here $\epsilon=2y/(1+y^2)$, where[6] $y=[(1+x^2)^{\frac{1}{2}}-1]/x$ and $x=4\mu H/\Delta E$; for our purposes μ is just the Bohr magneton; ΔE means energy separation, triplet minus singlet, at $H=0$.

With slit width w, the two-quantum coincidence rate at 180°,

$$\begin{aligned} R_w &\sim 1+g_1 n(1+\epsilon)+fg_3 n(1-\epsilon) \\ &=1+n(fg_3+g_1)-\epsilon n(fg_3-g_1). \end{aligned}$$

Here the number of annihilations in flight per unit time is taken as unity; $4n$ is the formation rate for ground-state positronium; g_3 is the amplification in counting rate (at 180°) for triplet states due to their two-photon angular correlation being narrower than that for annihilation in flight; g_1 is the corresponding amplification for singlet states; g_1 and g_3 are of course monotonically changing functions of w, and g_3 may depend on H, but presumably only slightly (H does of course alter the time available for slowing of the triplet positronium after formation); f is the probability that a triplet state goes by two photons[6]: $1/f=1+\gamma/y^2$, where γ is the singlet/triplet lifetime ratio.

One may define a "quenching ratio,"

$$Q_w=\frac{R_w(H)+R_w(-H)}{2R_w(0)}=\frac{1+n(fg_3+g_1)}{1+ng_1}.$$

If two-photon *yield* is measured, Q_w becomes

$$Q_\infty=\frac{1+n(f+1)}{1+n},$$

since g_1 and g_3 become unity for $w=\infty$.

Let all positrons be completely polarized up, say, just before capture. The ratio of coincidence rates, field down/field up, written $(1+\eta)/(1-\eta)$, is given by

$$\frac{\eta}{|\epsilon|}=\frac{n(fg_3-g_1)}{1+n(fg_3+g_1)}. \tag{A.1}$$

For the present purpose it is useful to convert this into the form

$$\frac{\eta}{|\epsilon|}=\frac{Q_w-Q_\infty}{Q_w(1+\alpha)}. \tag{A.2}$$

The Q's are easily and directly measurable. The number α (which is not so readily subject to direct measurement) is for conditions of the present experiment certainly positive, and one attempts to keep its probable value less than about 0.5; explicitly,

$$\alpha=\left(g_1-f\frac{ng_1+1}{n+1}\right)\bigg/(fg_3-g_1). \tag{A.3}$$

The small quantity to be measured is called δ; it is the observed value of 2η.

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Neutron Thresholds in the $Co^{59}(p,n)Ni^{59}$ Reaction

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The $Co^{59}(p,n)Ni^{59}$ reaction has been used to find energy levels in the residual Ni^{59} nucleus by a neutron-threshold technique. Thresholds were found at bombarding energies corresponding to excited states of 0.341, 0.439, 1.22, 1.343, 1.79, 1.964, 2.15, 2.545, 2.72, 3.054, and 3.19 Mev. On the basis of these levels in Ni^{59}, some of the thermal-neutron-capture gamma rays from natural nickel reported by Kinsey and Bartholomew have been given new isotopic assignments.

I. INTRODUCTION

WHEN the Q value of the $Ni^{60}(p,\gamma)Cu^{61}$ reaction was measured[1] at this laboratory, a discrepancy of some 700 kev was noted between this measured Q value and that expected by calculating it using the $Cu^{61}(\beta+)Ni^{61}$ Q-value[2,3] together with any one of the following three determinations: mass spectrometer measurements of the Ni^{60}-Ni^{61} mass difference,[4] the $Ni^{60}(d,p)Ni^{61}$ Q value,[5] or the $Ni^{60}(n,\gamma)Ni^{61}$ Q value.[6] A complete account of this situation[7] is given in a forthcoming article.[8] Since such a large discrepancy is more than an order of magnitude greater than the combined errors of all the nuclear Q-value measure-

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[1] Gossett, Butler, and Holmgren, Bull. Am. Phys. Soc. Ser. II, **1**, 40 (1956); C. R. Gossett, Bull. Am. Phys. Soc. Ser. II, **2**, 69 (1957).

[2] Owen, Cook, and Owen, Phys. Rev. **78**, 686 (1950).

