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Levels of ^{61}Cu, ^{64}Cu, ^{67}Ga, and ^{68}Ga Excited by the (p, n) Reaction*

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Neutron time-of-flight techniques were used to study the (p,n) reaction on the nuclei ^{61}Ni, ^{64}Ni, ^{67}Zn, and ^{68}Zn. The locations of excited states in the residual nuclei were measured with an energy resolution of about 10 keV. The absolute excitation energies are accurate to ±2 keV for low-lying states and to ±5 to 7 keV for the highest states (2–3-MeV excitation). The following results were obtained: ^{61}Cu, 17 levels (0 to 2.6 MeV); ^{64}Cu, 66 levels (0 to 2.75 MeV); ^{67}Ga, 57 levels (0 to 3.3 MeV); and ^{68}Ga, 32 levels (0 to 1.6 MeV). Comparisons with other information on these nuclei indicate that the (p,n) reaction is a very effective tool for locating all the levels. The relative intensities of the neutron groups displayed distinctive patterns. However, quantitative yields of a succession of closely spaced proton energies showed typically 30% fluctuations. To maintain good energy resolution and yet reduce the fluctuations we averaged many individual runs in order to have more meaningful comparisons with the Hauser-Feshbach predictions. Spin assignments were made to 10–20 levels in ^{64}Cu, ^{67}Ga, and ^{68}Ga. The results are generally consistent with other available information on spin parities.

I. INTRODUCTION

The (p,n) reaction has not been extensively used as a spectroscopic tool. Cross sections for the (p,n) reaction do not exhibit a strong dependence on the properties of the residual state, such as the shell-model configuration in the case of transfer reactions or the collectivity of the state in the case of inelastic scattering reactions. This nonselectivity can be an advantage if one's purpose is to map the location of all the levels. However, adequate energy resolutions must be achieved if this is to be a useful endeavor. We have used the terminal pulsed proton beam from the Oak Ridge National Laboratory (ORNL) 6-MV Van de Graaff to measure (p,n) reactions by the time-of-flight method. The pulsed-beam quality, proton bursts of 1-nsec width and several mA peak current, was such that target thicknesses and flight paths could be used to achieve an energy resolution of 10 keV for the

resulting neutron groups. Doublets with separations of 7 keV were detected. We report results of (p,n) reactions on the targets ^{61}Ni, ^{64}Ni, ^{67}Zn, and ^{68}Zn.

While measuring the neutron spectra at different proton energies it was observed that the pattern of intensities of the neutron groups was quite distinctive. Generally speaking, strong peaks remained strong and weak peaks remained weak, and the ratio of strong to weak peaks would range as large as 20. These observations lead us to carry out quantitative intensity measurements at several sets of closely spaced proton energy intervals. It was found that intensity fluctuations of 20–30% were typical. Thus, the simple statistical conditions represented by the smooth Hauser-Feshbach theory were not fully realized with energy-averaging intervals of a few keV. In order to compare intensities with the Hauser-Feshbach predictions and yet preserve the good energy resolution of the individual neutron groups it was necessary to take a series of spectra at closely spaced proton energies and average the resulting intensities. Spin assignments are made to a number of residual states in each nucleus.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

Pulsed proton beams were obtained over the energy range 2.9 to 6.3 MeV from the ORNL 6-MV Van de Graaff. In this machine the proton beam is chopped and klystron-bunched in the terminal. The pulses at the target were about 1 nsec in width and several mA in peak intensity. The pulse separation times were either 500 or 1000 nsec.

The ORNL Van de Graaff is a vertical machine located on the second floor. Directly below on the first floor is a rotatable 90° analyzing magnet which directs the beam to various experimental stations. The analyzing magnet is in a concrete-shielded room and in the present experiments was separated from the neutron detectors by a 3-ft-thick water wall. The target was mounted on a short length of beam tubing which was mounted on the rotatable magnet. In this way we could easily change the angle at which the neutrons were detected by rotating the magnet and slightly changing the positions of the neutron detectors. Neutron flight paths varied from 7 to 12 m. Neutron spectra were taken at both forward and backward angles in order to detect impurity neutron groups which would have kinematically shifted if the peaks were due to substantially lighter nuclei. No spurious peaks were detected in the experiments. Many of the common target impurities have prohibitively high negative Q values.

The targets were made by evaporating isotopically enriched metals onto thick platinum disks. The target thicknesses were approximately 100 μg/cm^2 which meant they were 4 keV thick at 3.0 MeV and 2 keV thick at 6.0-MeV proton energy. The isotopic composition and Q values are given in Table I.

The neutrons were detected by an array of three detectors. Each consisted of a 4.5-in.-diam by 1-in.-thick cylindrical NE-213 liquid scintillator mounted on an XP-1040 phototube fitted with an ORTEC Model 268 tube base. This base uses a fast-crossover technique to eliminate "walk" which occurs in leading-edge timing devices. The bias was typically set to cut off pulses coming from recoil protons with energy below 250 to 300 keV.

