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Angular Distribution of Neutrons from Targets Bombarded by 190-Mev Deuterons[1,2]

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It is found that 190-Mev deuterons striking a thin target produce a beam of neutrons concentrated about the forward direction of the deuterons. The angular distribution of intensity in this beam has been studied, using as target materials Be, Al, Cu, Mo, Sn, Ta, Pb, and U. The shape of the distributions is represented approximately by the function $(1+a\theta^2)^{-\frac{3}{2}}$, and the measured widths in radians between points of half-intensity can be given approximately as $0.155+0.00060Z$, where Z is the atomic number of the target material. It is pointed out that these data fit within a few percent a simple theory of neutron production, according to which the proton is "stripped" from the deuteron by striking a target nucleus, leaving the neutron free.

I. INTRODUCTION

WHEN the 184-inch synchro-cyclotron of the Radiation Laboratory at the University of California was first put into operation,[3] one of the earliest observations made was a rough survey of the angular distribution of the neutrons emitted from an internal target. This was done with a portable ionization chamber; it was found that the neutrons came out as a rather sharp beam, whose axis was along the direction of the incident deuterons. More accurate measurements seemed worth while, and a track was set up so that the chamber could be set at known positions across the beam, while the ratios of the readings to those of a fixed monitor chamber were obtained. In this way it was found that the beam had a half-width (width between points of half-maximum intensity) of about $\frac{1}{5}$ radian.

For the more detailed measurements reported here, another method was used. Small samples of materials capable of being activated by fast neutrons were placed in an array across the beam, and their activities measured by a Geiger counter after bombardment. This method has the following advantages: (1) all samples get exactly the same exposure time, obviating the need of a monitor and the consequent added chance of error; (2) since the samples could be placed immediately in contact with the $1\frac{3}{4}$-in. thick steel wall of the cyclotron vacuum chamber, any effect of scattering by this wall is minimized; and (3) by suitable choice of samples with high activation thresholds, neutrons degraded below a certain energy by inelastic scattering from surrounding matter are not detected.

II. EXPERIMENTAL ARRANGEMENT

Figure 1 is a plan view of the cyclotron, showing the location of the internal target on the end of the probe, the final orbit of the deuterons, and the direction of the neutron beam. The targets placed on the end of the probe were all of the same shape, being in the form of truncated wedges with a width at the edge of $\frac{1}{16}$ in. The target materials used were Be, Al, Cu, Mo, Sn, Ta, Pb, and U. The samples to be activated were fastened to the surface of the vacuum tank, along horizontal and vertical lines intersecting at the center of the neutron beam. All of the data given in this paper were taken using as detectors disks of pure graphite, $1\frac{11}{16}$ in. in diameter and $\frac{1}{8}$ in. thick. The only activity observed was the 20.5 minute C^{11} formed by the reaction $C^{12}(n,2n)C^{11}$, with a threshold at 20 Mev. Some other runs were made with copper samples, using the reaction $Cu^{63}(n,2n)Cu^{62}$ (threshold about 10 Mev); these agreed well with the carbon results. However, copper is a less satisfactory material than carbon because the presence of decay periods other than the desired 10-minute period complicates the decay correction.

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[1] Reported at the Stanford meeting of the American Physical Society, July 11–12, 1947.
[2] Observations of a similar kind at lower deuteron energy have been made by R. B. Roberts and P. H. Abelson, Phys. Rev. **72**, 76 (1947).
[3] W. M. Brobeck, E. O. Lawrence, *et al.*, Phys. Rev. **71**, 449 (1947).

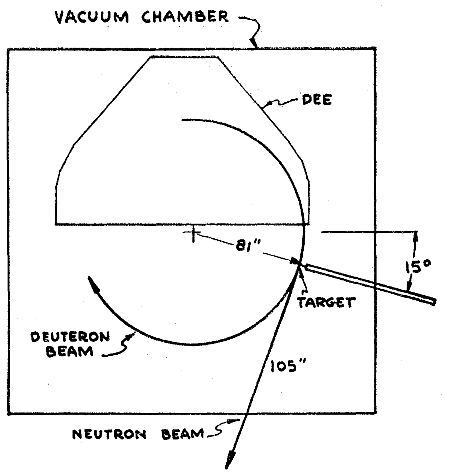

FIG. 1. Experimental arrangement, showing the path of the deuterons inside the cyclotron, the position of the internal target, and the direction of the neutron beam. The carbon samples were placed on the outer surface of the vacuum-chamber wall; the 105-in. dimension is the distance from the target to the sample in the center of the beam.

