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**NEUTRONS FROM DEUTERON BOMBARDMENT
OF LIGHT NUCLEI**

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(Ph.D. Thesis)

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MASTER

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NEUTRONS FROM DEUTERON BOMBARDMENT OF LIGHT NUCLEI *

ABSTRACT

Energy spectra of neutrons from deuteron bombardment of thick Be, Li, and C targets were measured at 5 lab angles from 3.5° to 32.3° by neutron time-of-flight techniques. Also measured were spectra of neutrons from deuteron bombardment of thin D_2 and Be targets. Deuteron energies ranged from 3 to 19 MeV. Deuterons lost about 1 MeV in the thin Be targets and about 0.25 MeV in the D_2 target.

The spectra were integrated to give absolute neutron yields or cross sections, and average neutron energies. For deuteron energies above 12 MeV, thick Be and Li produced approximately equal numbers of neutrons at 3.5° , while the 3.5° neutron yield from thick C was about two-thirds as great. For deuteron energies $E_d > 12$ MeV, cross sections for the $D(d,np)D$ reaction were determined. The average energies of neutrons from thick Be, Li, and C targets were $0.38 E_d$, $0.38 E_d$, and $0.39 E_d$, respectively, for E_d greater than 10 MeV. The average energy of neutrons from thin Be targets was about $0.5 E_d$ for $E_d > 6$ MeV.

From thin-target data neutron yields and average energies were calculated for thicker Be and D_2 targets. Dose rates from several neutron sources were compared.

This work was undertaken to investigate intense sources of fast neutrons.

* A Ph.D. thesis prepared under the supervision of Professor H.H. Barschall of the University of Wisconsin.

I. INTRODUCTION

Intense fast-neutron sources have uses outside the nuclear physics laboratory. Cancer radiotherapy is one such use. Fowler¹ has discussed the ability of fast neutrons to destroy poorly-oxygenated cancer cells more readily than γ -radiation does. This property has led to experiments at Hammersmith Hospital, London, England, where intense fast-neutron beams produced by 16 MeV deuteron bombardment of Be targets have been successfully used to treat tumors in patients. However, one of the Hammersmith neutron beam parameters is not ideal. A satisfactory source for radiotherapy should yield at least 5×10^{11} neutrons $\text{s}^{-1} \text{sr}^{-1}$ with an average energy of at least 10 MeV.² The average energy of the Hammersmith neutrons is about 7 MeV, and the decrease in beam intensity with penetration into tissue is too rapid for some applications. Bombarding energies or reactions other than those used at Hammersmith might produce a neutron beam more suitable for medical applications. A lack of detailed information on intense sources of fast neutrons makes it difficult to determine which neutron-producing reaction is best, or what size accelerator is needed for neutron therapy.

When controlled hydrogen fusion is achieved, thermonuclear reactor components will be subjected to high fluxes of neutrons with energies up to 14 MeV. Damage caused by such fluxes should be investigated before a thermonuclear reactor is built. An intense fast-neutron source could be used for this purpose. Because the defect production rate depends on the neutron flux and neutron energy,³ damage studies require the spectrum

and yield of neutrons from the source to be known.

Intense fluxes of fast neutrons may be produced by bombarding suitable targets with deuterons from small accelerators. Studies^{4,5} of neutrons from Be targets have shown that more neutrons are produced from 16 MeV deuteron bombardment of thick Be targets than from proton, ^3He or ^4He bombardment at the same energy; moreover, deuterons generally produce neutrons with higher average energy than do other projectiles with the same incident energy^{4,5,6} Allen et al.⁷ have shown that neutron production by deuteron bombardment generally decreases as the atomic number of the target material increases; therefore ^2H , ^3H , Be, Li, and C should be good target materials. The greatest number of neutrons are produced from a target thick enough to stop the deuterons, but the average neutron energy is higher if the target is thinner. The $\text{T(d,n)}^4\text{He}$ reaction has a 400 mb/sr 0° cross section at 150 keV deuteron energy and a reaction energy (Q-value) of 17.6 MeV, and can be used to produce fairly large fluxes of 14 MeV neutrons with a low-energy accelerator. Work is under way to eliminate the target-design problems that have limited neutron yield.⁸ Bombardment of the other materials with deuterons of energy greater than 8 MeV produces large numbers of fast neutrons; these reactions warrant a closer look.

Although a knowledge of the spectrum, yield, and average energy of the neutrons from a source used for radiotherapy or damage studies is desirable, extensive measurements of these data have not been performed. Radiologists have measured dose rates and depth doses for most of the reactions mentioned above at a few deuteron energies^{4,5,9} but such data are not very useful for non-medical purposes.

Energy spectra of neutrons from deuteron bombardment of thick Be targets have been published for deuteron energies from 7.5 MeV to 54 MeV.^{6,10-14} Most published spectra are relative measurements made with threshold detectors or emulsions, and these are summarized by Parnell¹⁵ (see Fig. 1). Average neutron energies are about 0.4 times the deuteron energy.

Allen *et al.*⁷ used activation detectors to measure the 0° yield produced by 15 MeV deuterons, and reported $\sim 10^{10}$ neutrons $\mu\text{C}^{-1}\text{sr}^{-1}$. Tochilin and Kohler⁶ also used activation detectors, and reported 0° yields of 5×10^{10} neutrons $\mu\text{C}^{-1}\text{sr}^{-1}$ and 9×10^{10} neutrons $\mu\text{C}^{-1}\text{sr}^{-1}$ for deuteron energies of 20 MeV and 24 MeV. Schweimer¹² measured absolute cross sections at deuteron energies of 40 MeV and 54 MeV; integrations of his extrapolated spectra give 0° yields of 2.3×10^{11} neutrons $\mu\text{C}^{-1}\text{sr}^{-1}$ and 4.5×10^{11} neutrons $\mu\text{C}^{-1}\text{sr}^{-1}$ at the two energies.

Parnell has discussed the possibility of increasing the average neutron energy by using a Be target thinner than the deuteron range,⁴ and has published spectra of neutrons from such targets.¹⁵ The spectra were measured with a proton-recoil telescope. 16.1 MeV deuterons striking a 51 mg/cm^2 Be target backed with Au produced neutrons with an average energy about 1 MeV higher than that of the neutrons from 16 MeV deuteron bombardment of a thick Be target. If average energies and cross sections of neutrons produced from thin Be targets were known for all deuteron energies up to some E_{max} , yields and average energies of neutrons from any thickness target bombarded by deuterons with any energy up to E_{max} could be calculated. No such measurements have been reported.

Figure 1: Relative spectra of neutrons emitted at 0° from thick Be targets bombarded by deuterons (from Ref. 15).

Parnell has also published a 0° spectrum of neutrons from 16.1 MeV deuteron bombardment of a thick C target.¹⁵ The average neutron energy was about 7 MeV, and was slightly higher than that of neutrons produced from Be under similar conditions. No measurement of yield was reported.

The neutron spectrum from the D + D interaction consists of neutrons from $D(d,n)^3\text{He}$ (Q-value: 3.3 MeV) and from $D(d,np)D$ (Q-value: -2.2 MeV). Dietrich et al.¹⁶ have recently measured differential cross sections for the $D(d,n)^3\text{He}$ reaction for 12 MeV-18 MeV incident energies, and have presented relative 0° spectra of neutrons from deuteron breakup. This work and earlier measurements¹⁷⁻²⁰ have shown that the $D(d,n)^3\text{He}$ 0° differential cross section is 100 ± 5 mb/sr from 10 MeV to 19 MeV deuteron energy. Lefevre et al.²¹ measured the spectra of neutrons from $D(d,np)D$ for 8 MeV-11 MeV incident energies, and presented 0° cross sections for this reaction. Earlier measurements of the $D(d,np)D$ 0° cross section at higher energies have been reported.^{19,22,23} Batra et al.²⁴ have used the cross sections given by Brolley and Fowler²² and by Goldberg¹⁷ to calculate yields and average energies of neutrons from deuterons bombarding a thick deuterium target. They have calculated an average neutron energy of 9.5 MeV and a yield of 2×10^{10} neutrons $\mu\text{C}^{-1} \text{sr}^{-1}$ for 12 MeV incident energy.

