Measurement of the Deuteron Binding Energy using a Bent-Crystal Spectrograph*†

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(Received March 20, 1961)

The deuteron binding energy has been determined by measuring the neutron-proton capture gamma-ray energy. This energy has been measured directly, relative to annihilation radiation, with the help of a 6-m radius bent-crystal spectrograph. The spectrograph is of the Cauchois type, in which a collimated but extended gamma-ray beam is incident on the convex side of an elastically bent quartz crystal, is diffracted, and is focused onto a focal circle defined by the radius of curvature of the crystal. The neutron-proton-capture gamma rays are produced by placing a polyethylene sample in the through port of the Massachusetts Institute of Technology research reactor. The (310) planes of quartz are used for diffraction, and the gamma-ray lines are recorded on glass mounted 600-μ-thick Ilford G-5 emulsions. The value of $B(D)$ obtained is 2225.5±1.5 kev, where the error is the standard deviation. This is the most precise direct measurement reported to date, and is in agreement with previous work. Using recent mass spectroscopic data, the mass of the neutron is found to be 1.008 984 ±0.000 002 amu. The efficiency of the spectrograph is low. At 2225 kev, 6000 curie hr is required to record a line; at 511 kev, 1200 curie hr is necessary. The error in $B(D)$ agrees with the estimated precision which varies from about 0.01% at 100 kev to 0.3% at 4000 kev. The latter energy is close to the practical upper energy limit of the instrument.

I. INTRODUCTION

THE first measurement of the deuteron binding energy $B(D)$ was made by Chadwick and Goldhaber in 1934,[1] and repeated in 1935.[2] They used the "nuclear photoelectric effect," or photodisintegration of the deuteron using ThC″ gamma rays, and measured the energy of the recoil protons in an ionization chamber. Analogous techniques were used by almost all of the early workers in the field. Interesting exceptions are the experiments of Fleischmann[3] and Kikuki *et al.*[4] In both of these experiments slow neutrons were used to bombard hydrogen, and the resulting recoil photons (or

TABLE I. Early measurements of the deuteron binding energy $B(D)$.

Year	Principal author	Incident particle	Particle detected	Method	$B(D)$ (Mev)	Error (Mev)	Reference
1934–35	Chadwick	ThC″ gamma	Proton	Ionization chamber	2.1	···	a, b
1936	Fleischmann	Neutron	Electron	Absorption	2.26	···	c
1936	Kikuki	Neutron	Electron	Absorption	2.2	···	d
1936	Ising	ThC″ gamma	Proton	Ionization chamber	1.76	···	e
1937	Chadwick	ThC″ gamma	Proton	Cloud chamber	2.25	±0.05	f
1938	Bethe	(Correction of 1937 work of Chadwick)			2.17	±0.04	g
1938	Stetter	ThC″ gamma	Proton	Ionization chamber	2.189	±0.022	h
1938	Richardson	Na^{24} gamma	Proton	Cloud chamber	2.18	±0.07	i
1939	Rogers	ThC″ gamma	Proton	Cloud chamber	2.17	±0.05	j
1940	Kimura	RaC gamma	Neutron	Slowing-down thickness	2.189	±0.007	k
1942	Myers	x rays	Neutron	Threshold	2.183	±0.012	l
1945	Wiedenbeck	x rays	Neutron	Threshold	2.185	±0.006	m
1948	Nagakawa	Neutron	Gamma	···	2.24	···	n
1949	Meyer	RaC″ gamma	Proton	Proportional counter	2.186	±0.005	o
					2.181	±0.005	p

