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*Differential Neutron Production
Cross Sections and Neutron Yields
from Stopping-Length Targets
for 113-MeV Protons*

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MASTER

DIFFERENTIAL NEUTRON PRODUCTION
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FROM STOPPING-LENGTH TARGETS
FOR 113-MeV PROTONS

by

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ABSTRACT

We have measured differential (p, xn) cross sections, $d^2\sigma/d\Omega dE_n$, from thin targets and absolute neutron yields from stopping-length targets at angles of 7.5° , 30° , 60° , and 150° for the 113-MeV proton bombardment of elemental beryllium, carbon, aluminum, iron, and depleted uranium. Additional cross-section measurements are reported for oxygen, tungsten, and lead. We used time-of-flight techniques to identify and discriminate against backgrounds and to determine the neutron energy spectrum. Comparison of the experimental data with intranuclear-cascade evaporation-model calculations with the code HETC showed discrepancies as high as a factor of 7 in the differential cross sections. These discrepancies in the differential cross sections make it possible to identify some of the good agreement seen in the stopping-length yield comparisons as fortuitous cancellation of incorrect production estimates in different energy regimes.

I. INTRODUCTION

Achievement of a calculational capability to successfully predict the neutron production for targets bombarded by medium energy (100 MeV – 1 GeV) protons depends on the existence of a reliable data base for testing the production and transport models upon which the calculations rest. This report documents differential cross-section measurements for thin targets, $d^2\sigma/d\Omega dE_n$, and absolute neutron-yield measurements made on stopping-length targets for 113-MeV protons and compares the measurements with the Bertini intranuclear-cascade evaporation (INCE) model¹ as embodied in the code HETC.² Other measurements under way or planned include thin-target (p,xn) cross sections $d^2\sigma/d\Omega dE_n$ at 256, 597, and 800 MeV and absolute neutron yields from stopping-length targets at 256 MeV. We have already reported a study of absolute neutron yields from a restricted set of stopping-length and near-stopping-length targets at 256 MeV.³

Previous work⁴ on (p,xn) cross sections and absolute yields in this energy range has shown that, at forward angles, HETC correctly estimates the production cross sections for a bombarding energy of 800 MeV for target masses between carbon and uranium, except in the region of delta-hole production ($250 \text{ MeV} < E_n < 600 \text{ MeV}$). At 590 MeV the agreement is still good in the evaporation region ($< 20 \text{ MeV}$), but it deteriorates at higher energies.⁵ In Ref. 4, it was found that this trend is continued at 318 MeV, and the calculations underestimate the measurements by a factor of 2.5–3.0 at the high neutron energies. At 50 MeV, the situation is evidently reversed.⁶ Thick-target yields are overpredicted by HETC, typically by a factor of 2–3. However, particular cases can be much worse: HETC overpredicts the high-energy neutron yield of carbon by as much as a factor of 10. In Ref. 3, it was found that at 256 MeV HETC and ISABEL, a code which includes nucleus-nucleus as well as nucleon-nucleon interactions, both gave very satisfactory fits to the experimental data for stopping-length and near-stopping-length absolute neutron yields. We attributed the agreement to cancellation of the over- and underestimation of production cross sections observed at 50 and 318 MeV respectively, plus possible dominance of transport mechanisms over production for the massive targets. Nakamura *et al.*⁷ have made other measurements at 30 and 52 MeV, and they have been compared with evaporation calculations by Shin *et al.*⁸ Nakamura and Shin conclude that the HETC code does not adequately describe the experiments and overestimates the experimental yields at small angles in agreement with Ref. 6.

From the above comparisons of experiment and theory, it is clear that the physics governing the production is not quantitatively embodied in the INCE model for the energy

range below 300 MeV. We felt that the most crucial measurements, therefore, were the differential production cross sections at 113 MeV and the neutron yields for stopping-length targets at 113 MeV. Data from stopping-length targets sample production over the entire energy range, 0–113 MeV, convolved with transport and secondary production effects, whereas the cross-section measurement samples production at the bombarding energy.

