Thresholds for the Proton-Neutron Reactions of Lithium, Beryllium, Boron, and Carbon

R. O. HAXBY,† W. E. SHOUPP,* W. E. STEPHENS‡ AND W. H. WELLS
Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania

(Received August 30, 1940)

The energy threshold for the production of neutrons by bombardment of targets of Li, Be, B, and C with high energy protons has been measured with a boron trifluoride ionization chamber, surrounded with paraffin, as a neutron detector. The energy of the protons was calibrated against the 0.862-Mev F(p, γ) resonance. With H_2^+ and H_3^+, this calibration was extended to 1.724 Mev and 2.586 Mev. The thresholds are: Li^7, 1.86 Mev; Be^9, 2.03 Mev; B^{11}, 2.97 Mev and C^{13}, 3.20 Mev. From these values can be calculated the mass differences $Be^7-Li^7=0.87$ Mev, $B^9-Be^9=1.08$ Mev, $C^{11}-B^{11}=1.97$ Mev and $N^{13}-C^{13}=2.22$ Mev. B^9 is shown to be certainly unstable with respect to disintegration into Be^8+H^1. The $N^{13}-C^{13}$ difference agrees closely with the maximum positron energy from N^{13}, and thereby confirms the voltage scale.

INTRODUCTION

THE first observation of a (p, n) reaction was made by DuBridge, Barnes, and Buck.[1] The excitation curve was shown to have a definite threshold first by measuring the radioactivity[2] produced as a function of proton energy, and later by measuring the neutron[3] yield as a function of proton energy. The $Li^7(p, n)Be^7$ [3] and Be^9 [4] thresholds have been measured by means of the neutron induced activity in silver foils. The thresholds of these two reactions are of interest because they furnish the best way of measuring the masses of the nuclei Be^7 and B^9. We have redetermined these thresholds as accurately as possible. The $B^{11}(p, n)C^{11}$ threshold has not heretofore been measured; in fact the reaction itself has only recently been detected.[5] The $C^{13}(p, n)N^{13}$ threshold closes a reaction and mass-doublet cycle whose components have been very accurately measured. If the neutrino mass is zero, this cycle gives a good check on the voltage calibration. The precise measurement of these thresholds, or rather the precise intercomparison of these thresholds with γ-ray resonances, was a good way of testing the performance of the Westinghouse pressure electrostatic generator, and of exhibiting its principal feature, namely, accurate and easy control of voltage. Preliminary results have already been reported.[6]

* Westinghouse Research Fellow.
† Now with Sperry Gyroscope Company.
‡ Now at Stanford University.
[1] DuBridge, Barnes, and Buck, Phys. Rev. **51**, 995 (1937).
[2] DuBridge, Barnes, and Buck, Phys. Rev. **53**, 447 (1938).
[3] J. E. Hill and G. E. Valley, Phys. Rev. **55**, 678A (1939).
[4] J. E. Hill, Phys. Rev. **57**, 567A (1940).
[5] W. H. Barkas, Phys. Rev. **56**, 287 (1939).

EXPERIMENT

The Westinghouse pressure electrostatic generator[6] was the source of the high energy protons. The magnetically deflected spot of mass one was used so that there was no possibility of contamination of the beam by deuterons. The target arrangement is shown in Fig. 1, in which the aperture in the Faraday cage was small enough to insure that all protons entering the cage hit the target. The alignment was checked visually by means of quartz plate which could be let down over the target. The proton beam current was integrated by a device similar to the one described by Herb.[7] Neutrons coming from the target were slowed down in the block of paraffin and detected by means of the BF_3 ionization chamber inserted in the paraffin near the target. The BF_3 ionization chamber was patterned after the one described by Powers[8] and is shown in Fig. 2. The quartz insulation and Picein sealing wax first tried were replaced by hard rubber insulation and soft rubber gaskets to make a stronger and more convenient structure. This insulation lasts at least four months, and can be easily changed. Commercial BF_3 was used to fill

[6] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **57**, 348 and 567 (1940); Wells, Haxby, Shoupp, and Stephens, Phys. Rev. **58**, 162 (1940).
[7] Herb, Kerst, and McKibben, Phys. Rev. **51**, 691 (1937).
[8] P. N. Powers, Phys. Rev. **54**, 827 (1938).

