TABLE I. Relative energy requirement per ion-pair.

Gas	This work	w_{gas}/w_{argon} V and C[a]	W, V, and K[b]
Argon	1.00	1.00	1.00
Hydrogen	1.45	1.41	1.55
Helium	1.28	1.20	1.26
Oxygen	1.18	1.19	—

[a] See reference 8.
[b] See reference 9.

thickness by

$$\mu/\rho = 0.693/d_{\frac{1}{2}}. \quad (4)$$

For tritium beta particles in hydrogen, then, the mass absorption coefficient is

$$\mu/\rho = 22 \text{ cm}^2/\text{mg}.$$

From the saturation current obtained with a known pressure of tritium for each of these gases, as well as for argon, the relative energy requirement per ion-pair may be determined. The values for w will be inversely proportional to the saturation current. These results are given in Table I which contains the numbers relative to argon. The results are compared with those of Valentine and Curran[8] for electrons and Wilzbach *et al.*[9] for tritium beta particles. There is reasonably close agreement among the values. The spread in the results for helium may be due to the trace impurity effect which has been pointed out in the recent work of Jesse and Sadauskis.[10] No attempt has been made to derive absolute values of the energy requirement from the data.

ACKNOWLEDGMENT

The author is grateful to Dr. D. L. Douglas for the advice he has given concerning the construction of the ion chamber and the operation of the electrometer.

[8] J. M. Valentine and S. C. Curran, Phil. Mag. **43**, 964 (1952).
[9] Wilzbach, Van Dyken, and Kaplan, Argonne National Laboratory Report No. 5143, October, 1953; Anal. Chem. **26** (5), 880 (1954).
[10] W. P. Jesse and J. Sadauskis, Phys. Rev. **94**, 764 (1954).

PHYSICAL REVIEW VOLUME 95, NUMBER 2 JULY 15, 1954

Photodisintegration Thresholds of Deuterium and Beryllium*†

J. C. NOYES,‡ J. E. VAN HOOMISSEN,‡ W. C. MILLER, AND B. WALDMAN
Department of Physics, University of Notre Dame, Notre Dame, Indiana

(Received March 22, 1954)

The photodisintegration thresholds of deuterium and beryllium have been determined by using the bremsstrahlung produced by monoergic electrons. The absolute energy of the electrons was measured with a cylindrical electrostatic analyzer. The binding energy of deuterium was found to be 2.227±0.003 Mev and that of beryllium was found to be 1.662±0.003 Mev.

INTRODUCTION

THE photodisintegration thresholds of deuterium and beryllium have been measured using a number of methods. Stephens,[1] in 1947, presented an exhaustive discussion of the work done on deuterium up to that time. Since 1948 two important experiments have been performed.

Bell and Elliott[2] measured the energy of the gamma ray accompanying the capture of a neutron by a proton. Their spectrometer was calibrated with the 2.615±0.001 Mev gamma ray[3] of ThC″. Their value for the binding energy of the deuteron is 2.230±0.007 Mev.

Mobley and Laubenstein[4] determined the photodisintegration thresholds of beryllium and deuterium with a novel method. Using the Argonne National Laboratory electrostatic generator, they accelerated a proton beam down the normal accelerator tube while an electron beam was accelerated up the differential pumping tube to the high voltage electrode. The electrons were stopped in a gold target, producing x-rays which were used for the photodisintegration. Energy calibration was accomplished by *comparison* with the Li(p,n) threshold,[5] known to ±0.1 percent. The values obtained for the binding energies of beryllium and deuterium are 1.666±0.002 Mev and 2.226 ±0.003 Mev, respectively.

The present experiment was undertaken because it is the most direct method for determining the binding energies. It is an absolute method requiring no nuclear reaction data for calibration.

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
† Preliminary report: Phys. Rev. **85**, 727 (1952). A more extensive account of this work appears in a technical report.
‡ Now at Boeing Aircraft, Seattle, Washington.
[1] W. E. Stephens, Revs. Modern Phys. **19**, 19 (1947).
[2] R. E. Bell and L. C. Elliott, Phys. Rev. **79**, 282 (1950).
[3] J. L. Wolfson, Phys. Rev. **78**, 176 (1950); W. L. Brown, Phys. Rev. **83**, 271 (1951); G. Lindstrom, Phys. Rev. **87**, 678 (1952).
[4] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).
[5] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).

EXPERIMENTAL ARRANGEMENT

The photodisintegration thresholds of beryllium and deuterium were determined as follows: Electrons from the electrostatic generator entered a 90-degree cylindrical electrostatic analyzer, which served as an energy selector. The electrons which emerged from the analyzer struck a thick gold target, producing a continuous x-ray spectrum with an upper energy limit equal to the electrons' energy. The x-rays above threshold disintegrated the beryllium or deuterium, producing neutrons. The neutron yields at various electron energies up to 30 kev above threshold were extrapolated to zero yield. On converting the energy corresponding to zero yield into the center-of-mass system, the binding energies of beryllium and deuterium were obtained.

