Measurements and parameterization of neutron energy spectra from targets bombarded with 120 GeV protons

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Abstract

The energy spectra of neutrons were measured by a time-of-flight method for 120 GeV protons on thick graphite, aluminum, copper, and tungsten targets with an NE213 scintillator at the Fermilab Test Beam Facility. Neutron energy spectra were obtained between 25 and 3000 MeV at emission angles of 30, 45, 120, and 150°. The spectra were parameterized as neutron emissions from three moving sources and then compared with theoretical spectra calculated by PHITS and FLUKA codes. The yields of the theoretical spectra were substantially underestimated compared with the yields of measured spectra. The integrated neutron yields from 25 to 3000 MeV calculated with PHITS code were 16–36% of the experimental yields and those calculated

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with FLUKA code were 26–57% of the experimental yields for all targets and emission angles.

Keywords: Neutron energy spectrum, 120 GeV proton, NE213 scintillator, Time-of-flight

1. Introduction

The neutron production rate and energy spectra produced when high-energy beam particles hit materials are crucial for estimating the induced activities and ambient dose equivalent behind the shielding walls of high-energy accelerators. Empirical formulas, such as the Moyer model [1] or multi-particle transport code, have been used to estimate the activities and ambient dose equivalent, which are necessary when designing shielding. The results must be verified by using experimental data to ensure the shield designs are appropriate. Neutron energy spectra measured behind a shielding wall have been reported for proton beam energies of up to several GeV. However, there are only two spectra above 100 GeV [2, 3]. There are no experimental data for neutron energy spectra directly from a target, which would allow neutron production to be evaluated separately from attenuation due to shielding materials.

Recently, Agosteo et al. [4] measured neutron energy spectra for 40 GeV/c mixed proton/pion beams on copper, silver, and lead targets by using a set of Bonner spheres. Their data relied on initial guess obtained by theoretical calculations during the unfolding procedure. Sanami et al. [5] have reported a method for measuring the neutron energy spectrum of 120 GeV protons on a copper target by using a time-of-flight (TOF) technique. Their technique

does not require initial guesses; however, a subsequent study suggests that the detection efficiency for high-energy neutrons should be replaced [6]. Furthermore, their results cannot be compared directly with theoretical results because their data contain contributions from room-scattered neutrons from the floor and from a beam dump.

In this study, neutron energy spectra free from room-scattered neutrons were obtained by a TOF technique for 120 GeV protons on various targets at the Fermilab Test Beam Facility (FTBF) [7]. The data were analyzed by using neutron detection efficiency, based on experimental data taken at LANSCE, Los Alamos National Laboratory [6]. For efficient data collection and analysis, we replaced the complex waveform data analysis reported by Sanami et al. [5] with a simple electronics circuit consisting of standard NIM and CAMAC modules. The simultaneous use of two detectors with the circuit allowed systematic experimental data to be obtained for various target materials, thicknesses, and neutron emission angles. The measured neutron energy spectra were parameterized as neutron emissions from three moving sources [8]. This parameterization gave neutron energy spectra at the measured angles and also at other angles. The measured spectra were compared with spectra calculated by PHITS [9] and FLUKA [10] code.

2. Experiment

We describe our TOF methods only briefly because they are similar to previously reported methods [5]. A data acquisition system that counted the number of pile-up events during the TOF period (see Section 2.3 for details) was used to collect data simultaneously from two detectors. To re-

move the contribution of indirect neutrons, such as room-scattered neutrons, separate data were taken with and without shadow bars for each target and angle. This modification allowed us to measure systematic neutron spectra for several targets and emission angles.

2.1. Experimental setup

Figures 1 and 2 show the experimental setups for the forward- and backward-angle measurements, respectively. The equipment was set up in the MT6-2 enclosure of the Fermilab test beamline, Fermi National Accelerator Laboratory, U.S.A. The two experimental configurations had different target positions to achieve a sufficient flight length for the energy resolution and neutron yields.

Figure 1: Experimental setup for forward-angle measurement.

