the laboratory system to the center-of-mass system, so that the points indicated should not be taken to be more than a mere indication of the general type of experimental results. One can see, however, that the theoretical angular distribution is not at all incompatible with the results of the observation.

As pointed out, it is possible that in various collisions of the general type discussed here one might find a variety of different angular distributions. Centered collisions should give angular distributions more isotropic than Fig. 2. Very eccentric collisions should give more peaked distributions.

The angular distribution calculated above is independent of the energy of the collision. The simple form of theory discussed here breaks down, however, at low energies for two reasons: The first is that the flattening of the volume V is no longer very pronounced, while the other is that it is no longer permissible to assume that all of the particles are extreme relativistic in the center-of-mass system.

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Relative High Energy Neutron Yields from Targets Bombarded with Protons and Deuterons*

WILLIAM J. KNOX
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
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Relative neutron yields in the forward direction from various target elements bombarded with 340-Mev protons and 190-Mev deuterons have been measured. Bismuth fission chambers with a threshold of about 50 Mev were used to detect the high energy neutrons. When a deuteron beam is used, the neutron yields for light elements agree with the values predicted by the deuteron stripping theory. For the heavy elements, the observed values are fitted best by adding a function proportional to Z^2 to the stripping theory values. This can be interpreted as evidence for the production of high energy neutrons by the electric field disintegration of the deuteron. The neutron yields from the proton beam vary approximately as $(A-Z)^{\frac{1}{3}}$ for target elements from carbon to uranium. This indicates that the heavy elements are not completely transparent to 340-Mev protons. Beryllium has an anomalous neutron yield 50 percent higher than that for carbon.

I. INTRODUCTION

THE production of a beam of high energy neutrons when 190-Mev deuterons were allowed to impinge upon a target was observed in the first stages of operation of the 184-inch cyclotron.[1] A similar beam of neutrons of higher energy was produced later by the action of 340-Mev protons on a target in the cyclotron. These beams have been investigated experimentally and theoretically by various observers. A mechanism has been proposed for the production of neutrons from deuterons in which the proton is stripped from the deuteron in a collision with a nucleus while the neutron continues on in its original direction.[2] Several features of this mechanism have been verified experimentally.[3–5] The production of high energy neutrons by the proton beam presumably takes place as a result of various types of collisions between the incident proton and the particles within the nuclei of the target material.

It is the purpose of this paper to present and discuss data on the variation of neutron yield with atomic number for various targets bombarded by both the deuteron and proton beams.

II. APPARATUS AND EXPERIMENTAL TECHNIQUE

The deuterons produced by the 184-inch cyclotron have a maximum energy of 190 Mev, and a beam of about 10^{-6}-amp average current can be obtained. The protons have a maximum energy of 340 Mev and can be produced with an average beam current of the order of 5×10^{-7} amp. A target of any desired material can be inserted into the path of these particles, through a vacuum lock in the cyclotron tank, by means of the target probe. The targets can be set at different radii to obtain different energies if desired. The maximum energies mentioned above are obtained at a radius of 81 inches from the center of the cyclotron. These experiments were performed with the targets at radii from $80\frac{1}{2}$ to 81 inches.

When the particles impinge on a target, neutrons are given off in the general forward direction. These neutrons can be intercepted in a wide beam just outside the cyclotron tank wall, or they can be obtained in a highly collimated beam, about 50 feet from the target, emerging from a two-inch diameter hole in the concrete shielding surrounding the cyclotron. In the present

* This work was performed under the auspices of the AEC.
[1] Brobeck, Lawrence, MacKenzie, McMillan, Serber, Sewell, Simpson, and Thornton, Phys. Rev. 71, 449 (1947).
[2] R. Serber, Phys. Rev. 72, 1008 (1947).
[3] Helmholz, McMillan, and Sewell, Phys. Rev. 72, 1003 (1947).
[4] Chupp, Gardner, and Taylor, Phys. Rev. 73, 742 (1948).
[5] Hadley, Kelly, Leith, Segrè, Weigand, and York, Phys. Rev. 75, 351 (1949).

