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Neutron Production by Medium-Energy Protons on Heavy Metal Targets

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of the University of California
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Neutron Production by Medium-Energy Protons on Heavy Metal Targets

by

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NEUTRON PRODUCTION BY MEDIUM-ENERGY

PROTONS ON HEAVY METAL TARGETS

by

R. R. Fullwood, J. D. Cramer, R. A. Haarman,

R. P. Forrest, Jr., and R. G. Schrandt

ABSTRACT

Neutron production resulting from medium-energy proton bombardment of heavy metal targets was calculated by Monte Carlo methods for cylinders and a sphere as a function of time, angle, and position. With one exception (550 MeV), all calculations were for 800-MeV proton energy and for targets of ^{238}U , lead, tantalum and a ^{238}U - ^{235}U composite. Gamma-ray production was calculated by a simplified model and the results were compared with those of Alsmiller and Moran for gamma-ray production for a 150-MeV electron bombardment of tantalum.

The ratio of escaping neutrons per incident proton (n/p) varied from 38.5 to 16.7 depending upon the target. The results reported here give n/p ratios for uranium about 25% lower than that reported by the workers on the Canadian Intense Neutron Generator (ING) project. Ninety percent of the evaporation neutrons that serve as the source for the low-energy neutron transport are produced within a 0.75-cm radius of the beam and have an axial distribution so that 63% are contained within a 12.3-cm length. This fact is manifest through the comparative insensitivity of neutron production to target geometry. The most probable energy for the escaping neutrons from the large targets is about 0.2 MeV resulting from the degradation of the evaporation spectrum by neutron inelastic and multiple production processes. For the large ^{238}U targets, there was one escaping photon for every 12 escaping neutrons. This low ratio is a consequence of the strong photon absorption in the target and the mechanism of neutron production.

Because the efficacy of this neutron production method depends on the strength of available proton sources, a comparison is made of a proposed facility time-sharing the beam of the Los Alamos Meson Physics Facility (LAMPF), the improved Columbia University Nevis Cyclotron's expected performance, and the Oak Ridge National Laboratory Electron Linear Accelerator (ORELA).

I. INTRODUCTION

Neutron production by medium-energy proton bombardment of heavy metal targets received considerable attention in the Canadian Intense Neutron Generator (ING) study. The Los Alamos Meson Physics Facility (LAMPF) has a different motivation, but will have proton currents, during the pulse, 25% of those of the ING study and at nearly the same energy (800 MeV). Because of different requirements, the study for

LAMPF has been toward a low-duty intense neutron burst facility, therefore the emphasis has been on uranium targets for their high density and high-neutron-to-incident-proton ratio rather than on the lower heat generating bismuth targets of the ING study.

This report is organized as follows. Section II is a discussion of neutron production by medium-energy proton bombardment of thick targets.

Section III gives a description of the two-step nucleon cascade-evaporation model for generating high-energy (>25 MeV) cross sections. The assumptions, limitations, and experimental tests of the model are also discussed. Section IV is a discussion of the Monte Carlo program Nucleon Meson Transport Calculation (NMTC) that computes the transport of particles between nuclear interactions and applies the continuous slowing-down approximation to the transport of charged particles down to a cutoff energy. A utility program follows, High Energy Analysis (HIANAL), that groups the cascade and evaporation neutrons according to energy, angle, and position to serve as input data to a general purpose, Monte Carlo Neutron (MCN) transport code, or to GAMGEN for gamma-ray generation and subsequent transport in the Monte Carlo Gamma transport code (MCG). All of these codes use evaluated cross sections. Following this, the output of MCN is grouped in the utility program, Low Energy Analysis (LOANAL), that correlates the escaping neutrons according to energy and angle. Similarly, the gamma output is correlated in GAMANAL. Section V gives comparisons with neutron spectrum experiments and other Monte Carlo calculations to establish the validity of these calculations. Following this, data are presented on the neutron spectra as a function of angle, energy, and target radius for ^{238}U targets. Spectrum tailoring is investigated by comparison with lead targets as well as a ^{235}U sleeve. Data are presented for target heating as well as the time, energy, and spatial dependence of emission. Finally, gamma-ray production data are given. Section VI compares the (p,xn) source based on the LAMPF accelerator and the Nevis cyclotron with the (e, γ ,xn) source as exemplified by the Oak Ridge Electron Linear Accelerator (ORELA). Appendix B gives the NMTC output with suggestions for extrapolation of the data in energy and atomic number. These data may be used as a source input to a transport calculation.

II. MOTIVATION

The production of neutrons by medium-energy proton bombardment of lead targets has been exploited for neutron time-of-flight experiments at the Columbia University Nevis Synchrocyclotron for many years. The lack of general acceptance of this technique is attributed¹ to using these accelerators for

other purposes and the consequent desire to remove the pulsed structure. Also another source, the electron linac, is available at a lower cost.

However, during the last decade, there has been a study of intense neutron sources at various laboratories. It is expected that ultimately the neutron sources using reactions that generate the least amount of target heating per neutron will dominate. Table I (Ref. 2) summarizes various reactions for this purpose and indicates that only (d,t) fusion is more efficient than (p,xn). Figure 1 (Ref. 3) indicates by experimental data that the (p,xn) production is strongly energy dependent, with a knee occurring at about 800 MeV. Figure 2 (Ref. 3) shows the ratio of neutrons/incident proton as a function of proton energy and target material. From these figures it might seem that the highest incident energies possible would be desired. However, as pointed out by Havens,¹ geometric factors must be considered. For most experiments, a high luminosity (n/cm^2), minimum spatial uncertainty, and minimum burst time variance are equally desirable. These factors are favored by low-energy beams and the highest possible target densities. The combination of factors would indicate that 800-MeV protons incident on thick ^{238}U targets would be very favorable for pulsed neutron experimentation.

III. NUCLEON CASCADE- EVAPORATION MODEL

A. Review of the Nucleon Cascade Model

Serber⁴ shows that, as the energy of an incident particle is increased, a target nucleus becomes

TABLE I^a
TARGET HEATING AND NEUTRON PRODUCTION EFFICIENCY

Reaction	Target Heating (MeV/n)	Neutron Production Efficiency (n/MJ)
T(d,n) ⁴ He (250 keV)	2500	2.4×10^{15}
U(e, γ ,xn) (35 MeV)	2000	3×10^{15}
⁹ Be(d,n) ¹⁰ B	1200	5×10^{15}
Fission	200	3×10^{16}
Bi(p,xn) (1 GeV)	23	2.6×10^{17}
T,d Fusion	3	2×10^{18}

^aFrom Ref. 2.

Fig. 1. Energy required to release a low-energy neutron by medium-energy proton bombardment of a thick (24-in.) lead target.

transparent and the reactions take on the character of free nucleon collisions in a degenerate Fermi sea. The forward momentum transfer $\hbar/a$ (a is the range of nuclear forces) is a constant and only a small fraction of the energy of the incident particle is removed with each collision, hence a cascade develops. The problem is to follow the trajectories of colliding free particles in the nucleus, subject to the constraint of the Pauli exclusion principle, until they escape leaving an excited nucleus that deexcites through particle evaporation.

Goldberger⁵ and others⁶⁻¹² implemented this idea through Monte Carlo techniques but were limited by computational methods. Metropolis et al.¹³ made refinements and applied an electronic computer (MANIAC) to the problem. Figure 3 shows the procedure followed to chart the history resulting from a particle incident on the nucleus. Bertini¹⁴ further refined the model and coded the problem in FORTRAN for a commercial computer, which greatly increased its universality. The nucleon cascade model is used to generate "cross-section" data in a general Monte Carlo program (NMTC^{15,16}) that treats particle transport in large systems. In application to the problem of thick targets, an internuclear cascade is involved. The NMTC program was adapted to the CDC 6600 computer by H. I. Israel (LASL Group H-1) and was applied to all the calculations in this report.

Before leaving the discussion of the intra-nuclear cascade as treated by Bertini, we list the physical considerations of the theory.

1. Above a certain cutoff energy (taken here

Fig. 2. Production ratio of low-energy neutrons per medium-energy proton incident on various thick targets as a function of proton energy.

as 25 MeV), the nucleus can be treated by using experimental free particle cross sections but by constraining the reactions to satisfy the Pauli exclusion principle.

2. Relativistic kinematics are used throughout.

3. The nonzero Fermi distribution of nuclear particles as evidenced by electron scattering data is step-wise approximated by a central sphere and two concentric spherical annuli. The neutron-to-proton density ratio is assumed constant and equal to the average for the nucleus.

4. The composite momentum distribution for the nucleus is approximated by a 15-MeV Gaussian.

5. The binding energy of the most loosely bound nucleon is assumed to be 7 MeV for all regions and all nuclei. The pion potential is assumed equal to the potential of the nucleon with which it is interacting.

6. Charge independence of the free particle cross sections is assumed.

7. Energy, momentum, and charge conservation are required.

8. Pion production is based on the isobar model with single or double pion production being allowed for nucleon-nucleon collisions and only single pion production being allowed for a pion-nucleon collision.

Effects not considered are:

1. The effects of refraction at the nuclear surface.
2. Clustering of nucleons.
3. Reduction of the nuclear density due to the cascade.

