Proton-Neutron Reactions and Thresholds*

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Threshold proton energies for neutron emission have been determined carefully for Be^9, B^{11}, C^{13}, O^{18}, Cl^{37}, K^{41}, V^{51}, Mn^{55}. Thin target yield data up to about 4 Mev proton energy are reported for Be^9, B^{11}, O^{18}, and K^{41}. A summary of all reported p-n thresholds for $Z \leq 25$ is included. Isobaric mass differences from p-n measurements and from beta-ray end points are compared. Data concerning the suitability of various p-n reactions as controlled energy neutron sources are included.

I. INTRODUCTION

THE general type reaction

$$Z^A + H \rightarrow (Z+1)^A + n + Q$$

is always endoergic if one starts with a stable nucleus Z^A. The threshold proton energy for neutron emission will therefore always be greater than 782 kev, the $n-H$ mass difference. Since the outgoing neutron has no coulomb barrier to penetrate, the neutron yield near threshold need not be vanishingly small. Hence such thresholds can often be located to a precision comparable with the resolution in energy of the incident proton beam. The threshold energy and the $n-H$ mass difference then permit accurate determination of the mass difference between the two isobaric nuclei involved.

Such (p, n) reactions are also of practical interest as possible laboratory sources of neutrons whose energy can be varied by control of the proton energy. Furthermore, the sharp thresholds of these reactions provide useful calibration points on the high voltage scale.

The present paper summarizes work on (p, n) thresholds and yields investigated at Wisconsin over the last several years.

II. EXPERIMENTAL ARRANGEMENTS AND RESULTS

Protons of energy up to 4 Mev and monoergic to 0.1 percent were available from the Wisconsin electrostatic generator and high resolution cylindrical electrostatic analyzer. Target arrangement and preparation are discussed separately for each element. Neutrons were detected by a shielded energy insensitive BF_3 (plus paraffin) counter placed in front of the target and subtending about π-steradians. All targets were kept heated to 200°C to minimize surface contamination. A liquid air cooled trap was also located between the targets and the diffusion pumps.

The voltage scale was checked several times during the measurements by sliding lithium targets in place and observing the $Li^7(p, n)Be^7$ threshold. Calibration curves for different lithium targets are shown in Fig. 1.

Beryllium

One thick and two thin Be targets were used. The thick target was metallic beryllium and the thin targets ($\frac{1}{2}$ kev and 2 kev stopping power) were prepared by evaporation onto tantalum. Figure 2 shows the thick and thin target yields near threshold. The thick target yield below threshold is believed to result from secondary $(p, d; d, n)$ reactions in the thick Be target. Such thick target effects for Be have been discussed by Jennings, Sun, and Leiter.[1] Thin target yield below threshold shows no effect above background. Hence the yield from $Be^9(p, pn)Be^8$ reaction (threshold $E_p = 1.84$ Mev) appears to be negligible at these bombarding energies. The maximum in yield near threshold is an effect associated with the forward bunching of the low energy neutrons which bunching results from the center of mass motion. Figure 3 shows the yield curve from

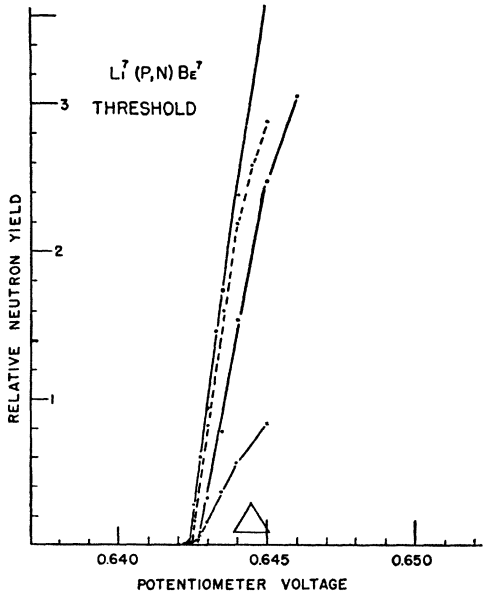

FIG. 1. Calibration measurements on the $Li^7(p, n)Be^7$ threshold taken with different lithium targets and at different times. The potentiometer setting of 0.6426 was taken to correspond to the lithium threshold, 1.882±0.002 Mev. The triangle is the proton energy spread calculated from the slit settings of the electrostatic analyzer.

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** Now at Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania.

[1] Jennings, Sun, and Leiter, Phys. Rev. 80, 109 (1950).