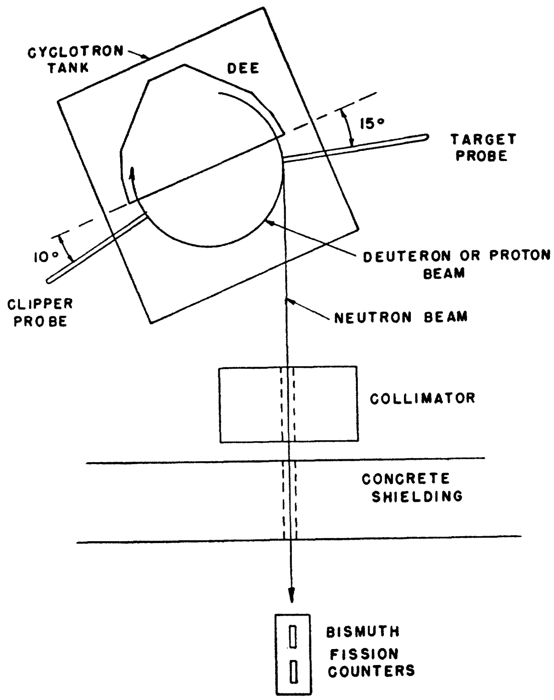

FIG. 1. Arrangement of apparatus.

experiments bismuth fission counters were placed in this collimated beam outside the shielding. The plates of the fission counters subtended a solid angle of about 10^{-6} steradian from the target, and the targets were placed in the beam so that the counters were located within one degree or less of the direction in which the beam was traveling when it struck the target.

The neutrons from the deuteron beam have a most probable energy of about 90 Mev and an energy distribution with a width at half-maximum[2,5] of about 27 Mev. The energy maximum and distribution vary slightly with different materials and thicknesses of targets. The energy distribution of neutrons from the proton beam appears to be a very broad distribution with a maximum at about 270 Mev and a width at half-maximum[6] of about 140 Mev.

Ideally, the particles in the proton or deuteron beam travel approximately midway between the top and bottom of the dee. Actually, the particles acquire vertical oscillations, varying in amplitude from 0 to 2.4 inches, which is the maximum allowed by the dee aperture. If a beam of smaller vertical dimension is desired, a beam clipper may be inserted on a special probe about 155° around the cyclotron from the target probe. This clipper is made of copper about 1 inch thick and 5 inches high with a horizontal slot cut in it to allow only the center of the beam to pass through without obstruction. The clipper cuts out all particles which acquire vertical oscillations greater than some prescribed amplitude. The clippers used in the present experiments had vertical apertures of 1 or $1\frac{1}{2}$ inches. They restricted the beam particles to amplitudes of less than $\frac{1}{2}$ or $\frac{3}{4}$ inch from the beam plane and extended from about 60-inch radius to about $81\frac{1}{2}$-inch radius in the cyclotron. The back of the clipper at about $81\frac{1}{2}$-inch radius also cuts off particles which have outward radial oscillations or deflections from the target of greater than $\frac{1}{2}$ or $\frac{3}{4}$ inch from the 81-inch orbit. The average beam current is reduced by a factor of about 3 when a 1-inch clipper is used. Figure 1 shows the arrangements described above diagrammatically.

In order to be able to change targets quickly in the cyclotron without going into the tank through the vacuum lock, a device was built which would rotate four different targets successively into the beam, and which could be controlled from the outside. This device is described in the following paper. Using the target rotator, targets could be changed without stopping the cyclotron beam and without altering any of its conditions of operation for more than a fraction of a second. Thus, one could assume a constant beam on the four targets in a single run.

Bismuth fission chambers were used to detect the high energy neutrons. The construction and operation of these chambers have been described in detail elsewhere.[7,8] They have a threshold of about 50 Mev, since this is the energy necessary to initiate fission in bismuth with neutrons. They are used in connection with linear amplifiers, and standard scaling and recording circuits. A collection voltage of about 500 to 700 v is used. The linear amplifiers have bias controls so that pulses below any specified height may be discriminated against. When a counting rate *versus* bias curve is taken, initially it shows a very steep slope because of pile-ups, or coincidences of protons or other ionizing particles passing through the chamber. Then the curve flattens out to a slope of about one or two percent per bias volt and then eventually drops off again when even the fission pulses are discriminated out. One operates in the flattest part of the curve at a bias high enough to insure that the counting rate of coincidences of the ionizing particles other than fission recoils is not appreciable. A sample counting rate *versus* discriminator voltage curve is shown in Fig. 2.

