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Photo-Neutron Thresholds of Beryllium and Deuterium*

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The photo-neutron thresholds of beryllium and deuterium have been measured by comparison with the $Li^7(p, n)$ threshold. For this purpose an electrostatic generator was used in which an electron beam and a positive ion beam were established simultaneously. Accurate control and measurement of the generator voltage was obtained by using an electrostatic analyzer on the H_2^+ component of the ion beam. Because the $Li^7(p, n)$ threshold lies between the $Be^9(\gamma, n)$ and $D(\gamma, n)$ thresholds, errors in extrapolation should be small. The electron beam was accelerated from ground to the accurately known potential of the high voltage electrode where x-rays were produced for the photo-disintegration process. From the photo-neutron thresholds the neutron binding energies of beryllium and deuterium were found to be 1.666 ± 0.002 and 2.226 ± 0.003 Mev, respectively.

I. INTRODUCTION

PERHAPS one of the most direct methods for determining the neutron binding energies of beryllium and deuterium is to measure their photo-neutron thresholds using x-rays produced by electrons accelerated in an electrostatic generator. Previous investigators[1,2] who measured the neutron binding energy in this manner used electrostatic generators which were designed only as electron accelerators and which had generating voltmeters for measurement and control of the electron energy. Because these generating voltmeters were calibrated at relatively low voltages, long extrapolations were necessary.

In this experiment an electron beam and a positive ion beam were established simultaneously in an electrostatic generator and the positive ion beam was used to control and measure accurately the energy of the electron beam. The energy scale was calibrated on the $Li^7(p, n)$ threshold and since this threshold lies between the $Be^9(\gamma, n)$ and $D(\gamma, n)$ thresholds, errors in extrapolation should be small.

II. APPARATUS

This experiment was performed with the pressure electrostatic generator of the Argonne National Laboratory. A schematic sketch of the arrangement is shown in Fig. 1.

The generator was operated in its normal fashion as a positive ion accelerator with the upper tube serving to accelerate positive ions and the lower tube providing differential pumping on the ion source. In addition, the differential pumping tube was used to accelerate a beam of electrons from ground to an x-ray target in the high potential electrode.

As shown in Fig. 1, the positive ion beam is separated by a magnetic analyzer into a proton and a H_2^+ beam. The H_2^+ beam is directed through a cylindrical electrostatic analyzer and onto a pair of slits where it is used to control the generator voltage at a value proportional to the voltage between the deflecting plates. Any inequality in division of current between the two exit slits is used to vary the corona current[3] electronically between the outside tank and the low potential shell so that the generator voltage is adjusted in the direction which minimizes this inequality.

The voltage between the analyzer plates is measured by means of a potentiometer and an oil-immersed resistor divider network. Calibration of the generator voltage scale in terms of the analyzer voltage was obtained by directing the proton beam onto a lithium target and making use of the $Li^7(p, n)$ threshold, which

* This work was supported in part by the AEC and in part by the Wisconsin Alumni Research Foundation.
[1] F. E. Meyers and L. C. Van Atta, Phys. Rev. 61, 19 (1942).
[2] M. L. Wiedenbeck and C. J. Marhoefer, Phys. Rev. 67, 54 (1945).
[3] R. M. Ashby and A. O. Hanson, Rev. Sci. Inst. 13, 128 (1942).

has been determined to be 1.882 Mev±0.1 percent[4] on the absolute voltage scale.

In order to obtain reasonable counting rates within a few kilovolts of threshold, the x-ray target, the beryllium or deuterium sample, and the neutron counters (Fig. 2) were placed as close together as possible in the high voltage electrode of the generator. At energies above threshold, x-rays generated in the target by the electron beam produced photo-neutrons in the sample. The neutrons were detected by three BF_3 filled proportional counters.