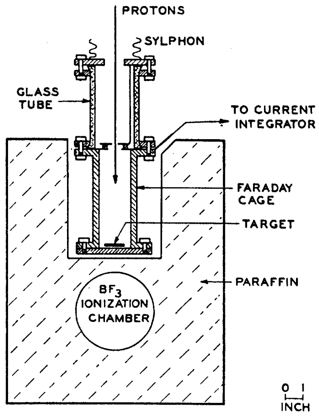

FIG. 1. Arrangement of target, paraffin, and BF_3 ionization chamber.

the ionization chamber to two atmospheres pressure. A 954 acorn tube was found convenient to use for a first stage of the linear amplifier, and was mounted on the ionization-chamber box. The linear amplifier has four resistance-capacity coupled stages[9] that feed a thyratron which drives a scaling circuit[10] and in turn actuates a Cenco counter. The thyratron was biased to count pulses approximately $\frac{1}{3}$ of the maximum α-particle pulses, this being about twice the background level. A potential of 2000 volts was used on the ionization chamber.

The voltage with which the protons are accelerated was measured by a generating voltmeter in which the principle of the compensating voltage plate described by Harnwell and Van Voorhis[11] was used. In this voltmeter, the generating voltmeter itself is used only to detect the absence of inhomogeneities in the field behind the voltage plate. Voltage is applied to this voltage plate until it coincides with an equipotential surface of the field from the high potential electrode. This condition is detected by the absence of pick-up in the generating voltmeter part. The high potential is then proportional to the voltage on the voltage plate and is measured by means of precision resistors and a good milliammeter.

The first voltmeter tried is shown diagrammatically in Fig. 3. The shutter and voltage plates consist of opposite quadrants. The pick-up plate was stationary and not sectored. The shutter was grounded through a slip ring and brush. This voltmeter worked well except that the presence of the front grounded plate and lack of proper alignment of the plates made it impossible to get a perfect balance point. The output from the pick-up plate as viewed in an oscillograph gave a complex pattern which was adjusted to an arbitrary but easily reproduced "balance pattern." This voltmeter was calibrated and checked for linearity against the 0.862-Mev fluorine gamma-ray resonance using H^+, HH^+, and HHH^+. The calibration curve was linear to an accuracy of 0.2 percent, but did not go through the origin. The limitation in accuracy was due to difficulty in setting the "balance pattern" on the oscillograph. Introduction of a pre-amplifier further distorted the pattern. To eliminate the imperfect balance effect (and hence eliminate the possibility that change in amplifier characteristics would shift the balance) a new and simpler voltmeter was made and is shown in Fig. 4. Here, instead of a rotating shutter and stationary pick-up plate, a rotating sectored pick-up plate was used. Since the pick-up plate is used only as a null detector, the a.c. amplifier gain need not be accurately constant. Variation in the brush resistance is unimportant, as long as it remains much less than the input resistance in the amplifier. To insure adequate brush contact, two brushes in parallel are provided for the pick-up plates. The most serious disadvantage is that the distance between the voltage plate and the pick-

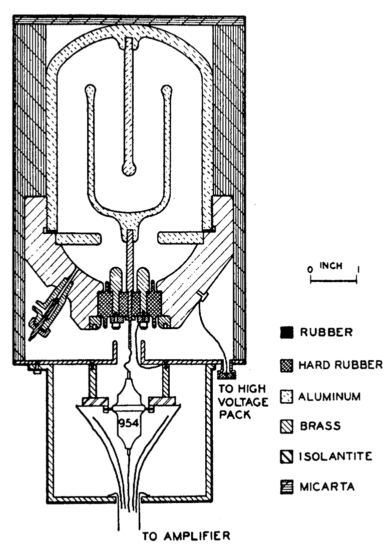

FIG. 2. Diagram of BF_3 ionization chamber.

[9] J. R. Dunning, Rev. Sci. Inst. **5**, 387 (1934).
[10] W. G. Shepherd and R. O. Haxby, Rev. Sci. Inst. **7**, 425 (1936).
[11] G. P. Harnwell and S. N. Van Voorhis, Rev. Sci. Inst. **4**, 540 (1933).

up plate must remain accurate to the precision desired in the voltage measurement. End play in the motor ball bearings is the probable limitation in accuracy of this spacing at present. With this voltmeter (using precision resistors and a potentiometer to measure the voltage on the voltage plate) readings can be reproduced to 0.2 percent and the voltage scale is linear to about 0.2 percent. This linearity was checked by measuring the 0.862-Mev fluorine gamma-ray resonance with H^+, HH^+, and HHH^+ at 0.862, 1.724, and 2.586 Mev. The yield of gamma-rays as a function of generating voltmeter reading is shown in Fig. 5. The gamma-rays are measured by a Geiger counter using otherwise the same procedure described by the Wisconsin group.[12] Hence their value of 0.862 Mev for the main resonance was used in our work. This value is $\frac{1}{2}$ percent less than the value 0.867 Mev given by Heydenburg from a thick target measurement.[13] Both values are based on the value 0.440 Mev for the $Li^7(p, \gamma)$ resonance. This value was measured at Washington, D. C. by a calibrated resistance voltmeter to 2 percent[14] and checked at Wisconsin.[15] However, the voltage scale used at Washington was calibrated to 1 percent by absolute measurement of the proton scattering in argon.[13] Hence, our voltage scale is accurate in absolute value to about $1\frac{1}{2}$ percent by this method of calibration. As will be discussed later, the $C(p, n)$ threshold measurement is a good check on our voltage calibration.

