Study of the Reactions $T^3(p,n)He^3$, $Li^7(p,n)Be^7$, $Be^9(p,n)B^9$, and $F^{19}(p,n)Ne^{19}$†

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A counter ratio study has been made of the (p,n) reactions on T^3, Li^7, Be^9, and F^{19}. The ground state threshold energy for the reaction $F^{19}(p,n)Ne^{19}$ was found to be 4.235±0.005 Mev. Other neutron thresholds were observed which indicated excited states in Be^7 at 0.434±0.004 Mev, in B^9 at 2.326±0.006 Mev and in Ne^{19} at 0.241±0.004 and 0.280±0.004 Mev. A broad maximum in the yield of slow neutrons from the bombardment of Be^9 was observed which could be due to the three-body breakup, $Be^9(p,pn)Be^8$, or to a broad, even parity state in B^9 at 1.4 Mev. The cross sections for the reactions $Be^9(p,n)B^9$, $B^{11}(p,n)C^{11}$, $C^{13}(p,n)N^{13}$, and $F^{19}(p,n)Ne^{19}$ were measured.

INTRODUCTION

THE accurate measurement of nuclear energy levels has been shown possible by using the "counter ratio" technique[1-3] for detecting the emission of slow neutrons near threshold in (p,n) and (d,n) reactions. This technique employs two paraffin-moderated BF_3 counters, one which is preferentially sensitive to low energy neutrons ("slow counter"), and one which is almost energy insensitive ("modified long counter"). A measure of the number of slow neutrons emitted in a reaction is obtained by observing, as a function of bombarding energy, the ratio of the counting rate in the slow counter to that in the modified long counter. Sharp increases in the counter ratio indicate the emission of slow neutrons leaving the residual nucleus in one of its energy states. Since the sensitivity of the modified long counter decreases rapidly for neutron energies less than about 0.3 Mev,[3] the rise in the counter ratio at a neutron threshold is enhanced. By arranging the two counters so that they subtend approximately the same solid angle at the target, irregularities in the ratio due to resonances for the production of neutrons are essentially eliminated.[1]

Since all (p,n) reactions on stable target nuclei have negative Q-values, it is possible to study with the counter ratio technique the low-lying level structure of the residual nuclei in such reactions. For reactions on odd-A light nuclei, these levels should be mirror to those of the target nuclei, and the latter have been investigated with precision inelastic scattering techniques. Therefore, the counter ratio method allows an accurate determination of nuclear energy levels which may be used in the comparison of mirror excited states. This technique has been applied to the (p,n) reactions on T^3, Be^9, Li^7, and F^{19} in order to investigate the level structures of He^3, B^9, Be^7, and Ne^{19}.

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[1] T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).
[2] Marion, Brugger, and Bonner, this issue [Phys. Rev. **100**, 46 (1955)].
[3] Brugger, Bonner, and Marion, this issue [Phys. Rev. **100**, 84 (1955)].

Since magnetic analysis of the charged-particle beam is used with the Rice Institute 6-Mev Van de Graaff accelerator, the bombarding energy is determined by measuring the field strength and the radius of curvature of the particle orbit. A nuclear resonance absorption magnetometer is used to measure the field strength, and the radius of curvature is determined by measuring the field strength at a number of well-known (p,n) thresholds. A detailed description of the technique used for precisely measuring the bombarding energy has been given previously.[2]

REACTION $T^3(p,n)He^3$

A counter ratio investigation was made of the reaction $T^3(p,n)He^3$, and the results are presented in Fig. 1. Since there are no known or expected low-lying levels in the He^3 nucleus, the ratio curve should be a smoothly decreasing function of the bombarding energy, and any irregularities that appear are probably characteristic of the counter ratio method and not of the He^3 nucleus. The target used in this experiment consisted of tritium gas adsorbed in a layer of Zr metal which had been evaporated onto a tungsten backing. This target was approximately 40 kev thick at a proton energy of 1 Mev. The counter ratio rises sharply at the threshold and then decreases smoothly until an energy of approximately 3.73 Mev is reached. At this bombarding energy, neutrons from the $T^3(p,n)He^3$ reaction have an energy