Target Assembly

With the exception of a long circular hole 1 in. in diameter through which the electron beam reached the x-ray target, the target and sample were completely surrounded by a minimum thickness of 2 in. of lead to provide x-ray shielding for the neutron counters and other equipment in the high voltage electrode. As shown in Fig. 2, the steel tube containing the x-ray target was insulated and connected through a micro-ammeter to the probe in order to obtain a rough measure of the electron current falling on the target. This meter could be read to an accuracy of about 1 μa by means of a telescope. A Vycor ring around the hole in the steel tube containing the x-ray target served as a visual aid in focusing the electron beam. Any electrons which missed the target caused fluorescence which could be observed by means of a mirror and window in the differential pumping tube.

The monoenergetic electron beam incident on the x-ray target produced x-rays of all energies up to that of the electron beam. Only x-rays with an energy greater than the photo-neutron threshold of the sample were effective in producing neutrons. Radiation of lower energy served only to produce an x-ray background in the neutron counters and ionization around other equipment. To minimize the intensity of low energy x-rays the target was constructed of a thin film of gold, with an absorption thickness of approximately 70 kev for 2-Mev electrons, on a thick carbon backing. Since data were taken to energies no greater than 50 kev above threshold, this target gave a thick gold target x-ray spectrum for all x-rays with an energy above threshold.

The sample placed close behind the x-ray target consisted either of a 286 g solid cylinder of beryllium metal or 145 g of deuterium oxide in a thin-walled brass container.

Neutron Detection and Data Transmission

The neutron counters shown in Fig. 2 consisted of three proportional counters filled with B^{10} enriched BF_3 to a pressure of 2 atmos. Voltage for the counters was provided by a 2100-v battery stack in a pressure-tight container. The counters had an i.d. of $\frac{1}{4}$ in., a 1.5-mil center wire, and an active length of 5-in. paraffin was placed behind the counters on the far side from the sample to give a maximum sensitivity for neutrons in the energy region near threshold. The position of the neutron counters was chosen to be as close to the sample as possible yet outside the region of highest x-ray intensity.

A special amplifier was built to modulate a small neon bulb[5] with a current proportional to the voltage output from the neutron counters. The amplifier consisted of a low noise triode coupled directly to the output from the neutron counters and followed by three stages of pentode amplification. All stages were highly degenerate

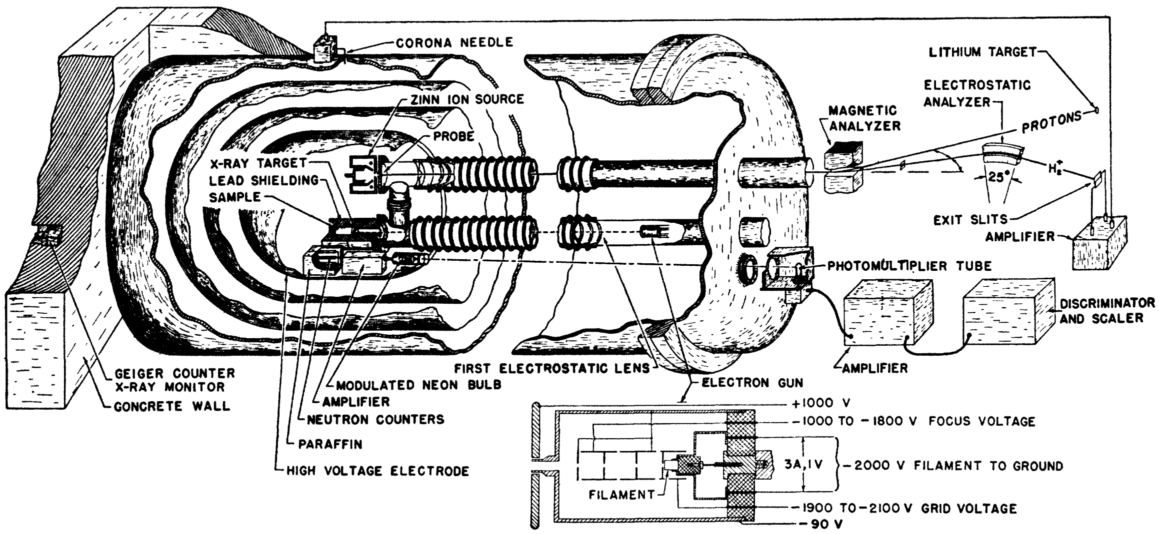

FIG. 1. Schematic diagram of the Argonne electrostatic generator and the auxiliary apparatus used for the photo-disintegration experiment.