The elements used as targets were beryllium, carbon (graphite), aluminum, copper, silver, lead, and uranium. Pieces of these elements were machined into blocks 1 inch by 1 inch square, and varying in thickness from $\frac{1}{8}$ to 1 inch. The densities of the targets were determined by weighing and measuring the blocks, and with the exception of the graphite, all the densities agreed closely with the accepted values. The densities of the graphite targets used varied from 1.45 to 1.49.

Graphite monitors were used to determine the fluxes of protons or deuterons traversing the targets. The monitors were attached to the target so that the beam

[6] Cladis, Crandall, and Hadley (to be published).

[7] C. Wiegand, Rev. Sci. Instr. **19**, 790 (1948).
[8] J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950).

passed, simultaneously, through both target and monitor. At the end of the bombardment the monitor was removed and the counting rate of the C^{11} activity in it was determined on a Geiger-Mueller counter at a suitable later time. These monitors were milled from C-18 graphite down to about 0.010 inch thick and cut into 1 inch × 1 inch squares. A chemical analysis of a specimen of this graphite showed that it contained a total of about 0.15 percent of impurities.

It was necessary to take precautions against the contamination of the monitors by recoils or fission fragments from the targets. Beryllium and carbon targets did not contaminate the monitors, but aluminum, copper, silver, lead, and uranium targets did. In order to avoid this contamination it was necessary to place additional graphite foils both between a target and its monitor, and on the outside of the monitor.

Monitors were placed on the front and back of each target. The activities in the front and back monitors on thin targets ($\frac{1}{4}$ inch or less) agreed to within 10 percent. When thicker targets were used, alignment of the target with respect to the beam became quite critical. Thin targets were used in most of the measurements.

In making a set of measurements, the following procedure was generally used. The clipper was inserted into the cyclotron and a current reading target was put on the target probe. The beam was turned on and maximized, and the cyclotron field was adjusted to give the maximum amount of beam current through the aperture of the clipper. Then a beryllium target was put on and the bias voltage *versus* counting rate curves were taken on the bismuth fission chambers in the neutron beam. Finally, a target rotating device with its four aligned targets and monitors was put on the target probe and its rotating action was tested by watching it rotate, through a window in the cyclotron tank wall. At a given recorded instant the beam was turned on and held, at a steady level, on the first target, while the bismuth fission chambers and their related circuits recorded the counting rate in the neutron beam. After the beam had run for a prescribed length of time on the first target, the second target was rotated into place without stopping or altering the cyclotron beam, and the counting rate in its neutron beam was recorded. The same procedure was followed for the third and fourth targets, and then the beam was turned off. The time at the beginning and end of bombardment of each target was recorded. A decay curve was taken on the C^{11} activity in each monitor after it had decayed to a level suitable for counting on a Geiger-Mueller counter.

III. CALCULATIONS

The neutron counts registered by the one or more bismuth fission chambers in the neutron beam were converted to counts per second for each target that was bombarded in a given run. The counting rates were always quite low, ranging from 1 to 10 counts/sec, so there was no necessity to make coincidence corrections. The resolving time of the counters and circuits is of the order of 5 μsec. The cyclotron beam is pulsed for about 100 μsec 60 times per second, so that for a counting rate of 10 counts/sec there is very seldom more than one count per beam pulse.