[a] J. Chadwick and M. Goldhaber, Nature **134** 237 (1934).
[b] J. Chadwick and M. Goldhaber, Proc. Roy. Soc, (London) **A151**, 479 (1935).
[c] R. Fleischmann, Z. Physik **103**, 113 (1936).
[d] S. Kikuki, H. Aoki, and K. Husimi, Nature **137**, 186 (1936).
[e] G. Ising and M. Helden, Nature **137**, 273 (1936).
[f] J. Chadwick, N. Feather, and E. Bretscher, Proc. Roy. Soc. (London) **A163**, 366 (1937).
[g] H. A. Bethe, Phys. Rev. **53**, 313 (1938).
[h] G. Stetter and W. Jentschke, Z. Physik **110**, 214 (1938).
[i] J. R. Richardson and L. Emo, Phys. Rev. **53**, 234 (1938).
[j] F. T. Rogers and M. M. Rogers, Phys. Rev. **55**, 263 (1939).
[k] K. Kimura, Mem. Coll. Sci., Univ. Kyoto **22**, 237 (1940).
[l] F. E. Myers and L. C. Van Atta, Phys. Rev. **61**, 19 (1942).
[m] M. L. Wiedenbeck and C. J. Marhoefer, Phys. Rev. **67**, 54 (1945).
[n] S. Nagakawa, J. Sci. Research Inst. Tokyo, **43**, 1185 (1948).
[o] P. Meyer, Z. Physik **126**, 336 (1949).
[p] $B(D)$ of reference "o" corrected for new value of incident gamma-ray energy, see P. Marin, G. R. Bishop, and H. Halban, Proc. Phys. Soc. (London) **A66**, 608 (1953).

* Work supported by the National Science Foundation.

† Based on material presented by one of the authors (A.H.K.) in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Nuclear Engineering at the Massachusetts Institute of Technology.

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[1] J. Chadwick and M. Goldhaber, Nature **134**, 237 (1934).
[2] J. Chadwick and M. Goldhaber, Proc. Roy. Soc. (London) **A151**, 479 (1935).
[3] R. Fleischmann, Z. Physik **103**, 113 (1936).
[4] S. Kikuki, H. Aoki, and K. Husimi, Nature **137**, 186 (1936).

TABLE II. Recent measurements of the deuteron binding energy. These measurements are characterized by a consistently higher value of $B(D)$ than the earlier measurements listed in Table I.

Year	Principal author	Method	$B(D)$ (Mev)	Reference
1949	Hanson	Gamma disintegration	2.229±0.020	a
			2.221±0.013	b
1948–1950	Bell	Measure conversion electrons due to capture gamma rays with thin-lens spectrometer	2.230±0.007	c
1950	Mobley	X-ray disintegration threshold	2.226±0.003	d
1950	Smith	Proton disintegration threshold ($H+D \rightarrow 2H+n$)	2.227±0.010	e
1954	Noyes	X-ray disintegration threshold	2.227±0.003	f
1960	Chupp and John	Two-meter radius bent-crystal spectrograph. Measure neutron-proton capture gamma ray.	2.225±0.003	g

[a] A. O. Hanson, Phys. Rev. **75**, 1794 (1949).
[b] $B(D)$ of reference a corrected for new value of incident gamma-ray energy; see Table I, reference p.
[c] R. E. Bell and L. G. Elliot, Phys. Rev. **79**, 282 (1950).
[d] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).
[e] R. V. Smith and D. H. Martin, Phys. Rev. **77**, 752 (1950).
[f] J. C. Noyes, J. E. Hoomissen, W. C. Miller, and B. Waldemann, Phys. Rev. **95**, 396 (1954).
[g] E. L. Chupp, R. W. Jewell, Jr., and W. John, Phys. Rev. **121**, 234 (1961).

capture gamma rays) were measured by determining the maximum energy of secondary electrons.

A break in the general approach up to that time is the work of Myers and Van Atta,[5] who were apparently the first to use the so-called "threshold" technique. This involves bombarding a target containing deuterons with high-voltage x rays of variable energy, and determining the threshold energy when protons, or neutrons, appear. These and other early experiments are listed in Table I. In 1947[6] Stephens critically reviewed some of this early work and arrived at an average of $B(D)=2.187\pm0.011$ Mev.

Another major departure in technique was the experiment of Bell and Elliot, 1948–1950.[7,8] Neutron-proton capture gamma rays were produced in the Chalk River pile and were converted, and the resulting photoelectrons were measured with a thin magnetic lens beta-ray spectrometer. It is noteworthy that their $B(D)$, together with the measurement of Hanson,[9] is considerably higher than that of the early measurements. This higher value has since been amply confirmed. The latest addition to the techniques of determining $B(D)$ is the direct measurement of $E(D)$ using crystal diffraction. This method was first used in connection with the 2-m-radius bent-crystal spectrograph at the Lawrence Radiation Laboratory in Livermore,[10,11] and the present work is a direct outgrowth of this.