[4] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).
[5] NE 51, 1/25 watt.

in order to insure linearity and good frequency response. The last stage was condenser coupled directly to one electrode of the neon bulb. A d.c. current was used to bias the neon bulb so that only one-half of one of the two parallel wire electrodes was surrounded by a cathode glow when there was no modulating current from the amplifier. The gain of the amplifier was then adjusted to about 10,000 where the maximum modulating current was never as large as the bias current. Viewed along its axis, the illuminated wire was essentially an intensity modulated point light source. Light in this direction was focused by a lens system through a port in the pressure tank enclosing the generator and into a photo-multiplier tube. The voltage output of the photo-multiplier tube was found to be closely proportional to the input voltage of the modulating amplifier at all frequencies up to 200 kc, while the gain of the system was found to be independent of frequency up to 50 kc, after which it decreased gradually. Whether this falling off above 50 kc was due to the circuit or to the neon bulb was not investigated, since the output from the photo-multiplier tube resembled the output from the neutron counters sufficiently well to permit it to be treated as such. The output of the photo-multiplier tube was amplified by a Model 100 amplifier which then drove a continuously variable discriminator and a scale-of-64.

Electron Gun

The electron beam was obtained from a well-shielded cathode-ray gun modified by replacing the oxide-coated cathode with a 6-mil tungsten filament. When this gun was initially mounted about 5 ft. from the first electrostatic lens in the ground portion of the differential pumping tube, a satisfactory focus could not be obtained at the high voltage electrode. After some check work using a mounting which made the gun fully adjustable in position, satisfactory results were obtained when the distance between the first electrostatic lens and the electron gun structure was between 4 and 10 in. At the distance of 8 in. which was used in the experiments, a spot about $\frac{1}{4}$ in. in diameter could be obtained at the target. For the final measurements the spot was defocused to a diameter of about $\frac{3}{4}$ in. to avoid local heating and to decrease possible variations in x-ray intensity which might accompany slight changes in position of a small image.

When the electron gun was initially placed near the first electrostatic lens, positive ions coming down the differential pumping tube and bombarding the electron gun shield released large numbers of secondary electrons which traveled back up the tube. To trap these secondary electrons, a circular plate at a positive potential of 1000 v was placed immediately in front of the electron gun shield as shown in Fig. 1.

A steel tube attached to the shield and extending through the plate was used to conduct the electron beam through the plate with a minimum disturbance

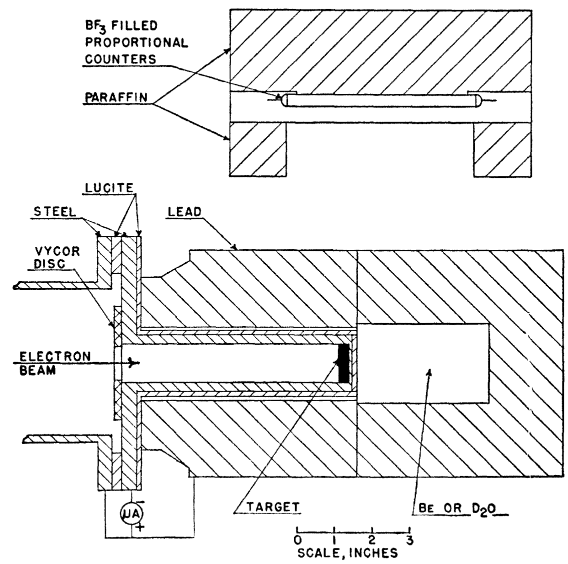

FIG. 2. Scale drawing of the x-ray target, sample, and neutron counters housed in the high voltage electrode.

to the focusing of the beam from the potential of the plate. Secondary electrons formed behind the electron gun were prevented from going up the differential pumping tube by a negative potential of 90 v on the electron gun shield. The current leaving the electron gun and that arriving at the x-ray target were the same within the accuracy of 1 μa with which the latter could be read.