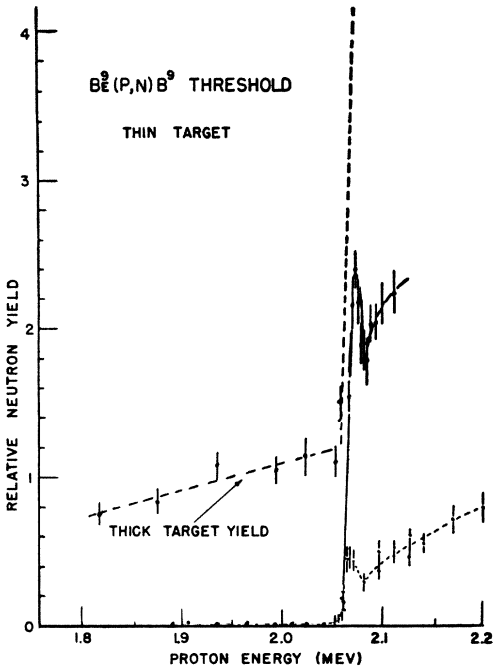

FIG. 2. Threshold data from thin and thick beryllium targets. See text for discussion of thick target yield.

threshold to 4.0 Mev proton energy. Only one resonance (previously reported by Hushley)[2] at $E_p = 2.56$ Mev was observed. Neutron spectrum studies[3] and differential cross section measurements[4] have also been completed in this laboratory and are being reported separately.

Boron

Thin targets of ordinary boron on tantalum were formed by running a high voltage discharge between a tantalum cathode and an aluminum anode in BF_3 at a few cm pressure. The targets so prepared were only a few kev thick for 3 Mev protons. Threshold runs on two different targets are shown in Fig. 4. The change in slope at $E_p = 3.03$ Mev is again the effect associated with the opening cone of neutrons. Yield data at higher energy have been taken but with no indication of resonances. The (p, n) reaction is with the B^{11} isotope, not B^{10}, since C^{11} is observed to be formed and mass values put the $B^{10}(p, n)C^{10}$ threshold above 5 Mev.

Carbon

A thick target of spectroscopic carbon was used. The neutron yield is low even from a thick target, since the

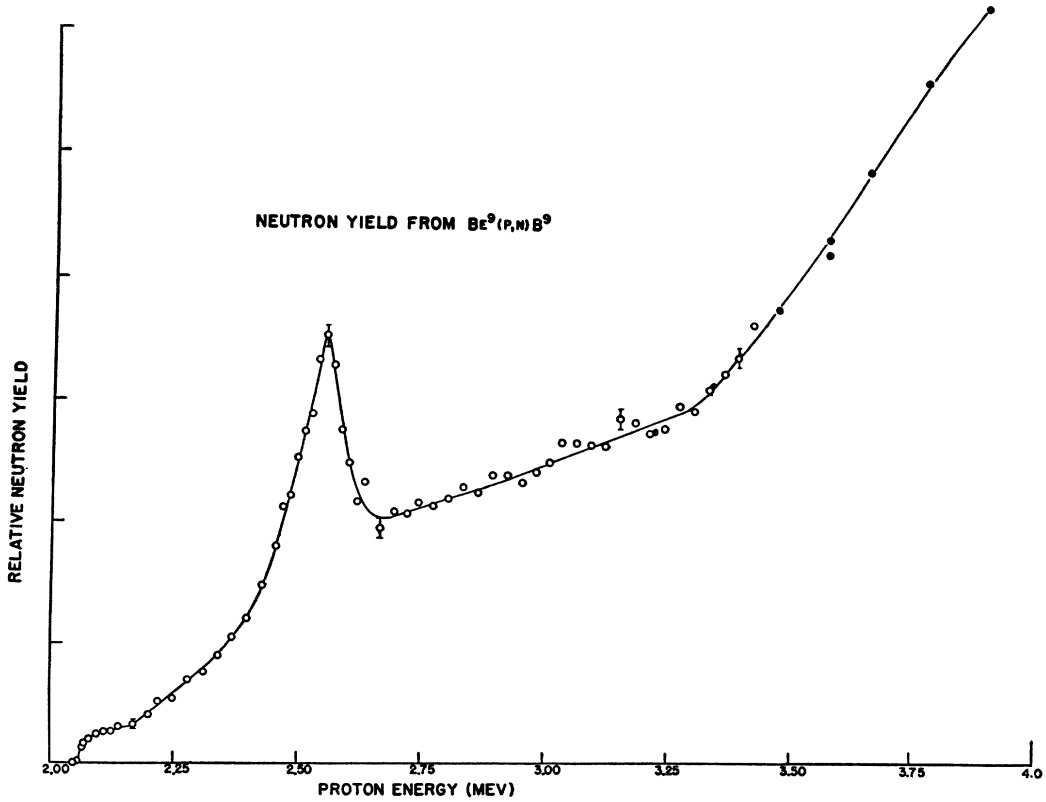

FIG. 3. Forward direction neutron yield from beryllium. The solid circles are data taken at a later time with a thicker target and normalized at 2.23 Mev.