The more recent experiments, characterized by the higher $B(D)$ value, are listed in Table II. In addition, a number of other experiments are currently in progress; however, no final results have been published. Similarly, a number of very low-precision measurements are not listed.

[5] F. E. Myers and L. C. Van Atta, Phys. Rev. **61**, 19 (1942).
[6] W. E. Stephens, Revs. Modern Phys. **19**, 19 (1947).
[7] R. E. Bell and L. G. Elliot, Phys. Rev. **74**, 1552 (1948).
[8] R. E. Bell and L. G. Elliot, Phys. Rev. **79**, 282 (1950).
[9] A. O. Hanson, Phys. Rev. **75**, 1794 (1949).
[10] E. L. Chupp, J. W. M. DuMond, R. W. Jewell, and Hans Mark, Bull. Am. Phys. Soc. **4**, 141 (1959).
[11] E. L. Chupp, R. W. Jewell, and W. John, Phys. Rev. **121**, 234 (1961).

$B(D)$ can also be obtained indirectly using various nuclear reaction cycles and their measured Q values. Values representative of this method are listed in Table III.

Recent years have seen the increasing availability of nuclear research reactors. As a result, strong neutron-capture gamma-ray sources are becoming available. This allows the use of high-precision but low-efficiency instruments such as diffraction spectrographs, as in the present work.

II. EXPERIMENTAL TECHNIQUES

The instrument in question is a six-meter radius bent-crystal spectrograph. Use is made of the Cauchois-type geometry in which a collimated but extended gamma-ray beam is incident on the convex side of an elastically bent crystal, is diffracted, and is focused onto a focal circle defined by the radius of curvature of the crystal.

The design, construction, and operation of this instrument has been described previously in detail in the literature.[12] Use is made of the (310) planes of quartz. A combination copper-polyethylene sample is placed into the 6-in.-diam through port of the 1-Mw (thermal) Massachusetts Institute of Technology research reactor (MITR), in a thermal flux of about 2.5×10^{12} n/cm^2-sec. The sample can be adjusted, without removal from the

TABLE III. Indirect determinations of the deuteron binding energy from nuclear reaction Q values.

Year	Principal author	$B(D)$ (Mev)	Reference
1950	Tollestrup	2.230 ±0.007	a
1955	Wapstra	2.2264±0.0018	b
1957	Li	2.2255±0.0015	c
1958	Kravtsov	2.2241±0.0011	d

[a] A. V. Tollestrup, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **78**, 372 (1950).
[b] A. H. Wapstra, Physica **21**, 367 (1955).
[c] C. W. Li, Sci. Sinica (Peking) **6**, 51 (1957).
[d] V. A. Kravtsov, Uspekhi Fiz. Nauk, **65**, 451 (1958).

[12] A. H. Kazi, N. C. Rasmussen, and Hans Mark, Rev. Sci. Instr. **31**, 983 (1960).

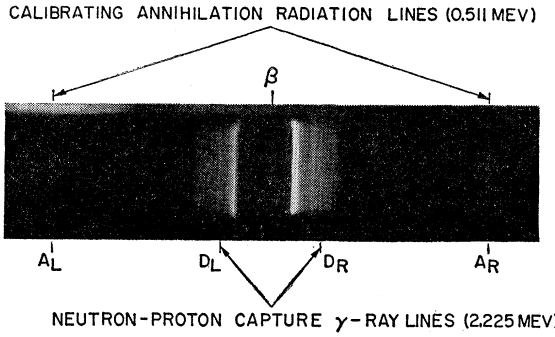

FIG. 1. Contact print of typical data plate. The two outer lines are the calibrating 0.511-Mev annihilation radiation lines. The two inner lines are the neutron-proton capture gamma ray lines to be measured. Data consist of the distances between these lines. The error is a function of linewidth and contrast. At higher energies it becomes increasingly difficult to separate the lines from the undiffracted beam. In the present case this poses no problem.

reactor through port, so that the crystal sees either the copper or the polyethylene. The 12.8-hr positron activity of Cu^{64} results in an effective annihilation radiation (0.511 Mev) source, as seen by the crystal during operation, of about 30 curies. The lines from this source are used as a calibration standard; the neutron-proton capture gamma-ray energy $E(D)$ is measured relative to them, i.e., relative to the rest mass of the electron. The effective source strength of the polyethylene neutron-proton capture gamma-ray source, as seen by the crystal, is also estimated at about 30 curies.