To provide information on fast neutron sources, this thesis presents measured spectra, yields, and average energies of neutrons from deuteron bombardment of thick Be, Li, and C targets. Also presented are spectra, cross sections, and average energies of neutrons

from thin Be and D_2 targets. Yields, cross sections, and average energies are shown as a function of incident energy and angle. Thick-target neutron yields and average energies are calculated using the Be and D_2 excitation functions.

II. Experimental Procedure

A. Deuteron Beam Production

Spectra of neutrons from deuteron-induced reactions were measured with pulsed-beam neutron time-of-flight techniques. Deuterons were accelerated to energies up to 11 MeV by a tandem Van de Graaff accelerator, and to energies greater than 11 MeV by a cyclotron-Van de Graaff combination (Fig. 2).

1. Cyclotron

The CNI-15 - model cyclotron is a fixed-energy machine made by Cyclotron Corp., Berkeley, Calif. The 81-cm diameter magnet pole faces are contoured with protruding iron wedges in alternate 60° sectors. This configuration produces a radially-increasing, azimuthally-varying field designed to focus relativistic particles travelling in isochronous orbits, and to keep these particles in proper phase with the RF dee voltage. Eight-MeV negative deuterium ions are produced in bunches 3 ns wide (FWHM) at a rate of 12.7 MHz. After acceleration the beam was swept across a 7.6-mm wide slit between Ta plates, so that one beam pulse in five reached the Van de Graaff. Typical swept-beam currents were 100 nA. Negative 1V pulses 10 ns wide were obtained from the oscillator which regulated the frequency of dee RF voltage; these pulses occurred with half the frequency of the beam pulses and served as timing markers.

2. Ion Source and Sweeper

When deuteron energies less than 11 MeV were required, negative

Figure 2: The LLL cyclograaff facility. The DC ion source and sweeper are between the cyclotron and the EN tandem Van de Graaff.

ions were obtained from a duoplasmatron ion source made by High-Voltage Engineering Corp., Burlington, Mass. The source contains a hot filament which produces a deuterium-ion plasma. Negative ions were electrostatically extracted and accelerated to 50 keV. Typical beam current was 20 μ A. The beam was swept across 6.4-mm wide slits to produce beam pulses 40 ns wide every 400 ns. A klystron buncher, consisting of 3 colinear cylindrical sections, decreased the time spread of the pulses to about 4 ns. Widths of beam pulses were measured by observing the widths of γ bursts produced when the beam struck a target. A timing unit containing a 10 MHz crystal oscillator and numerous frequency dividers regulated the frequency of both the sweeper RF voltage and the buncher RF voltage, and provided fast negative 1V pulses at half the frequency of the beam pulses to serve as timing markers. Swept-beam currents were typically 500 nA.

3. Van de Graaff Accelerator

The EN-model tandem Van de Graaff accelerator made by High-Voltage Engineering Corp. accelerated negative ions from the cyclotron or the duoplasmatron source. Dome voltages up to 5.8 MV were used for the work described in this thesis.

Beam pulses from the Van de Graaff were bent through 90° twice (see Fig. 2), thence bent upward at 3° into the time-of-flight (TOF) target pit, shown schematically in Fig. 3, and focused on a solid Be, Li, or C target or on a D₂ gas target.

B. Target Chambers and Assemblies

1. Chamber for Solid Targets

Solid targets were enclosed in a cylindrical brass chamber, shown in Fig. 4. Targets were fastened to a 0.76-mm thick Ta plate attached

Figure 3: Neutron time-of-flight pit (not to scale). Only the time-of-flight tubes used for these measurements are shown.

Figure 4: Chamber for solid targets.

to the shaft of a motor on top of the chamber. The plate was thick enough to stop the most energetic deuterons used. When the motor was turned on, the target assembly rotated until movable wedges on a disk attached to the motor shaft contacted microswitches and turned the motor off; rotation in the other direction was then possible. Thick targets were often clamped to both sides of the Ta plate, but thin targets were usually mounted singly so that backgrounds of neutrons from high-energy deuteron bombardment of Ta could be measured. The target chamber was electrically insulated so that beam current could be measured and integrated.

An Elcor model A310C current integrator measured collected charge. A Power Designs model 4010 precision power source, a $0.909 \text{ M}\Omega \pm 1\%$ resistor, and a $10 \text{ M}\Omega \pm 5\%$ resistor were used to check the accuracy of the current meter and current integrator. Uncertainties in meter readings in 10^{-6} A , $3 \times 10^{-7} \text{ A}$, and 10^{-7} A full-scale ranges were found to be smaller than 2%. Meter readings in $3 \times 10^{-8} \text{ A}$ and 10^{-8} A full-scale ranges were accurate to less than 5%. Voltage and resistance uncertainties limited the precision of the check of the two most sensitive meter ranges.

2. Gas Target Assemblies

Two gas target assemblies were used. The low volume assembly, shown in Fig. 5, was used for efficiency-curve measurements. The $(1.91 \pm 0.04) - \text{cm}$ long gas cell was filled with 99.9% D_2 to 1 atm. A $2.5\text{-}\mu\text{m}$ thick pinhole-free Havar* foil cemented to a Ta washer separated the D_2 from the beamline vacuum. Air blown through a slit in the gas-

 *42% Co, 20% Cr, 19% Fe, 13% Ni, 6% other.

Figure 5: Low-volume gas target assembly. The Ta collimator nearer the gas cell was removed for some measurements.

cell holder onto the washer edge cooled the beam-heated foil. Deuterons stopped in an Au disk.

The large D_2 target assembly, shown in Fig. 6, was used to measure D-D neutron spectra. The 10.2-cm long gas cell was filled to 2 atm with 99.9% D_2 . A 13- μ m thick Ta foil supported by an Au grid separated the gas from the beam-line vacuum. Deuteron beam spots larger than 6 mm in diameter were used to avoid burning holes in the Ta foil; up to 50% of the beam stopped in the Au grid. An air jet cooled the end of the gas cell, where deuterons stopped in a Ta disk. A -300 V potential applied to an insulated ring between either gas cell and the beam line suppressed electron emission from the foils and Au grid. Both cells were evacuated for background measurements.

C. Solid Targets

The Be targets were prepared by the LLL beryllium shop from blocks and sheets of 98.5% pure Be metal obtained from several commercial sources (e.g., Fisher Scientific Co.). We measured target diameters to $\pm 10 \mu$ m with a vernier caliper. Target thicknesses were measured to $\pm 1 \mu$ m with a micrometer. Targets were weighed with a Mettler balance accurate to $\pm 2 \mu$ g. Skin contact with the Be targets was avoided.

The thick Be target was a disk 5.08 cm in diameter and 2.56 mm thick weighing 9.57 g. The 1.84 g cm^{-3} calculated density agreed closely with the accepted value of 1.85 g cm^{-3} .²⁵ The target thickness was greater than the range of the most energetic deuterons used (deuteron ranges calculated from information in Janni's tables²⁶).

Figure 6: Large gas cell.

Thin Be targets were 5.08-cm diameter disks cut from 50- μ m or 75- μ m thick sheets. Thickness nonuniformities were about 3%. A third thin target was made by cementing together two 50- μ m thick disks. Areal densities of 9.9 mg cm⁻², 14.7 mg cm⁻², and 19.2 mg cm⁻² were calculated from masses and areas of the three targets; multiplying measured thicknesses by a density of 1.84 g cm⁻³ gave similar, but less precise results. Three target thicknesses were chosen to correspond to approximately 1 MeV energy loss by deuterons with energies in different ranges.

The Li targets were prepared at Lawrence Berkeley Laboratory from 98% pure natural (93% ⁷Li, 7% ⁶Li) Li obtained in lumps from various commercial sources. Each target was a disk 5 cm in diameter and 2.5 mm thick. Two targets clipped together stopped the most energetic deuterons used. The targets had to be kept under vacuum or immersed in kerosene to prevent oxidation. Before the targets were installed in the chamber kerosene was wiped from them with paper towels.

The thick C target was a 6.4 mm-thick rectangle of natural (99% ¹²C, 1% ¹³C) reactor-grade (99+ %) graphite.

D. Neutron Detectors

Deuterons striking a target produced neutrons and γ 's. Neutrons emitted at 5 lab angles ranging from 3.5°* to 32.3° traveled about 10.8 m and were detected with 5-cm diameter by 5-cm long NE 213 organic liquid scintillators made by Nuclear Enterprises, Inc. NE 213 has an H to C ratio of 1.23 and allows pulse shape discrimination against γ 's.