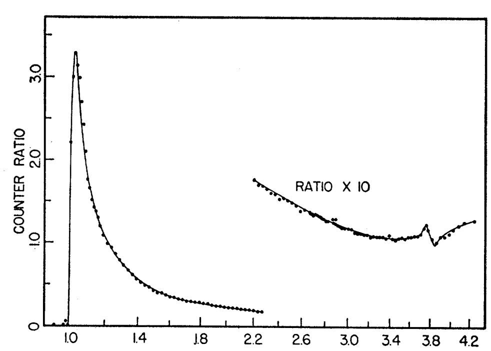

FIG. 1. $T^3(p,n)He^3$. Counter ratio as a function of bombarding energy.

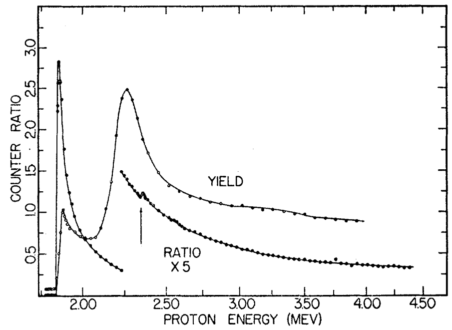

FIG. 2. $Li^7(p,n)Be^7$. Counter ratio and yield of neutrons in the forward direction as a function of bombarding energy.

of 2.95 Mev. This neutron energy corresponds to that for a resonance in the neutron total cross section for carbon.[4] Since the paraffin of the slow counter is interposed between the target and the modified long counter, the number of neutrons reaching the modified long counter will be reduced because of the greater scattering in carbon, and the counter ratio will rise. Therefore, the shape of the ratio curve will be approximately the same as the shape of the total cross section resonance. In the $T^3(p,n)He^3$ reaction, this is, indeed, seen to be the case. An additional resonance in this energy region, due to 2.08-Mev neutrons[4] ($E_p=2.80$ Mev), was not observed due to its very narrow width.

REACTION $Li^7(p,n)Be^7$

Since the yield of neutrons near threshold is quite large, and since the threshold energy is easily accessible with most present-day Van de Graaff accelerators, the threshold for the reaction $Li^7(p,n)Be^7$ has long been used as an energy calibration point for proton energies near 2 Mev. Consequently, the threshold energy has been measured quite accurately. The currently accepted value is 1.8811 ± 0.0005 Mev.[5] As was stated earlier,[2] this threshold was used as the primary calibration in these experiments.

The results obtained by the counter ratio technique in the bombardment of a 20-kev LiF target are presented in Fig. 2. The ratio rises sharply at the ground-state threshold and then decreases for bombarding energies up to the maximum of 4.4 Mev. The pronounced resonance in the yield of neutrons, which occurs at a bombarding energy of 2.30 Mev, has no effect on the ratio curve. The only significant departure from a smooth decrease in the ratio is the slight rise at a bombarding energy of 2.38 Mev, indicated by the arrow in Fig. 2.

The first excited state of Be^7 is known from several reactions to have an energy of 0.430 Mev.[6] Since a bombarding energy of 2.38 Mev should correspond to the threshold for neutron emission to this state, the energy region near 2.4 Mev was investigated more closely and under conditions slightly different from the normal counter geometry.[1–3] First, the slow counter was moved as close to the target as was possible, and the counter ratio was measured as a function of bombarding energy from 2.330 to 2.450 Mev. The results are shown in Curve "*A*" of Fig. 3, in which the experimental points are plotted on an expanded scale with a false zero. With points taken at an energy interval of approximately 2 kev, a significant increase occurs at a bombarding energy of 2.379 ± 0.003 Mev. After rising for about 20 kev (target thickness), the ratio decreases in the expected manner.