The proton beam generated by the line accelerator (LINAC), booster, and main injector of the Fermilab accelerator complex comes from the left side of Figures 1 and 2 after passing through the beam switch yard and a meson test beamline more than 1000 m long [7]. The neutron production target was placed at the beamline height, in the middle of the MT6-2 enclosure. The

Figure 2: Experimental setup for backward-angle measurement.

target was supported by a table made from a low-mass material to avoid neutron scattering. An iron beam dump was placed behind the target as a part of the shielding wall. Two iron calorimeter plates of other experiments were placed between the target and the dump in an off-beam position. There were no other high-mass materials or structures in the enclosure. Two beam profile monitors (multi-wire proportional chambers; MWPCs) and two beam counters (BM1 and BM2) were placed on the beamline to maintain the beam conditions.

The target characteristics are given in Table 1. Several materials were used to study the dependency of the mass number on neutron yield. The thickness of the copper targets was varied to study the effect on the neutron production rate and spectrum for hadron shower development. The target thicknesses were determined for each target by estimating the energy loss of incident protons with PHITS code [9]. The losses were less than 1% of the 120 GeV protons. The target was placed at the beam height, 1.65 m from floor level.

Two NE213 liquid organic scintillators 12.7 cm in diameter and 12.7 cm

Table 1: Material, size, density, and calculated energy loss for 120 GeV protons of the targets.

Material	Size [cm]	Density [g/cm ³]	Energy loss [MeV]
Graphite	Ø5.0×60.0	1.81	2.5×10^2
Aluminum	Ø3.5×50.0	2.70	2.9×10^2
Copper	5.0×5.0×20.0	8.96	3.5×10^2
Copper	5.0×5.0×40.0	8.96	7.1×10^2
Copper	5.0×5.0×60.0	8.96	1.1×10^3
Tungsten	Ø3.0×10.0	18.1	3.1×10^2

in length were used as neutron detectors. The detectors were set at four angles by changing their distance from the target. For the forward-angle setup (Fig. 1), the detectors were placed 6.3 and 5.6 m from the target, at 30 and 45° to the proton beam axis. For the backward-angle setup (Fig. 2), the detectors were placed 4.0 and 2.9 m from the target, at 120 and 150° to the proton beam axis. A thin plastic scintillator was placed in front of each neutron detector as a veto detector to identify charged particle events.

Background neutrons that were produced from materials other than the target or scattered from the floor were measured for each target by placing 1.0-m-thick iron blocks, “shadow bars”, between the target and each neutron detector. The shadow bars blocked neutrons from the target reaching the detector directly. Therefore, we obtained neutron spectra from the target with no background neutrons by subtracting the spectra measured with the shadow bars from the corresponding spectra without shadow bars.

The thickness of the shadow bars was determined by the transmission rate for neutrons with energies of 25–3000 MeV and the rate was calculated from the neutron total cross section of iron. The total cross section was derived from data reported by Abfalterer et al. [11] for the energy region below 560 MeV and calculated by the TOTELA code [12] for the energy region above 560 MeV. The maximum rate, 2.0×10^{-4} , was obtained at 264 MeV, demonstrating that the shadow bar thickness was sufficient to block direct neutrons.

2.2. Proton beam preparation

A 120 GeV proton beam pulsed at $2\text{--}4 \times 10^5 \text{ s}^{-1}$ was extracted to the air through an aluminum window at the end of the MTest beamline and delivered into the MT6-2 enclosure, as shown in Ref. [5]. The intensity of the beam was controlled by a pinhole collimator and monitored by using a 1-mm-thick plastic scintillator placed on the beamline, just downstream of the aluminum window. In addition to this, two thin plastic scintillators (BM1 and BM2) were placed on the beamline just before the target to count the number of protons. These plastic scintillators each had a cross section of $10 \times 10 \text{ cm}^2$ and a thickness of 0.5 cm.

The beam spot on the target was monitored by using two MWPCs placed just after the aluminum window and the target. Prior to neutron measurement, the beam spot sizes at both MWPCs were adjusted to have full width at half maximum (FWHM) diameter of 5 mm, and the positions were centered. Once the target was set, the beam spot on the downstream MWPC disappeared because the beam was scattered by the target. The beam position and size were checked several times by removing the target. During the

neutron measurements, the position and size were recorded pulse-by-pulse for both MWPCs to ensure beam quality.

