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ARTICLE

Measurement of Thick Target Neutron Energy Spectra at 15° and 90° Bombarded with 120-GeV Protons

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Neutron energy spectra at 15° and 90° produced from aluminum, copper and tungsten targets bombarded with 120-GeV protons were measured at Fermilab Test Beam Facility. The target thicknesses were 50 cm for aluminum, 2 0 cm and 40 cm for copper, and 10 cm for tungsten, respectively. The neutron time-of-flight measurements were performed using an NE213 organic liquid scintillator (12.7 cm diameter, 12.7 cm long) at 5.2 m for 90° and 8.0 m for 15° measuring from the center of the target to the surface of the detector. The raw signals (waveforms) obtained from photomultiplier tubes were recorded using the 10 bit digitizer (Agilent-Acqiris DC282) with 0.5 ns sampling and 500 ns duration. To compare the experimental results, Monte Carlo calculations with the PHITS, FLUKA and MARS codes were performed. It was found that these calculated results at 90° underestimate the experimental results due to the strong forward emission of particles in the models, while calculated results at 15°gives good agreement with the data.

KEYWORDS: super-high-energy, neutron energy spectrum, TOF, benchmark calculation

I. Introduction

In the shielding design of super-high-energy (above 10 GeV) proton accelerator facilities, it is important to estimate the energy spectra of the secondary particles, especially neutrons and muons, produced by beam losses in thick portions of the beam line apparatus and the beam dump for use as reference values. The data of energy and angular distributions of thick target neutron yields are very useful to validate simulation codes for their characterization of total secondary particle production and propagation of particles in the intra-nuclear cascade inside a thick target. These data are also very important to predict external exposure to personnel and radiation damage in targets and construction materials especially due to high-energy neutrons.

A detailed neutron shielding design can be done with Monte Carlo transport calculation codes (PHITS[1]), FLUKA[2]) and MARS[3]) for example) describing the interaction and transport of all particles created in nuclear reactions. Characteristics of inelastic hadron-nucleus interactions in PHITS, FLUKA and MARS are summarized in **Table 1**. For neutron energy spectra produced by super high-energy reactions, the measurement upon bombardment of 40-GeV/c mixed beam (proton and pion+) on copper, silver and lead at the CERN Super Proton Synchrotron has been reported.[4]) The measurement of neutron spectra behind shielding at the CERF 120 GeV/c hadron beam facility has also been reported.[5]) These data were taken from not direct measurements, but the unfolding method using Bonner spheres or NE213 organic liquid scintillators. No other experimental neutron data at super high-energies are available, and thus the present codes have not been thoroughly checked against experimental data.

We report on measurements of neutron energy spectra at 15° and 90° in the energy regions above 20 MeV from thick aluminum, copper and tungsten targets bombarded with

Table 1 Characteristics of inelastic hadron-nucleus interactions.

Code	High-energy (> ~5GeV/c)	Low-energy (< ~5GeV/c)
PHITS[1])	Hadronic cascade model JAM	Intra nuclear-cascade model Bertini
FLUKA[2])	Glauber-Gribov multiple scattering	Preequilibrium-cascade model PEANUT
MARS[3])	Los Alamos Quak-Gluon String Model	Cascade-exciton model CEM

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120-GeV protons using time-of-flight (TOF) method at Fermilab Test Beam Facility (FTBF), Fermi National Accelerator Laboratory (FNAL). The comparisons of the measured data with PHITS, FLUKA and MARS codes are also described.

II. Measurements

The experiments were carried out at the MT6-2 area of FTBF. A schematic layout of the experimental arrangement for neutron detectors at 15^o and 90^o is illustrated in **Figure 1**. The characteristics of the targets used in this work are summarized in **Table 2**. The neutron TOF measurements were performed using an NE213 organic liquid scintillator (12.7 cm diameter, 12.7 cm long) coupled to a Hamamatsu R1250 photomultiplier. The distances measuring from the center of the target to the surface of the detector was 8.0 m for 15^o and 5.2 m for 90^o, respectively. A 3.5-mm-thick plastic scintillator NE102A placed in front of the neutron detector tagged the events induced by a charged particle.

The incident proton beam was monitored by multi wire proportional counters on the beam line to see the beam profile. The time structure of proton beam consisted of three levels. The smallest structure was the bunch with 19 ns interval. The second was called the train which included 20 – 36 bunches and had 11 μs interval. The largest structure was the spill which contained trains of four seconds.