Decay curves were taken of the C^{11} activity produced in the monitors attached to each target. The C^{11} activity was then extrapolated back to the time at the end of bombardment of the target, and a correction was made for the length of bombardment to give the activity, which would have been produced in a bombardment of infinite length. Usually, the decay curve showed almost pure C^{11} activity and the extrapolation could be made directly. However, sometimes it was necessary to wait for 12 to 15 half-lives of the C^{11} before the level was low enough to count and a small amount of long-lived impurity would appear. In this case the long-lived activity was subtracted out of the curve before extrapolating back to the end of bombardment. Sometimes decay curves were taken through an aluminum absorber so that the positron annihilation radiation of the C^{11} was counted instead of the positrons themselves. The relative fluxes through the targets calculated

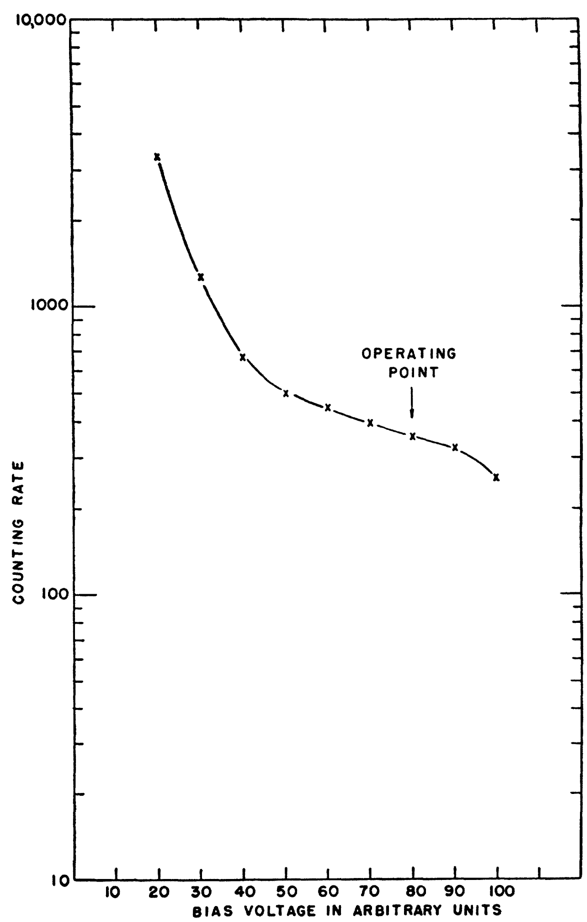

FIG. 2. Sample counting rate *versus* bias voltage curve for a bismuth fission counter.

TABLE I. Relative neutron yields per atom for targets bombarded with 190-Mev deuterons.

Target	Thickness	Yield in forward direction	Forward direction probability	Relative total yield
Be	0.25″	0.93	0.995	0.93
C	0.25″	1.00	0.99	1.00
Al	0.25″	1.34	0.97	1.37
Cu	0.25″, 0.20″	1.44	0.90	1.58
Ag	0.184″	1.88	0.85	2.19
Pb	0.25″, 0.21″	2.69	0.73	3.65
U	0.121″	2.77	0.71	3.86

from the annihilation radiation decay curves, or from the positron decay curves, agreed within the error of the measurements. Since the relative fluxes through the targets were all that were desired, and since all the monitors were of the same shape and thickness, there was no necessity to make absorption corrections. The fluxes through the targets were considered to be proportional to the activities induced in the monitors after the extrapolation to the end of bombardment and the correction for length of bombardment were made.

For each of the four targets used in a given run, the neutron counting rate was determined and corrected for the neutrons produced in the monitors and the relative neutron yields for the four targets were calculated. The relative fluxes of particles traversing the targets were used to correct the neutron yields to some constant flux value for all of the targets. Then the number of atoms per unit area exposed to the beam in a target was calculated, and finally, the relative neutron yields per atom were obtained by comparing the corrected yields from each target to the yield from a standard carbon target.