[2] W. J. Hushley, Phys. Rev. **67**, 34 (1945).
[3] Johnson, Ajzenberg, and Wilson-Laubenstein, Phys. Rev. **79**, 187 (1950).
[4] Richards, Wilson-Laubenstein, Johnson, and Ajzenberg (report in preparation).

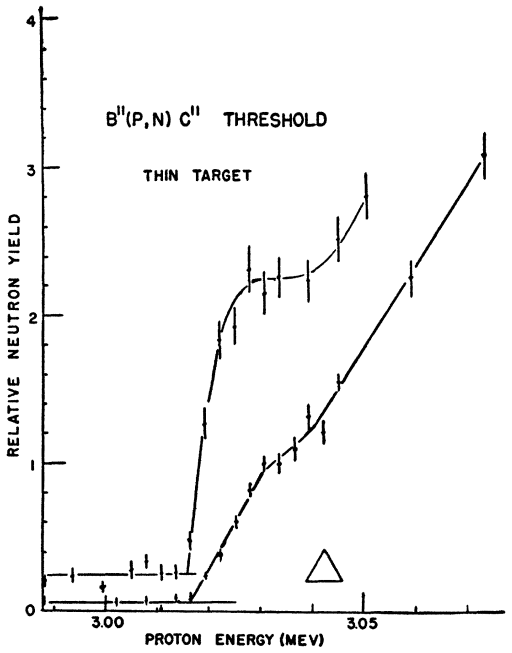

FIG. 4. Threshold data for two thin targets of boron.

reaction is with C^{13} whose abundance is only 1.1 percent. Results for two targets are shown in Fig. 5.

Oxygen

O^{18} is the only oxygen isotope with a threshold below 4 Mev. Thin O^{18} targets on aluminum and tantalum anode backings were formed by electrolysis of water enriched[5] to 1.5 percent O^{18}. Several hours of electrolysis at low currents (10 mamp.) gave thin and fairly uniform targets. The threshold data with the tantalum backed target are shown in Fig. 6. The yield above threshold is shown in Fig. 7. Numerous resonances are observed corresponding to excited states of the compound nucleus F^{19}.

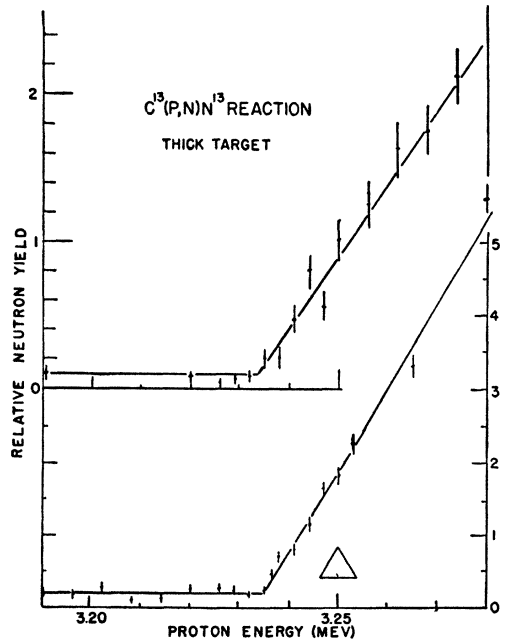

FIG. 5. Threshold data from thick targets of spectroscopic carbon.

[5] This water was obtained from Stuart Oxygen Company on allocation from the AEC.

Chlorine

Thick targets of LiCl and NaCl have been used. The results on the NaCl target are given in Fig. 8. The yield near threshold is low. Mass values necessitate assigning the reaction to the Cl^{37} isotope. However, the threshold is higher than that predicted theoretically[6] and is probably the result of the special stability of Cl^{37} which results from its closed shell of 20 neutrons. The observed threshold energy also confirms the K capturing classification for A^{37}. Because of its long half life (34 days) and its gaseous nature, A^{37} might have some interest for neutrino recoil experiments. Some thin target yield data was taken which indicated the presence of many resonance levels in A^{38} but the yield is low and difficulty was experienced in maintaining stable targets. More work on Cl^{37} is planned.

