(p,n) Reaction Thresholds in Ti^{48}, Fe^{56}, and Sr^{88}†

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The counter-ratio method has been used to determine the ground-state (p,n) reaction threshold in Ti^{48}, Fe^{56}, and Sr^{88} and to locate low-lying excited states in V^{48}, Co^{56}, and Y^{88}. The measured threshold energies are 4.905 Mev for Ti^{48}, 5.451 Mev for Fe^{56}, and 4.457 Mev for Sr^{88}. Additional thresholds were found corresponding to excited states at 0.306, 0.416, 0.514, and 0.752 Mev in V^{48}; at 0.159, 0.186, 0.225, and 0.280 Mev in Co^{56}; and at 0.391 Mev in Y^{88}. The estimated errors in the energy determinations are all ± 10 kev or less.

INTRODUCTION

BECAUSE of the absence of exit-channel Coulomb barrier inhibition, the (p,n) cross section generally rises rapidly as the bombarding energy is increased above the threshold value. The rapidly rising neutron yield makes the (p,n) reaction a convenient energy calibration experiment for accelerators in cases where the threshold energies are well known. Conversely, a proton beam of well-resolved and precisely determined energy may be used to directly measure (p,n)-reaction threshold energies which are otherwise established from mass values and beta-decay data.

Observed ground-state threshold values[1] for the (p,n) reactions on Ti^{48}, Fe^{56}, and Sr^{88} will be compared with published results of positron decay experiments. The $Sr^{88}(p,n)Y^{88}$ ground-state threshold has been previously measured with relatively large uncertainties, using the stacked foil technique. The onsets of the slow-neutron groups corresponding to ground-state or excited-state thresholds in the residual nuclei V^{48}, Co^{56}, and Y^{88} were observed as sharp rises in the slow-to-fast neutron counter ratio.

EXPERIMENTAL PROCEDURE

The counter-ratio experimental arrangement shown in Fig. 1 is similar to that of Bonner and Cook.[2] The slow-neutron counter was placed directly behind the target at 0° with respect to the incident proton beam, while the larger fast-neutron counter was placed 10 in. away, so that it subtended approximately the same solid angle as the slow counter. The neutron counters were BF_3-filled proportional counters (45-cm-Hg BF_3, enriched to 90% in B^{10}).

Proton beams of 1 to 3 μa from the Florida State University Tandem Van de Graaff accelerator were momentum analyzed in a 90° magnet of radius 86 cm. Calibration of the analyzing magnet was based on the $C^{13}(p,n)N^{13}$ ground-state threshold, 3237.2 ± 1.6 kev.[3] With this calibration, the observed $Al^{27}(p,n)Si^{27}$ ground-state threshold is 5800 ± 8 kev, which is in good agreement with previous measurements of this threshold.[4–6]

Since all ground-state thresholds of the nuclei under study lie below that of Al^{27}, targets were prepared by evaporation on thick aluminum backings. The thickness, chemical form, and isotopic enrichment of the targets are given in Table I. Isotopically enriched compounds were obtained from the Oak Ridge National Laboratory.

TABLE I. Targets.

Target nucleus	Chemical form	Isotopic enrichment (percent)	Thickness (mg/cm^2)
Ti^{48}	TiO_2	99	0.55
Fe^{56}	Fe_2O_3	99.6	0.13
Sr^{88}	$SrCO_3$	90	0.21

EXPERIMENTAL RESULTS

Counter-ratio excitation curves are shown in Figs. 2–4. Proton energies at thresholds are indicated to

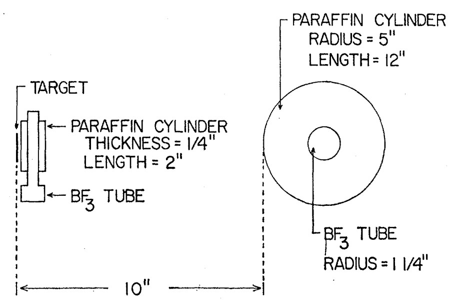

FIG. 1. Geometry of fast- and slow-neutron counters. The arrangement of the slow- and fast-neutron counters is similar to that originated by Bonner and Cook (see reference 2). The slow-neutron counter with a $\frac{1}{4}$-in. thick paraffin jacket is positioned close to the target. The fast-neutron counter, a BF_3 tube with a $3\frac{3}{4}$-in. thick paraffin jacket was placed 10 inches from the target.

