and as shown in Fig. 4, were taken from the literature.[3,8,13] Our own absorption measurements of these energies were, within experimental uncertainty, in complete accord with these values. However, we do not, on the basis of our measurements, take any stand on the question of which of the two isomeric states of Sn^{125} lies lower in energy. With the quoted energies, it appears that the $h_{11/2}$ state lies lower by about 0.03 Mev; it has been pointed out[18] that this may represent a singular case of an $h_{11/2}$ ground state. However, the value of 2.35 Mev for the 9.7-day beta is the average of two independent values which disagree by 0.04 Mev, and the only spectrometer measurement of the 9.4-minute beta[13] is from a different source than either of these. Consequently, we do not believe that the question of which is the ground state can be regarded as settled.

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(p,n) Reactions in Mn^{55}, Co^{59}, Zn^{67}, and Zn^{68}†

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The counter ratio technique has been applied to the study of (p,n) thresholds in Mn^{55}, Co^{59}, Zn^{68}, and Zn^{67}. The ground state thresholds were found at proton energies of 1.895±0.005 Mev for Co^{59}, 3.762±0.005 Mev for Zn^{68}, and 1.805±0.005 Mev for Zn^{67}. Thresholds were found corresponding to excited states in Fe^{55} at 0.924, 1.327, 2.16, 2.554, 2.92, and 3.76 Mev; in Ni^{59} at 0.325, 1.195, 1.776, 2.551, 3.043, 3.543, and 3.340 Mev; in Ga^{68} at 0.188, 0.342, 0.574, and 0.848 Mev; and in Ga^{67} at 0.357, 0.85, and 1.54 Mev. Absolute cross sections were measured for neutrons at 0° to the incident beam.

INTRODUCTION

THE study of (p,n) reactions in elements of atomic number greater than 20 is more complicated than in the lighter elements because of the usual presence of several isotopes for each element and the smaller cross sections for the reactions in the 2- to 4-Mev range of bombarding energy. Cobalt and manganese are ideal for (p,n) investigations since they occur normally as single isotope elements.

Enriched samples of Zn^{67} and Zn^{68} are available from electromagnetic separation at Oak Ridge allowing separate study of these isotopes. The ground state thresholds for these elements lie in the lower portion of the proton energy range of the 6-Mev Rice Institute Van de Graaff accelerator. This allows, by means of the counter ratio technique, the study of the various excited states of the residual nucleus as well as the ground state thresholds.

The method of detection of neutron thresholds by the counter ratio method has been described in a number of articles.[1–3] This method utilizes two paraffin-moderated BF_3 proportional counters; the one, called the modified long counter, has a fairly uniform sensitivity for neutrons with energies above 200 kev and the other counter, called the slow counter, has its strongest sensitivity for neutrons of less than 400 kev. The yields shown in the present paper are determined by the modified long counter in its position behind the slow counter and are not corrected for variation of its sensitivity with neutron energy. The geometrical arrangement of the counters and the counter efficiencies are similar to those given by Brugger, *et al.*[2]

When one uses this arrangement, the ratio of the counts in the slow counter to that in the modified long counter will indicate the presence of thresholds in the production of neutrons. When there is considerable yield of high-energy neutrons below the energy of a particular neutron threshold, the counter ratio rises to a maximum value above each threshold in an energy increment roughly equal to target thickness provided that the slow-neutron yield shows no strong resonances in this energy increment. In the absence of resonances, the rise of the ratio is due to the increasing number of slow neutrons relative to the high-energy neutron yield and continues until the whole target is contributing to the slow-neutron yield. When the proton energy is increased further, the ratio will in general decrease because of the increase in the energy of the threshold neutrons.

If there is no appreciable yield of high-energy neutrons below a threshold, then the ratio will rise to its value immediately above the threshold.

Resonances may occur which have strong effects on the counter ratio for proton energies of less than a few hundred kev above an excited state threshold. A rough estimate of this effect can be obtained from the variation of counter efficiencies with neutron energy.[2] Consider the case of a residual nucleus whose first excited state $(5/2^-)$ is one Mev above the ground state $(3/2^-)$ and a resonance in the compound nucleus that is 1^-. At this resonance, neutrons with $l=0$ are emitted when the nucleus is left in the ground state but $l=2$ neutrons are required to leave the nucleus in the first excited state.