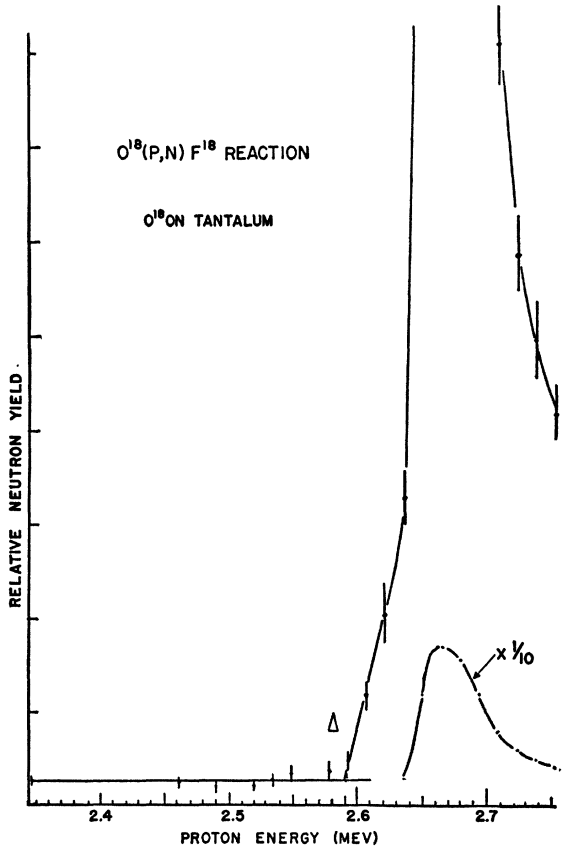

FIG. 6. Thin target threshold data from an enriched O^{18} target.

[6] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley & Sons, Inc., New York, 1947), p. 126.

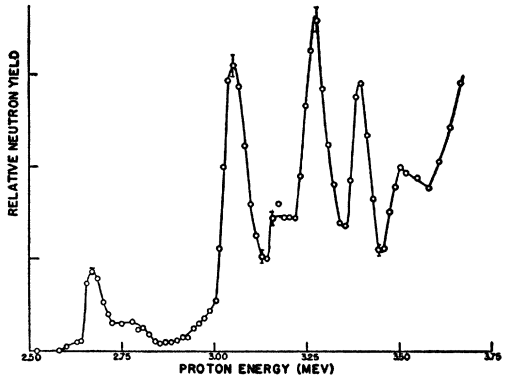

FIG. 7. Forward direction neutron yield from O^{18}.

Potassium

Thin evaporated targets of potassium metal were used. The yield near threshold is small (Fig. 9). The observed neutron reaction is attributed to K^{41} since K^{40} is of too low abundance to account for the observed yield and the reaction with the K^{39} isotope should be endoergic by several Mev according to theoretical arguments[7] and according to the 1.06-sec. activity[8] attributed to Ca^{39}. The $Ca^{41}-K^{41}$ mass difference as computed from our threshold excludes the possibility of a 1.1 Mev gamma-ray previously attributed to Ca^{41} K-capture.[9]

A thin target yield curve (Fig. 10) shows many excited states of the compound nucleus, Ca^{42}.

Vanadium

Thick targets were prepared by melting V_2O_5 onto a tantalum backing. A large probable error is assigned to the threshold because the yield near threshold (Fig. 11) was only slightly above the neutron background of the counter.

Manganese

Thick metallic manganese was used for a target. Definite neutron yield above background was detected (Fig. 12) down to $E_p=1.19$ Mev and reasonable extrapolation of the yield would indicate a threshold of $E_p=1.18\pm0.01$ Mev. This value is our lowest observed proton energy capable of giving neutrons from proton bombardment of a stable nucleus.

It is of interest that both the K^{41} and $Mn^{55}(p, n)$ reactions form residual nuclei which are actually of lower energy than the target nuclei. Thus, our present (p, n) data together with the n-p mass difference $(=n-H+mc^2)$ show that the K^{41} nucleus is 70 kev heavier than the Ca^{41} nucleus and that the Mn^{55} nucleus is about 130 kev heavier than the Fe^{55} nucleus. The reason that the

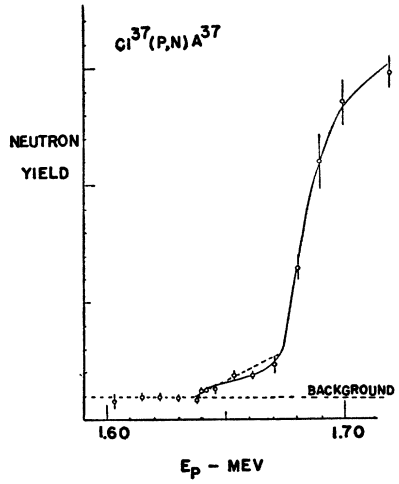

FIG. 8. Threshold data from a thick target of NaCl.

"heavier" nucleus is actually the stable nucleus is, of course, that the "lighter" nucleus can capture its K electron and thereby becomes the "heavier."