The gamma rays are recorded photographically on Ilford G-5 nuclear emulsions placed on the focal circle. Two emulsions are exposed in any one run, one placed behind the other. The spectrograph frame can be pivoted about the crystal so that gamma rays can be diffracted from both sides of the crystal planes. In this way, lines corresponding to a given energy can be made to appear on both sides of the β point (the infinite-energy position). Each plate of the present experiment therefore has four lines, two 0.511-Mev calibration lines and two unknown $E(D)$ lines.

In order to obtain a good readable line at 0.511 Mev, an exposure of at least 40 Mw hr is necessary. This equals an exposure of 1200-curie hr. In practice 3000-curie hr is usually used to produce extra strong lines. For $E(D)$ an exposure time of 200 Mw hr, or an exposure of 600-curie hr, is necessary. This means that one run takes about six weeks of normal 1-Mw MITR operation. For such a length of time, it is imperative that the general background radiation be rigidly controlled. It has been found that a background of 0.4–0.5 mr/hr at the line position is tolerable. Another problem is the prevention of latent image fading and of cracking due to drying of the glass-backed emulsion. It is advisable to use only fresh emulsions, tightly wrapped and taped in layers of Saran Wrap and photographic paper, at a room temperature not much above 22°C.

In order to assure that a line is actually being recorded on the emulsions, use is made of x-ray film monitors. The 0.511-Mev line can be recorded on "No-Screen"-type x-ray film in about 50-Mv hr; however, such thin film is too inefficient for the 2.22-Mev n-p capture gamma-ray line. No trace of it was observed directly on either No-Screen or KK film in exposures up to 180 Mw hr. The line can be obtained with the help of an image intensifier. In the present work, use has been made of a $\frac{1}{16}$-in.-thick CsI crystal, which enables one to obtain an $E(D)$ line on No-Screen film in about 170 Mw hr. A total of five runs were made, i.e., 10 emulsions were exposed. Of these five were satisfactory. Two pairs were unreadable because of image fading. One emulsion had too high a background.

The lines on the emulsions are read with a high-precision optical comparator, such as a Gaertner-type M 1205 C. The line centers are determined by reading both edges of a line and taking the mean. In practice the lines are read in a number of different ways, by several observers, and on several different comparators in order to minimize systematic errors. The reading error depends upon the linewidth and the line separations. The fact that lines appear on both sides of the β point ideally reduces this error by a factor of two over the case when only one side of the crystal plane is used for diffraction.

III. DATA REDUCTION AND ANALYSIS

A contact print of a typical data plate is shown in Fig. 1. The data obtained consists of sets of $x(A)$ and $x(D)$, the distances between the A (annihilation radiation) and D (neutron-proton capture gamma ray) lines, respectively. The width of the A lines is about 400 μ (0.4 mm), that of the D lines about 350 μ. The center positions of the former are reproducible to about 5 μ, the latter to about 10 μ because of lower intensity and higher background.

Using Bragg's law and a number of approximations, justified because of the small Bragg angles involved, one can obtain the following equation for $\lambda(D)$:

$$\frac{\lambda(D)}{\lambda(A)}=\frac{x(D)}{x(A)}+\delta$$

$$=\frac{x(D)}{x(A)}+\frac{x(D)x(A)}{24C^2}, \tag{1}$$

from which

$$E(D)=E(A)\frac{24C^2x(A)}{24C^2x(D)+x^2(A)x(D)}, \tag{2}$$

C, the radius of curvature of the bent crystal can be found from

$$C=\frac{x(A)}{2}\left\{\frac{\lambda(A)}{2d}+\frac{1}{6}\left[\frac{\lambda(A)}{2d}\right]^3\right\}^{-1}. \tag{3}$$