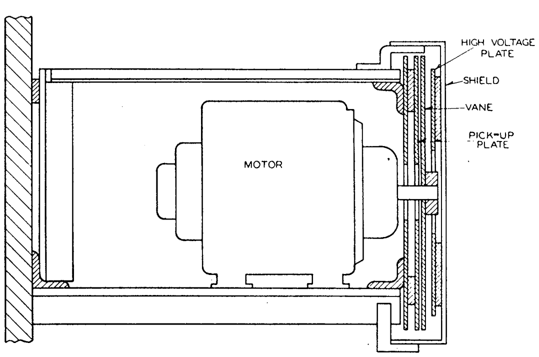

FIG. 3. Diagram of first generating voltmeter.

[12] Bernet, Herb, and Parkinson, Phys. Rev. **54**, 398 (1938).
[13] Heydenburg, Hafstad, and Tuve, Phys. Rev. **56**, 1078 (1939).
[14] Hafstad, Heydenburg, and Tuve, Phys. Rev. **50**, 504 (1936).
[15] Parkinson, Herb, Bernet, and McKibben, Phys. Rev. **53**, 642 (1938).

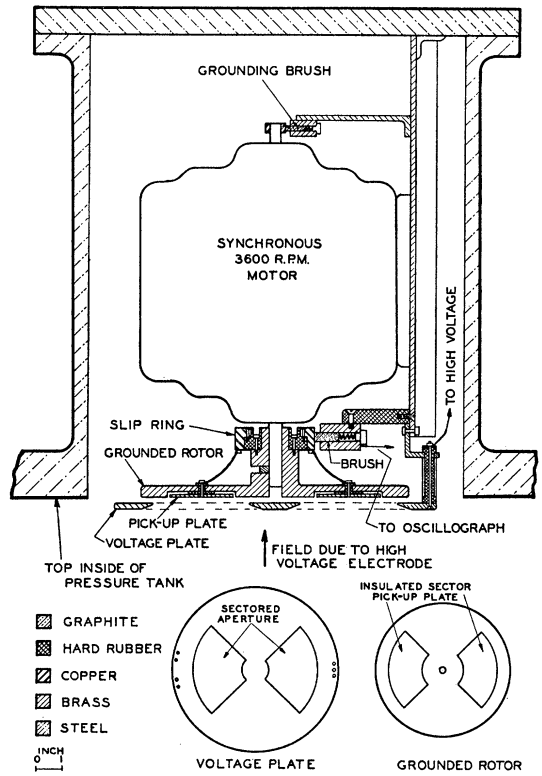

FIG. 4. Diagram of second generating voltmeter.

RESULTS

The number of neutrons counted by the detector per proton current integrator count was plotted as a function of proton energy read on the generating voltmeter to give the curves shown in Figs. 6 to 11. In our first exploratory experiments we used a BF_3 Geiger counter[16] surrounded by several pieces of paraffin. A $Be(p, n)$ yield curve taken with the counter is shown in Fig. 6. The BF_3 ionization chamber had a sensitivity about 40 times greater than the counter, and we were then able to investigate more carefully the dotted rectangle of Fig. 6. The resulting curve is shown in Fig. 7. With the second generating voltmeter we were able to increase the voltage resolution and secure the curve which is shown in Fig. 8. In all these curves the vertical lines through the points represent the statistical uncertainty of the number of counts. The horizontal lines represent the variation of voltage during a reading, as read on the generating

[16] S. A. Korff and W. E. Danforth, Phys. Rev. **55**, 980 (1939).

