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Relative High Energy Neutron Yields from Targets Bobmarded with Protons and Deuterons

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William J. Knox

September 12, 1949

Berkeley, California

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Relative High Energy Neutron Yields from Targ[redacted] Bombarded with Protons and Deuterons

William J. Knox

September 12, 1949

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ABSTRACT

Relative neutron yields in the forward direction from various target elements bombarded with 350 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. The actual flux of protons or deuterons traversing each target was determined from the activities induced in graphite monitors attached to the target. 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 may 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 $(A - Z)^{2/3}$ for target elements from carbon to uranium. This indicates that the heavy elements are not completely transparent to 350 Mev protons. Beryllium has an anomalous neutron yield 50 percent higher than that for carbon. Calculations and measurements on the problem of multiple traversals of beam particles through thin targets are presented.

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

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September 12, 1949

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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 350 Mev protons on a target in the cyclotron. These beams have been investigated experimentally and theoretically by various observers. Serber(2) has proposed a mechanism 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. The angular distribution and the variation of angular distribution with atomic number of the neutrons predicted by this mechanism have been verified experimentally by Helmholz, McMillan and Sewell.(3) 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 in the nuclei of the target material.

It is the purpose of this paper to present and interpret experimental data on the neutron yields in the forward direction from different target elements for both the deuteron and proton beams. The problem of multiple traversals of high

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(1) W. M. Brobeck, E. O. Lawrence, et al., Phys. Rev. 71, 449 (1947)

(2) R. Serber, Phys. Rev. 72, 1008 (1947)

(3) A. C. Helmholz, E. M. McMillan, and D. C. Sewell, Phys. Rev. 72, 1003 (1947)

energy particles through thin tagets in the cyclotron was encountered in the investigation and will be discussed.

Apparatus and Experimental Technique

The deuterons produced by the 184-inch cyclotron have a maximum energy of 190 Mev and beam of about 10^{-6} amperes average current can be obtained. The protons have a maximum energy of 350 Mev and can be produced with an average beam current of the order of 5×10^{-7} amperes. A target of any desired material and dimensions within reasonable limits can be inserted into the path of these particles through a vacuum lock in the cyclotron tank by means of the target probe. The target 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 80-1/2 to 81 inches.

When the particles impinge on a target, neutrons are given off in the general forward direction. These neutrons may be intercepted in a wide beam just outside the cyclotron tank wall or they may 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 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} steradians from the target, and the counters were located within one degree or less of the direction in which the proton or deuteron beam was travelling 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 of about 27 Mev.(2) The energy maximum and distribution vary slightly with different materials and thicknesses of targets. The energy distribution of neutrons from the proton beam is not known precisely, but the best known value at present is about 280

± 20 Mev for the maximum with a width at half maximum of about 80 Mev.(4)

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(4) J. Hadley, preliminary results

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 degrees 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 1-1/2 inches. They restricted the beam particles to amplitudes of less than 1/2 or 3/4 inch from the beam plane and extended from about 60 inch radius to about 81-1/2 inch radius in the cyclotron. The back of the clipper at about 81-1/2 inch radius also cuts off particles which have outward radial oscillations or deflections from the target of greater than 1/2 or 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 consisted of four arms spaced 90 degrees apart mounted on a rotating shaft which in turn was mounted parallel to the target probe face. On the end of each arm was a clamp for holding targets. A mechanical positioning device was made so that the arms could assume only four discrete positions. This consisted of a flat spring with a small half round piece soldered to its end which was made to mesh with four semicircular cuts in a piece fastened to the rotating arms. The device was actuated by a coil which was pivoted on the same shaft as the rotating arms and which had its axis perpendicular to the magnetic field of the cyclotron. A small catch attached to the coil engaged one of the four target arms. When power was supplied to this coil from an outside source, the coil rotated through 90 degrees so that its axis lined up with the magnetic field, and in so doing the coil caused the target arms to rotate through 90 degrees. When the power was turned off, the coil fell back to its original position through the action of gravity, and its catch engaged the next arm and the device was ready for another rotation. A single rotation through 90 degrees could be accomplished in a time of the order of one half second. Hence, one could change targets 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 various targets in a given run. The actual number of particles traversing different targets, however, varied because of multiple traversals which will be discussed later. A photograph of the target rotating device is shown in Figure 2.

Bismuth fission chambers were used to detect the high energy neutrons. The construction and operation of these chambers have been described in detail elsewhere.(5,6) 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 volts 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

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(5) C. Wiegand, Rev. Sci. Instr. 19, No. 11, 790 (1948)

(6) J. DeJuren and N. Knable, Phys. Rev., to be published

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 cruve 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 Figure 3.

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 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 very closely with the accepted values. The densities of the graphite targets used varied from 1.45 to 1.49. This graphite is known as C-18 and chemical analysis of a specimen of it showed that it contained a total of about 0.15 percent of impurities.