Fig. 3. Block diagram of the course of a Monte Carlo nucleon cascade calculation.

4. Nonsphericity of nuclei.
5. Spin-correlation effects.
6. Radiative transport that result from π^0 annihilation.

B. Review of the Evaporation Model

The second step of this two-step nucleon cascade-evaporation model occurs as the energy of the cascade is depleted and particles can no longer escape. The struck nucleus has an excitation energy $E^* = T_1 - T_0 - E_0(n-1)$, where T_1 is the incident particle kinetic energy, T_0 is the sum of kinetic energies of the emitted cascade particles, r is the number of emitted particles, and E_0 is the assumed binding energy of the most loosely bound nucleon (assumed constant for all nuclei). If the energy of excitation E^* is large compared with the lowest excitation levels of the nucleus and the atomic mass is fairly high, the problem can be treated statistically as was done by

Weisskopf.¹⁷ He considers the problem of a nucleus A excited to an energy E_A^* emitting a particle x with kinetic energy between ϵ and $\epsilon + d\epsilon$. After emission the new nucleus B is excited to an energy E_B^* so that $E_B^* = E_A^* - E_0 - \epsilon$. The probability per unit time $W_x(\epsilon)$ of this occurring can be obtained by thinking of the inverse capture reaction in which the particle goes back into the nucleus. By this reasoning Weisskopf obtains the probability

$$W_x(\epsilon) = \sigma_x(E_A^*, \epsilon) G \frac{\epsilon \omega_B(E_B^*)}{\omega_A(E_A^*)} d\epsilon, \quad (1)$$

where $\sigma_x(E_A^*, \epsilon)$ is the cross section for the capture of a particle x with a kinetic energy ϵ in a nucleus B to form a nucleus of type A having an excitation E_A^* . $\omega_B(E_B^*)$ and $\omega_A(E_A^*)$ are the level densities in B and A around energies E_B^* and E_A^* , respectively. G is

a geometric factor such that $G = (2S_x + 1) m_x / \pi^2 h^3$ where S_x is the spin of particle x and m_x is its mass.

Monte Carlo techniques were applied to this evaporation approach by Dostrovsky et al.¹⁸ and more recently by Dresner¹⁹ and Guthrie.²⁰ Guthrie's program is contained in the latest version of NMTC, but all three approaches are similar. The idea is to approximate the experimentally measured inverse cross section $\sigma_x(E^*, \epsilon)$ by an empirical equation¹⁸ whose parameters are only a function of the compound mass A and emission energy ϵ for the neutron. For charged particle emission, the cross section is a function of various tabulated quantities including the charge Z , the charge of the exiting quantity Z_x , nuclear and particle radii, etc.¹⁷ The level density is essentially that of a degenerate Fermi gas but includes pairing energy.¹⁸ In Guthrie's treatment this is extended to include shell plus pairing energies. The nuclear masses used are those of Mattauch et al., given in tabular form.

The next procedure is to calculate the emission probability by integrating Formula 1 over allowable energies for neutrons, protons, deuterons, tritons, helium-3 nuclei, and alpha particles. The probability is normalized by dividing each probability by the sum, and the type of particle is selected at random with this probability distribution. Similarly, the kinetic energy of the emitted particle is selected at random with a modified Maxwellian distribution. If the particle is charged, an effective Coulomb energy is added. The procedure is repeated for the new nucleus, evaporating more particles until it is no longer energetically possible.

The assumptions in the evaporation model are:

1. That there are many nucleons in the nucleus and that the density of states is high.
2. That the excitation energy is much higher than the lowest levels.
3. That the analytic representations of the inverse cross sections, level density functions, and energy distribution functions are correct and that the shell and pairing effects are adequate.

The fact that fission and radiative emission cannot be treated is unfortunate. Also most experimental tests are limited to medium-weight nuclei.

C. Experimental Tests of the Nucleon Cascade-Evaporation Model

In principle, if the input data, which in this case are generated by the nucleon cascade-evaporation model to a Monte Carlo transport program, are correct, correct answers should result. There have been numerous checks of the Nucleon Cascade Model.⁴⁻¹⁴ In the most recent review, Bertini²¹ compares his results with 39 experiments. Table II attempts to summarize the agreement between the model and the experiments. Unfortunately, except for the radiochemical experiments, the experiments do little to test the evaporation model; however, Dostrovsky¹⁸ presents data in its support. From these evidences,

TABLE II
COMPARISON OF THE NUCLEON CASCADE-EVAPORATION MODEL WITH EXPERIMENTS

Experiment	Average Deviation (%)
Nonelastic cross sections for protons and neutrons of energies 84 to 305 MeV on Be, Al, Cu, Pb, and U targets	7
Average number of neutrons emitted per inelastic event for incident protons on targets of C, Al, Cu, Pb, and U for protons of energies	
400 MeV	11.2
500 MeV	9.6
660 MeV	15.6
Cross section for π^0 emission due to 660-MeV protons on C, Al, Cu, and Pb	36.8
Cross sections for the formation of iodine isotopes for incident protons on ^{127}I for protons of energies	
720 MeV	36.2
2000 MeV	20.0
Cross sections for the formation of tellurium isotopes from protons on ^{127}I for proton energies	
720 MeV	43
2000 MeV	37
Nonelastic cross sections for pions of energies 216 to 2040 MeV on C, Al, Cu, Ru, and Pb	9.4
Cross sections for the formation of various isotopes due to π^- on carbon and argon for π^- energies from 600 to 1600 MeV	35
Nonelastic cross sections for nuclei from $A = 12$ to 208 for incident proton energies	
30 MeV	14
40 MeV	3
50 MeV	3.4
60 MeV	5.4
Proton-nucleus inelastic cross sections from 300 to 3400 MeV for Pb, Cu, Al, C	
Pb	2
Cu	5.5
Al	11.5
C	13.2
Neutron-nucleus inelastic cross sections for neutron energy range 300- to 3500-MeV targets of Pb, Cu, Al, C	
Pb	7.6
Cu	12.2
Al	6.4
C	23.3
Secondary neutron spectrum at 2° from 143-MeV protons on aluminum	49
Secondary proton spectrum at 30° from 160-MeV protons on bismuth	12
Secondary proton spectrum at 30° from 340-MeV protons on carbon	8
Secondary proton spectrum at 30° from 430-MeV protons on aluminum	20
Secondary proton spectrum at 18° from 660-MeV protons on copper	15
Secondary π^+ spectrum at 0° from 725-MeV protons on copper	16
Secondary proton spectrum at 9.1° from 1000-MeV protons on carbon	9
Secondary proton spectrum from 0 to 30° for 2700-MeV protons on heavy emulsions	2
Angular distribution of secondary protons of energies 80 to 850 MeV from 2700-MeV protons on heavy emulsions	8
Secondary π^- spectrum from 1300-MeV π^- on heavy emulsions	1
Secondary proton spectrum from 1300-MeV π^- on heavy emulsions	18
Angular distribution of secondary π^- from 1500-MeV π^- on heavy emulsions	21

and for 800-MeV protons on heavy metal targets, an estimate would put the accuracy of the model at about 20%.

IV. COMPUTATIONAL PROCEDURE

The nucleon cascade-evaporation model allows the calculation of nucleon-nucleus, pion-nucleus interactions down to a cutoff energy taken to be 25 MeV, but procedures are needed for transporting the particles in thick targets and allowing for ionization energy loss. Procedures are also needed for transporting particles down to thermal energies and for treating fission and gamma production. Figure 4 shows the procedures followed.

A. Nucleon Meson Transport Code NMTC

This code, which originated at the Oak Ridge National Laboratory (ORNL), was written in FORTRAN IV for the IBM 360/75 and 360/91 computers and was converted for use on LASL's CDC 6600. This code calculates the reactions induced in other nuclei

resulting from the neutrons and charged particles generated by nucleon cascade and evaporation from the nucleus struck by the initial particle. These calculations are performed by Monte Carlo particle transport techniques that differ in some particulars from the usual neutron Monte Carlo transport calculations. These differences are listed.

1. Cross sections are generated internally using the nucleon cascade-evaporation model predictions.

2. The continuous-slowing-down approximation is applied to the transport of charged particles.

3. Elastic collisions of protons, neutrons, and pions with all nuclei other than hydrogen are neglected.

4. π^0 's are assumed to decay in place into two gamma rays. The decay in flight or at rest of charged pions into muons is treated. The capture at rest of π^- 's is treated through the nucleon cascade-evaporation model. The decay of muons is also treated.

Fig. 4. Block diagram of computational procedures in this report.

5. NMTC has an upper limit of 2.5 GeV and a lower limit imposed by the nucleon cascade-evaporation model of 15 to 50 MeV, selectable in the program. In this work 25 MeV was used based upon the experience of Alsmiller et al. (ORNL)³¹ and upon our determinations that the calculations were insensitive to ± 10 MeV variation in the cutoff energy of about 25 MeV.

6. The geometry package in the LASL version of NMTC has been modified to include only spheres and cylinders. The low-energy transport (> 25 MeV) in this version is handled by several other programs (Fig. 4) rather than by the O5R (Ref. 22) routine in the ORNL program. With these changes, the program occupies 302500_g core locations and has a central processor running time of 0.9 sec per starting proton.

