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LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

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ABSTRACT

Fast neutrons of energies in the multi-MeV region are of great interest for biological and medical applications because of their special type of interaction with tissue-like material. The neutron energy is delivered to the tissue by one or several of the following means: (a) recoil protons, (b) recoil heavy particles, (c) nuclear disintegration, and (d) low-energy protons from neutron reactions with nitrogen and γ rays from neutron capture in hydrogen.

This report discusses intensity estimations for different types of neutron beams, and is based on averaged and interpolated values from published and unpublished sources. In making the estimates, we have assumed realistic values for the distance from neutron source to exposure area. This assumption is necessary for two reasons: (a) to allow for the installation of sufficient shielding to reduce the background radiations in the irradiation area, and (b) to allow for neutron beam divergence so that reasonably large objects can be irradiated uniformly.

INTRODUCTION

Fast neutrons of energies in the multi-MeV region are of great interest for biological and medical applications because of their special interaction with tissue-like material. Energy is delivered to tissue by

a. recoil protons,
b. recoil heavy particles,
c. nuclear disintegration,
d. low-energy protons from neutron reactions with nitrogen, and γ rays (which produce electrons) from neutron capture in hydrogen.

Depending on the neutron energy, the importance of the different processes for the total dose delivered to tissue varies considerably. For energies below 14 MeV, J. F. Fowler[1] gives the proportions which are reproduced in Fig. 1. In the same figure, values given by Irving et al.[2] for 30-MeV neutrons, incident normally, are also plotted. At about 30 MeV, elastic and inelastic events contribute with about the same percentage to the total absorbed energy. In the neutron energy region of 30 MeV the depth-dose curves for absorbed dose start to become reasonably flat for a tissue slab of 30 cm thickness. In this energy region, the large contribution to the absorbed dose from secondary particles with a high LET provides a high relative biological effectiveness. For these particles, the oxygen-enhancement effect on radiation damage decreases to nearly unity. This is of particular interest for medical applications of neutrons in the treatment of malignant diseases.

We studied in this report how an intense and fairly monochromatic neutron beam could best be produced. Economic considerations suggest that energy requirements for the neutron beam not be excessive. We concentrated therefore on a neutron beam of about 25 to 30 MeV with a half width of a couple of MeV. This energy region is accessible for a number of existing high-current accelerators--at LRL, the 88-inch sector-focused cyclotron.

This report discusses intensity estimations for neutron beams, and is based on averaged and interpolated values from published and unpublished sources. In making these estimates, we have assumed realistic values for the distances from the neutron source to the exposure area. The distance assumptions are necessary for two reasons: (a) to allow for the installation of sufficient shielding to reduce the background radiations in the irradiation area, and (b) to allow for neutron beam divergence so that reasonably large objects can be irradiated uniformly.

Neutron Production

There are essentially three neutron production processes for neutrons between 25 and 30 MeV. They are (p, n) reactions, (d, n) stripping reactions, and the final-state $T(d,n)^4He$ reaction. Most of the work done on stripping reactions is in the field of low energy in order to obtain information about nuclear states and to check the validity of Butler's stripping theory.[3] At higher energies ($\geq$ 20 MeV) only a few experiments have been performed, and most of these are concerned with the angular distribution and relative yields of the emitted neutrons. At such energies, absolute cross sections are given only for particular reactions with defined final states, e.g., R. J. Slobodrian[4] gives 62 mb/sr at 15 deg for $^{13}C(d,n)^{13}C$-3.68 MeV,[5] and 3.5 mb/sr at 9 deg for $^{3}Be(d,n)^{10}Be$-3.37 MeV,[5] etc.

For monoenergetic neutrons, most of the available experimental data are from the (p, n) reaction in light nuclei. The reason for this is that (a) most accelerators accelerate protons only, and (b) the neutron energy from stripping is only half the deuteron energy, whereas the neutrons from (p, n) have a peak at the proton energy less the Q value.

In the following, we compare the three types of reactions with respect to intensity, monochromatic behavior, and angular distribution.