A block diagram of the electronic equipment used to measure the time-of-flight spectra is given in Fig. 1. Much of the electronics was triplicated to handle the three detector systems. However, the three detectors shared a common time-to-pulse-height converter and a common dynode pulse-height system. Isolation of the information from each detector was maintained by accompanying each output with a logical signal from a detector identification unit. This device received outputs of the crossover detectors and provided an appropriate identification number to the on-line PDP-7 computer which routed the information to be stored in the appropriate spectrum.

Pulse-shape discrimination was used to block γ-ray pulses in the detectors from being stored in the spectra. This feature was extremely important in obtaining clear neutron time-of-flight spectra.

The time-to-pulse-height converter had a slight nonlinearity. The ratio of time to channel number was calibrated by a method producing narrow pulses (~0.2-nsec width) precisely spaced (±0.1 nsec) a few tens of nsec apart. The apparatus was similar to a device discussed by Langsford.[1]

TABLE I. Principal target components and their ground-state (p,n) reaction Q values.

Target	Q Value (MeV)	Isotopes present	Atomic percent
^{61}Ni	−9.35	58	1.6
	−6.91	60	5.2
	−3.024 ± 0.003	61	92.1
	−4.74	62	1.1
^{64}Ni	−2.459 ± 0.002	64	99.8
^{67}Zn	−7.85	64	1.8
	−5.96	66	4.4
	−1.783 ± 0.002	67	89.6
	−3.70	68	4.2
^{68}Zn	−3.701 ± 0.003	68	98.5

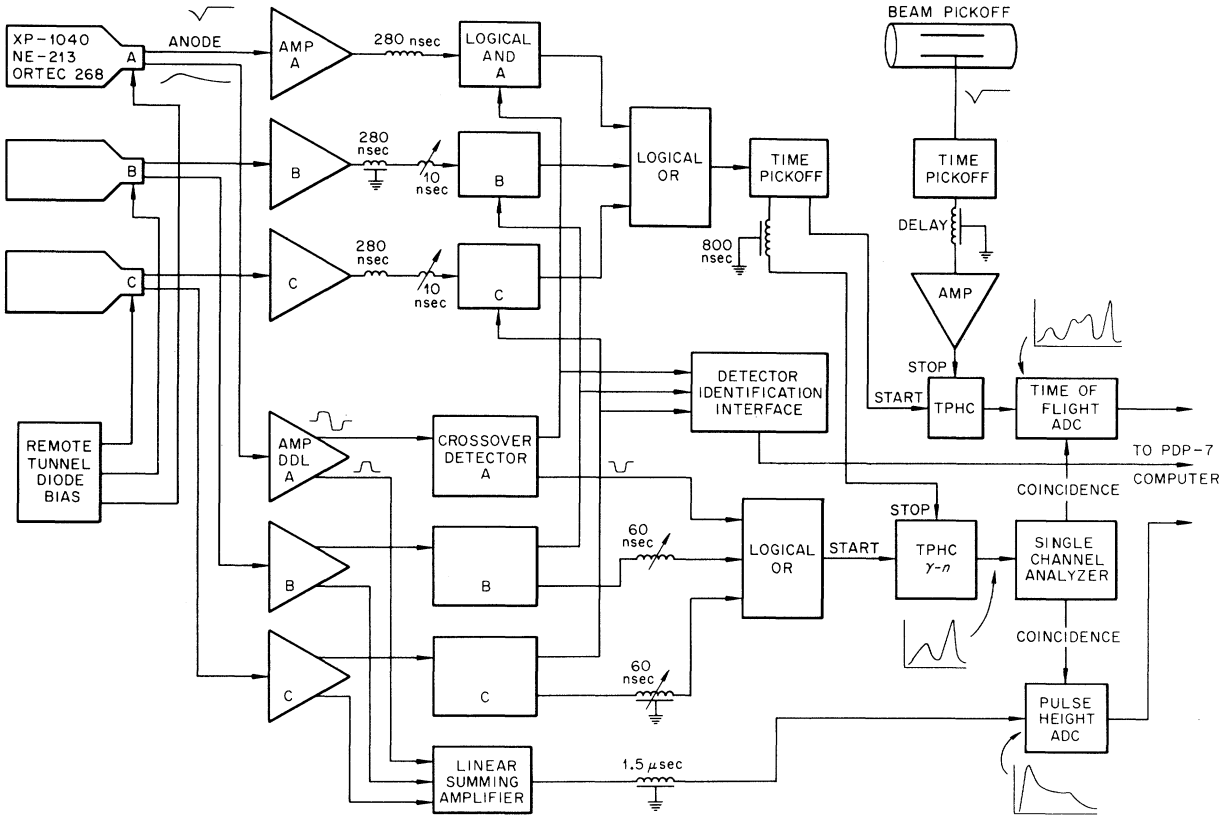

FIG. 1. Block diagram of the electronic equipment for neutron time-of-flight measurements with three detectors.