There are two output tapes from NMTC. One tape was used in the ORNL version as the input to O5R for the low-energy transport and is not used in the LASL version. The nucleon-pion history tape used in this version contains a record of each event that occurs in the collision process. This tape was processed in three different ways (Fig. 4): high-energy neutrons, low-energy neutrons, and gamma rays.

B. High-Energy Neutron Spectra

The program High energy ANALysis (HIANAL) searches the history tape and correlates the neutrons leaving the target with energy above the low-energy cutoff into angle and energy bins resulting in numbers of statistical significance. The azimuthal angle relative to the direction of the incident proton is divided into 12 equal solid-angle groups. The energy bins were divided into constant lethargy intervals.

C. Low-Energy Neutron Spectra

1. The history tape is again searched by the program SHRTP (Search TaPe) for two classes of neutrons. Class I: Those neutrons produced by the nuclear cascade but having energy below the cutoff energy. They are recorded by position, direction cosines, and energy. Class II: Those neutrons produced by evaporation. The two classes are recorded by position and energy only, because of assumed isotropic production. They are assembled on an output tape in a suitable neutron source form.

2. The neutron transport is calculated by a Monte Carlo Neutron transport program (MCN) written

by LASL Group TD-6.²³ It includes a versatile geometry package, uses optional standard variance reduction techniques, and treats neutron thermalization by using the free-gas model. The code uses pointwise cross sections from several compilations. Unfortunately, the maximum energy of these compilations is 14.6 MeV; hence cross sections must be extrapolated up to 25 MeV. This was done by Schrandt, Cramer, and Beyster²⁴ for ^{238}U by using nuclear systematics. Appendix A describes their procedure. The output data of MCN includes currents, fluxes, point detector responses, and other data not applicable to this problem. It also includes a history tape output used in LOANAL.

3. The Low Energy ANALysis program (LOANAL) searches this tape, and correlates the neutrons in intervals of energy, angle, and time to obtain numbers of statistical significance, and produces an output similar to HIANAL so that the two outputs may be grouped to produce the complete neutron output spectrum from source to thermal energies.

D. Gamma-Ray Spectra

The gamma-ray production calculation is based on the suggestion of R. G. Alsmiller, Jr., (ORNL) that most of the gamma rays are produced by interaction of the low-energy neutrons with the target nuclei resulting in inelastic scattering and capture with subsequent radiative deexcitation of the nuclei. Therefore, the gamma-ray production from the nucleon-meson cascade or from particle evaporation is not considered. The rationale for this approximation is the 5:1 dominance of evaporation neutrons over all other cascade or evaporation particles. These neutrons are the primary source for the gamma-ray production calculation.

1. The history tape is again searched by SHRTP to provide the low-energy cascade and evaporation neutron source for transport in MCN, which generates a collision tape. The position, energy, time, call number, and weight is recorded for each event.

2. The program Gamma-Ray Generator (GANGEN) was written by W. G. Praeg (LASL Group TD-3) to use the collisions to generate a gamma-ray source based on the ratio of the gamma-ray production cross section to the total cross section. The emergent gamma rays are randomly selected from a cumulative probability table. A user-selected importance function may be used to affect the gamma-ray multiplicity for

each event. Multigroup production cross sections from the ENDF/B file may be used. However, for the calculations involving ^{235}U and ^{238}U , the TD-Division data set was employed.

3. The transport of the gamma rays from GAMGEN is done by MCG, a general purpose Monte Carlo Gamma transport code written by LASL Group TD-6. The interaction mechanisms in this code are (1) pair production, (2) Compton scattering, and (3) photoelectric capture. The deposited gamma-ray energy is calculated as is the energy spectrum of the gamma rays transported out of the system.

4. The output of MCG is the same as MCN in that events are tabulated on a history tape. These histories are summarized to obtain statistically significant data by the Gamma-Ray Analysis (GAMANAL) code. This code summarizes the gamma-ray output according to energy, angle, and time of emission, similar to LOANAL.

E. Alternative Neutron Transport Calculation

Before leaving the discussion of the calculation procedure for particle production and transport, an alternative approach not used in this report is discussed. This approach, used by Bertini, consists of generating differential cross sections using the nucleon cascade-evaporation model. In this manner cross sections are generated for incident neutrons and protons from 25 to 40 MeV and incident π^+ and π^- from 25 to 300 MeV on nuclei from carbon to uranium.^{25,26} This was later extended to cover 500 to 3000 MeV for incident protons and neutrons and 500 to 2500 MeV for incident π^+ and π^- mesons on ^{16}O , ^{27}Al , ^{65}Cu , ^{100}Ru , and ^{207}Pb .²⁷ These results were given an analytic representation by Alsmiller²⁸⁻³⁰ by least-squares fitting to a power series in exiting particle energy. The coefficients for this representation are a function of angle, exiting particle type, and incident particle type and energy. The NCDATA program³⁰ interpolates between these analytic representations to give values for all incident energies in the allowable range and all mass values between 12 and 238. These cross-section data are combined with standard reactor-type cross-section sets and are used in neutron transport codes in which the continuous slowing down approximation has been added for the transport of charged particles.^{31,32}

This approach does the particle transport in one code and hence avoids the joining region at 25

MeV. It would appear to be a faster method because the cross sections are not generated in the course of the program, but are retrieved. Hence greater geometric complexity as to shape and material can be treated for the same computer usage. At the Los Alamos Scientific Laboratory, D. R. Harris, Jr., D. L. Roeder, R. A. Haarman, R. P. Forrest, Jr., and H. I. Israel have collaborated in generating the nucleon-cascade events for the elements C, O, Al, Mo, Fe, W, and ^{238}U for nucleons and ions from 25 to 800 MeV. To date these data have not been compiled for use in transport codes but are viewed as the correct approach for complex shielding and target problems.

V. COMPARISON AND RESULTS

As was stated in Sec. III.C, if the nucleon cascade-evaporation model is correct, in principle the Monte Carlo transport results should also be correct and there is no reason for integral comparisons. Unfortunately, the calculational procedures are sufficiently complex to warrant integral comparisons. This section presents comparisons with other work both calculational and experimental. In addition, details of the spectra from various targets, time dependence, spatial profiles, and gamma-ray production are presented.

Table III summarizes the calculations of this report and compares total neutron output from other calculations and experiments. Problem 1 statistically is the most reliable problem of this report. It required about 3 hr CDC 6600 time just for the NMTC calculation. We planned to zone this problem by radius at 3 and 5 cm for high-energy neutron production in these sleeves, thus making one problem useful for the calculation of three different cylinders. Ninety percent of the neutron production from evaporation occurs in the first 0.75 cm (Fig. 5); therefore, NMTC calculations for a 15-cm-diam by 30-cm-long target were used for Problems 1, 2, and 3 (Table III) with the correct diameter used in the MCN calculation. Problem 4 is a direct test of this approximation in that both NMTC and MCN were calculated for the correct geometry. Problems 5 and 6 are studies of the effect of target geometry on the angular neutron spectra. Because the 800-MeV protons have a range of 24.1 cm in ^{238}U (40.1 cm in Pb), it may seem strange to study targets

TABLE III
CALCULATION SUMMARY

Problem No.	Material	Shape	Size	Incident Proton Energy (MeV)	No. of Incident Protons	Neutrons Per Proton (n/p) $E_n > 25$ MeV	n/p $E_n > 15$ MeV	n/p Total	n/p Other Work
1	^{238}U	Cyl	15-cm diam by 30 cm	800	12000	0.7	0.9	28.6	
2	^{238}U	Cyl	10-cm diam by 30 cm	800		0.7	1.0	26.4	23a, 35b
3	^{238}U	Cyl	6-cm diam by 30 cm	800		0.7	1.1	23.3	32d
4	^{238}U	Cyl	10-cm diam by 30 cm	800	2500	0.8			
5	^{238}U	Cyl	10-cm diam by 10 cm	800	2500	0.7			
6	^{238}U	Sph	15-cm diam, 5-cm reentrant	800	2000	0.7	0.9	18.6	
7	^{238}U ^{235}U	Cyl	6-cm diam core, 10-cm o.d. by 30 cm	800	6000	0.7	0.8	38.5	
8	Pb	Cyl	20-cm diam by 30 cm	800	2000				18c
9	Pb	Cyl	15-cm diam by 30 cm	800	2000	0.9	0.9	16.7	17b
10	Pb	Cyl	2.6-cm diam by 15.2 cm	550	2000	0.6	0.6	7.4	17c
11	Ta	Cyl	4-cm diam by 5.1 cm	800	4999		0.5		

^aRef. 33, 10-cm-diam by 60-cm target, number is total neutron captures in 1.8 m cube of water, linear interpolation to 800 MeV-Monte Carlo calculation.

^bRef. 3, 10.2-cm-diam by 61-cm target foil activation in 6-ft cube of water, linear interpolation to 800 MeV-experiment.

^cSame as b except 20.4-cm-diam by 61-cm target.