III. FIRST SERIES OF MEASUREMENTS

In this series, carbon samples were placed on 2-in. or 3-in. centers covering a horizontal range of ± 56 in. or a vertical range of ± 20 in. from the center of the neutron beam. Greater vertical heights come into the shadow of the magnet poles. The samples were exposed for a time sufficient to give an initial activity on the center sample of about 5000 to 10,000 counts per minute; the exposure times required were of the order of 5 to 15 minutes, depending on the deuteron current, the maximum current being estimated at about $\frac{1}{2}$ microampere. The activities were then measured with a Geiger counter, taking at least 1000 counts for each reading. All of the measurements were corrected for decay and for lack of counting resolution at the higher rates. In the case of the horizontal distributions, it was also necessary to correct for the variation of distance with angle.

Vertical distributions were taken with targets of Be, Cu, Sn, Pb, and U. These curves are very similar to one another in shape, but have slightly different widths. The curve with a Cu target is shown by the circles and solid line in Fig. 2; the curves with Be and U targets are given in the following paper by Dr. Serber. The shape of these curves can be represented with considerable accuracy by the empirical relation: intensity $\sim(1+a\theta^2)^{-\frac{3}{2}}$, where θ is the distance from the center in radians, and a is a constant characteristic of the target material.

Horizontal distributions were taken with targets of Be, Cu, Sn, and U. The central portions of these are nearly identical to the corresponding vertical distributions. The outer portions on the left side correspond to extensions of the vertical curves to greater angles; on the right side (away from the center of the cyclotron) they deviate appreciably from the vertical curves. For the case of a copper target, the outer parts of the horizontal distribution are shown as dashed lines in Fig. 2. The extra intensity on the right is certainly caused by deuterons striking the dee, which was confirmed by the fact that the dee acquired an appreciable induced activity on an area near the target. Because of this distortion of the horizontal curves, only the vertical curves were used in the half-width measurements. The empirical equation given above, when extended to $\theta=-0.4$, falls below the dashed line by about a factor of two. The shape of the extreme wings of the curve is not to be taken too seriously because of the probable presence of a weak background arising from nuclear processes in the target other than that responsible for the sharp neutron beam. No attempt was made to evaluate this background or to correct for it, since it can have only a small effect on the shape of the main part of the beam.

IV. SECOND SERIES OF MEASUREMENTS

Since the results of the first series showed that the distributions all have the same form, but have apparently significant variations in width, a second series of measurements aimed particularly at determining the half-widths was made. Only vertical distributions were measured, and for each exposure only nine samples were used, in groups of three with $1\frac{11}{16}$-in. spacing between centers bracketing the peak of the curve and the two half-intensity points. With the smaller number of samples it was possible to get three or four readings on each one, and to plot for each a decay curve, minimizing the possibility of error in the activity determinations. All the target elements used in the first series were repeated in this way, and, in addition, Al, Mo, and Ta were used. Also, in order to obtain some idea of the precision of the measurements from internal consistency, several independent runs were made for each of the target materials; these were done in random order among the various targets. All of the half-width measurements are given in Table I. These values are plotted against atomic number in Fig. 3. The mean of the total spreads of values for the different targets is ± 3 percent, which can be taken as a rough measure of the degree of precision of the measurements. The theoretical values are also given in Fig. 3.

V. PROPERTIES OF DEUTERON BEAM

In order to interpret these results, it is necessary to know certain things about the deuterons striking the target, particularly their energy and their spatial and angular distribution. The discussion of these matters is closely tied in with the more general problem of understanding the operation of the synchro-cyclotron, and some of the material used in the following discussion comes from observations made by members of the cyclotron group for the latter purpose.