The graphite monitors which were used to determine the fluxes of protons or deuterons traversing the targets were also machined from C-18 graphite. These monitors were milled down to about .010 inch thick and cut into 1 inch by 1 inch squares. The monitors were measured with micrometer calipers and weighed and for a given set of measurements a group of monitors was selected which did not vary more than a few percent in weight or thickness. Each monitor itself had several bumps on it 10 to 20 percent thicker than the rest of the monitor where the thin graphite sheet was held by a vacuum chuck during the milling operation, but the monitors were used so that these bumps did not occur near the leading edge of the target where the beam actually traversed the monitor. The parts of the monitors which were traversed by the beam were quite uniform in thickness both within a single monitor and within a group of monitors used in a given set of measurements.

The monitors and targets were clamped to the target rotating device by means of a small plate which screwed onto the end of each arm. Each target with its monitors was lined up so that its edge protruded one-half inch beyond the end of the target arm. This was accomplished by means of a platform which clamped onto the main shaft of the rotating device. The platform was fixed to the shaft with a clearance of one-half inch from the ends of the target arms and then each target with its monitors was allowed to sit on the platform while its target arm was rotated into place and clamped to the target. This method insured uniform alignment of the targets.

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 activating its coil and 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-Muller counter.

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 per second so there was no necessity to make coincidence corrections. The resolving time of the counters and circuits is of the order of 5 microseconds. The cyclotron beam is pulsed for 100 microseconds about 100 times per second, so that for a counting rate of 10 counts per second 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 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. 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 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. If a shield was not used on the outside of a monitor, some fragments or recoils would evidently fly from the target and curl around in the magnetic field and lodge on the outside of the monitor although this effect was not as great as the contamination directly from the target if the inside shield was not used.

A correction was made to the neutron counting rates for the production of neutrons in the monitors and their shields as well as the neutrons produced in the targets. This correction was made on the basis of the relative numbers of atoms per unit area in the monitors and the targets and the relative neutron yields per atom for the carbon monitors and the target element in question.

Monitors were placed on the front and back of each target. The average of the observed fluxes traversing the front and back monitors was assumed to be the flux actually traversing the target. The fluxes through the front and back monitors on thin targets (1/4 inch or less) agreed to within 10 percent. When thicker targets were used, alignment of the target became quite critical. Several runs were made in which beryllium targets ranging in thickness from 1/4 inch to one inch were exposed so that the beam struck the targets at a slight angle to the face of the target. A trend of decreasing ratio between the fluxes shown by the back monitor and the front monitor was observed with increasing target thickness. This ratio fell as low as 0.5 for a one inch thick target inclined at about one degree. The effect is probably mostly due to the inclination of the target to the beam but may be partly because of the scattering of the beam as it traverses the edge of the target. As stated above, thin targets (1/8 to 1/4 inch) were used for most of the measurements so that fluxes through the front and back monitors agreed to within about 10 percent or better.

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 then calculated. The relative numbers 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 from the density, thickness and atomic weight of the target 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.

Multiple Traversals of Particles through Targets

In the course of the investigation before the monitoring technique was developed it was found that the neutron yields per atom from beryllium targets of different thicknesses were not constant. Subsequently monitors were put on the targets and it was found that the number of particles traversing targets of different thicknesses or of different materials varied even when the cyclotron conditions were constant. From then on all targets were monitored and the neutron yields were corrected to some standard flux value for all targets as described above. Certain regularities were noticed in the variations among different targets. These results are of sufficient experimental interest that they will be given in some detail in this section, although the calculations presented on this effect are not directly related to the original problem of neutron yields.

The effect is correlated with multiple scattering. A particle which does not receive a deflection in traversing the target sufficient to cause it to hit the clipper or the dee may continue on around in the cyclotron and traverse the target one or more times in addition to the initial traversal. A thick target or a target of high atomic number will cause particles to suffer large deflections and most of them will be cut out by the clipper before traversing the target again while a thin target of a light element will not scatter the particles very much and they may traverse the target several times. This effect is called "multiple traversals" of the target by the particles in the beam. The number of traversals is the average over all the particles in the beam of the numbers of times that single particles traverse the target.

One can calculate the expected number of traversals through a given set of targets and compare the calculated values with the observed ratios of fluxes through the targets as determined from the activities induced in the monitors on the targets. Unfortunately one can only check the relative numbers of traverals through different targets experimentally and not the absolute number through any given target.