The uncertainty in threshold energy as determined by this experiment is about 0.1 percent. To realize this accuracy the uncertainties in individual measurements contributing to the threshold measurement had to be kept well below this value. The energy measurement depended only upon a knowledge of the geometry of the analyzer system, and the determination of the deflecting voltage.

A. Electrostatic Analyzer

The theory of the electrostatic analyzer has been reviewed by Bainbridge.[6] Honnold and Miller[7] have developed the relativistic ion optics of an electrostatic analyzer with application to this particular analyzer. They have shown that electrons of kinetic energy T_0 and velocity $\beta_0 c$ emerging from an object slit (see Fig. 1) placed a distance l' from the entrance to the field O' will be imaged at a distance l'' from the exit from the field O'' given by the lens equation,

$$(l'-g)(l''-g)=f^2, \tag{1}$$

where $f=a/[\kappa \sin(\kappa\Phi)]$ = focal length, $g=f\cos(\kappa\Phi)$ = coordinates of focal points, $\kappa=(2-\beta_0^2)^{\frac{1}{2}}$, and a = mean line trajectory, provided the potential difference X between the plates P_1 and P_2 is

$$X=\frac{T_0}{e}\left(\frac{T_0+2R}{T_0+R}\right)\frac{d}{a}, \tag{2}$$

where R = rest energy of electron and d = separation of plates. Furthermore, the energy resolution is determined by the width of the slits in the object and image planes, W' and W'', respectively. For the case where these widths are in the ratio of the lateral magnification of the lens the resolution is given by

$$\frac{dT}{T_0}=\left(\frac{T_0+2R}{T_0+R}\right)\frac{W''}{a(1-M)}, \tag{3}$$

where dT is the energy increment needed to displace the image beyond the slit W'' and M is the lateral magnification.

The analyzer is similar to the one at the University of Wisconsin.[8] The dimensions were based on the available laboratory space and the required deflection voltage, the latter depending on the separation of the plates and their mean radius [Eq. (2)]. Furthermore, the separation had to be large enough so that the beam would not strike the plates. A separation of $\frac{5}{16}$ in. and mean radius of 24 in. were used. The angle Φ was made 90° on the basis of ease of construction and direction of exit beam. This angle was in a horizontal plane. Since l' and l'' are functions of energy, it was decided in the interest of mechanical simplicity to fix one and vary the other. The object distance l' was set at 30 in. The values of l'' at 1.67 and 2.22 Mev were 16.65 in. and 17.54 in., respectively.

The two analyzer plates P_1 and P_2 were cut from one piece of steel. In cross section they were $1\frac{3}{16}$ in. thick and $2\frac{1}{4}$ in. wide and were supported on 6 Mykroy cylinders fastened to a 30-in. by 36-in. steel surface plate. The analyzer plates and slit systems were enclosed in a vacuum housing.

There were four pairs of beam-defining slits used with the analyzer. The object slits S_1, were in the object plane, 30-in. from the entrance end of the analyzer. Two pairs of slits, S_2 and S_3, were located at the entrance and exit ends of the analyzer, and were spaced 0.100 in. from the ends of the analyzer plates. Slits S_2 and S_3 served to define the electric field at the ends of the analyzer. The fourth pair of slits, S_4, was in the image plane. Since the image distance varied with beam

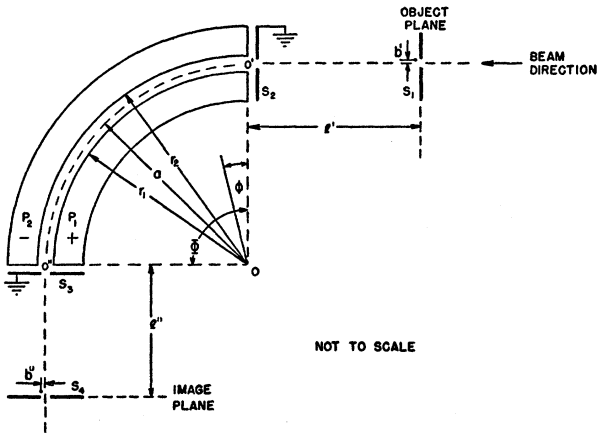

FIG. 1. Plan of electrostatic analyzer.

[6] K. T. Bainbridge in *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. 1.
[7] V. R. Honnold and W. C. Miller, Nuclear Physics Technical Report No. 2, University of Notre Dame, 1953 (unpublished).
[8] Warren, Powell, and Herb, Rev. Sci. Instr. 18, 559 (1947).

energy provision was made to vary the distance of S_4 from the analyzer by means of a carriage driven by a screw.

B. Alignment

The inner analyzer plate P_1 was bolted into place on its three Mykroy insulators and two sets of measurements were made on the surface of radius r_1. First, relative variations of the radius of curvature at three different depths from the top surface of the analyzer were obtained by means of a traveling dial gauge moving perpendicularly to the surface plate. The dial gauge was zeroed at a position $\frac{1}{8}$ in. from the top of the analyzer, then readings were taken at a position $\frac{5}{8}$ in. from the top (center of analyzer) and at a position $1\frac{1}{16}$ in. from the top surface. The measuring apparatus was then moved to another angular position, the gauge re-zeroed at the $\frac{1}{8}$ in. depth, and deviations again noted at the other two depths. These sets of three relative measurements were made at a total of eleven angular positions, approximately 9° apart.