In an attempt to improve the sensitivity to the neutrons from this weak threshold, this energy region was re-investigated after covering the exposed ends of the slow counter with thin brass tubing onto which had been painted a $\frac{1}{16}$-inch layer of boron, enriched to 96 percent B^{10}. Commercial "Nitroseal" was used as an adhesive for the boron. It was anticipated that the presence of the B^{10} would decrease the background due to the slow, "room" neutrons, and thereby enhance the effect of the threshold. The results are shown in Curve "*B*" of Fig. 3, where, again, the points are plotted on an expanded scale. The threshold occurs at an energy of 2.377 ± 0.003 Mev, but the amount of rise is only slightly greater than in the former case. This indicates that "room" neutrons are of little importance at this bombarding energy, even in the investigation of such weak thresholds.

The average of these two runs gives a threshold energy of 2.378 ± 0.004 Mev and a Q-value of -2.079 ± 0.004 Mev for this state. Since the ground state Q-value is -1.645 ± 0.001 Mev,[5] the first excited state of Be^7 has an energy of 0.434 ± 0.004 Mev, in excellent agreement with the previous measurements.

By measuring the increase in the counting rate in the slow counter at the ground state threshold and at the threshold for the emission of neutrons leaving Be^7 in the first excited state, the intensity of the first excited state threshold was found to be 1.8 ± 0.6 percent of that of the ground-state threshold. This is a slightly lower figure than was obtained by Willard and Preston,[7] who found a value of 3% using a similar method.

The relative intensities of the neutron groups emitted to the ground and first excited states of Be^7 have been measured by a number of investigators in the energy range from 2.5 to 4.4 Mev.[8,9] Above 3 Mev, the average intensity of the group emitted to the 0.43-Mev state is about 10 percent of that of the ground state group. At 2.52 Mev, the intensity of the

[4] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).
[5] Jones, Douglas, McEllistrem, and Richards, Phys. Rev. **94**, 947 (1954).
[6] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[7] H. B. Willard and W. M. Preston, Phys. Rev. **81**, 480 (1951).
[8] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
[9] R. Batchelor, Proc. Phys. Soc. (London) **A68**, 452 (1955).

low energy group at 0° is 2.8% of the intensity of the high energy group.[9] At a bombarding energy of 2.40 Mev, the ratio of the total cross sections of the two neutron groups was calculated to be $0.18\pm0.06\%$, by correcting for the difference in counter sensitivity[3] for the two groups and for the fact that the low energy group at this bombarding energy is emitted entirely into a forward solid angle less than that subtended by the counter.

The threshold corresponding to the 0.434-Mev state of Be^7 occurs while the system is under the influence of the 2.30-Mev resonance. The fact that neutron emission to this state is extremely weak is consistent with the recent analysis of Adair,[10] which indicates that the 2.30-Mev resonance is due to a 3^+ state in Be^8 at 19.2 Mev which is superimposed on a "background" of $(1,2)^-$ states. Since the ground states of Li^7 and Be^7 are $3/2^-$ and since the first excited state of Be^7 is $\frac{1}{2}^-$, protons with $l=1$ are most likely to form the 3^+ compound nucleus state, and neutrons emitted from this level to the first excited state of Be^7 must have $l=3$, while p-wave neutron emission to the ground state is possible. Since the yield of f-wave neutrons vanishes with zero slope at threshold, the number of these neutrons would not become appreciable until a considerable energy above threshold was reached. The fact that some neutrons are emitted to the first excited state near threshold is probably due to the background influence of the $(1,2)^-$ states, postulated by Adair, which would allow s-wave neutron emission near threshold from the 1^- states. The ratio curve rises to peak value above this threshold in approximately target thickness, indicating s-wave emission. Emission of p-wave neutrons would cause the rise to continue for a considerably larger energy interval, and d- and higher-wave emission would not occur near threshold with a measurable probability.