^dRef. 34, 5-cm-diam by 40-cm target, linear interpolation to 800 MeV-Monte Carlo calculation.

^eSame as d except 10-cm-diam by 60-cm target.

shorter than the incident particle range. Figure 5 illustrates that the neutron production is dropping faster than exponentially toward the end of the

Fig. 5. Radial and axial distribution of the production of evaporation neutrons in a 7.5-cm-radius, 30-cm-long ^{238}U target with 800-MeV protons incident on axis.

proton range. An eye fit curve to that portion of the axial distribution that is approximately exponential gives an e-folding of 12.3 cm. Figure 1 shows the rapid drop of neutron production with energy, which is another approach to this problem. If proton energy below 300 MeV is nonproductive, then, from range-energy curves, 17 cm of ^{238}U will degrade the 800-MeV protons to 300 MeV. All of this is consistent with 15 cm of ^{238}U being a "most efficient" length of target although a beam dump would be needed for the exiting protons.

Problems 7 through 11 explore the effects of different material on the neutron spectra with a view to spectrum tailoring of the targets. Problem 10 models the target for the Columbia Nevis synchrotron. Data for this facility¹ indicated a ratio of neutrons/incident proton (n/p) of 16. These calculations predict this ratio to be 7.4.

Table III (right two columns) indicates that the n/p ratios are in close agreement with the work of ORNL. This result is not surprising because these calculations use the relatively unchanged ORNL-NMTC program. Calculating the low-energy transport with MCN is different and uses different cross-section sets so that the end agreement is gratifying. Surprisingly, the Monte Carlo predictions of Milton and Fraser³⁴ give an n/p ratio 27% higher than the ORNL work. The Canadian-U.S. thermalization-foil-activation experiment results³ are also higher than these by 25%.

Fig. 6. Neutron spectra comparisons between these calculations and the experiment of Milton, Hewitt, and Walker (Ref. 36). The lead target was 20-cm diam by 30-cm long. The incident proton energy was 1000 MeV.

Figure 6 is a comparison of the results of Problem 9 with the neutron time-of-flight experiment performed by Fraser, Hewitt, and Walker³⁵ on the Birmingham Synchrotron. Comparisons of the data around 10 MeV place these experiments 20 to 40% higher than our calculations. From 30 to 150 MeV the agreement is good for the 45° spectrum, fair at 90°, and poor at 135°. In the joining region between NMTC and MCN at 25 MeV, the statistics are very poor and the data are omitted.

Recently, Veaser et al.³⁶ measured the angular neutron spectrum from a 15-cm-diam by 30-cm-long ^{238}U target bombarded by 750-MeV protons from the Lawrence Berkeley Laboratory's 184-in. synchrocyclotron. Several detection techniques were used³⁷ and the agreement below 10 MeV (Figs. 7 and 8) is very good. The data above 10 MeV are consistently higher than these calculations but are still subject to revision. However, the small number of neutrons in this region that are above 10 MeV cannot alone account for the discrepancies in the n/p ratio. In summary, the ~25% discrepancy in the n/p ratio for

Fig. 7. Neutron spectra comparisons between these calculations and the experiment of Veaser et al. (Ref. 35). The ^{238}U target 15-cm diam by 30-cm long was measured at 50°. The incident proton energy was 750 MeV.

^{238}U as calculated by NMTC and that measured³ and calculated³⁴ is not understood.

Table IV on target heating does not provide a test of our calculations. This was not an original objective of this work and cannot now be recovered

Fig. 8. Neutron spectra comparisons between these calculations and the experiment of Veaser et al. (Ref. 35). The ^{238}U target 15-cm diam by 30-cm long was measured at 130°. The incident proton energy was 750 MeV.

TABLE IV
URANIUM TARGET HEATING (MEV) PER EXITING NEUTRON ($n/p = 23$)

	Ref. 33 ^a	Ref. 34 ^b	This Work
Ionisation loss for charged particles above 25 MeV excluding mesons	18.3		
Nuclear excitation due to reactions above 25 MeV	0.36		
Kinetic energy of π^0 mesons	0.39		
Ionisation loss by mesons	0.02		
Reactions due to particles below 25 MeV	37.2		16 ^c
Total heat in target	56.3	77	

^a900-MeV incident proton energy.

^bInterpolated to 800 MeV.

^cThis includes only fission heating.

from the calculations. Data on fission heating are presented, however. It is surprising that the ORNL work should disagree with experiment by as much as 37%. Again, this is only true of ^{235}U , a fact that may be significant.

This completes the neutron production comparisons with previous work. Figure 9 presents results for Problem 1, Table III, below 25 MeV. An unexpected result of this work is the "softness" of the

Fig. 9. Calculated neutron spectra below 25 MeV for 15-cm-diam, 30-cm-long ^{238}U cylinder with 800-MeV protons incident on axis.

Fig. 10. Calculated neutron spectra above 10 MeV for a 15-cm-diam, 30-cm-long ^{238}U cylinder with 800-MeV protons incident on axis.

spectrum, as shown for the large targets, resulting from neutron elastic and multiple production reactions. We expected the spectrum to be similar to an evaporation spectrum, but this was not the case. Figure 10 shows the neutron spectra above 10 MeV for this same problem. Appendix B contains tabular results for all the calculations above 25 MeV. Figure 11 summarizes Figs 9 and 10 by presenting the percentage neutron output as a function of the upper limit of integration.

Fig. 11. Percentage neutron output above a neutron energy E as a function of that energy.

Fig. 12. Calculated neutron spectra below 25 MeV by zoning method for a 10-cm-diam, 30-cm-long ^{238}U cylinder with 800-MeV protons incident on axis.

Fig. 13. Calculated neutron spectra above 10 MeV by zoning method for 10-cm-diam, 30-cm-long ^{238}U cylinder with 800-MeV protons incident on axis. Also included for comparison is Byers' calculation for actual geometry.

Fig. 14. Calculated neutron spectra below 25 MeV by zoning method for 6-cm-diam, 30-cm-long ^{238}U cylinder with 800-MeV protons incident on axis.

Figure 12 shows the angular variation in neutron spectra below 25 MeV for Problem 2; the 10-cm-diam by 30-cm long ^{238}U target was calculated by the zoning technique. Figure 13 shows the spectra above 10 MeV, which is the same as shown in Fig. 10 but is repeated to show comparisons with Byers' calculations performed for the correct geometry.

Figure 14 presents data for Problem 3 with the 6-cm-diam by 30-cm-long ^{238}U target again done by zoning. Because the spectra above 10 MeV are identical (by this method) to those shown in Figs. 10 or 13, they are not repeated.

Figure 15 shows, in a polar plot, the angular distribution of the high-energy neutrons. Because evaporation and fission-produced neutrons are assumed isotropic, a low-energy plot is not presented.

Figures 16 and 17 compare the effects of target shape on the angular distribution. The comparison is made for Problem 1, the 15-cm-diam by 30-cm-long

Fig. 15. Calculated angular neutron spectrum for 15-cm-diam, 30-cm-long ^{238}U cylinder with 800-MeV protons incident on axis.

^{238}U cylinder; Problem 5, the 10-cm-diam by 10-cm-long ^{238}U cylinder; and Problem 6, a 15-cm-diam ^{238}U solid sphere. As would be expected from Fig. 5, the geometry is really established by the beam and is not strongly influenced by the shape of the target. Figure 18 shows dramatically the process contributing to the 0.2-MeV spectral maximum. The evaporation neutron spectra are essentially the same in both lead and ^{238}U , but the escaping neutron spectrum from ^{238}U is considerably modified by $(n,2n)$ and $(n,n'\gamma)$ processes that have a much higher threshold in lead.

Figure 19 compares the 4π spectra from ^{238}U and lead cylinders 15-cm diam by 30-cm long. In the region above 10 MeV, there is very little difference between the materials, but very large differences exist at low energies due to (n,xn) and (n,f) reactions.

Figure 20 presents results for Problem 11, a 4-cm-diam by 5.1-cm-long tantalum cylinder with 800-MeV protons incident. This problem was done preliminary to the experiment of Veaser et al.³⁶ This

Fig. 16. Comparison of the calculated angular neutron spectra 800 to 100 MeV for 15-cm-diam, 30-cm-long ^{238}U cylinder and 15-cm-diam ^{238}U solid sphere with 800-MeV protons incident on axis.

target was in a beam line at the Berkeley cyclotron and was considered as a possible source of neutrons to check out detectors.

Figure 21 shows the results from Problems 3 and 7 that represent an attempt both to harden the spectrum and to increase the neutron output by using a ^{235}U sleeve 2-cm thick outside a 3-cm-diam ^{238}U cylindrical core. Both results are achieved but at the expense of emission time. Figure 22 shows the 4π time-dependent neutron spectra for the ^{238}U cylinder and Fig. 23 shows the spectra for the ^{235}U - ^{238}U composite target. The number of neutrons in the later time groups is increased, as well as the energy span, thus making the composite target more difficult to use for neutron time-of-flight experiments.

Figure 24 presents the time-dependent neutron spectra from a 15-cm-diam by 30-cm-long ^{238}U target for a few energy groups.