III. DISCUSSION

Table I summarizes the data on observed p-n thresholds in elements up to $Z=25$. The Q of each reaction[10] $[Q=-E_{th}M_2/(M_1+M_2)]$ is calculated from the observed thresholds and is recorded in column three. The energy difference ΔE between the two isobars is given in the fourth column assuming 782 kev for the $n-H$

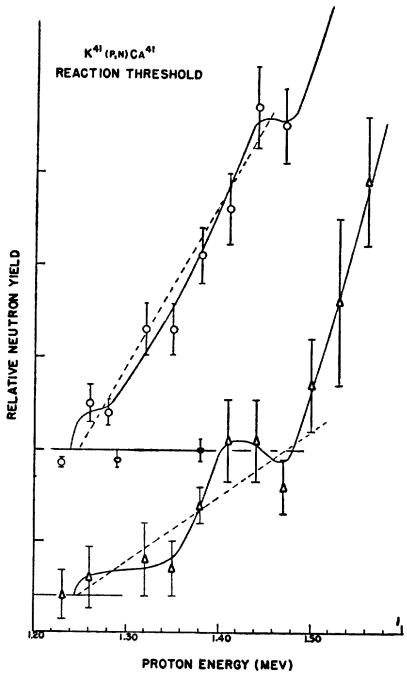

FIG. 9. Threshold data from two thin potassium targets.

[7] E. P. Wigner, quoted by H. Walke, Phys. Rev. **57**, 183 (1940).
[8] Huber, Leinhard, Scherrer, and Waffler, Helv. Phys. Acta **16**, 33 (1943).
[9] H. Walke, Phys. Rev. **57**, 179 (1940).
[10] Hanson, Taschek, and Williams, Rev. Mod. Phys. **21**, 635 (1949).

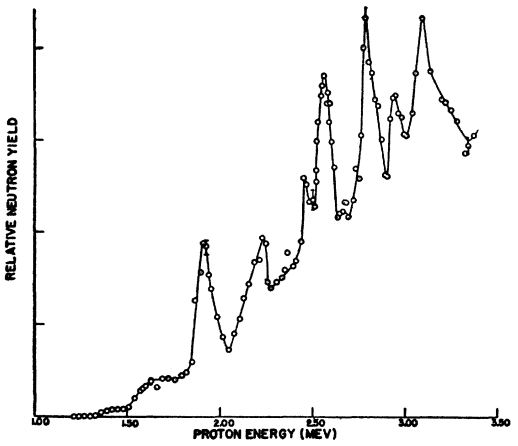

FIG. 10. Forward direction neutron yield from potassium.

mass difference. The fifth column gives this energy difference $\Delta E'$ as inferred† from the endpoints of beta-spectra.[11] There are only two cases in which serious disagreement exists. The first is for the $B^{11}-C^{11}$ pair where Townsend's beta-ray value is 23 kev higher than the p-n value. We feel that the discrepancy may be the result of a systematic error in the beta-ray measurement since Townsend's end point for the N^{13} spectra is also about 20 kev higher than the more recent measurements. The second case is the $Sc^{45}-Ti^{45}$ mass difference where the discrepancy‡ is about 270 kev and is in the wrong direction to be explained by a cascade beta-gamma-decay. No estimated uncertainty in the $Sc^{45}(p, n)Ti^{45}$ threshold was quoted by Hanson, Taschek, and Williams,[10] but it is hard to see how it could be large enough to account for the discrepancy.

For the K capturing residual nuclei and for B^9 the p-n measurement is of course the only good information available on the mass differences.

The earlier Westinghouse data[12] on Li^7, Be^9, B^{11}, and $C^{13}(p, n)$ thresholds are consistent with the present measurements if their voltage scale is normalized to the value now accepted for the $Li^7(p, n)Be^7$ threshold. The present data have, however, about a factor of ten smaller uncertainty in the threshold determinations. For the Be^9, B^{11}, and C^{13} thresholds, the error assigned (0.1 percent) is that of the absolute voltage scale. The comparison of these thresholds to the $Li^7(p, n)Be^7$ threshold as a standard can be made more precise than the absolute voltage scale is known. For all the other reactions, the yield near threshold is small enough that the selection of the extrapolated threshold is somewhat uncertain. Those assigned errors represent, therefore, a somewhat subjective estimate of this uncertainty.

Two earlier measurements of the O^{18} threshold have been reported.[13,14] Both used stacked foils technique and cyclotron accelerated protons. These measurements are unsuited for precise threshold determination.

