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NEUTRON YIELDS FOR REACTIONS INDUCED BY 120 GEV PROTONS ON THICK COPPER TARGET*[†]

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Abstract

We developed an experimental method to measure neutron energy spectrum for 120-GeV protons on a thick copper target at Fermilab Test Beam Facility (FTBF). The spectrum in the energy range from 16 to 1600 MeV was obtained for 60-cm long copper target by time-of-flight technique with an NE213 scintillator and 5.5-m flight path.

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Neutron yields for reaction induced by 120 GeV proton on thick copper target

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We developed an experimental method to measure neutron energy spectrum for 120 GeV proton on a thick copper target at Fermilab Test Beam Facility (FTBF). The spectrum in the energy range from 16 to 1600 MeV was obtained for 60 cm long copper target by time-of-flight technique with an NE213 scintillator and 5.5 m flight path.

1 Introduction

Energy spectra of neutrons generated from an interaction with beam and materials are important to design shielding structure of high energy accelerators. Until now, the energy spectra for the incident energy up to 3 GeV have been measured by several groups, Ishibashi et al.[1], Amian et al.[2], and Leray et al.[3]. In the energy region above 3 GeV, few experimental data are available because of small number of facilities for neutron experiment. On the other hand, concerning simulation codes, theoretical models for particle generation and transportation are switched from intermediate to high energy one around this energy. The spectra calculated by the codes have not been examined using experimental data.

In shielding experiments using 120 GeV hadron beam, experimental data shows systematic differences from calculations[4]. Hagiwara et al. have measured leakage neutron spectra behind iron and concrete shield from 120 GeV proton on target at anti-proton target station in Fermilab by using Bonner Spheres with unfolding technique[5]. In CERN, Nakao et al reported experimental results of neutron spectra behind iron and concrete wall from 120 GeV/c proton and pion mixed beam on copper by using NE213 liquid scintillators with unfolding technique[6]. Both of the results reported systematic discrepancies between experimental and calculation results. Therefore, experimental data are highly required to verify neutron production part of calculations.

In this study, we developed an experimental method to measure neutron energy spectrum for 120 GeV proton on target. The neutron energy was determined using time-of-flight technique. We used the Fermilab Test Beam Facility (FTBF)[7] in Fermilab that provided 120 GeV proton beam with intensity of 2×10^5/4 sec in every minute. The point of this study was determination of experimental configuration to satisfy enough statistic and energy resolution of neutrons.

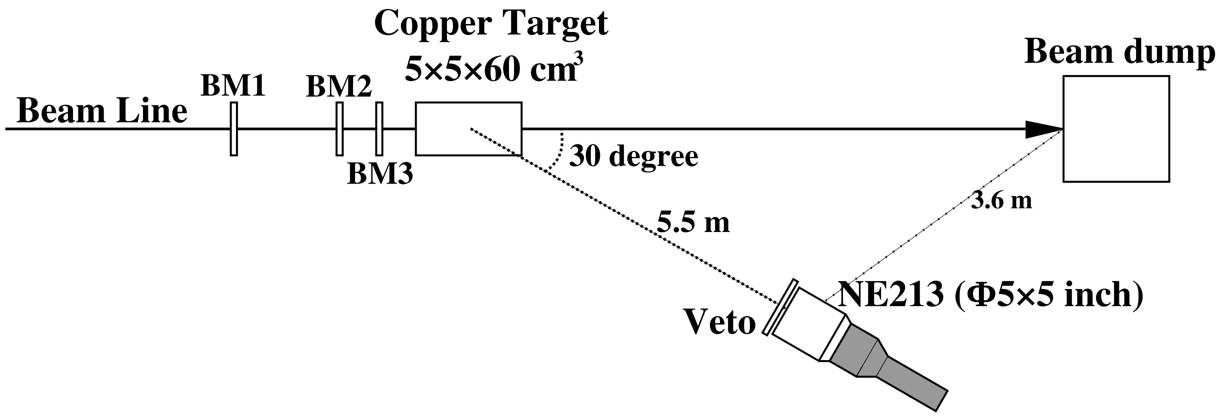

Fig. 1 Schematic view of experimental setup. 120 GeV proton beam comes from left side. Number of protons were counted by three plastic scintillator (BM1,2,3). Copper target, the dimension of which is 5 x 5 x 60 cm, was placed on the beam path. NE213 scintillator with Veto plastic scintillator was placed at 5.5 m from the target, 30° with respect to beam axis.