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[1] J. W. Nelson, H. S. Adams, R. H. Davis, J. D. Fox, N. P. Heydenburg, H. S. Plendl, R. K. Sheline, and G. M. Temmer, Bull. Am. Phys. Soc. **5**, 424 (1960).
[2] T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).
[3] R. O. Bondelid and C. A. Kennedy, Phys. Rev. **115**, 1601 (1959).
[4] J. D. Kington, J. K. Bair, H. O. Cohn, and H. B. Willard, Phys. Rev. **99**, 1393 (1955).
[5] J. B. Marion, T. W. Bonner, and C. F. Cook, Phys. Rev. **100**, 91 (1955).
[6] D. A. Bromley, A. J. Ferguson, H. E. Gove, J. A. Kuehner, A. E. Litherland, E. Almqvist, and R. Batchelor, Can. J. Phys. **37**, 1514 (1959).

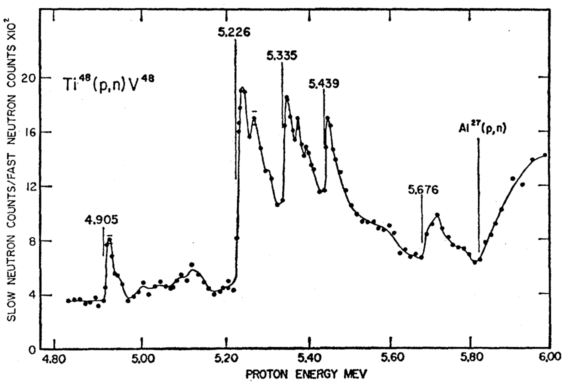

FIG. 2. Counter ratio excitation curve for $Ti^{48}(p,n)V^{48}$. The ratio of slow- to fast-neutron counter yields is plotted as a function of energy. The ground-state threshold was observed at 4.095 Mev. Steep rises at higher energies were interpreted as thresholds for excited states in the residual nucleus. Above 5.8 Mev the curve rises due to the $Al^{27}(p,n)Si^{27}$ reaction.

four significant figures. Since all targets were backed by aluminum, all three curves end at 5.800 Mev, the $Al^{27}(p,n)$ threshold. To confirm the identification of the target nucleus associated with structure in the excitation curves, additional Fe^{56} and Sr^{88} excitation curves were obtained using targets of normal isotopic abundance.

Very steep rises followed by a more gradual fall in ratio are characteristic of thresholds in counter-ratio excitation curves. The most prominent rises were interpreted as thresholds due to levels in the residual nucleus rather than due to resonances in the compound nucleus. Such interpretation was confirmed in some cases by previous gamma-ray energy measurements cited in the references for Table II. Additional weak thresholds may be present in the $Fe^{56}(p,n)$ excitation curve, as suggested by the small rise at 5.5-Mev proton energy. Small rises following a more prominent threshold were not interpreted as thresholds, since they may well be due to resonances in the compound nucleus.

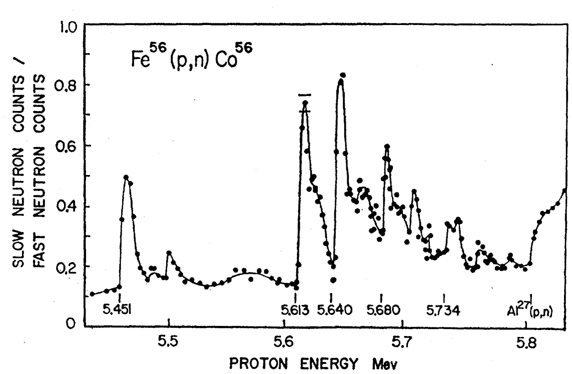

FIG. 3. Counter ratio excitation curve for $Fe^{56}(p,n)Co^{56}$. The slow- to fast-neutron counter ratio dependence on bombarding energy is plotted up to the $Al(p,n)$ threshold. Thresholds for the ground state and two excited states are indicated by steep rises in the curve. The peak at 5.7 Mev may be due to either a new threshold or resonances in the compound nucleus.