The multiplicity of protons in a train was evaluated using two 3.5-mm thick plastic scintillators with photomultiplier

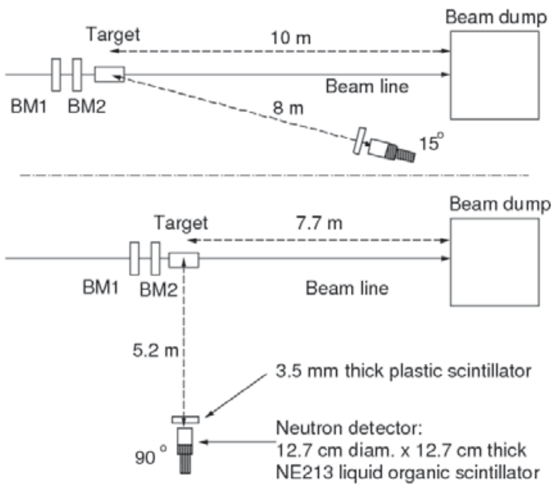

Fig. 1 Schematic layout of the experimental arrangement for neutron detectors at 15^o and 90^o.

Table 2 Target characteristics and their energy loss for 120-GeV proton.

Target	Size (cm)	Energy loss (GeV)
Al	ϕ3.5 × 50	0.29
Cu	5 × 5 × 20	0.36
Cu	5 × 5 × 40	0.71
W	ϕ3.0 × 10	0.33

tubes (Beam monitors BM 1 and 2) in front of the target to count the number of incident protons. The average number of proton was limited to 3 × 10^5 particles/spill due to the radiation safety limitation.

A 10 bit digitizer (Agilent-Acqiris DC282) was used to obtain waveforms of light outputs from scintillators of NE213, NE102A and beam monitors with 0.5 ns sampling and 500 ns duration as a function of time. This system acquired the neutron flight time between the target and the scintillator.

Each run was supplemented by a background run with an iron shadow bar of 1 m length being inserted at the front of the detector into the TOF path. Background events were considered as room-scattered-neutrons and neutrons produced at a beam dump.

III. Data Analysis

1. Neutron energy spectrum

The stored waveforms were analyzed after data accumulation. As the first step, the waveforms that had a single BM event prior to an NE213 signal were chosen. Then, the entire and tail of NE213 signal was integrated for the neutron-gamma separation in an NE213 detector. The integration of the entire NE102A signal was used to the separation of charged particles. The time difference between NE213 and BM1 was also computed event by event to determine the TOF of neutron. The integrations of waveforms were calibrated to light output for "MeV electron equivalent (MeVee)" using Compton edge for ^{60}Co radioactive gamma sources. In the TOF spectrum analysis to obtain the neutron energy spectra, neutron events above 10.74 MeVee (10 × ^{60}Co threshold) were summed up. Neutron energy spectra only in the energy range above 20 MeV were finally obtained, due to a threshold (bias) at 10.74MeVee, which is equivalent to the light output from protons of approximately 16MeV.

The neutron energy spectrum can be expressed as,

$$\frac{d^2Y}{dEdS}(E)=\frac{C_n(E)\cdot f_{tof}\cdot f_{dead}}{(BM\cdot f_{multi})\cdot\varepsilon(E)\cdot S\cdot\ E} \qquad (1)$$

with $C_n(E)$ is number of neutrons obtained from the waveform analysis by choosing non-charged particles, removing gamma events, choosing events having more than 10.74 MeVee light output, and choosing events without ambiguity that had a single BM event prior to an NE213 signal. f_{tof} is the ratio of the number of total events to that of events without ambiguity and ranges from about 5 to 10 in each run. f_{dead} is the ratio of the number of total trigger of the waveform digitizer to that of the recorded waveforms and ranges from 1.0 to 1.5. BM is the number of proton beam bunch during measurements and f_{multi} is the average number of protons in one bunch. It ranges from 1.1~1.5. $\varepsilon(E)$ is the detection efficiency calculated by SCINFUL-QMD.[6] S is the area of front surface of NE213 and ΔE is the energy bin width.

The total neutron energy resolution for 20 cm thick copper at 8.0 m and 15^o was 30 %, for example, and the TOF method enabled neutron energy measurement with a resolution better than 30 % in the energy region below 1 GeV.