The relative efficiency of the neutron detectors as a function of incident neutron energy was calculated by a Monte Carlo code which was developed and experimentally verified by Textor and Verbinski.[2]

In addition to achieving good energy resolution for the neutron groups, we also wanted to obtain good absolute values for the positions of the excited states in the residual nucleus. We used the following method to obtain excitation energies: Having calibrated the time-to-pulse-height converter system, we obtained accurate differences in flight times for the different neutron groups. We then calculated the neutron energy of the ground-state group from the known Q value and incident proton energy. Knowing the flight path we calculated the flight time of this group, and from the measured time differences we obtained the flight times of the other groups and, hence, the neutron energies and Q values.

The proton energies of 5 to 6 MeV were known to ±2 to 3 keV. From Table I we see that the ground-state Q values are also known to ±2 to 3 keV. An analysis of the expected errors in energy differences of excited states caused by errors in proton energy, ΔE_p, and errors in Q values, ΔQ, shows the following:

$$\Delta(E_f - E_0) = [\Delta E_p^2 + \Delta Q^2]^{1/2}\left[1 - \left(\frac{E_{nf}}{E_{n0}}\right)^{3/2}\right].$$

In this formula E_0 is the excitation energy of the calibration neutron group and E_f is the unknown excitation energy. E_{nf} and E_{n0} are the energies of the two neutron groups. This expression shows that if E_{nf} is much less than E_{n0}, then the error in excitation energy is about equal to the errors in E_p and Q. This case applies to the determination of the energies of the highest excited states. On the other hand, for low-lying excited states E_{nf} is not very different from E_{n0} and in this case the above relation shows that errors in E_p and Q have little influence on the error in the excitation energy. For low-lying states the principal source of error results from inaccuracies in the time difference of the neutron groups.

The best energy resolution was obtained for neutron groups with energies in the range 0.5 to 1.5 MeV. We therefore restricted our time-of-flight spectra to neutron groups in this energy range. The general procedure was to take a series of spectra at successively higher proton bombarding ener-

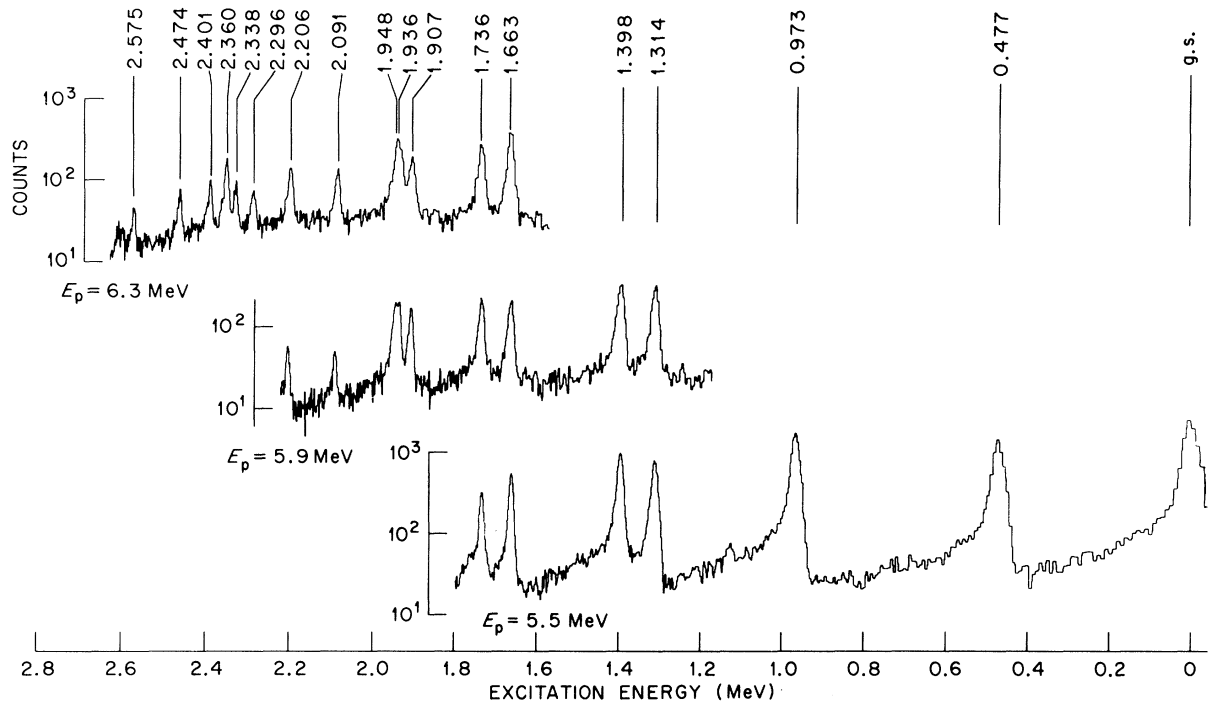

FIG. 2. Time-of-flight spectra for the ^{61}Ni$(p,n)^{61}$Cu reaction at three proton energies. The horizontal scale has been converted to excitation energy (MeV), with labels for the levels in the residual nucleus ^{61}Cu.

gies. In this way we were assured that the levels in each region of the residual nucleus were scrutinized with our best resolution.