III. EXPERIMENTAL PROCEDURE

Photo-neutron thresholds for beryllium and deuterium were obtained by extrapolating the neutron yield *versus* energy curve to zero yield. A Geiger counter outside the generator, behind 1 ft. of concrete and approximately on the axis of the electron beam, was used to monitor the high energy x-ray yield. A constant number of counts from the Geiger counter caused by x-rays from the electron beam were used to normalize the photo-neutron yield. During each run the number of x-ray counts was sufficiently large so that the probable error in normalization was 0.3 percent or less. Normalization in this manner should minimize errors due to fluctuations in the electron current or possible changes in x-ray intensity as the beam moved slightly on the target. With an electron current of 15 μa at an energy of 2.23 Mev the x-ray intensity around the box containing the Geiger counter was about 5 mr/hr., six percent of which was due to secondary electrons caused by the positive ion beam.

Data in this experiment were taken with electron currents of 10 or 15 μa. With an electron current of 15 μa, the x-ray background in the neutron counters was approximately one-quarter of the maximum neutron pulse height. Higher currents were not used because of lack of sufficient cooling for the target assembly and because higher x-ray intensity caused an undesirable

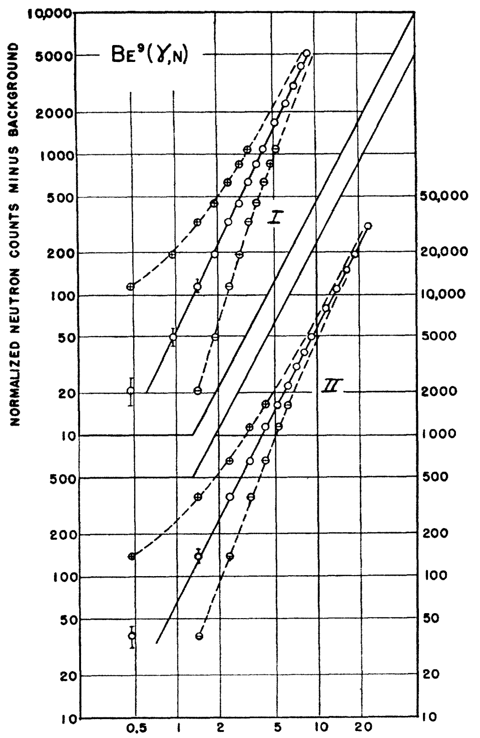

Fig. 3. Logarithmic plots of the photo-disintegration yield of beryllium *versus* the electron voltage above threshold. The solid lines are for an assumed threshold which gives a straight-line plot. The dotted curves result from assuming a threshold 0.93 kev either side of this. Statistical errors are smaller than the circles except where indicated. The neutron counts were normalized to a constant number of counts on the Geiger counter owing to x-rays from the electron beam. The number of Geiger counts chosen as a base for normalization was the average of all the 5-min. runs used in taking a set of data and the normalized neutron yield thus obtained is approximately equal to the actual neutron yield. The background below threshold for both curves was approximately six counts in 5 min. The electron current for both curves was 15 μa.

shortening of the plateau in the curve giving neutron counts *versus* discriminator bias.

High positive ion currents were observed to result in a secondary electron current in the ion accelerating tube sufficiently large to cause an objectionable x-ray background in the neutron counters. For this reason the generator was operated with the positive ion current as small as possible while still permitting effective operation of the energy control circuits.

The electron beam has not as yet been used for voltage control of the Argonne generator. At the Rice Institute this method of control has proved highly successful below[6] 2 Mev and electron currents up to about 20 μa were found to be sufficient. When the Argonne machine was operated at 2.2 Mev with an electron current of 15 μa, the x-ray intensity at the front of the machine and at the side and back of the machine beyond the shielding was approximately 1 mr/hr. or less. This intensity should be reduced appreciably when the present target is replaced by one consisting only of thick carbon. The shielding consists principally of the heavy lead immediately around the target and a concrete wall 2 ft. thick extending along one side of the machine and a concrete wall 32 in. thick across the back. If the x-ray intensity beyond the shielding varies approximately as the fifth power of the generator voltage, as indicated by the work at the Massachusetts Institute of Technology,[7] the shielding of the Argonne machine may be adequate for continuous use of the electron beam up to a generator voltage of about 4 Mev.