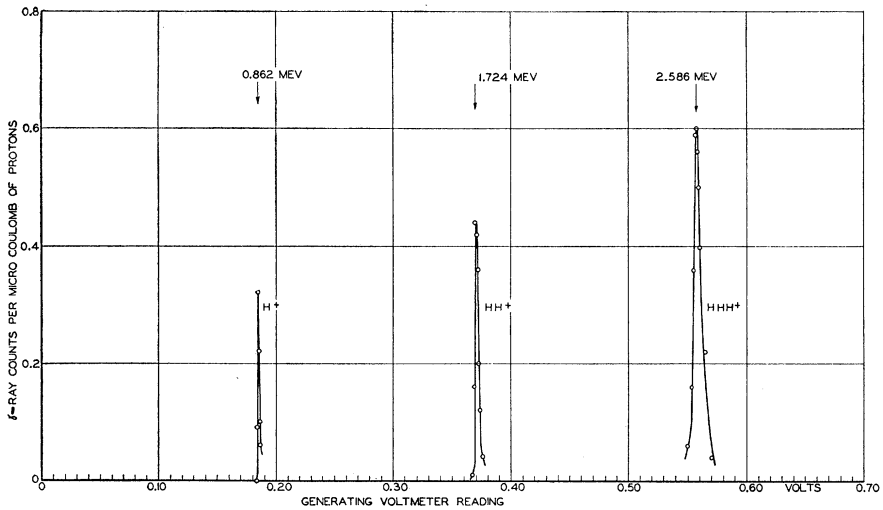

FIG. 5. Thin target γ-ray yield curve for the F(p, γ) 0.862-Mev resonance taken with H^+, HH^+, and HHH^+ at $E_p=0.862$ Mev, 1.724 Mev, and 2.856 Mev.

voltmeter. The ripple or any fast variation in voltage could not be read on the generating voltmeter, and can only be estimated from the width of a thin target γ-ray resonance curve assuming all the width to be experimental. The width at half-maximum varied from 3 kv to 10 kv for a 1-kv thick target, and seems to depend on the length of time of the readings and also on some uncontrollable features of the generator. There seems to be a tendency for the voltage to drop below, rather than fluctuate around, the value read on the generating voltmeter; this may explain the occasional points below the general run of points on the excitation curves. The reproducibility of the thresholds is about 0.2 percent, and is of the same order as the accuracy of calibration against the F(p, γ) resonance. The curve of Fig. 8 is the best evidence we have for the sharpness of these (p, n) thresholds. Here the resolving power seems to be as good as 0.05 percent and the curve intercepts the background without any evidence of tailing. This resolution is better than we have obtained from γ-ray curves, and is probably due to the short time required to take the readings. It will be noticed that there is an appreciable neutron background in the Be(p, n) curve. This effect is ascribed to the secondary reaction system $Be^9(p, d)$, $Be^9(d, n)$ and could probably be reduced by using a thin Be target.

The yield curve for $Li^7(p, n)$ is shown in Fig. 9. It is to be noted that the background is quite small. In fact, it is the same as the natural background and is probably due to natural α-particles from the walls of the ionization chamber and to cosmic-ray neutrons.[17] Because of the small background and large yield from this reaction, its threshold can be observed visually by watching the linear amplifier monitor oscilloscope. The voltage at which neutron pulses appear visually on the screen is taken as the threshold. These values, shown by the arrows on the curve, agree quite well with the

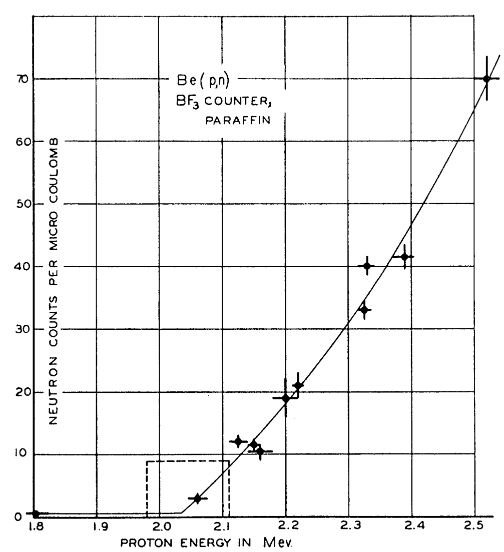

FIG. 6. Thick target neutron yield curve for Be(p, n) taken with BF_3 Geiger counter, a few pieces of paraffin, and the first generating voltmeter.

[17] C. G. Montgomery and D. D. Montgomery, Phys. Rev. 56, 10 (1939).

extrapolated value. The $B^{11}(p, n)$ yield curve is given in Fig. 10, and $C^{13}(p, n)$ in Fig. 11. The yield from $C^{13}(p, n)$ is distinctly smaller than the others, and is consistent with the fact that C^{13} is only 1 percent of carbon. Both the B and C curves have appreciable backgrounds of undetermined origin.

A summary of the observed threshold energies E_p of the (p, n) reactions investigated is given in Table I. The probable errors given are only those involved in the comparison of these values with the 0.862-Mev $F(p, \gamma)$ resonance. As has been pointed out, this value of 0.862 Mev is known to an absolute accuracy of only $1\frac{1}{2}$ or 2 percent.