These data may be eye-fitted to give the most probable emission time as a function of exiting neutron energy

$$t = 3.5 \text{ nsec}/\sqrt{E(\text{MeV})}$$

(2)

Fig. 17. Comparison of the calculated angular neutron spectra 100 to 25 MeV for 15-cm-diam, 30-cm-long ^{238}U cylinder and 15-cm-diam ^{238}U solid sphere with 800-MeV protons incident on axis.

Fig. 18. Comparison of neutron evaporation and escape spectra below 10 MeV for ^{238}U and Pb cylinders 15-cm diam, 30-cm long with 800-MeV protons incident on axis.

Fig. 19. Comparison of 4π neutron spectra for ^{238}U and Pb cylinders 15-cm diam, 30-cm long with 800-MeV protons incident on axis.

and the time dispersion of the emission taken here as the full width at $1/e$ of the maximum value. This gives

$$\Delta t = 5.2 \text{ nsec} / E^{0.73} \text{ (MeV)}. \quad (3)$$

The fact that the mean emission time shifts inversely with the velocity of the exiting neutron is to be expected because the target manifests some aspects of a "slowing-down time" spectrometer. If the target were large enough, "velocity focussing" would be manifest.

Using the usual relationship for energy resolution in neutron time-of-flight and substituting Eq. (3), the fractional energy resolution for a flight distance l is given as

$$\frac{dE}{E} = \frac{0.144}{l(m) E^{0.23}} \quad (4)$$

For 1-MeV neutrons and a 100-m flight distance, the energy resolution should be about 0.14% (spatial uncertainty is not considered).

Fig. 20. Calculated neutron spectrum for Ta cylinder 4-cm diam, 5.1-cm long with 800-MeV protons incident on axis.

Fig. 22. Calculated time and energy neutron spectra from 80 to 99° for a ^{235}U cylinder 5.0-cm radius, 30-cm long with 800-MeV protons incident on axis.

Fig. 21. Comparison of neutron spectra for a ^{235}U cylinder 5.0-cm radius, 30-cm long with that for a ^{235}U cylinder 3-cm radius, 30-cm long inside a ^{235}U cylindrical sleeve 2-cm thick with 800-MeV protons incident on axis.

Fig. 23. Calculated time and energy neutron spectra from 80 to 99° for a ^{235}U cylinder 3.0-cm radius, 30-cm long inside a ^{235}U cylindrical sleeve 2-cm thick with 800-MeV protons incident on axis.

Fig. 24. Time dependent 90° neutron spectra for several energy groups from a 7.5-cm-radius, 30-cm-long ^{238}U target with 800-MeV protons incident on axis.

Figure 25 shows the distribution of the last collisions the neutrons experience before leaving the target. If it is assumed that the reactions are isotropic, then this represents the spatial distribution of a diffuse source. These results show that the last collisions tend to occur at the outer boundary in spite of the fact that the source is concentrated along the beam line (Fig. 5). These results would indicate that for experiments requiring high luminosity, the diameter of the targets should be as small as possible.

Figure 26 presents the gamma-ray escape spectrum for the 15-cm-diam by 30-cm-long ^{238}U target as a function of angle. This shows considerable photon absorption in the forward direction due to target material in this direction. The results would be

Fig. 25. Axial and radial distribution of last collisions in a ^{238}U target 15-cm diam, 30-cm long with 800-MeV protons incident on axis.

Fig. 26. Calculated angular gamma-ray emission spectrum for a ^{238}U cylinder 5.0-cm radius 30-cm long with 800-MeV protons incident on axis.

Fig. 27. Calculated angular gamma-ray emission spectra for a ^{238}U cylinder, 3.0-cm radius, 30-cm long inside a ^{235}U cylindrical sleeve 2-cm thick with 800-MeV protons incident on axis.

considerably different for the shorter targets of Problems 5 and 6. In these thick uranium targets the gamma absorption is such that for 35 photons produced, only 1 escapes.

Figure 27 shows the same thing for the composite target of Problem 7. Now there is considerable gamma-ray production on the surface of the target and the angular effect is not as pronounced. For every seven gamma rays produced, one escapes. Thus the composite target improved the n/p ratio by 45%, but increased the gamma-ray production by five times and resulted in poorer time emission characteristics.

Table V is presented for general information to show the relative abundance of particles produced by 800-MeV proton bombardment of a 10-cm-diam by 30-cm-long ^{238}U target (Problem 4, Table III). Many of these particles never leave the target.

VI. COMPARISON OF THE (p,xn) SOURCE WITH THE (e, γ ,xn) SOURCE

For the reasons stated in Sec. II, medium-energy protons are not commonly used as an MeV neutron source. However, its potential for this purpose has been demonstrated in the previous sections of this report. Because the neutron spectrum and applications are similar to the thick target (e, γ ,xn)

TABLE V
RELATIVE ABUNDANCES OF PARTICLES
IN THE NUCLEON-MESON CASCADE
(from Problem 4, Table III)

Particle	Number
Incident protons	2500
Above cutoff escape protons	89
Below cutoff escape protons	1281
Above cutoff escape neutrons	2114
Below cutoff escape neutrons	2528
π^+ mesons	31
π^- mesons	14
π^0 mesons	25
Evaporation protons	2551
Evaporation neutrons	49031
Evaporation alphas	634
Evaporation deuterons	278
Evaporation tritons	6
Evaporation ^3He	332

spectrum of neutrons produced by high-powered microwave electron linear accelerators, a comparison is presented in Table VI. The advantages (except for luminosity) appear to favor the use of medium-energy proton bombardment of heavy metal targets over electron bombardment. However, these comparisons are on a per incident particle basis and, until recently, the high-powered microwave linacs have been vastly superior in peak or average currents to proton accelerators. A comparison of the relative strengths of two examples of these accelerators will be deferred until a discussion of the relative merits of the production mechanisms is completed.

TABLE VI
COMPARISON OF PROTON AND ELECTRON SOURCES FOR NEUTRON PRODUCTION

Comparison	Protons (p,n)	Electrons (e, γ ,xn)
Production efficiency n/M Joules	2.5×10^{17} (Prob. 1, Table III)	2.2×10^{15} (100 MeV on Ta, Ref. 30) 2.6×10^{15} (80 MeV on U, Ref. 30)
Target heating MeV/g	56.5 (Table IV)	2000 (Ref. 30)
Gamma-ray production Photons/n-steradian	9.9×10^{16} (Prob. 1, Table III) 3.4×10^{16} (Prob. 7, Table III)	15.6 (Ref. 30)
Luminosity n/M Joule-cm ²	1.1×10^{10}	2.2×10^{11}
Time densities neutrons	5	<1
90° spatial uniformity cm	0.75 (Fig. 3) 7.5 (Fig. 7)	1 (Ref. 30)

Fig. 28. Comparison of calculated 90° neutron spectra between 15-cm-diam, 30-cm-long ^{238}U cylinder with 800-MeV protons incident on axis with the 2π spectra from 7.646-cm Ta and 36.75-cm Be slabs with 150-MeV electrons perpendicularly incident (from Ref. 40).

Figure 28 presents a comparison of the 90° neutron spectrum from a 15-cm-diam by 30-cm long ^{238}U cylinder with 800-MeV protons incident on axis with the 2π neutron production from 150-MeV electron bombardment of 7.646-cm tantalum and 36.75-cm beryllium slabs.⁴⁰ For the $\text{U}(p,xn)$ process from 1 to 100 MeV, the spectrum is approximately $E^{-1.83}$; for $\text{Be}(e,\gamma,xn)$ from 5 to 50 MeV, the spectrum is approximately $E^{-2.48}$; for $\text{Ta}(e,\gamma,xn)$ from 5 to 60 MeV, the spectrum is approximately $E^{-3.48}$. Thus, the (p,xn) process is clearly superior for neutron production in the 1 to 100 MeV range. Table VI shows a factor of 100 advantage in total neutron production over electrons on a per incident particle basis, whereas the target heating per neutron is only 1/50 of that for electrons.

The gamma-ray production per neutron is 1400 times greater by the (e,γ,xn) process than by the (p,xn) process for the target of Problem 1, and 400 times more for the composite ^{235}U - ^{238}U target of Problem 7.

Fig. 29. Calculated 90° gamma-ray emission spectra from 1-cm-radius, 7.646-cm-long Ta cylinder, 150-MeV electrons incident on axis (from Ref. 38).

Figure 29, taken from the work of Alsmiller and Moran,³⁸ shows the photon spectrum at 90° to the beam line for the 150-MeV electron incident on the axis of a tantalum cylinder 1-cm radius by 7.646-cm long. Figure 29 should be compared with Figs. 26 and 27. The similarity is noticeable although the electron produced spectrum goes to higher gamma-ray energies. No doubt the thickness of the uranium targets is a large factor in this suppression.⁴¹

To suppress the gamma flash, numerous techniques are employed. It is not unusual to reduce the neutron fluence by a factor of 10 for the instrumentation to recover shortly after the pulse. Perhaps the most sophisticated approach is that of Macklin,⁴² who uses a "halo" moderator 6-in. o.d. by 2-in. i.d. with the (e,γ,xn) target in the center and with a shadow bar of copper preventing direct viewing of the target. This moderator has a solid angle of about 38%. For this thickness of moderator the probability of an interaction is 60% so that about 1/5 of the neutron production is usable. This figure is only approximate because neutrons cannot scatter 90° off hydrogen in the laboratory system.