*0° neutron flux from a target is contaminated by neutrons from deuteron breakup on collimators and scanners in the beam tube.

Scintillators were mounted on RCA 8575 photomultipliers, which converted light pulses produced by charged particles recoiling in the scintillator into electrical signals. Fast -0.6 V signals from the photomultiplier anode marked the occurrence of a scattering event, and were used to determine time of flight. Linear pulses from the 9th dynode gave information about the amount of energy deposited in the scintillator and were also used for n- γ discrimination.

Scintillator-photomultiplier assemblies were placed in protective Al containers and were affixed to the ends of 2 m long, water-filled collimators. The collimators shielded the detectors from room-scattered neutrons.

A detector assembly and a collimator are shown in Fig. 7.

E. Electronics

The electronics used to obtain neutron time spectra are shown schematically in Fig. 8. Anode pulses from the detectors were fed into the "start" input of the time-of-flight (TOF) time-to-amplitude converter (TAC) while delayed "stop" signals came from the cyclotron oscillator or the sweeper timing unit. The amplitude of the TOF TAC output signal was proportional to the time difference between the "start" and "stop" pulses, and was related to neutron or γ flight time. The TOF TAC output pulses were fed into an analog-to-digital converter (ADC), which was gated by signals from discrimination circuitry described below. TAC linearity was checked by starting the TAC with signals from a scintillator detecting γ 's from a ^{22}Na source and stopping it with the oscillator pulses used normally. The resulting spectrum is shown in Fig. 9; deviations from linearity were smaller than

Figure 7: Collimator and scintillator-phototube assembly. Cables for -1800 V photocathode bias, preamp power supply, and detector outputs were spiraled to avoid providing a second neutron path through the collimator.

Figure 8: Electronics. Circuitry for n - γ discrimination is enclosed by a dashed line.

Figure 9: TOF TAC random spectrum (not all points in the measured spectrum are shown). Typical statistical uncertainties are shown by error bars on some points.

2% over most of the TAC range.

Alexander and Goulding²⁷ have discussed the difference between the light pulses produced in some scintillators by neutron-induced proton recoils and light pulses produced by γ -induced electron recoils; different light pulses give rise to differently-shaped linear pulses from the photomultiplier. Pulses from the detector dynodes went to a linear shaping amplifier, which produced bipolar pulses. Proton recoils resulted in bipolar pulses that crossed the voltage abscissa later than the ones from electron recoils. The linear-amplifier output was connected to a single-channel analyzer (SCA) working in integral (discriminator) mode. The SCA produced an output pulse when the bipolar input went through zero voltage. This output stopped a TAC started by the detector anode signal. Therefore, the n- γ TAC spectrum, shown in Fig. 10, had two peaks: one corresponded to neutrons and one to γ 's. The n- γ TAC output went to 2 SCA's operating in differential (window) mode. One SCA had a pulse height window set on the neutron peak; the other had a window set on the γ peak. The outputs of the SCA's expressed electronically whether the detected particles were neutrons or γ 's, and the "neutron" SCA output could be used to eliminate γ 's from the neutron spectra.

Slower neutrons from one beam pulse could arrive at the detector at the same time as faster neutrons from the next pulse. To eliminate pulses from overlapping low-energy neutrons and to eliminate low-energy γ pulses not removed by the n- γ discrimination circuitry, we required that recoiling charged particles deposit more than some specifiable minimum amount of energy in the scintillator. A ²²Na γ -source, whose

Figure 10: $n - \gamma$ TAC spectrum (not all points in the measured spectrum are shown). The arrow at channel 350 indicates the position of the lower edge of the neutron window.

Compton recoil spectrum is shown in Fig. 11, was used to set discriminator levels (biases). Discriminator cut-offs were set for the pulse height corresponding to the 0.511 MeV γ Compton edge, half this pulse height, and twice this pulse height. These discriminator levels corresponded to recoil-proton energies of 1.6 MeV, 1.0 MeV, and 2.5 MeV respectively.²⁸ Amplified linear pulses with amplitudes larger than the chosen discriminator level produced signals that were used in coincidence with signals from the neutron-identification circuitry to gate the ADC.

The ADC processed TOF TAC signals only if gating signals from the n- γ and pulse-height discrimination circuitry were present. (The neutron requirement was removed when γ 's were needed in the spectrum to provide timing calibration.) The ADC converted TAC pulses, which could have any height up to 10 V, into digital pulses with 512 possible amplitudes. The digital pulses went to a PDP-8 computer with storage for 16 512-channel spectra. Each 512-channel group stored pulses from a single detector; coincidences from the discriminator circuitry routed ADC pulses to the proper group. Each digital pulse caused a count to be added to the total in one channel; the pulse amplitude determined in which channel the count would be recorded. γ -signals from the 24° detector were stored in a special group (called group zero) and were used to correct small timing shifts.

A pulse-height spectrum is shown in Fig. 12. Neutron counts are represented by dots, and crosses represent γ counts. The γ -peak at channel 469 and the neutron distribution in channels lower than 335 were produced by the same set of beam pulses. The neutron counts in

Figure 11: ^{22}Na pulse-height spectrum (not all points in the measured spectrum are shown). The arrow at the midpoint of the 0.511 MeV γ Compton edge indicates the position of the 1.6 MeV neutron bias; uncertainty in the midpoint position was less than ± 2 channels. The spectrum is cut off at a pulse height approximately corresponding to the 1.0 MeV neutron bias. The solid line was drawn to guide the eye.

Figure 12: Time spectrum of neutrons from 18 MeV deuteron bombardment of a thick Be target (not all points in the measured spectrum are shown). Neutrons were detected at 3.5° . Crosses indicate γ 's. Typical statistical uncertainties are shown by error bars. The absence of counts in channels 340 through 380 is caused by the 2.5 MeV neutron bias. Arrows indicate neutron energies.

channels greater than 380 were produced by beam pulses striking the target about 400 ns before the pulses producing the other neutrons. The 2.5 MHz beam pulse rate produced spectra with no overlap when a 2.5 MeV neutron energy bias was used, but produced overlapping spectra when neutron energies exceeded 14 MeV and a 1.6 MeV bias was used. A slower pulse rate would have prevented overlap, but would also have excessively reduced beam current. Neutron flight times (and hence energies) could be calculated for any channel from a knowledge of the γ flight time (36 ns), the number of channels between γ peaks, and the beam pulse rate.

III. Data Analysis

Differential cross sections can be calculated from the number of neutron counts per channel:

$$\sigma(\theta, E_n, E_d) = \frac{C}{\epsilon a} \frac{m_A}{N_O} (t\rho_m)^{-1} (\Delta\Omega)^{-1} \frac{q}{Q} (\Delta E_n)^{-1} \prod_{i=1}^n (1 + \chi_i) \quad (1)$$

where $\sigma(\theta, E_n, E_d)$ is the differential cross section at deuteron energy E_d for production of neutrons with energy E_n at angle θ , C is the number of neutrons counted in time T in a channel ΔE_n MeV wide, χ_i is the correction for the i th source of dead time, ϵ is the detection efficiency of the scintillator, $a = 0.90$ and is the factor by which the neutron flux was attenuated in passing through container walls and 11 m of air, m_A is the atomic mass of the target material, $N_O = \text{Avogadro's number}$, $6.024 \times 10^{23} \text{ (g-mole)}^{-1}$, $t\rho_m$ is the areal density of the target, $\Delta\Omega$ is the solid angle subtended by the scintillator, Q is the charge collected in time T (i.e., $Q = \int_0^T I_b dt$, where I_b is the beam current), and $q = 1.602 \times 10^{-19}$ coulomb. Because a cross section for neutron production from a thick target is not a well-defined quantity, spectra of neutrons from thick targets are given in terms of neutron yield:

$$Y(\theta, E_n, E_d) = \frac{C}{\epsilon a} (\Delta\Omega \Delta E_n Q)^{-1} \prod_{i=1}^n (1 + \chi_i), \quad (2)$$

where $Y(\theta, E_n, E_d)$ is the yield per steradian per MeV per μC of E_n - MeV neutrons produced at angle θ by E_d - MeV deuteron bombardment, and the other parameters are the same as in Eq. 1. Two parameters requiring further discussion are the dead-time correction and the detector efficiency.