Discussion

The general (p, n) reaction may be written as

$$_ZX^A + {}_1H^1 \rightarrow {}_{Z+1}Y^A + {}_0n^1 + Q_1,$$

where Q_1 is actually negative, since the reaction is endoergic and the value of Q_1 is given in terms of the measured threshold of proton bombarding energy E_p, as

$$Q_1 = -\left(\frac{A}{A+1}\right)E_p.$$

The product nucleus Y may return to X either by emitting positrons,

$$_{Z+1}Y^A \rightarrow {}_ZX^A + {}_-e + {}_+e + \mu + E_+$$

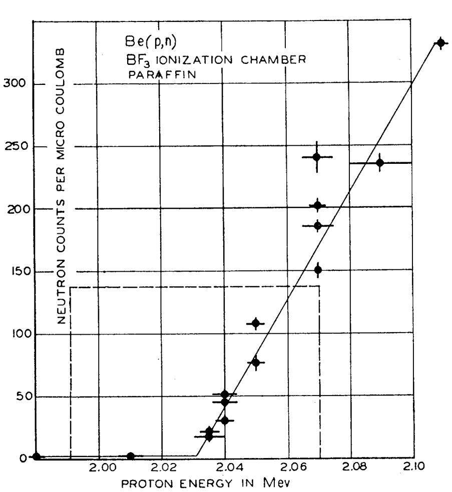

FIG. 7. Thick target neutron yield curve for $Be(p, n)$, taken with BF_3 ionization chamber in paraffin and with the first generating voltmeter.

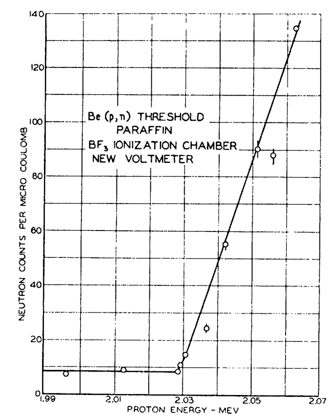

FIG. 8. Thick target neutron yield curve for $Be(p, n)$ taken with BF_3 ionization chamber in paraffin and with the second generating voltmeter.

or by K-electron capture

$$_{Z+1}Y^A \rightarrow {}_ZX^A + \mu + Q_2.$$

In these equations, X, Y, refer to atomic masses $_-e$ and $_+e$ to the rest mass of the electron and positron, μ to the rest mass of the neutrino, and Q_2 to the total kinetic energy of the products. In the case of the positron emitters E_+ is the maximum energy of the positron spectrum.

First we can give the masses of the Y nuclei by putting our results together with other measured values for the X masses and adopting the value

$$({}_0n^1 - {}_1H^1) = 0.750 \pm 0.056 \text{ Mev}.$$

This value is derived from Mattauch's[18] mass-spectroscopic value,

$$(HH - D) = 1.433 \pm 0.002 \text{ Mev}.$$

or alternatively on the value of Bainbridge and Jordan[19]

$$(HH - D) = 1.424 \pm 0.04 \text{ Mev}.$$

Also involved in $({}_0n^1 - {}_1H^1)$ is the value for the dissociation energy of the deuteron $({}_0n^1 + {}_1H^1 - {}_1D^2)$. There are four experimental values for this, as follows:

(a)	2.17 ±0.04 Mev	(c)	2.18 ±0.07
(b)	2.189±0.0022	(d)	2.174±0.05

The sources of these are (a) Bethe's correction[20] of the Cambridge cloud-chamber range, (b) Stetter and Jentschke's[21] ionization-chamber

[18] J. Mattauch, Zeits. f. tech. Physik **12**, 578 (1939).
[19] K. T. Bainbridge and E. B. Jordan, Phys. Rev. **49**, 883 (1936).
[20] H. A. Bethe, Phys. Rev. **53**, 313 (1938).
[21] G. Stetter and W. Jentschke, Zeits. f. Physik **110**, 214 (1938).

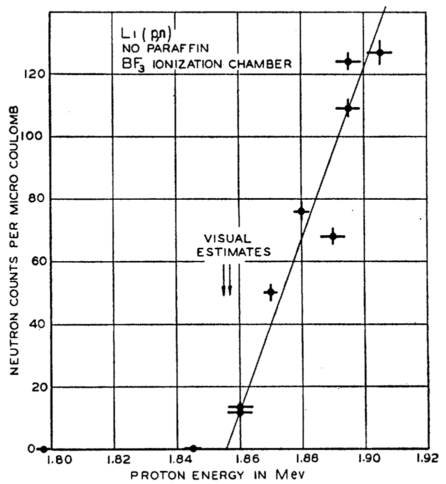

FIG. 9. Thick target neutron yield curve for LiOH(p, n) taken with BF_3 ionization chamber and with the first generating voltmeter.