2.3. Data taking

Figure 3 shows a scheme of the detector signals as a function of time. The BM1 counter provided at least one signal for one of NE213 detectors. Two or more signals, shown as dotted lines, could be obtained when the beam was fluctuated. The time differences between the first and second pulses were multiples of 19 ns, equivalent to the LINAC repetition rate. The veto detector produced a signal whenever a charged particle was detected by the NE213 detector; this is shown by dotted lines in the figure.

Figure 3: Schematic drawing of the detector signals as a function of time. (a) Time difference between BM1 and NE213 (TOF); (b) NE213 pulse height; (c) veto pulse height; (d) BM1 pulse height; (e) number of BM1 pulses in the TOF gate; and (f) bit pattern of the fired detector.

Figure 3 shows the 6 parameters, (a)–(f), that should be recorded event by event. The integrated values of the NE213 signal (b) were recorded with two different gates (b1) and (b2) to distinguish neutrons from γ rays. The

veto pulse signal (c) was used to distinguish charged particles. The BM1 pulse height (d) was used to correct the number of protons and avoid proton pile-up within a bunch. The number of protons in a TOF gate (e) was used to avoid ambiguity in determining the TOF caused by detecting more than two protons for a single neutron event. The bit pattern (f) was used to distinguish signals from two neutron detectors.

2.4. Data readout

Figure 4 shows a simplified block diagram of the electronics. We used electronics consisting of standard NIM and CAMAC modules instead of the waveform data recording equipment reported by Sanami et al. [5]. CAMAC modules were used to record the six parameters shown in Fig. 3: a time-to-digital converter (TDC) was used for parameter (a); charge-integral analog-to-digital converters (ADCs) were used for parameters (b)–(d); a scaler was used for parameter (e); and a coincidence register was used for parameter (f). An output register was used to control the inhibition of the CAMAC controller and NIM modules were employed to generate logic signals to control the CAMAC modules. The logic signals were generated for a trigger for data acquisition, gates of the ADCs and coincidence register, and the start and stop signals for the TDC.

There were two timings in the logic signals for controlling the CAMAC modules. The trigger signal, the ADC gates for parameters (b) and (c), the coincidence register gate, and the start signal for the TDC were all timed by signals originating from the NE213 detectors. The ADC gate for parameter (d) and the stop signal for the TDC were timed by signals from the BMs. Because the CAMAC controller was operated by the timing of signals from

Figure 4: Simplified data acquisition electronics.

the NE213 detector, the timing originating from signals from the NE213 detectors was converted into the timing from a signal from the BMs at the coincidence 5 (COIN5). A logic signal from COIN1 and a TOF gate from a gate generator 2 (G.G.2) were fed to COIN5. The TOF gate was 200 ns long. The logic signal from COIN1 was delayed to reverse the time relation between the signals from the BMs and the NE213 detector.

Data acquisition (DAQ) was controlled by a trigger signal and a signal from the output register. The CAMAC controller initiated the DAQ process by means of a trigger signal. Once the DAQ process began, no other DAQ processes were allowed to begin for further events. The inhibition was initiated by a signal from G.G.1, which was set to latch mode. During the inhibition, the parameters gathered by the CAMAC controller were transmitted to a PC, which recorded the parameters. After the DAQ process ended, the output register provided a stop signal to G.G.1 to stop the inhibition. The inhibition produced dead events, which were corrected for by counting the number of signals from the BM and the NE213 detectors during

the measurement with NIM scalers.