The second set of measurements on this surface was a determination of the variation of radius of curvature as a function of angular displacement from the entrance end, the variations in radius being measured relative to the entrance end. The traveling dial gauge was fastened to a radius arm pivoted at *0*, Fig. 1, and was zeroed at a point $\frac{1}{8}$ in. below the top of the analyzer plate at the entrance end (0°). Variations from zero were then observed at the ten other angular positions previously mentioned, all at the same depth of $\frac{1}{8}$ in.

From these sets of measurements one could compute the relative variations of radius from a point $\frac{1}{8}$ in. below the top of the analyzer plate at the entrance end.

The outer analyzer plate P_2 was then moved into position and separated from the inner plate by three machined steel spacers of 0.3042 in. thickness. The plate was adjusted for a snug fit of the spacers, then was bolted down and the spacers removed. The same measurements that were previously made on the inner plate were then made on the surface of radius r_2. This outer plate had been machined much more accurately than the inner plate, as no variations in radius from upper to lower position could be detected. The variations in radius as a function of angle at a depth of $\frac{1}{8}$ in. from the top surface were recorded.

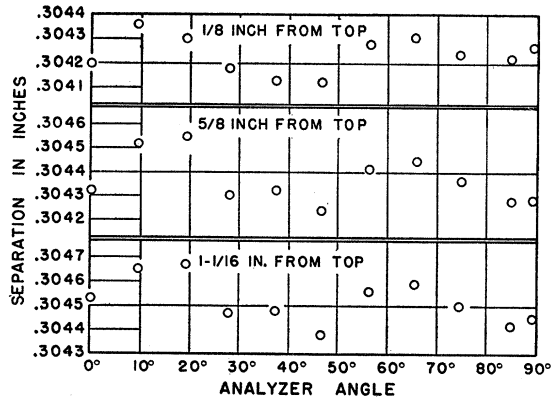

FIG. 2. Measurements of analyzer plate separation as a function of the angle from the analyzer entrance.

Assuming then that the separation of the two plates at the top at 0° was 0.3042 in., one could compute the separation between the two plates at the eleven angular positions and at three different depths from the top of the analyzer plates. These are shown in the graph of Fig. 2. From this graph the separation of the plates in the usable portion of the analyzer ($\frac{5}{8}$ in. depth) was taken as 0.3044±0.05 percent.

Absolute measurement of the radius of curvature of the inner plate was made with a cathetometer. The inner radius r_1 is 23.851 in.±0.005 percent. The outer radius r_2 is 24.155 in.±0.005 percent, and the geometric mean radius a is 24.002 in.±0.01 percent.

The next alignment step was the location of the entrance slit S_1 on a line tangent to the arc $O'O''$ and perpendicular to the line OO'. This was done by triangulation.

Herzog[9] has shown that for an analyzer spacing of 0.304 in., the fringe field at the ends of the analyzer can be considered equal to zero if the field confining slits S_2 and S_3 are opened to a separation of 0.060 in. and spaced from the analyzer ends by 0.075 in. The spacing was adjusted with feeler gauges. However, during the running of the experiment it was found necessary to increase the spacing, due to voltage breakdown from the analyzer plates, and to open slit S_2 wider to permit more beam current to enter the analyzer. The final experimental data were taken with both slits at a distance 0.100 in. from the analyzer ends, with S_2 opened to 0.075 in. and S_3 opened to 0.060 in. The effect of these changes was to increase the effective analyzer angle slightly, due to greater fringing at the ends. The change in analyzer angle causes a negligible shift in the image distance l'' and in the magnification M, and hence in the resolution.

Slit S_4 was set at the proper value of l'' and its position in the image plane (transverse to the beam) was adjusted so that the beam current passing through it was a maximum. This method of location of S_4 compensates for the increased angle of the analyzer due to the fringe fields.

It can be shown by use of Honnold and Miller's[7] Eq. (18) that for the particular conditions of this experiment slit S_3 limits the electron beam energy to about ±3 kev. More recently, further experiments to check this method of positioning S_4 were undertaken by Bhattacherjee, Waldman, and Miller.[10] Their data show that the position of slit S_4 for maximum current through it corresponds to the location of S_4 on the

[9] R. Herzog, Z. Physik **89**, 447 (1934); **97**, 596 (1935); Physik. Z. **41**, 18 (1940).

[10] Bhattacherjee, Waldman, and Miller, Phys. Rev. **95**, 404 (1954).

tangent line to the circular orbit in the analyzer drawn at the *effective* end of the electrostatic field.

C. Measurement of Voltage

A tapped resistance voltage divider was placed from each analyzer plate to ground. The potential difference between the plates was computed from the measured potential difference between the two taps.