The yield curve of Fig. 2, as measured by the modified long counter at 0°, shows the rise at the ground state threshold caused by the emission of all of the neutrons into the forward cone. The subsequent decrease results from the opening of the cone to 180°. In addition to the well-known resonance at 2.30 Mev, there is some indication of a broad resonance at a bombarding energy of 3.2 Mev. This effect has also been observed by Bair *et al.*[11] It is possible that this broad resonance is at least partially responsible for the "background influence" on the yield near the 2.30-Mev resonance, mentioned earlier.

REACTION $Be^9(p,n)B^9$

The level structure of the Be^9 nucleus has been investigated with considerable accuracy up to excitations of a few Mev by observing inelastic proton

[10] R. K. Adair, Phys. Rev. **96**, 709 (1954).
[11] Bair, Willard, Snyder, Hahn, Kington, and Green, Phys. Rev. **85**, 946 (1952).

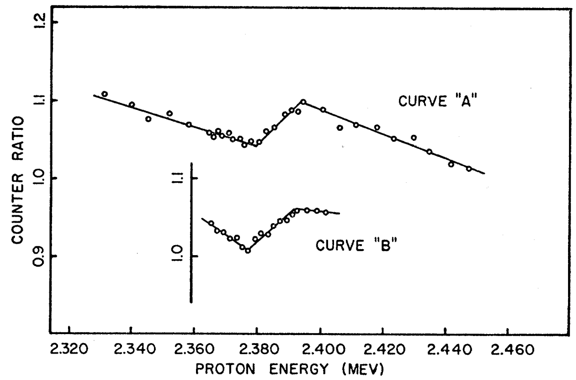

FIG. 3. $Li^7(p,n)Be^7$. Counter ratio as a function of bombarding energy in the region of the threshold corresponding to the first excited state of Be^7.

scattering.[6,12] For excitations of less than 3 Mev, the existence of only one state, at 2.432 ± 0.004 Mev,[12] has been definitely established. The possibility of additional states at 1.8 and 3.1 Mev has been reported.[12–16] Measurements by Ajzenberg and Buechner[17] on the reaction $Be^9(p,n)B^9$, using photographic plates, indicate a level in the mirror nucleus, B^9, at 2.37 ± 0.04 Mev. No narrow states of lower excitation were found. A broad continuum of neutrons was observed,[17,18] attributed to the three-body breakup, $Be^9(p,pn)Be^8$, but the possibility of a broad state was not excluded.

In order to obtain a more accurate value for the 2.37-Mev state and to investigate further the possibility of additional states, the reaction $Be^9(p,n)B^9$ was investigated with the counter ratio technique. An evaporated beryllium target, about 8 kev thick at a proton energy of 2 Mev, was used in the experiment. The counter ratio and the yield of neutrons in the forward direction were measured for proton energies from threshold to 5.8 Mev. The results are presented in Fig. 4. In addition to the ground state threshold, only one sharp threshold, at 4.645 ± 0.005 Mev, was found. A rather broad rise in the ratio was observed to be centered about a bombarding energy of 3.6 Mev. These neutrons probably correspond to the continuous distributions previously found.[17,18] The threshold energies, Q-values, and excitation energies in B^9 are summarized in Table I.

The measurements made in this experiment do not allow an unambiguous interpretation of the broad maximum at 3.6 Mev. Slow neutrons from the three-body breakup could account for this effect, as could a broad state in B^9. The observed width of the maximum

[12] Gossett, Phillips, Schiffer, and Windham, this issue [Phys. Rev. **100**, 203 (1955)].
[13] C. J. Mullin and E. Guth, Phys. Rev. **76**, 682 (1949).
[14] Moak, Good, and Kunz, Phys. Rev. **96**, 1363 (1954).
[15] Almqvist, Allen, and Bigham, Phys. Rev. **99**, 631(A) (1955).
[16] L. L. Lee and D. R. Inglis, Phys. Rev. **99**, 96 (1955).
[17] F. Ajzenberg and W. W. Buechner, Phys. Rev. **91**, 674 (1953).
[18] Johnson, Ajzenberg, and Laubenstein, Phys. Rev. **79**, 187 (1950).