3. Data analysis

The neutron energy spectrum ($d^2Y(E)/dEd\Omega$) with an energy bin width of dE , centered at an energy of E , and at a solid angle of $d\Omega$, was calculated with

$$\frac{d^2Y(E)}{dE d\Omega} = \frac{1}{\varepsilon(E) \Delta\Omega \Delta E} \left[\left(\frac{C_n(E) f_{dead}}{N_p f_{tof} f_{multi}} \right)_{out} - \left(\frac{C_n(E) f_{dead}}{N_p f_{tof} f_{multi}} \right)_{in} \right], \quad (1)$$

where the subscripts $_{in}$ and $_{out}$ denote measurements with and without the shadow bars, respectively. $C_n(E)$ is the spectrum obtained from the analysis: extracting events with a single incident proton, removing charged particle events, extracting neutron events, and selection of events exceeding the finite light output threshold. N_p is the number of the proton beam which was counted by NIM scaler beam (Fig. 4), $\varepsilon(E)$ is the neutron detection efficiency of the NE213 detector, $\Delta\Omega$ is the solid angle of the NE213 detector, and ΔE is the energy bin width of the spectrum.

There are three correction factors in Eq. 1. f_{dead} is the factor for correcting for dead events, defined as the ratio of the number of counts for NIM scaler 1 or 2 (Fig. 4) to the number of the data recorded by each neutron detector. f_{tof} is the factor for correcting for the number of events removed because of multiple BM pulses (Fig. 3 (e)). f_{multi} is the correction factor for multiple incident protons (Fig. 3 (d)).

Figure 5 shows a TDC histogram with a time per channel of 50.8 ps. The histogram contains a cyclic structure with 19 ns intervals, which is equal to the time interval between bunches in the proton beam. The cyclic structure

occurred from events for which the TDC was stopped by a signal earlier than real that. When protons arrived at intervals smaller than the acceptable flight time width (TOF gate in Fig. 4), an early signal from BM1 stopped the TDC. Whenever several protons arrived, the earliest BM1 signal in the acceptable flight time width became the TDC stop signal. However, the stop signal was ambiguous, and we could not use the TOF technique. Therefore, we obtained the number of BM1 pulses during TOF gate (e) in order to identify these ambiguous events. The events for which the value of the number was 1 were selected for further analysis. The TDC histogram for the selected events is also shown in Fig. 5 as a broken line. The cyclic structure was eliminated from the TDC histogram.

The value of f_{tof} was 0.2–0.4 for the measurements without the shadow bars and 0.1–0.2 for the measurements with the shadow bars. Because the ratio of lower probability events to all events was larger for the measurements with the shadow bars than without the shadow bars, f_{tof} was larger in the measurements without the shadow bars.

In addition, single proton incident events were selected with the ADC histogram for BM1, as shown in Fig. 6. Peaks for single, double, and triple proton incident events were observed in the histogram, and multiple incident events were removed. The correction factor, f_{multi} , was determined based on the number of removed events and was 0.9–0.98 for all measurements.

Charged particle events were removed using the pulse height data from the veto detector. Fig. 7 shows two dimensional plot of TDC and ADC of NE213 total component before and after removing charged particle events. Events of proton, deuteron, and pion from the target can be observed in

Figure 5: TDC histogram at 30° for the tungsten target. The solid line shows all events, including those with an ambiguous flight time. The broken line indicates events with unique flight times.

Figure 6: ADC histogram for BM1 for all events. The histogram was recorded at 30° for the tungsten target.

Fig. 7 (a) (before removing charged particle events). These charged particle events are clearly eliminated in Fig. 7 (b) (after removing charged particle events).

Figure 7: Scatter plots of TDC and ADC of NE213 total component before (a) and after (b) removing charged particle events. The plots are for the carbon target at 45° .

Neutron events were separated from the uncharged particle events by pulse shape discrimination. Events for the neutron-induced charged particles escaping from the NE213 scintillator and γ -ray-induced events were eliminated because it was difficult to distinguish them. The separation of neutron events can be confirmed from Fig. 8 which is scatter plots of TDC and ADC of NE213 total component for events extracted and eliminated in pulse shape discrimination.