The angle of deflection caused by multiple scattering in passing through the target may be calculated from the usual formula.(7) The frequency of vertical oscillations in the cyclotron is given by:

$$f_v = \sqrt{n}\, f_o$$

where n is the logarithmic decrement of the magnetic field and f_o is the frequency of revolution of the particles in the cyclotron. At 81 inches $n = 0.15$ and $f_v = 0.4\, f_o$. Hence it can be seen that the clipper which is set at 150° from the target probe is approximately at the point of maximum amplitude of vertical oscillation for a particle which is scattered in the target. Also it can be shown that the maximum allowable scattering angle for a particle to escape being cut out by the clipper is given by:

$$\theta_m = \sqrt{n}\, \frac{y}{r}$$

where y is the maximum vertical aperture of the clipper or the dee and r is the radius from the center of the cyclotron. Using this relationship one can make an approximate calculation of the number of traversals through a target with a few additional reasonable assumptions. First, assume that the particles when approaching the target for the first time have vertical oscillations with a root mean square amplitude of about half the maximum amplitude allowed by the clipper or dee. Second, particles that are scattered in the target vertically or those scattered horizontally toward a greater radius than the target are limited by the clipper but those which are scattered horizontally toward a smaller radius

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(7) E. J. Williams, Proc. Roy. Soc. 169, 531 (1939)

than the target are not limited. Third, the particles have a Gaussian distribution of amplitudes after traversing the target and particles that acquire an amplitude greater than that allowed by the clipper are removed from the beam while all others continue on around and traverse the target again. Fourth, the root mean square deviations from the initial oscillations or from traversals of the target are compounded as the square root of the sum of the squares. Fifth, the root mean square amplitude of oscillation of the particles as they approach the clipper can never exceed a value obtained by compounding the maximum amplitude passed by the clipper and the amplitude acquired in one traversal through the target. These assumptions are not rigorously true nor are they complete but they constitute a basis for an approximate calculation. Observed relative fluxes through various targets divided by values calculated by the above method are shown in Table I for targets bombarded with 350 Mev protons. The multiple traversal effect for targets bombarded with 190 Mev deuterons was much smaller.

It must be emphasized that only relative numbers of multiple traversals through various targets have been measured experimentally and not absolute numbers. If the second assumption above is eliminated and particles scattered in all directions are assumed to be limited by the vertical aperture of the clipper, all the calculated numbers of traversals are decreased by about one fourth, but the agreements between the calculated values and the observed relative values is still about the same. Also the calculated relative values for different targets are quite insensitive to changes in the clipper aperture while the absolute values vary considerably. If the attempt is made to eliminate multiple traversals completely by using a very thick target, other effects such as alignment of the target, beam attenuation and large energy losses in the target become important and it is difficult to make good measurements.

The agreement of the calculated values with the observed relative values is fairly good for light element targets of various thicknesses. The agreement is not as good when the targets differ greatly in scattering power. However, one

Table I

Calculations and observations on multiple traversals of 350 Mev protons through thin targets. Each group of four values constitutes a separate set of observations for which the cyclotron beam is assumed to be constant on the four targets.

Target	Thickness	Rms angle of scattering in radians x 10^{-3}	Clipper aperture	Calculated number of traversals	Activity in monitors divided by calculated number of traversals
Be	0.25"	2.7	1.5"	4.1	1.01 , 1.10
Be	0.50"	3.8		3.2	1.02 , 1.12
Be	0.75"	4.6		2.9	1.00 , 1.01
Be	1.00"	5.3		2.7	-- , 1.00
Be	0.25"	2.7	1.0"	3.1	0.85
Al	0.25"	5.8		2.1	1.07
Cu	0.25"	14.7		1.6	0.99
Ag	0.18"	16.8		1.5	1.00
Be	0.50"	3.8	1.0"	2.6	1.05
C	0.50"	4.2		2.4	1.03
Al	0.49"	8.1		1.8	1.25
Cu	0.49"	20.8		1.5	1.00
C	0.25"	3.0	1.0"	2.9	0.71
Cu	0.25"	14.7		1.6	0.96
Pb	0.25"	24.5		1.5	1.03
U	0.25"	33.1		1.4	1.00

seems justified in concluding that the processes limiting the number of multiple traversals are understood and that this is a correct explanation for the fact that different beam intensities are observed through different targets when cyclotron conditions are maintained constant.

Results and Discussion

I. Neutron yields from deuteron beam.

Table II 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 $A^{1/3}$. However, the yield in the forward direction also depends upon the effect of the Coulomb field of the target nuclei on the angular distribution of the neutrons. One can calculate the probability for production of neutrons in the forward direction from the equation for the angular distribution of neutrons produced in the stripping process.(8) The angular distribution predicted by this equation has been verified experimentally.(3) The equation takes into account the intrinsic bending of the deuterons 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 factors for the probabilities of neutrons being given off in the forward direction are approximately the same as those given by the inverse squares of the half widths of the distributions of the neutron beams, i.e., if the spread of the beam becomes greater, the yield in the forward

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(8) Ref. (2), equation 25

Table II

Relative neutron yields per atom in the forward direction from targets bombarded with 190 Mev deuterons.