II. EXPERIMENT

A. Target 2 Facility at the Weapons Neutron Research Facility (WNR)

1. Accelerator and Pulse Structure. The measurements were performed at the Target 2 area of WNR, where proton beams from the Clinton P. Anderson Meson Physics Facility (LAMPF) are delivered at energies up to 800 MeV. The proton beam is accelerated only up through the RF module needed for the required energy during low-energy operation, drifting through subsequent unused cavities along the LINAC. The additional drift length in the LINAC is approximately 1 m per MeV below 800 MeV. During the acceleration process, the beam is tightly bunched in time because of the longitudinal focusing properties of the LINAC. The initially well-bunched beam spreads in time while drifting to the target because of the finite energy spread in the beam. For the experiment at 113 MeV, the total drift length was approximately 905 m to the (p,xn) target. This drift length translates into a 26-ns time spread per MeV energy spread at the target. Such a time spread would dominate the energy resolution of the time-of-flight measurements.

To compensate for the time spread, a new technique⁹ developed for the Neutron Time-of-Flight (NTOF) facility at LAMPF was implemented. Subsequent cavities in the LINAC that would normally be off during low-energy acceleration are turned on at appropriate phase and amplitude set points to act as rebunchers on the beam before it exits the LINAC, producing a nearly isochronous beam of particles. For a typical 1.5-MeV energy spread, the beam's unbunched width on target would be 39 ns.

We calculated a four-cavity solution using a ray-tracing program, SIMILAC, which reduced the time spread to 600 ps. The observed width was 800 ps. However, side lobes at 5 ns caused by inefficient chopper operation limited the effective width to a worst-case value of 5 ns. This value corresponds to a worst-case energy resolution of less than 5% at 100-MeV neutron energy for the shortest flight path (30 m). Under these operating conditions the LINAC was run in sole-user mode for this experiment. An integrated system for the rebunching mode now exists for the NTOF facility, allowing simultaneous operation with normal LINAC operation. The beam was tailored with the low-energy chopper to

produce 12- μ s-separated micropulses. The tailoring permitted detection of 250-keV neutrons at the longest flight path without frame overlap.

The Target 2 low-scatter experimental area and associated flight paths are extensively documented in Ref. 3. Five flight paths with detector stations are currently operational: 7.5° at 50 m, 30° at 30 m, 60° at 60 m, 120° at 60 m, and 150° at 30 m. At the time of these measurements, a 120° flight path was unavailable for use.

2. Collimation. Figure 1 shows the generic collimation scheme embodying the design goals for the flight paths. The collimation provides a minimum 9-cm-diameter field of view at the Target 2 center and a neutron beam uniform over 25 cm at the detector station. The actual collimation used was, in some cases, compromised from these design goals due to facility constraints. This thin-target collimation design was also appropriate for stopping-length targets at 113-MeV energy.

Table I summarizes the collimation properties for each flight path. The collimator distance is the distance of the first neutron collimator from the target, and the aperture is its inside diameter. The target field of view, which is normally limited by the inside diameter of the first neutron collimator, is the diameter completely visible from a 5-cm circular detector at the middle of the detector station. Beam and penumbra diameters are calculated for uniform and partial illumination of the plane of the detector for a 5-cm-diameter extended source at the target location. The background/signal ratios associated with inscattering of direct and penumbral beams depend on the ratios of the solid angles of these beams to the

TABLE I
FLIGHT-PATH COLLIMATION AND FILTERS

	Flight-Path Angle			
	7.5°	30.0°	60.0°	150.0°
Flight-Path Length (m)	50.0	28.7	58.5	30.2
Target/Collimator Distance (m)	4.80	4.80	4.80	4.80
Collimator Aperture (cm)	10.16	8.52	10.16	9.64
Target Field of View (cm)	10.71	9.23	10.62	10.96
Beam Diameter (cm)	25.0	25.0	25.0	25.0
Penumbra Diameter (cm)	31.1	31.6	42.3	49.3
Beam/Detector Solid-Angle Ratio	19.0	38.0	19.0	38.0
Penumbra/Detector Solid-Angle Ratio	29.4	60.6	54.5	148.1
Tuff Thickness (cm)	3927.0	2164.0	1237.0	1572.0
Iron Collimator Thickness (cm)	209.6	209.6	248.9	188.0
$(x_{\text{tuff}}/\lambda_{\text{tuff}}) + (x_{\text{iron}}/\lambda_{\text{iron}})$	86.8	52.6	36.8	40.1

solid angles of the particular detector used in that flight path. Table I lists shielding thicknesses of the total tuff and iron collimation in the vicinity of the flight paths along with the number of dose-attenuation mean free paths for the two materials. The latter are useful in comparing the shielding of the detectors against neutrons that are produced in the beamline components for the different flight paths. x_i and λ_i are the path length and dose-attenuation length for the intervening materials, and the λ_i were taken to be 19.3 cm for iron and 51.8 cm for compacted tuff.¹⁰