Neutrons Produced by Deuteron Stripping

For the required neutron energy, 25 to 30 MeV, we need information about the stripping cross sections of 50- to 60-MeV deuterons. Serber[6] predicts a cross section of 104 mb for Be ($5A^{1/3} \times 10^{-26}$ cm^2). At a much higher energy (160-MeV deuterons) Millburn et al.[7] have found that the stripping cross section for beryllium and carbon targets is about three times as high ($\approx$ 330 mb and 430 mb respectively) as predicted by Serber's formula. For 190-MeV deuterons, Knox has compared the stripped neutron yield from different target elements.[8] The relative yields follow Serber's formula. Knox mentions that the neutron yield from 190-MeV deuterons is 40 times the neutron yield from 340-MeV protons on Be at 0 deg. The total high-energy neutron production cross section for 190-MeV deuterons on Be is about three times that for protons. The total neutron production cross section for protons on Be is on the order of 130 mb, therefore we assume that the total production cross section for neutrons from 190 MeV protons is $\approx$ 400 mb (total inelastic cross section 522 mb); an upper limit for higher energy stripping.

At lower energies (10-MeV deuterons) Smith and Kruger[9] report a total neutron yield of 3.23×10^{10} neutrons/microcoulomb of deuterons, or 5.2×10^{-3} neutrons/deuteron. The range of these deuterons is 80 mg/cm^2 in Be, therefore the total neutron cross section is

$$\sigma \approx \frac{3.23\times10^{10}\times9}{0.08\times6.023\times10^{23}\times6.25\times10^{12}}$$

$$\approx 1.35 \text{ barn.}$$

Neutrons of all energies were measured in this experiment. Also, this cross section is an upper limit for the stripping reaction.

William Wadman[10] gives the following yields from a thick Be target:

a. 60-MeV deuterons: 5×10^{11} neutrons/microcoulomb,

b. 15- to 20-MeV deuterons: 1×10^{11} n/μC.

Absolute yields from deuteron bombardments at 24 and 15 MeV are given by Crandell et al.[11] For thick Be targets they obtained 18.5×10^{10} and 1.9×10^{10} n/μC of deuterons respectively. Total neutron yields from deuterons on Cu and Ta targets are considerably smaller than for Be targets (Fig. 2). However, for stripping, according to the Serber theory, one should expect higher cross sections (Fig. 3). This shows that only relatively few of the neutrons are due to the stripping reaction.

In his report, "Shielding for the 70-Inch Cyclotron Experimental Facility at USNRDL," Moyer[12] gives a compilation of available data comparing neutron production for protons up to 100 MeV and deuterons up to 50 MeV. He mentions that the actual data in most cases are obtained by reasonable interpolations from published information. For neutrons produced by 50-MeV deuterons he obtained the curves reproduced in Fig. 4.

Essentially three processes are responsible for the neutron production in Be when bombarded with deuterons:

(a) stripping of a deuteron by the Be,

(b) direct interaction, producing a recoiling neutron,

(c) evaporation of neutrons.

All these processes contribute to the total neutron yield.

The numbers given above are total yields, and therefore the neutrons are from all three types of reactions. However, for applications in biological or medical experiments it is important to have a neutron beam with a small contribution of low-energy neutrons.

The neutron spectra produced by stripping are Gaussian-like distributions with a maximum at one-half the deuteron energy (Fig. 5):

$$n(E)dE = \frac{\sqrt{B_d\times E_0\,dE}}{\pi\,[E - 1/2\,E_0]^2 + B_d\times E_0} \times\text{half width } \sqrt{B_d\times E_0}$$

where E_0 = deuteron energy, and B_d = deuteron binding energy = 2.2 MeV.

The angular distribution for stripped neutrons follows a Gaussian distribution,[13]

$$\sigma(\theta) = \sigma_0 \exp(-\theta^2/b^2);\quad b = 1.8\,(2.2/E_0)^{1/2}.$$

For neutrons from 190-MeV deuterons, Helmholtz et al.[14] measured an angular width of 0.15 radian, which is in agreement with the Serber model. In contrast to the stripping reaction, the spectra from evaporation and direct processes vary considerably with the target element. Using the experimental data of Bostick[15] and Adelson,[16] Moyer has constructed neutron spectra from Be bombardment with 60-MeV deuterons. These spectra are reproduced in Figs. 6 and 7, and are the basis for the smooth spectra given in Fig. 4. For E_d = 60 MeV the total emission spectrum gives a yield of 2.3×10^{-1} neutrons/deuteron for a thick Be target[17] (Fig. 2).