The resistors for the voltage dividers were manufactured by the Shallcross Manufacturing Company. Each divider consisted of twenty-five one-megohm two-watt resistors and a 750-ohm tap resistor. The resistors were of 1 percent accuracy and 0.01 percent stability.

One of these one-megohm resistors was chosen as a standard and the ratio of each of the fifty resistors in the dividers to the standard was measured with a simple circuit containing a Leeds and Northrup-type K potentiometer and a Vibrating Reed Electrometer as a null detector. The two 750-ohm tap resistors were connected in series and their ratio to the standard one megohm was measured. This was done in two steps through two precision resistors (10K and 100K) in order to keep the resistance ratios to a maximum of ten. From these ratios the ratio of the fifty one megohm resistors to the two 750-ohm tap resistors was computed. The accuracy of this ratio is ± 0.02 percent. The voltage between the analyzer plates was the product of this ratio and the potentiometer voltage.

The resistor temperature coefficient was 0.002 percent per degree C. A test voltage of 1000 volts applied to one of the one-megohm resistors produced a temperature change of 20°C, or an increase of resistance of 0.04 percent. Since 700 volts was the largest voltage drop per resistor needed during the photodisintegration experiments, the maximum error in the voltage divider ratio due to resistor temperature coefficient was approximately 0.02 percent. This error would result if the tap resistance did not change value due to heating, while the one-megohm resistors heated up. An air circulating system minimized this effect.

The voltage divider resistors were mounted in groups of three between corona-free shields supported by 1-in. Lucite insulating columns. Each stack assembly was inclosed in a 7-in. diameter Lucite cylinder 24 in. high, similar to the method of Henkel and Petree.[11] The whole assembly was sealed after a desiccant had been placed inside to reduce the effect of humidity. A blower circulated air inside the stacks.

The potentiometer used to measure the voltage across the tap resistors was a Rubicon Portable Precision Potentiometer. The limit of error of the potentiometer was the voltage corresponding to one slide wire division plus 0.05 percent of the voltage reading of the dial switch. The potentiometer measured a standard cell to within 0.02 percent of its Bureau of Standards certified value.

The voltage supply for the analyzer plates was composed of two 30 kv power supplies in series, additional filters, the resistor voltage dividers, and a stabilizing network. In series with the output of the positive supply was a series regulator tube whose bias was controlled by the light from the galvanometer in the potentiometer circuit. The stabilization of the analyzer voltage effected by this feedback system and by deriving the input ac power from a Sorensen Regulator was such that, with no beam through the analyzer, the voltage varied less than 3 volts out of 30 000 volts. During operation, small breakdowns would cause the voltage to jump at times, but the average stability was of the order of 0.02 percent or 0.03 percent.

MAGNETIC FIELD

A small magnetic field in an analyzer used for electrons will affect the energy determination. The radial component of this field, directed from one plate to the other, would produce beam deflection perpendicular to the plane of the analyzer. Deflection in this direction would not affect the accuracy of the experiment, but would tend to bend the beam out of the analyzer. On the other hand, the vertical component of magnetic field would produce deflection in the plane of the analyzer.

The steel analyzer plates were degaussed until the vertical component was comparable to the earth's field. The radial component was sufficiently small so that the electron beam was not deflected out of the central portion of electric field.

The magnetic field was measured by two methods, one used before the threshold determinations, the other used afterward. In the first method, the measurement of the magnetic field in the gap, was made with a flip coil and ballistic galvanometer. In the second method the magnetic field was measured by the peaking strip method and has been described by Bhattacherjee, Waldman, and Miller.[10] The results of the two methods are in good agreement even though the measurements were spaced many months apart. Presumably the magnetic field is stable.

A plot of the vertical component of the magnetic field is shown in Fig. 1 of the following paper by Bhattacherjee *et al.*[10] The magnetic field in the region of the analyzer between 0° and 55° has an average value of 0.12 gauss up and in the region between 55° and 90° an average value of 0.20 gauss down. Honnold and Miller[7] have developed the relativistic ion optics for crossed electric and magnetic fields using the results of Millett.[12] Thus these two regions can be considered as two lenses in series. Electrons which satisfy Eq. (2) would suffer deflections in both regions. Moreover, in the region between S_1 and S_2, and again between S_3

[11] R. L. Henkel and B. Petree, Rev. Sci. Instr. **20**, 720 (1949).

[12] W. E. Millett, Phys. Rev. **74**, 1058 (1948).

and S_4 where the electric field is zero, the electrons will be deflected by mainly the earth's field. Honnold and Miller have shown that the effect of these magnetic fields is to deflect the beam passing through the analyzer toward larger radius of curvature. Thus the value of the kinetic energy computed by use of Eq. (2) must be reduced. The corrections are 3.5 kev for the deuterium threshold and 3.4 kev for the beryllium thresholds (see Table I).[13]

EXPERIMENTAL PROCEDURE

The general plan of the electrostatic generator, analyzer, and counters is shown in Fig. 3. The target was a $\frac{1}{16}$ in. thick gold disk, a "thick" target for the energies under consideration. The material to be disintegrated, beryllium or deuterium oxide, was placed in a cavity in a cylindrical lead shield, of 6 in. outer diameter and $8\frac{1}{2}$ in. length. The cavity containing the sample was $3\frac{1}{4}$ in. in diameter and 7 in. long, concentric with the cylinder. A $\frac{3}{4}$ in. hole was drilled along the cylinder axis, from the base to the cavity.

