Measurements of Neutron Spectra Produced from a Thick Tungsten Target Bombarded with 1.1 and 2.3 GeV/c Protons and π^+ Mesons

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For the validation of the nucleon-meson transport code, spectra of neutrons produced from a thick tungsten target bombarded with 1.1 and 2.3 GeV/c protons and π^+ mesons were measured. The calculated results with NMTC/JAERI97 was compared with the present experimental results. It is found the NMTC/JAERI97 generally shows in good agreement with experiment for protons and pions incident. However, for the neutrons in the energy region between 20 and 100 MeV, the NMTC/JAERI97 shows 50 % underestimation of the experiment, which is consistent with the results of lead 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/JAERI[1, 2] and LAHET[3] 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[4]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)[5]. For the spectrum of the thick target, the spectrum of neutrons produced from a thick lead target was measured[6]. 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. However, these experimental data were scarce for the projectiles above 0.8 GeV, especially for pion projectiles measurements have not been performed. In this study, the spectrum produced in the tungsten target bombarded with 1.1-

and 2.3 GeV/c protons and π^+ mesons was measured. These experimental data were compared with the calculation of NMTC/JAERI.

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 at KEK in a series of double differential neutron production cross section measurements[7]. 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, 1.1 and 2.3 GeV/c protons and π^+ mesons were employed, whose energies are 0.5- and 1.5- GeV for protons and 0.96- and 2.1- GeV for π^+, respectively. The incident particles were identified 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 photomultipliers on opposite sides to obtain good time resolution. Čerenkov detector was employed so as to eliminate the μ^+ from the π^+ projectiles. In order to subtract the neutrons produced from the beam scintillator, background measurements were performed without target.

A tungsten target was bombarded by the proton and π + beams. The target was a rectangular parallelepiped 15×15×20 cm^3 whose purity was 94.81%. It was thick enough to stop 0.5-GeV protons completely, while it caused the partially energy loss for other projectiles. For 1.5-GeV protons, 0.96- and 2.1-GeV π^+ mesons, the average energy deposition is 1.0, 0.49 and 0.56 GeV, respectively.

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 of 30°, 60°, 90°, 120° and 150° 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 17×17×1 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[8] were used. Hence, the results of SCINFUL-R were utilized for detection efficiencies below 80 MeV. Above 80 MeV, the calculated efficiency of CECIL[9] 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 was adopted. 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/JAERI97[2] and MCNP-4A. NMTC/JAERI97 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 processed from the nuclear data file JENDL-3.2 In NMTC/JAERI97, the Pearlstein's systematics[10] was implemented to estimate total, elastic and non-elastic nucleon-nucleus cross sections in the transport calculation part. The level density parameter derived by Baba[11] was also employed in the statistical decay calculation in NMTC/JAERI97.

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/JAERI97. The in-medium NNCS parametrized[12] similarly to those of Cugnon[13] were employed in this calculation.

In order to compare the experimental results, the calculation results are smeared with the energy resolution. By the comparisons 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 up to 150 MeV.

4. Results and Discussion

4.1 Neutron spectra produced from the tungsten target

The calculated results with the NMTC/JAERI97-MCNP-4A code system are compared with the present experimental results shown in Figs. 3 and 4 for protons and Figs. 5 and 6 for π^+ mesons, respectively. It is observed that the calculation with the free NNCS (shown by solid lines in the figures) is in good agreement with the experiment at an energy region below ~10 MeV for both incident energies. In an energy range 20 and 80 MeV, free NNCS , however, gives about 50 % or more lower than that of the experiment.

On the other hand, the calculation with the in-medium NNCS (shown by dot lines in the figures) gives much better agreement with the experiment in the an energy region above 20 MeV. 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. It is simply because of being smaller *n*-*p* cross sections. The enhancement of high energy nucleon emission diminishes the excitation energy of a residual nucleus so that the neutron emission from the evaporation process is suppressed. Consequently, the calculation gives slightly lower neutron flux than the experiment does for the energy range below 10 MeV for 0.5 GeV protons. For the backward emission of neutron above 20 MeV, the underestimation still remains.

4.2 Consistency with lead target results

In order to comprehend the discrepancy between calculation and experiment, here we discuss the results comparing with the results for the study on lead target[6]. In the result of the lead target, the same discrepancy between the calculation with free NNCS and experiment was found above 20 MeV. Furthermore, it is reported in Ref. [6] that the calculation using in-medium NNCS improves the transport of secondary particles in that energy region. The result obtained from the comparison between calculation and experiment of the tungsten target is consistent with those of the lead target.