[3] Nussbaum, Wapstra, Bruil, Sterk, Nijgh, and Grobben, Phys. Rev. **101**, 905 (1956).

[4] Collins, Nier, and Johnson, Phys. Rev. **86**, 408 (1952).

[5] D. C. Hoesterey, Ph.D. thesis, Yale University, 1952 (unpublished); verbal report quoted in Nuclear Sci. Abstr. **6**, 24B (1952).

[6] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).

[7] Since this paper was written, a revised table of mass values has been published: Quisenberry, Scolman, and Nier, Phys. Rev. **104**, 461 (1956). The new values are in agreement with our results. They will be discussed fully in a later paper. *Note added in proof.*—A preliminary account of the present results has been published. Bull. Am. Phys. Soc. Ser. II, **1**, 327 (1956).

[8] J. W. Butler and C. R. Gossett (to be published).

ments used in the calculation, it was felt necessary to explore the possibilities of error. Since natural nickel is 68% Ni^{58}, one possible source of error is in the isotopic assignments of proton groups from the $Ni^{60}(d,p)Ni^{61}$ reaction and gamma rays from the $Ni^{60}(n,\gamma)Ni^{61}$ reaction. A knowledge of the energy-level structure of Ni^{59} and Ni^{61} would therefore be of great usefulness in testing these assignments and suggesting new ones. One way of finding energy levels in Ni^{59} is to look for slow-neutron thresholds in the $Co^{59}(p,n)Ni^{59}$ reaction. This was done and is herein reported.

II. EXPERIMENTAL PROCEDURE

Neutrons emitted at bombarding energies just above their threshold have energies in the kev region. These are herein called "slow neutrons" to distinguish them from the "fast neutrons," having higher energies (greater than 100 kev), which are emitted when the residual nucleus is left in a lower state of excitation. The technique used in this experiment to detect the appearance (as a function of bombarding energy) of a new group of "slow neutrons" in a flux of "fast neutrons" involves the use of two different counters having different efficiencies for "fast" and "slow" neutrons. The threshold for the appearance of a new group of slow neutrons is indicated by a rise in the ratio of slow neutrons to fast neutrons. This procedure is essentially the same as that reported by the Rice Institute group.[9,10]

The geometrical arrangement of the counters is shown in Fig. 1. Three BF_3 tubes are used in the slow-neutron counter, and five are used in the fast-neutron counter, whereas the Rice group uses only one tube in each counter. The extra tubes give higher counting efficiency which is important when using very thin targets. In order to resolve levels that differ by 100 kev, it is necessary that the target be considerably thinner than 100 kev to the incident protons. The ratio method reduces the effects of resonances in the compound nucleus but does not eliminate them completely. When it is doubtful whether a break in the ratio curve is caused by a threshold or a resonance, it is frequently useful to use targets of different thicknesses in order to obviate the uncertainty. If the resonances are very narrow, as they are for protons on Co^{59}, a resonance effect will have a width comparable with the thickness of the target (or the beam width for extremely thin targets). A threshold break on the other hand has a rise, for our particular arrangement, of about 30 kev plus the target thickness. The length of rise is influenced by the efficiency *vs* energy dependence of the slow- and fast-neutron counters. Thus, we found it convenient to use targets about 10 kev thick. For such thin targets, a relatively high detector efficiency is very important in order to obtain reasonably good statistics with conveniently short runs.

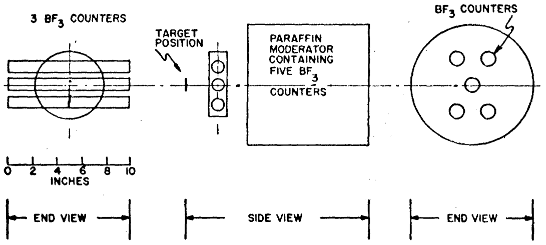

FIG. 1. Geometrical arrangement of the neutron counters.

The geometry of Fig. 1 was used for data below 4.0 Mev of proton energy. Between 4.0 and 4.8 the distances were doubled. They were doubled again for energies above 4.8 Mev. It was found that for the first few thresholds, the threshold effect was enhanced by the back scattered neutrons leaving the fast counter and re-entering the slow counter. For the higher thresholds, however, these back scattered neutrons diminished the ratio effect at threshold. Moving the counters back, therefore, increased the threshold sensitivity at the higher energies. The fast-neutron counts of Fig. 2 were corrected for this change in solid angle in order to make the yield curve continuous.