The beryllium and deuterium (γ, n) threshold voltages were each measured four times. Calibration of the voltage scale on the $Li^7(p, n)$ threshold were made before and after each (γ, n) threshold measurement. Although these two calibrations never differed by more than 0.05 percent, their average was used for calculation. Pure lithium targets about 5 kv thick were prepared by evaporation onto a tantalum backing while it was in place on the generator. Because the targets were heated to only about 80°C, they were renewed frequently to prevent any appreciable shift in the $Li^7(p, n)$ threshold due to surface accumulations on the target.

At the beginning of this experiment the electrostatic analyzer plates were polished to remove any non-

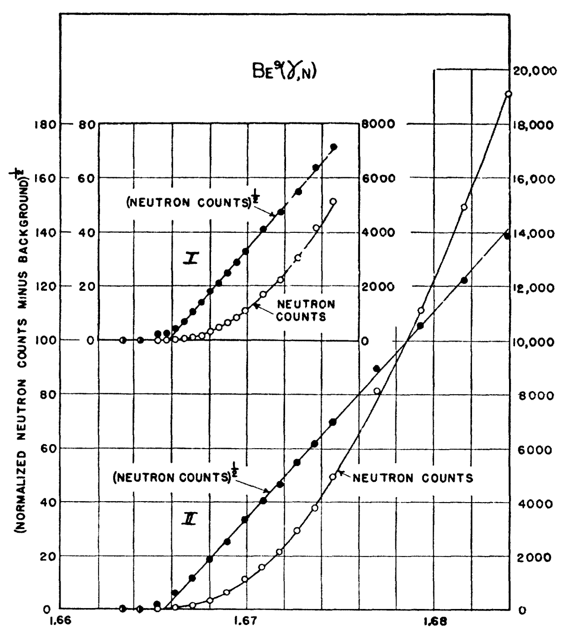

Fig. 4. The photo-neutron yield of beryllium near threshold. The neutron counts were normalized to a constant number of counts on the Geiger counter owing to x-rays from the electron beam. The number of Geiger counts chosen as a base for normalization was the average of all the 5-min. runs used in taking a set of data and the normalized neutron yield thus obtained is approximately equal to the actual neutron yield. The background below threshold for both curves was approximately six counts in 5 min.

[6] S. J. Bame, Jr., and L. M. Baggett, Rev. Sci. Inst. 20, 839 (1949).

[7] Petrauskas, Van Atta, and Myers, Phys. Rev. 63, 389 (1943).

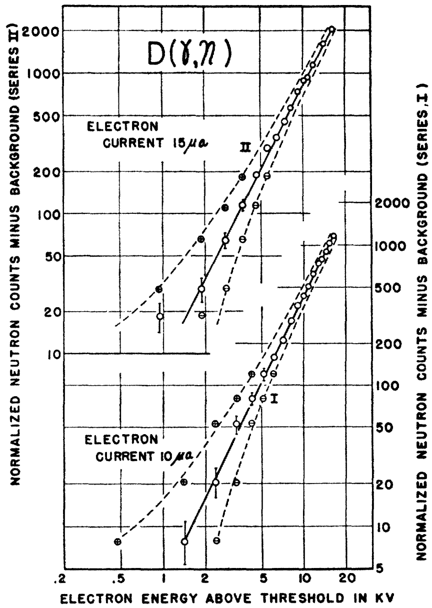

FIG. 5. Logarithmic plots of the photo-disintegration yield of deuterium *versus* the electron voltage above threshold. The solid lines are for an assumed threshold which gives a straight-line plot. The dotted curves result from assuming a threshold 0.93 kev either side of this. Statistical errors are smaller than the circles except where indicated. The neutron counts were normalized to a constant number of counts on the Geiger counter owing to x-rays from the electron beam. The number of Geiger counts chosen as a base for normalization was the average of all the 5-min. runs used in taking a set of data and the normalized neutron yield thus obtained is approximately equal to the actual neutron yield. The background below threshold for both curves was approximately six counts in 5 min.