Target	Thickness	Relative neutron yield
Be	0.25"	1.00
C	0.25"	1.07
Al	0.25"	1.44
Cu	0.25" , 0.20"	1.55
Ag	0.184"	2.01
Pb	0.25" , 0.21"	2.88
U	0.121"	2.97

direction becomes less. The forward direction probabilities together with the half-widths and inverse squares of the half-widths of the neutron beams calculated from the formula mentioned above are given in Table III. 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 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.(9) This effect has been predicted and calculated(10) for 200 Mev deuterons but has not been verified by the experimental measurements on the angular distributions of the neutrons. The angular distribution 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

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(9) J. R. Oppenheimer, Phys. Rev. 47, 845 (1935)

(10) S. M. Dancoff, Phys. Rev. 72, 1017 (1947)

Table III

Angular widths at half maximum and probabilities for neutrons in the forward direction for neutron beams produced by 190 Mev deuterons on various targets.

Target	Thickness	Angular width at half maximum in radians	Inverse square of angular width (relative)	Forward direction probability
Be	0.25"	0.1605	1.00	1.00
C	0.25"	0.161	0.994	0.995
Al	0.25"	0.164	0.96	0.98
Cu	0.225"	0.173	0.86	0.90
Ag	0.184"	0.180	0.80	0.85
Pb	0.23"	0.192	0.70	0.74
U	0.121"	0.195	0.69	0.72

the stripping theory, a fairly good fit can be obtained for all the points. Figure 4 shows the observed relative neutron yields with their estimated probable errors plotted versus $A^{1/3}$. Also shown are the values for the yields in the forward direction calculated from stripping theory and a curve for which stripping theory has been combined with a function proportional to Z^2. The points calculated from stripping theory do not give a smooth curve because the densities of the target elements 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. The total stripping cross section is theoretically equal to $5\ A^{1/3} \times 10^{-26}\ \mathrm{cm}^2$ while the electric disintegration cross section is about $1.35\ Z^2 \times 10^{-29}\ \mathrm{cm}^2$ for heavy elements. These values give a ratio of about 1/3 for uranium.

II. Neutron yields from proton beam.

Table IV gives the relative neutron yields per atom in the forward direction from various targets when bombarded with 350 Mev protons. No detailed mechanism has been worked out yet for the production of neutrons by high energy protons. The neutrons presumably are produced 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 $(A - Z)^{2/3}$ dependency for elements from carbon to uranium.

Corrections for differences in angular distributions of the neutrons from

Table IV

Relative neutron yields per atom in the forward direction from targets bombarded with 350 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

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 350 Mev protons show very wide distributions which vary only slightly for targets from beryllium to uranium.(11) Hence the present measurements indicate that the heavy nuclei are not completely transparent even to 350 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 5 shows the observed relative neutron yields per atom in the forward direction for targets bombarded with 350 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. The cross section for bismuth fission by neutrons increases rapidly with respect to the energy of the neutrons in the range 60 to 90 Mev.(12) It is thought that the cross section is still rising at the energy of neutrons produced by 350 Mev protons.(13) 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

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(11) R. Miller, D. Sewell, and R. Wright, to be published

(12) E. Kelly and C. Wiegand, Phys. Rev. 73, 1135 (1948)

(13) J. DeJuren and N. Knable, unpublished data

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

Errors

The relative neutron yield from a given element was obtained by comparing 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 III and IV 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 III and IV 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 Figures 4 and 5 except the arbitrary value for carbon which was the standard.

Summary

High energy neutron yields in the forward direction from deuteron bombarded targets agree with stripping theory for the light elements. In order to fit the values observed for the heavy elements it is necessary to add a function proportional to Z^2 which may be interpreted as 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 350 Mev protons. The neutron yield from beryllium has an anomalous value 50 percent higher than that for carbon.

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9/15/49 md

Figures

Figure 1.

Figure 2.

Figure 3. Sample counting rate versus bias voltage curve for a bismuth fission chamber.

Figure 4. 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. 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.

Figure 5. Relative neutron yields in the forward direction from targets bombarded with 350 Mev protons.