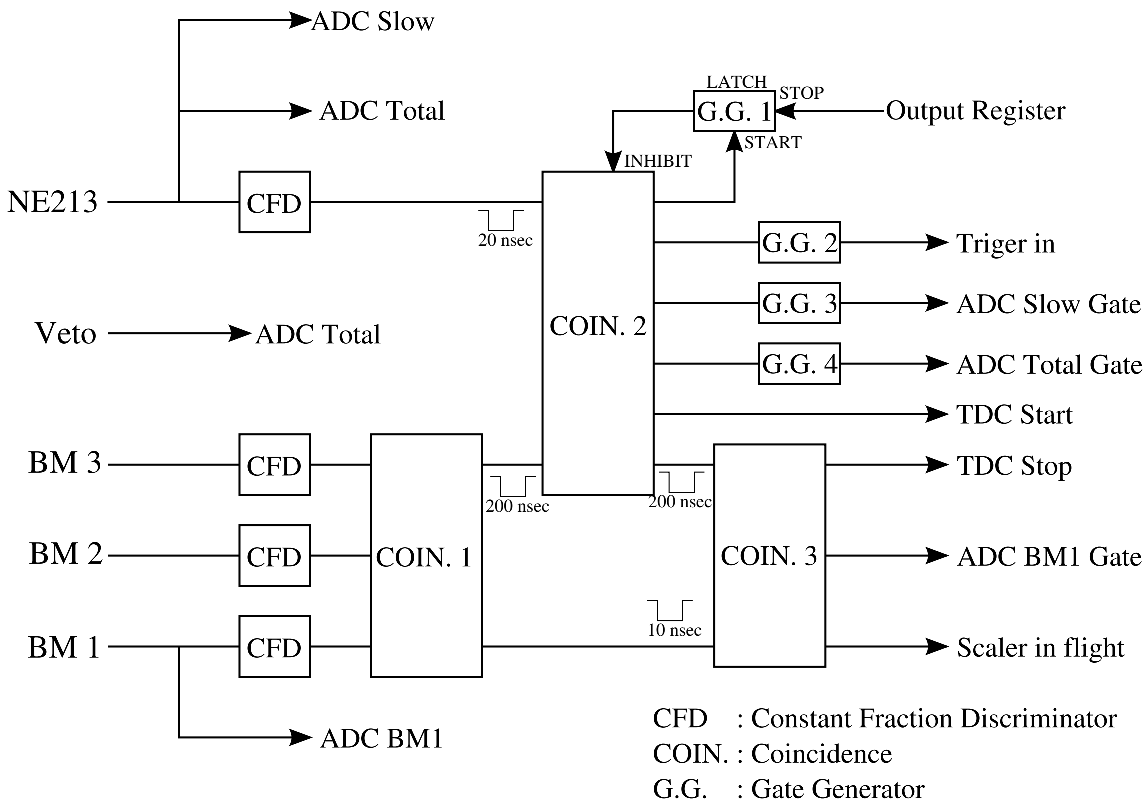

Fig. 2 Block diagram of data acquisition electronics. The electronics consisted of standard NIM and CAMAC modules. Trigger signal for data accumulation was generated from coincidence of the NE213 scintillator and the BMs. the time difference between coincidence of the BMs and the NE213 scintillator were stored as neutron flight time. Integrals of signals from the NE213 scintillator, the BM1, and veto detector were digitized using ADCs. Counts of the scaler in flight were recorded for correction of multi proton event during neutron time-of-flight.

2 Experiment

Figure 1 shows schematic view of experimental arrangement. The 120 GeV proton from the main injector are delivered to an area of 8×20 m^2. The number of incident protons were counted by three thin NE102A plastic scintillators (Beam monitors - BM 1, 2 and 3) which were located at upstream the target. The beam profile and position were monitored by a multi-wire proportional chamber. The sigma of beam radius was about ϕ 5 mm at the target position. The copper block, the dimension of which was 60 cm long and 5×5 cm^2 cross section, was employed as the neutron production target. The neutron detector was located at 5.5 m from the target and 30° with respect to the beam axis.