work, (c) Richardson and Emo[22] cloud-chamber range, and (d) Rogers and Rogers[23] cloud-chamber curvature. A weighted average of these gives

$$({}_0n^1+{}_1H^1-{}_1D^2)=2.183\pm0.017 \text{ Mev}$$

from which the stated value of $({}_0n^1-{}_1H^1)$ is derived. If, more conservatively, one uses the Bainbridge and Jordan value for (HH−D) and the Bethe value for $({}_0n^1+{}_1H^1-{}_1D^2)$, the result is

$$({}_0n^1-{}_1H^1)=0.750\pm0.02 \text{ Mev}.$$

This value for $({}_0n^1-{}_1H^1)$, together with our observed values of Q_1 from Table I and the following assumed masses for the X nuclei give these values for the Y nuclei,

X, Li^7	7.01814±0.00011	Ref. (24)	Y, Be^7	7.01908±0.00011
Be^9	9.01484±0.00013	(25)	B^9	9.01600±0.00013
B^{11}	11.01286±0.00020	(26)	C^{11}	11.01499±0.00020
C^{13}	13.00766±0.00015	(26)	N^{13}	13.01004±0.00015

The value $E_p=1.85$ Mev for the $Li^7(p, n)$ threshold is somewhat lower than that observed by Hill and Valley,[3] but is within their experimental uncertainty. Recently, Hudson, Herb, and Plain[27] found a sharp rise in γ-ray intensity at $E_p=1.83$ Mev which, as they mention, may be due to neutrons from $Li^7(p, n)$.

Knowledge of the Be^7-Li^7 mass difference makes possible a discussion of the branching ratio of the K-capture activity of Be^7. When Be^7 captures a K electron, it may go to Li^7 in the normal state, in which case the energy taken away by the emitted neutrino is 0.87 Mev; likewise it may go to excited $(Li^7)^*$, which subsequently emits a 0.45 Mev γ-ray,[28] in which case the emitted neutrino carries off only $0.87-0.45=0.42$ Mev. On the β-decay theory, using the Fermi interaction assumption for allowed transitions, the relative likelihoods of the two modes of disintegration should be as the square of the released neutrino energy, or 0.232 for the ratio of $(Li^7)^*$ to Li^7 yield. Similarly with the Konopinski-Uhlenbeck form the variation is as the fourth power of the released neutrino energy or 0.054. The Gamow-Teller[29] spin dependent form assuming the two states of Li^7 to be ${}^2P_{3/2}$ (ground) and ${}^2P_{\frac{1}{2}}$ (excited) gives a value of 0.149 for the ratio. The experimental estimate[28] of the ratio is quite crude, and puts it only in the range 0.03 to 0.3, and so does not afford a decisive comparison with the theories. A more accurate experimental value would be interesting.

In regard to the Be(p, n) reaction, one might

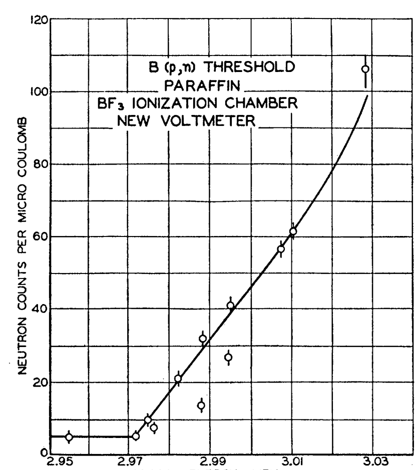

FIG. 10. Thick target neutron yield curve for $B_4C(p, n)$ taken with BF_3 ionization chamber in paraffin and with second generating voltmeter.

[22] J. R. Richardson and L. Emo, Phys. Rev. **53**, 234 (1938).
[23] F. T. Rogers, Jr., and M. M. Rogers, Phys. Rev. **55**, 269 (1939).
[24] N. M. Smith, Jr., Phys. Rev. **56**, 548 (1940); Allison, Miller, Perlow, Skaggs, and Smith, Phys. Rev. **58**, 178 (1940).
[25] Allison, Skaggs, and Smith, Phys. Rev. **57**, 550 (1940).
[26] W. H. Barkas, Phys. Rev. **55**, 691 (1940).
[27] Hudson, Herb, and Plain, Phys. Rev. **57**, 587 (1940).
[28] Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).
[29] G. Gamow and E. Teller, Phys. Rev. **49**, 895 (1936); B. O. Grönblum, Phys. Rev. **56**, 508 (1939).

expect an alternative reaction producing neutrons to be the noncapture disintegration,

$$_4Be^9 + {}_1H^1 \rightarrow {}_4Be^8 + {}_0n^1 + {}_1H^1 + Q_1.$$

Since the threshold for γ-ray disintegration of Be^9 has been found[30] to be 1.63 ± 0.05 Mev, the expected threshold of this reaction would be $1.81[=(10/9)\times1.63]$ Mev, definitely below the observed threshold of 2.03 Mev. Because of background, we can only detect a reaction cross section greater than 10^{-27} cm^2 within 0.2 Mev of the threshold. This is in accord with a theoretical estimate of Guth (private communication) that the cross section is about 10^{-28} cm^2 at 0.3 Mev above the threshold.