Targets were prepared by electrodeposition of Co^{59} onto 0.010-inch Ag disks from a $CoCl_2$ solution containing boric acid as a buffer. Protons were supplied by the Naval Research Laboratory's large Van de Graaff accelerator. The analyzing magnet was calibrated with the $Li^7(p,n)Be^7$ threshold,[11] and field measurements were made with nuclear-magnetic-resonance equipment. The resolution of the analyzer was about 0.1% during this experiment, and the proton energy calibration during the threshold runs is believed to be accurate within 0.1%.

III. RESULTS

In Fig. 2 are plotted the fast-counter yield (solid curve) and the slow-to-fast ratio (dots) as a function of proton bombarding energy. Since the reaction yield increased rapidly as a function of bombarding energy, several changes in scale of the fast-counter yield were necessary. It should be emphasized that the actual differential cross section is not necessarily strictly proportional to the fast-counter yield curve because the precise energy response of the fast counter is not known. However, local changes (over an interval of less than about 30 kev) in the absolute yield of the "fast" neutrons should be accurately reflected in the "fast-counter" yield.

The target used to obtain the curves of Fig. 2 was about 10 kev thick for 2-Mev protons. The arrows indicate threshold breaks in the ratio curve and give the corresponding level of excitation in the Ni^{59} residual nucleus. In all, twelve thresholds were observed, including the ground-state threshold. The bombarding energies at threshold are listed in Table I, which in-

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[9] T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).
[10] Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955).
[11] Jones, Douglas, McEllistrem, and Richards, Phys. Rev. **94**, 947 (1954).

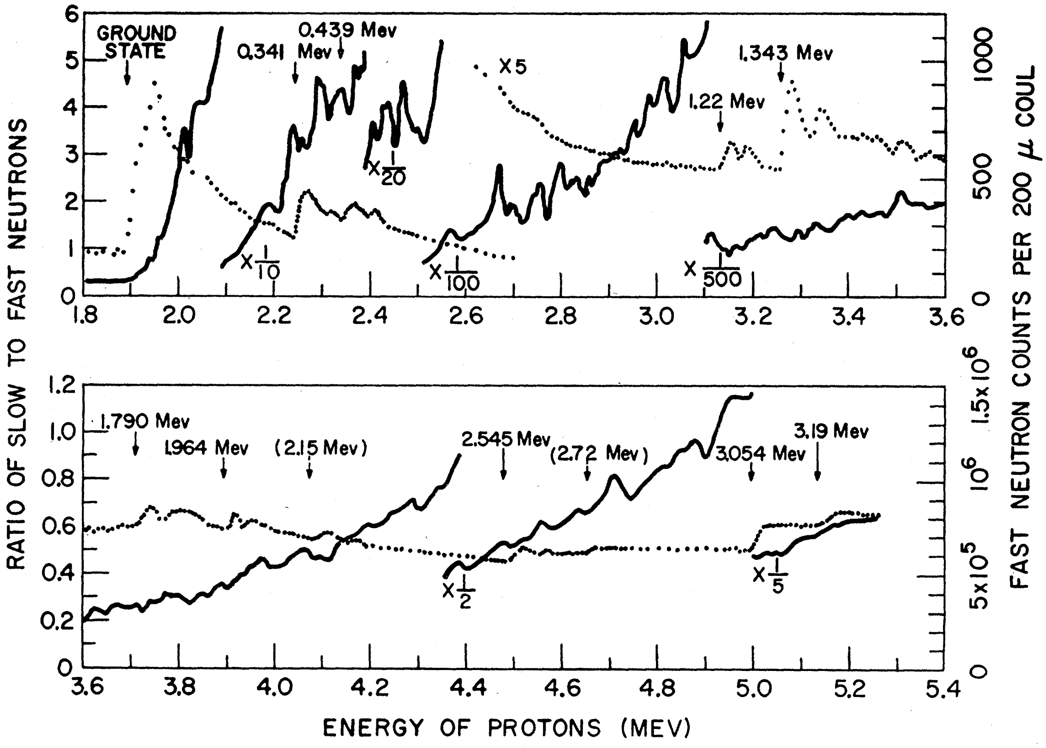

FIG. 2. Excitation curve for "fast" neutrons (solid curve) and "slow" to "fast" ratio (dots). Arrows indicate neutron thresholds.

cludes probable errors and the positions of the excited states in Ni^{59}, with their probable errors.