† Supported in part by the U. S. Atomic Energy Commission.
[1] T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).
[2] Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955).
[3] Marion, Brugger, and Bonner, Phys. Rev. **100**, 46 (1955).

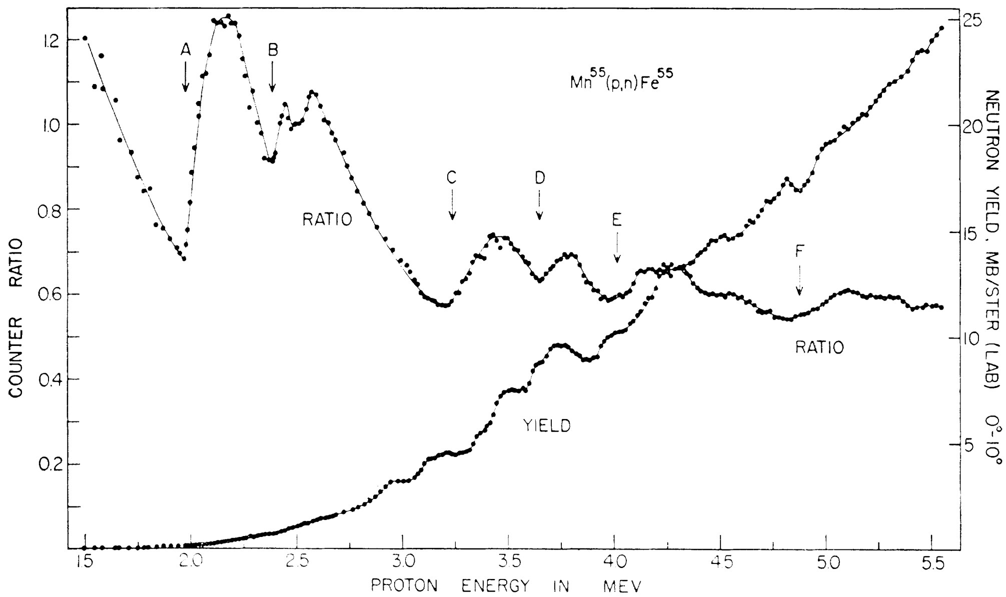

FIG. 1. $Mn^{55}(p,n)$-Fe^{55}. The thresholds are marked by labeled arrows.

Near threshold the number of these neutrons with $l=2$ will be very small and so the number of fast neutrons might be doubled at the resonance with no increase in the number of threshold neutrons. If such a resonance comes at 100 kev above the first excited state threshold, the counter ratio will decrease by approximately 30%. On the other hand, if this resonance occurs 500 kev above the threshold, the effect on the ratio will be less than 4%.

Experiments carried out with targets that are thick compared to the spacing between resonances increase the number of neutrons which are not due to the resonance in question and thus decreases its relative effect.

Nevertheless, pronounced decreases in the counter ratio can occur at a resonance and the subsequent rise in the counter ratio above the resonance may be mistaken for a threshold.

Because of these anomalies in the counter ratio which are not due to thresholds, an effort has been made throughout this work to be conservative in assigning the thresholds. Questionable effects in the ratio will not be listed as thresholds but will be discussed in the text as anomalies.

The energy calibration of the beam-analyzing magnet is accomplished by means of a proton and lithium resonance magnetometer and the conventional electronics. The $Li^7(p,n)Be^7$ threshold served as the primary standard for the calibration.[4] A correction to the calibration was applied at higher energies because of saturation effects. The correction was derived by checking the calibration at higher energies against several well-known thresholds.[3]

[4] A. H. Wapstra, Physica **21**, 367 (1955). Proton energy at threshold: 1882.5±0.9 kev.

CROSS SECTIONS

Cross sections were obtained in the case of Co^{59}, Zn^{67}, and Zn^{68} by comparison to the $Li^7(p,n)Be^7$ cross section[5] at equal neutron energies to avoid having to know the exact counter efficiency variation with neutron energy.

