Excited States in B^{10} and Be^8†

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(Received June 16, 1954)

A new technique for detecting neutron thresholds by using a slow neutron counter and a conventional long counter is described. By means of this technique, neutron thresholds from the deuteron bombardment of Li^7 have been studied at energies from 0.4 Mev to 4.7 Mev. Thresholds were observed at energies of 1.34, 2.18, 3.37, 3.6, and 4.07 Mev. These thresholds indicate excitation levels in Be^8 at 16.06, 16.72, 17.65, 17.8, and 18.19 Mev.

By the same method, excited states of B^{10} from the $Be^9(d,n)B^{10}$ reaction were found at 4.78, 5.11, 5.17, 5.93, 6.06, 6.16, 6.43, and 6.57 Mev.

INTRODUCTION

PRECISE energy determinations of excited states of nuclei have been made by using magnetic and electrostatic analyzers, which measure the energies of charged particles such as protons, deuterons, and alpha particles. Similar measurements of the energies of fast neutrons with comparable accuracy are not possible. However, in experiments measuring the energies of "neutron thresholds," Bonner and Butler[1] were able to obtain precise measurements of Q values in a number of reactions of the (p,n) and (d,n) type. Extension of this method to other reactions depends on the sensitivity of detection of a relatively small number of "threshold neutrons" with energies of from 5 to 50 kev in the presence of neutrons with higher energies.

APPARATUS

Considerable improvements in the techniques have been possible in the new Nuclear Research Laboratory where a 6-Mev Van de Graaff accelerator, built by the High Voltage Engineering Corporation, has recently been installed. Improvements have been made in two ways. In our old laboratory the target which was bombarded by protons or deuterons was only 4 feet above a thick concrete floor which moderated the fast neutrons and scattered these back to our "threshold detector," which was a BF_3 proportional counter surrounded by approximately 4 cm of paraffin. A smaller thickness of paraffin gives a detector with a better discrimination for kev-neutrons relative to Mev-neutrons, but is only useful if relatively few scattered neutrons reach the counter. Our new laboratory was designed so that the target is 4 feet above a floor of $\frac{1}{4}$-in. aluminum which is relatively transparent to fast neutrons. There is a pit 8 feet deep below the aluminum floor and so the target is 12 feet from an effective neutron moderator. Another improvement is derived from placing the target 20 feet away from our analyzing magnet. Some neutrons are always made when the diatomic and triatomic beams strike materials, especially when deuterons are accelerated. The inverse square law is especially helpful in reducing the effects of these background neutrons. Figure 1 shows the experimental arrangement which has been used. A paraffin layer $1\frac{3}{4}$ in. long and $\frac{3}{8}$ in. thick covers the middle portion of a BF_3 counter which has a diameter of 1 in. This threshold counter C_1 is placed 2 in. from the target and so subtends a cone of half-angle 24°. A second counter C_2 is placed 14 in. from the target and subtends approximately the same solid angle as C_1. This counter is the inner part of the usual "long counter" which has about equal efficiency for detecting neutrons of all energies from 0 to 5 Mev. The ratio of the number of counts in C_1 and C_2, taken at the same time, gives a measure of the relative number of slow neutrons to total neutrons. This ratio is independent of the beam current and of the uniformity of the target which is being bombarded.

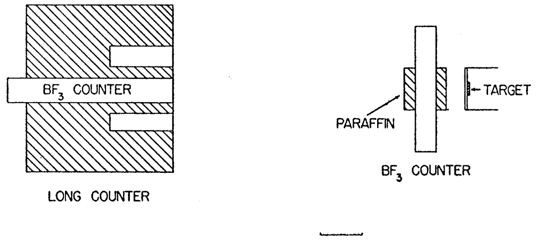

FIG. 1. Experimental arrangement of conventional long counter and BF_3 counter for neutron-threshold detection.