Note that each of the eight lower excited-state thresholds is accompanied by one "satellite" break within an interval of 50 kev of the primary threshold break. It is possible that these satellites were caused by some characteristic of our detection equipment. It is difficult to check this possibility against neutron-scattering data, however, because neutron-scattering cross sections in the kev region are not well known for most materials. Another possible cause is the effect of resonances in which the relative numbers of fast and slow neutrons change. Future experience with the same equipment and other reactions should enable us to determine the cause of these satellites.

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

Threshold energy (Mev)	Excited state in Ni^{59} (Mev)
1.887±0.004	0
2.234±0.005	0.341±0.004
2.333±0.005	0.439±0.005
3.13 ±0.01	1.22 ±0.01
3.254±0.010	1.343±0.010
3.707±0.010	1.79 ±0.01
3.884±0.010	1.964±0.010
(4.07 ±0.01)	(2.15 ±0.01)
4.475±0.010	2.545±0.010
(4.65 ±0.02)	(2.72 ±0.02)
4.992±0.010	3.054±0.010
5.13 ±0.02	3.19 ±0.02

The behavior of the curve in the vicinity of 3.5 Mev of bombarding energy does not exhibit the typical threshold characteristics of a rise over an interval of about 30 kev preceded by a flat or slowly falling region of at least 50 kev. It is therefore believed that no threshold is indicated in this region.

The apparent thresholds at bombarding energies of 4.07 and 4.65 Mev are indicated by broken arrows in Fig. 2 because the indication for them is weaker than for the other thresholds. Their existence is therefore somewhat uncertain.

IV. DISCUSSION

Our value of 1.887±0.004 Mev for the ground-state threshold agrees with that obtained by McCue and Preston,[12] 1.888±0.003 Mev, when their value is corrected for the most recent determination[11] of the $Li^7(p,n)Be^7$ threshold.

The first excited-state threshold occurs at a bombarding energy of 2.234 Mev, indicating a state in Ni^{59} at 0.341±0.004 Mev which is in good agreement with a state reported at 0.33±0.05 Mev by Stelson and Preston[13] using the photographic-plate neutron-spectrometer technique. Pratt[14] found a state at 0.33±0.1 Mev by using the $Ni^{58}(d,p)Ni^{59}$ reaction and photographic-plate range analysis.

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[12] J. J. G. McCue and W. M. Preston, Phys. Rev. **84**, 384 (1951).

[13] P. H. Stelson and W. M. Preston, Phys. Rev. **86**, 807 (1952).

[14] W. W. Pratt, Phys. Rev. **95**, 1517 (1954).

The existence of a threshold at 2.333 Mev is rendered somewhat uncertain by its proximity to the 2.234-Mev threshold. The break at 2.333 Mev did behave like a threshold, however, showing the proper length of rise for targets of different thickness. It is therefore listed as a threshold corresponding to an excited state of 0.439±0.005 Mev. Stelson and Preston[13] did not see a group of neutrons corresponding to this level. Perhaps, at their bombarding energy, the yield of this particular excited state is low. The 0.439-Mev state could be the same as the 0.42-Mev state reported by McFarland *et al.*[15] using the $Ni^{58}(d,p)Ni^{59}$ reaction and magnetic analysis.

The 1.22±0.01 Mev state is probably the same as the 1.15±0.10 Mev state reported by Pratt.[14] All other thresholds indicate new excited states in Ni^{59} insofar as definite isotopic assignments have been made.

It is seen from Fig. 3 that a definite correspondence can be made between certain of the thresholds and the gamma rays following thermal-neutron capture by natural nickel[6] (68% Ni^{58} and 26% Ni^{60}). The energy scale on the right is a measure of the neutron-capture-gamma energy. The energy values to the left of each lettered gamma-ray line give the corresponding state of excitation in Ni^{59} if one assumes neutron capture by Ni^{58}. The letters were assigned by Kinsey and Bartholomew[6] to each high-energy gamma ray they observed. Their problem was to assign them to the nickel isotopes.