conducting surface deposits. Since a current from 1 to 3 μa normally flowed between the plates of the electrostatic analyzer, small corrections (less than 0.04 percent) were made to the measured analyzer voltage in order to account for the voltage drop across the 1-megohm resistor in series with each plate.

Use of an electrostatic generator having a Zinn-type ion source[8] with a probe as a first ion accelerating electrode, suggested the possibility that the H_2^+ ions and the protons might originate in regions of different potentials lying between the potential of the arc and that of the probe, with the result that H_2^+ and proton beams would emerge from the probe with a difference in energy. Since the H_2^+ beam was used for measurement of the generator voltage and the proton beam for calibration of the voltage scale, a difference in energy between these two beams would result in a small error in calibration. Also, since the x-ray target was connected electrically through a microammeter and the metal structure near the ion source to the probe, changes in energy of the H_2^+ beam emerging from the probe as a function of the potential difference between the arc and the probe (probe voltage) would affect the position of the $Be^9(\gamma, n)$ threshold on the generator voltage scale.

Tests made by changing the probe voltage from 1 to 2.5 kv were found to raise both the $Li^7(p, n)$ and $Be^9(\gamma, n)$ thresholds on the generator voltage scale. Because of the shift in these thresholds as a function of probe voltage, all data were taken at the lowest practical probe voltage of 1 kv. Making use of test results at probe voltages of 1 and 2.5 kv, all data were extrapolated to zero probe voltage.

The filament of the electron gun was operated at a negative potential of 2 kv with respect to ground, and 2 kev was therefore added to the energy obtained by the electron beam in traveling from ground to the x-ray target.

III. EVALUATION OF DATA

At energies near the photo-neutron threshold the photo-neutron cross section for either beryllium[9] or

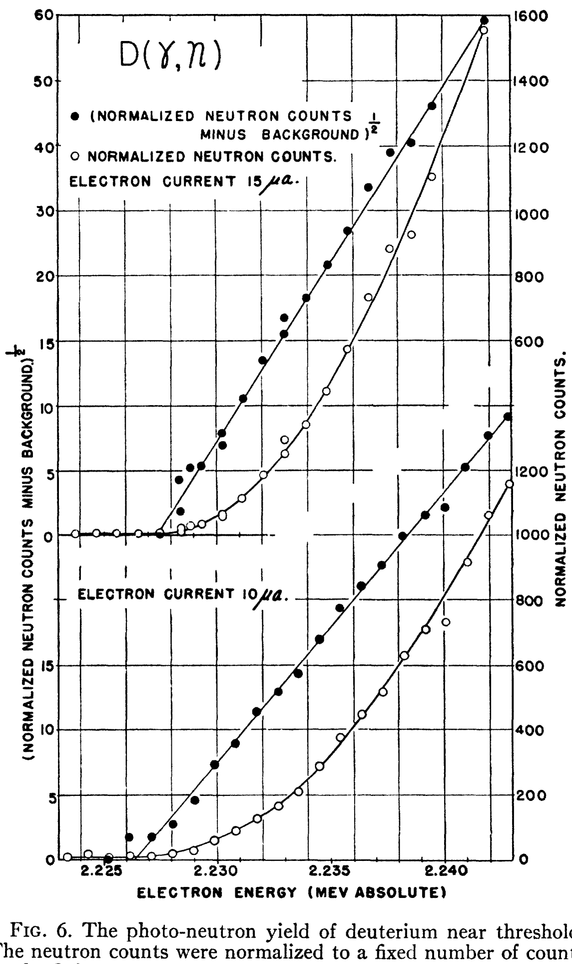

FIG. 6. The photo-neutron yield of deuterium near threshold. The neutron counts were normalized to a fixed number of counts on the Geiger counter owing to x-rays from the electron beam. The number of Geiger counts chosen as a base for normalization was the average of all the 5-min. runs used in taking a set of data and the normalization neutron yield thus obtained is approximately equal to the actual neutron yield. The background below threshold for both curves was approximately six counts in 5 min.

