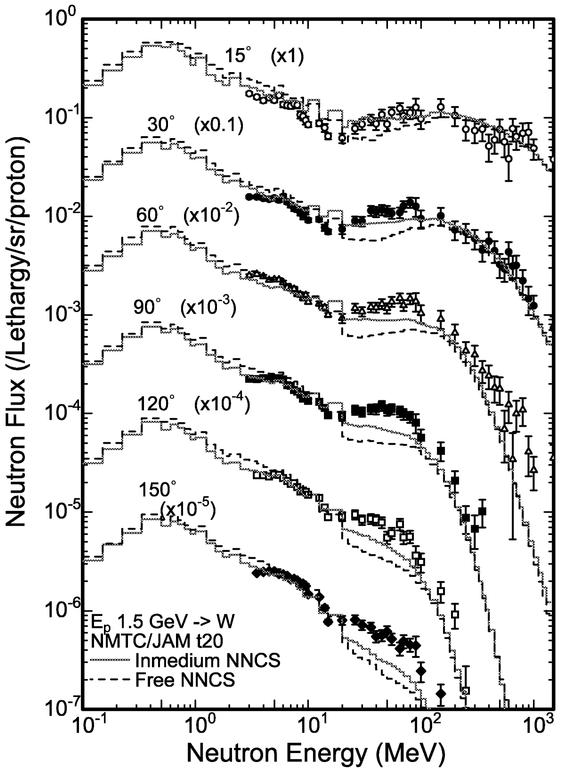

Fig. 5: Comparison of neutron spectra between NMTC/JAM and experiment data for 1.5-GeV protons bombarded with tungsten target.

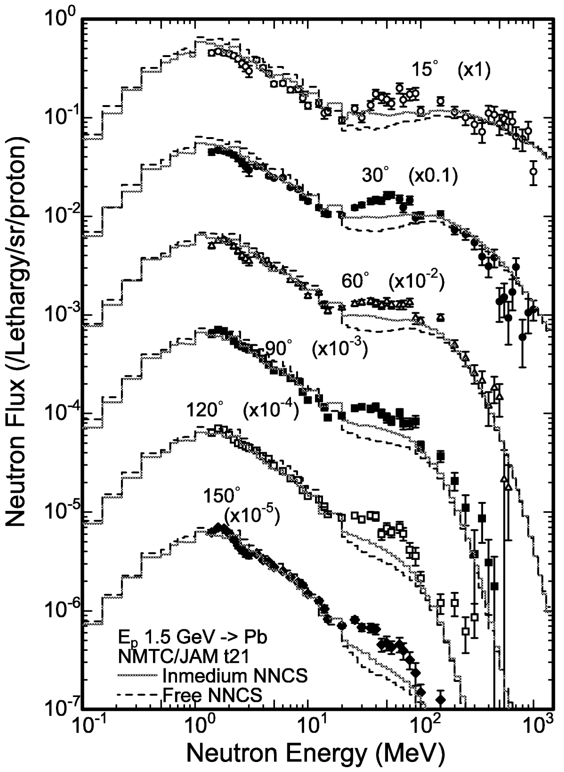

Fig. 6: Comparison of neutron spectra between NMTC/JAM and experiment data for 1.5-GeV protons bombarded with lead target.