III. RESULTS ON ENERGY LEVELS

A. ^{61}Cu Nucleus

Three representative neutron time-of-flight spectra for the ^{61}Ni$(p,n)^{61}$Cu reaction are shown in Fig. 2. Eighteen levels up to an excitation energy of 2.6 MeV were observed for ^{61}Cu. The present results are compared in Table II with the previously summarized information of Vervier.[3] This summary is based principally on the $(^3\mathrm{He},d)$ work by Pullen and Rosner[4] and the (p,α) work of Brown *et al.*[5] There is good over-all agreement. The triplet of levels at 1.93 MeV is confirmed. Tests for doublet structure in the ^{61}Cu spectra gave no hint of closely spaced levels. This should eliminate possible doublets spaced farther apart than 7 keV unless one peak of the pair is quite weak.

Hoffman and Sarantities[6] recently published a study of the decay of ^{61}Zn to states in ^{61}Cu. The levels they observed are also given in Table II. We are particularly pleased with the good agreement in absolute energies obtained by the present (p,n) results and the more accurate results from measurement of γ-ray energies.

B. ^{64}Cu Nucleus

Representative neutron time-of-flight spectra for the ^{64}Ni$(p,n)^{64}$Cu reaction are shown in Fig. 3. Some 62 levels were identified up to an excitation energy of 2.8 MeV. The ^{64}Cu levels are compared with other work in Table III. The table shows a summary of levels from neutron capture γ rays[7]

TABLE II. A listing of the level energies and uncertainties from the present ^{61}Ni$(p,n)^{61}$Cu reaction with a comparison with earlier work.

Level number	Excitation energy (keV) Present work	Summary (Ref. 3)	^{61}Zn decay (Ref. 6)
1	0	0	0
2	477±1	474±6	476.3±0.2
3	973±2	969±8	970.7±0.1
4	1314±2	1306±9	1311.1±0.6
5	1398±2	1388±8	1394.9±0.9
6	1663±2	1645±11	1661.4±0.4
7	1736±2	1726±15	
8	1907±2	1897±15	1908.1±2.0
9	1936±3	1927±11	1934.8±0.5
10	1948±3	1947±15	
11	2091±2	2093±9	2090.9±0.5
12	2206±2	2207±11	
13	2296±2	2287±15	
14	2338±2	2330±15	
15	2360±3	2362±9	2359.2±1.0
16	2401±3	2391±9	
17	2474±3	2473±9	2474.3±0.9
18	2575±3	2574±15	