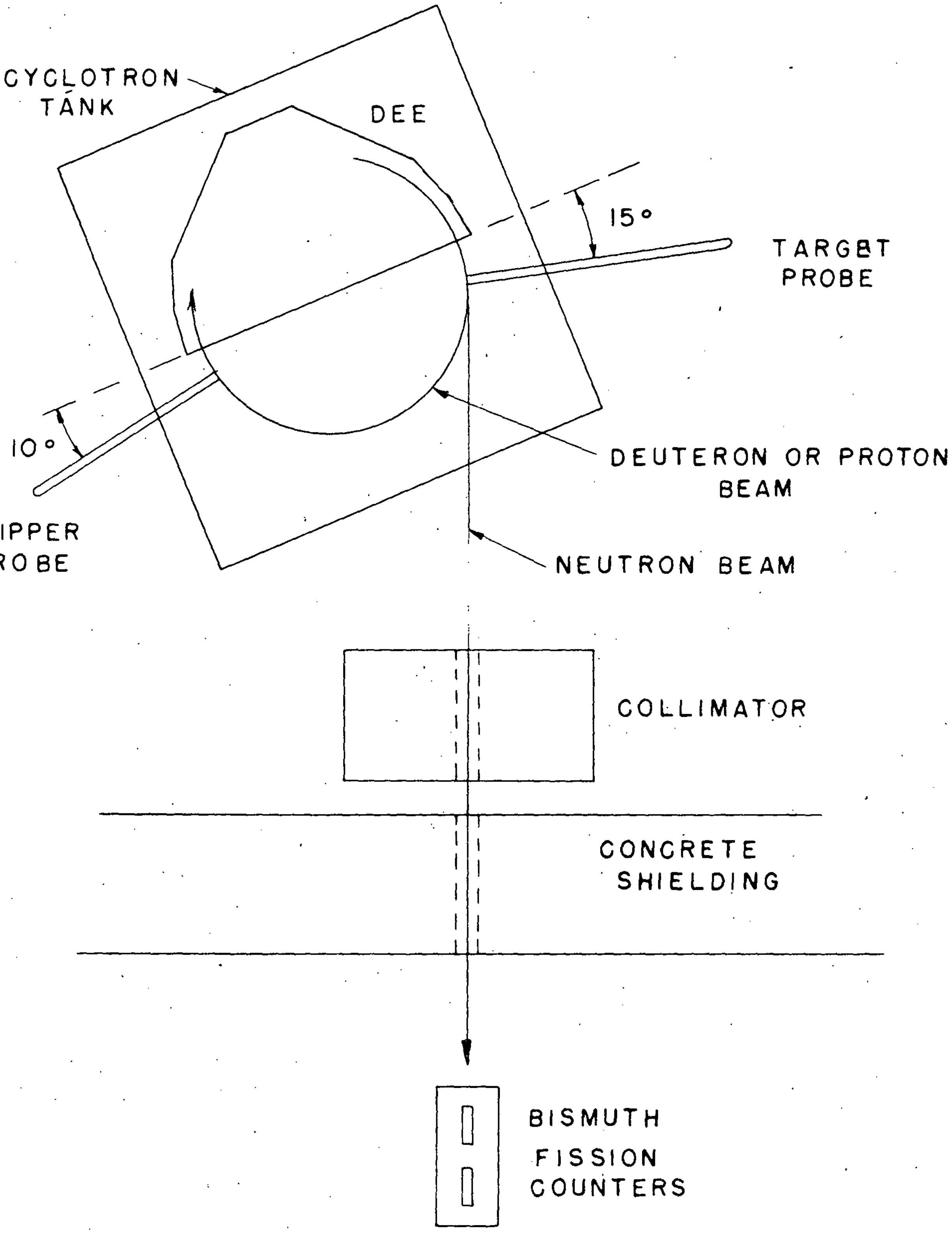
CYCLOTRON TANK
DEE
15°
TARGET PROBE
10°
CLIPPER PROBE
DEUTERON OR PROTON BEAM
NEUTRON BEAM
COLLIMATOR
CONCRETE SHIELDING
BISMUTH FISSION COUNTERS