B. Targets

The target materials selected for the stopping-length study were beryllium, carbon, aluminum, and iron, all in their natural isotopic abundances, and ²³⁸U. The physical characteristics of the targets used are summarized in Table II. For the differential cross-section measurements, the same materials were selected plus BeO (to obtain the oxygen cross section), tungsten, and lead. The latter targets were generally less than 3.5 MeV thick to 113-MeV protons, except for Be, which was less than 7 MeV thick.

C. Detectors

The neutron detectors used in these measurements were cylindrical BC-418 plastic scintillators, 5.08 cm in diameter. They were 5.08 cm long at the 7.5° and 60° detector stations and 2.54 cm long at the 30° and 150° stations. The efficiencies for both detectors were determined at several biases using light-ion reactions as neutron sources of known intensity for neutron energies below 35 MeV.³ More recently, the efficiency has been additionally calibrated for the 5.08-cm-diameter x 5.08-cm-long detector at 30, 55, 90, 140, and 200 MeV in a nearly monoenergetic flux of neutrons from the ⁷Li(p,n)⁷Be reaction.¹¹ Because data above 35 MeV were not available for the smaller detector, spline fits to the

TABLE II
STOPPING-LENGTH TARGETS

<u>Element</u>	<u>Radius (cm)</u>	<u>Length (cm)</u>	<u>Mass (g)</u>
Beryllium	3.65	5.70	434.2
Carbon	3.65	5.83	394.8
Aluminum	3.65	4.03	455.2
Iron	3.65	1.57	517.1
²³⁸ U	4.00	3.00	2819.9

experimental data below 35 MeV and to the code of Ref. 11 were used as the efficiencies of the two detectors. The efficiency data for the 5.08 cm x 5.08 cm detector are plotted along with the spline fits in Fig. 2. Because the spline fits are in good agreement with the new experimental data, using these calculated data is justified. Although a slightly more accurate efficiency might be obtained by fitting the new experimental data above 30 MeV instead of the calculations, use of the old spline fits has the advantage of a consistent efficiency for the measurements reported here and those of Ref. 3.

D. Proton Charge Monitor and Time Pickoff

1. Secondary Electron Monitor (SEM). An SEM monitored the proton beam and absolutely determined the total charge for each data set. We calibrated the SEM by measuring its rate relative to the production of ^{24}Na , ^7Be , and ^{22}Na in an aluminum foil located at the target position. The relative error of the calibrations is $\sim 1\%$, consistent with the system stability reported in Ref. 4 and with the statistics of counting the foils. The absolute uncertainty of the calibration is the 5% uncertainty associated with the aluminum activation cross section.

2. Proton Beam Charge Distribution Monitor. An inductive charge pickoff generated a bipolar signal from the passage of each proton micropulse ($\sim 2 \times 10^8$ protons). The signal was digitized and histogrammed as a measure of the proton beam intensity distribution, which was a necessary ingredient in the dead-time correction. In addition, the signal generated a time fiducial for the neutron time-of-flight measurement and for a beam-pulse transit-time measurement that monitored beam energy stability as discussed below.

E. Data Acquisition

The data acquisition system employed here is identical to that employed in Ref. 3, and the speed and capacity requirements are documented there. We very briefly describe the system here. Figure 3 is a simplified block diagram of the front-end electronics for each detector. The signal from the photomultiplier anode is fanned out to three sections of a quad-constant fraction discriminator with thresholds set at ^{241}Am , ^{137}Cs , and $2 \times ^{22}\text{Na}$ biases. Outputs from the three channels are processed by fast logic to present a single channel to the tagging and stop electronics of the time digitizer (TDC). Events that produced more than half the light of a minimum ionizing particle in the veto detector and that were in time coincidence with an event above ^{241}Am bias in the neutron detector triggered a veto gate to

the TDC for the entire time frame in which it was detected. The veto gate rejected events that were generated by afterpulsing of large light-level pulses.