A. Dead Time

The PDP-8 computer takes about 25 μ s to process a digital pulse and cannot accept another input during this time. Similarly, the TOF TAC cannot respond to signals arriving in a 9 μ s interval after a valid start signal is received. Signals arriving during these "dead" periods are lost.

Computer dead-time corrections were determined by comparing counts in two scalers. One scaler counted the number of valid start signals accepted by the TOF TAC in a data-gathering period. The other scaler also counted TOF TAC starts, but was gated off when the computer was busy. The ratio of counts in the two scalers was $(1 + \chi_{\text{comp}})$ and was typically 1.1.

TOF TAC dead time was measured with two intense sources. One source was placed near a scintillator-photomultiplier assembly. Anode pulses from the photomultiplier were used to start the TAC. The same pulses were delayed and also used as stop signals. After TAC output pulses had been counted for a measured time, another source was placed near the scintillator, and pulses produced by both sources were counted. The first source was then removed, and the count rate due to the second source alone was determined. The dead time was determined by using

$$R_{12} = R_1 + R_2 - 2 R_1 R_2 \tau, \quad (3)$$

where R_{12} is the counting rate with both sources present, R_1 and R_2 are the counting rates with single sources present, and τ is the TAC dead time. τ was used to calculate the TAC dead-time correction $\bar{R}\tau$, ($\bar{R}\tau = \chi_{\text{TAC}}$) where $\bar{R}$ was obtained by dividing the number of counts in

the TAC "starts" scaler by the duration of the counting period.

$(1 + \bar{R}\tau)$ typically equalled 1.03.

Dead time correction for other electronic components were much smaller than those of the computer and the TOF TAC.

B. Detector Efficiencies

Some of the neutrons passing through an organic scintillator interact with H and C atoms, and the neutron flux is exponentially attenuated. Neutrons scattering from H produce recoiling protons. Neutrons interacting with C can scatter elastically or inelastically and can produce C recoils or α 's from $^{12}\text{C}(n,\alpha)^9\text{Be}$ and $^{12}\text{C}(n,n')^3\alpha$ reactions if the neutron energy is high enough. In addition, neutrons scattered from H and C can have further interactions. If the pulses produced by recoiling charged particles are larger than the detection threshold, the neutrons producing the recoils will be counted. The detection efficiency for neutrons is the number of neutrons detected divided by the number impinging on the detector.

Detector efficiencies for the three proton-energy biases used are shown in Fig. 13 (1.0-MeV bias was used very little). Efficiencies were calculated with an expression given by Elwyn et al.:²⁹

$$\epsilon(E_n) = (1 - \frac{B}{E_n}) P_1 / [1 - (1 - \lambda) P_2], \quad (4)$$

where (E_n) is the detection efficiency for neutrons with energy E_n (MeV), B is the bias in MeV, $\lambda = (\frac{n_H \sigma_H}{n_H \sigma_H + n_C \sigma_C})$ and is the fraction of interacting neutrons that interact with H, n_H and n_C are the numbers of H and C atoms per unit volume, σ_H and σ_C are the H and C total cross sections for

neutrons of energy E_n , $p_1 = \lambda(1 - e^{-(n_C \sigma_C + n_H \sigma_H)t})$ and is the probability that a neutron will interact with a proton, $p_2 = 1 - \frac{3}{2x} (1 - \frac{2}{x^2}) - \frac{3e^{-x}}{x^2} (1 + \frac{1}{x})$ and is the probability that a neutron will interact after scattering from C, $x = (\frac{3}{2} h^2 t)^{1/3} (n_C \sigma_C + n_H \sigma_H)$, h is the diameter of the cylindrical scintillator, and t is the scintillator thickness. Eq. 3 pertains to a cylindrical scintillator with its axis pointing toward the neutron source and takes into account the production of recoil protons by direct n-p collisions and by proton collisions with neutrons scattered from one or more C atoms. Edge effects, the anisotropy of the n-p center-of-mass angular distribution, multiple scattering of neutrons by protons, and energy loss by scattered neutrons are not taken into account.

α 's that produce pulses with amplitudes above detection bias are produced in significant numbers by neutrons with energies greater than 14 MeV. For 1.0 MeV and 1.6 MeV biases, Eq. 3 was modified to include the effects of these α 's in the efficiency calculation: $\epsilon = p_1 [(1 - \frac{B}{E_n}) + \frac{n_C \sigma'_C}{n_H \sigma_H}] / [1 - (1-\lambda) p_2]$, where σ'_C is a cross section for the production of detectable α 's by neutrons interacting with C and is estimated from values given by Bowen et al.³⁰

Niiler et al.³¹ have measured relative efficiency curves for biases of 1.9 MeV and 3.1 MeV; their curves have shape uncertainties of $\pm 5\%$. Relative efficiency values for 2.5 MeV bias were interpolated from these measurements and were converted to absolute values by using Eq. 3 to calculate the efficiency at $E_n = 8$ MeV. Between 6 MeV and 16 MeV the values of the interpolated and the calculated curves differ by less than 2%. Above 16 MeV, where α -production affects the efficiency at this

bias, interpolated values were used in place of calculated values. Efficiency differences below 6 MeV were probably caused by multiple scattering of neutrons by protons, but because the scintillators used by Miller et al. were 2.5 times larger in diameter than the ones we used, the interpolated shape was not used to correct the calculated values.

Pulse heights corresponding to 2.5 MeV and 1.6 MeV biases were twice ($\pm 1\%$) and half ($\pm 1\%$) the pulse height corresponding to the 1.6 MeV bias. Because the proton pulse-height response curve is not linear, a small error in the pulse-height setting for the 1.6 MeV bias could cause a sizeable difference in cross sections calculated from spectra measured at two different biases. For example, if a bias level were set at 1.5 MeV rather than 1.6 MeV, the bias at twice the pulse height would be 2.35 MeV instead of 2.5 MeV, and cross sections at 4 MeV calculated from the high-bias measurement would be 8% larger than those calculated from the lower-bias measurement. Sufficient care in setting the 1.6 MeV bias was taken to make bias-position uncertainties less than 3%; biases were checked daily.

Neutrons from the $D(d,n)^3\text{He}$ reaction were used to measure efficiencies at energies ranging from 8 MeV to 18 MeV. The energy spread of the neutron group was about 100 keV at 8 MeV, and was caused by deuteron energy loss in 0.3 mg/cm^2 of D_2 gas. Efficiencies were calculated from neutron counts with Eq. 1; $D(d,n)^3\text{He}$ cross sections were obtained from Refs. 17 and 20. Uncertainties in the measured efficiencies were about 5% from 8 MeV to 13 MeV and were due to uncertainties in cross sections and in the number of neutron counts. As the

deuteron energy increased, neutron backgrounds also increased, and integration of the monoenergetic peak became more difficult. Above 13 MeV, measurement uncertainties were greater than 10%. Differences between measured efficiency values and values shown in Fig. 13 were about the same as measurement uncertainties. These and other³² measurements indicate uncertainties in the calculated efficiencies of about 7%, except within 2 MeV of the bias, where multiple scattering make uncertainties larger than 10%.

C. TOF8 Computer Code

A CDC-6600 computer code named TOF8* calculated lab and CM cross sections from neutron counts. Neutron flight times corresponding to any channel position were calculated from a knowledge of the γ flight time, the separation of successive γ peaks, and the beam pulse rate; a random TAC spectrum was used to correct for TAC nonlinearities: if $\sum_{i=a}^b n_i = A$, where n_i is the number of random counts in channel i , b is the channel number of one γ peak, and a is the channel number of the γ 's arriving a pulse period later, then $t_x = t_y + \frac{P}{A} \sum_{i=x}^b n_i$, where t_x is the flight time of neutrons in channel number x , $t_y = 36$ ns, and P is the pulse period. Neutron energies were calculated relativistically from flight times. The code had provisions for subtracting backgrounds, for averaging points in a specifiable energy interval, and for calculating statistical errors.