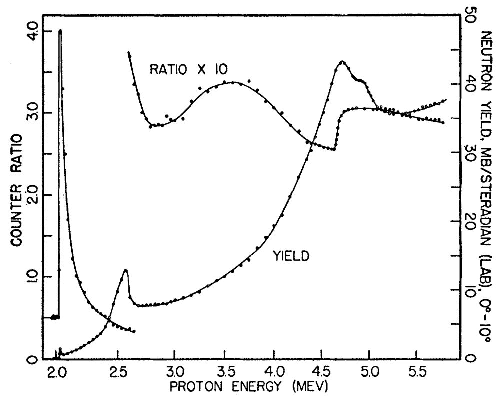

FIG. 4. $Be^9(p,n)B^9$. Counter ratio and yield of neutrons in the forward direction as a function of bombarding energy.

is approximately 1 Mev; the corresponding "state" would have the same width. Such a state in B^9 would be unstable to the emission of a proton to the ground state of Be^8, and a width of 1 Mev would indicate decay by s-wave proton emission.[19] This would imply even parity for the state, contrary to the systematics of the nuclei in the $p_{\frac{3}{2}}$ subshell, which indicate that all of these nuclei with unpaired $p_{\frac{3}{2}}$ particles have odd parity for the first excited state. An odd parity state at this energy that could decay by p-wave proton emission would have a width of approximately 0.3 Mev,[19] much narrower than the observed width of the maximum in the ratio curve. If the observed effect is due primarily to a broad state in B^9 and not to the three-body breakup, then this state probably has even parity and violates the shell model prediction.

An investigation has recently been made of the level structure of the mirror nucleus, Be^9, in this energy region. In a precision measurement of the protons inelastically scattered from Be^9, Gossett *et al.*[12] observed an asymmetric group of protons corresponding to an excitation in Be^9 of about 1.8 Mev. These data were not conclusive as to whether the protons arose from the three-body breakup or from a broad state in Be^9 which decays by s-wave neutron emission. A Be^9 state that decays by s-wave neutron emission must also have even parity.

Since unambiguous interpretations of these sets of data are not possible, it must be concluded that the observed effects are due either to the three-body breakup or to even-parity states in the mirror nuclei, Be^9 and B^9.

The threshold at 4.645 Mev rises to peak value in approximately 70 kev. Since the target thickness is considerably less than 70 kev, this slow rise is indicative either of level width or of the emission of threshold neutrons with $l=1$. The fact that the mirror state in Be^9 is quite narrow is strong evidence against the possibility of level width. Gossett *et al.*[12] report a width of $\leqslant 1$ kev for the Be^9 level. This state is known to decay mainly by neutron emission[20] and to have large spin, probably 5/2, 7/2, or 9/2, and odd parity.[12,21] The spin predicted by Inglis[22] is 5/2. The spin, parity, and level width should be the same for the B^9 state. Furthermore, the ratio curve does not decrease rapidly above threshold as it does above the ground state threshold. This implies that the yield of neutrons emitted to the 2.326-Mev state of B^9 is continuing to rise for a considerably larger energy interval above threshold than is to be expected for s-wave emission. This indicates that p-wave neutrons are largely responsible for the rise, and that the ratio is prevented from decreasing by the continued rise in the yield of neutrons with $l \geqslant 1$.

The 4.645-Mev threshold occurs near the resonance energy of 4.7 Mev, as is indicated in Fig. 4. The compound nucleus state involved is the 10.8-Mev level in B^{10}. If it is assumed that the larger part of the neutrons emitted near threshold have $l=1$ and that the B^9 state has spin 5/2, 7/2, or 9/2 and odd parity, then the resulting possible compound nucleus state has $J \leqslant 6^+$, and the incoming protons have odd angular momentum.