The timing signal generated by the inductive charge pickoff started the clock and defined the time-frame gate during which the TDC was enabled to accept stops. We adjusted the gate width and delay for each detector to generate a frame beginning several hundred nanoseconds before the γ -flash and ending at the time of arrival of ~ 500 -keV neutrons. A CAMAC scaler was part of the electronics for each detector and was enabled by the same time-frame gate as the TDC so that scaled quantities for a given detector corresponded to the time-of-flight spectra. Quantities scaled for each detector were events for each of the three biases, veto/ ^{241}Am coincidences (vetoed frames), TDC busy signals, and TDC data-ready signals. An ungated scaler counted total clock starts derived from the proton-pulse pickoff, SEM output, and clock time.

With the primary neutron data acquisition tasks running autonomously in the CAMAC histogram memories and scalers, the computer was devoted to acquisition of data from the proton-pulse pickoff and of reference γ -ray spectra during periods between beam bursts. During each macropulse, ~ 70 proton bursts were digitized in a CAMAC charge digitizer and transmitted to the computer via direct memory access where they were histogrammed. Similarly, between macropulses, CAMAC charge digitizers processed anode signals from each of the neutron detectors. We placed low-intensity ^{88}Y sources in the vicinity of the detectors to produce count rates of $\sim 100/\text{s}$. The pulse-height spectra so obtained provided a real-time check on the gain stability of the detectors and on the discriminator bias used for stopping the digitizer.

To monitor the beam energy stability, the signals from two inductive pickups located in the proton beam line started and stopped a time-to-amplitude converter. The resulting time spectrum was monitored by a multichannel analyzer for shifts in the time peak that would indicate proton energy changes. No significant drifts were observed.

III. MEASUREMENTS

A. Time-of-Flight Spectra

For each angle, three different time-of-flight spectra, each corresponding to one of the three biases, were obtained. The spectra taken with the $2 \times ^{22}\text{Na}$ bias have substantially better sensitivity than those taken with ^{241}Am or ^{137}Cs bias because of higher γ -ray rejection in the vicinity of the highest-energy neutrons. Because of the enhanced signal-to-background ratio, the $2 \times ^{22}\text{Na}$ -bias data were used to generate the high-energy part of the cross sections

($E_n > 35$ MeV), and the ^{241}Am bias was used below that energy. No bias shifts were observed, and the cross sections derived from the different biases agreed to better than a few percent except near threshold. The signal-to-background ratios at the highest energies are slightly better than those reported in Ref. 3 for 256-MeV protons.

B. Shadowbar Background

We measured the background, which we expected to be dominated by in-scattering, by interposing a massive iron bar that just shadowed the detector from the source neutrons. We made these measurements with a thin lead target bombarded with 800-MeV protons. Figures 4–7 show the measured correction factors for 7.5° , 30° , 60° , and 150° , which we applied to all the cross-section data. The corrections are $<5\%$ for the bias/energy regions used. Because of the smaller field of view required for stopping-length targets at 113 MeV and consequent improvement in the collimation, it was possible to significantly reduce this background from that encountered at 256 MeV. (Compare Table I of this work to Table I of Ref. 3 and Figs. 4–7 of this work to Figs. 9 and 10 of Ref. 3.)

IV. ANALYSIS

A. General Procedures

The analysis procedures are fully documented in Ref. 3 and will be only briefly described here. Each of the differential bias spectra was dead time corrected according to the Moore¹² formalism, shifted to a common time scale that was determined by the position of the γ -flash, and summed to give the integral ^{241}Am spectrum, integral ^{137}Cs spectrum, and integral $2 \times ^{22}\text{Na}$ spectrum. These spectra were then normalized to effective total charge as determined from the SEM and the fraction of frames for which no veto was generated. The time-independent background correction was estimated by averaging over ~ 100 channels preceding the γ -flash. Subtraction of a background spectrum (obtained with no target) for each bias from the foreground resulted in the corrected spectra, which were in turn rebinned to energy bins (35 energy bins per decade) and normalized to counts per MeV.