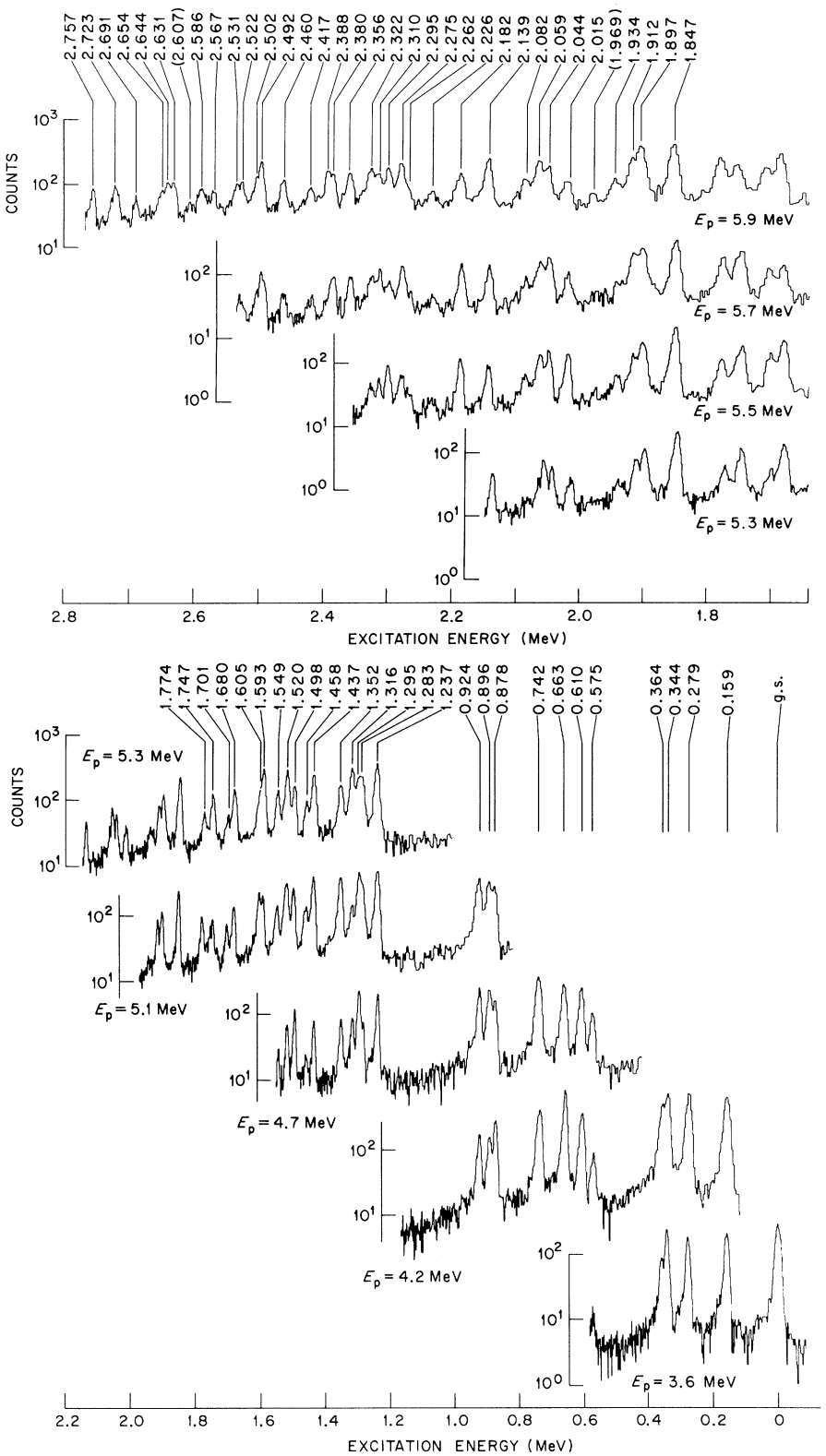

FIG. 3. Eight time-of-flight spectra for the ^{64}Ni$(p,n)^{64}$Cu reaction. The horizontal scale is expanded for the more complicated higher energy levels.

TABLE III. A listing of the level energies and uncertainties from the present ^{64}Ni$(p,n)^{64}$Cu reaction with a comparison with earlier work. Values in parentheses denote tentative values.

Level number	Excitation energy (keV) Present work	(n,γ) (Ref. 7)	(d,p) (d,α) (Ref. 8)	Level number	Present work	(n,γ) (Ref. 7)	(d,p) (d,α) (Ref. 8)
1	0	0	0	38	(1969) ± 6		1980
2	159 ± 2	159.3	158	39	2015 ± 4		2016
3	279 ± 2	278.2	276	40	2044 ± 4	2050	2050
4	344 ± 2	343.9	342	41	2059 ± 4		2069
5	364 ± 2	362.0	361	42	2082 ± 6		2090
6	575 ± 2	574.1	573	(43)			(2115)
7	610 ± 2	608.7	606	44	2139 ± 5	2145	2141
8	663 ± 2	662.9	661	45	2182 ± 5		2191
9	742 ± 2 [a]	739.0	742 [a]	(46)			2212
10		746.1		47	2226 ± 6		2230
11	878 ± 3	877.8	876	(48)			(2249)
12	896 ± 3	895.1	893	49	2262 ± 6		2265 [a]
13	924 ± 3	926.8	923	50	2275 ± 5	2280	
14	1237 ± 3	1242	1236	51	2295 ± 5		(2294)
15	1283 ± 4	1288	(1285)	52	2310 ± 5	2316	2311
16	1295 ± 4	1299	1294	53	2322 ± 5		2327
17	1316 ± 3	1322		54	2356 ± 5		(2354)
18	1352 ± 3		1349	55	2380 ± 6		2375
(19)		1363	(1360)	56	2388 ± 7		2389
20	1437 ± 3	1440	1435	57	2417 ± 6		(2415) [b]
21	1458 ± 3		(1458) [a]	58	2460 ± 6	2466	2462
22	1498 ± 3	1498	1495	59	2492 ± 6	2498	2494
23	1520 ± 4	1522	1517	60	2502 ± 7		
24	1549 ± 4		1546 [a]	61	2522 ± 7		(2520) [a]
25	1593 ± 5	1594	1589 [a]	62	2531 ± 7		(2534) [a]
26	1605 ± 5		1607	63			(2550)
(27)			(1630)	64	2567 ± 6	2575	
(28)			(1648) [a]	65			2581
29	1680 ± 4	1683	1678 [a]	66	2586 ± 6		(2596)
30	1701 ± 4		1701	67	2607 ± 7		(2611) [a]
31	1747 ± 4 [a]		(1737)	68			(2622)
32	1774 ± 4	1780	1775	69	2631 ± 7	2636	2634 [a]
33	1847 ± 4	1854	1848	70	2644 ± 8		2647 [a]
(34)			(1884)	71	2654 ± 8		(2670)
35	1897 ± 4	1906	1900	72	2691 ± 7		2692 [a]
36	1912 ± 4			73	2723 ± 7 [a]	2727	2720 [a]
37	1934 ± 5		(1939)	74	2757 ± 7	2764	2760 [a]

[a] Doublet.

[b] Triplet.

and the recent work of Park and Daehnick[8] on the (d,p) and (d,α) reactions. Values enclosed by parentheses indicate doubtful levels.