In an attempt to locate any higher energy state in B^9 which might be the analog of the reported 3.1-Mev state in Be^9, the ratio curve was extended to a bombarding energy of 5.8 Mev. No indication of additional thresholds was observed. This bombarding energy corresponds to an excitation energy in B^9 of 3.4 Mev and should be sufficiently high to include the region in which the threshold would be expected to occur. The fact that no threshold was observed does not exclude the possibility of the existence of a state or states, since there could be selection rules imposed by the compound nucleus states which would greatly reduce the probability of neutron emission near threshold. It may be stated, however, that no levels exist in this energy region for which the intensity of neutron emission near threshold is greater than about 0.2 of that for the 4.645-Mev threshold.

The yield curve of Fig. 4 shows the well-known resonance at a bombarding energy of 2.56 ± 0.02 Mev and, superposed on a general rise, another broad

TABLE I. Neutron thresholds in the reaction $Be^9(p,n)B^9$.

Threshold energy (Mev) Present work	Threshold energy (Mev) Other measurement	Q-value (Mev)	Excitation energy in B^9 (Mev) Present work	Excitation energy in B^9 (Mev) Other measurement
2.060 ± 0.003	2.059 ± 0.002[a]	-1.852 ± 0.002[a]	0	0
3.6(?)		-3.25(?)	$1.4(?)\Gamma \approx 1$ Mev	
4.645 ± 0.005		-4.178 ± 0.005	2.326 ± 0.006	2.37 ± 0.04[b]

[a] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[b] See reference 17.

[19] R. F. Christy and R. Latter, Revs. Modern Phys. **20**, 185 (1948).

[20] G. A. Dissanaike and J. O. Newton, Proc. Phys. Soc. (London) **A65**, 675 (1952).

[21] F. L. Ribe and J. D. Seagrave, Phys. Rev. **94**, 934 (1954).

[22] D. R. Inglis, Revs. Modern Phys. **27**, 76 (1955).

maximum at 4.68±0.03 Mev. These resonances have been observed by Hahn *et al.*,[23] who obtained a resonance energy of 4.72±0.01 Mev for the latter peak. A close examination of the energy region near 5.0 Mev revealed the presence of a weak satellite to the 4.68-Mev resonance, located at a bombarding energy of 4.94±0.03 Mev.

REACTION $F^{19}(p,n)Ne^{19}$

The low-lying level structure of the F^{19} nucleus has been studied with great care by many investigators. The energies, spins, and parities of the first two excited states have been measured with considerable accuracy.[6] In order to establish the corresponding level structure of the mirror nucleus, Ne^{19}, about which no information had been previously obtained, the reaction $F^{19}(p,n)Ne^{19}$ was investigated with the counter ratio technique.

An evaporated AlF_3 target, which was about 7 kev thick at a proton energy of 4.5 Mev, was used in the experiment. The counter ratio and the forward yield of neutrons were measured from threshold to 5.9 Mev. The results are presented in Fig. 5. The ground-state threshold energy obtained was 4.235 ±0.005 Mev, in excellent agreement with that determined by Kington *et al.*,[24] who found a value of 4.240 ±0.008 Mev. In addition, two thresholds, corresponding to the first two excited states of Ne^{19}, were observed at 4.489±0.005 and 4.530±0.005 Mev. Both of these thresholds rise to peak value in an energy interval approximately equal to target thickness. The excitation energies in Ne^{19} are 0.241 and 0.280 Mev, respectively. Table II summarizes the threshold energies, Q-values, and excitation energies in Ne^{19}.

Since the first two excited states of F^{19} have energies of 0.110 and 0.197 Mev,[6] there is a considerable upward energy shift of the low-lying level structure between the mirror nuclei, F^{19} and Ne^{19}, with the nucleus of higher Z having levels of greater energy. In the light mirror nuclei ($A \leqslant 17$), there is no known case in which such an upward shift occurs for the first excited states. In the p-shell mirror nuclei, no such shift occurs even for the next two excited states within the accuracy to which these energy levels have been measured. Besides the case of F^{19} and Ne^{19}, it is perhaps significant that the only other well established departure from the rule that the energy levels of the mirror nucleus of higher Z lie lower also occurs in the d-shell. The second and third excited states of F^{17} have energies of 3.10 and 3.86 Mev, while the corresponding levels of O^{17} have energies of 3.06 and 3.85 Mev. Of the five well-known, low-lying pairs of levels in the d-shell mirror nuclei ($A=17$, 19), four exhibit the upward energy shift.