RESULTS

Experiments have been carried out with this technique when a thin lithium target is bombarded by protons. The results are shown in Fig. 2. The threshold for the nuclear reaction $Li^7(p,n)Be^7$ is at 1.883 Mev. When protons with energies lower than this strike the lithium target no neutrons are produced and the counting rate in counters C_1 and C_2 is very small. Above this threshold the counting rates in both counters increase rapidly; the ratio of the counting rates C_1/C_2 shows a threshold at 1.883 Mev and decreases as the bombarding energy is increased. The counting ratio decreases to $\frac{1}{2}$ its maximum rate when the proton energy is increased to 50 kev above the threshold. The ratio continues to drop smoothly until it is $\frac{1}{10}$ the threshold value when

† Supported in part by the U. S. Atomic Energy Commission.
[1] T. W. Bonner and J. W. Butler, Phys. Rev. 83, 1091 (1951).

the neutrons have energies of 0.6 Mev. The second curve shown in Fig. 2 is that of the counting rate in the long counter C_2 as a function of proton energy. The long-counter yield curve shows the neutron threshold at 1.883 Mev followed by a decrease in the neutron flux through this counter as the cone of neutrons opens to 180°. At a proton energy of 2.3 Mev, the known resonance caused by an excited state in the compound nucleus Be^8 is observed with the long counter. However, the ratio curve does not show any irregularity because of this resonance. This fact makes it possible to differentiate between neutron thresholds and resonances.

$Be^9(d,n)B^{10*}$

Experiments with the reaction $Be^9(d,n)B^{10*}$ have been carried out by means of the same techniques as described above. The evaporated beryllium target was 10 kev thick for 2-Mev deuterons. Threshold neutrons were investigated when the deuteron beam was increased from 0.45 Mev to 5.4 Mev. Data obtained below 3 Mev are shown in Fig. 3. Neutron thresholds observed are indicated in Fig. 3 at *A*, *B*, *C*, *D*, *E*, and *F*.

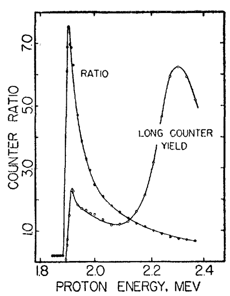

FIG. 2. Neutrons from the reaction $Li^7(p,n)Be^{7*}$. The solid circles give the ratio of the number of slow neutrons to the total number of neutrons from the reaction as a function of proton energy. The open circles give the long-counter yield in arbitrary units as a function of proton energy.

There is also a small effect at *H* caused by a "wide threshold" and a weak threshold at *G*.

Table I lists the thresholds shown in Fig. 3, the deuteron-bombarding energy at each threshold, the calculated *Q* values, the corresponding energies of the excited states of B^{10}, and the observed half-width. The last column of Table I lists excited states of B^{10} from measurements of recoil protons in photographic plates obtained by Ajzenberg.[2] Data taken with deuteron energies of 3–5.4 Mev indicate no additional thresholds. The states at 5.11, 5.17, and 5.93 Mev were obtained by Bonner and Butler.[1] The results reported here are in agreement with the results of Ajzenberg,[2] except that we do not observe the weak lines at 5.58 and 6.77 Mev and with higher-energy resolution we have resolved the doublet at 5.11 and 5.17 Mev, and the triplet at 5.93, 6.06, and 6.16 Mev.

All of the states of B^{10*} above 4.45 Mev can break up with α-particle emission, and so the widths of these states will be much greater than in the case of the lower states where γ emission only takes place. The widths of the states will be expected to increase with excitation

[2] Fay Ajzenberg, Phys. Rev. **82**, 43 (1951); **88**, 298 (1952).