The levels labeled 1 through 16 are supported by evidence from all the reactions. By the nature of the process we would not expect the (n,γ) reaction to populate all the levels in observable intensity, and we note that as we proceed to higher excitation energies there are progressively fewer entries in the (n,γ) column. In general the present (p,n) results agree well with the (d,p) and (d,α) results of Park and Daehnick. They list ten additional states which were not seen by us. Eight of these states were listed as doubtful. We believe the states numbered 19, 27, 28, 34, 43, 46, and 48 are spurious. The state labeled 19 is also said to be seen in the (n,γ) reaction; however, the evidence is quite weak. On the other hand, Park and Daehnick list the states 15, 21, 31, 37, 51, 54, 57, 61, 62, etc., as doubtful and we have confirmed that these states are present in the (p,n) reaction. The five levels labeled 17, 36, 50, 60, and 64 were not seen in the (d,p) and (d,α) reactions but were seen as fairly strong peaks in the (p,n) reaction. Some evidence for the states 17, 50, and 64 is also from the (n,γ) reaction.

C. ^{67}Ga Nucleus

Representative neutron time-of-flight spectra for the ^{67}Zn$(p,n)^{67}$Ga reaction are shown in Fig. 4.

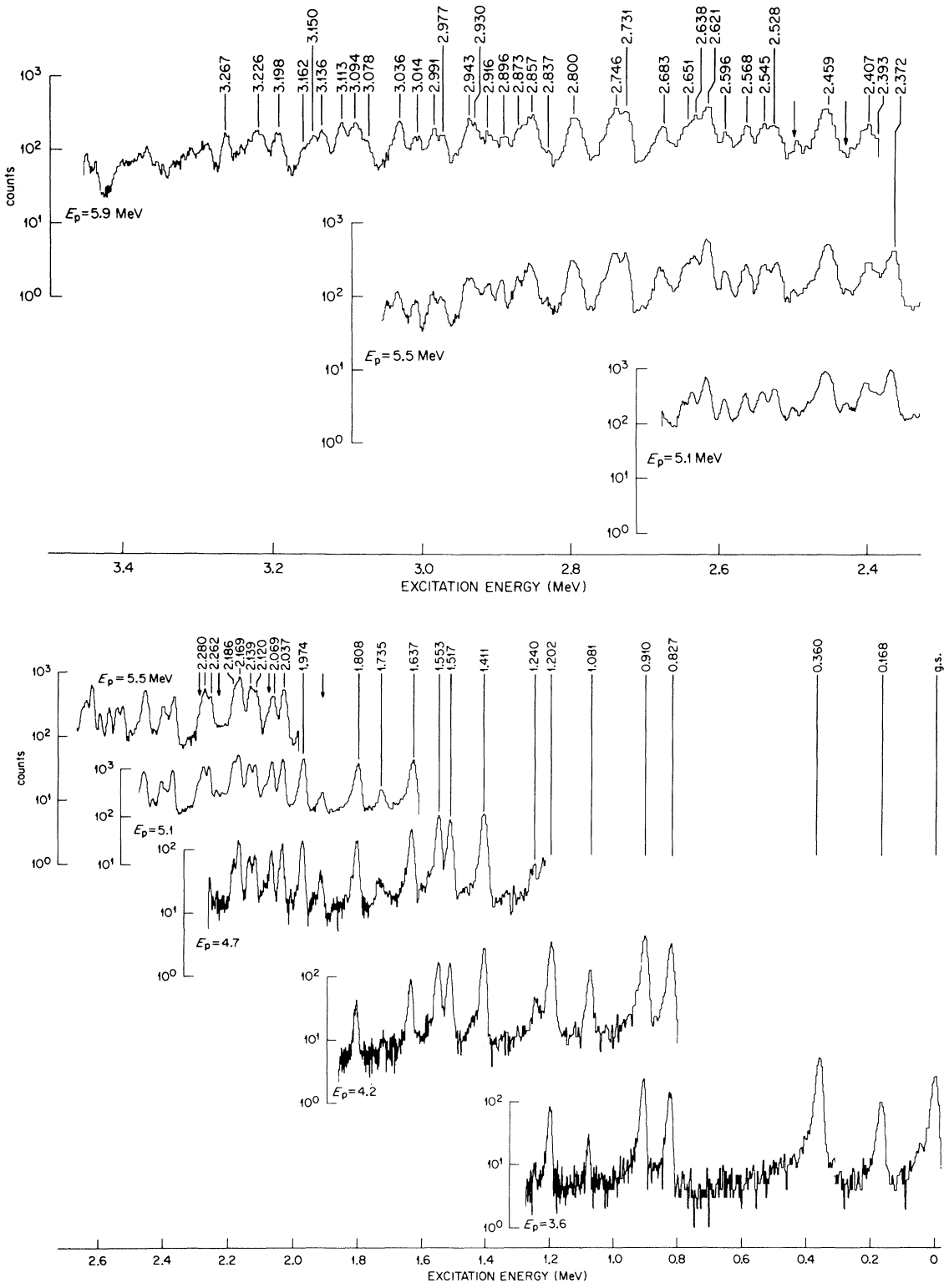

FIG. 4. Six time-of-flight spectra for the ^{67}Zn$(p,n)^{67}$Ga reaction. The horizontal scale is expanded for the more complicated higher energy levels.