IV. RESULTS AND DISCUSSION

(A) Neutron Yields from Deuteron Beam

Table I gives the relative neutron yields per atom, in the forward direction, for various target elements when bombarded with 190-Mev deuterons. Serber's mechanism[2] for the production of high energy neutrons postulates that the proton is stripped from the deuteron by striking the edge of a target nucleus and the neutron misses and continues on its way. The total stripping cross section is proportional to $A^{\frac{1}{3}}$. However, the yield in the forward direction also depends upon the effect of the Coulomb fields of the target nuclei on the angular distribution of the neutrons. One can calculate the probability for the production of neutrons in the forward direction from the equation for the angular distribution of neutrons produced in the stripping process.[9] The angular distribution predicted by this equation has been verified experimentally.[3] The equation takes into account the intrinsic bending of the deuteron's orbit in the field of the nucleus, at whose surface the deuteron is stripped, and multiple scattering of the deuteron beam in the target. Also, in order to take into account energy losses, the kinetic energy of the deuteron at the time of stripping is taken as the bombarding energy, minus the Coulomb energy lost in approaching the stripping nucleus, minus one-half the energy loss of the deuteron in one traversal of the target. The forward direction probabilities calculated from the formula mentioned above are given in Table I. The relative total yields are then obtained by dividing the experimental yields by the forward direction probabilities. No attempt was made to take into account additional energy losses or scattering arising from more than one traversal of the target. This effect is relatively small for the neutrons from stripping of 190-Mev deuterons. If it were taken into account, the forward direction probabilities would be slightly lower than given in the table for the heavy elements.

The observed values for the light nuclei fit the shape of the calculated curve fairly well but the values for the heavy nuclei lie above the curve. An explanation for this deviation may lie in another mechanism for the production of high energy neutrons by deuterons, the disintegration of the deuteron in the Coulomb field of the nucleus.[10] This effect has been predicted and calculated[11] for 200-Mev deuterons but has not been verified by the experimental measurements on the angular distributions of the neutrons. The angular distribution

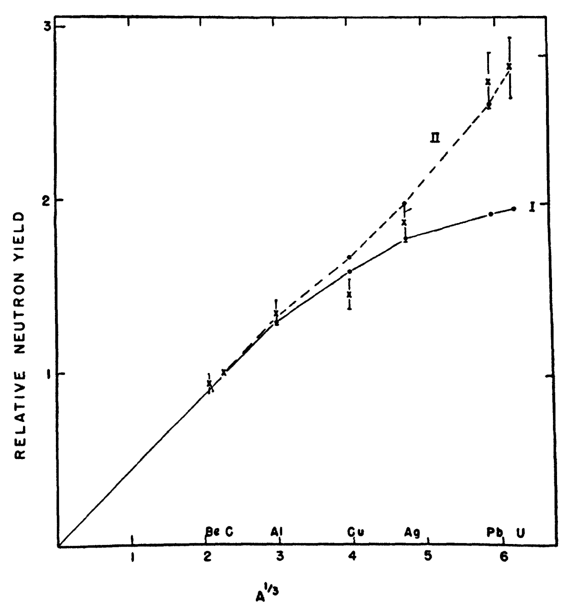

FIG. 3. Relative neutron yields in the forward direction from targets bombarded with 190-Mev deuterons. The crosses are the observed neutron yields in the forward direction in arbitrary units. Curve I (solid) shows the values predicted by stripping theory relative to the value for carbon. Curve II (dotted) shows the values obtained by adding a function proportional to Z^2 to the stripping theory values. A probable error of ± 6 percent is shown on each point, except the value for carbon to which the other values are relative.

[9] Reference 2, Eq. (25).

[10] J. R. Oppenheimer, Phys. Rev. 47, 845 (1935).

[11] S. M. Dancoff, Phys. Rev. 72, 1017 (1947).

calculated for neutrons coming from the electric disintegration of the deuteron was narrower than the distribution from the stripping process. The experimental points for heavy elements fitted the distribution predicted by stripping but not the distribution predicted by the combined processes of stripping and electric disintegration. However, it is possible that the distribution of neutrons from the electric disintegration process could be widened by Coulomb effects of the target nuclei enough, so that the width of the distribution would be about the same as that for the stripping process. In this case the angular distribution measurements would fit either the stripping process, or the combined stripping and electric disintegration processes.