FIG. 1

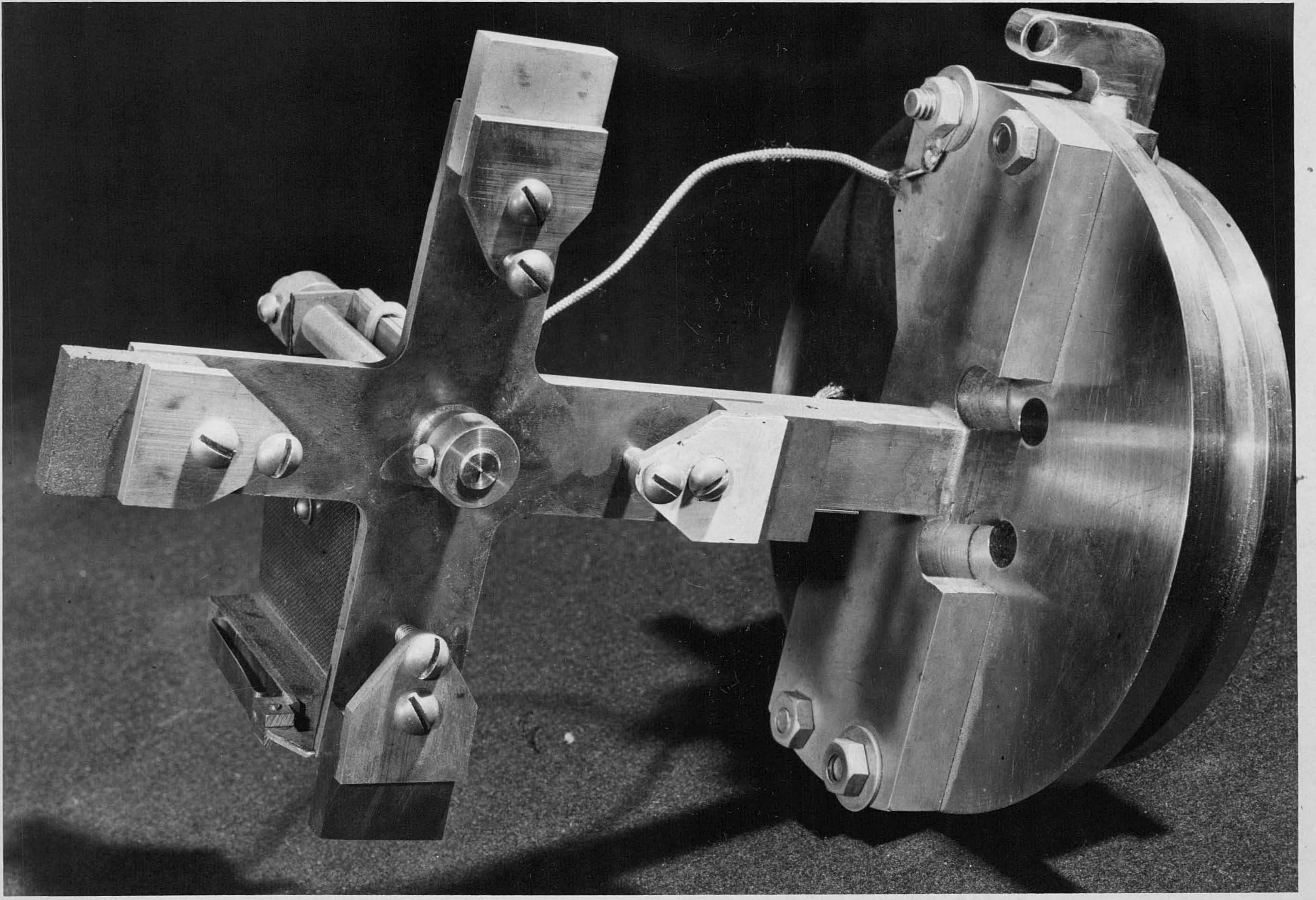

FIG. 2

OZ 633

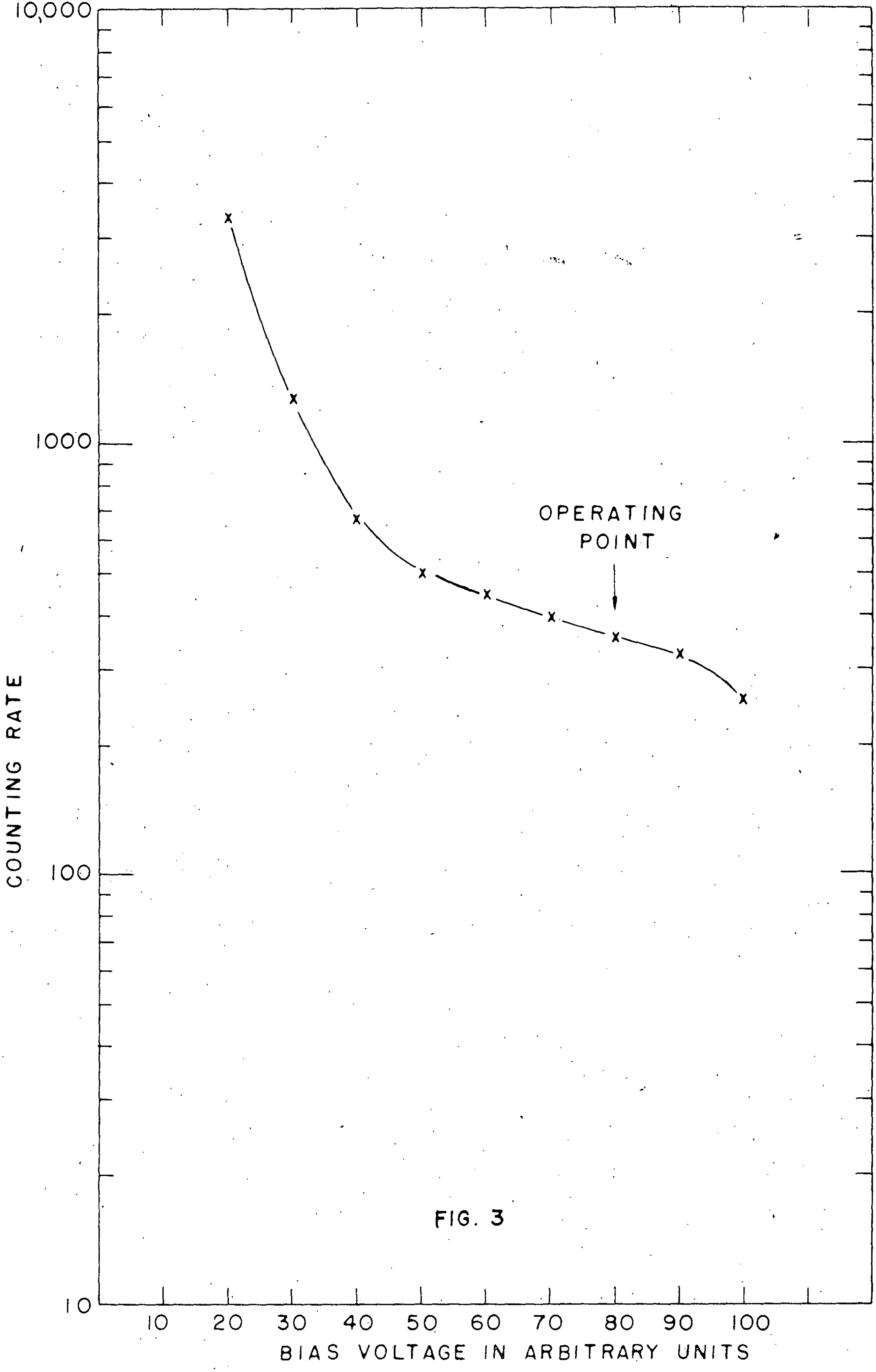
10,000
1000
100
10
COUNTING RATE
10
20
30
40
50
60
70
80
90
100
BIAS VOLTAGE IN ARBITRARY UNITS
OPERATING POINT