If neutrons are being produced for use at energies from 100 keV to 20 MeV, the moderator scatter technique of gamma flash suppression is not suitable,

Fig. 30. Simplified drawing of the WNR facility for time-shared usage of the LAMPF proton and H beams.

and filters and reduction of intensity must be used. We expect that direct viewing of the target will be possible with the (p, xn) process because of the small and suppressed gamma flash. Whether or not this can be done for all experiments we must await experimental confirmation.

Luminosity is an area in which the (p, xn) reaction is inferior to the (e, γ, n) , but if the moderator scatter technique is used here there is not much difference. Another area of inferiority is the time duration of the burst. The electron targets are faster and the spatial uncertainty is less because of the smaller size.

The advantages of the (p, xn) reaction have been appreciated for some time but have been exploited only for low-energy physics at the Columbia University Nevis synchrocyclotron. However, the world's most powerful proton source, LAMPF, will soon be operational with an energy about optimum for neutron production by the $U(p, xn)$ reaction. To use a portion of this beam, a time-sharing scheme has been devised. This project is called the Weapons Neutron Research (WNR) facility.⁴³ Figure 30 is a simplified drawing of the facility excluding the beam-sharing apparatus. A primary consideration in the design of WNR was the angular neutron spectrum shown in Fig. 15. Most experimental areas were designed to use neutrons emitted at 90° or 135° , although some use is made of the forward high-energy spectrum. Target Room 2, (Fig. 30) designed to take a full 25 kW of beam power, has a trench in which remotely selected targets rise from an integral shield and may be located at various places, depending upon experimental requirements.

Target Room 1 is intended for low-power operation to minimize wall activation that would interfere with personnel access. The grating floor and the large size of the room are to minimize room return radiation. The general arrangement is to have the highest radiation areas down stream. Target Room 1 is intentionally located between Target Room 2 and the lab-office area to provide extra shielding.

Comparison of this proposed research facility using the LAMPF beam to generate neutrons through the (p, xn) reaction and other outstanding facilities will now be made. The proton beam from LAMPF is designed to be 17 mA when averaged over the 202 MHz fine structure of 0.2 nsec bunches. It is planned, by simply chopping and time-sharing the beam, to have pulses of duration from 20 nsec to 2 μ sec available, 120 pulses per sec (pps). To achieve 5 nsec or less pulse duration, subharmonic bunching of the beam is required which could also result in substantial increases in the neutron production rate.

A later step in the development of WNR is a storage ring to serve as a beam concentrator. In the high duty mode we hope to inject a 7.5- μ sec proton pulse into the betatron space of the storage ring. With a ring period of 290 nsec, 25 turns would be stored to be compressed by radiofrequency bunching into five bunches of 5-nsec duration, each having a peak current of 300 mA. The bunches would be extracted uniformly at a 600 pps rate. The low-duty mode would utilize charge exchange injection whereby the 1.7 mA, ^3H beam designed for LAMPF would be multiturn injected for 2×10^6 turns in the storage ring. This would require 0.1 sec, then after bunching a pulse of 100 A protons of 100 nsec duration would be available but at a very low duty (one every 10 min). It must be emphasized that such a storage ring is a state-of-the-art development and accomplishment is by no means certain. Table VII summarizes these remarks and makes comparisons with the Oak Ridge ORELA, which has been in operation for several years and is the best example of high intensity achieved through stored electromagnetic energy.⁴⁴ Also compared is the Columbia University Nevis synchrocyclotron that, after completion of the improved program, will be a spiral-ridge fixed-field alternating gradient synchrocyclotron.⁴⁵

The problem of gamma flash is considered crudely in items 6 and 7 of Table VII, but in the

TABLE VII
COMPARISON OF ACCELERATOR NEUTRON SOURCES

Characteristic	WNS (no storage ring)	WNS high-duty storage ring	WNS low-duty storage ring	ORNL	Improved WNS
Max neutrons/pulse	5×10^{12} ^a	3×10^{12}	2.4×10^{12}	1.2×10^{11}	4×10^{11}
Neutrons/fission particle	30	30	400 ^b	0.053 (Ref. 30)	7.4
Peak neutrons/sec	3×10^{14} ^c	4×10^{13}	2.4×10^{13}	4.8×10^{10}	7.7×10^{10}
Average neutrons/sec	7.2×10^{13}	1.8×10^{13}	4×10^{11}	1.2×10^{11}	1.2×10^{10}
Repetition rate (pps)	120	600	0.0016	1000	300
Peak neutrons/sec after moderator scatter ^d	1×10^{14}	4×10^{12}	2.4×10^{11}	9.6×10^{11}	7.7×10^{10}
Average neutrons/sec after moderator scatter ^d	7.2×10^{13}	1.8×10^{12}	4×10^{11}	6×10^{11}	1.2×10^{11}
Neutrons in 5 msec pulse	8.8×10^{12}	3×10^{12}	—	2.5×10^{10}	4×10^{11}
Max target power	6.5 kW	23 kW	1.3 kW	50 kW	5.8 kW

^a2-sec pulse duration.

^bFission neutron chain boost of 10 is included in the n/p target ratio of 40.

^cConstant from 20 msec to 2 msec.

^dThis is not too realistic because in suppressing the gamma flash by moderator scatter, the neutron spectrum has been very strongly affected.

^eBased on 25 μ A of current into the lead target of Problem 10 at 550-MeV proton energy.

We believe that any further calculations should involve group cross sections in a single Monte Carlo calculation without the arbitrary break where this report joins two calculational methods. We hope that this would permit more expeditious problem solution and at the same time include details of cooling channels in the target design.

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last analysis such comparisons become meaningless and the experimental usage dictates the techniques. As an example, if the facility is used for neutron experiments requiring energies between 1 and 20 MeV, the moderator scatter technique for gamma-flash suppression is unsuitable because of its extremely strong degradation of neutrons of these energies.

VII. CONCLUSIONS

This report summarizes a series of calculations on various aspects of neutron production by medium-energy proton bombardment of heavy metal targets.

APPENDIX A

CROSS-SECTION EXTRAPOLATION TECHNIQUES USED BY SCHRANDT, CRAMER, AND BEYSTER

In the Schrandt-Cramer-Beyster studies of the target problem,²⁴ the cross sections for ^{238}U between 14.6 MeV and 25 MeV were obtained by the following procedures.

1. The total and fission experimental cross sections from the Lawrence Livermore Laboratory (LLL) Howerton compilation for neutron energies of 17, 20, 23, 26, and 30 MeV were used.

2. The average number of neutrons per fission ($\bar{\nu}$) was calculated using the formula of Hunter et al.⁴⁶ $\bar{\nu} = 2.38 + 0.149 E(\text{MeV})$.

3. Cross sections for the (n,2n) and (n,3n) reactions were supplied by Leona Stewart (LASL Group TD-4) up to about 20 MeV. A smooth falloff of the (n,3n) reaction was assumed, and for this reason data in the LLL compilation were not used.

4. The thresholds for the (n,4n) and (n,5n) reactions were spaced above the (n,3n) reaction by the

same spacing as that between the (n,2n) and (n,3n), approximately 6 MeV.

5. The elastic cross section was assumed to be 0.5 of the total cross section.

6. At each energy, the least well-known cross section was adjusted to make the sum of the partial cross sections equal the total cross section. The requirement of smooth variation was imposed on the changes.

7. Because the transport program was not set up to handle (n,4n) and (n,5n) reactions, these were incorporated in the fission cross section by defining a new fission cross section: $\sigma_{nf} = \sigma_f + \sigma(n,4n) + \sigma(n,5n)$.

8. Also, $\bar{\nu}_{\text{eff}}$ is redefined to be

$$\bar{\nu}_{\text{eff}} = \frac{\sigma_f + 4\sigma(n,4n) + 5\sigma(n,5n)}{\sigma_f + \sigma(n,4n) + \sigma(n,5n)}$$

9. The elastic scattering angular distribution to 14.6 MeV was used at all higher energies in these calculations.

10. The fission neutron spectral temperature was taken to be 1.29 MeV.

11. The capture cross section $\sigma(n,\gamma)$ was assumed to be zero, as was the cross section for charged particle reactions.

12. For the emission spectrum for the $(n,n'\gamma)$ reaction and the reactions $(n,2n)$ and $(n,3n)$, the cross sections of the LLL Howerton compilation at 14.6 MeV were assumed.