The cross section for the electric disintegration process is proportional to Z^2, and if a function proportional to Z^2 is added to the values predicted by the stripping theory, a good fit can be obtained for all the points. Figure 3 shows the observed relative neutron yields with their estimated probable errors plotted *versus* $A^{\frac{1}{3}}$. Also shown are the values for the yields in the forward direction calculated from stripping theory, and a curve for which the stripping theory predictions have been combined with a function proportional to Z^2. The points calculated from stripping theory do not give a smooth curve because the densities and thicknesses of the targets enter into the corrections. The proportionality factor for the Z^2 function which gives the best fit for the observed points indicates an electric field disintegration cross section for uranium equal to about one-half of the stripping cross section in the forward direction, which is the correct order of magnitude according to theory.[11] The total stripping cross section is theoretically equal to $5A^{\frac{1}{3}}\times10^{-26}$ cm^2, while the electric disintegration cross section is about $1.35Z^2$

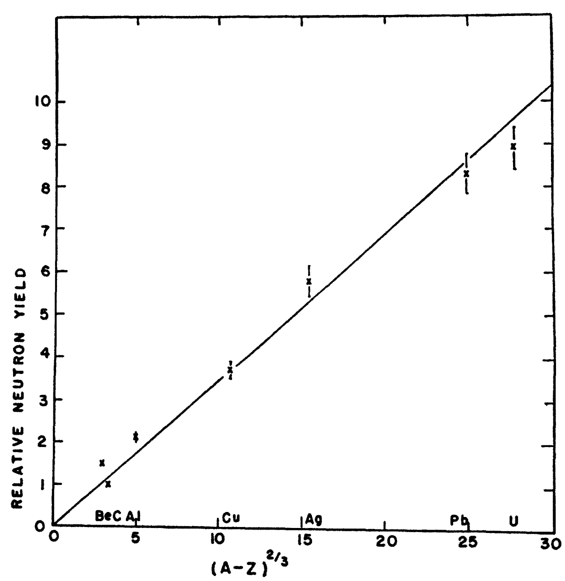

FIG. 4. Relative neutron yields in the forward direction from targets bombarded with 340-Mev protons.

TABLE II. Relative neutron yields per atom in the forward direction from targets bombarded with 340-Mev protons.

Target	Thickness	Relative neutron yield
Be	0.25″, 0.50″	1.5
C	0.25″, 0.50″	1.0
Al	0.25″, 0.50″	2.1
Cu	0.20″, 0.25″	3.7
Ag	0.184″	5.8
Pb	0.21″, 0.25″	8.3
U	0.12″, 0.25″	8.9″

$\times10^{-29}$ cm^2 for heavy elements. These values give a ratio of about $\frac{1}{3}$ for uranium.

The energy distribution of neutrons from heavy elements is lower than that from light elements because of the barrier energy loss before the stripping of the deuteron. This energy loss is regained by a stripped proton, but not by a neutron. Since the Bi fission cross section increases with energy, neutrons from uranium or lead should be detected with lower efficiency than those from beryllium or carbon. Consequently, the experimental values for uranium and lead are lower limits with respect to this source of error. Ionization energy loss in the target is a further effect in the same direction. Corrections for these effects, if made, would increase the difference between the experimental values and the curve predicted, without electric disintegration.

(B) Neutron Yields from Proton Beam

Table II gives the relative neutron yields per atom in the forward direction from various targets when bombarded with 340-Mev protons. No detailed mechanism has been worked out as yet for the production of neutrons by high energy protons. The neutrons are produced presumably in various types of collisions between the incident protons and particles in the nuclei of the target material. The collisions in which high energy neutrons are produced in the forward direction are most probably those in which the proton gives up only a small amount of energy to a neutron in the nucleus, but exchanges charge with it and continues essentially undeviated in its forward flight as a high energy neutron. In this case for the transparent nucleus model, one might expect the cross section to be approximately proportional to the number of neutrons or particles in the nucleus. This does not agree with the observed values for the forward direction, which have approximately an $(A-Z)^{\frac{2}{3}}$ dependency for elements from carbon to uranium.

