Thick Target Fast Neutron Yield from 15-Mev Deuteron and 30-Mev Alpha-Bombardment*

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The total yield and angular distribution of fast neutrons from bombardment of thick targets of pure Be, Al, Ti, Cr, Mn, Co, Cb, Mo, Ag, Cd, Ta, Au, Pb, and Bi by 15-Mev deuterons and 30-Mev alpha-particles was measured. These studies were made using the reaction $S^{32}(n,p)P^{32}$ as a threshold detector and also with fission ionization chambers. The total neutron yield per second per μamp of the cyclotron beam, N, was observed to decrease with increase in nuclear charge, Z, of the target according to the approximate empirical equations, $\log N = 10.18 - 0.0234Z$ for deuteron bombardment and $\log N = 9.68 - 0.0234Z$ for alpha. In all cases studied, the angular distribution of fast neutrons from target bombarded by deuterons showed a pronounced peak in the yield in the forward direction.

I. INTRODUCTION

IT would be advantageous to know, for practical experimental purposes, the absolute high energy neutron yield from the cyclotron bombardment of various materials. This is important, not only in the use of the cyclotron and high energy electrostatic generator as a fast neutron source for experimental purposes, but also in the design of charged particle beam slits, beam tubes, etc., where a minimum neutron background is desirable owing to the impinging of the beam on these parts.

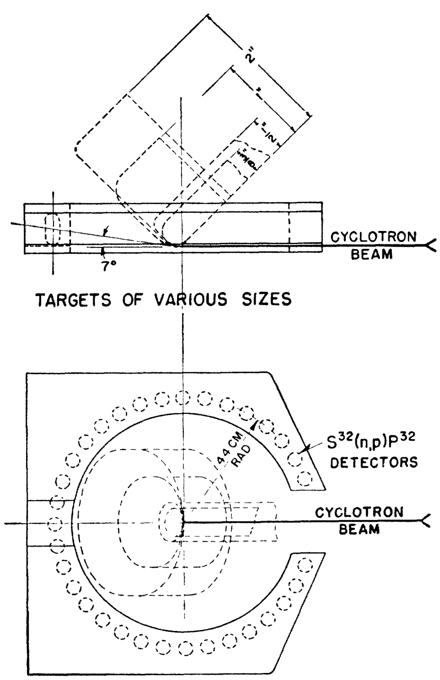

FIG. 1. Target and detector arrangement.

The present study[1] is concerned with the measurements of the angular distribution and total number of neutrons of over 1-Mev energy emitted from various thick targets, made of chemically pure but not necessarily single isotopes, when they are bombarded with 15-Mev deuterons or 30-Mev alphas from the University of Pittsburgh's 47-in. cyclotron. No attempt is made to distinguish neutrons from (d,n), $(d,2n)$, $(d,n\gamma)$, and other simultaneously occurring processes.

II. EXPERIMENTAL

The experiment was carried out using the internal beam of the cyclotron which was capable of producing 300 μamp of 7.5-Mev protons, 250 μamp of 15-Mev deuterons, and 15 μamp of 30-Mev alpha-particles. The

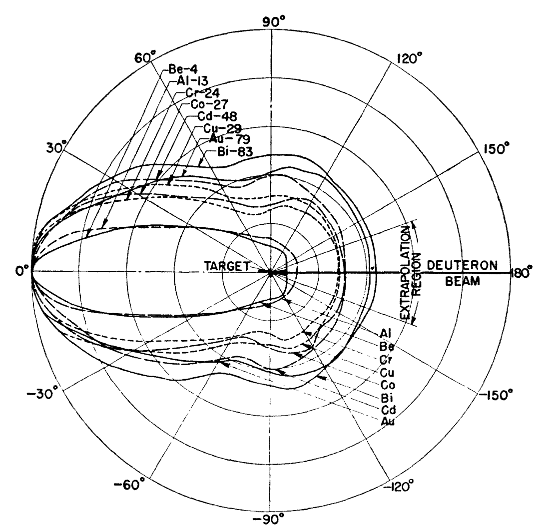

FIG. 2. Angular distribution of fast neutrons from 15-Mev deuteron bombardment of various thick targets.