A code subroutine named TOFPLIT ^{ψ} integrated the energy spectra to give differential cross sections $\sigma(\theta)$ and average energies $\bar{E}$: $\sigma(\theta) = \int_0^{E_{\max}} \sigma(\theta, E_n) dE_n$, and $\bar{E} = \frac{1}{\sigma(\theta)} \int_0^{E_{\max}} E_n \sigma(\theta, E_n) dE_n$. $\sigma(\theta, E_n)$ values

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ψ Written by author

Figure 13: Detector efficiencies. Efficiencies used by computer code TOF8 were specified every 100 keV out to some energy $E_{\max}$. The efficiency at $E_{\max}$ was used for neutron energies larger than $E_{\max}$.

did not extend to $E_n = 0$ because of bias cutoff; therefore, the spectra were extrapolated. The first three $\sigma(\theta, E_n)$ values for which E_n was more than 1 MeV larger than the bias energy were averaged, and this average value was extended to zero energy.

IV. Results

A. Spectra

Figures 14-24 show representative neutron spectra.* Measurements at two different biases were made for each target and each deuteron energy. The spectra shown are all from the higher-bias measurements, in which arrival times of neutrons from succeeding beam pulses were well-separated. Cross sections were averaged over 250 keV intervals. (Not all calculated points are shown.) Because multiple scattering of neutrons with energies near bias by protons in the scintillator increases the efficiency uncertainty, and therefore the cross-section uncertainty, we ignored points in the spectra whose energies were not at least one MeV greater than the neutron bias; however, two or three low-energy points from a spectrum measured with a low bias were often included in a spectrum measured at a higher bias to increase the spectral energy range. Statistical uncertainties are indicated by error bars. Cross-section uncertainties due to bias-position error, neutron loss in $n - \gamma$ discrimination, correction uncertainties, error in number of target nuclei and error in collected charge are all smaller than 3%. The largest uncertainties are due to the efficiency uncertainties discussed previously: the spectra have scale errors of about $\pm 7\%$ above 4 MeV and about $\begin{matrix} + 5\% \\ - 15\% \end{matrix}$ below 4 MeV. (The errors at the lower energies are not symmetric because multiple-scattering corrections, if included in the efficiency calculations, could only decrease the cross sections.)

Figures 14 and 15 show energy spectra of neutrons produced by 18 MeV deuteron bombardment of thin Be targets and detected at 3.5° and 16.7° .

*All measured spectra will be presented in a forthcoming Lawrence Livermore Laboratory report.

Figure 14: Cross section for production of neutrons at 3.5° by 18.1 MeV deuteron bombardment of a 19.2 mg cm^{-2} Be target as a function of lab neutron energy. Neutron bias was 2.5 MeV. The solid line was drawn to guide the eye. The dashed lines, which also appear in succeeding figures, indicate alternate extrapolations to zero energy.

Figure 15: Cross section for production of neutrons at 16.7° by 18.1 MeV deuteron bombardment of a 19.2 mg cm^{-2} Be target as a function of lab neutron energy. Neutron bias was 2.5 MeV. The solid line was drawn to guide the eye.

Figure 16: Cross section for production of neutrons at 2.5° by 8.8 MeV deuteron bombardment of a 9.9 mg cm^{-2} Be target as a function of lab neutron energy. Neutron bias was 1.6 MeV. The solid line was drawn to guide the eye.

Figure 17: Cross section for production of neutrons at 16.7° by 8.8 MeV deuteron bombardment of a 9.9 mg cm^{-2} Be target as a function of lab neutron energy. Neutron bias was 1.6 MeV. The solid line was drawn to guide the eye.

Figure 18: Neutron yield at 3.5° from 18.1 MeV deuteron bombardment of a thick Be target as a function of lab neutron energy. Neutron bias was 2.5 MeV.

Figure 19: Neutron yield at 16.7° from 18.1 MeV deuteron bombardment of a thick Be target as a function of lab neutron energy. Neutron bias was 2.5 MeV.

Figure 20: Neutron yield at 3.5° from 14.0 MeV deuteron bombardment of a thick Be target as a function of lab neutron energy. Neutron bias was 2.5 MeV.

Figure 21: Neutron yield at 3.5° from 8.8 MeV deuteron bombardment of a thick Be target as a function of lab neutron energy. Neutron bias was 1.6 MeV.

Figure 22: Neutron yield at 3.5° from 18.1 MeV deuteron bombardment of a thick C target as a function of lab neutron energy. Neutron bias was 2.5 MeV.

Figure 23: Neutron yield at 3.5° from 19.0 MeV deuteron bombardment of a thick Li target as a function of lab neutron energy. Neutron bias was 2.5 MeV.

Figure 24: Relative yield of neutrons emitted at 3.5° from deuteron bombardment of D_2 . Deuteron energy at the center of the gas cell was 16.5 MeV. Multiplication of the ordinate scale by 1.73 converts the ordinate to $\sigma(3.5^\circ, E_n)$ in mb/(sr MeV). Neutron bias was 2.5 MeV. The dashed line indicates an assumed extrapolation.

The peaks in the spectra correspond to neutrons leaving the ^{10}B nucleus in the ground state and various excited states. Table I lists ^{10}B states and the corresponding neutron groups; states having similar excitation energies E_x are listed under the same group number. From the figures we see that neutrons leaving the residual nucleus in the ground state and first excited state are more numerous at 16.7° than at 3.5° , while neutron groups corresponding to other levels stay the same size or become smaller as the angle increases. Niller et al.³⁴ have measured the angular distributions of group-0 and group-1 neutrons and have reproduced the distribution shapes with stripping theory for $\Delta l = 1$ angular momentum transfer. Their results show that the angular distributions of the group-0 and group-1 neutrons have maxima at about 30° .

Because of the neutron energy bias, points in the spectra do not extend down to zero energy. The dashed lines in the figures illustrate two extreme extrapolations. The line of longer dashes (extrapolation A) has a constant ordinate equal to the average of the ordinates of the three lowest-energy points and extends from the abscissa of the third (highest-energy) point to zero energy. The line of shorter dashes (extrapolation B) extends from the origin to a point on the long-dash line one-third of the way from its high-energy end to the ordinate axis.

Figures 16 and 17 show spectra of neutrons produced by 8.8 MeV deuteron bombardment and detected at 3.5° and 16.7° . If we compare Fig. 14 and 16, we see that the cross sections for production of group-5 and group-7 neutrons are much larger for 8.8 MeV bombarding energy than for 18 MeV incident energy, but the cross sections for production of the other neutron groups are about the same size for the two incident energies. The previously-described increase with angle of the cross sections for

Table I: Neutron groups and corresponding energy levels in ^{10}B . (Not all the levels above 5.2 MeV excitation energy are listed.) The numbers in parentheses by some excitation energies indicate the number of levels with approximately that energy. Additional information about the levels may be found in Ref. 33.

Neutron Group	0	1	2	3	4	5	6	7	8	9
^{10}B level excitation energy (MeV)	0 (g.s)	.7	1.7	2.2	3.6	4.8 5.2(3)	6(3)	7.5(4)	8.9(2)	11
Approx. neutron energy (MeV) for 18 MeV deuteron energy	21	21	20	20	18	16	15	13.5	12.5	10
Approx. neutron energy (MeV) for 9 MeV deuteron energy	12.5	12	11	10.5	9	7.5	6.5	5	3.5	--

production of group-0 and group-1 neutrons is evident for 9 MeV bombarding energy.

Figures 18-21 show energy spectra of neutrons from thick Be targets. Figs. 18 and 19 show spectra of neutrons produced by 18 MeV deuteron bombardment and detected at 3.5° and 16.7° . Some structure is visible; for example, the bump at 12.5 MeV in Fig. 18 probably corresponds to the large peak at 12.5 MeV in Fig. 14. The 16.7° spectrum differs from the 3.5° spectrum in the same way that the thin-target spectra at the same angles differ: the 16.7° points have somewhat smaller values at 3 MeV, much smaller values from 4 MeV to 17 MeV, and somewhat larger values above 17 MeV than the 3.5° points have. 3.5° spectra for 14 MeV and 9 MeV bombarding energies are shown in Figs. 20 and 21. Features in Fig. 21 may be related to structure in Fig. 16; for example, the sharp ledge between 7 MeV and 8 MeV in Fig. 21 probably corresponds to the large peak at the same energy in Fig. 16.