The value used for $E(A)$, or m_0c^2, is that given by Cohen *et al.*[13]:

$$E(A)=0.510\,976\pm-0.000\,007 \text{ Mev}. \quad (4)$$

The correction term δ in Eq. (1) corresponds to a $\Delta E(D)$ of about -0.1 kev, and is just on the threshold of significance in the present experiment. The value of $2d$ for the (310) planes of quartz enters the equation only through this correction term. The numerical value used in Eq. (3) is that given by Lind *et al.*[14] at 20°C, namely,

$$2d_{(310)}=2355.34\pm0.04\ x \text{ units}. \quad (5)$$

The conversion constant for $\lambda(A)$ used is that also given by Cohen *et al.*[15]

$$E\lambda=12372.44\pm0.16 \text{ kev } x \text{ units}. \quad (6)$$

In practice, 60 pairs of $x(A)$ and $x(D)$ are usually obtained from each data plate. $E(D)$ is calculated for each of these pairs, and $E(D)_{\text{av}}$ and its standard deviation are then determined in the usual way. Finally, $B(D)_{\text{av}}$ for each plate is found by adding a 1.3-kev recoil correction. The statistical standard deviation thus found is usually equal to about 0.5 kev. However, there are a number of instrumental sources of error.

Geometrical effects cause only very small instrumental errors. A ΔC, i.e., imperfect positioning of the emulsion on the focal circle, causes an instrumental error in $E(D)$ only through the dependence of the latter on C. As seen from Eq. (2), $E(D)$ depends on C only in the second approximation, and is thus very insensitive to a ΔC. $\partial E(D)/\partial C$ is equal to about 1×10^{-4} kev/cm, and ΔC in the geometry used is less than 5 mm. A ΔC results, of course, in a broadening of the line profile and hence in a greater statistical reading error [hence the Hartmann tests (reference 12)].

Another source of error is lateral deviation of the emulsion from the focal circle. If it is assumed that the emulsion is perfectly straight, i.e., unbent, and touches the focal circle only at the β point, then the true x's equal the measured x's minus 2α, where α is of the order of $C(\tan\theta-\sin\theta)$. The resultant $\Delta E(D)$ is less than 0.1 kev. A twist of the focal circle, say about the β point, is negligible; it really amounts to an irregular ΔC, and moreover tends to be self-correcting since it adds a δx to one side of the β point while subtracting it from the other. The fact that in general the emulsion is not placed into the holder with its long edge exactly parallel to the base of the crystal is no source of error. To account for all these geometrical effects, an error of 0.1 kev is assigned to the $E(D)_{\text{av}}$ of each plate.

A more serious source of instrumental error is emulsion movement during development. One can distinguish between uniform shrinkage, of say 5% in both $x(A)$ and $x(D)$, i.e., $s(A)=s(D)$, systematic differential shrinkage in which $s(A)\neq s(D)$ but $s(A)=f[s(D)]$, and random movement in which $s(A)\neq s(D)$ and $s(A)\neq f[s(D)]E(D)$, in the first approximation, is independent of uniform shrinkage, and any effect through the second approximation correction term δ is negligible. A number of experimental tests have been carried out[16] which indicate that, within the error inherent in the method of line measurement used in the present work, there is no detectable systematic differential shrinkage. There is, however, evidence of random emulsion movement. The over-all average of this movement, neglecting end effects (the last 2 cm of the emulsion) is a shrinkage of 5×10^{-2}%. In a unit distance of 10 000 μ the usual variations are a few microns. Variations of $\pm10\,\mu$ are observed fairly frequently, with maximum variations several times as large. If this s is assumed to affect $x(A)$ only, $AE(D)=sE(D)$, and for $s=5\times10^{-2}$%, $\Delta E(D)\approx1$ kev.

Differences of several kev can therefore easily arise between the $E(D)_{\text{av}}$ of several different plates, and this is found to be the case. There is no indication to assume, based on the information known about the present measurement techniques, that there is any regularity to this movement, and it is therefore assumed to be random. This being the case, it does not cause any instrumental error. In other words, the different $E(D)_{\text{av}}$ are averaged into the grand mean with equal weight as regards this type of emulsion movement.