The lead shield containing the sample, was oriented with its axis horizontal, and pushed up to the gold target so that the target projected approximately $\frac{3}{8}$ in. inside the cavity. By shielding in this manner, only x-rays from the direction of the target could disintegrate the sample.

The lead shield was encased in a block of paraffin 10 in.×11 in.×15 in. A BF_3 (enriched boron 10) neutron counter was inserted in a hole in the paraffin directly above the target and sample, with its axis horizontal and perpendicular to the direction of the beam. By placing the counter above the target, the highly forward-directional x-rays from the target caused little background in the counter.

A Geiger counter was located directly behind the $\frac{3}{4}$-in. hole in the lead shield. It was well shielded by lead from all directions except on the line to the target.

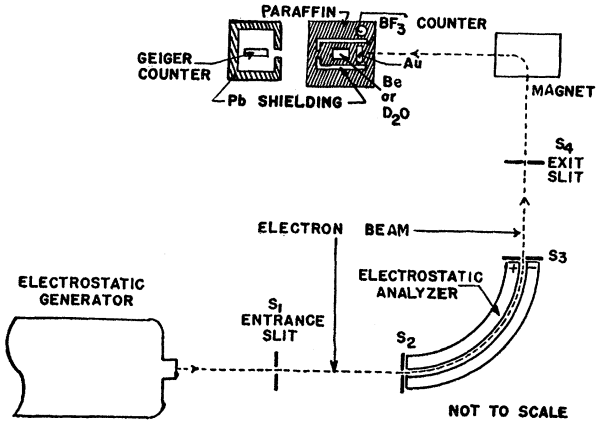

FIG. 3. Schematic layout of apparatus.

[13] The major portion of this correction is due to the deflection produced by the earth's field in the region outside the analyzer plates.

This counter was used to monitor the x-rays from the target.

For the beryllium disintegration experiment, a cylinder of Be, 2 in. in diameter and 2 in. long, weighing 192 grams, was placed in the shield next to the target. A resolution of 2 kev was used, which required slit widths of 0.041 in. and 0.031 in. for S_1 and S_4 respectively.

The beam impinging on the gold target produced bremsstrahlung. A sufficient number of monitoring x-ray counts was taken to insure good statistical accuracy. The number of neutron counts in the time required to accumulate a standard number of x-ray counts was then recorded. This number of neutron counts, less background, furnished one point on the yield curve.

To change the analyzer voltage it was sufficient merely to change the potentiometer to the new setting, the high gain of the stabilizer causing the analyzer voltage to follow. At this new voltage the neutron counts for the standard number of x-ray counts were again recorded. This process was continued to below threshold, where only background neutrons were recorded. (Background *ca* 20 counts/1000 sec.)

The target assembly was originally installed just beyond the image slit S_4. It was found that when the generator voltage was slightly high, so that the beam entered the analyzer but struck the outer half of slit S_3, a greater number of neutron counts was recorded than when the beam was directed down the middle. This was caused by x-rays from slit S_3 disintegrating the sample. To eliminate this the target was moved to the position shown in Fig. 3, adequate shielding being interposed between slits S_3 and S_4 and the sample. The necessary change in direction of the beam was effected by an electromagnet. This magnet served merely to change the beam direction by 90°, and was not used in energy determination. It was located 49 in. from S_4, a distance great enough so that its small stray field would have no effect on the beam in the analyzer. The target was 14 in. from the exit edge of the magnet.

The disintegration of deuterium was carried out in the same manner as for the beryllium. The sample was 130 grams of heavy water D_2O, 99.9 percent pure, sealed in a brass container. A resolution of 3 kev at 2.2 Mev was obtained by opening slits S_1 and S_4 to 0.063 in. and 0.048 in., respectively.

A greater slit opening was found necessary at the higher energy because of the poorer stability of the voltage of the electrostatic generator. The generator potential was stabilized by both a capacitive stabilizer[14] and a slow-acting spray voltage regulator,[15] which together maintained an average long-time generator stability of about ±0.4 percent. A poor stability

[14] Miller, Waldman, Noyes, and Van Hoomissen, Phys. Rev. 77, 758 (1949).

[15] A. O. Hanson, Rev. Sci. Instr. 15, 57 (1944).

required a longer period of time to obtain a given normalizing x-ray count, and hence meant a larger background count in the Geiger counter, with greater attendant errors.