* Assisted by the joint program of the ONR and AEC.

[1] Allen, Nechaj, Sun, and Jennings, Phys. Rev. 76, 188 and 463 (1949); 77, 752 (1950).

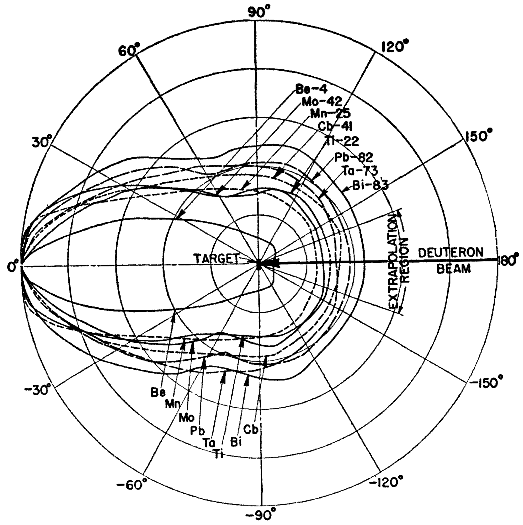

FIG. 3. Angular distribution of fast neutrons from 15-Mev deuteron bombardment of various thick targets.

voltages were estimated from the characteristics of the cyclotron and checked by measurements of the range in air of the external beam and were good to ± 0.5 Mev. The beam current was measured both electrically and from the heat generated in the target.

The target, shown in Fig. 1, consists of a water-cooled cup at an angle of 45° with the cyclotron beam. During the early part of the work this cup was 2 in. in diameter, but in some of the targets used this dimension was reduced to $\frac{3}{8}$ in. in order to achieve better geometry and performance. The targets were made, when possible, by machining or spinning the purest available elements into the form of the target cup. Low melting elements such as Pb, Sb, Bi, Sn, and Zn were "smeared" in a thick layer on a grooved Cu target, while elements

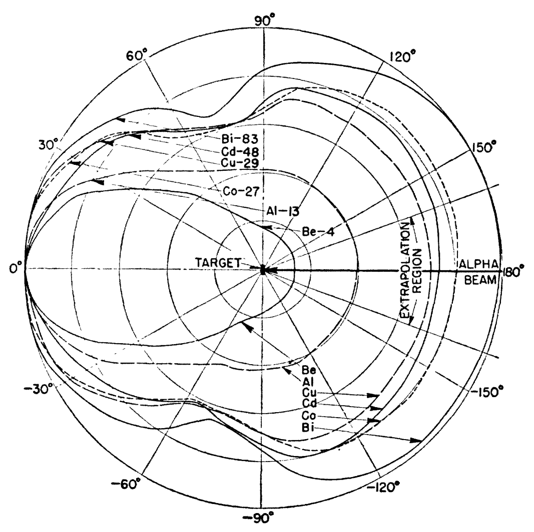

FIG. 4. Angular distribution of fast neutrons from 30-Mev alpha-bombardment of various thick targets.

such as Mn, Cr, and Au were electroplated on a copper target.

The neutron yield was determined by two methods; the measurement of the secondary activity induced in a detector by the integrated neutron flux through the detector, and the direct measurement of the neutron flux by a fission ionization chamber. For the majority of the measurements the activation method was adopted because of its simplicity and convenience. The $S^{32}(n,p)P^{32}$ reaction was chosen for the radioactive detector because the excitation function of this reaction is known,[2] and P^{32} has a convenient half-life (14.3 days) and emits only β-rays with fairly high energy (1.71 Mev max). The decay curve of this "sulfur" detector showed that one day after bombardment the activity was from P^{32} alone. The neutron cross section near the threshold of the reaction $S^{32}(n,p)P^{32}$ (0.97 Mev) is small, according to Klema and Hanson,[2] and rises rapidly as the energy