From a comparison of the total neutron yields and the stripping cross sections, it is obvious that for a monoenergetic neutron beam with a small contribution of low-energy neutrons, beryllium or possibly lithium should be used as a stripping target and not heavy elements.

Cross-section estimates can also be obtained from the inverse reaction, the pickup reaction, which has a similar reaction probability--more precisely, the cross section of the pickup reaction is a lower limit for the stripping reaction. In stripping at 60 MeV, both particles--the proton and neutron--can leave the nucleus, but in the pickup reactions the incoming particle must form a deuteron in a defined final state. Hadley and York[18] observe a total deuteron production cross section of 26 mb from a 90-MeV proton beam. About half of all the deuterons are in the forward direction, 0 to 25 deg. The cross sections found by Hess and Moyer[19] for deuteron production with 300-MeV neutrons at large angles is smaller. The production mechanism in this case is thought to be an indirect pickup on the surface of the nucleus. The authors mention that the direct pickup process might be larger at lower energies, thus we can say that the total pickup at 60 MeV should be on the order of 50 mb. We are left with a considerable uncertainty for the absolute stripping cross section. With a lower limit of 50 mb and an upper limit of 500 mb the most probable value is ≈ 300 mb for Be.

(p, n) Reactions

Much experimental work has been devoted to (p, n) reactions in light nuclei like Be, Li, He ^{3}H, and ^{2}H. In the energy region from several MeV to a few hundred MeV, monoenergetic neutron beams have been produced by use of these reactions. We discuss some of the work that provides the information for cross sections and angular and energy distributions.

At high energies Larson has used the D(p, n)2p reaction by irradiating liquid deuterium (30-cm-long target) with 710-MeV protons.[20] The neutron energy width was not much larger than the 11-MeV energy loss of the protons in the target. At 7 deg from beam axis and 4.50 m from a 0.75×1.25-in. target Larson measured 10^4 neutrons per 1.3×10^{10} protons. Ball produced a 300-MeV neutron beam of 44 MeV width, by inserting a 0.5-in. LiD target into the LRL 184-inch cyclotron beam.[21] He reports more neutrons in the 0-deg direction with the LiD target than with a Be target with the same number of atoms. The neutron yield for 0.5-in. LiD is about half that for a 2-in. Be target. No absolute values are given.

In a recent paper Measday[22] discusses the quality of neutron beams from the ^{2}H(p, n)2p reaction in liquid deuterium. Parameters for the energy range from 80 to 150 MeV are given in Table I.

The ^{2}H(p, n) reaction was further studied by Langsdorf et al.[22] for 144-MeV and 96-MeV protons. For the peak they obtain 15.7 mb/sr. MeV and 16.7 mb/sr. MeV respectively. They state that the energy spectra observed agree with the calculated spectra.

At the UCLA spiral-ridge cyclotron York et al.[2] introduced a heavy water target into the cyclotron to obtain a monoenergetic neutron beam of 50 MeV. At a distance of 3.5 meters from the internal target they measured a neutron beam intensity of 10^5 n/cm^2 sec. The authors do not quote the proton beam intensity, but mention that its maximum was 100μA. The energy spread at full width half maximum was about 4 MeV. Batty et al.[25] discuss the most suitable monoenergetic neutron sources at 30 and 50 MeV. Tables in their report (included here as Tables II and III) compare the neutron cross sections and the spectra from different (p, n) reactions (Figs. 8 and 9). The "cleanest" and most intense beams are obtained with a tritium target.

According to Batty, at higher proton energies Li and D still seem to be a suitable target material for a monoenergetic neutron beam. However, according to the neutron spectra given by Moyer for 100-MeV protons on Be the neutron energy peak is rather broad, even at 0 deg (Fig. 10). The low-energy neutrons are much more abundant when Be is used instead of D or Li.