Using these rules, the extrapolated cross sections (in barns) are:

E_n (MeV)	σ_T	σ_{nn}	$\sigma_{nn'\gamma}$	σ_{n2n}	σ_{n3n}	σ_{nF}	σ_{eff}
17	6.04	3.10	0.24	0.3	1.10	1.30	4.92
20	6.18	3.09	0.10	0.1	1.18	1.71	5.14
23	6.05	3.00	0.0	0.0	0.6	2.45	5.36
26	6.05	3.00	0.0	0.0	0.3	2.75	5.64
30	5.81	2.90	0.0	0.0	0.1	2.81	6.10

APPENDIX B

TABULATED HIGH-ENERGY DATA

The tabulated results of the NMTC calculations are valuable because various other problems can be calculated using these as a source. From the discussion of Sec. III, it is apparent that nuclear effects in this model are not strongly mass or energy dependent. Indeed because the incident particle energy is divided into small energy increments, to interpolate these results to slightly different energy values, an extrapolation proportional to E should be used. Similarly, because the cascade views the nucleons as individual particles, an extrapolation proportional to the nuclear mass (A) number should be used. Figure 2 is an example of the correctness of the former conjecture. The lines for Sn through U. if extrapolated back, intersect at a point displaced from the origin by 100 MeV. Whether or not the rule stated for the A dependence is useful, is

not clear. Table III shows that $n/p = 0.7$ for ^{238}U , whereas $n/p = 0.9$ for lead, but this difference could be due to spectral differences such as caused by $(n,n'\gamma)$ and (n,xn) reactions.

Table B-Ia presents a summary of cascade neutrons for Problems 1 through 7, excluding 6. Table B-Ib presents a summary of the evaporation protons and neutrons for the same problems. Similarly, Tables B-IIa and b apply to Problem 6. Tables B-IIIa and b apply to Problems 8 and 9. Tables B-IVa and b apply to Problem 10, the Columbia University Nevis target, and Tables B-Va and b apply to Problem 11. The spatial groups used in the six tables are 1/10th of the full size of the dimension under consideration; the energy spectrum groups are in intervals of 1 MeV from 0 to 50 MeV.

TABLE B-1a
SPECTRUM OF HIGH ENERGY NEUTRONS ESCAPING THE TARGET
12000 Protons, 800-MeV Incident on Axis of a ^{238}U Cylinder 7.5-cm Radius, 30-cm Long
A total of 8653 were produced

Angle Energy	0	33.56	48.19	60.00	70.53	80.61	90.00	99.59	109.47	120.03	131.81	146.44	180.00	Total
25	68	102	111	99	100	101	87	59	69	42	37	26		901
30	89	157	160	156	144	125	128	99	91	75	48	35		1307
40	95	122	154	121	145	111	76	67	59	41	21	26		1038
50	80	110	119	100	75	68	62	43	37	30	14	18		756
60	83	87	87	83	88	50	39	35	26	21	11	7		617
70	55	65	73	86	59	39	30	28	24	23	11	9		502
80	62	72	71	58	45	41	37	22	16	11	10	12		447
90	47	62	41	59	49	31	25	12	11	5	7	3		352
100	104	165	128	117	87	56	36	28	15	12	3	3		724
125	86	100	105	68	46	40	18	18	10	1	2	2		493
150	88	94	65	31	30	19	16	11	3	1	0	1		359
175	73	68	47	42	19	7	9	4	0	1	1	0		271
200	51	57	35	17	11	3	1	1	0	0	0	0		176
225	40	47	17	17	7	2	0	2	1	0	0	0		133
250	71	67	43	13	5	5	0	1	0	0	0	0		205
300	64	35	20	5	2	0	0	0	0	0	0	0		126
350	40	24	10	1	1	0	0	0	0	0	0	0		76
400	43	14	4	1	0	0	0	0	0	0	0	0		62
450	19	8	3	1	0	0	0	0	0	0	0	0		31
500	41	6	1	0	0	0	0	0	0	0	0	0		48
600	21	3	0	0	0	0	0	0	0	0	0	0		24
700	5	0	0	0	0	0	0	0	0	0	0	0		5
800														
Total	1325	1635	1294	1072	913	698	554	430	362	263	165	142		

TABLE B-1b
SUMMARY OF EVAPORATED PARTICLES FROM PRECEDING TARGET

Evaporation Spectra for 12301 Protons											
Particle Spectrum from Radial Dist											
11595	261	143	97	56	58	28	24	24	15		
Length Dist in Direction of Incident Beam											
4439	3219	2003	1254	757	362	188	49	13	17		
Energy Spectrum											
0	0	0	0	0	0	0	4	216	1546		
2205	1890	1574	1200	905	708	513	384	289	201		
158	124	90	67	65	38	28	24	20	14		
7	4	5	7	1	1	1	4	2	2		
1	9	0	0	0	2	1	0	0	0		
Evaporation Spectra for 255126 Neutrons											
Particle Spectrum from Radial Dist											
177189	15850	12955	10783	9003	7676	6435	5658	5156	4421		
Length Dist in Direction of Incident Beam											
35871	52328	42708	32236	26556	19045	13494	8319	2889	1678		
Energy Spectrum											
62408	57725	40446	27829	19244	13349	9287	6718	4898	3464		
2592	1851	1350	996	721	578	421	311	248	164		
132	75	68	62	38	33	34	18	13	19		
6	5	4	4	3	2	3	2	0	2		
0	1	0	0	1	0	0	0	0	0		
Evaporation Particles Produced											
H P Alpha E T ^3He											
255126	12301	3122	1319	51	1532						

14195 charged particles were slowed to below cutoff energy in the target

TABLE B-IIa
SPECTRUM OF HIGH ENERGY NEUTRONS ESCAPING THE TARGET
2000 Protons, 800-MeV Incident on Axis of a ^{238}U Sphere 7.5-cm Radius
A total of 1385 were produced

Angle Energy	0	33.56	48.19	60.00	70.53	80.41	90.00	99.59	109.47	120.00	131.81	146.44	180.00	Total
25	14	12	21	13	8	6	9	9	4	7	6	2		111
30	40	39	21	20	26	23	19	13	7	10	5	3		226
40	32	21	22	13	9	8	9	3	8	5	2	3		135
50	19	15	14	9	15	8	8	2	1	5	2	0		98
60	26	15	10	14	8	6	2	0	4	1	0	0		86
70	19	9	13	8	5	7	1	4	2	0	1	0		69
80	15	7	12	6	12	9	3	2	2	3	1	1		73
90	11	12	13	8	7	3	2	2	0	0	1	0		59
100	25	19	17	11	8	7	7	0	5	4	1	0		104
125	23	24	14	14	14	2	5	1	2	1	1	1		102
150	17	17	12	9	6	4	0	2	2	0	0	0		69
175	12	4	10	2	7	0	1	1	0	0	0	0		37
200	22	12	7	5	3	0	1	0	0	0	0	0		50
225	14	9	4	2	1	1	1	0	0	0	0	0		32
250	27	10	6	2	1	0	0	0	0	0	0	0		46
300	16	12	2	0	0	0	0	0	0	0	0	0		30
350	9	1	2	0	0	0	0	0	0	0	0	0		12
400	7	3	0	1	0	0	0	0	0	0	0	0		11
450	5	0	0	0	0	0	0	0	0	0	0	0		5
500	18	1	0	0	0	0	0	0	0	0	0	0		19
600	10	0	0	0	0	0	0	0	0	0	0	0		10
700	1	0	0	0	0	0	0	0	0	0	0	0		1
800														
Total	382	242	200	137	130	84	68	39	37	36	20	10		

TABLE B-IIb
SUMMARY OF EVAPORATED PARTICLES FROM PRECEDING TARGET

Evaporation Spectra for 1680 Protons

Particle Spectrum from Radial Dist

1637 18 15 3 2 2 1 2 0 0

Length Dist in Direction of Incident Beam

0 0 0 325 338 316 192 188 201 120

Energy Spectrum

0 0 0 0 0 0 0 0 30 223
271 279 199 161 131 110 64 54 28 27
21 19 14 10 13 6 3 2 3 2
1 2 1 2 1 0 2 6 0 0
0 1 0 0 0 0 0 0 0 0

Evaporation Spectra for 26699 Neutrons

Particle Spectrum from Radial Dist

21743 1338 1145 713 635 392 273 224 150 86

Length Dist in Direction of Incident Beam

2 52 59 3702 4925 4785 3867 3295 3264 2744

Energy Spectrum

5824 5665 4248 2991 2171 1561 1046 881 653 441
310 233 172 114 83 73 61 42 25 27
14 12 9 6 7 10 7 3 1 6
1 0 1 0 0 0 0 0 1 0
0 0 0 0 0 0 0 0 0 0

Evaporation Particles Produced

N P Alpha D T ^3He

26699 1680 449 200 4 221

1387 charged particles were slowed to below cutoff energy in the target

TABLE B-IIIa
SPECTRUM OF HIGH ENERGY NEUTRONS ESCAPING THE TARGET
2000 Protons, 800-MeV Incident on Axis of a Pb Cylinder 7.5-cm Radius, 30-cm Long
A total of 1700 were produced