The observed energy difference (B^9-Be^9) would permit a positron radioactivity with maximum positron energy of 0.06 Mev or a K-electron capture. Such positron activity was not observed by Hill.[4] We looked for K-capture activity, by inserting a bombarded Be target into a Geiger counter, but found none. One may account for the absence of such activity in B^9 by the fact that B^9 is unstable with regard to dissociation into Be^8+H^1. This explanation follows at once from the fact that the $Be^9(p, n)B^9$ threshold is 0.20 Mev higher than the $Be^9(p, pn)Be^8$ threshold, as already discussed. Hence we conclude that the $Be^9(p, n)B^9$ reaction is immediately followed by the $B^9\rightarrow Be^8+H^1$ disintegration or perhaps a $B^9\rightarrow He^4+He^4+H^1$ disintegration. This was originally suggested as a possibility by Hill. The unstability of B^9 was predicted by Bethe from binding energy considerations.[31]

TABLE I. *Summary of results.*

TARGET $_ZX^A$	THRESHOLD ENERGY E_p* (MEV)	REACTION ENERGY Q_1 (MEV)	$Y-X$ OR Q_2 (MEV)	MAX. POSITRON ENERGY E_+ (MEV)
Li^7	1.85 ± 0.02	1.62 ± 0.02	0.87 ± 0.03	—
Be^9	2.03 ± 0.01	1.83 ± 0.01	1.08 ± 0.02	—
B^{11}	2.97 ± 0.01	2.72 ± 0.01	1.97 ± 0.02	0.95 ± 0.02
C^{13}	3.20 ± 0.03	2.97 ± 0.03	2.22 ± 0.04	1.20 ± 0.04

Mass Differences

Be^7-Li^7	$(9.4\pm0.3)\times10^{-4}$ m.u.
B^9-Be^9	$(11.6\pm0.2\times10^{-4})$ m.u.
$C^{11}-B^{11}$	$(21.3\pm0.2\times10^{-4})$ m.u.
$N^{13}-C^{13}$	$(23.8\pm0.4\times10^{-4})$ m.u.

* Values based on 0.862 Mev for the $F(p, \gamma)$ resonance. The stated uncertainties cover those in our comparison with this value. There is an additional uncertainty in these values of slightly less than 1 percent due to the uncertainty of this absolute value. Previously the uncertainty of the fluorine value was about 2 percent, but this seems to be considerably reduced in view of the results for the carbon cycle discussed below.

30 Collins, Waldman, and Guth, Phys. Rev. **56**, 876 (1939).

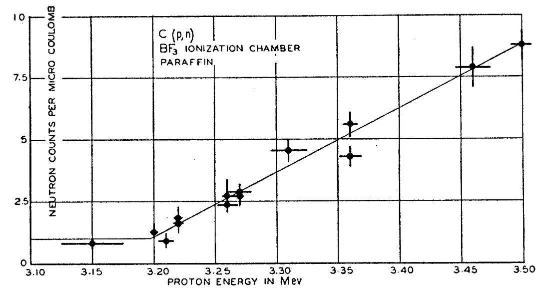

FIG. 11. Thick target neutron yield curve for $C(p, n)$ taken with BF_3 ionization chamber in paraffin and with first generating voltmeter.

The observed boron threshold is interesting in that it leads to a prediction of 0.95 ± 0.02 Mev for the maximum positron energy from C^{11}, which is definitely lower than the values 1.15 and 1.03 ± 0.03 Mev previously reported.[32] However, the most recent measurement, 0.95 ± 0.05 Mev, is in perfect agreement with our result.[33]

The boron threshold also permits a calculation of the $B^{10}(d, n)$ reaction in combination with other known data:

$$B^{11}(p, n)C^{11} = -2.72\pm0.03 \text{ Mev}$$
$$B^{10}(d, n)C^{11} = Q$$
$$B^{10}H - B^{11} = 10.80\pm0.1$$
$$HH - D = 1.433\pm0.002.$$

The $B^{10}H-B^{11}$ difference is from Bainbridge and Jordan.[34] These combine to give $Q=6.65\pm0.11$, which, at a bombarding energy of $E_D=1.0$ Mev, would give 6.85 ± 0.1 Mev for the energy of the neutrons emitted at 90° to the deuteron beam. The neutrons ascribed to this reaction by Bonner and Brubaker[35] have an energy of 6.15 ± 0.2 Mev, as measured by Staub and Stephens,[36] so it would seem that the neutrons are probably really due to $B^{11}(d, n)$ and that the neutrons from $B^{10}(d, n)$ have not as yet been measured.