The $^{3}H(d, n)\,^{4}He$ Reaction

This is one of the most suitable reactions for obtaining a monoenergetic neutron beam in the region of 14 to 18 MeV.[26] The reaction cross section is still high for 10-MeV deuterons (24 mb/sr) giving a neutron beam of about 27 MeV. However, at this energy, tertiary reactions also can take place--for example, $D + T \rightarrow n + p + T$ and $D + T \rightarrow 2n + {}^{3}He$. The neutrons from these reactions have a much lower energy than in the reaction leading to an α particle and a neutron. The total neutron cross section for 6-MeV deuterons is about 60 mb/sr and for 14-MeV deuterons it is about 300 mb/sr at 0 deg. Most of the neutrons produced by 10-MeV deuterons on tritium therefore have energies much lower than 27 MeV. There is a second peak at about half the dueteron energy.[27]

Estimation of Dose Rate in 30-MeV Neutron Beam Produced by $D(p, n)^{2}p$ Reactions

For an estimation of the dose delivered by 30-MeV neutrons, we make the following assumptions:

1. $2 \times 10^{8}\,n/cm^{2} = 1$ rad (Irving et al.:[2] $\approx 10^{8}\,n/cm^{2} = 1$ rad).
2. Cross section for the D(p, n)2p reaction 40 mb/sr.
3. Proton current = 100 μA(i.e., 6.25×10^{14} protons/sec = ϕ).
4. D_2 target thickness = 0.1 g/cm^2 (or 4 MeV energy loss for 30-MeV protons).

Number of D_2 atoms in target = $(6.023 \times 10^{23}/2) \times 0.1$ D atoms = 3.0×10^{22} D atoms/cm^2.
Therefore

neutrons/sr sec = $N\sigma\phi = 3 \times 10^{22} \times 40 \times 10^{-27} \times 6.25 \times 10^{14} = 7.5 \times 10^{11}$ neutrons per sec sr
or $\approx 10^{12}$ n/sec sr.

At 3 meters the neutron flux and dose rate are:
(a) $\Phi = (10^{12}\,n/sec\ sr)/(300\ cm)^{2} \approx 10^{7}\,n/cm^{2}\ sec$;
(b) dose rate = $10^{7}\,n/cm^{2}\ sec \div 2 \times 10^{8}\,n/cm^{2}$ rad = 0.05 rad/sec, or 3 rad/min.

About 5 to 10 times this dose rate can be obtained from neutrons produced by deuteron stripping, assuming a cross section of 300 mb for D, Li, or Be and a deuteron beam of 50 to 100 μA. The main disadvantage with this type of neutron beam is the significant dose from the many lower-energy neutrons that accompany the stripped neutrons. This dose is of the same order of magnitude as the dose from the 30-MeV neutrons.

We can calculate the energy distribution of the neutrons produced by a 60-MeV deuteron beam on a Li or Be target. If a target thickness equivalent to 3 MeV is assumed, it will be small in comparison with the full width at half maximum of the neutron spectrum at 20 MeV (30 ± 10 MeV). With this target thickness (100 mg/cm^2 ≈ 3 MeV) and a stripping cross section of 300 mb, we would expect:

neutrons/sec = $\sigma N \Phi$ (protons/sec) = $3 \times 10^{-25} \times 6.7 \times 10^{21} \times 6.25 \times 10^{14} = 1.3 \times 10^{12}$ neutrons/sec.

The angular distribution of these neutrons would be

$$f_{(\theta)} = f_{(0)} \times \exp(-\theta/b)^2$$

where

$$b = 1.8\ (2.2/E_0)^{1/2} = (2\times\omega)^{1/2};$$

therefore the width ω of the distribution = 0.24 radian.

We have $\approx 7.0\times 10^{11}$ neutrons/sec which are emitted into a cone with an open angle of 0.48 radian. At 3 meters, the area extended by this cone is

$$A = \pi r^2,$$

$$A = (300\ \text{cm}\times 0.24)^2\pi = 1.8\times 10^4\ \text{cm}^2;$$

therefore; the average flux density is

$$1.3\times 10^{12}\ \text{n/sec} \div 1.8\times 10^4\ \text{cm}^2 \approx 7\times 10^7\ \text{neutrons/cm}^2\ \text{sec},$$

or a dose of 0.35 rad/sec or 20 rad/min.

CONCLUSIONS

Presently available accelerators can produce by (n, p) reactions neutrons with fairly good energy resolution--a necessity for biological experiments and medical applications. For such beams, the dose delivered to the center of a 30-cm-thick tissue slab is reasonably large compared with the surface dose. However, the maximum dose obtained in such a beam, 3 meters downstream from the target, is low for many experimental and medical applications. Depending on the type of exposure, the requirement for a reasonably large distance between the irradiation site and the target may be relaxed. For many applications, a strong magnetic field for sweeping away the charged particles and space for 6 to 8 feet of shielding material between the neutron target and the irradiation site is necessary. For high neutron intensities, the broad energy distribution of the neutrons from deuterons interacting with light target elements might be an acceptable compromise. Dose rates of nearly 5 to 10 times as high might be obtained.