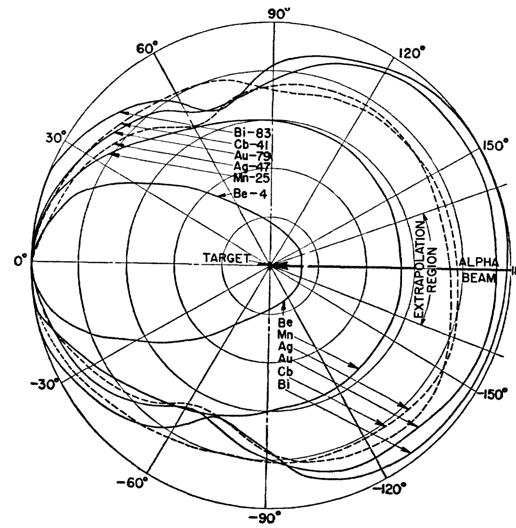

FIG. 5. Angular distribution of fast neutrons from 30-Mev alpha-bombardment of various thick targets.

increases and then levels off to a constant value (0.32 barn) from 4 Mev to about 6 Mev, where the measurement ends. There are indications that a majority of the neutrons involved in the present study will be in the neighborhood of a few Mev (say, 2 to 10 Mev) based on information from the neutron spectrum of deuteron bombardment on Be, Al, Co, and Cu by photographic techniques.[3] It was considered reasonable for the first approximation to adopt a constant value, namely, 0.32 barn for the $S^{32}(n,p)P^{32}$ cross section in all the measurements. Powdered sulfur (about 200 mg) was placed in small medical capsules and mounted around the target inside the cyclotron vacuum chamber as shown in Fig. 1. These detectors were placed approximately every 10° around the target on a 4.4-cm radius. In order to

[2] E. D. Klema and A. O. Hanson, Phys. Rev. 73, 106 (1948).
[3] B. L. Cohen and C. E. Falk, Carnegie Institute of Technology thesis, 1950, unpublished.

Table I. Fast neutron yield.

Target nuclei	φ, fast neutrons/sec/steradian/μamp in forward direction $\times 10^{-8}$		N, total fast neutrons/sec/μamp $\times 10^{-8}$		K, No. bombarding particles required to yield one fast neutron $\times 10^{-3}$	
	15-Mev deuterons	30-Mev alpha	15-Mev deuterons	30-Mev alpha	15-Mev deuterons	30-Mev alpha
$_{4}$Be	94	22	190	65	0.33	0.48
$_{13}$Al	30	3.1	64	18	0.98	1.6
$_{22}$Ti	12		65		2.4	
$_{24}$Cr	7.2		29		1.8	
$_{25}$Mn	12	1.7	52	14	1.3	
$_{27}$Co	5.5	1.1	26	10	2.0	2.9
$_{29}$Cu	4.8	1.1	29	10	3.0	2.9
$_{41}$Cb	3.0		15		3.3	
$_{42}$Mo	3.1		15		4.0	
$_{47}$Ag	2.2	0.54	14	5.4	4.7	9.6
$_{48}$Cd	2.4	0.56	12	5.2	5.1	5.5
$_{73}$Ta	0.56		3.3		19	
$_{79}$Au	0.37	0.062	2.1	.65	27	48
$_{82}$Pb	0.36	0.18	2.1	1.6	30	19
$_{83}$Bi	0.23	0.044	1.3	.47	49	70

prevent the beam from striking the detector holder, the plane containing the detectors is displaced from that of the beam and target by 0.5 cm. This is equivalent to having the center of the capsule in the forward directions displaced from the beam plane by 7°, thus providing an angular measurement from ±7° to ±153° in approximately 10° intervals. The neutron flux at 0° was extrapolated. After bombardment with fast neutrons, the capsules were taken out and a weighted portion (5 to 100 mg) of the sulfur was spread out in an aluminum dish in ether, the radioactive P^{32} in the thin sulfur layer was counted in a calibrated end-window Geiger counter. The counts were then corrected for decay time. The neutron flux or neutrons/cm^2/sec/μamp of the beam current was calculated from the Geiger counts/sec/unit weight of sulfur, the counter geometry factor, length of bombardment and beam current. From the angular neutron flux, the total neutron flux was evaluated by graphical integration.