TABLE IV. A listing of the level energies and uncertainties from the present ^{67}Zn$(p,n)^{67}$Ga reaction with a comparison with earlier work.

Level number	Excitation energy (keV) Present work	^{67}Ge decay (Ref. 9)	(p,n) (Ref. 10)	Level number	Present work	^{67}Ge decay (Ref. 9)	(p,n) (Ref. 10)
1	0	0	0	30	2568±6		
2	168±2	167.0	165	31	2596±6		
3	360±2	359.5	355	32	2621±6	2619.5	
4	827±2	828.3	826	33	2638±7		
5	910±3	911.2	909	34	2651±7		
6	1081±3	1081.8	1082	35	2683±6		
7	1202±3	1203	1205	36	2731±6	2730.6	
8	1240±5			37	2746±6		2737
9	1411±3		1414	38	2800±6 [b]		2795
10	1517±4		1515	39	2837±8		
11	1553±4	1556	1548	40	2857±7		2852
12	1637±4	1639.9	1640	41	2873±8		
13	1735±5			42	2896±7		2890
14	1808±4	1810.0	1810	43	2916±7		
15	1974±4	1967	1967	44	2930±8		2929
16	2037±4		2030	45	2943±8		
17	2069±4		2063	46	2977±7		2975
18	2120±5		2120	47	2991±7		
19	2139±5			48	3014±7		3024
20	2169±5		2173	49	3036±7		
21	2186±6			50	3078±8		3080
22	2262±5		2275	51	3094±7		3100
23	2280±5			52	3113±7		3130
24	2372±5			53	3136±7		
25	2393±7 [a]		2393	54	3150±7		
26	2407±6 [a]			55	3162±8	3162.3	
27	2459±6 [b]		2463	56	3198±7		
28	2528±6	2527		57	3226±8 [c]	3225.3	
29	2545±6		2541	58	3267±8		

[a] These two levels could form a triplet. [b] Doublet. [c] Triplet.

Some of the neutron groups are assigned to the ^{68}Zn$(p,n)^{68}$Ga reaction due to the small amount of ^{68}Zn in the target. These groups (beginning with the ground-state group at an apparent excitation energy of 1.916 MeV) are indicated by arrows in the figure. A total of 58 levels in ^{67}Ga up to an excitation energy of 3.3 MeV were identified. Table IV shows the present (p,n) results with information coming from the decay of ^{67}Ge [9] and another (p,n) reaction study by Finckh *et al.*[10] Fifteen new levels are identified. Eight previously unresolved doublets and one triplet were separated at energies of about 2.27, 2.54, 2.74, 2.94, 2.98, 3.03, 3.08, and 3.10 MeV.

D. ^{68}Ga Nucleus

Representative neutron time-of-flight spectra for the ^{68}Zn$(p,n)^{68}$Ga reaction are shown in Fig. 5. A total of 33 levels were identified in the first 1.6 MeV of excitation in ^{68}Ga. The present results are compared with the recent summary by Rao[11] and the recent (p,n) results of Egan *et al.*[12] in Table V. A triplet of levels at 556, 568, and 587 keV suggested by Birstein *et al.*[13] is confirmed by our work. A level at 1088 keV from the previous (p,n) work of Egan *et al.* is resolved into a doublet of levels at 1066 and 1107 keV.

A very narrow doublet with a separation of 1 keV has been suggested by Birstein *et al.* for the state at 378 keV. We see no broadening of this state as would be expected if the spacing is so close. However, the yield of this neutron group indicates that it is indeed a doublet (see below).

IV. RESULTS ON SPIN ASSIGNMENTS

From the sample spectra shown in Figs. 2–5 it is evident that the pattern of relative intensities of the neutron groups is roughly independent of the proton bombarding energy. Presumably these intensity patterns reflect the spin-parity characteristic of the residual excited states. This would be the case if one accepts the validity of the simple