For the vanadium reaction, Hanson, Taschek, and Williams[10] quote a threshold some 36 kev less than our observation. They do not estimate the uncertainty in

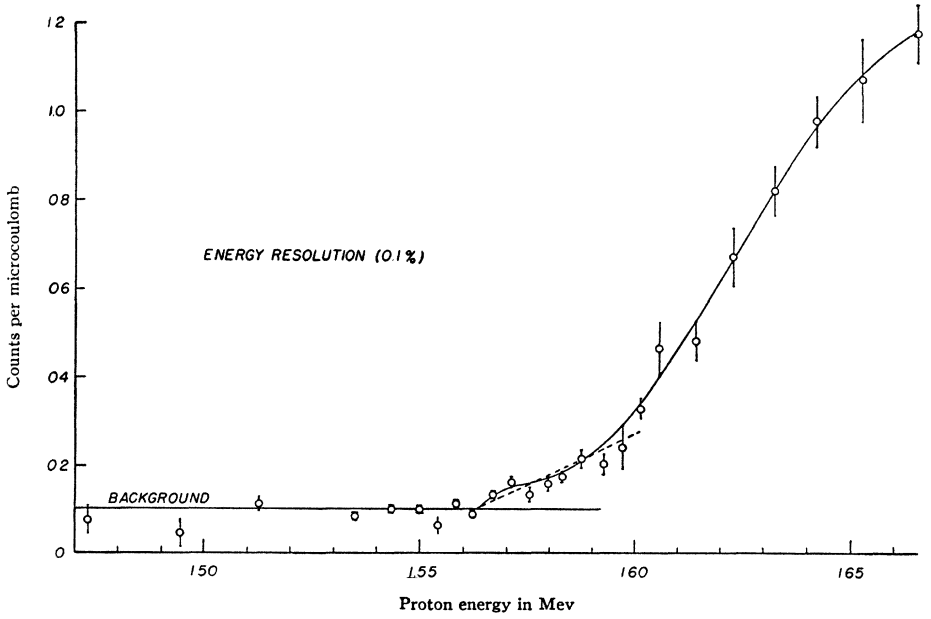

FIG. 11. Threshold data from a thick V_2O_5 target.

† For positron emitters $\Delta E' = E_{max} + 2mc^2$; for negatron emitters, $\Delta E' = -E_{max}$.

[11] Except for the H^2-2H difference which comes from mass spectroscopic data.

‡ *Note added in proof:* This discrepancy is removed by the recent work of Kubitschek (Phys. Rev. **79**, 23 (1950)) whose E_{max} from Ti^{45} corresponds to a $\Delta E' = 2.02 \pm .02$ Mev.

[12] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **58**, 1035 (1940).

[13] Dubridge, Barnes, Buck, and Strain, Phys. Rev. **53**, 447 (1938); $E_{th} = 2.56 \pm 0.04$ Mev.

[14] Blaser, Boehm, Marmier, Preiswerk, and Scherrer, Helv. Phys. Acta **22**, 598 (1949); $E_{th} = 2.5$ Mev.

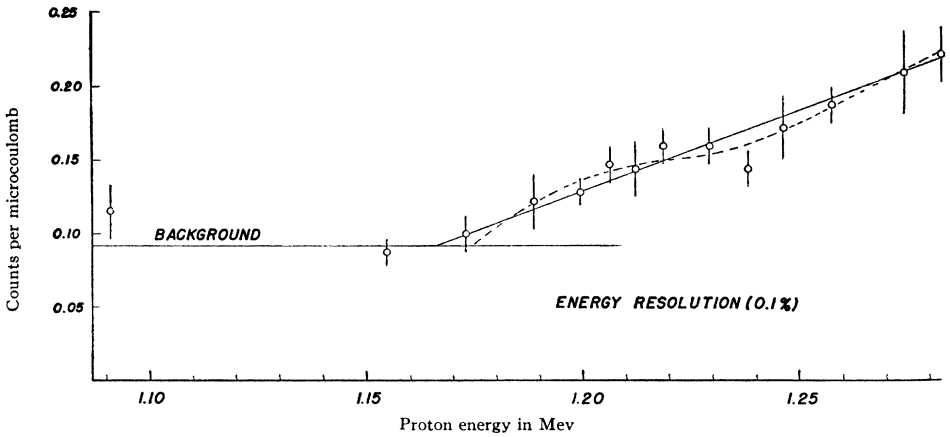

FIG. 12. Threshold data from a thick manganese target.

the result, but the published yield curve (Fig. 21, reference 10) would not appear to be in serious disagreement with our result.

The last three columns contain information useful to those contemplating these reactions as neutron sources. The neutron energy at threshold[10] (from center of mass motion) is $E_{th}/(M_1+M_2)^2$. The minimum energy monochromatic neutrons in the forward direction occur after the forward cone fills the forward hemisphere. This minimum energy is calculated in the next to the last column by setting $A_3=B_3$ (McKibben diagram notation)[10] and noting that $E_3=A_3^2+B_3^2+2A_3B_3\cos\phi=4A_3^2$ for $A_3=B_3$ and $\phi=0$.