We corrected the spectra for air attenuation, using the ENDF-B/V evaluation values for the nitrogen and oxygen cross sections, where available, and values from the literature for the region above 20 MeV.¹³ We monitored the absolute barometric pressure and temperature throughout the course of the measurements, and their average values during each measurement were used in the air correction. We additionally corrected the data for the

TABLE III
FLIGHT PATH LENGTHS

Angle	l (m)	$\sigma_{\perp}(\text{Stat})$ (m)	χ^2/Deg	$\sigma_{\perp}(\text{Total})$ (m)
7.50	49.99	0.03	0.90	0.03
30.00	28.71	0.03	2.75	0.05
60.00	58.46	0.04	2.17	0.06
150.00	30.22	0.04	6.67	0.10

background measured with a shadowbar in place and divided all four data sets by the efficiency for the appropriate detector and bias and by the detector solid angle. Thus, the reduced data for the stopping-length targets were the absolute neutron yield per incident proton per MeV per steradian for each of the three biases. The thin-target data were additionally divided by the target areal density and thus had units of barns per MeV per steradian. A single, composite data set was then generated, normally from the ^{241}Am data below 35 MeV and from the $2 \times ^{22}\text{Na}$ data above that energy.

B. Carbon Runs

In an auxiliary measurement with 800-MeV protons, we placed graphite samples in each of the flight paths and obtained transmission data for natural carbon. These measurements determined source-detector distances for all flight paths by using a least-squares fitting technique on low-energy resonances that have velocities that are well known from the ENDF-B/V-evaluated total cross-section data. Table III lists the final values. $\sigma_{\perp}(\text{Stat})$ is the error in the flight path due to the counting statistics in the transmission and χ^2/Deg is the chi-squared statistic divided by the number of degrees of freedom in the fit. Where χ^2/Deg is appreciably larger than unity, the product of its square root and $\sigma_{\perp}(\text{Stat})$ is taken to be the overall flight-path uncertainty, $\sigma_{\perp}(\text{Total})$. The rather high values for χ^2/Deg are attributed to the use of Gaussians to fit the transmission shapes.

V. RESULTS AND COMPARISON WITH INCE CALCULATIONS

Table IV summarizes the corrections and factors that are necessary to reduce the raw data to cross sections or yields. All three background uncertainties are dominated by the statistics of the measurements and are negligibly small. The air attenuation uncertainty is

dominated by cross-section uncertainties. As noted above, the nitrogen and oxygen cross sections were taken from ENDF-B/V below 20 MeV, where the correction was highest, and from an evaluation for the higher energies, where it was relatively small. Below 35 MeV, the uncertainty in the efficiency is dominated by uncertainties in the evaluated cross sections³; at higher energies the estimated uncertainty is that for the efficiency determination of Ref. 11 and ranges from 7% to 12%. The dead time was less than 20% for these measurements, and its uncertainty was determined by using extreme limits on the beam variance in the Moore formalism. The absolute charge determination was limited by the uncertainty in the activation cross section. Measurements of target areal densities were made with commercial scales, and their uncertainties are negligible relative to the other uncertainties discussed here. The expressions for yield and cross section include the product of detector efficiency and detector solid angle. The detector area enters these two factors in such a way as to cancel, thereby making the solid angle uncertainty negligible for the flight-path-length determinations of Table III.

Figures 8-15 compare the experimental differential cross-section results with HETC calculations. For all nuclei, except C and O at low neutron energies, HETC reproduces the 30° and 60° data to better than a factor of 2, and the agreement for these two angles is remarkably good for nuclei more massive than Fe. The 7.5° data are reminiscent of the 318-MeV cross sections. Above about 20 MeV, the calculation underestimates the measured cross section by as much as a factor of 7, possibly indicating that pre-equilibrium processes are the dominant neutron production mechanism in this energy and angle regime. The 150° differential cross section always exceeds the HETC calculations, in qualitative agreement with all other measurements made in the energy range 50-590 MeV.