An NE213 liquid scintillator with 12.7 cm diameter, 12.7 cm long was employed as the neutron detector. The scintillator is suitable for neutron time-of-flight measurement due to pulse shape discrimination capability and fast decay time of its scintillation. To eliminate charged particles, a 2 mm thick NE102A plastic scintillator as the veto detector was placed in front of the NE213 scintillator.

Figure 2 shows a block diagram of data acquisition electronics. The electronics consisted of standard NIM and CAMAC modules. Trigger signal for data accumulation was generated from coincidence among the NE213 scintillator and the BMs. The data were recorded event by event. The time difference between the BMs and the NE213 scintillator was recorded with a TDC for determination of neutron time-of-flight. Charge-sensitive ADCs were employed in order to record total component charge of pulses from the NE213 scintillator, the BM1, and the veto detector. Slow component charge of pulse from the NE213 scintillator was also recorded for pulse shape discrimination. In addition, the number of protons during 200 ns before neutron signal was recorded (scaler in flight shown in Fig. 2) to ensure that time-of-flight was determined properly, as described in the next section.

Target-in measurement was carried out with beam intensity of 2×10^5 protons /min, during 3.5 hours. The counts of the BMs and the NE213 scintillator were 5×10^7 and 8×10^6, respectively. The dead time of data acquisition was about 62 %. Target-out measurement was also performed to check contribution of background neutron from the dump since the dump was closer than one from the target, as shown in Fig. 1.

3 Analysis

The energy spectra of neutrons, i.e. double differential thick target neutron yield (TTNY), $d^2Y(E)/dEd\Omega$, was deduced by the following equation,

$$\frac{d^2Y(E)}{dEd\Omega} = \frac{C(E)}{\phi \cdot \varepsilon(E) \cdot \Omega \cdot \Delta E} \tag{1}$$

where E is the neutron energy, $C(E)$ the neutron counts in an energy bin, ϕ the number of protons, $\varepsilon(E)$ the neutron detection efficiency, Ω the solid angle subtended by neutron detector, and ΔE the width of energy bin. Neutron events were identified by charged particle discrimination based on the veto detector signal, and gamma-ray discrimination based on the pulse shape of the NE213 scintillator. Neutron energy was determined by time-of-flight technique. We eliminated neutron event which could not uniquely determine its time-of-flight since two or more protons were counted by BM1 during neutron flight. The elimination was performed using data of scalar in flight and ADC BM1 shown in Fig.2. The scalar in flight was effective when the counts belong in different beam bunch. The ADC BM1 was effective when the counts belong in a same bunch. The count loss from the eliminations was corrected through the correction factor for the number of protons, as described in the next paragraph.

The number of protons was determined using the following equation,

$$\phi = \phi_{bm} \cdot \rho_{tof} \cdot \rho_{multi} \quad (2)$$

where ϕ_{bm} is the count of coincidence among the BMs, ρ_{tof} is the ratio of events that consist of single proton count during neutron flight to all events, and ρ_{multi} is the ratio of events that consist of single proton in a beam bunch to events of single proton count during neutron flight. The former and later could be determined using data of scalar in flight and ADC BM1 shown in Fig.2. The numerical values of ρ_{tof} and ρ_{multi} were 0.82 and 0.46, respectively.

The neutron detection efficiency, $\varepsilon(E)$, was determined experimentally based on the $^{238}\mathrm{U}(n,f)$ cross sections[8] at Los Alamos Neutron Science Center (LANSCE). The detail of the experiment will be discussed in elsewhere. **Figure 3** shows the detection efficiency determined from the experiment as well as calculations by SCINFUL-QMD code[9]. The difference between experimental and calculation data was less than 15 % except for energy region from 80 to 150 MeV. Therefore, the uncertainty of the detection efficiency was determined as 10 %.