The presented estimations, which are based on available information, should be verified with measurements of the neutron spectrum and yield for a given practical situation. This is necessary since there is not a large margin with respect to intensity.

At the LRL 88-inch cyclotron an experiment utilizing a LiD target and an intense 60-MeV deuteron beam could be performed with only modest requests for machine time ($\approx$ 10 shifts). The neutron spectra and yield information would be obtained with neutron-activation threshold detectors. Our estimates have shown that neutron beams with sufficient intensity for biological and medical applications can be produced with existing accelerators, particularly when some of the requirements for monochromatic neutrons are relaxed.

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Table I Characteristics of the neutron beams for energies of 80 to 150

Energy (MeV)	Solid Angle (sr)	Intensity (2.6×10^{23} D atoms)	Cross Section (mb/sr)	Energy Width of Peak (MeV)	Low-Energy Tail (%)
150	1.8×10^{-4}	$4\times10^{+4}$n	30	6	16
140				6	32
115				11	28
80		10^{+4}n		10	19

Table II Neutron energy spectra produced at 0 deg by 30-MeV protons (from Batty et al., Ref. 25).

	Neutron peak		Background within energy region (%)				
			Energy interval (MeV)				
Target material	Cross section (lab) (mb/sr)	Width (fwhm) (MeV)	0–5	5–10	10–15	15–20	0–20
D	40.0	2.05	6	26	27	30	89
T	48.5	1.2	1	9	19	26	55
^{7}Li	27.7	1.05	9	12	20	30	71
^{9}Be	29.3	0.9	66	43	36	37	182

Table III. Neutron energy spectra produced at 0 deg by 30–MeV protons (from Batty et al., Ref. 25).

Target mate- rial	Neutron peak Cross section (lab) (mb/sr)	Width (fwhm) (MeV)	Background within energy region (%) Energy interval (MeV) 0–5	5–10	10–15	15–20	0–20
D	36.2	2.5	1	13	13	18	45
T	44.2	2.3	1	7	14	15	37
^{7}Li	35.2	1.6	7	10	19	26	62
^{9}Be	20.0	1.6	81	36	34	42	193

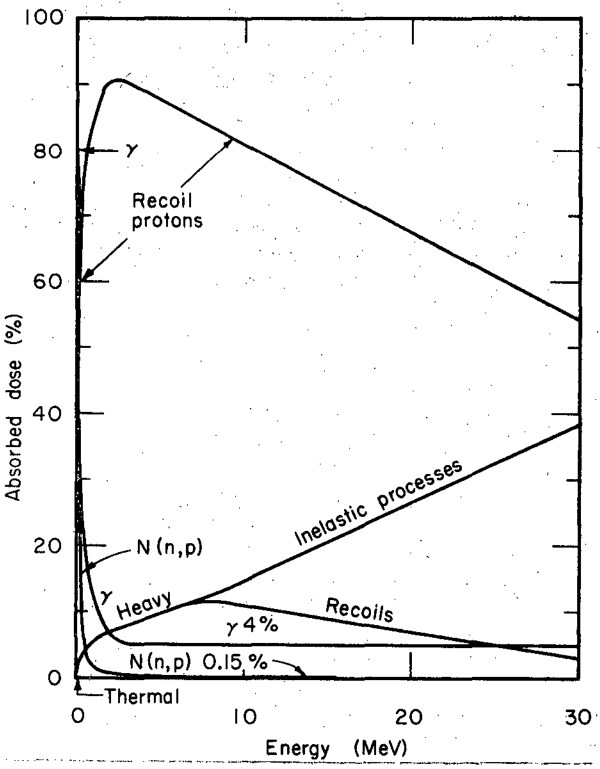

Fig. 1. The percent of absorbed dose contributed by the different processes of energy loss from a beam neutron incident upon tissue. (XBL708-3594)