The neutron energy was determined from the flight time with relativistic kinematics. The neutron flight time was derived from time difference between the neutron event and a peak of prompt γ -rays. A sharp peak is clearly

Figure 8: Scatter plots of TDC and ADC of NE213 total component for events extracted (a) and eliminated (b) in pulse shape discrimination (PSD). The plots are for the aluminum target at 30° . The plot (b) consists of events for the neutron-induced charged particles escaping from the NE213 scintillator and γ -ray-induced events. In the plot (b), a sharp peak is formed by prompt γ -rays from the target. The peak was used as a time base.

observed as shown in Fig. 8 (b), which consists of events by prompt γ -rays from the target. The TDC value of the peak depends on the ADC value, which is the time walk. When the neutron flight time was determined, the time walk of the prompt γ -ray peak was corrected.

The ADC channel of the total component of the NE213 detector signals was converted into the electron equivalent light output. Calibration points were obtained from radioactive γ -ray sources as well as from the proton data. The procedure for obtaining the proton data is described in Ref. [5]. The proton energy was determined by considering the energy loss during the flight, and was converted into the light output by using the empirical equation of Nakao et al. [13].

The spectra for the measurements without the shadow bars included background events from neutrons produced by materials other than the target or scattered by the floor. The background events were analyzed in the same way as signal events and the background spectra were obtained by analyzing data for measurements with shadow bars. Figure 9 shows the spectra of neutrons detected with and without the shadow bars, and the spectrum derived by subtracting the spectrum with the shadow bars from that without the shadow bars. In the high-energy region above 400 MeV, the contribution from background events was small because background events have longer flight times to the NE213 detector than those from neutrons emitted from the target and directly entering the NE213 detector.

The double-differential neutron spectra were derived from Eq. 1. Neutron detection efficiency was obtained by using SCINFUL-QMD code [14, 6]. In these calculations, events from charged particles escaping from the NE213

Figure 9: Energy spectra of neutrons for measurements with and without the shadow bars, and the spectrum obtained by subtraction. These spectra are for the 40-cm-thick copper target at 45° .

scintillator were discarded. The light output thresholds for the neutron detection efficiency were set at a higher level to suppress the background events. The light output thresholds were set as 10 MeVee below 50 MeV, 15 MeVee between 50 and 100 MeV, and 20 MeVee above 100 MeV. By setting the light output threshold of 10 MeVee, the lowest energy of the spectra was 25 MeV to avoid zero and large fluctuations in the efficiency with changes in the incident neutron energy. The solid angle was altered by moving the target toward a point source because the solid angle agreed with an accurate value calculated by the Monte Carlo method to within 1%.

The uncertainties were taken into account for statistical and systematic errors. The statistical error was derived from the number of neutron events, and the systematic error was considered for only the neutron detection ef-

iciency. The uncertainty in the efficiency was estimated to be 15% on the basis of experimental values [6]. The geometrical error and uncertainty in the correction factors were relatively small [5] in comparison with the statistical and systematic errors.

4. Monte Carlo calculation

To compare our experimental results with theoretical spectra, neutron spectra were calculated with PHITS code, version 2.63, and FLUKA code, version 2011.2.17. The default models and parameters were used in the PHITS calculations and the defaults for precision simulations were used in the FLUKA calculations. A cut-off energy of 5 MeV was used for both the calculations.

The shape of the targets in the calculations was a right circular cylinder. Because the copper targets in this experiment were rectangular parallelepipeds, the diameter of the target in the calculation was equal to its width. The diameter and length of the other targets were the same as the experimental targets.

The beam energy was set to 120 GeV, the beam shape was a round Gaussian distribution with a FWHM of 5 mm, and the beam was positioned at the center of the target.

The emitted neutrons were scored with ring-type detectors [15] centered on the target. The distance between the target and each ring was 5.0 m and the angular width of the rings was $\pm 1.0^\circ$. The angular width was equivalent to that at the 120° detector in the experimental setup. At the other experimental detector angles, differences in the angular width in the calculations

compared with the experimental setup were below a factor of 2.

The space between the target and detectors was filled with an ideal vacuum and the statistical uncertainty was below 5% for each energy bin.