First, some conclusion must be made about the *energy* of the deuterons. The nominal energy given by the radius (81 in.) and magnetic field (14,250 oersteds) is 195 Mev. However, the possibility must not be ignored that the radius of curvature of the orbit may differ from the geometrical radius at the probe; this can be caused by a displacement of the magnetic center of the field from the geometrical center of the tank, or by radial oscillations of the deuterons in their orbit. The first effect mentioned is easily checked. From measurements of the azimuthal and radial variations of the field, it is possible to compute the displacement of the magnetic center; at the 81-in. radius, this was found to be about $\frac{3}{4}$ in, in a direction nearly perpendicular to the probe radius. This displacement was verified by measurements of the current to the probe when two defining vanes were put in from the left and bottom of Fig. 1; it makes a negligible change in the energy. The other effect is harder to measure, and a detailed discussion would go beyond the limits of the subject of this paper. The observations made show that radial oscillations certainly exist, and that their amplitudes probably range from about zero to about two inches. Since the oscillating ions always strike the target near the peak of

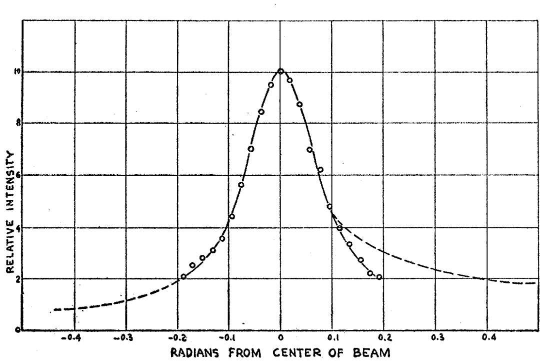

FIG. 2. Distribution curves for neutrons from a copper target. Circles and solid line: Vertical distribution. Dashed lines: Outer parts of horizontal distribution. Central part of horizontal distribution coincides with vertical distribution. The horizontal curve on the right contains some neutrons caused by deuterons striking the dee.

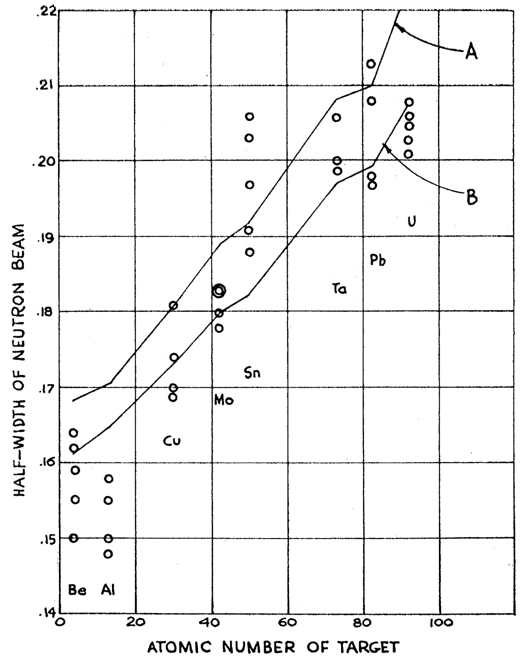

FIG. 3. All measurements of neutron beam half-width (width between points of half-maximum intensity) plotted against atomic number of target. The ordinate scale is in radians; note that its origin is below the bottom of the plot. The broken lines *A* and *B* connect the theoretical half-widths computed for the various targets in the "opaque nucleus" and "transparent nucleus" approximations, respectively. These lines are irregular because the corrections for energy loss and scattering depend on the density of the material.

TABLE I. Half-widths of neutron beams in radians.

Target	Be	Al	Cu	Mo	Sn	Ta	Pb	U
1st series	0.162	—	0.174	—	0.203	—	0.213	0.205
2d series	0.159	0.155	0.181	0.178	0.206	0.200	0.208	0.201
	0.164	0.158	0.170	0.183	0.197	0.199	0.197	0.208
	0.155	0.148	0.169	0.183	0.191	0.206	0.198	0.203
	0.150	0.150		0.180	0.188			0.206

the oscillation, the amplitude must be subtracted from the probe radius to get the radius of curvature. We therefore estimate the effective radii to range from 79 in. to 81 in., and the deuteron energies from 185 to 195 Mev, the mean energy being about 190 Mev.

We must next consider the question of what happens to the deuterons while passing through the target. Dr. Serber has computed the energy losses and the R.M.S. scattering angles for a single passage through $\frac{1}{16}$ in. of the various materials, with the results noted in Table II.

Since the vertical angle of the deuteron orbit is limited to about 0.01 radian by the dee aperture, it is apparent that for targets from Cu to U most of the deuterons passing through the target once will strike the dee before making a second passage through the target, and the contribution from those that do go through again with reduced energy will not be important. In the cases of Be and Al, it would take several passages for the R.M.S. scattering angle to reach 0.01 radian, and therefore, there must be an appreciable number of deuterons going through the target several times. However, the energy loss in these cases is small, and the multiple passages through the target do not make a serious error in the mean energy. A small correction for the energy losses in a single passage has been applied to all the computed half-widths.