The lithium targets used were in the form of weighted LiF evaporated on 2-mil pure aluminum blanks. To reduce the chance of error, at least two different LiF targets were used for each comparison. The comparisons were made at proton energies of 2.18, 1.95, and 3.92 Mev for Co^{59}, Zn^{67}, and Zn^{68}, respectively, and at these energies the cross sections were found to be 0.074, 0.025, and 1.65 mb/sterad, respectively, at 0° to the beam of protons. These cross sections are believed to be accurate to about 30%. The cross sections noted on the figures are less accurate because the yields have not been corrected for the variation of counter efficiency with neutron energy. This correction would be impossible to apply without knowledge of the percentage of neutrons going to the various excited levels. Thus, a cross section read off one of the figures is accurate to only about 50%.

Because of the low yield involved, the cross section for $Mn^{55}(p,n)Fe^{55}$ had to be checked at a bombarding energy of 1.97 Mev where two neutron groups were present. The approximate energy of the two groups were 900 kev and 500 kev. Monoenergetic 630-kev neutrons from $Li^7(p,n)Be^7$ were used for cross-section comparison, and since the efficiency of the modified long counter does not change materially in this energy range, no additional errors were introduced by the two groups of neutrons. Thus, for Mn^{55} the cross section of 0.15

[5] R. F. Taschek and A. Hemmindinger, Phys. Rev. **74**, 373 (1948).

mb/sterad at 1.97 Mev is approximately of the same accuracy as the other cross sections.

All cross sections given are averaged values from 0° to 10° in the laboratory system and represent the averaged values of the true cross sections over target thickness immediately below the comparison proton energies.

$Mn^{55}(p,n)Fe^{55}$

Initial difficulties were encountered in making thick manganese targets by evaporation. It was later found that aluminum blanks, sanded with No. 320 emery paper, would accept the manganese without flaking. This was either due to the removal of the thin oxide layer or to the roughness of the surface.

Figure 1 shows the ratio and yield obtained with a target of 2.1 mg/cm^2 which corresponds to a thickness of approximately 175 kev for 2.0-Mev protons. Even with a target of this thickness, several resonances in the yield can be noted. Owing to the small yield at low energies, the data were not extended below 1.5 Mev. Thus, the ground state threshold and possibly an excited state threshold were missed.[6] Table I presents a list of thresholds observed, the calculated Q values, and the excited levels in Ni^{59}. Since the ground state threshold was not observed in the present investigation, all excitation energies are given relative to the ground state Q value of 1.015±0.003 Mev as measured by Johnson.[7]

Some anomalous effects can be seen in the ratio curve of Fig. 1. Threshold A rises for 150 kev which agrees with the known target thickness at this energy. Threshold B, however, rises for 60 kev and is then followed by a dip in the ratio at 2.496 Mev. Experiments with a target approximately $\frac{1}{3}$ as thick, showed a dip which is much more pronounced. However, since the dip is associated with several resonances in the yield and since the ratio above B has not risen for target thickness before the anomalous effect, the anomaly at 2.496 Mev is attributed to resonance effects. Stelson and Preston,[6] using nuclear emulsion plates to measure proton recoil energies, reported level B to be 60 kev wider than level A and suggested the possibility of a doublet for B. The present results do not prove the existence of such a doublet but cannot rule out this possibility.

Threshold C rises for 200 kev which is somewhat larger than the 140-kev target thickness at this energy. This rise might be caused by a delayed rise in the slow-neutron yield due to high-angular-momentum slow neutrons.

Thresholds E and F have indications of resonance dips immediately below threshold at 3.97 Mev and 4.8 Mev, respectively. This possibility introduced a larger error in choosing the energy at which the threshold occurs. Thresholds A, B, and C all agree within quoted errors to the excited levels observed by Stelson and Preston.[6]

TABLE I. Neutron thresholds in the reaction $Mn^{55}(p,n)Fe^{55}$.

	Threshold energy (Mev)	Q (Mev)	Fe^{55*} (Mev)
		-1.015 ± 0.003^a	
A	1.975±0.010	−1.939	0.924^b
B	2.385±0.015	−2.342	1.327
C	3.24 ±0.03	−3.18	2.17
D	3.635±0.015	−3.569	2.554
E	4.01 ±0.04	−3.94	2.92
F	4.87 ±0.04	−4.78	3.76

[a] See reference 7.
[b] This is only the lowest level measured. It is possibly the second excited level.