5. Results and discussion

The measured neutron energy spectra at angles of 30, 45, 120, and 150° for graphite, aluminum, copper, and tungsten targets bombarded with 120 GeV protons are shown in Fig. 10. The neutron energy spectra at 120 and 150° for the graphite and the 60-cm-long copper targets were not measured. The lower energy limit of the neutron spectra was 25 MeV, whereas the upper edge of the highest energy bin was 3000 MeV, at which the TOF energy resolution did not exceed 100% at 30 and 45°. Figure 11 shows the neutron yields integrated between 25 and 3000 MeV for each emission angle.

The neutron energy spectra contained errors of 15–30% from the statistical uncertainty and systematic errors, except for the graphite and the aluminum targets. For the graphite and the aluminum targets, we did not obtain a sufficient yield difference between the measurements with and without shadow bars for the energy region below 200 MeV. In particular, the shape of the neutron energy spectra for the graphite target fluctuated in this energy region. Thus, the neutron energy spectra for graphite and aluminum targets had errors of 15–60%.

The measured neutron energy spectra were parameterized with the moving source model [8]. This model was originally developed to evaluate double-differential cross sections of light-ion production, namely the thin target yield. However, the model has been also used to estimate thick target neutron yields

Figure 10: Energy spectra of neutrons from graphite, aluminum, copper, and tungsten targets bombarded with 120 GeV protons. The experimental data are shown as symbols, the spectra calculated with PHITS code are shown as solid lines, the spectra calculated with FLUKA code are shown as broken lines, and the spectra from fitting the experimental data by Eq. 2 are shown as dash-dotted lines.

Figure 11: Angular distributions of neutron yields obtained by integrating the energy spectra between 25 and 3000 MeV. The symbols and lines are the same as those in Fig.

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[16, 17, 18, 19, 20]. We assumed that the neutrons were emitted isotropically from three moving sources. The neutron spectrum ($d^2Y/dEd\Omega$) emitted with energy E and in direction θ is expressed by [21, 22]

$$\frac{d^2Y}{dE d\Omega} = \sum_{i=1}^3 p A_i \exp \left[- \left\{ \frac{E + m - p \beta_i \cos \theta}{\sqrt{(1 - \beta_i^2)}} - m \right\} / T_i \right], \quad (2)$$

where i stands for the i th moving source, p is the momentum of an emitted neutron, and m is the neutron rest mass. The parameters A , β , and T are the amplitude, velocity, and temperature, respectively, and can be adjusted when fitting the experimental neutron energy spectra. The parameters are summarized in Table 2. The neutron energy spectra fitted by Eq. 2 with the obtained parameters are also shown in Fig. 10 and agree well with the experimental data.

Table 2: Fitting parameters of the moving sources in Eq. 2.

	Amplitude			Temperature			Velocity		
	A_1	A_2	A_3	T_1	T_2	T_3	β_1	β_2	β_3
	[neutrons/MeV/sr/(MeV/c)]			[MeV]					
C (60 cm)	4.60×10^{-5}	5.35×10^{-6}	3.16×10^{-7}	4.25×10^1	1.34×10^2	2.55×10^2	6.32×10^{-2}	5.63×10^{-1}	8.62×10^{-1}
Al (50 cm)	1.02×10^{-4}	1.08×10^{-5}	7.70×10^{-7}	4.02×10^1	1.05×10^2	2.38×10^2	4.85×10^{-2}	5.17×10^{-1}	7.13×10^{-1}
Cu (20 cm)	2.74×10^{-4}	2.13×10^{-5}	1.90×10^{-6}	4.34×10^1	1.11×10^2	2.30×10^2	3.77×10^{-2}	4.46×10^{-1}	7.60×10^{-1}
Cu (40 cm)	5.48×10^{-4}	4.80×10^{-5}	2.86×10^{-6}	4.86×10^1	1.10×10^1	2.51×10^2	4.75×10^{-2}	4.25×10^{-1}	8.30×10^{-1}
Cu (60 cm)	6.14×10^{-4}	5.41×10^{-5}	4.01×10^{-6}	4.39×10^1	1.26×10^2	2.57×10^2	6.51×10^{-2}	3.83×10^{-1}	8.74×10^{-1}
W (20 cm)	3.62×10^{-4}	1.61×10^{-5}	1.69×10^{-6}	4.28×10^1	1.18×10^2	2.47×10^2	3.40×10^{-2}	4.43×10^{-1}	8.53×10^{-1}