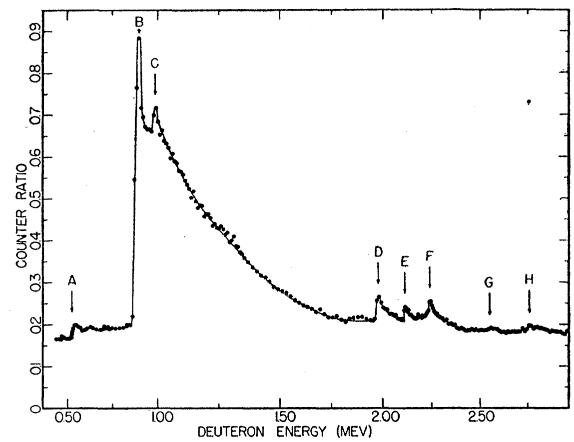

FIG. 3. Neutrons from the reaction $Be^9(d,n)B^{10*}$. The curve gives the ratio of the number of slow neutrons to the total number of neutrons from the reaction as a function of deuteron energy.

because of the increased penetrability of the α particle. Widths will also depend on the angular momentum carried away by the α particles and the isotopic spin. The states near 6-Mev excitation are unstable for α emission by $\sim$1.5 Mev and so would be expected to have widths $\sim$100 kev if *s* α-particle decay is possible. Since their widths are less than 10 kev, this would indicate that the *J* values of these states are probably $J=2$ or greater.

An energy-level diagram for B^{10} is given in Fig. 4. Spin, parity, and isotopic spin assignments are shown where known. The two levels at 5.11 and 5.17 Mev appear to form a doublet, the splitting between them being only 60 kev while the distance to the next levels above and below are 760 kev and 330 kev, respectively; the three levels at 5.93, 6.06, and 6.16 Mev appear to form a triplet with separations of 130 kev and 100 kev. Figure 3 also shows that the intensities of the two lines in the doublet at 5.11 Mev are nearly equal, also the three lines of the triplet at 6.06 Mev appears to have nearly equal intensities in the forward yield of low-

TABLE I. Neutron thresholds—excited states of B^{10}. Energies of excited states are based on a Q_0 value of 4.360 Mev.

Thresholds	Deuteron energy (Mev)	*Q* value Mev	Excitation energy B^{10} Mev	Level width Mev	Excitation energy B^{10} Ajzenberg[a] Mev
A	0.52	−0.42	4.78	<0.010	4.78
B	0.92	−0.75	5.11	<0.010	
					5.14
C	0.99	−0.81	5.17	<0.010	
					5.58
D	1.92	−1.57	5.93	<0.010	5.93
E	2.08	−1.70	6.06	<0.010	
					6.12
F	2.20	−1.80	6.16	<0.020	
G	2.53	−2.07	6.43		6.38
H	2.70	−2.21	6.57	~0.030	6.57
					6.77

[a] See reference 2.

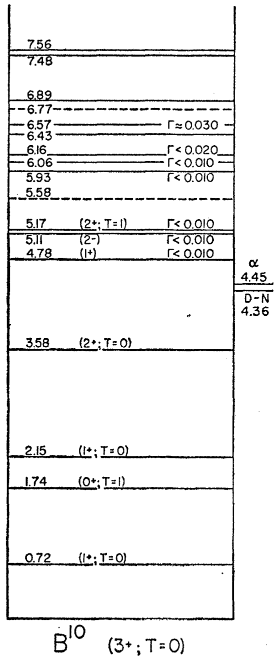

FIG. 4. Energy level diagram of B^{10}.

energy neutrons. Inglis[3] has pointed out that the two lines of the doublet may correspond to the two orientations of an s-proton spin relative to another j or J_p; however, the possibility seems to be at variance with the recent results of Wilkinson and Jones[4] which indicate that the 5.11-Mev level is 2(−) and the 5.17-Mev level is 2(+) and $T=1$. Both levels would be expected to have odd parity and J's of 1 and 2 when produced by s deuterons according to the suggestion of Inglis. The group of levels at 5.93, 6.06, and 6.16 Mev seem more likely to be physically significant instead of an accidental juxtaposition than does the doublet.

The small relative yield of threshold neutrons from the 4.78-Mev state is expected if it has even parity, since s deuterons will be predominant at a bombarding energy of 0.5 Mev, and then s-neutron emission is forbidden. The fact that the ratio curve does not fall off rapidly above the 0.52-Mev threshold indicates that p-neutron emission is involved.