Figs. 22 and 23 show spectra of neutrons emitted at 3.5° from 18 MeV deuteron bombardment of a thick C target and 19 MeV deuteron bombardment of a thick Li target. Like the 18 MeV thick-Be spectrum in Fig. 18, these spectra exhibit maxima at about 7 MeV; however, the maxima in the Li and C spectra are more pronounced than the one in the Be spectrum, which is rather flat from 3 MeV to 7 MeV. At larger angles the C and Li spectra generally show monotonically decreasing yield for increasing neutron energies, as the Be spectra did. A persistent feature in the C spectra is the ledge at about 14 MeV in Fig. 22. Like the Be spectra, the Li spectra show an increase with increasing angle in the number of neutrons in the high-energy tail (above 18 MeV in Fig. 23).

Figure 24 shows a relative spectrum of neutrons emitted at 3.5° from 16.5 MeV deuteron bombardment of D_2 gas contained in the large cell. The deuteron energy quoted is the energy at the center of the cell. Neutrons from the $D(d,n)^3He$ reaction had a 200 keV energy spread due to deuteron energy loss in the D_2 gas; 6-ns wide beam pulses resulted in a neutron energy uncertainty of ± 700 keV. Neutrons with energies below 13 MeV were from deuteron breakup. Because an unknown fraction of deuterons stopped in the Au grid, relative neutron yield was calculated. To obtain absolute cross sections we normalized the spectra to the known^{17,20} $D(d,n)^3He$ cross section at 3.5° (multiplying the arbitrary ordinate scale in Fig. 24 by 1.73 converts the scale to mb/(sr MeV).)

B. Cross Sections, Yields and Average Energies

Two sets of spectra, corresponding to two neutron biases, were measured for each incident energy and each target. TOFPLT2 integrated the neutron spectra and calculated average neutron energies using extrapolation A. When 1.6 MeV was the lower of the two biases, an average integral value $I_A = \frac{I(\text{Bias} = 1.6 \text{ MeV}) + I(\text{Bias} = 2.5 \text{ MeV})}{2}$, where I is the integral of a spectrum measured with the indicated bias, was calculated. Spectra measured with 1.0-MeV bias were seldom used because this bias always allowed high-energy neutrons to be contaminated by low-energy neutrons from the previous pulse. Use of extrapolation B caused the integrals of the spectra to be reduced by an ΔI . The integrals I_A calculated with extrapolation A were multiplied by $(1 - \frac{\Delta I}{2I_A})$, and the results for spectra of neutrons emitted at 3.5° from Be targets are plotted in Fig. 25 as a function of deuteron energy. The two main sources of error are the 47% efficiency uncertainty discussed previously

Figure 25: Cross sections and yields calculated by integrating $3.5^\circ {}^9\text{Be}(d,n){}^{10}\text{B}$ spectra are shown as functions of deuteron energy. The abscissae of the cross-section points are the deuteron energies at the centers of the targets. Smooth curves were drawn to guide the eye.

and the extrapolation uncertainty ($\frac{\Delta I}{I}$); these were combined quadratically. Uncertainties in yields of neutrons emitted at 3.5° from thick Be targets are $\pm 10\%$ above 12 MeV deuteron energy and increase to $\pm 15\%$ at 8 MeV deuteron energy. Uncertainties in integrated cross sections for production of neutrons at 3.5° from thin-Be targets are $\pm 10\%$ above 9 MeV deuteron energy and increase to $\pm 15\%$ at 6 MeV deuteron energy. Henceforth, uncertainties in cross sections and yields will be $\pm 10\%$ unless otherwise noted.

Fig. 26(a) shows the angular variation in yield of neutrons produced from a thick Be target for three deuteron energies. For 9 MeV bombarding energy, yield uncertainties are $\pm 17\%$ for all angles larger than 3.5° . Fig. 26(b) shows the angular variation in cross section for production of neutrons from thin Be targets for three deuteron energies.

Fig. 27 shows the integrated yields of neutrons emitted at 3.5° from thick Li and C targets as functions of deuteron energy. Uncertainties in Li yields are $\pm 15\%$ at deuteron energies smaller than 9 MeV.

Fig. 28(a) shows the integrated neutron yields from 19 MeV deuteron bombardment of Li and 18 MeV deuteron bombardment of C as a function of lab angle.

Fig. 29(a) shows integrated D-D breakup cross sections for 16.5 MeV, 14.4 MeV, and 12.3 MeV deuteron energies as a function of lab angle. Uncertainties in the cross sections vary from $\pm 10\%$ at 3.5° to $\pm 15\%$ at 23.8° and are mainly due to $\pm 7\%$ efficiency uncertainty, $\pm 5\%$ error in the $D(d,n)^3\text{He } 0^\circ$ cross section, and 5% - 10% extrapolation uncertainty. Fig 29(b) shows the angular distribution of the $D(d,n)^3\text{He}$ neutrons produced by 16.5 MeV deuterons as a function of lab angle. The distribution was normalized to 100 mb/sr at 0° ; this value is uncertain by $\pm 5\%$.

Figure 26: (a) Neutron yields from thick Be targets as a function of lab angle. Curves were drawn through the prints to guide the eye.

(b) Cross sections for neutron production by deuteron bombardment of thin Be targets as a function of lab angle. Curves were drawn through the points to guide the eye.

Figure 27: Yields calculated by integrating spectra of neutrons emitted at 3.5° from thick Li and C targets bombarded with deuterons are shown as functions of deuteron energy. Smooth curves were drawn through the points to guide the eye.

Figure 28: (a) Neutron yields from thick Li and C targets as functions of lab angle. Smooth curves were drawn to guide the eye.

(b) Average energy of neutrons from deuteron bombardment of thick Li and C targets shown as a function of lab angle. Curves were drawn to guide the eye.

Figure 29: (a) Cross section for production of breakup neutrons by deuteron bombardment of D_2 shown as a function of lab angle. Deuteron energies were 16.5 MeV, 14.4 MeV, and 12.3 MeV; higher energies correspond to larger cross sections. Curves were drawn through the points to guide the eye.

(b) $D(d,n)^3He$ cross section for 16.5 MeV deuteron energy as a function of lab angle.

Figure 30 shows the 0° breakup cross sections from Fig. 29(a) plotted as a function of deuteron energy. Also shown are measurements listed by Lefevre *et al.*; ²⁴ these measurements have uncertainties of 10% (Anderson) to 20% (Lefevre *et al.*).

Average neutron energies $\bar{E}_A$ (Bias = 2.5 MeV) and $\bar{E}_A$ (Bias = 1.6 MeV) calculated with extrapolation A from spectra measured at 2.5-MeV bias and 1.6-MeV bias usually differed by less than 3%. The increase $\Delta\bar{E}$ in the average neutron energy caused by using extrapolation B was determined. $\bar{E}_A$ (Bias = 2.5 MeV) was multiplied by $(1 + \frac{\Delta\bar{E}}{2\bar{E}_A})$, and the results for spectra of neutrons emitted at 3.5° from Be targets are shown in Fig. 31. Above 8 MeV deuteron energy the average energy of neutrons from thin Be targets is approximately $0.5 E_d$. Above 10 MeV deuteron energy the average energy of neutrons from a thick Be target is approximately $0.38 E_d$. Average-energy uncertainties are due mainly to extrapolation uncertainties and are $\pm 5\%$ unless otherwise noted. For neutrons from thin Be, average-energy uncertainties increase to $\pm 10\%$ at 7 MeV deuteron energy. For neutrons from thick Be, average-energy uncertainties are $\pm 10\%$ at 8 MeV deuteron energy.

Fig. 32 shows average energy of neutrons from thick and thin Be targets for three deuteron energies as a function of lab angle. The slow decrease, and in some cases, small increase, in average neutron energy with increasing angle is explained by the angular distribution of the group-0 and group-1 neutrons discussed previously. For 18 MeV and 14 MeV deuteron bombardment of thick Be, average-energy uncertainties are $\pm 8\%$ for angles larger than 16.7° . For 9 MeV incident energy, average-energy

Figure 30: 0° cross section for production of $D(d,np)D$ neutrons plotted as a function of deuteron energy. Values from Ref. 20 are also shown.

Figure 31: Average energy of neutrons emitted at 3.5° from deuteron bombardment of thin (circles) Be and thick (crosses) Be targets plotted as a function of deuteron energy. Lines were drawn through the points to guide the eye.