To validate the parameters, the neutron energy spectrum calculated for the 60-cm-thick copper target at 90° was compared with the experimental data reported by Sanami et al. [5] as shown in Fig. 12. The parameterized and reported neutron yields integrated between 25 and 3000 MeV are also shown in Fig. 11. Their data was obtained at the same proton energy,

although the readout electronics were different, and they did not perform a shadow bar run. The calculated neutron energy spectrum agreed well with their data above 100 MeV; however, it underestimated the values below 100 MeV. The agreement and underestimation were probably because the data reported by Sanami et al. [5] included contributions from background neutrons originating in the proton beam, and the background neutrons have longer flight times than those from directly entering the NE213 detector. The validity of the parameterized neutron energy spectrum was confirmed by the agreement of the spectra above 100 MeV.

Figure 12: Neutron energy spectra at 90° from the 60-cm-thick copper target bombarded with 120 GeV protons. The experimental data reported by Sanami et al. [5] is compared with the curve calculated from Eq. 2 with the experimental parameters shown in Table 2.

Figure 13 shows target mass dependency of the amplitude parameters

which were corrected to compensate for differences of the number of reactions between the target nuclei and 120 GeV protons for each target. The quantity A' obtained from correcting the amplitude parameter, A , was

$$A'_i = A_i \frac{1 - e^{-1}}{1 - e^{-n \sigma_t t}}, \quad (3)$$

where n is the number density of the target, σ_t is the hadronic total cross sections of the 120 GeV proton for target, and t is the target thickness. The value of σ_t was taken from PHITS code. However, there were still differences in the development of hadronic cascades in each target. The difference could be observed from the difference between values of A' for the copper targets. Nevertheless, for smaller mass numbers the value of A' increased with the mass number and it became saturated around a mass number of 60. The trend in A' was the same for each moving source; the ratio between the values of A' for each moving source did not change substantially with mass number. Measurements with thinner targets are required for revealing the target mass dependency.

The experimental neutron energy spectra were compared with the spectra calculated by PHITS and FLUKA code. Figures 10 and 11 show the calculated neutron energy spectra and yields integrated between 25 and 3000 MeV for each emission angle. The calculated spectra and yields both underestimated the experimental values for all energies and angles. The ratios for the calculated yields to the measured yield were 0.16–0.36 for PHITS code and 0.26–0.57 for FLUKA code. This ratio decreased as the emission angle increased.

To investigate why the calculated values were low compared with the experimental values, the neutron production processes were investigated step-

Figure 13: Mass dependency of the value of A'_i corrected to be equal to the number of reactions between the target nuclei and the 120 GeV protons for each value of A . A'_i is derived from Eq. 3.

by-step. The number of neutrons released from the target is determined by the following factors: (1) the reaction rate of incident protons with the target nuclei, (2) the number of neutrons produced by the interaction, and (3) the development of the hadronic cascade.

For factor (1), the reaction rate was evaluated from the hadronic total cross sections. The reaction rate, R , were derived from

$$R = 1 - e^{-n \sigma_t t}, \quad (4)$$

where n is number density of the target, σ_t is the hadronic total cross section of 120 GeV protons for target, and t is the target thickness. Table 3 summarizes the hadronic total cross section and reaction rate. The experimental hadronic total cross sections reported by Murthy et al. [23], Biel et al. [24], and Dersch et al. [25] were used, ignoring the difference between protons and neutrons. The calculated hadronic total cross sections were extracted from the PHITS source code. The deviation in the reaction rate of PHITS code compared with experimental data was less than 3%, which could not explain the underestimation of neutron yields.

The development of the hadronic cascade in the target was verified from the increase in neutron emission probability from the copper target to reaction between target nuclei and 120 GeV protons together with thicknesses of copper targets. The neutron emission probability from the target to reaction at each angle was derived from dividing the neutron yield by the reaction rate. The experimental and calculated neutron yields for copper targets shown in Fig. 11 were used. The reaction rate was derived from Eq. 4 with the hadronic total cross section from the PHITS code. Table 4 summarizes neutron emission probability from the target to reaction for copper targets

Table 3: Reaction rate calculated from hadronic total cross sections [23, 24, 25, 9] for each target.