Angle Energy	0	35.56	48.19	60.00	70.53	80.41	90.00	99.59	109.47	120.00	131.81	146.44	180.00	Total
25	19	14	16	19	18	11	10	13	11	9	1	5		146
30	27	35	26	23	26	23	19	16	11	10	4	4		224
40	19	22	23	23	22	19	22	8	8	3	4	4		177
50	13	18	18	18	21	13	6	7	4	2	3	1		124
60	11	19	19	17	20	4	8	4	5	1	1	2		111
70	22	18	14	19	14	16	3	7	4	4	2	3		126
80	14	18	13	8	10	5	6	4	2	1	4	1		86
90	10	13	13	8	7	7	3	1	2	1	1	1		67
100	27	27	23	21	16	15	8	6	3	0	3	1		150
125	24	22	23	20	11	5	5	2	1	1	3	0		117
150	15	21	17	11	11	3	5	1	0	0	0	1		85
175	12	16	11	12	1	2	3	0	0	1	0	0		58
200	10	13	8	3	5	1	1	0	1	0	0	0		42
225	19	14	5	0	0	2	0	0	1	0	0	0		41
250	25	14	6	2	1	0	0	0	0	0	0	0		48
300	19	11	6	2	0	1	0	0	0	0	0	0		39
350	10	7	1	0	0	0	0	0	0	0	0	0		18
400	10	6	0	0	0	0	0	0	0	0	0	0		16
450	7	1	0	0	0	0	0	0	0	0	0	0		8
500	10	1	1	0	0	0	0	0	0	0	0	0		12
600	3	0	0	0	0	0	0	0	0	0	0	0		3
700	2	0	0	0	0	0	0	0	0	0	0	0		2
800														
Total	328	310	243	206	183	127	99	69	52	33	26	23		

TABLE B-IIIb
SUMMARY OF EVAPORATED PARTICLES FROM PRECEDING TARGET
Evaporation Spectra for 2205 Protons and 29855 Neutrons

Particle Spectrum from Radial Dist										
1998	59	42	31	25	10	11	7	16	6	
Length Dist in Direction of Incident Beam										
519	461	333	255	227	116	99	97	70	28	
Energy Spectrum										
0	0	0	0	0	0	1	11	150	304	
360	324	219	190	148	124	79	60	46	38	
32	25	19	17	13	9	11	4	3	7	
4	2	1	0	1	0	1	0	0	0	
0	0	0	0	0	0	0	1	0	0	
Particle Spectrum from Radial Dist										
21897	1696	1325	971	823	687	557	639	450		
Length Dist in Direction of Incident Beam										
4786	4942	4195	3732	3154	2513	2056	2032	1476	959	
Energy Spectrum										
6611	6514	4749	3326	2359	1696	1210	818	661	515	
333	239	205	164	108	71	68	43	31	30	
37	14	11	10	7	3	8	2	5	3	
1	0	1	0	0	0	1	1	1	0	
0	0	0	0	0	0	0	0	0	0	
Evaporation Particles Produced										
N	P	Alpha	D	T	³ He					
29855	2205	462	121	9	179					

1946 charged particles were slowed to below cutoff energy in the target

TABLE B-IVa
SPECTRUM OF HIGH ENERGY NEUTRONS ESCAPING THE TARGET
2000 Protons, 550-MeV Incident on Axis of a Pb Cylinder 1.3-cm Radius, 15.2-cm Long
A total of 1105 were produced

Angle Energy	0	33.56	48.19	60.00	70.53	80.41	90.00	99.59	109.47	120.00	131.81	146.44	180.00	Total
25	16	13	12	11	6	7	7	6	4	2	1	2		87
30	23	15	20	23	17	9	8	9	2	4	3	3		139
40	11	19	17	21	16	14	6	5	3	3	2	1		118
50	14	14	11	17	15	11	5	6	3	3	1	1		101
60	12	12	11	10	4	10	5	5	1	2	1	0		73
70	8	13	13	8	14	3	2	4	3	0	0	0		68
80	11	7	7	12	5	2	2	5	0	0	0	0		51
90	8	9	5	9	3	2	2	0	1	0	1	0		40
100	19	17	17	12	9	7	4	0	1	0	0	0		86
125	23	17	14	8	9	3	2	0	0	0	0	0		76
150	14	20	15	8	0	1	1	0	0	0	0	0		59
175	15	12	8	3	3	0	1	1	0	0	0	0		43
200	12	7	5	1	1	1	0	0	0	0	0	0		27
225	12	7	2	0	1	0	0	0	0	0	0	0		22
250	31	11	4	2	0	0	0	0	0	0	0	0		48
300	11	15	1	0	0	0	0	0	0	0	0	0		27
350	12	1	1	0	0	0	0	0	0	0	0	0		14
400	16	2	0	0	0	0	0	0	0	0	0	0		18
450	5	0	0	0	0	0	0	0	0	0	0	0		5
500	3	0	0	0	0	0	0	0	0	0	0	0		3
600	0	0	0	0	0	0	0	0	0	0	0	0		0
700	0	0	0	0	0	0	0	0	0	0	0	0		0
800														
Total	276	214	163	145	103	70	45	41	18	14	9	7		

TABLE B-IVb
SUMMARY OF EVAPORATED PARTICLES FROM PRECEDING TARGET
Evaporation Spectra for 850 Protons and 13241 Neutrons

Particle Spectrum from Radial Dist										
818	7	4	2	1	4	6	4	3	1	
Length Dist in Direction of Incident Beam										
122	151	142	109	81	62	49	62	39	33	
Energy Spectrum										
0	0	0	0	0	0	0	1	53	116	
137	139	103	79	66	34	27	21	31	12	
6	8	6	2	2	1	3	1	1	1	
0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	
Particle Spectrum from Radial Dist										
12059	141	115	115	182	122	149	129	127	102	
Length Dist in Direction of Incident Beam										
1486	2046	1708	1678	1414	1102	1104	985	816	902	
Energy Spectrum										
2898	2843	2234	1547	1124	760	520	374	260	209	
138	84	71	56	27	24	18	9	13	10	
9	2	5	2	1	1	0	0	0	1	
0	0	0	0	0	0	1	0	0	0	
0	0	0	0	0	0	0	0	0	0	
Evaporation Particles Produced										
N	P	Alpha	D	T	³ He					
13241	850	147	46	2	45					
28 charged particles were slowed to below cutoff energy in the tan										

628 charged particles were slowed to below cutoff energy in the target

TABLE B-Va
SPECTRUM OF HIGH ENERGY NEUTRONS ESCAPING THE TARGET
5000 Protons, 800-MeV Incident on Axis of a Ta Cylinder 2-cm Radius, 5.1-cm Long
A total of 2512 were produced

Angle Energy	0	33.56	48.19	60.00	70.53	80.41	90.00	99.59	109.47	120.00	131.81	146.44	180.00	Total
25	28	31	21	30	20	23	13	12	19	10	11	7		225
30	38	42	34	32	28	28	23	22	20	23	10	13		313
40	41	40	42	20	27	18	16	14	17	13	12	6		266
50	30	29	27	20	22	13	15	10	11	9	9	2		297
60	25	22	19	30	19	17	12	10	5	3	4	2		168
70	21	19	24	19	14	8	2	10	2	3	0	3		124
80	23	25	17	13	17	8	7	2	1	1	3	2		119
90	16	13	13	15	10	14	6	7	4	2	1	1		102
100	41	36	43	28	26	13	11	8	2	5	0	1		214
125	41	19	17	18	15	4	1	8	3	2	2	1		131
150	26	26	22	12	8	1	5	1	0	1	0	0		102
175	29	13	16	10	6	3	2	0	1	0	1	0		82
200	30	20	12	9	3	1	0	0	0	0	0	0		75
225	24	16	11	7	1	0	1	2	0	0	0	0		62
250	37	16	14	5	1	0	0	0	0	0	0	0		73
300	38	14	7	1	1	0	0	0	0	0	0	0		61
350	40	10	6	1	1	0	0	0	0	0	0	0		58
400	26	2	2	0	0	0	0	0	0	0	0	0		30
450	19	7	0	0	0	0	0	0	0	0	0	0		26
500	23	3	0	0	0	0	0	0	0	0	0	0		26
600	36	1	0	0	0	0	0	0	0	0	0	0		37
700	20	0	0	0	0	0	0	0	0	0	0	0		20
800														
Total	652	405	547	270	219	131	114	106	85	72	53	38		

TABLE B-Vb
SUMMARY OF EVAPORATED PARTICLES FROM PRECEDING TARGET

Evaporation Spectra for 3106 Protons

Particle Spectrum from Radial Dist

2973 27 45 8 14 16 9 6 5 3

Length Dist in Direction of Incident Beam

369 326 323 359 307 307 292 299 190 0

Energy Spectrum

0 0 0 0 0 0 18 160 403 438

391 367 264 209 191 135 103 95 76 52

50 36 23 22 19 9 12 10 8 6

5 5 2 3 2 0 0 0 0 0

1 0 0 0 0 0 0 1 0 0

Evaporation Spectra for 25134 Neutrons

Particle Spectrum from Radial Dist

21452 768 742 444 430 376 244 218 233 2785

Length Dist in Direction of Incident Beam

2667 2479 2700 2627 2526 2515 2467 2565 2030 334

Energy Spectrum

4397 4971 3824 2886 2171 1651 1244 894 698 557

452 326 261 161 140 97 88 67 60 45

31 27 15 15 15 9 3 9 2 6

1 5 2 0 0 0 1 0 0 0

1 0 0 0 0 0 1 0 0 0

Evaporation Particles Produced

N P Alpha D T ³He

25134 3106 688 197 26 314

1743 charged particles were slowed to below cutoff energy in the target

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