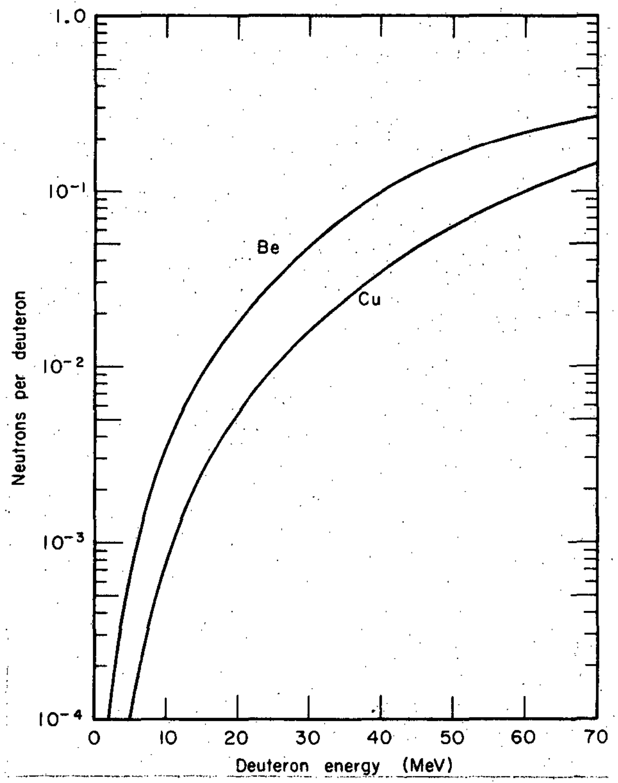

Fig. 2. Total neutron yields from deuteron bombardment of thick Be and Cu targets (reproduced from Ref. 28; also see Ref. 32). (XBL708-3595)

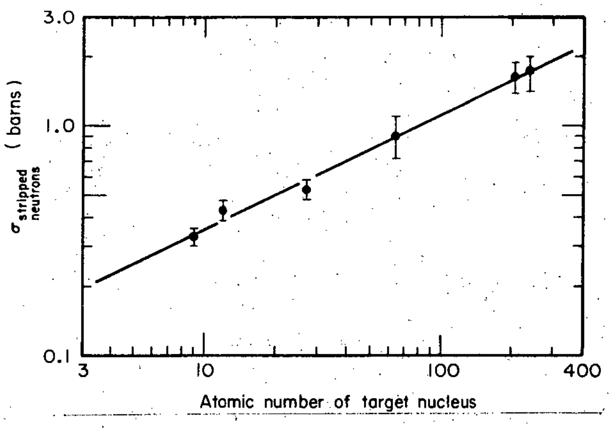

Fig. 3. Cross section for neutron production by deuteron stripping (E_d = 160 MeV) (reproduced from Ref. 28. (XBL708-3596)

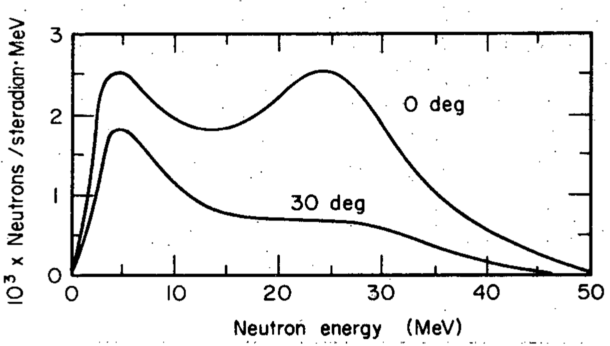

Fig. 4. Spectral yield of neutrons at 0 and 30 deg from a thick beryllium target per incident 50-MeV deuteron (from Ref. 12, using data from Refs. 6, 7, 15, 16, and 29-31). (XBL708-3597)