THEORY

The deuteron problem is well known and has been solved exactly as far as the limits of error in this experiment are concerned. Bethe[16] in a summary of the work done on the problem shows that the deuteron near threshold is photomagnetically disintegrated. He gives the following expression as the photomagnetic disintegration cross section,

$$\sigma_m=\frac{2\pi}{3}\frac{e^2}{\hbar c}\frac{\hbar^2}{M}\frac{(W_1E)^{\frac{1}{2}}(W_1^{\frac{1}{2}}+W_0^{\frac{1}{2}})^2}{(E+W_1)(E+W_0)Mc^2}(\mu_P-\mu_N)^2, \quad (4)$$

where $E=h\nu-W_1$, W_1 is the deuteron binding energy, W_0 is the fictitious binding energy for the singlet state, and μ_N and μ_P are the nuclear magnetic moments of the neutron and proton respectively. This expression involves E which has a definite value for a given incident x-ray energy. We are concerned with all x-ray energies in the energy interval between threshold and the energy of the electrons. We call this interval y and integrate this cross section over y. The result is

$$\sigma_x=k'[4638.22y^{\frac{5}{2}}+(3297.78y-6500.5023)\tan^{-1}0.671156y^{\frac{1}{2}}-(1088.485y+69.66304)\tan^{-1}3.9528050y^{\frac{1}{2}}], \quad (5)$$

where σ_x is a measure of the total probability of a disintegration taking place, and k' is a slowly varying function of the incident x-ray energy and is a constant over the range of energies under consideration. It should be noted that this expression is dependent only on y. A plot of σ_x/k' against y on log-log paper results in a straight line with a slope of 2.365. Thus a linear plot of the 2.365th root of the neutron yield against the electron beam energy should result in a straight line. The extrapolation of this line to zero neutron yield determines the threshold energy.

In applying the above theoretical relations the energy must be referred to the center-of-mass system. In the case of deuterium 1.3 kev must be subtracted from the electron energy (for the 30-kev interval).

Because of the complexity of the beryllium nucleus, the situation viewed from the theoretical standpoint is not nearly so clear-cut as in the case of deuterium. Guth and Mullin[17] developed the photodisintegration cross section for Be^9. Making the proper approximations due to near-threshold energies in their expression and integrating over y gives

$$\sigma_x=Af(E_i)\int_{E_0}^{E_i}(E-E_0)^{\frac{1}{2}}(E_i-E)dE,$$
$$\sigma_x=B(E_i-E_0)^{5/2}=By^{5/2}, \quad (6)$$

where E_i is the energy of the incident electron beam, E is the x-ray energy, E_0 is the threshold energy, $f(E_i)$ is a slowly varying function of energy and is constant over y, and A and B are constants. σ_x is a measure of the total probability of a disintegration taking place and is therefore directly proportional to the neutron yield in a disintegration experiment. Thus theory predicts that the neutron yield should vary directly as the 5/2 power of y.

As mentioned above it is necessary to subtract a center-of-mass correction of 0.2 kev.

TABLE I. Summary of errors.

Ratio of separation of plates to mean radius (d/a)	
Inner radius (r_1)	0.005%
Outer radius (r_2)	0.005%
Mean radius (a)	0.01 %
Separation of plates (d)	0.05 %
Total	0.05 %
Voltage measurement	
Voltage divider ratio	0.02 %
Potentiometer	0.05 %
Voltage stabilization	0.03 %
Total	0.06 %
Magnetic field correction	
Correction of 3.5 kev ±10%	0.02 %
Grand total	0.08 %
Energy resolution due to slit widths (at 2.23 Mev)	0.13 %
(at 1.66 Mev)	0.12 %

EVALUATION OF DATA

Using the procedure described in the experimental section six runs were made to determine the binding energy of beryllium. Slit widths corresponding to 2-kev resolution of the beam energy were used. Because of this, 2-kev steps in beam energy from 20 kev above threshold down to threshold were used.

Each run was plotted individually on a log-log plot and the best straight line for the 20-kev beam variation was chosen. The average slope of these straight lines was close to 2 instead of the theoretical value of 5/2. Because of this the square root of the neutron yield was plotted against beam energy on a linear plot and these straight lines extrapolated to zero neutron yield to determine the threshold.

Figure 4 is a plot of neutron yield *vs* corrected electron energy. The correction consisted of −3.4 kev for the magnetic field effect and −0.2 kev for the motion of the center-of-mass. Figure 5 is a plot of the square root of the neutron yield *vs* corrected electron energy.

[16] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).
[17] E. Guth and C. J. Mullin, Phys. Rev. **76**, 234 (1949).