Figure 32: (a) Average energy of neutrons from a thick Be target plotted as a function of lab angle.

(b) Average energy of neutrons from thin Be targets plotted as a function of lab angles.

uncertainties are about 10% for all angles. For 18 MeV, 14 MeV, and 9 MeV deuterons bombarding thin Be, average-energy uncertainties are $\pm 8\%$ for angles larger than 16.7° .

Fig. 33 shows average energies of neutrons emitted at 3.5° from thick Li and C targets plotted as a function of deuteron energy. Uncertainty in average energy of neutrons from Li decreases from $\pm 15\%$ at 5 MeV to $\pm 10\%$ at 9 MeV.

Fig. 28(b) shows the average energy of neutrons from thick Li and C targets plotted as a function of lab angle. 19 MeV deuterons bombarded Li, and 18 MeV deuterons bombarded C.

Average energy of 3.5° neutrons from $D(d,n)$ are 8.8 MeV, 9.6 MeV, and 10.7 MeV for deuteron energies of 12.3 MeV, 14.4 MeV, and 16.5 MeV.

C. Calculated Yields and Average Energies

Neutrons from a Be target 1 MeV thick have higher average energy than those from a thick Be target, but the thin-target yield is, of course, smaller. A Be target of intermediate thickness might produce neutrons whose average energy is significantly higher than that of neutrons from a thick target, but whose numbers are only slightly fewer. The thin-target data shown in Figs. 25 and 32 may be used to calculate yields and average energies of neutrons from a Be target with any thickness greater than 1 MeV.

Yields of neutrons from thick targets may be calculated from thin-target data:

$$Y_T(\theta, \epsilon_D) = N_O (q m_A)^{-1} \int_{\epsilon_x}^{\epsilon_D} \sigma(\theta, \epsilon) \left(\frac{d\epsilon}{d(\rho x)} \right)^{-1} d\epsilon, \quad (5)$$

Figure 33: Average energy of neutrons emitted at 3.5° from thick Li (circles) and thick C (crosses) targets shown as a function of deuteron energy.

where $Y_T(\theta, \epsilon_d)$ is the yield per μC per sr of neutrons produced at lab angle θ by ϵ_d -MeV deuteron bombardment of a target T whose atomic mass is m_A , $N_O = 6.024 \times 10^{23} \text{ (gram-mole)}^{-1}$, $q = 1.602 \times 10^{-13} \mu\text{C}$, ϵ_x is the energy of deuterons leaving T ($\epsilon_x = 0$ if T is a stopping target), $\sigma(\theta, \epsilon)$ is the cross section for neutron production at angle θ by ϵ -MeV deuteron bombardment of a target $d\epsilon$ -MeV thick, and $-\langle \frac{d\epsilon}{d(\rho x)} \rangle$ is the mass stopping power ($\text{MeV g}^{-1} \text{ cm}^2$) by deuterons in T. If T is composed of layers that have different compositions, m_A is a function of ϵ .

Eq. 6 defines the average energy of neutrons from T:

$$\bar{E}_T(\theta, \epsilon_d) \equiv [Y_T(\theta, \epsilon_d)]^{-1} \int_0^{E_{\max}} Y_T(\theta, E, \epsilon_d) E dE ; \quad (6)$$

substituting Eq. 5 into Eq. 6, we see that

$$\begin{aligned} \bar{E}_T(\theta, \epsilon_d) &= [Y_T(\theta, \epsilon_d)]^{-1} N_O (qm_A)^{-1} \int_{\epsilon_x}^{\epsilon_d} \int_0^{E_{\max}} \sigma(\theta, E, \epsilon_d) E dE \left\langle \frac{d\epsilon}{d(\rho x)} \right\rangle^{-1} d\epsilon \\ &= [Y_T(\theta, \epsilon_d)]^{-1} N_O (qm_A)^{-1} \int_{\epsilon_x}^{\epsilon_d} \sigma(\theta, \epsilon) \bar{E}(\epsilon) \left\langle \frac{d\epsilon}{d(\rho x)} \right\rangle^{-1} d\epsilon, \quad (7) \end{aligned}$$

where $\bar{E}_T$ is the average energy of neutrons from T, $Y_T(\theta, E, \epsilon_d)$ is the yield per MeV per μC per sr of E -MeV neutrons produced at lab angle θ by ϵ_d -MeV deuteron bombardment of T, $\sigma(\theta, E, \epsilon)$ is the cross section for production of E -MeV neutrons at angle θ by ϵ -MeV deuteron bombardment of a target $d\epsilon$ -MeV thick, $\bar{E}(\epsilon)$ is the average energy of neutrons from ϵ -MeV deuteron bombardment of a target $d\epsilon$ -MeV thick, and the other parameters are as in Eq. 5. Deuteron ranges and stopping powers were obtained from Refs. 26

and 35; data from these sources differed by about 3%.

Using Eqs. 5 and 6, we calculated the yield and average energy of neutrons emitted at 3.5° from a thick Be target bombarded with 18 MeV deuterons to be 5.4×10^{10} neutrons $\text{sr}^{-1} \mu\text{C}^{-1}$ (7% higher than the measured value) and 6.45 MeV (0.3 MeV lower than the measured value). We also calculated the yield and average energy of neutrons emitted at 3.5° from 18 MeV deuteron bombardment of a Be target in which the deuterons lose 9 MeV to be 4.4×10^{10} neutrons $\mu\text{C}^{-1} \text{sr}^{-1}$ and 7.15 MeV. The uncertainty in the calculations is about 10% and is due to cross-section uncertainties, uncertainties in deuteron stopping powers, and removal of an uncertain number of deuterons from the beam by nuclear reactions in the thick target. (The (d,n) reactions alone remove about 2% of 18 MeV deuterons incident on a thick target; this process was taken into account in the calculations.)

From Figs. 31 and 33 we see that 5 MeV deuteron bombardment of a thick Li target produces neutrons with about 1.5 MeV higher average energy than the neutrons from 5 MeV deuteron bombardment of thick Be targets have. To see if a thick composite target would produce neutrons with higher average energy than those from single-element targets, we calculated the yield and average energy of neutrons from a target in which 18 MeV deuterons lost 13 MeV in Be and stopped in Li. The results, 5.3×10^{10} neutrons $\mu\text{C}^{-1} \text{sr}^{-1}$ and 6.5 MeV, differ only slightly from thick-Be results.

For calculating the yield and average energy of 0° neutrons from thick D_2 targets, we used cross sections interpolated from the data given

in Fig. 29 and in Refs. 17 and 18. Deuteron energy-loss values were obtained from Ref. 26. Average neutron energies were obtained from kinematics calculations at deuteron energies below breakup threshold, from estimates by Barschall,² and from our measurements. (We assumed no difference to exist between 0° energies and 3° energies.) Table II shows the results of the calculations. These results have uncertainties of about 10% due to uncertainties in the thin-target cross sections and average energies used.

D. Doses

Therapists who use radiation to treat patients must know what effect the radiation has on tissue. One measure of radiation's effect is the radiation dose or the energy deposited per unit mass of absorber. Dose is expressed in rads (one rad = 100 erg g⁻¹).

Neutron yield may be converted to dose rate at any distance from the neutron source:

$$\phi = Y r^{-2} \frac{\kappa}{100}, \quad (8)$$

where ϕ ($\frac{\text{rads}}{\mu\text{C}}$) is the dose rate per μA produced in a material r cm from a neutron source yielding Y neutrons $\mu\text{C}^{-1} \text{ sr}^{-1}$, and κ (erg cm² g⁻¹) is a conversion factor.³⁶ κ is a function of the irradiated material and the neutron energy;* values of κ for tissue are listed in Ref. 35. Table III lists dose per μC at 100 cm for several neutron sources discussed above.

* Average energies were used--dose rates calculated from subdivisions of spectra were added, and the sum was equal to the dose rate calculated from yield and average energy of the whole spectrum.

Table II: Calculated yields and average energies of neutrons produced at 0° by deuteron bombardment of a thick D_2 target

Deuteron Energy (MeV)	Yield ($10^{10} \frac{\text{neutrons}}{\mu\text{C sr}}$)	Average Neutron Energy (MeV)
17	8.0	9.6
15	5.0	9.1
12	2.3	8.9
8	.65	8.3

Table III: Dose per μC at 100 cm from a neutron source.