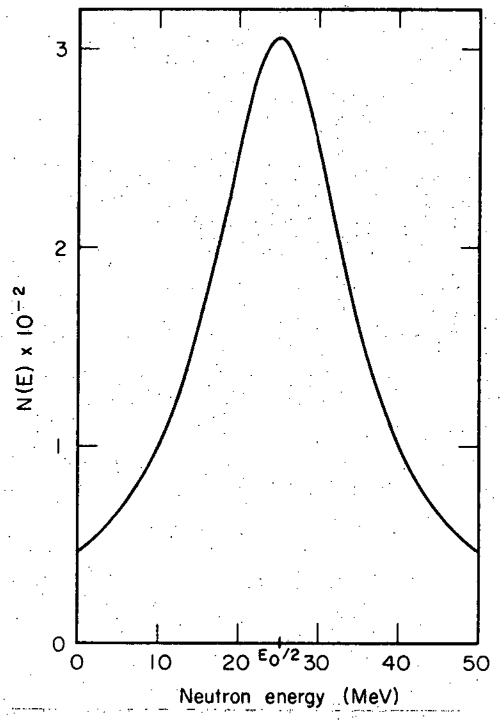

Fig. 5. Energy distribution of stripped neutrons according to Serber's formula,

$$\eta(E)dE = \frac{(B_0 \times E_0)^{1/2}}{\pi[E-1/2E_0]^2+B_d \times E_0}\, dE ,$$

with B_d = binding energy of deuterons = 2.2 MeV,

E_0 = incident energy of deuteron = 50 MeV.

This holds up to a factor of $(B_d \times E_0/2)^{1/2}$; identical to a student distribution which is given by

$$f(t/\nu) = \frac{\Gamma[(\nu+1)/2]}{\Gamma(\nu/2)\sqrt{\nu}\pi} \times (1+t^2/\nu)^{-[(\nu+1)/2]} ,$$

where ν, the degree of freedom = 1;

$t = (x - \mu)/ S$; $S = B_d \times E_0$, and $\mu = E_0/2$.

(XBL708-3598)

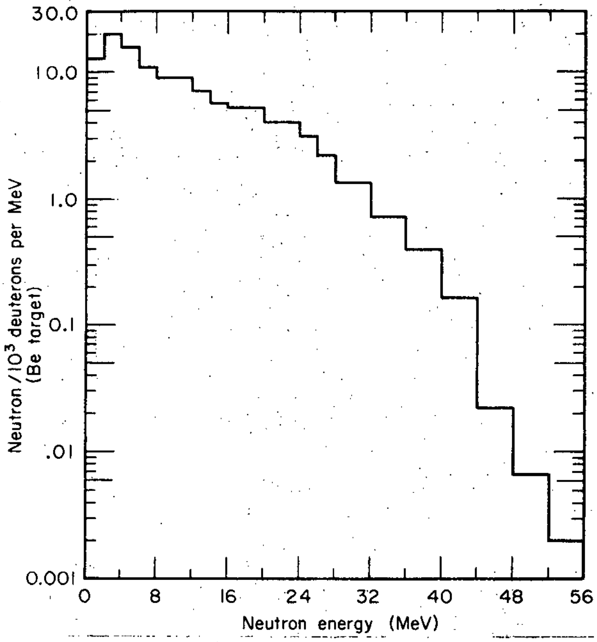

Fig. 6. Total neutron spectra from the bombardment of a thick Be target with 60-MeV deuterons. (XBL708-3599)

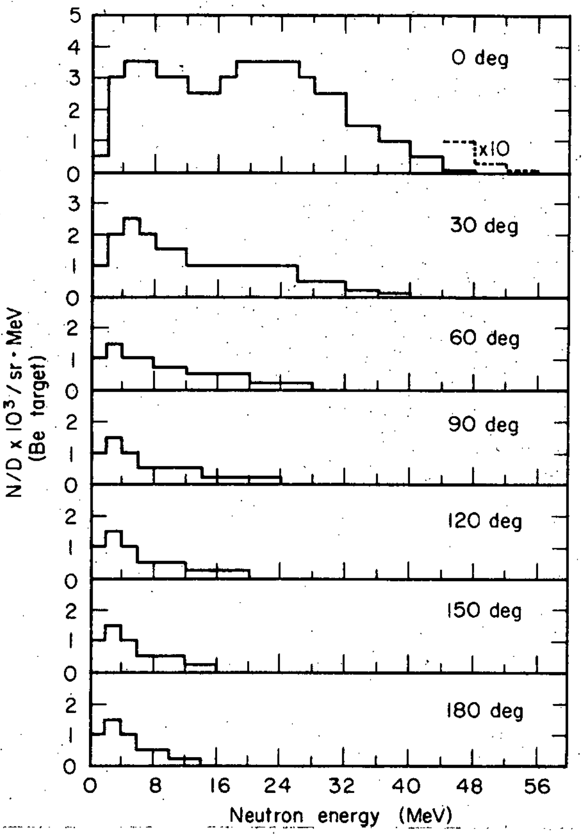

Fig. 7. Neutron spectra at different angles from the bombardment of a thick Be target with 60-MeV deuterons. (XBL708-3600)