Figures 16-20 compare the experimental results with HETC calculations for the stopping-length targets. For these targets, neutron production is sampled over the bombarding energy range of 0-113 MeV, and the HETC overestimation of the yields

TABLE IV
UNCERTAINTIES

<u>Factor/Correction</u>	<u>Magnitude</u>	<u>Uncertainty</u>
Time-Independent Background	< 1%	5%
Time-Dependent Background	< 5%	20%
Shadowbar Background	< 5%	< 3%
Air Attenuation	< 2.2%	< 2.5%
Efficiency	3 - 20%	5 - 20%
Dead Time	< 20%	< 5%
Charge Normalization	1.0%	5%

observed at 50 MeV is apparent in these data as well, most notably in the lighter targets ($A < 60$). The failure of HETC to reproduce the back angle data is again apparent, although less pronounced than in the differential cross sections, presumably because of the averaging effects of transport in the targets. In the forward hemisphere, the results are mixed. For uranium, the agreement with data is typically better than 25%. For the lighter elements the yields are overestimated by HETC, indicating that the lower energy production is also overestimated, in agreement with the 50-MeV work.

In summary, the previously noted underestimation of the forward angle, high-energy differential cross section at 318 MeV persists at 113 MeV as does the underestimation of the back angle cross section. The yields for this set of stopping-length targets are in reasonable agreement with experiment, notably for uranium, at forward angles. However, because the forward angle differential cross section is underestimated, it is likely that this agreement is a fortuitous cancellation of incorrect production estimates or dominance of transport as also noted at 256 MeV in Ref. 3. For stopping-length targets of lower mass, the overestimation of the yield reported at 50 MeV in Ref. 6 is apparent in these data as well.

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Figure 1. Generic flight path showing the location and aperture of collimation, beam and penumbra diameters, and target field of view. The vertical scale has been compressed by a factor of 100.

Figure 2. Detector efficiencies for the 2 in. x 2 in. detector. The plotted points are the calibrations performed at the Van de Graaff and at the Indiana University Cyclotron Facility. The solid curves are spline fits to the Van de Graaff data below 35 MeV and to Stanton code calculations above 35 MeV. For the data analysis, the Am efficiency was used for energies below 35 MeV and the 2 x Na efficiency was used for higher energies. For consistency with Ref. 3, the efficiency values used in this work were taken from the spline fits.

Figure 2. (cont)

Figure 2. (cont)

Figure 3. Simplified block diagram of the front-end electronics for each detector.

Figure 4. Shadowbar background correction factor for 7.5°. The raw data are shown for the indicated detector biases, and the actual corrections applied to the cross-section and yield data were spline fits to this data.

Figure 5. Shadowbar background correction factor for 30°. See the caption for Fig. 3.

Figure 6. Shadowbar background correction factor for 60°. See the caption for Fig. 3.

Figure 7. Shadowbar background correction factor for 150°. See the caption for Fig. 3.

Figure 8. Experimental differential cross sections for Be compared with HETC calculations. The solid curves are the statistical $\pm 1\sigma$ uncertainties due to the finite number of histories sampled in the HETC calculations, and the symbols are the experimental data. Error bars on the experimental data points are uncertainties due to the counting statistics of the foreground, time-independent and time-dependent backgrounds, and shadowbar correction.

Figure 9. Experimental differential cross sections for C compared with HETC calculations.

Figure 10. Experimental differential cross sections for O compared with HETC calculations.

Figure 11. Experimental differential cross sections for Al compared with HETC calculations.

Figure 12. Experimental differential cross sections for Fe compared with HETC calculations.

Figure 13. Experimental differential cross sections for W compared with HETC calculations.

Figure 14. Experimental differential cross sections for Pb compared with HETC calculations.

Figure 15. Experimental differential cross sections for U compared with HETC calculations.

Figure 16. Experimental absolute neutron yields for the stopping-length Be target compared with HETC calculations.

Figure 17. Experimental absolute neutron yields for the stopping-length C target compared with HETC calculations.

Figure 18. Experimental absolute neutron yields for the stopping-length Al target compared with HETC calculations.

Figure 19. Experimental absolute neutron yields for the stopping-length Fe target compared with HETC calculations.

Figure 20. Experimental absolute neutron yields for the stopping-length U target compared with HETC calculations.