A similar detector using the reaction $P^{31}(n,p)Si^{31}$ was also used in some of the measurements. The cross section of this reaction as a function of neutron energy up to 4 Mev was measured by Taschek[4] and for this work a constant value of 0.08 barn was assumed. Since the half-life of Si^{31} formed is only 170 minutes, corrections were made for the decay of this nucleus during the bombardment time. The results were found to be consistent.

Fast neutron fission ionization counters with very thin uranium (Cd shielded) and thorium deposits were also used. An average fission cross section of 0.6 and 0.15 barn were assumed, respectively, based on the experimental data by Ladenburg, *et al.*[5] and Ageno, *et al.*[6] These detectors measure neutrons with energy above 1 Mev,[7] the fission thresholds for U^{238} and Th^{232}. The measurements agreed with those using the sulfur detector. Since the sulfur detectors were convenient, and yield data for all angles at the same bombardment, it then was adopted for all the angular measurements.

III. RESULTS AND DISCUSSION

Thick targets of pure Be (2 in. diameter), Mg (2 in.), Al (2 in.), Ti (2 in.), Cr (2 in.), Mn (1 in.) Co (2 in.), Cu ($\frac{3}{8}$ in.), Mo (2 in.), Cb (1 in.), Ag (2 in.), Cd (2 in.), Ta (1 in.), Au (1 in.), Pb (2 in. and $\frac{3}{8}$ in.), Bi (2 in. and $\frac{3}{8}$ in.), were bombarded with both 15-Mev deuterons and 30-Mev alphas.

The results are summarized as follows.

The angular distribution normalized with respect to the forward direction which was extrapolated from the corrected experimental curves is given in Figs. 2–5. The experimental points, 33 in number for each curve, fall closely on the curves and were omitted in the much condensed drawing to avoid confusion. The neutron flux at any angle for any target investigated can be obtained from these figures and the flux in the forward direction (see below). The angle at half-intensity for the case of

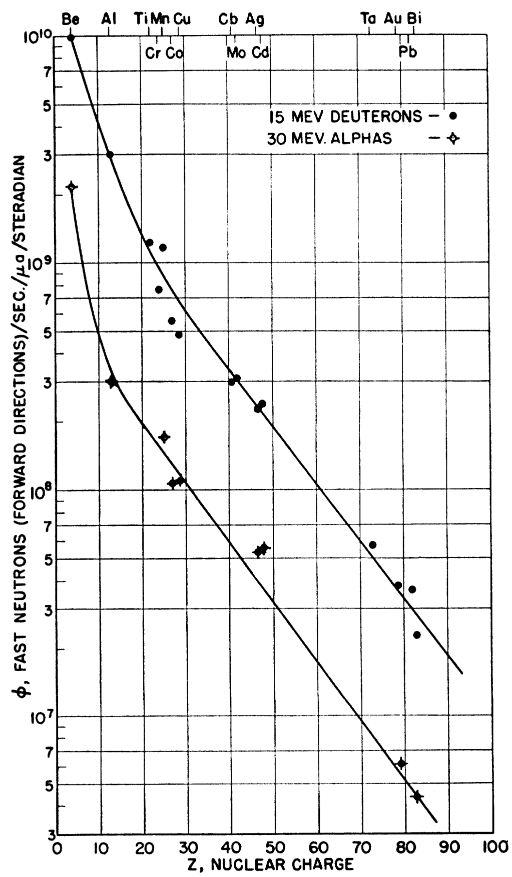

Fig. 6. Fast neutron flux in the forward direction, φ, *vs* nuclear charge of the target, Z.

[4] R. F. Taschek, MDDC 360, LADC 135, unpublished.

[5] Ladenburg, Kanner, Barschall, and Van Voorhis, Phys. Rev. **56**, 168 (1939).

[6] Ageno, Amaldi, Borimarelli, Cacciapuoti, and Trabacchi, Phys. Rev. **60**, 67 (1941).

[7] W. E. Shoupp and J. E. Hill, Phys. Rev. **75**, 785 (1949).

deuteron bombardment increases with the increasing nuclear charge of the target.