$Li^7(d,n)Be^{8*}$

Experiments with neutrons from the (d,n) reaction on normal lithium were carried out using metallic lithium evaporated onto the target in the vacuum system of the accelerator. From threshold measurements with the (p,n) reaction, the lithium target was found to be 20-kev thick at 2 Mev. Under similar conditions to the experiments already described, the counting rates in the two counters C_1 and C_2 were observed as deuteron energy was increased from 0.45 Mev to 4.8 Mev. Figure 5 shows the results of the yield of neutrons in the long counter and the ratio of the counts in the two counters. The known resonances in the yield of neutrons at deuteron energies 0.7 and 1.0 Mev were observed but are not shown. Above 1.5 Mev there is evidence for a broad resonance at 2.0 Mev, and another broad resonance at 3.2 Mev which correspond to wide states in Be^9 at ~18.2 Mev and ~19.6 Mev.

The ratio curve is flat from 0.45 to 0.80 Mev and then rises slowly until it becomes flat again at 1.5 Mev. This shape of curve is that expected from a broad state in Be^{8*}; in this case the yield of threshold neutrons should follow the shape of the energy state. The maximum number of threshold neutrons from this level in Be^8 occurs at A. Another rise in the ratio curve begins at 1.7 Mev and reaches a peak value at B. The third rise in the curve at C indicates a neutron threshold at the same energy as an intense threshold in oxygen, so it seems probable that it is caused by a small amount

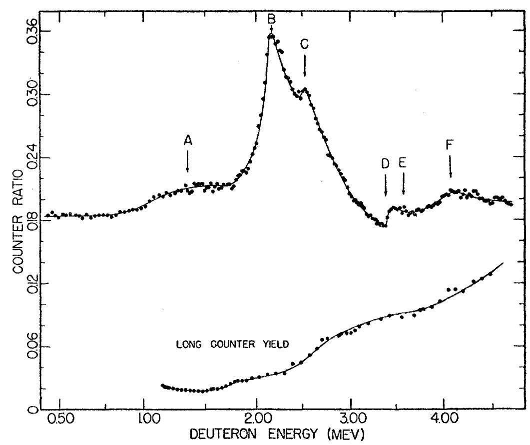

FIG. 5. Neutrons from the reaction $Li^7(d,n)Be^{8*}$. The upper curve gives the ratio of the number of slow neutrons to the total number of neutrons from the reaction as a function of deuteron energy. The lower curve gives the long-counter yield in arbitrary units as a function of deuteron energy.

of oxygen on the target. Other thresholds are indicated at D, E, and F in Fig. 5.

Table II lists the thresholds shown in Fig. 5, the deuteron-bombarding energy at each threshold, the calculated Q values, the corresponding energies of the excited states of Be^8, and the observed half-width of each level.

All of the thresholds found are wide except that at 3.37 Mev, which has a width less than 20 kev. The Q value obtained for this narrow threshold agrees well with the known level[5] in Be^8 at 17.63 Mev (width 12 kev) made by 440-kev protons on Li^7. The width of this neutron threshold is less than the target thickness of 20 kev, and so it seems very likely that the two levels are the same. The level at 18.19 Mev has also been observed[6] in elastic scattering of protons on Li^7; a level

[3] D. R. Inglis, Revs. Modern Phys. 25, 390 (1953).
[4] D. H. Wilkinson and G. A. Jones, Phys. Rev. 91, 1575 (1953).
[5] T. W. Bonner and J. E. Evans, Phys. Rev. 73, 666 (1948).
[6] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. 82, 159 (1951).

width of 0.17 Mev was found. The state at 16.72 Mev can only emit a γ ray or break up into two α particles; the observed width of 0.19 Mev indicates α emission. The α particles have a total energy of 16.72 Mev and the level in Be^8 would be expected to show a width of $\sim$1 Mev unless the isotopic spin selection rule made the α emission considerably slower. A level in Be^8 with isotopic spin $T=1$ is expected[7] near 16.7 Mev. It seems likely that the level at 16.72 Mev with a width of 0.19 Mev is the first $T=1$ state in Be^8. From the 0.6-Mev width of the level at 16.06 Mev, it seems probable that this level is a $T=0$ state with $J=2+$ or $4+$; this follows from the fact that the $J=2+$ level at 19.9 Mev has a width of 1 Mev.