An example of the interplay[6] between excited residual nucleus states and compound nucleus states is made evident by plotting the slow-counter yield versus the fast-counter yield. This is done for the Fe^{56} target in Fig. 5. In the limiting case of a statistical compound nucleus, the curve would rise sharply at the threshold and smoothly decrease with the slow-counter response; structure in the curve results from discrete compound nucleus levels. The slope of the rise associated with a compound nucleus level decreases as the energy above threshold increases. Application of this analysis[6] to the slopes of the ground-state peak and the peak at 5.5 Mev suggests that the latter is a compound nucleus modulation rather than a new threshold. Difficulties in background correction and unknown branching intensities made the use of this technique at high energies hazardous.

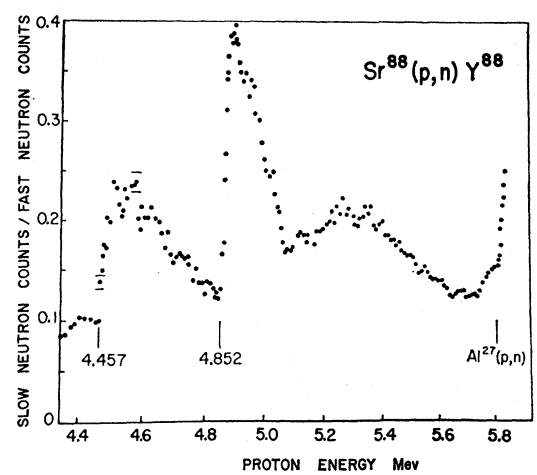

FIG. 4. Counter ratio excitation curve for $Sr^{88}(p,n)Y^{88}$. Steep rises in the excitation curve at 4.457 and 4.852 Mev were interpreted as ground-state and first-excited state thresholds, respectively.

The results are summarized in Table II. Previous results from positron and gamma decay work are given for comparison. The results for states in V^{48} and Co^{56} agree within the experimental errors. The observed ground level Q value for $Sr^{88}(p,n)Y^{88}$ is in agreement with the most recent work at Purdue University[7] but is not in agreement with previous work. A measurement of this threshold by Shafroth is also in agreement with the observed value.[8]

DISCUSSION

A correlation between the total angular momentum of a residual nucleus level and the yield of slow neutrons is evident in Figs. 2 and 4. All three experiments involved the bombardment of even-even nuclei, which have zero spin. The ground and first-excited states in

[7] J. I. Rhode, D. E. Johnson, and W. G. Smith, Bull. Am. Phys. Soc. 6, 228 (1961).
[8] S. M. Shafroth, Bull. Am. Phys. Soc. 6, 228 (1961).

TABLE II. Observed ground-state Q values and energies of the residual nucleus excited states. The results of the present experiments are tabulated and compared with previously published data.

		Ground-state (p,n) $-Q$ (kev)	Levels above ground in residual nucleus (kev)			
$Ti^{48}(p,n)V^{48}$	F. S. U.	4803±10	306±4	416±4	514±4	752±6
	Previous[a]	4801±6	306±10	430±11		
		4800±5[b]				
$Fe^{56}(p,n)Co^{56}$	F. S. U.	5353±10	159±4	186±6	225±6	280±6
	Previous[a]	5393±30	160±5			260−280[d]
		5383±15[b]				
$Sr^{88}(p,n)Y^{88}$	F. S. U.	4406±10	391±6			
	Previous[a]	4421±13[c]	394±10			
		4229±10[b]				

[a] See C. L. McGinnis *et al.*, *Nuclear Data Sheets*, NAS-NRC 58-1-23 (A =48), 59-4-50 (A =56), and 60-3-67 (A =88) (National Research Council, Washington, D. C.).
[b] *1960 Nuclear Data Tables* (National Research Council, Washington, D. C., 1961), Parts 1 and 2.
[c] See reference 7. [d] See reference 8.