The most serious source of instrumental error is the so-called "asymmetry" effect. Ideally the pattern of the lines on a nuclear emulsion should be symmetrical, i.e., the β point (midpoint) of the two A lines should coincide with the β point of the two D lines. In practice, it has been found that there are varying amounts of asymmetry, characterized by $\eta\equiv\beta_A-\beta_D$.

The upper limit in the resulting $\Delta E(D)$ is found by assuming that $\beta_A=\beta_{\text{true}}$, i.e., is completely due to a shift of the D lines, and $E(D)\approx x(A)/[x(D)+\eta]$. The lower limit is found by assuming that $\beta_D=\beta_{\text{true}}$. The ratio between the $\Delta E(D)$'s in these two limits is equal to 4.5. As a compromise, in the present work the asymmetry error has been estimated by adding $\frac{1}{2}\eta$ to both $x(A)$ and $x(D)$, i.e., $E(D)\approx[x(A)+\frac{1}{2}\eta]/[x(D)+\frac{1}{2}\eta]$.

The cause of this asymmetry is not known with certainty, but is thought to be also emulsion movement. It has also been observed in connection with the 2-m-radius spectrograph at the Lawrence Radiation Laboratory in Livermore, and a great deal of effort was spent there to locate its source.[17] As far as these studies show, the asymmetry is not due to any misalignments or asymmetries in the source, crystal, etc. There are several facts which speak for the emulsion movement hypo-

[13] E. R. Cohen, K. M. Crowe, and J. W. M. DuMond, *The Fundamental Constants of Physics* (Interscience Publishers, Inc., New York, 1957), p. 269.

[14] D. A. Lind, W. J. West, and J. W. M. DuMond, Phys. Rev. **77**, 475 (1950).

[15] See reference 13, p. 270.

[16] A. H. Kazi, Ph.D. thesis, Department of Nuclear Engineering, Massachusetts Institute of Technology, 1961 (unpublished), Secs. 7–10 and 8–3.

[17] Hans Mark (private communication).

thesis. First, η varies from plate to plate, and η may be positive, negative, or zero. Second, and more important, η varies for plates which have undergone identical exposure conditions and which vary only in their development. Thus in the present work P-7 and P-8 were exposed simultaneously, placed one behind the other; η for the former equals $4\,\mu$, for the latter it is $28\,\mu$. Also the magnitudes of η for the present 6-m-radius instrument and for the 2-m-radius Livermore one are about the same. If η were due to something in the geometrical system, one might expect a factor of two or three between the asymmetries of the two spectrographs. It might be noted here that since η is the same in the two cases, the resulting $\Delta E(D)$ is $\frac{1}{3}$ smaller in the six-meter case than in the two-meter case.

Inherently random emulsion movement takes place during development. The variations of $E(D)_{\text{av}}$ from plate to plate are caused by the differences between the net result of the over-all random movement in each plate; η is the result of the asymmetric component of this movement. The former can thus be treated statistically, and the latter results in an instrumental error.

IV. DEUTERON BINDING ENERGY

The results of the neutron-proton capture gamma-ray measurements are listed in Table IV. The five values of $B(D)_{\text{av}}$, on the basis of the statistical standard deviations and using Birge's criterion, are inconsistent. On the basis of their total assigned errors they are consistent.[18] The weights are inversely proportional to the square of the total errors. The grand mean is then given by

$$B(D)=\sum_{i=1}^{5} w_i B_i(\mathrm{D})_{\text{av}}/\sum_{i=1}^{5} w_i,$$

and its standard deviation

$$\sigma(B)=[\sum_{i=1}^{5} w_i|B_i-\bar{B}|^2/(n-1)\sum_{i=1}^{5} w_i]^{\frac{1}{2}}.$$

TABLE IV. Deuteron binding energy data. Listed are the average values of $B(D)$ obtained from each of the five data plates, the associated errors, and the resultant weight assigned to each of the average values. The weights are inversely proportional to the squares of the total errors, which are taken equal to the sum of the squares of the individual errors.