2. Background analysis with a shadow-bar

Figure 2 shows the experimental and calculated ratios of flux without shadow-bar to that of flux with shadow-bar for 20-cm-thick copper target at 15^o and 90^o, respectively. PHITS was used for the calculation with the detailed geometry including floor, beam dump and wall. Since the measured and calculated ratio is over 1 in the wide energy range, background events is removed by the subtraction of the data with a shadow bar from the data without a shadow bar. Note that the ratio at 15^o is close to 1 at energies below 200 MeV due to the detection of many neutrons from the beam dump.

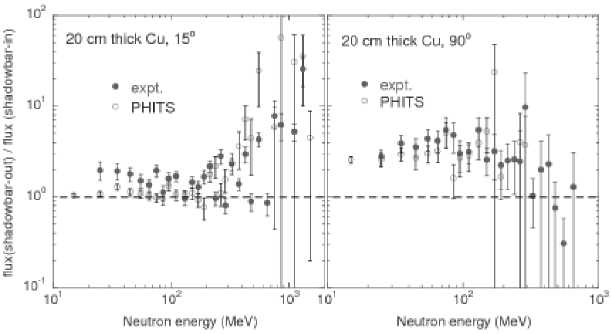

Fig. 2 Experimental and calculated ratios of flux without shadow-bar to that of flux with shadow-bar at 15^{o}and 90^o

IV. Results

Experimental and calculated neutron energy spectra at 15^o and 90^o for 10-cm-thick tungsten are shown in **Figure 3** and **4** respectively. The difference between PHITS, FLUKA and MRAS results is almost negligible. Proton events were obtained from the scatter plots of the TOF versus light output of NE213 for charged events[7]. Note that proton energy spectra are preliminary results because the detection efficiency in NE213 was regarded as 100 %. More detail analysis for proton will be needed. At 15^o, the calculated results agree well with experimental data. On the other hand, at 90^o, calculated results underestimate the experimental data. This may be resulted from the strong forward emission of particles in the high-energy physics model.

Figures 5 and **6** show results at 15^o and 90^o for a 20-cm-thick copper target, respectively. The tendency of the relation between calculated and experimental results is almost same with that for a 10-cm-thick tungsten target. **Figures 7** and **8** show results for a 40-cm-thick copper target. For the neutron and proton energy spectra at 15^o, calculated results give good agreements with experimental data, while the difference at 90^o between calculated results and experimental data is larger than that for 20-cm-thick copper target. Especially, the difference between PHITS results and experimental data is large over the region where experimental data exist. It seems that a thicker target enhances the disagreement at 90^o due to the strong emission to the forward angle in physics model.

Calculated and experimental results for a 50-cm-thick aluminum target are shown in **Figure 9** and **10**. The statistics of experimental data was not enough though measuring time for aluminum was almost the same as that for copper. In

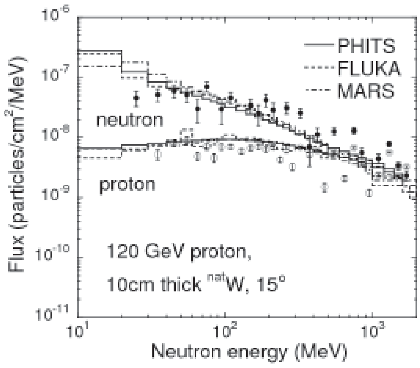

Fig. 3 Neutron energy spectra for 120 GeV proton incident reaction on a 10-cm-thick tungsten target at 15^o.

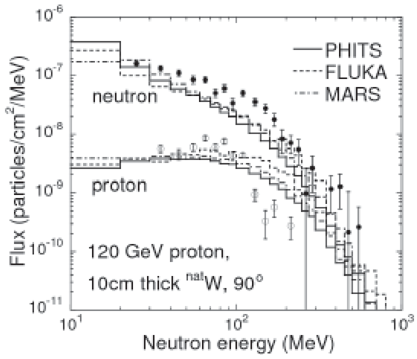

Fig. 4 Neutron energy spectra for 120 GeV proton incident reaction on a 10-cm-thick tungsten target at 90^o.

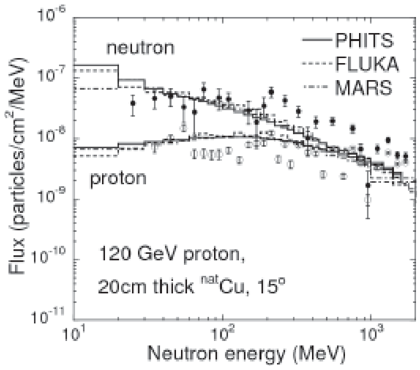

Fig. 5 Neutron energy spectra for 120 GeV proton incident reaction on a 20-cm-thick copper target at 15^o.