In Ref [6], the calculated result of double-differential cross sections of the Pb(p,xn) reaction were compared with the experiment. The calculations using both free and in-medium NNCS gave good agreement with the experiment as same as the calculations for the thick target using in-medium NNCS. For the neutrons in the energy region between 20 and 80 MeV, the difference between those calculations for the thin target was smaller than the difference for the thick target. As a result, these facts will suggest that the calculation using in-medium NNCS improves the transport of secondary particles in the energy region above 20 MeV.

The calculation of the differential cross sections showed that the results for the backward neutron emission, however, gave smaller results than the experiment. By this fact, the underestimation for the thick target at deeper angles can be explained. A study [12] suggested that the inclusion of the pre-equilibrium process or the refraction and reflection process improved the backward neutron emission significantly. It is, thus, anticipated that the disagreement for the thick target will be reduced by the inclusion of those processes.

5. Conclusion

For the validation of the nucleon meson transport code, the neutron spectra from a thick lead target bombarded with 1.1- and 2.3-GeV/c protons and π^+ mesons were measured at 6 angles between 15° and 150°. The accurate neutron spectra were obtained in the energy region between 2 and 150 MeV by the time-of-flight technique.

The calculation was carried out with the NMTC/JAERI97-MCNP-4A code system. It was found that results showed fairly good agreement with the experiments, but gave about 50 % lower neutron flux in the energy region between 20 and 80 MeV. This discrepancy was consistent with the result of lead target. For the neutrons between 20 and 80 MeV, the calculation using with the in-medium nucleon-nucleon cross sections(NNCS) reproduced the experiment fairly well. It suggests that the calculation by using in-medium NNCS improves the agreement with the experiment for the transport of particles. By the inclusion of pre-equilibrium process or the refraction and reflection process, a better agreement with the experiment can be anticipated for the backward neutron emission.

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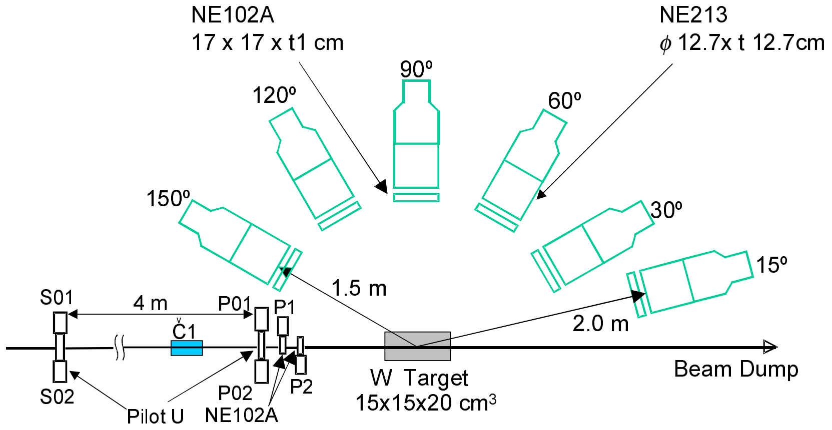

Fig. 1: Illustration of the experimental arrangement.

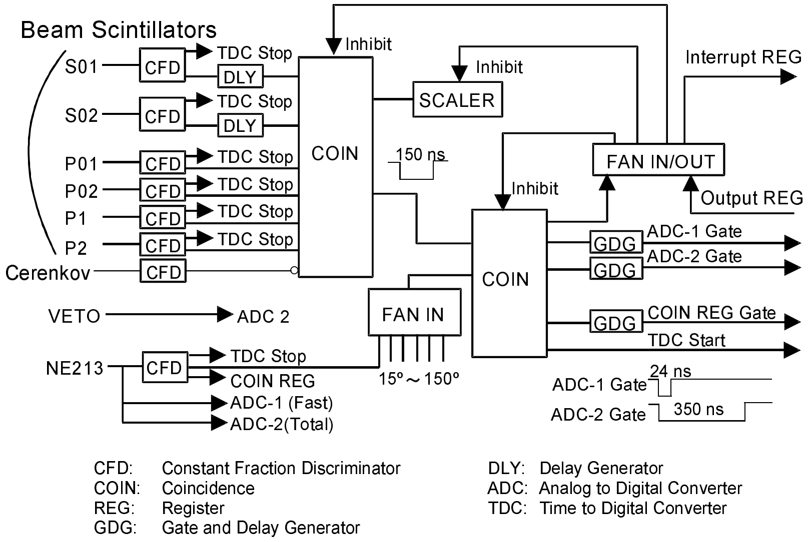

Fig. 2: Diagram of the electronic circuit used in the present experiment.