The last column gives information which permits a calculation of the maximum neutron energy available from the reaction before the monoergic character of the neutrons is lost by possible excitation of the first excited state of the residual nucleus.

TABLE I. Summary of observed P-N thresholds for $Z\leq 25$.

Target and Product nuclei	Observed E_{th} (Mev)	$-Q$ (Mev)	ΔE (Mev)	$\Delta E'$ (Mev)	Threshold E_n (kev)	Min. E_n at 0° (kev)	Lowest excited level in Mev
H^2 2H	3.339±0.015[a]	2.225	1.442±0.010	1.442 ±0.00?[h]	371	1979	
H^3 He^3	1.019±0.001[b]	0.764	(used for $n-H$ diff.)	−0.0189±0.0005[i]	63.7	286.5	>2.5[m]
Li^7 Be^7	1.882±0.002[c]	1.646	+0.864±0.002	e_k^-	29.4	120.1	0.435[n]
Be^9 B^9	2.059±0.002	1.852	1.070±0.002	P	20.6	83.4	>1.5[o]
B^{11} C^{11}	3.015±0.003	2.762	1.980±0.003	2.003 ±0.005[j]	20.9	84.5	2.02[p]
C^{12} N^{12}	20.0±0.1[u]	18.5	17.7 ±0.1	17.6[u]	118	477	—
C^{13} N^{13}	3.236±0.003	3.003	2.221±0.003	2.222 ±0.003[k]	16.5	66.4	2.383[q]
C^{14} N^{14}	0.664±0.009[d]	0.620	−0.161±0.009	−0.156 ±0.001[k]	2.9	11.8	2.3[k]
O^{18} F^{18}	2.590±0.004	2.453	+1.671±0.004	+1.657 ±0.015[v]	7.2	28.8	
F^{19} Ne^{19}	4.18 ±0.25[e]	3.97	3.09 ±0.25	3.22[e]	10.5	42	
Na^{23} Mg^{23}	4.78 ±0.3[e]	4.58	3.80 ±0.30	3.84[e]	8.3	33	
Cl^{37} A^{37}	1.640±0.004	1.598	0.816±0.004	e_k^-	1.1	4.6	1.4[r]
A^{40} K^{40}	≤2.4(?)[f]	2.3(?)	≤1.5(?) also see ref. s	e_k^-	1.6	5.7	0.81[s]
K^{41} Ca^{41}	1.25 ±0.02	1.22	0.44 ±0.02	e_k^-	0.7	2.8	1.95[t]
Sc^{45} Ti^{45}	~2.85[g]	2.79	2.01	2.28[l,w]	1.35	5.4	
V^{51} Cr^{51}	1.562±0.006	1.532	0.750±0.006	e_k^-	0.58	2.3	
Mn^{55} Fe^{55}	1.18 ±0.01	1.16	0.38 ±0.01	e_k^-	0.38	1.5	

[a] R. V. Smith, Ph.D. thesis, Univ. of Wisconsin, 1950 and unpublished work.
[b] Taschek, Argo, Hemmendinger, and Jarvis, Phys. Rev. **76**, 325 (1949).
[c] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949); also Shoupp, Jennings, and Jones, Phys. Rev. **76**, 502 (1949).
[d] Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).
[e] White, Delsasso, Fox, and Creutz, Phys. Rev. **56**, 512 (1939).
[f] H. T. Richards and R. V. Smith, Phys. Rev. **74**, 1870 (1948).
[g] Hanson, Taschek, and Williams, Rev. Mod. Phys. **21**, 635 (1949).
[h] T. R. Roberts and A. O. Nier, Phys. Rev. **77**, 746A (1950).
[i] G. C. Hanna and B. Pontecorvo, Phys. Rev. **75**, 983 (1949).
[j] A. A. Townsend, Proc. Roy. Soc. **A177**, 357 (1940–1941).
[k] NRC Nuclear Science Series No. 5.
[l] Allen, Pool, Kurbatov, and Quill, Phys. Rev. **60**, 425 (1941).
[m] H. T. Richards and E. Hudspeth, Phys. Rev. **58**, 382 (1940).
[n] Johnson, Wilson-Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).
[o] Johnson, Ajzenberg, and Wilson-Laubenstein, Phys. Rev. **79**, 187 (1950).
[p] W. M. Gibson, Proc. Phys. Soc. Lond. **A62**, 586 (1949).
[q] D. M. Van Patter, Phys. Rev. **76**, 1264 (1949).
[r] J. C. Grosskreutz and K. B. Mather, Phys. Rev. **77**, 580 (1950).
[s] V. L. Sailor, Phys. Rev. **77**, 794 (1950).
[t] V. L. Sailor, Phys. Rev. **75**, 1836 (1949).
[u] L. W. Alvarez, Phys. Rev. **75**, 1815 (1949).
[v] Blaser, Boehm, and Marmier, Phys. Rev. **75**, 1953 (1949).
[w] *Note added in proof:* This discrepancy is removed by the recent work of Kubitschek (Phys. Rev. **79**, 23 (1950)) whose E_{max} from Ti^{45} corresponds to a $\Delta E'=2.02\pm.02$ Mev.