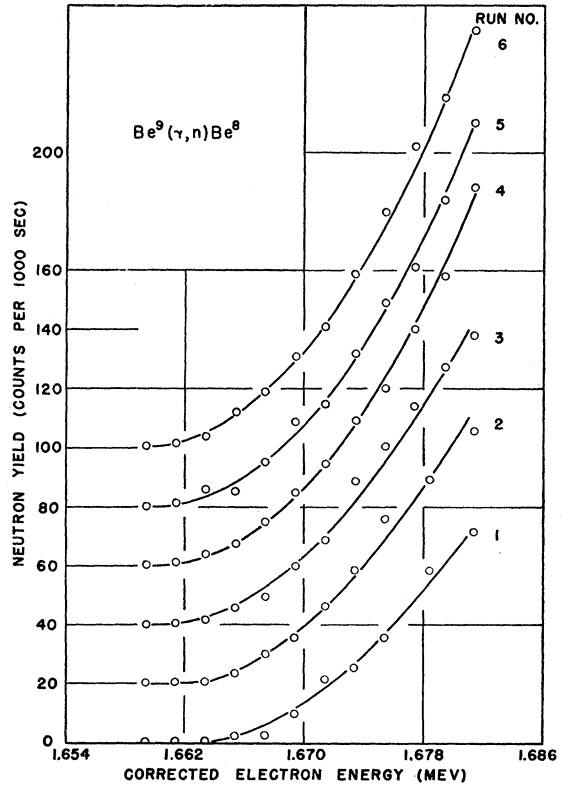

FIG. 4. Neutron yield for photodisintegration of beryllium. The ordinates for the different runs have been shifted for clarity.

Table II summarizes the determination of the binding energy from the data.

The internal consistency of these data is not as good as that for the deuterium determination nor does the yield follow the theoretical 5/2 power. In virtue of this we do not feel justified in attaching an error of less than 3 kev to the binding energy.

Four runs were made to determine the binding energy of deuterium. A run consisted of measuring the neutron yield at various beam energies from 35 kev above threshold down to threshold. Five-kev steps in beam energy in the upper energy region and three-kev steps in the lower energy region were used. Each run was analyzed individually using the method outlined above.

Figure 6 is a plot of neutron yield *vs* corrected electron energy. The correction consisted of -3.5 kev for the magnetic field effect and -1.3 kev for the motion of the center-of-mass. Figure 7 is a plot of the 2.365th root of the neutron yield *vs* corrected electron

TABLE II. Neutron binding energies for beryllium, in Mev.

Run number	1	2	3	4	5	6
Binding energy	1.6640	1.6624	1.6617	1.6606	1.6606	1.6598
	Average 1.662±0.003 Mev					

TABLE III. Neutron binding energies for deuterium, in Mev.

Run number	1	2	3	4
Binding energy	2.2270	2.2272	2.2271	2.2270
	Average 2.227±0.003 Mev			

energy. In an attempt to use another method for the location of the threshold a log-log plot of neutron yield *vs* excess electron energy was made.[4] In the region of the log-log plot which distinguished between possible thresholds, the errors associated with each point were so large on the log scales as to obliterate the distinction.

Table III summarizes the determination of the binding energy from these figures.

The results of the four runs show a much better internal consistency than that indicated by the stated error of 3 kev. As shown in the experimental section the limiting error in this experiment was the energy resolution of the analyzer. This energy resolution was determined by the slit openings used, and was ±3 kev in this case.

DISCUSSION

Li *et al.*[18] have made a compilation of the nuclear disintegration energies of light nuclei. They considered

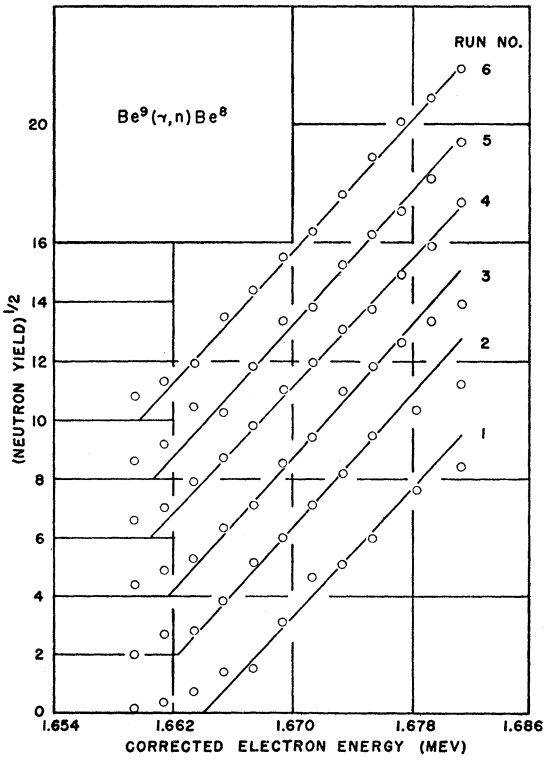

FIG. 5. (Neutron yield)$^{\frac{1}{2}}$ for photodisintegration of beryllium. The ordinates for the different runs have been shifted for clarity.

[18] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 516 (1951).