Plate No.	$B(D)_{\text{av}}$ (kev)	η (microns)	Errors, kev Statis.	Geom.	Asymm.	Total	Weight
P-2	2222.3	50	0.6	0.1	1.5	1.6	0.38
P-7	2228.1	4	0.6	0.1	0.2	0.6	2.4
P-8	2224.0	28	0.5	0.1	1.0	1.1	0.80
P-9	2222.5	23	0.6	0.1	0.7	0.9	1.2
P-10	2222.9	66	0.6	0.1	2.0	2.1	0.23

[18] A. G. Worthing and J. Geffner, *Treatment of Experimental Data* (John Wiley & Sons, Inc., New York, 1943), p. 199. (For the present data, $hx-1.68=1.83$, using the total assigned errors).

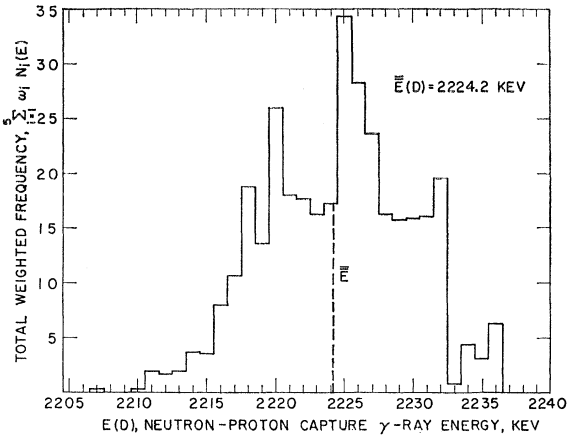

FIG. 2. Total weighted frequency distribution of $E(D)$. This frequency histogram is obtained by plotting the individual values of $E(D)$ versus their frequency as obtained from five data plates. The data of each plate have been multiplied by a weight inversely proportional to the square of the total error of the mean of that plate.

Using the above data, one obtains 2225.5 ± 1.3 kev. The standard error has been arbitrarily increased to ±1.5 kev, so that the final result is therefore

$$B(D)=2225.5\pm1.5 \text{ kev}. \tag{7}$$

As noted above, the error given is the standard deviation.

Note added in proof. The latest result of the Livermore Group (W. John) for $B(D)$ is 2224.6 ± 1.5 kev. Since eight separate exposures have been made by this group, the calculated standard error is only ±0.7 kev. Four of the five most recent plates had a negligible asymmetry which contributes to the small computed standard error. The error quoted in their result here has again been somewhat arbitrarily increased to account for possible systematic errors in the experiment. The fact that the binding energy reported in this paper and the Livermore number are in close agreement is good evidence that the diffraction method is sound.

Figure 2 shows the weighted frequency distribution of $E(D)$ obtained from the five data plates. The appropriate weights are shown in Table IV. The data from P-2 has been normalized from $N=91$ to $N=60$ in order to allow comparison with the other plates, for each of which $N=60$.

A comparison of the present value of $B(D)$ with some earlier measurements, as listed in Tables II and III, is given in Fig. 3. In general, it is not always quite clear whether a standard or probable error is involved in a particular quoted number. In the case of the values calculated from reaction cycle data, this distinction is somewhat arbitrary.[19]

[19] See for example C. W. Li, *Treatment of Experimental Data* (John Wiley & Sons, Inc., New York, 1943), p. 54.

V. MASS OF THE NEUTRON

The mass of the neutron is given by

$$n=H-M+B(D), \tag{8}$$

where H is the mass of hydrogen and M the HH-D mass spectroscopic doublet. One recent measurement of these quantities is that of Demirkhanov *et al.*[20] They use a Bainbridge-Jordan-type mass spectrometer with a resolving power which varies between 70 000 and 100 000. Their value for $H=1.008\ 142$ amu$\pm$1 amu, and $M=1.5483$ mmu$\pm$1 μmu. The use of these data and the present value of $B(D)$ yields for the mass of the neutron