FIG. 3

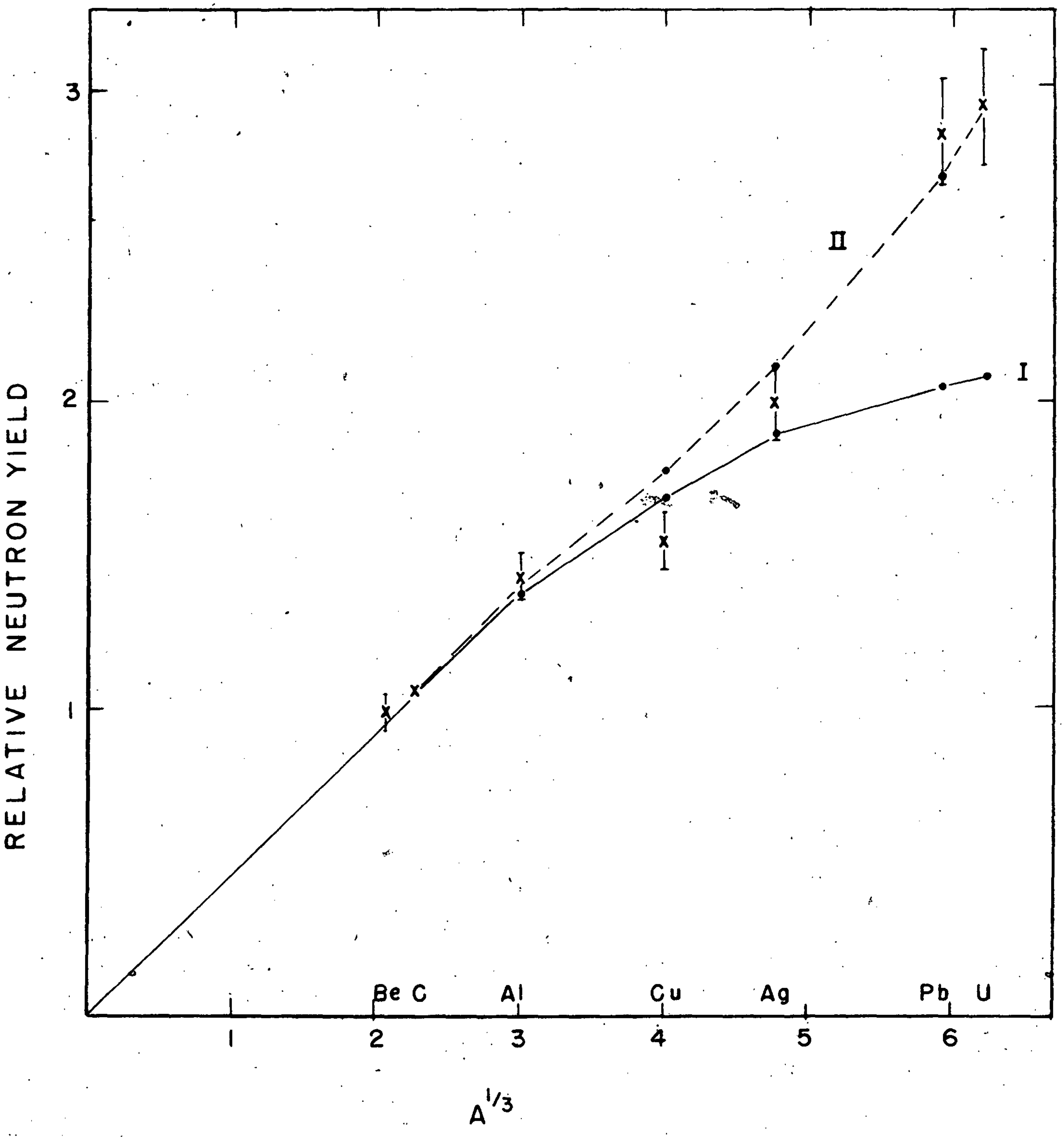

FIG. 4

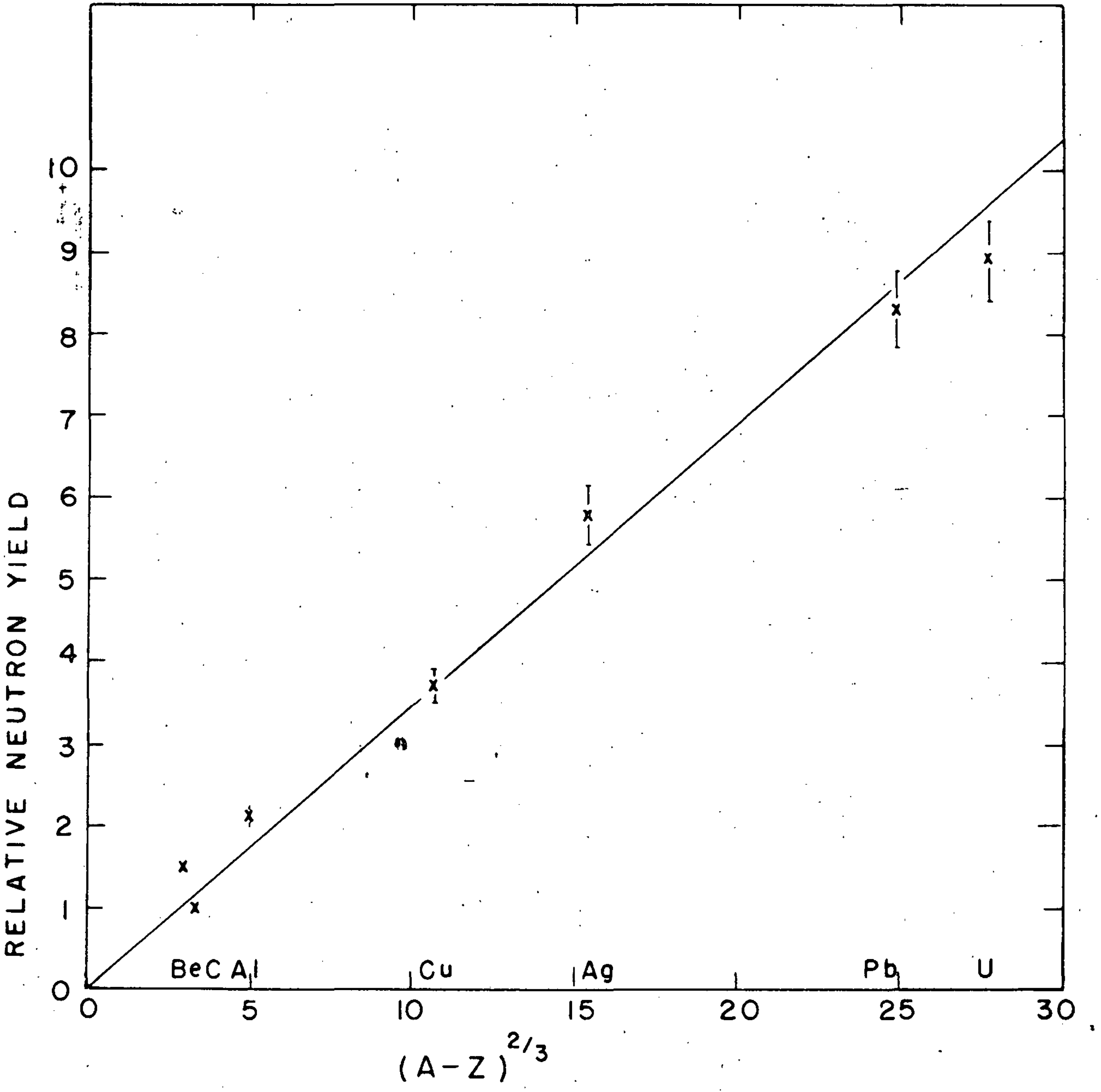
RELATIVE NEUTRON YIELD
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
$(A-Z)^{2/3}$
Be
C
Al
Cu
Ag
Pb
U

FIG. 5

DECLASSIFIED

[redacted]