[8] W. H. Zinn, Phys. Rev. **52**, 655 (1937).

[9] E. Guth and C. J. Mullin, Phys. Rev. **76**, 234 (1949).

deuterium[10] should, according to theory, be approximately proportional to the square root of the energy above threshold. Also, if V_0 is the total potential difference traversed by the electrons in reaching the x-ray target and k is a constant, then experimentally[11] the intensity I_V of an isochromat corresponding to a voltage V which is less than V_0 is given by

$$I_V = k(V_0 - V). \tag{1}$$

Using this equation to represent the x-ray spectrum from threshold to the energy of the electron beam, some 50 kev or less above threshold, gives the expected neutron yield as proportional to

$$(E - E_0)^n, \tag{2}$$

where E_0 is the photo-neutron threshold energy, E is the energy of the electron beam, and $n = 2.5$. Owing to the method of normalizing the neutron yield and the decreasing efficiency of the neutron counters with increasing neutron energy, the normalized experimental neutron yield minus background would not be expected to rise as rapidly as is predicted by Eq. (1), but rather in a manner approximated by a somewhat lower value of n. Experimentally it was found that the data for both beryllium and deuterium could be fitted reasonably well by an expression of this form with a value of n equal to approximately 2, i.e.,

$$Y = K(E - E_0)^n, \tag{3}$$

where Y is the normalized neutron yield minus background, E is the energy of the electron beam, E_0 is the photo-neutron threshold, K is a constant, and $n = 2$.

To find n for a given yield curve, values of E_0 were assumed and curves of Y *versus* electron energy above threshold $(E - E_0)$ were plotted on logarithmic graph paper as shown in Figs. 3 and 5. The slope of the straightest line on this plot was taken as n. Values of n between 1.93 and 2.05, with an average very nearly 2.00, were obtained for both beryllium and deuterium. Taking the value of n as 2.00 for each yield curve, a graph of $Y^{\frac{1}{2}}$ *versus* E was made (Figs. 4 and 6) and the value of E_0 was taken to be the intercept with the energy axis of what was judged to be the best straight line through the resultant points. The neutron binding energies were then determined by subtracting 0.2 kev from the average photo-neutron threshold of beryllium and 1.3 kev from the average photo-neutron threshold of deuterium in order to correct for the motion of the center of mass due to the momentum of the incident x-ray photon.

[10] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947), p. 59.
[11] W. C. Miller and B. Waldman, Phys. Rev. **75**, 425 (1949).

TABLE I. Neutron binding energies of deuterium and beryllium.

Neutron binding energy of beryllium (Mev)	Neutron binding energy of deuterium (Mev)	Reference
1.666±0.002	2.226±0.003	Present paper
	2.230±0.007	Bell and Elliott[b]
	2.227±0.010	Smith and Martin[c]
1.681±0.013	2.221±0.013[a]	Hanson[d]
	2.181±0.005[a]	Meyer[e]

[a] These values have been corrected for the new value of 2.615±0.004 Mev for the ThC″ gamma-ray. A. L. Wolfson, Phys. Rev. **78**, 176 (1950).
[b] R. E. Bell and L. G. Elliott, Phys. Rev. **79**, 282 (1950).
[c] R. V. Smith and D. H. Martin, Phys. Rev. **77**, 752 (1950).
[d] A. O. Hanson, Phys. Rev. **75**, 1794 (1949).
[e] P. Meyer, Zeits. f. Physik **126**, 336 (1949).

IV. RESULTS

The neutron binding energy of beryllium was found to be 1.666±0.002 Mev and that of deuterium 2.226 ±0.003 Mev. These probable errors include the 0.1 percent uncertainty in the $Li^7(p, n)$ threshold. The agreement, as shown in Table I, between these results and other recent measurements is, with one exception,[12] within the probable errors.