TABLE II. Neutron thresholds in the reaction $F^{19}(p,n)Ne^{19}$.

Threshold energy (Mev) Present work	Other measurement	Q-value (Mev)	Excitation energy in Ne^{19} (Mev)
4.235±0.005	4.240±0.008[a]	−4.022±0.005	0
4.489±0.005		−4.263±0.005	0.241±0.004[b]
4.530±0.005		−4.302±0.005	0.280±0.004[b]

[a] See reference 24.
[b] The error assignment is somewhat less than that determined from the errors in the Q-values since the energy of the excited state was obtained directly from an energy difference measurement.

[23] Hahn, Snyder, Willard, Bair, Klema, Kington, and Green, Phys. Rev. **85**, 934 (1952).
[24] Kington, Bair, Cohn, and Willard, Phys. Rev. **99**, 0000 (1955).

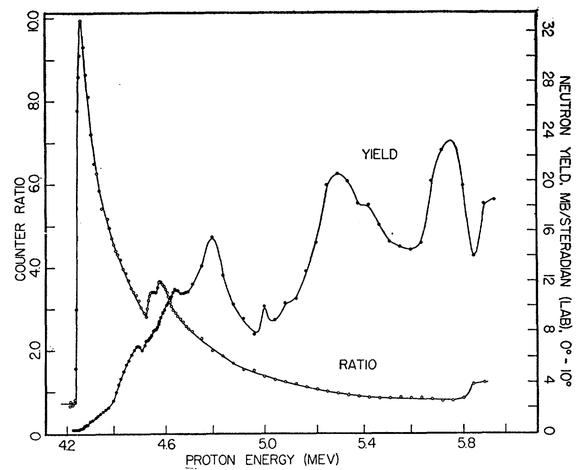

FIG. 5. $F^{19}(p,n)Ne^{19}$. Counter ratio and yield of neutrons in the forward direction as a function of bombarding energy, obtained with an AlF_3 target.

It was anticipated that the levels in Ne^{19} corresponding to the 1.35-Mev state and the reported state at 0.9 Mev in F^{19} might be observed, unless they were also shifted upward or were extremely weak near threshold. No indication of a threshold of intensity greater than 0.2 of that of the 4.489-Mev threshold was observed up to a bombarding energy of 5.8 Mev, corresponding to an excitation of 1.5 Mev in Ne^{19}.

At an energy of 5.82 Mev, an intense threshold was observed, due to the aluminum content of the AlF_3 target. In order to obtain a more accurate value for the threshold energy, this region was re-investigated using a thick aluminum target. The counting rate in the slow counter as a function of bombarding energy is shown in Fig. 6. The extrapolated point at which the yield rises above background is 5.816±0.008 Mev. This threshold energy is to be compared with the value of 5.792±0.010 Mev, obtained by Kington *et al.*[24]

The yield of neutrons in the forward direction from the reaction $F^{19}(p,n)Ne^{19}$, shown in Fig. 5, indicates several resonances. All of those resonances found below a bombarding energy of 5.2 Mev had been observed previously.[25] Since the yield curve was not taken with a very thin target, some of the resonances previously reported were not clearly resolved. Above 5.2 Mev,

[25] Willard, Bair, Kington, Hahn, Snyder, and Green, Phys. Rev. **85**, 849 (1952).