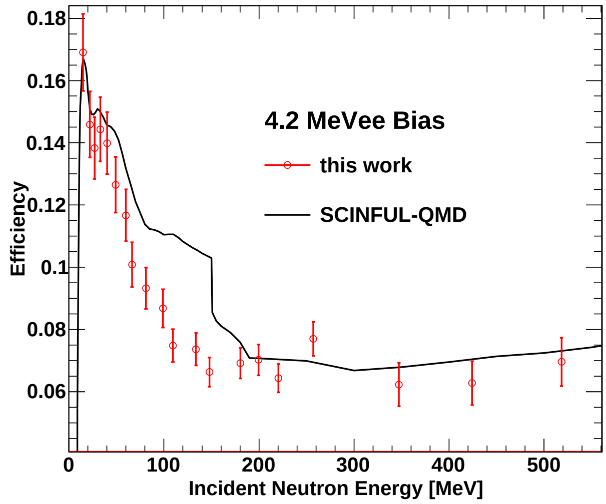

Fig. 3 Experimental and calculated neutron detection efficiencies of the NE213 scintillator at 4.2 MeVee bias.

4 Results and discussions

Figure 4 shows TTNY as well as one for target-out measurement. The experimental data cover the energy region between 16 and 1600 MeV. The threshold energy was attributed to the lower limit of detection efficiency. The upper energy was determined with considering the energy resolution for time-of-flight. Enough statistics were obtained since the uncertainty from statistics was 3 % for 1600 MeV at maximum. The uncertainty of experimental results was dominated by that of the detection efficiencies. Therefore, the detection efficiency of NE213 scintillator should be studied further for high energy neutrons to improve accuracy of TTNY.

As shown in Fig. 4, the target-out result shows markedly increase at 80 MeV. The fact indicates the target-in result includes contribution of background neutron from the beam dump. As well as the dump, certain amount of

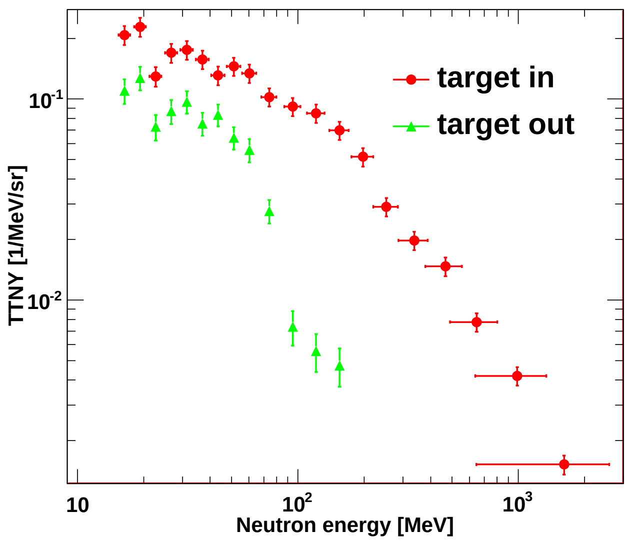

Fig. 4 Double differential neutron yield for 120 GeV proton incidence on 60 cm copper target. The results are compared with results of target out measurement, and include neutrons from floor and dump below 200 MeV.

background neutrons is expected from the floor scattering. These background neutrons have less impact in the energy region above 200 MeV because events from the dump and the floor have longer flight time than that from target. The background can be reduced by relocation of the dump.

The energy resolution of the TTNY was determined from the following equation

$$\frac{\sigma}{E} = \gamma(\gamma+1)\sqrt{\left(\frac{\sigma_L}{L}\right)^2 + \left(\frac{\sigma_t}{t}\right)^2} \qquad (3)$$

where E is neutron energy, γ is the Lorentz factor, L is the flight length, σ_L is the uncertainty of flight path, t is the flight time, and σ_t is the uncertainty of flight time. The geometrical component, σ_t , was derived from the thickness of the target (0.6 m) and the detector(0.13 m). The time component, σ_t, was estimated by the full width at half maximum (FWHM) of the prompt gamma peak on the time-of-flight spectra. The σ_t was determined to be 0.68 ns under the present condition. **Figure 5** shows the energy resolution. The total neutron energy resolution was better than 28 % below 1 GeV. The energy resolution can be improved by using thinner target since statistics were enough under the present experimental condition.