In the case of the carbon threshold, Q_1 enables

31 H. A. Bethe, Phys. Rev. **54**, 436 (1938).

32 Fowler, Delsasso, and Lauritsen, Phys. Rev. **49**, 561 (1936); B. L. Moore, Phys. Rev. **57**, 355A (1940).

33 Barkas, Creutz, Delsasso, Fox, and White, Phys. Rev. **57**, 562A (1940).

34 K. T. Bainbridge and E. B. Jordan, Phys. Rev. **51**, 385 (1937).

35 T. W. Bonner and W. M. Brubaker, Phys. Rev. **50**, 308 (1936).

36 H. Staub and W. E. Stephens, Phys. Rev. **53**, 212A (1938).

TABLE II. *Coulomb differences in Mev.*

Pair	Q_1	Triton Model	Homo-geneous Distri-bution Model	Central Nucleus Model
Be^7-Li^7	1.62 ± 0.03	1.72	1.86	1.85
B^9-Be^9	1.83 ± 0.02		2.28	1.83
$C^{11}-B^{11}$	2.72 ± 0.02	2.72*	2.68	2.84
$N^{13}-C^{13}$	2.97 ± 0.04		3.03	2.98*

* Calculated values fitted to these values.

us to close an energy cycle in which the only unknown quantity is the rest mass of the neutrino. If we regard this as zero from evidence from β-decay theory, then this cycle gives an independent check on the accuracy of our voltage scale. Or if we accept the voltage scale as calibrated from the $F(p, \gamma)$ resonance, the result gives an upper limit for the rest mass of the neutrino. The reactions involved are

$$_6C^{13}+{}_1H^1\rightarrow{}_7N^{13}+{}_0n'+Q_1$$

$$_7N^{13}\rightarrow{}_6C^{13}+{}_+e+{}_-e+\mu+E_+.$$

Using the previously cited value for

$$({}_0n^1-{}_1H^1)=0.750\pm0.02\text{ Mev},$$

our value for $Q_1=-2.970\pm0.05$ Mev and the value obtained by Lyman[37] for the maximum energy of the positron spectrum $E_+=1.198\pm0.006$ Mev, we get for the rest mass of the neutrino

$$\mu=-({}_0n^1-{}_1H^1)-({}_+e+{}_-e)-E_+-Q_1,$$
$$\mu=-0.750\pm0.02-1.021-1.198\pm0.006+2.970\pm0.05,$$
$$\mu=0.001\pm0.056\text{ Mev}.$$

Hence if one accepts the voltage calibration, the results indicate the neutrino rest mass is probably less than one-tenth the electron rest mass. Or if one believes that the neutrino rest mass is zero, the close balance gives a very good check (to better than 1 percent) of the absolute voltage scale used in this work.

[37] E. M. Lyman, Phys. Rev. **55**, 234A (1939).

The reaction energy Q_1, as given in Table I, is also the "Coulomb difference" or the difference in binding energy between pairs of isobaric nuclei for which $Z=\frac{1}{2}A\pm\frac{1}{2}$. Since these pairs differ only in the interchange of a neutron and proton, this binding energy difference indicates the amount of Coulomb repulsion of the interchanged proton (assuming n–n and p–p forces are equal). It is interesting to compare the observed values with various calculated values, as shown in Table II.[38] The Be^7-Li^7 value is closest to that calculated on the alpha-triton model.[39] This might be expected, since this model also gives the spin and magnetic moment of Li^7 and for this pair the binding of alpha to triton is less than the intra group binding. The B^9-Be^9 value is remarkably well fitted by the central nucleus model.[40] This seems to indicate that the extra proton is in a p state outside a closed alpha-particle shell. The other two pairs and also pairs of higher atomic number[38] agree quite well with calculations on the homogeneous distribution model,[40] indicating that from here on the nuclei behave, in this respect at least, as if the nuclear particles were homogeneously distributed in a sphere of radius $=1.46A^{\frac{1}{3}}\times10^{-13}$ cm.

In conclusion, the experiments presented here have demonstrated the value of the large pressure electrostatic generator for precision measurements in nuclear physics. The sharpness of the thresholds of the (p, n) reactions indicates that they will be useful as calibration points in high voltage work.

We wish to express our appreciation of the generous support of this work by the Westinghouse Electric and Manufacturing Company, and of the friendly help and discussions with Dr. L. W. Chubb, Director, and Dr. E. U. Condon, Associate Director of the Westinghouse Research Laboratories.

[38] W. E. Stephens, Phys. Rev. **57**, 938L (1940).
[39] H. Brown and D. R. Inglis, Phys. Rev. **55**, 1182 (1939).
[40] H. A. Bethe, Phys. Rev. **54**, 436 (1938).