Next, we can examine sources of angular spread other than the intrinsic width of the neutron beam. One such source is the multiple scattering in the target, as given in Table II. This becomes appreciable in the heavier targets, and is included in the calculated results of the accompanying theoretical paper. Other sources of spread are the spatial and angular spread of the incident deuterons. The easiest to determine is the *spatial distribution* of the deuteron beam striking the target. This is found by making a radio-autograph of the target after bombardment. The activity is concentrated in a thin band not over $\frac{1}{8}$ in. wide along the edge, with a vertical distribution in the form of a peaked curve having a half-width of $\frac{7}{8}$ in., corresponding to an angle of 0.01 radian at the sample position. The *vertical angular spread* of the deuterons is limited by the dee aperture to ± 0.01 radian, and is actually less than that, since the vertical oscillations of the orbits are observed to be considerably smaller than the available aperture; the half-width is certainly not greater than 0.01 radian. These spreads are random, and therefore must be combined with the intrinsic widths according to the rules for random errors—that is, the total spread is of the order of the square root of the sum of the squares of the separate spreads and the intrinsic width. Thus the resultant errors are of the order of 1 percent and can be neglected.

VI. DISCUSSION

The fact that measurements with detectors having different thresholds, or with an ionization chamber, lead to consistent results, can be interpreted in two ways. Either most of the neutrons in the beam have energies above the highest threshold, or else if there is present a considerable fraction of lower energy neutrons, these are also distributed in a beam of about the same width. The theoretical interpretation of the mechanism of neutron production favors the former possibility. This is also consistent with measurements of the transition effects observed when paraffin is placed in front of an ionization chamber.

The theoretical interpretation of the angular distributions is given in detail in a following paper by Dr. Serber. It is shown there that the probable chief mechanism is a process in which the proton of the deuteron strikes the nucleus,

TABLE II. Effect of target on deuteron beam.

Material	Energy loss	R.M.S. scattering angle
Be	1.9 Mev	0.0025 radian
Al	2.6	0.0060
Cu	7.0	0.017
Mo	7.0	0.021
Sn	5.0	0.019
Ta	10.3	0.035
Pb	6.5	0.030
U	11.8	0.043

leaving the neutron free. The neutron velocity at this instant is compounded of the deuteron velocity and the relative motion of the neutron with respect to the center of mass of the deuteron. The transverse component of the relative motion gives the angular spread, and the longitudinal component should give a spread of energy with a half-width of about 30 to 40 Mev about the mean neutron energy, which should be about 95 Mev. It is easy to see from this picture that the magnitude of the angular spread should be of the order of the ratio of the relative internal momentum to the total momentum, or the square root of the ratio of the deuteron-binding energy to its kinetic energy. Thus the spread should be about $(2.18/190)^{\frac{1}{2}}$ or 0.11 radian, which is indeed of the correct order. There is also to be expected an additional spread caused by the deflection of the deuterons in the Coulomb fields of the nuclei responsible for their dissociation, and this additional spread should increase with atomic number. The observed shapes of the curves obtained in the first series of measurements agree with the computed shapes, as illustrated in the following paper. The theoretical half-widths as a function of atomic number are indicated by the solid lines in Fig. 3, which are computed using the two limiting forms of the theory, the "opaque nucleus" approximation A being probably better for the heavier elements, and the "transparent nucleus" approximation B for the lighter elements. It will be seen that either curve fits the experimental data with reasonable accuracy; in only two cases, Al and Sn, are the means of the experimental points more than 3 percent from the nearest theoretical curve, and these deviations we believe are probably not significant. Nothing has been said so far about the relative neutron yields from the different targets. These ratios were hard to determine, since no means were available for measuring the deuteron currents passing through the thin targets, and only very crude estimates were made; the theory indicates that there should be no great variation of yield with atomic number, and the experimental estimates are not inconsistent with this.

To conclude, we can say that a simple theory involving no arbitrary parameters fits the observed distribution curves with regard to shape, absolute width, and variation of width with atomic number within a few percent, and, therefore, that the presumption is strong that the theory is a correct interpretation of the mechanism of neutron production responsible for the beam.

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