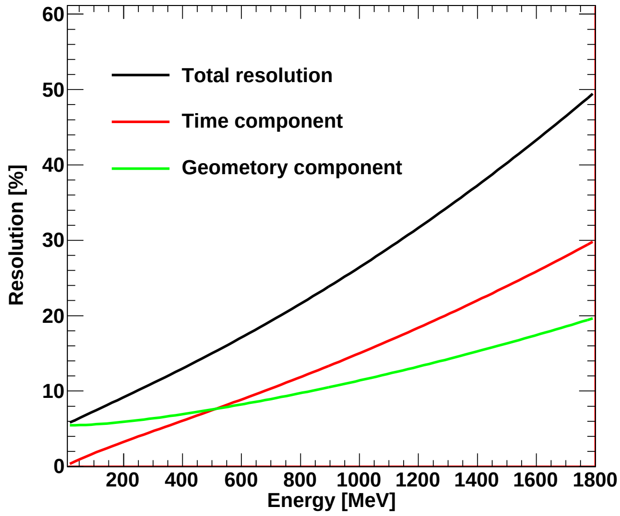

Fig. 5 Energy resolution for TOF measurement. The geometry component depends on thickness of the target and the NE213 scintillator. The time component is derived by full width at half maximum of flash gamma peak.

5 Summary

We developed the experimental method of TTNY measurement from 120 GeV proton on copper. The TTNY covers the energy range from 16 to 1600 MeV. The effects from multiple protons in a single neutron events could be eliminated successfully using the electronics circuit. It is important to reduce error of the neutron detection efficiency in high energy region for accurate TTNY. It should be noted that the present results provides prospect of a thin target experiment with improved energy resolution.

The measurement with a thin target can be anticipated to obtain systematic data taking for target mass and angle. For the measurement, contribution of background from the dump and the floor can be removed by the measurement with shadow bar. The data would be standard as the bench mark data of neutron production spectrum by high energy proton. It must contribute to the improvement and development of neutron production models in simulation code.

Acknowledgement

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References

[1] K. Ishibashi, H. Takada, T. Nakamoto, *et al.*, *"Measurement of Neutron-Production Double-Differential Cross Sections for Nuclear Spallation Reaction Induced by 0.8, 1.5 and 3.0 GeV Protons"*, J. Nucl. Sci. Technol., **34**, 529-537 (1997).

[2] W. B. Amian, R. C. Byrd, C. A. Goulding, *et al.*, *"Differential neutron production cross sections for 800-MeV protons"*, Nucl. Sci. Eng., **112**, 78 (1992).

[3] S.Leray, F.Borne, S.Crespin, *et al.*, *"Spallation neutron production by 0.8, 1.2, and 1.6 GeV protons on various targets"*, Phys. Rev., **C65**, 044621 (2002).

[4] H, Nakashima, N. V. Mokhov, Y. Kasugai, *et al.*, *"JASMIN: Japanese-American Study of Muon Interactions and Neutron detection"*, Proc. SATIF-10, Geneva, Switzerland, June 2-4, 2010, to be published.

[5] M. Hagiwara, T. Sanami, Y. Iwamoto, *et al.*, *"Shielding experiments at high energy accelerators of Fermilab (III): neutron spectrum measurements in intense pulsed neutron fields of the 120-GeV proton facility using a current bonner sphere technique"*, Proc. ISORD-5, Kitakyushu, Japan, July 15-17, 2009, to be published.

[6] N. Nakaoa, S. Taniguchi, S. H. Rokui, *et al.*, *"Measurement of neutron energy spectra behind shielding of a 120 GeV/c hadron beam facility"* Nucl. Instr. and Meth. **A562**, 950 (2006).

[7] http://www-ppd.fnal.gov/MTBF-w/

[8] P. W. Lisowski, A. Gavron, W. E. Parker, *et al.*, *"Fission cross sections in the intermediate energy region,"* Proc. Specialists' Meeting on Neutron Cross Section Standards for the Energy Region above 20 MeV, Uppsala, Sweden May 21–23, 177 (1991).

[9] D. Satoh, T. Sato, N. Shigyo, *et al.*, *"SCINFUL-QMD: Monte Carlo based computer code to calculate response function and detection efficiency of a liquid organic scintillator for neutron energies up to 3 GeV"*, JAEA-Data/Code, 2006-023(2006).