Wilkins and Goward[8] have presented evidence for states in Be^8 from the photo reactions $C^{12}(\gamma,3\alpha)$ which were observed in nuclear emulsions. They reported levels in Be^8 at 16.8±0.2 Mev and 17.6±0.2 Mev with widths <0.3 Mev. From the angular distribution of the α particles, they were able to conclude that the 16.8-Mev state has $J=2$. It seems likely that the level which we observed at 16.72±0.01 Mev is the same as that observed by Wilkins and Goward. It seems improbable that the level that we observe at 17.65 Mev is the same as reported by Wilkins and Goward at 17.6 Mev. They suggest that this level is $J=4+$ and $T=1$. Such a state would be expected to be narrower than the 16.72-Mev level ($J=2+$, $T=1$), but a width less than 20 kev is unexpected. The threshold at D (17.65-Mev state) is sharp on the low-energy side but does not drop off as fast as expected on the high-energy side. The best explanation is that the threshold at D is a doublet including a sharp level at 17.65 Mev and a wider one at 17.8 Mev (E) with a width of approximately 0.1 Mev.

TABLE II. Neutron thresholds—excited states Be^8. Energies of excited states are based on a Q_0 value of 15.02 Mev.

Threshold	Deuteron energy Mev	Q value Mev	Excitation energy Be^8 Mev	Level width Mev
A	1.34	−1.04	16.06	0.6
B	2.18	−1.70	16.72	0.19
C	2.5	···	Oxygen contamination	
D	3.37	−2.63	17.65	<0.02
E	3.6	−2.8	17.8	0.1
F	4.07	−3.17	18.19	0.17

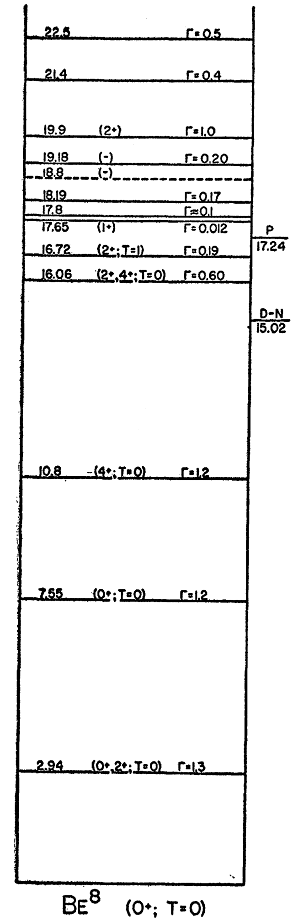

FIG. 6. Energy level diagram of Be^8.

An energy-level diagram for Be^8 is given in Fig. 6. A number of the previously reported levels between 3 and 7 Mev are omitted. Evidence for the non-existence of several of these levels comes from several sources.[9] There is still some question about levels at 4.05 and 5.3 Mev.[10] The experimental levels fit in very well with the intermediate coupling calculations of Inglis, except for the unpredicted levels at 7.75 and 16.06 Mev.

[7] T. Lauritsen, Ann. Revs. Nuclear Sci. **1**, 67 (1952).
[8] J. J. Wilkins and F. K. Goward, Proc. Phys. Soc. (London) **66**, 661 (1953).
[9] R. F. Sinclair, Phys. Rev. **93**, 1082 (1954); R. Malm and D. R. Inglis, Phys. Rev. **92**, 1326 (1953); Kunz, Moak, and Good, Phys. Rev. **91**, 676 (1953); C. C. Trail and C. H. Johnson, Phys. Rev. **95**, 640A (1954); F. E. Steigert and M. B. Sampson, Phys. Rev. **92**, 660 (1953).
[10] E. W. Titterton, Phys. Rev. **94**, 206 (1954).