The fast neutron flux, φ, in the forward direction (0°) expressed in number of fast neutrons per second per steradian per μamp of the beam current is given in Table I and plotted against nuclear charge of the targets, Z, as shown in Fig. 6. Figure 6 indicates that the neutron flux decreases with increase in the nuclear charge of target as would be expected. The number of fast neutrons in the forward direction per cm^2 per second per μamp at a distance r cm from the target may be obtained by dividing the value φ by r^2.

The total number of fast neutrons for various targets per second per μamp deuterons or alphas, N, is also given in Table I and plotted against nuclear charge of the target, Z, in Fig. 7. The total yield, N, can be calculated from the nuclear charge, Z, of the target by the following simple empirical relationship:

$$\log N = 10.18 - 0.0234Z \text{ for deuterom bombardment,}$$

and

$$\log N = 9.68 - 0.0234Z \text{ for alpha-bombardment.}$$

The values calculated from these equations might be somewhat low for those targets with a nuclear charge smaller than 10. Smith and Kruger[8] measured the total neutron yield (including slow neutrons) from various targets bombarded with 10-Mev deuterons. Their result also indicates a decrease in the yield with an increase in the nuclear charge of the targets. However, the total yield is higher than that found in the present investigations.

As shown in Figs. 2–5, the angular distribution for the production of fast neutrons by 15-Mev deuterons on a thick target has a very pronounced forward peak for all the targets studied (Z from 4 to 83). Conversion into the center-of-mass system using the limiting values for the energy of deuterons (2 Mev, the potential barrier for Be, to 15 Mev, the maximum energy of the bombarding particles) does not essentially change the shape of the angular distribution even for the lightest nucleus (Be) studied. For targets heavier than Be, the shapes and position of the angular distributions for the laboratory and center-of-mass systems would be very similar. Similar, though fragmentary, results were also observed by Roberts and Abelson,[9] Falk, Creutz, and Seitz,[3,10] and Ammiraju,[11] by using higher energy threshold detectors. Recently, Falk[3] found the similar forward peaks using a hydrogen recoil proportional counter telescope. As yet, no satisfactory theory has been developed to account for these results.

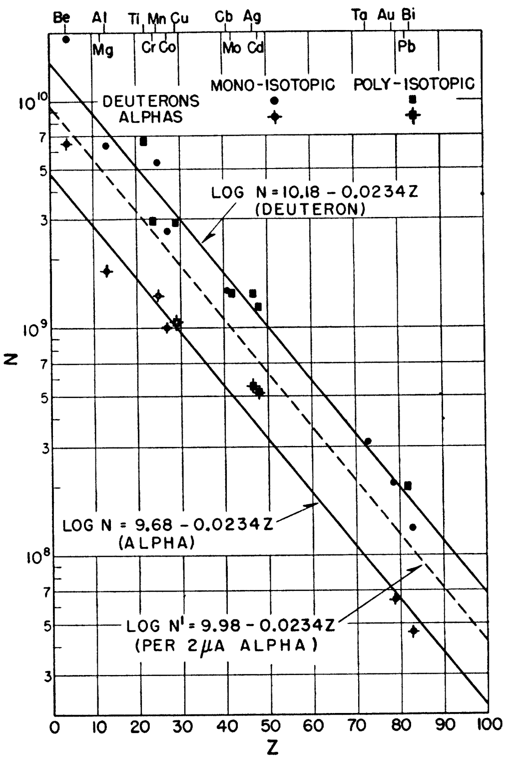

FIG. 7. Total number of fast neutrons per second per μamp. 15-Mev deuterons and 30-Mev alphas, N, *vs* nuclear charge of the thick target, Z.

There were indications that the forward neutron yield may be resolved into two peaks. This was also found by Falk.[3]

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[8] L. W. Smith and P. G. Kruger, Nuclear Science Series, Preliminary Report No. 4, NRC by A. O. Hanson and R. F. Taschek.

[9] R. B. Roberts and P. H. Abelson, Phys. Rev. **72**, 76 (1947).

[10] Falk, Creutz, and Seitz, Phys. Rev. **76**, 332 (1949).

[11] P. Ammiraju, Phys. Rev. **76**, 1421 (1949).