V^{48} and Y^{88} have been assigned spins of 4 and 1, respectively.[9] The relative weakness of the ground-state threshold intensities compared with those of the first excited states tend to support this assignment from penetrability arguments. A similar situation exists in the case of Co^{56} (Fig. 3). The ground state of Co^{56} has been assigned a spin of 4. The more intense yield for the first two excited states would suggest lower spins than that of the ground state. Glagolev *et al.*[10] have proposed a level in Y^{88} of spin 7 at 240 kev above the ground state. Figure 4 shows no threshold at this point. Detection of such a high-spin state was not likely in this experiment since it was not possible to definitely confirm the ground-state threshold in the $Cr^{52}(p,n)Mn^{52}$ reaction where the residual nucleus ground state is known to have an angular momentum of 6. Experiment showed no thresholds below 5.800 Mev. In a later experiment[11] the first excited state threshold was located at 5.98 Mev by counting the residual Mn^{52} activity.

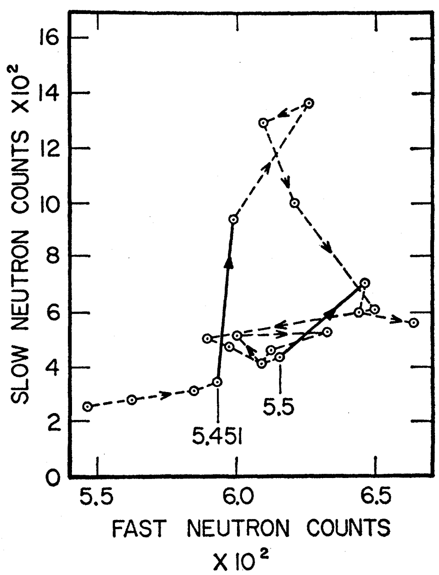

FIG. 5. Slow vs fast neutron counter yields for the 5.451- and 5.5-Mev peaks in $Fe^{56}(p,n)Co^{56}$. The slow-neutron counter yield is plotted against the fast- neutron counter yield. Successive points in the excitation curve are connected with a dashed line and arrows indicate the direction of increasing energy. Points determining the steepest rise of peaks in the excitation curve are connected with solid lines. As pointed out by Bromley (see reference 6), the slope of the solid line will be nearly vertical when the compound nucleus resonance width overlaps the threshold energy and will fall off as the resonance energy increases above the threshold energy. The slope at 5.451 Mev is much steeper that that observed at 5.5 Mev; consequently, the peak at 5.5 Mev is attributed to a compound nucleus resonance.

Several similarities in the ratio excitation curves for $Ti^{48}(p,n)V^{48}$ and $Fe^{56}(p,n)Co^{56}$ (Figs. 2 and 3) were observed. In both curves the ground-state threshold is followed by three more prominent, almost equally spaced, thresholds. In addition, there is a weak but repeatable rise in ratio at one quarter the energy difference from ground level to the first-excited threshold (70 kev for V^{48}, 40 kev for Co^{56}). Though the curves exhibit these similarities in shape, the absolute level spacing in Co^{56} is much smaller than in

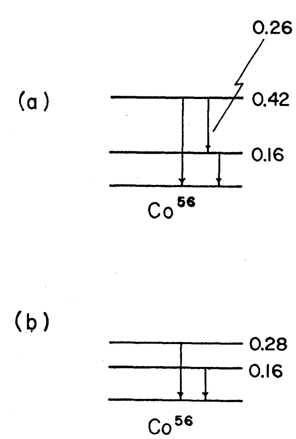

FIG. 6. (a) Decay scheme for the lowest states of Co^{56} as shown on *Nuclear Data Sheets*, NRC 59-4-50 (National Research Council, Washington, D. C.). (b) A possible alternative decay scheme to account for the observed 280-kev gamma ray.

[9] *Nuclear Data Sheets*, edited by C. L. McGinnis, NAS-NRC 58-1-23, 60-3-67 (National Research Council, Washington, D. C.).

[10] V. L. Glagolev, O. M. Kovrizhnykh, Y. V. Makarov, and P. A. Yampolskii, Soviet Phys.—JETP 9, 742 (1959).

[11] J. A. Becker and J. D. Fox, Bull. Am. Phys. Soc. 6, 47 (1961).

V^{48}. Considerably more detail is evident in Fig. 3 than in Fig. 2 because of the use of a thinner target.