There is a small anomaly in the ratio at 4.44 Mev which stays flat for target thickness. This could possibly be attributed to a threshold, but since it is close to a resonance and is not prominent, the effect is not listed as a threshold.

No level in the present work corresponds to the 1.84-Mev excited Fe^{55} level reported by Caird and Mitchell,[8] who examined the positron decay of Co^{55}. Other levels which they report at 0.935, 1.41, and 2.17 Mev roughly correspond to ones observed here.

$Co^{59}(p,n)Ni^{59}$

The Co^{59} target was normal cobalt electroplated from a colbalt chloride solution buffered with boric acid onto a tungsten blank which had been cleaned in boiling potassium hydroxide. The cobalt was evenly electroplated so that, after finishing the threshold investigation, the foil was peeled from the tungsten backing and weighed on a quartz spring balance and found to be 1.6 mg/cm^2, which corresponds to a thickness of approximately 120 kev for 2.0-Mev protons.

The ratio and yield for $Co^{59}(p,n)Ni^{59}$ are shown in Fig. 2. Many resonances appear in the yield. Table II presents the thresholds observed. The ground state threshold of 1.895±0.005 Mev is in agreement with the value given by McCue and Preston[9] of 1.889±0.003 Mev.

Anomalies in the ratio, which might be interpreted as thresholds, occur immediately following thresholds C, D, E, and F. However, since these effects follow so soon after thresholds and therefore are probably connected with resonances, they cannot be regarded as thresholds on the basis of present data. The ratio effect at G is chosen as a threshold since it occurs 300 kev above threshold F and is a relatively large effect considering that it occurs where the ratio would be dropping normally. The ratio effect at H is chosen as a threshold since if we considered it a resonance effect the ratio would rise for three times target thickness above

[6] P. H. Stelson and W. M. Preston, Phys. Rev. 82, 655 (1951).
[7] Private communication from C. H. Johnson correcting the original report by C. C. Trail and C. H. Johnson, Phys. Rev. 91, 474(A) (1953).
[8] R. S. Caird and A. C. G. Mitchell, Phys. Rev. 94, 412 (1954).
[9] J. J. G. McCue and W. M. Preston, Phys. Rev. 84, 384 (1951).

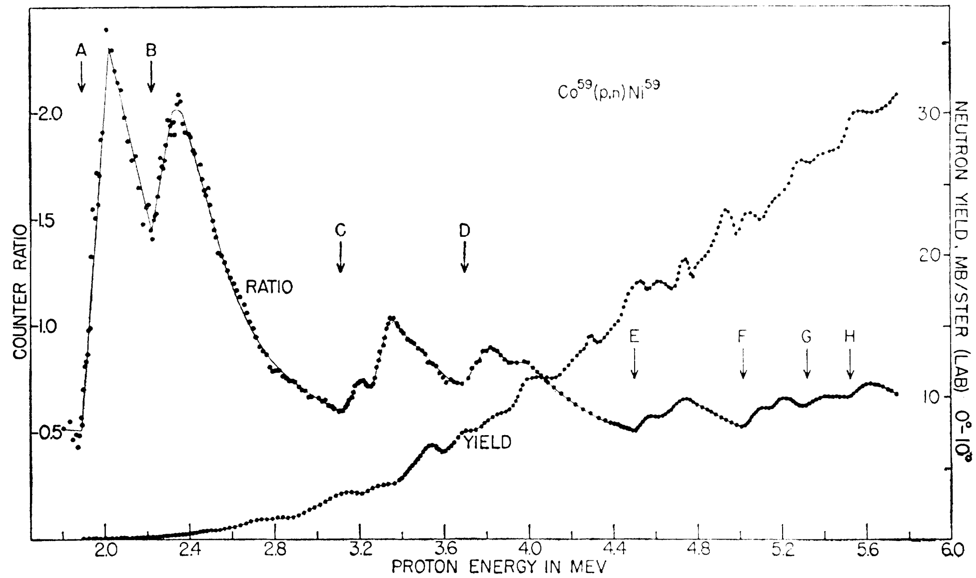

FIG. 2. $Co^{59}(p,n)$-Ni^{59}. The thresholds are marked by labeled arrows. See in text concerning thresholds G and H.

threshold G. There is a definite possibility that either effect G or H is not due to a threshold. There must be at least one threshold, however, to explain the fact that the ratio remains high for such a long energy interval above threshold F. The levels in Ni^{59} at 0.325, 1.195, and 1.776 Mev agree with the results of Pratt[10] who studied the $Ni^{58}(d,p)Ni^{59}$ reaction.