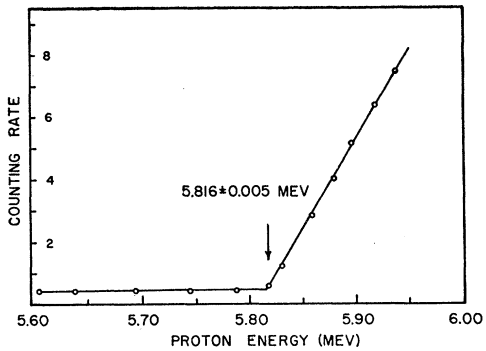

FIG. 6. $Al^{27}(p,n)Si^{27}$. Ground-state threshold obtained with a thick Al target. The counting rate in the slow counter is given as a function of bombarding energy.

strong resonances at 5.3 and 5.75 Mev and some indication of a resonance at 5.4 Mev were found. The excitation function for this reaction agrees well with that obtained by Blaser *et al.*,[26] who measured the Ne^{19} activity in a stacked foil experiment, except that the maximum at 5.75 Mev is much more pronounced in the present work.

MEASUREMENT OF ABSOLUTE CROSS SECTIONS

In order to obtain absolute cross sections for the production of neutrons in the proton bombardment of Be^9 and F^{19}, it was necessary to calibrate the relative yield curves that were obtained in the counter ratio studies. A Be^9 target of 171 $\mu g/cm^2$ and an AlF_3 target of 447 $\mu g/cm^2$ were prepared by techniques previously described.[3] The cross sections were determined by comparing the counting rates in a long counter[27] from the proton bombardment of these targets with that from a weighted LiF target, since the cross section for the reaction $Li^7(p,n)$ is well known.[28] In each case a bombarding energy was chosen so that the ground-state neutrons had an energy of approximately 0.6 Mev. In this manner, variations in the counter sensitivity with neutron energy were minimized.[3] At a bombarding energy of 2.52 Mev, the $Be^9(p,n)$ cross section was measured to be 11 mb/sterad, and at 4.74 Mev, the $F^{19}(p,n)$ cross section was 13 mb/sterad. Figures 4 and 5 show the cross sections for the emission of neutrons in these reactions into the forward cone of half-angle 10° in units of millibarns per steradian in the laboratory system. No corrections have been applied for the variations of the sensitivity of the modified long counter with neutron energy. The sensitivity of this counter[3] decreases rapidly for neutron energies below about 0.3 Mev, and, consequently, the measured cross sections near threshold are low by as much as a factor of 2. For the neutron energies encountered in these experiments, the counter sensitivity does not change appreciably above 0.3 Mev.

[26] Blaser, Boehm, Marmier, and Scherrer, Helv. Phys. Acta **24**, 465 (1951).
[27] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[28] R. F. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

TABLE III. Absolute cross sections for the reactions $B^{11}(p,n)$ and $C^{13}(p,n)$.

Reaction	Target thickness ($\mu g/cm^2$)	Proton energy (Mev)	Cross section (mb/sterad, lab system, 0°–10°)
$B^{11}(p,n)$	46	3.46	15
$C^{13}(p,n)$	190	3.70	6.7

REACTIONS $B^{11}(p,n)C^{11}$ AND $C^{13}(p,n)N^{13}$

A counter ratio study was made of the reactions $B^{11}(p,n)C^{11}$ and $C^{13}(p,n)N^{13}$ in an effort to locate neutron thresholds corresponding to the first excited states of the residual nuclei. These thresholds should have been observed at bombarding energies of 5.09 and 5.79 Mev, respectively. At these high energies, an increasing background of slow neutrons made difficult the detection of weak thresholds and the expected thresholds were not observed. Since thresholds with reasonable intensities could have been detected, it is not clear why these first excited state thresholds should be so weak that they were lost in the background. Excitation curves for the $B^{11}(p,n)$ reaction[26,29] and for the $C^{13}(p,n)$ reaction[26,30] have been given previously and they are not repeated here since good agreement was found with the earlier work. Absolute cross section measurements were made for these reactions with the techniques described above. The results are summarized in Table III.

[29] Bair, Kington, and Willard, quoted in reference 6.
[30] Bair, Kington, and Willard, Phys. Rev. **90**, 575 (1953).