Corrections for differences in angular distributions of the neutrons from different elements have not been made. These corrections should be small. Angular distribution measurements using carbon detectors on the neutrons produced from targets bombarded with 340-Mev protons show very wide distributions which vary only slightly for targets from beryllium to uranium.[12] Hence, the present measurements indicate that

[12] Miller, Sewell, and Wright, Phys. Rev. 81, 374 (1951).

the heavy nuclei are not completely transparent, even to 340-Mev protons. Beryllium has an anomalous value with respect to the dependency on $A-Z$ which is 50 percent higher than the value for carbon. Figure 4 shows the observed relative neutron yields per atom in the forward direction for targets bombarded with 340-Mev protons plotted *versus* $(A-Z)^{2/3}$. The values lie fairly close to a straight line passing through the origin.

A qualitative explanation for the anomalous behavior of beryllium may lie in its peculiar nuclear structure. If the odd neutron in the beryllium nucleus is bound much more loosely than the remaining neutrons, the cross section for this neutron will be higher than that for the rest of the neutrons, and also the energy distribution may be higher.[13] The cross section for bismuth fission by neutrons increases rapidly with respect to the energy of the neutrons[14] in the range 60 to 90 Mev. The cross section is still rising at the energy of neutrons produced by 340-Mev protons.[15] This would make the present detection method somewhat dependent on the differences in energy distributions of the neutrons from the various targets. No correction has been made for this effect. Because of the very high energy of the incident protons, it is thought that the differences in the energy distributions of neutrons from the various target elements are not very great, with the possible exception of the distribution from beryllium. The group of neutrons produced by exchange collisions with the loosely bound neutron in the beryllium nucleus might have a significantly higher energy distribution than the rest of the neutrons. In this case, the detection efficiency for these neutrons would be higher and the apparent yield from beryllium would be increased.

It is intended to make absolute measurements on the neutron yields from both proton and deuteron bombarded targets. These values will be published at a later date.

It is estimated from the present work that 190-Mev deuterons yield about 40 times more neutrons per unit solid angle in the forward direction than 340-Mev protons when a carbon target is bombarded with a given particle flux. The total high energy neutron production by deuterons is of the order of three times greater than that by protons. This estimate includes an increase by a factor of three in the bismuth fission cross section in going from 90- to 270-Mev neutrons[15] and uses values of 65 mb for the $C^{12}(d,dn)C^{11}$ cross section[16] and 38 mb for the $C^{12}(p,pn)C^{11}$ cross section.[17]

[13] G. Chew (private communication).
[14] E. Kelley and C. Wiegand, Phys. Rev. **73**, 1135 (1948).
[15] J. DeJuren, Phys. Rev. **80**, 27 (1950).
[16] V. Peterson (unpublished data).
[17] Aamodt, Peterson, and Phillips (to be published).

V. ERRORS

The relative neutron yield from a given element was obtained by comparison of its corrected neutron yield to the yield from a standard carbon target. The estimated probable error of a single determination of such a ratio is about 10 percent. This error arises mainly in the determination of the flux of deuterons or protons traversing a target, but also has contributions from the neutron counting statistics and from the correction made for the production of neutrons in the carbon monitors. The errors in measurements of the thicknesses and densities of the targets are negligible. The results given in Tables I and II are the averages of from 2 to 4 individual determinations. Preliminary results which were obtained before the final technique was developed are not included, but they were in agreement with the final values. The probable error calculated from the mean square deviation of all of the individual results from the average values given in Tables I and II is about 3 percent. This gives a measure of the reproducibility of the results. A combination of the reproducibility of the individual results with an estimate of the possible errors involved in the technique leads to a probable error of about 6 percent for the final values. This is the error shown on all values in Figs. 3 and 4, except the arbitrary value for carbon, which was the standard.

VI. SUMMARY

Relative high energy neutron yields in the forward direction from deuteron bombarded targets agree with stripping theory for the light elements. A better fit is obtained for both light and heavy elements if a function proportional to Z^2 is added. This may be interpreted as evidence for the process of electric field disintegration of the deuteron. This function indicates an electric disintegration cross section for uranium of about one-half the stripping cross section.

Neutron yields in the forward direction from proton bombarded targets vary approximately as $(A-Z)^{2/3}$, for elements from carbon to uranium. This indicates that the heavy elements are not completely transparent even to 340-Mev protons. The neutron yield from beryllium has an anomalous value 50 percent higher than that for carbon.

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