Thresholds C, D, F, and G give levels in Ni^{59} which agree within the experimental errors to levels obtained from the $Ni(n,\gamma)$ data of Kinsey and Bartholomew,[11] if one assumes that γ rays of energy 7.817, 7.22, 5.99, and 5.70 Mev are due to neutron capture in Ni^{58}.

The present results are in agreement with threshold work from 1.8 to 5.0 Mev performed by Butler, Dunning, and Bondelid,[12] although interpretation is different. The anomalies in the ratio curves above thresholds C, D, and E of the present work are not listed as thresholds while Butler *et al.*,[12] have designated these effects as thresholds.

TABLE II. Neutron thresholds in the reaction $Co^{59}(p,n)Ni^{59}$.

	Threshold energy (Mev)	Q (Mev)	Ni^{59*} (Mev)
A	1.895±0.005	−1.863	0
B	2.225±0.015	−2.188	0.325
C	3.110±0.010	−3.058	1.195
D	3.701±0.010	−3.639	1.776
E	4.489±0.015	−4.414	2.551
F	4.990±0.010	−4.906	3.043
G	5.292±0.015	−5.203	3.340
H	5.499±0.015	−5.406	3.543

Zn(*p*,*n*)Ga

Enriched samples of Zn^{68} and Zn^{67} were obtained in the form of zinc oxide by loan from the Isotopes Division of the Oak Ridge National Laboratory. One sample had a composition (weight percent) of 93.9% Zn^{68} and 0.4% Zn^{67}, while the other sample had a composition of 8.1% Zn^{68} and 56% Zn^{67}. The remainder of the isotopes present to an appreciable extent were Zn^{64} and Zn^{66} whose (p,n) ground state thresholds of 8.1±0.5 Mev[13] and 6.05±0.05 Mev,[14] respectively, are beyond the range of the present investigations.

Because of the small amounts of zinc oxide available, several methods of target making were investigated by using normal zinc. The low boiling point of zinc made reduction and evaporation of the metal quite inefficient. Electroplating was found to be more efficient and to produce satisfactory targets.

Some targets were made on aluminum blanks and weighed on a quartz balance. Those made on tungsten backings were more uniform and were used. The weights used for the Zn^{67} and Zn^{68} targets were obtained by assuming the same weight as for weighed targets made on aluminum blanks under identical conditions.

TABLE III. Neutron thresholds in the reaction $Zn^{68}(p,n)Ga^{68}$.

	Threshold energy (Mev)	Q (Mev)	Ga^{68*} (Mev)
A	3.762±0.005	−3.707	0
B	3.953±0.006	−3.895	0.188
C	4.109±0.008	−4.049	0.342
D	4.345±0.012	−4.281	0.574
E	4.623±0.010	−4.555	0.848

[10] W. W. Pratt, Phys. Rev. **95**, 1517 (1954).
[11] B. B. Kinsey and G. A. Bartholomew, Phys. Rev **89**, 375 (1953)
[12] Butler, Dunning, and Bondelid (private communication).
[13] B. L. Cohen, Phys. Rev. **91**, 74 (1953).
[14] Blaser, Boehm, Marmier, and Peaslee, Helv. Phys. Acta **24**, 3, 441 (1951).