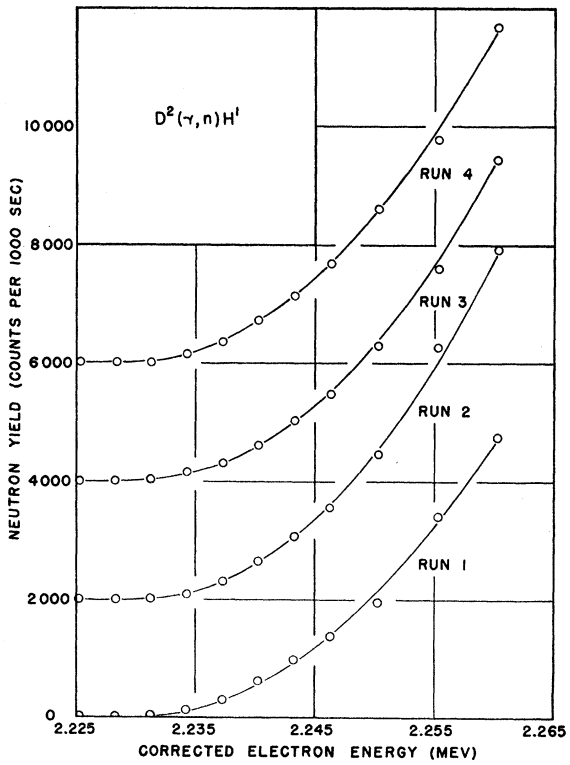

FIG. 6. Neutron yield for photodisintegration of deuterium. The ordinates for the different runs have been shifted for clarity.

only recent experiments and their value for the binding energy of deuterium is a weighted mean of all the nuclear experiments measuring that binding energy directly. Van Patter[19] has extended the work of Li *et al.* His weighted mean for the direct experimental determinations of the deuteron binding energy includes the preliminary Notre Dame value which neglected the magnetic field corrections. Both Li and Van Patter computed a binding energy determined as an internally consistent weighted mean of all the nuclear cycles involving light nuclei that could be combined to give

TABLE IV. Neutron binding energies for deuterium and beryllium, in Mev.

	B.E. of deuterium	B.E. of beryllium
Notre Dame	2.227±0.003	1.662±0.003
Bell and Elliott	2.230±0.007	
Mobley and Laubenstein	2.226±0.003	1.666±0.002
Li *et al.* (weighted exp mean)	2.227±0.002	1.666±0.002
Van Patter (weighted exp mean)[a]	2.228±0.002	1.665±0.002
Li *et al.* (internally consistent mean)	2.226±0.002	1.666±0.002
Van Patter (internally consistent mean)	2.226±0.002	1.666±0.002

[a] Includes preliminary Notre Dame values of 2.231 and 1.664 Mev.

[19] D. M. Van Patter, Massachusetts Institute of Technology Technical Report No. 57, 1952 (unpublished).

n+H−D. Their values, along with those of Bell and Elliott, and Mobley and Laubenstein are presented in Table IV.

Using the HH−D mass difference of 1.445±0.002 Mev from mass spectroscopic data,[20] and our binding energy of deuterium, the n−H difference is 782±4 kev. This, together with the atomic mass of hydrogen,[18] leads to a value of 1.008982 for the mass of the neutron.

In order to provide a check of the accuracy of our electrostatic analyzer, Bhattacherjee, Waldman, and Miller[10] measured the conversion electron energy accompanying the disintegration of Cs^{137}. Their value for the transition energy of 662.6±0.9 kev is in agreement with the 661.60±0.14 kev value of Muller, Hoyt, Klein, and Dumond,[21] and the 661.65±0.15 kev value of Lindstrom, Siegbahn, and Wapstra.[22]

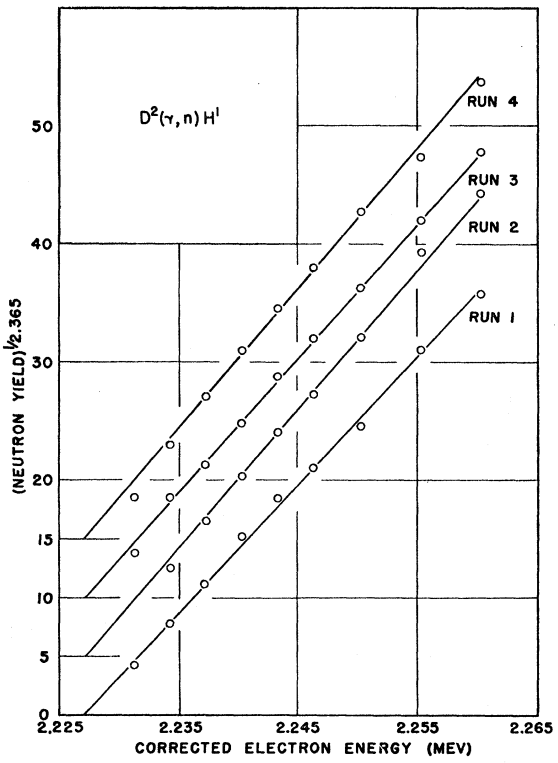

FIG. 7. (Neutron yield)$^{1/2.365}$ for photodisintegration of deuterium. The ordinates for the different runs have been shifted for clarity.

The authors wish to thank T. F. Ruane for the numerical integration of Eq. (4). One of us (J.E.V.), received support during the course of the experiment from the Research Corporation, another (J.C.N.), was a predoctoral fellow of the U. S. Atomic Energy Commission.

[20] T. R. Roberts, Phys. Rev. **81**, 624 (1951).

[21] Muller, Hoyt, Klein, and DuMond, Phys. Rev. **88**, 775 (1952).

[22] Lindstrom, Siegbahn, and Wapstra, Proc. Phys. Soc. (London) **B66**, 54 (1953).