There is little doubt that the highest energy gamma ray, A, results from capture by Ni^{58} and represents a transition to the ground state of Ni^{59}. This assignment, among others, is discussed by Kinsey and Bartholomew. There is no gamma ray corresponding to an excited state of 0.341 Mev in Ni^{59}, but this is quite understandable because the selection rules permit gamma-ray transitions to states having only a very limited range of spin and parity combinations. Since both Ni^{58} and Ni^{60} have 0^+ ground states (even-even nuclei), thermal-neutron capture can excite only $\frac{1}{2}^+$ states in the intermediate nuclei. Since the shell model predicts $\frac{3}{2}^-$ for both Ni^{59} and Ni^{61} ground states, a transition directly to the ground state would be of the $E1$ type and would therefore be expected (barring unusual circumstances) to have a relatively high probability. Cascades through low-lying states of $\frac{5}{2}^-$ or any higher spin could have relatively low transition probabilities.

There is no threshold corresponding to gamma-ray B since it is doubtful that the 0.439±0.005 Mev "threshold state" could be the same as the 0.465±0.008 Mev "gamma state." There is no correspondence between gamma rays and neutron thresholds for any gamma between gammas A and F. At F, however, there is a clear correspondence between the "threshold state" at 1.79±0.01 Mev and the "gamma state" at 1.78±0.02 Mev. A similar statement holds for gamma ray G. The thresholds leading to the 2.15- and 3.19-Mev states give weak indications, but since they correspond with gamma states H and M, respectively, having essentially the same energies within very small uncertainties, there can be little doubt that they are real.[16]

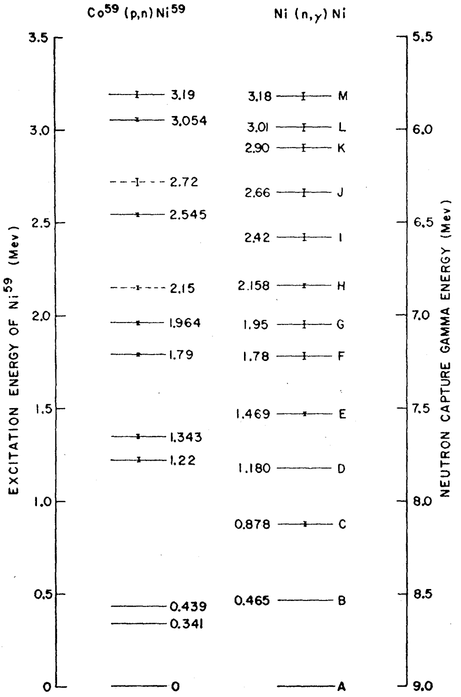

FIG. 3. Comparison of excited states in Ni^{59} found by the neutron-threshold technique with the high-energy gamma rays following thermal-neutron capture[6] by natural nickel.

V. CONCLUSIONS

Since we were bombarding an isotope of essentially 100% purity, there is no doubt about the isotopic assignment of the excited states which we have found by application of neutron-threshold techniques. By comparing the level scheme of Ni^{59} thus obtained with the precise thermal-neutron-capture gamma rays from natural nickel,[6] we have been able to assign gammas A, F, G, H, and M of reference 6 to the Ni^{59} isotope. A subsequent paper will make use of these assignments and information from other experiments[17] to present a consistent set of level schemes for Ni^{59} and Ni^{61}.

The authors wish to acknowledge the aid of Dr. C. R. Gossett in helping with the data-taking on some of the runs.

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[15] McFarland, Bretscher, and Shull, Phys. Rev. **89**, 892A (1953).

[16] We are informed by R. A. Chapman (private communication) that the Rice Institute group has looked for neutron thresholds in this reaction and found thresholds at bombarding energies of 1.895±0.005, 2.225±0.015, 3.110±0.010, 3.701±0.010, 4.489 ±0.015, 4.990±0.010, 5.292±0.015, 5.499±0.015 Mev. *Note added in proof.*—R. A. Chapman and J. C. Slattery, Phys. Rev. **105**, 633 (1957).

[17] Butler, Gossett, and Holmgren, Bull. Am. Phys. Soc. Ser. II, **1**, 163 (1956).