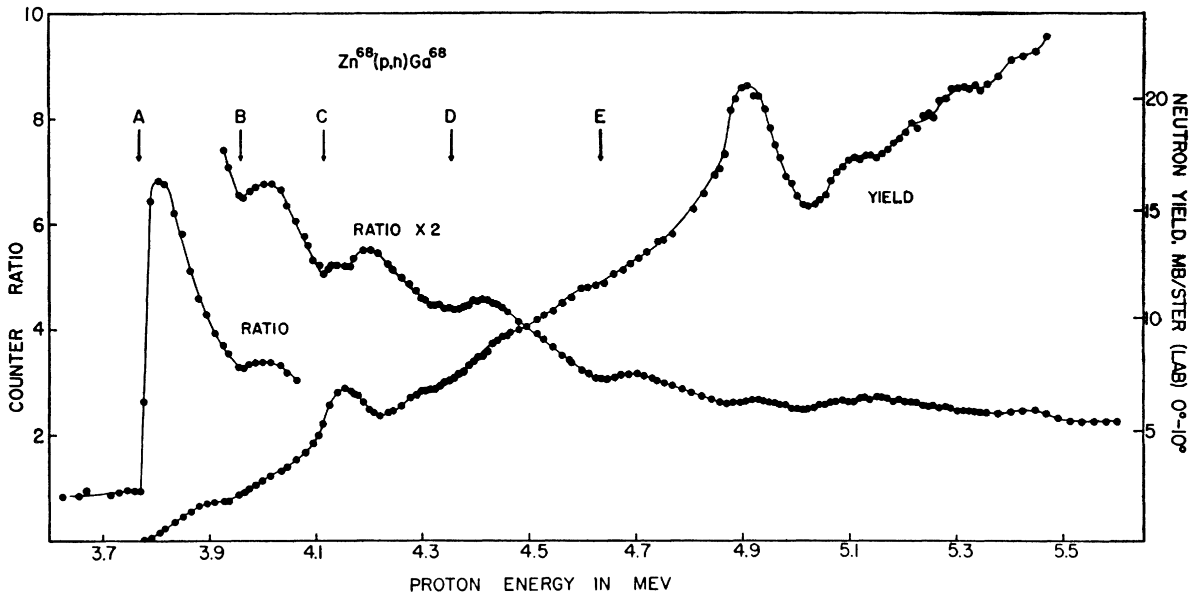

FIG. 3. $Zn^{68}(p,n)Ga^{68}$. The thresholds are marked by labeled arrows.

$Zn^{68}(p,n)Ga^{68}$

The ratio and yield for a 1.6-mg/cm^2 Zn^{68} enriched target is shown in Fig. 3. This weight corresponds to a thickness of approximately 90 kev for 3.7-Mev protons. The data extend from 3.6 Mev, which is below the $Zn^{68}(p,n)Ga^{68}$ ground state threshold, to 5.6 Mev where the effects due to new thresholds are already becoming quite small. The region from 3.6 Mev to 5.05 Mev was also examined with a normal zinc target (results not shown). There was a one-to-one correspondence between the thresholds observed with the normal zinc target in this region and the Zn^{68} thresholds. The two strong resonances which appear in the Zn^{68} yield at 4.15 Mev and 4.92 Mev also appear in the normal zinc data.