Neutron Source	Yield ($10^{10} \frac{\text{neutrons}}{\mu\text{C}\cdot\text{sr}}$)	Average Neutron Energy (MeV)	κ ($10^{-7} \frac{\text{erg cm}^2}{\text{g}}$)	Dose Rate ($\frac{\text{rad}}{\mu\text{C}}$)
18 MeV deuterons, thick Be target 3.5°	5.0	6.8	4.7	.024
18 MeV deuterons*, 9 Mev thick Be target, 3.5°	4.0	7.4	5.0	.020
18 MeV deuterons, thick C target, 3.5°	3.4	7.0	4.7	.016
18 MeV deuterons, thick Li target, 3.5°	4.9	6.8	4.7	.023
17 MeV deuterons, thick D ₂ target 0°	8.0	9.6	5.4	.043

*calculation normalized by comparing thick-target calculation and measurement.

V. Comparison with Previous Measurements

The results described in the preceeding section may be compared with previous measurements. The shapes of spectra of neutrons from Be presented in Figs. 18, 20, and 21 differ from the relative spectra in Fig. 1 mainly at lower neutron energies; for example, the spectrum in Fig. 17 is fairly flat below 7 MeV, while the spectra in Fig. 1 produced at similar bombarding energies drop steeply in this energy region. Lack of a multiple-scattering correction in our detector efficiencies may account for some of the differences, but we believe that for measuring low-energy neutrons, time-of-flight techniques are generally superior to those involving emulsions or activation detectors.

The relative spectrum of neutrons from 16 MeV deuteron bombardment of C published by Parnell¹⁵ is quite similar in shape to his spectra of neutrons from Be. Our spectra of neutrons from C have shapes that differ from the shapes of our spectra of neutrons from Be: for example, the spectrum in Fig. 22 has a more pronounced peak than the spectrum in Fig. 18 produced at the same angle and incident energy. Above 6 MeV neutron energy, the shape of the spectrum in Fig. 22 is similar to the shape of Parnell's spectrum of neutrons from C.

Parnell extrapolated the spectra in Fig. 1 to zero energy and from them calculated average neutron energies to be about $0.42 E_d$, where E_d is the incident deuteron energy.¹⁵ This result is about 10% higher than our result of $0.38 E_d$. The difference exists because the number of low-energy neutrons is relatively larger in our spectra than in the spectra of Fig. 1. From his spectrum of neutrons from a thick C target, Parnell

calculated an average energy 7 MeV, which is 13% higher than our value of 6.2 MeV; however, both measurements suggest that the average energy of neutrons from a thick C target is 0.1-0.2 MeV higher than that of neutrons from a thick Be target.

The yield of 10^{10} neutrons $\mu\text{C}^{-1} \text{ sr}^{-1}$ from a thick Be target measured by Allen *et al.*⁷ for 15 MeV incident energy is much lower than our value of 3×10^{10} neutrons $\mu\text{C}^{-1} \text{ sr}^{-1}$. Allen *et al.* give no uncertainty for this measurement made with activation detectors. Tochilin and Kohler's yield measurement at 20 MeV deuteron energy is about 20% lower than an extrapolation of our yield curve would predict. The other yield measurements discussed in the introduction lie on a curve that is a reasonable extrapolation of the yield curve in Fig. 25.

The results of our measurements of the $\text{D(d,np)D } 0^\circ$ cross section are 20% - 30% higher than the results of other measurements.^{19,21,23,32,38} Because we normalized our spectra to the $\text{D(d,n)}^3\text{He}$ cross section, a possible explanation of this discrepancy is that the uncertainty in the shapes of our efficiency curves above 16 MeV is greater than our estimate of 10%.

Batra *et al.* calculated spectra of neutrons from deuteron bombardment of thick D_2 targets and from these spectra calculated neutron yields and average neutron energies.²⁴ Their yields differ by 10% - 20% from the results of our calculations; for example, they reported yields of 2.1×10^{10} neutrons $\text{sr}^{-1} \mu\text{C}^{-1}$ for 12 MeV incident energy and 5.2×10^{10} neutrons $\text{sr}^{-1} \mu\text{C}^{-1}$ for 16 MeV incident energy, while our results were 2.3×10^{10} neutrons $\mu\text{C}^{-1} \text{ sr}^{-1}$ and 6.3×10^{10} neutrons $\mu\text{C}^{-1} \text{ sr}^{-1}$ for the same energies. For 8 MeV deuteron energy, their average-energy value of 8.24 MeV differs by less than 1% from our value; at higher deuteron

energies, however, the difference is greater: for 16 MeV deuteron energy, they report an average neutron energy of 11.30 MeV, which is 0.6 MeV higher than the average energy we measured for neutrons from 16.5 MeV deuteron bombardment of a thin (200 keV energy loss) D_2 target. We calculated an average energy of 9.3 MeV for neutrons from 16 MeV deuteron bombardment of a thick D_2 target. In their calculations, Batra et al. used cross sections from Refs. 17 and 22, which present data for deuteron energies only up to 13 MeV; calculations at higher energies must have been made with estimated cross sections.

Numerous measurements and calculations of dose rates from various neutron sources have been published, and these are summarized in Table IV. Also presented in Table IV are dose rates calculated from the measurements described in this thesis. Our dose rates range from 7% to 40% higher than those determined by other investigators. In an attempt to measure dose rates due to neutrons from 7 MeV and 11 MeV deuteron bombardment of a thick Be target, we used a tissue-equivalent ionization chamber similar to one described by Rossi;³⁷ however, the measurements were inconclusive because our measured dose rates fell between our calculated values and values suggested in Ref. 9, and had errors approximately equal to the difference between the two values. The uncertainty in the measurement with the tissue-equivalent chamber is partly caused by a lack of knowledge of the conversion factor from collected charge to dose for neutrons. Additional dose-rate measurements are planned at higher incident energies, where the disagreement between our determinations and those in Ref. 9 is larger.

Table IV: Comparison of dose per μC at 100 cm in the forward direction from neutron sources.

Reference	Neutron Source	Dose as quoted in reference ($\frac{\text{rad}}{\mu\text{C}}$)	Dose from present measurements ($\frac{\text{rad}}{\mu\text{C}}$)
4*	16 MeV deuterons, thick Be target	0.013	0.016
	16 MeV deuterons, thick C target	0.010	0.012
	16 MeV deuterons, thick Li target	0.011	0.016
9 ^ψ	18 MeV deuterons, thick D target	0.017	0.024
23 ^ψ	12 MeV deuterons, thick D target	0.011	0.012
	16 MeV deuterons, thick D target	0.030	0.032

*10cm x 10cm neutron collimator

ψ5cm x 5cm neutron collimator. The author gives an expression for calculating dose per 6000 μC at 125 cm target-to-detector distance: $\Phi = 0.00027 E_d^{2.7}$, where E_d is the incident energy in MeV.

ψno neutron collimation.

VI. Conclusion

From the results of our measurements we may conclude that the $D(d,n)$ and ${}^9\text{Be}(d,n)$ reactions are more suitable neutron sources for radiotherapy and damage studies than are the other reactions investigated. For use in radiotherapy, a small and relatively inexpensive cyclotron capable of accelerating $40\text{ }\mu\text{A}$ of deuterons to 10 MeV could produce 5×10^{11} neutrons $\text{s}^{-1} \text{sr}^{-1}$ from a thick D_2 target, and while the 8.6 MeV average neutron energy is less than ideal for therapy, it is higher than the average energy of the neutrons used for therapy at Hammersmith Hospital. Neutrons with about 10 MeV average energy could be produced from a thin Be target or a thick D_2 target bombarded by 20 MeV deuterons from a large cyclotron; a Be target would be easier to handle than a D_2 target and hence would be preferable if deuteron beam currents large enough to produce a sufficiently high neutron flux were available. For neutron damage studies, wherein maximum flux is more important than maximum average energy, a thick D_2 or Be target should be used. Li targets produce neutrons in about the same quantity and with about the same average energy as Be targets do, but handling and storage problems are much greater for highly reactive Li. The average energy of neutrons from C targets is not sufficiently higher than that of neutrons from Be targets to justify the 30% smaller neutron yield from C.

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