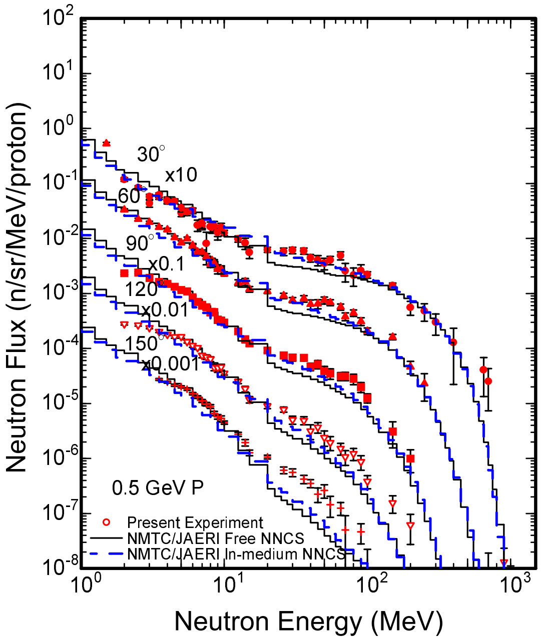

Fig. 3: Comparison of neutron spectra for 0.5-GeV protons between NMTC/JAERI97 and present experiment.

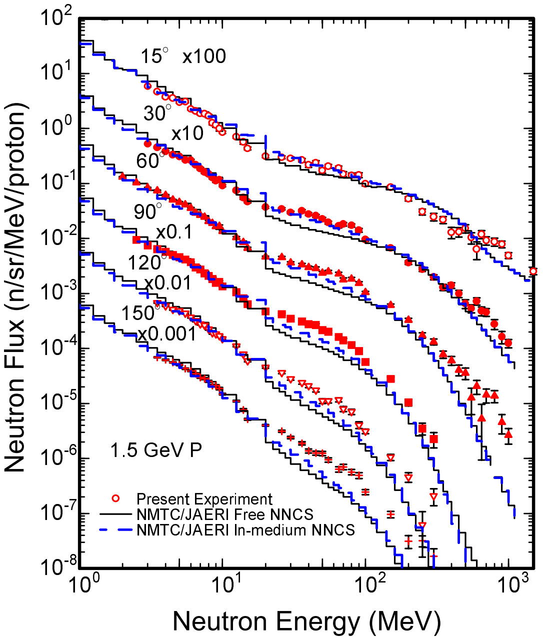

Fig. 4: Comparison of neutron spectra for 1.5-GeV protons between NMTC/JAERI97 and present experiment.

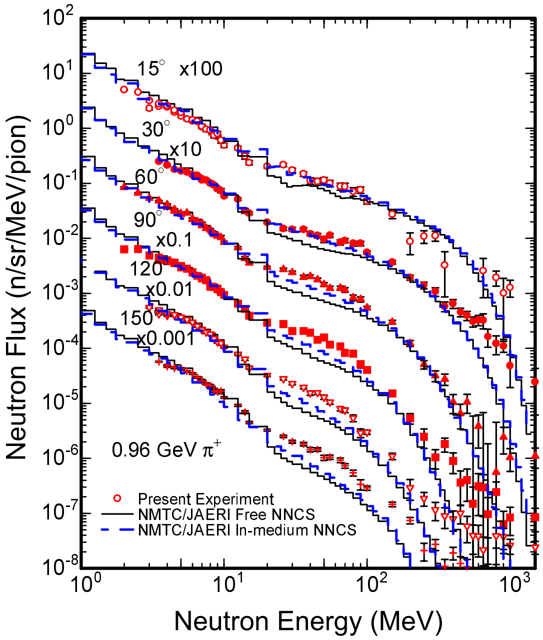

Fig. 5: Comparison of neutron spectra for 0.9-GeV π^+ mesons between NMTC/JAERI97 and present experiment.

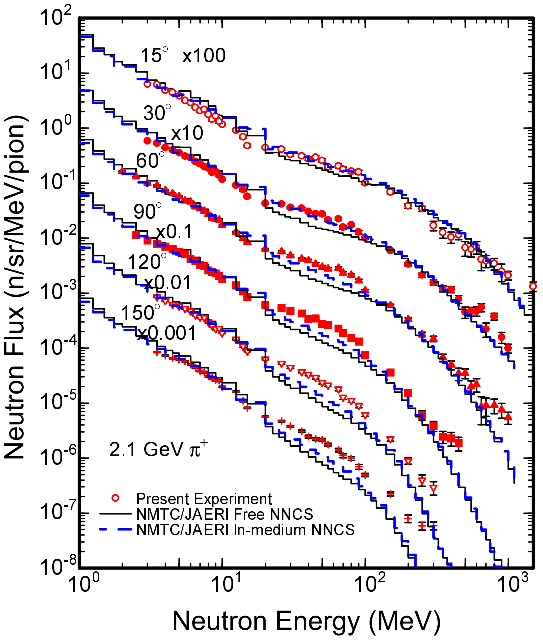

Fig. 6: Comparison of neutron spectra for 2.1-GeV π^+ mesons between NMTC/JAERI97 and present experiment.