Sheline and Stoughton[12] observed eight gamma rays in Co^{56} after bombardment of Fe^{54} by 39-Mev alpha particles. While an approximately 280-kev gamma ray may be attributed to a transition[9] from a level at 420 kev to the level at 160 kev, the origin of the gamma ray was not uniquely determined by the experiment.[13] The present experiment offers a possible alternative interpretation (see Fig. 6) of a 280-kev gamma ray as representing a transition to the ground state from the level corresponding to the 5734-kev threshold of Fig. 3.

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Early phases of this work served to acquaint the research personnel of this laboratory with the operation of the Tandem Van de Graaff accelerator. Consequently, the authors are indebted to H. S. Adams, J. D. Fox, N. P. Heydenburg, R. K. Sheline and G. M. Temmer for their assistance in the measurements. The authors also wish to thank the many graduate students who helped to construct, test, and operate the equipment.

[12] R. K. Sheline and R. W. Stoughton, Phys. Rev. **87**, 1 (1952).
[13] R. K. Sheline (private communications).

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Nuclear Spin of Gallium-70*

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The atomic-beam magnetic-resonance method has been used to determine the nuclear angular momentum of 21-minute Ga^{70}. Measurements performed in both the $^2P_{1/2}$ and the $^2P_{3/2}$ electronic states show that the nuclear spin is $I=1$.

INTRODUCTION

PREVIOUS measurements of the nuclear spins and moments of odd-odd gallium isotopes have yielded several interesting results. The nuclear spins of Ga^{66}, Ga^{68}, and Ga^{72} were found to be 0, 1, and 3, respectively.[1–3] Also, the nuclear magnetic moments of both Ga^{68} and Ga^{72} were observed to be small, causing an inversion of the hyperfine-structure energy levels.[3,4] Previously the shortest-lived isotope of gallium investigated by atomic beams possessed a 68-minute half-life. This paper describes the spin measurement of 21-min Ga^{70}.

ISOTOPE PRODUCTION AND TRANSPORTATION

Ga^{70} is produced most easily by thermal-neutron activation of 60.1%-abundant Ga^{69}, using the $Ga^{69}(n,\gamma)Ga^{70}$ reaction. However, 14.1-hr Ga^{72} is produced simultaneously by the same reaction on 39.9%-abundant Ga^{71}. Because radioactive decay is used for detection, the Ga^{72} causes an undesirable background in the Ga^{70} measurements. Calculations based on the thermal-neutron-capture cross sections and relative half-lives of these isotopes indicated that the expected activity of Ga^{70} would be approximately four times that of Ga^{72} 30 min after a 1-hr bombardment. Experimentally the ratio was observed to be slightly smaller. Although the presence of Ga^{72} made the experiment more difficult, it was still possible through decay analysis to distinguish the two isotopes by their different half-lives.

The highest-flux nuclear reactor for use in producing the radio-isotope in the vicinity of Berkeley is at the General Electric Vallecitos Atomic Laboratory, approximately 40 miles away. Because of this distance, rapid transportation of the bombarded sample presented a major problem. With the assistance of the U. S. Office of Naval Research, arrangements were made to deliver the sample by Navy helicopter. This method reduced the transportation time to 17 min.

Because of the short half-life, all planning for the experiment centered around making every operation as rapid as possible. In order to avoid wasted time in transferring the bombarded material to the oven container, the entire graphite oven ($\frac{3}{8}$-in. cube) was bombarded with the gallium already enclosed. This was possible because of the low neutron-capture cross section of carbon. Typically, about 30 mg of Ga was irradiated. In addition, the oven contained 4 mg of CsF to aid in aligning it when placed in the atomic-

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[1] J. C. Hubbs, W. A. Nierenberg, H. A. Shugart, and J. L. Worcester, Phys. Rev. **105**, 1928 (1957).
[2] J. C. Hubbs, R. Marrus, and J. L. Worcester, Phys. Rev. **110**, 534 (1958).
[3] W. J. Childs, L. S. Goodman, and L. J. Kieffer, Phys. Rev. **120**, 2138 (1960).
[4] V. J. Ehlers and W. A. Nierenberg, Bull. Am. Phys. Soc. 4, 452 (1959); and V. J. Ehlers and H. A. Shugart (to be published).