The $Li^7(p, n)Be^7$ still seems to be the preferred source for neutrons of energy from 120 kev to 640 kev. Above 640 kev (where the lithium neutrons lose their monoergic character) the $T(p, n)He^3$ and $C^{14}(p, n)N^{14}$ reactions seem promising for low voltage accelerators. The $B^{11}(p, n)C^{11}$ reaction might be useful where higher voltages are available. For neutron energies below 120 kev C^{14} and O^{18} targets would be attractive. Use of targets of higher Z is seriously limited by the very low neutron yields.

Assistance in data taking and in operation and maintenance of the electrostatic generator was generously contributed by Stanley Bashkin, Gerson Goldhaber, V. R. Johnson, and R. M. Williamson.

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The Disintegration of Boron by Slow Neutrons

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The total ionization produced by the Li^7 and α-particles from the $B^{10}(n, \alpha)Li^7$ reaction has been measured in an argon-boron trifluoride gas mixture, and that produced by the two particles separately with a thin boron film. Electron collection has been employed, using a fast amplifier feeding a 30-channel pulse-analyzer. The results indicate a departure from linearity in the relation between ionization and energy. Using the formula suggested by Cranshaw and Harvey in their work on natural α-emitters, values of the Q of the boron reaction have been obtained. They are 2.793 ± 0.027 Mev and 2.320 ± 0.020 Mev for the ground state and excited state transitions, in agreement with the recently published values of Tollestrup, Fowler, and Lauritsen. The branching ratio, that is the probability of the reaction going to the ground state, has been measured as 5.8 ± 0.1 percent.

I. INTRODUCTION

THIS investigation was undertaken primarily to measure the relative probabilities of the two reactions $B^{10}(n, \alpha)Li^7$ and $B^{10}(n, \alpha)Li^{7*}$. At that time (1947) the best value 1:15, due to Bøggild,[1] appeared to be limited in statistical accuracy. Moreover, the measurements on the energy release, which were summarized by Bøggild, were not in good agreement. It therefore seemed worth while to extend the scope of the experiment and make an accurate comparison of the ionizations produced by the boron reactions with that of Pu^{239} α-particles.

At first the total ionization of the Li^7 and α-particles was measured relative to that of the Pu^{239} α-particle in an ionization chamber containing boron trifluoride and argon. Later a thin boron film was used and the ionizations of the Li^7 and α-particles were measured separately, thus permitting a more reliable estimate to be made of the ionization-energy relation.

II. DESCRIPTION OF APPARATUS

The Ionization Chamber

The ionization chamber contained two plane parallel electrodes, 10 cm square and 6.6 cm apart, with a grid of parallel wires placed 1.5 cm in front of the electron collecting electrode. The wires in the grid were 0.12 mm in diameter and were spaced 0.95 mm apart. Such a grid is adequate for shielding the collector from the induced effect of the slowly moving positive ion component of the ionization.[2,3] The calibration source of Pu^{239}, deposited on a 1-cm diameter platinum disk, was mounted in the center of the negative electrode and covered with a simple collimator, a sheet of $\frac{1}{2}$-mm brass drilled with 1-mm holes. The electrodes were supported on glass insulators.

The chamber was sealed with a lead gasket so that it could be baked out (at about 200°C) in preparation for a boron trifluoride filling. The gasket was made of lead containing 1 percent of tin, an alloy which creeps much less than pure lead. High tensile steel bolts, $3\frac{1}{2}$ inches long and $\frac{1}{4}$ inch in diameter, were used to compress the gasket between heavy flanges. If short thick bolts were used the extension of the bolt for a given force on the gasket would be less, and any creep of the lead would quickly result in a loss of gasket compression.[4] A leak would then be likely to develop, particularly during the baking out procedure.

Chamber Fillings

The chamber was filled with argon (99.8 percent pure) containing 2 percent of boron trifluoride to a pressure of one atmosphere. The boron trifluoride was prepared from calcium fluoroborate by J. F. Steljes. No deteriora-

[1] J. K. Bøggild, Kgl. Danske Vid. Sels. Math.-Fys. Medd. **23**, No. 4 (1945).

[2] Bunemann, Cranshaw, and Harvey, Can. J. Research **A27**, 191 (1949).

[3] T. E. Cranshaw and J. A. Harvey, Can. J. Research **A26**, 243 (1948).

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