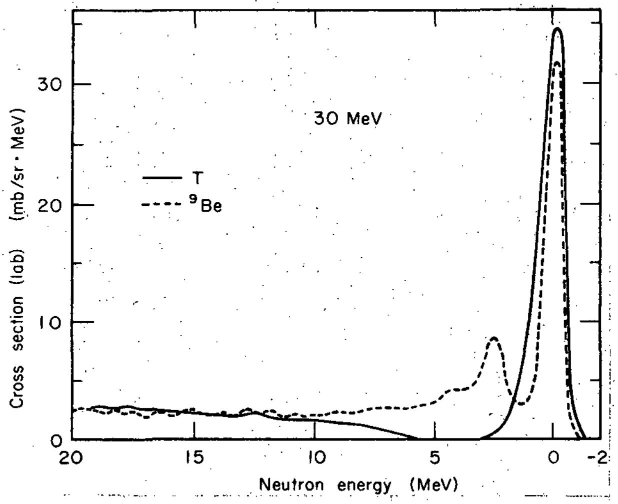

Fig. 8. Neutron spectra observed at 0 deg from T and ^{9}Be targets bombarded with 30-MeV protons. The energy scales have been adjusted so that all the peaks coincide and the neutron energies are referred to by the peak positions. (Reproduced from Ref. 25.) (XBL708-3601)

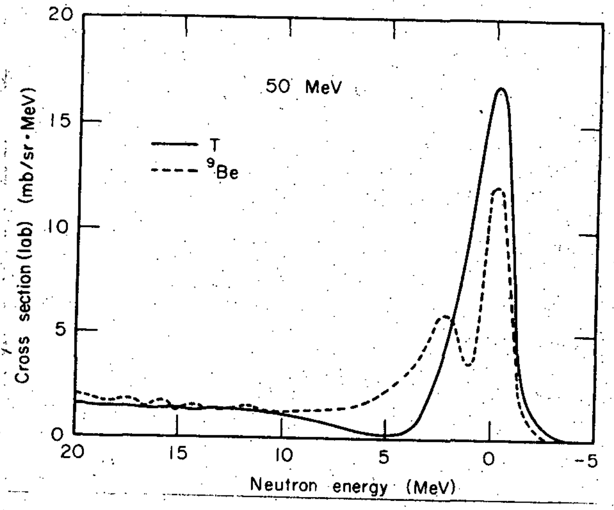

Fig. 9. Neutron spectra observed at 0 deg from T and ^{9}Be targets bombarded with 50-MeV protons. The energy scales have been adjusted so that all the peaks coincide and neutron energies are referred to by the peak position. (Reproduced from Ref. 25.) (XBL708-3602)

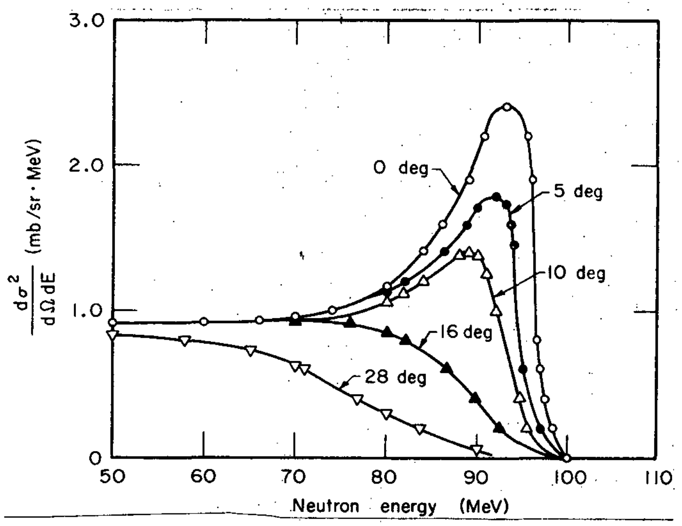

Fig. 10. Differential cross sections $d^2\sigma/d\Omega dE$ for neutrons produced by 100-MeV protons on Be (from Ref. 12).

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