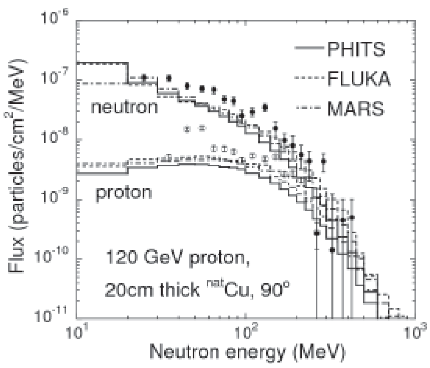

Fig. 6 Neutron energy spectra for 120 GeV proton incident reaction on a 20-cm-thick copper target at 90^o.

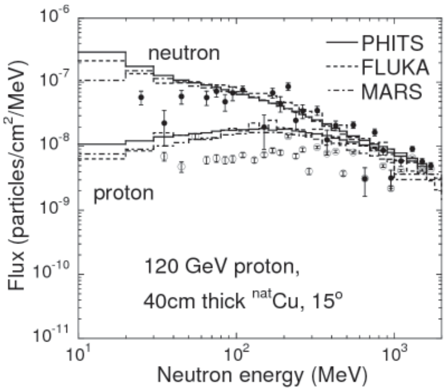

Fig. 7 Neutron energy spectra for 120 GeV proton incident reaction on a 40-cm-thick copper target at 15^o.

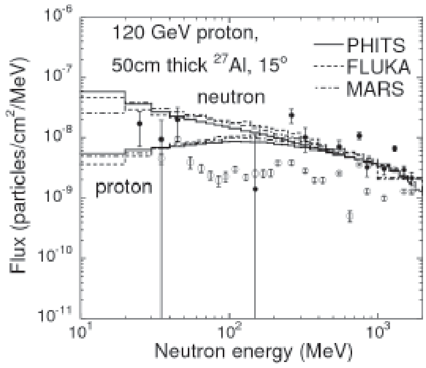

Fig. 9 Neutron energy spectra for 120 GeV proton incident reaction on a 50-cm-thick aluminum target at 15^o.

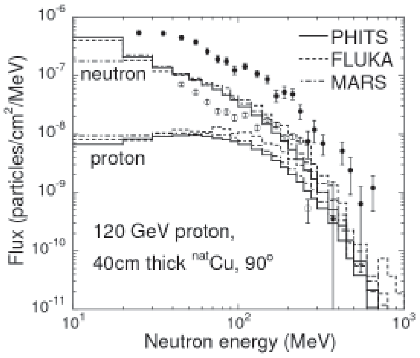

Fig. 8 Neutron energy spectra for 120 GeV proton incident reaction on a 40-cm-thick copper target at 90^o.

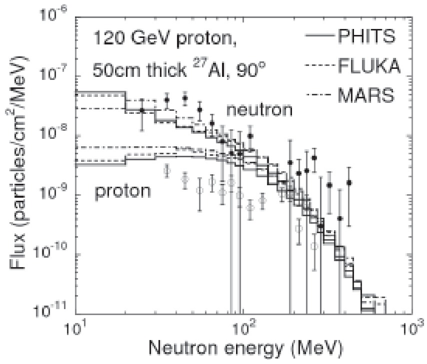

Fig. 10 Neutron energy spectra for 120 GeV proton incident reaction on a 50-cm-thick aluminum target at 90^o.

general, calculated results give agreement with experimental data.

V. Summary

Neutron energy spectra at 15^o and 90^o produced from 50 cm thick aluminum, 20 and 40 cm thick copper and 10 cm thick tungsten targets bombarded with 120-GeV protons were measured at FTBF. The neutron time-of-flight measurements were performed using an NE213 organic liquid scintillator at 5.2 m for 90^o and 8.0 m for 15^o. The waveforms were recorded using the 10 bit digitizer. To compare the experimental results, Monte Carlo calculations with the PHITS, FLUKA and MARS codes were performed. It was found that all calculated results at 15^o gives good agreement with the data, while these calculated results at 90^o underestimate the experimental results due to the strong forward emission of particles in the models.

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