The ratio of the deuterium to beryllium photo-neutron thresholds from this experiment is 1.337±0.001, which agrees very closely with the value of 1.338±0.004 given by Waldman and Miller.[13]

Using the value of 1.442±0.002 Mev obtained by Roberts and Nier[14] for the HH–D mass difference, together with the deuterium binding energy obtained in this experiment, the neutron-hydrogen mass difference is found to be 784±4 kev. This agrees within the probable errors with the value of 782±2 kev given by Taschek, Argo, Hemmendinger, and Jarvis,[15] with the value of 789±6 kev given by Tollestrup, Jenkins, Fowler, and Lauritsen,[16] and with the value of 783±4 kev given by Franzen, Halpern, and Stephens.[17]

We wish to thank Professor R. G. Herb for suggesting this problem and for his continued support and many helpful suggestions during the course of the experiment. We also wish to thank the staff of the Argonne National Laboratory, and particularly the Van de Graaff group, for their much appreciated cooperation.

[12] P. Meyer, Zeits. f. Physik **126**, 336 (1949).
[13] B. Waldman and W. C. Miller, Phys. Rev. **74**, 1225A (1948).
[14] T. R. Roberts and A. O. Nier, Phys. Rev. **77**, 746 (1950). The value they give for the HH-D mass difference is 1.442 Mev plus or minus a few kev.
[15] Taschek, Argo, Hemmendinger, and Jarvis, Phys. Rev. **76**, 325 (1949).
[16] Tollestrup, Jenkins, Fowler, and Lauritsen, Phys. Rev. **75**, 1947 (1949).
[17] Franzen, Halpern, and Stephens, Phys. Rev. **76**, 317 (1949).

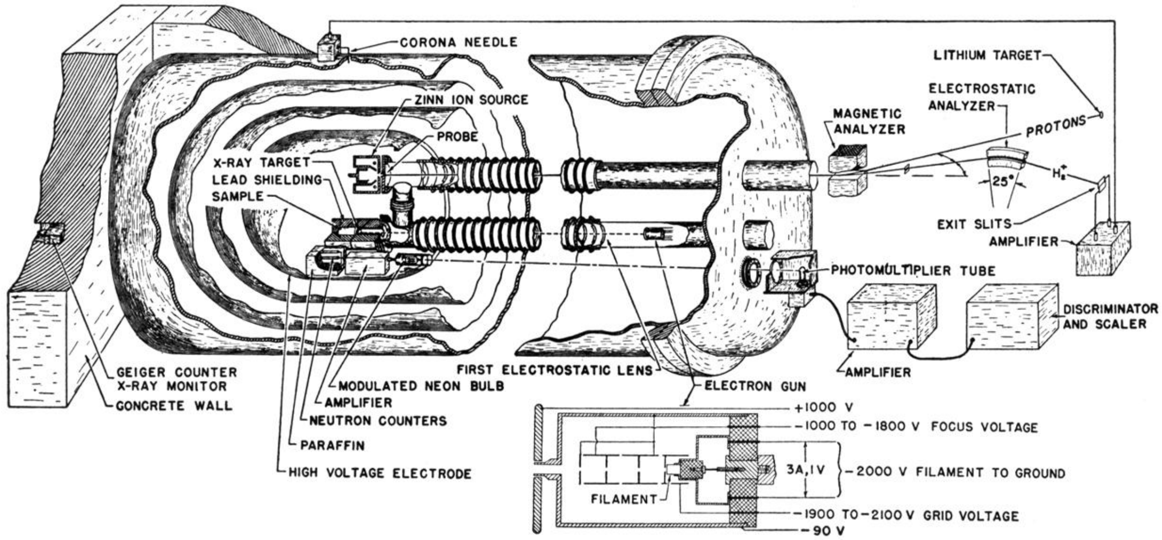

FIG. 1. Schematic diagram of the Argonne electrostatic generator and the auxiliary apparatus used for the photo-disintegration experiment.