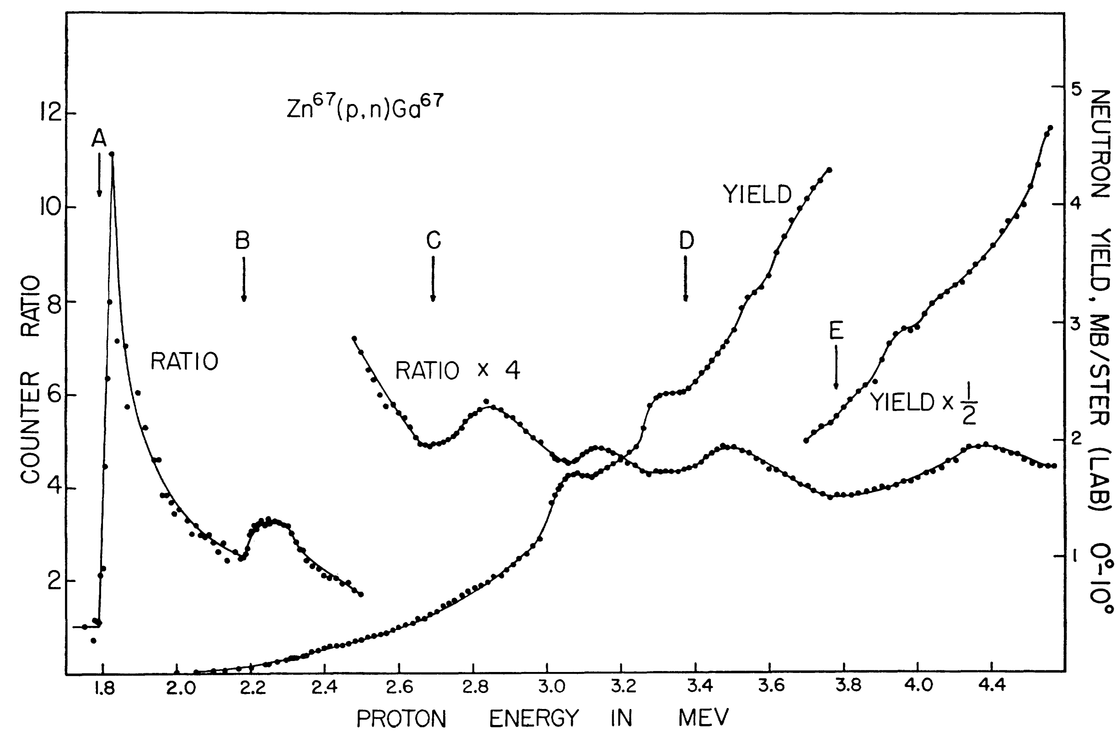

FIG. 4. $Zn^{67}(p,n)Ga^{67}$. The thresholds are marked by labeled arrows.

TABLE IV. Neutron thresholds in the reaction $Zn^{67}(p,n)Ga^{67}$.

Threshold energy (Mev)	Q (Mev)	Ga^{67*} (Mev)
A 1.805±0.005	−1.778	0
B 2.167±0.010	−2.135	0.357
C 2.67 ±0.02	−2.63	0.85
D 3.37 ±0.02	−3.32	1.54
E Zn^{68}	...	...

The thresholds observed in $Zn^{68}(p,n)Ga^{68}$ are presented in Table III.

The ground state threshold rises quite rapidly due to the smallness of the background in comparison to the neutron yield slightly above threshold. This ground state threshold of 3.762±0.005 Mev, which represents an average of three runs, is slightly higher than 3.749±0.006 Mev as measured by Brugger *et al.*[2] The first excited state at 188±8 kev is to be compared to 170±9 kev as measured by Brugger *et al.* In the present data, with separated isotopes, the first excited threshold is more pronounced and should be more accurate than the older measurements.

The resonance at 4.15-Mev bombarding energy seems to affect threshold C in Fig. 4. Data with a slightly thicker target of 1.8 mg/cm² did not show the dip above threshold C. A ratio anomaly at 4.884 Mev can be associated with the strong resonance at 4.92 Mev. Another ratio anomaly at 5.02 Mev can be associated with a resonance at 5.1 Mev. A small anomaly occurs at 5.36 Mev. Although this last anomaly shows a rise in the ratio for target thickness and does not appear to be connected with a strong resonance, it is such a small effect that it is not listed as a threshold.

$Zn^{67}(p,n)Ga^{67}$

The Zn^{67} target was made under identical conditions to the Zn^{68} target used and is also 1.6 mg/cm². For 2.0-Mev protons this target has a thickness of approximately 120 kev. The ratio and yield for this target are shown in Fig. 4. The data extend from 1.75 Mev, which is below the $Zn^{67}(p,n)Ga^{67}$ ground state threshold, to 4.5 Mev which is some distance above the $Zn^{68}(p,n)Ga^{68}$ ground state threshold. The ratio has been corrected for background below 2.35 Mev. Several resonances appear in the yield. The thresholds are given in Table IV.

Owing to the presence of 8.1% Zn^{68} in this sample, the data above E (3.762 Mev) are complicated by the Zn^{68} yield. Knowing the percentages of Zn^{67} and Zn^{68} in the target and the $Zn^{68}(p,n)Ga^{68}$ cross section, a correction could be applied to the yield above the Zn^{68} threshold. Figure 4 does not include this correction which would lower the ratio above 3.762 Mev by roughly 10%. It appears from the experimental curve that there are one or more thresholds in Zn^{67} above E in the energy range of from 3.9 to 4.1 Mev.

No previous information is available on the excited levels in Ga^{67}. Trail and Johnson,[15] however, have measured the ground state threshold to occur at 1.812±0.005 Mev. There is a ratio anomaly at 3.06 Mev which is attributed to the resonance at 3.08 Mev.

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[15] C. C. Trail and C. H. Johnson, Phys. Rev. **91**, 474(A) (1953).