$$n=1.008\ 984\pm0.000\ 002 \text{ mu}. \tag{9}$$

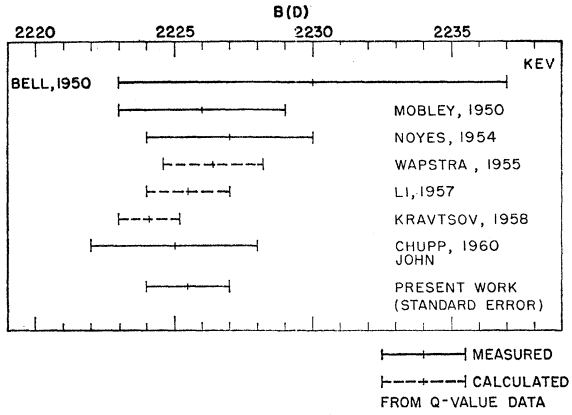

FIG. 3. Recent values of the deuteron binding energy. The results of a number of recent determinations of $B(D)$ are shown in comparison. The values are either direct measurements or the result of an analysis of a number of reaction cycles and their measured values. The error quoted in the present work is a standard deviation. The agreement of the present measurement with previous work is seen to be good.

[20] R. A. Demirkhanov, T. I. Gutkin, V. V. Dorokhov, and A. P. Radenko, Atomnaya Energ. **2**, 21 (1956); also in J. Nuclear Energy **3**, 251 (1956).

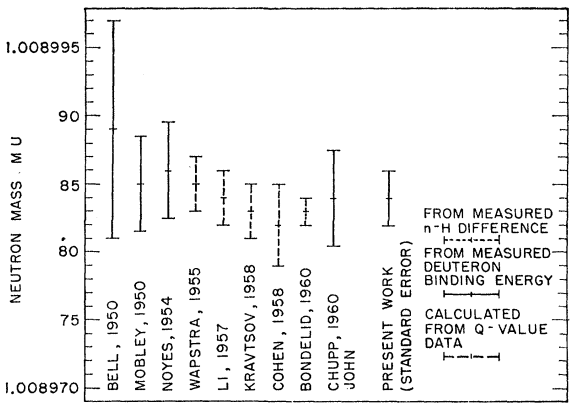

FIG. 4. Recent values of the mass of the neutron. This figure compares the results of the mass of the neutron from a number of recent experiments. The values derived from $B(D)$ are based on one recent set of mass spectroscopic measurements of the hydrogen mass and the HH$-$D doublet. Bondelid's value is based on a measured $n-$H difference of 782.9$\pm$0.4 kev.

For comparison, n has been similarly calculated using a number of the other $B(D)$ determinations. This is plotted in Fig. 4. In addition, two other values are shown. The value due to Cohen is a calculated one, based on Q-value data.[21] His error is a standard deviation. The value of Bondelid *et al.* is based on a recent precise measurement of the n-H difference[22] and Demirkhanov's value of H. The agreement among the various values, in the case of both $B(D)$ and n, is seen to be good.

ACKNOWLEDGMENT

The authors are indebted to Professor T. J. Thompson and the staff of the Massachusetts Institute of Technology research reactor for their kind interest and efficient and courteous services.

[21] E. R. Cohen *et al.*, reference 18, p. 266.

[22] R. O. Bondelid, J. W. Butler, C. A. Kennedy, and Achilles del Callar, Phys. Rev. **120**, 887 (1960).

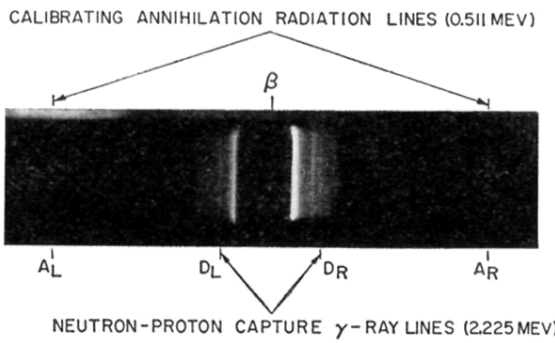

FIG. 1. Contact print of typical data plate. The two outer lines are the calibrating 0.511-Mev annihilation radiation lines. The two inner lines are the neutron-proton capture gamma ray lines to be measured. Data consist of the distances between these lines. The error is a function of linewidth and contrast. At higher energies it becomes increasingly difficult to separate the lines from the undiffracted beam. In the present case this poses no problem.