Target	σ_t [b]				Reaction rate			
	Murthy ^a	Biel ^b	Dersch ^c	PHITS	Murthy	Biel	Dersch	PHITS
C(60 cm)	0.3295	0.319	0.3336	0.336	0.834	0.824	0.837	0.839
Al(50 cm)	0.6333	0.603		0.649	0.852	0.837		0.858
Cu(20 cm)	1.228	1.167		1.29	0.876	0.862		0.888
Cu(40 cm)	1.228	1.167		1.29	0.985	0.981		0.987
Cu(60 cm)	1.228	1.167		1.29	0.998	0.997		0.999
W(10 cm)	2.786			2.91	0.808			0.822

^a data for neutrons at 131 GeV/c.

^b data for neutrons at 80-130 GeV/c.

^c data for protons at 457 GeV/c.

of various thicknesses and the increase in the ratio for various thicknesses compared with that of the 20-cm-thick target. The increase in the ratio for the PHITS code agrees with the experimental data. Thus, the development of the hadronic cascade did not cause the underestimation of the neutron yield by PHITS code compared with the experimental results.

This confirms that for factor (2), the number of neutrons from the interaction is the main cause of the difference between experimental data and the calculations. Experiments with thinner targets should show this difference; however, there would be experimental problems with low neutron yield.

6. Conclusion

Neutron energy spectra from targets bombarded with 120 GeV protons were measured by using the TOF technique at MT6-2 of the FTBF. The

Table 4: Ratio of neutron emission probability from the target to reaction (NEPR), and the ratio of NEPRs of 20, 40, and 60 cm long copper targets compared with that of 20-cm-thick copper.

Angle [degree]	Thickness [cm]	NEPR [neutrons/sr]		$\frac{\text{NEPR}}{\text{NEPR}(20\text{cm})}$	
		Exp.	PHITS	Exp.	PHITS
30	20.0	9.57±0.49	2.52	1.00	1.00
	40.0	17.9±0.9	5.05	1.87±0.13	2.00
	60.0	20.4±0.8	6.74	2.14±0.15	2.67
45	20.0	5.96±0.31	1.85	1.00	1.00
	40.0	13.9±0.7	3.80	2.34±0.16	2.05
	60.0	15.8±0.8	5.11	2.64±0.19	2.76
120	20.0	2.67±0.15	0.468	1.00	1.00
	40.0	5.56±0.30	0.954	2.09±0.16	2.04
150	20.0	1.86±0.12	0.305	1.00	1.00
	40.0	3.60±0.22	0.618	1.93±0.17	2.03

targets were 60-cm-thick graphite, 50-cm-thick aluminum, 10-cm-thick tungsten, and 20-, 40-, and 60-cm-thick copper. The measured angles were 30, 45, 120, and 150°. Neutron energy spectra, which did not include background events from neutrons scattered from the floor and the beam dump, were obtained by subtracting the neutron spectra measured with shadow bars from that without shadow bars. The measured neutron energy spectra were parameterized with three moving sources. The parameterization gave neutron energy spectra at the measured angles and also at other angles. Furthermore, the measured neutron spectra were compared with spectra calculated with PHITS and FLUKA code. The calculated spectra underestimated the experimental neutron spectra. Ratios of the calculated neutron yields obtained by integrating the neutron spectrum between 25 and 3000 MeV to the experimental yields were 0.17–0.36 for PHITS code and 0.26–0.57 for FLUKA code. The model for neutron production from the interaction between 120 GeV protons and the target nuclei is the main cause of the difference.

To investigate the dependence on the target mass, the contribution of the hadronic cascade in the target should be removed from the measured neutron spectra. It will be necessary to develop a method to correct the contribution or for measuring double-differential cross sections. The double-differential cross sections should elucidate the cause of differences between the calculated and experimental yields. These cross sections could be measured by using our technique with a thinner target.

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