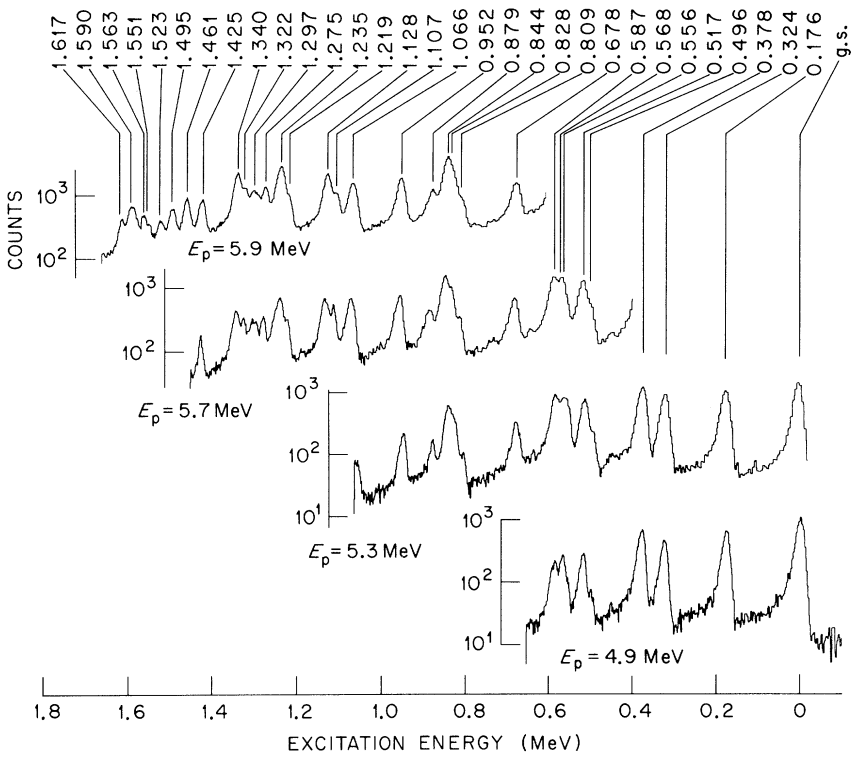

FIG. 5. Four ^{68}Zn(p,n)-^{68}Ga time-of-flight spectra. Excitation energies for ^{68}Ga levels are labeled.

Hauser-Feshbach statistical theory for the (p,n) mechanism. From an experimental viewpoint we were interested in finding out just how constant the intensity ratios for the neutron groups were when small changes were made in the proton bombarding energy. Figures 6–8 show a series of relative cross sections for the (p,n) reactions on the targets ^{64}Ni, ^{67}Zn, and ^{68}Zn. The cross sections were measured at a series of closely spaced proton energies (about 10-keV steps) at several widely spaced proton energy regions. The statistical uncertainty is smaller than the size of the points except where indicated. We immediately perceive that there are sizeable fluctuations in the relative cross sections. The fluctuations are more pronounced for ^{64}Ni than for ^{68}Zn. It is curious that the fluctuations seem to occur with equal intensity at low and high proton bombarding energies.

These fluctuations suggest that we have not achieved a good statistical average within a sampling interval of a few keV. If we were to increase the target thickness to 100 keV to achieve better averaging, we would ruin the energy resolution needed to separate the individual neutron groups. Therefore, to obtain a better statistical average and yet maintain good energy resolution, we took a series of spectra at closely spaced proton energies and averaged over the total (~100 keV width).

Another source of difficulty in applying the Hauser-Feshbach theory is the presence of isobaric analog resonances in the (p,n) reaction. Cross sections inadvertently measured at such resonances will not reflect the purely statistical averaging of compound states envisaged by the Hauser-Feshbach theory. Resonances in the ^{64}Ni$(p,n)^{64}$Cu reaction which were attributed to analog states have been reported by Lee and Schiffer.[14] Resonances were observed at proton energies of 3.90, 4.53, and 5.10 MeV and, as can be seen from Fig. 6, these proton energies were avoided in our measurements. Similarly, the known analog resonances in the ^{68}Zn$(p,n)^{68}$Ga reaction were avoided (Egan *et al.*[12]). In the case of the ^{67}Zn$(p,n)^{67}$Cu reaction the density of analog states is expected to be quite high at our proton bombarding energies and so they can scarcely be avoided. Hopefully, under these circumstances the situation will tend to revert back to the statistical case.

We used the computer program of Wilmore[15] to calculate Hauser-Feshbach cross sections. The optical-model potentials of Perey[16] for protons and of Buck and Perey[17] for neutrons were used to calculate the barrier transmission coefficients. The spin-orbit term was omitted. We must also face the question of whether or not to include the effect of width fluctuations. As Moldauer[18] has pointed out, the inclusion of fluctuations can alter the absolute cross very appreciably if one has only a few channels open for decay. Our cases involved many channels for decay, which reduces the fluctuation

TABLE V. A listing of the level energies and uncertainties from the present ^{68}Zn$(p,n)^{68}$Ga reaction with a comparison with earlier work.

Level number	Excitation energy (keV) Present work	Summary (Ref. 11)	(p,n) (Ref. 12)
1	0	0	0
2	176 ± 2	174.9	180
3	324 ± 2	321	331
4	378 ± 2 [a]	374.7	378
5		375.6	
6	496 ± 4		
7	517 ± 3	511	513
8	556 ± 5	555	562
9	568 ± 4	565	580
10	587 ± 3	585	
11	678 ± 3		673
12	809 ± 4		
13	828 ± 5	828	828
14	844 ± 4		
15	879 ± 3	879	
16	952 ± 3		948
17	1066 ± 3		1088
18	1107 ± 4	1109	
19	1128 ± 3		
20	1219 ± 5		
21	1239 ± 4 [b]		
22	1275 ± 3		
23	1297 ± 3 [b]		
24	1322 ± 4		
25	1340 ± 4		
26	1425 ± 4		
27	1461 ± 4		
28	1495 ± 4		
29	1523 ± 4		
30	1551 ± 5		
31	1563 ± 4		
32	1590 ± 4 [b]		
33	1617 ± 4		

[a] Thought to be a doublet from Hauser-Feshbach analysis.
[b] Doublet.

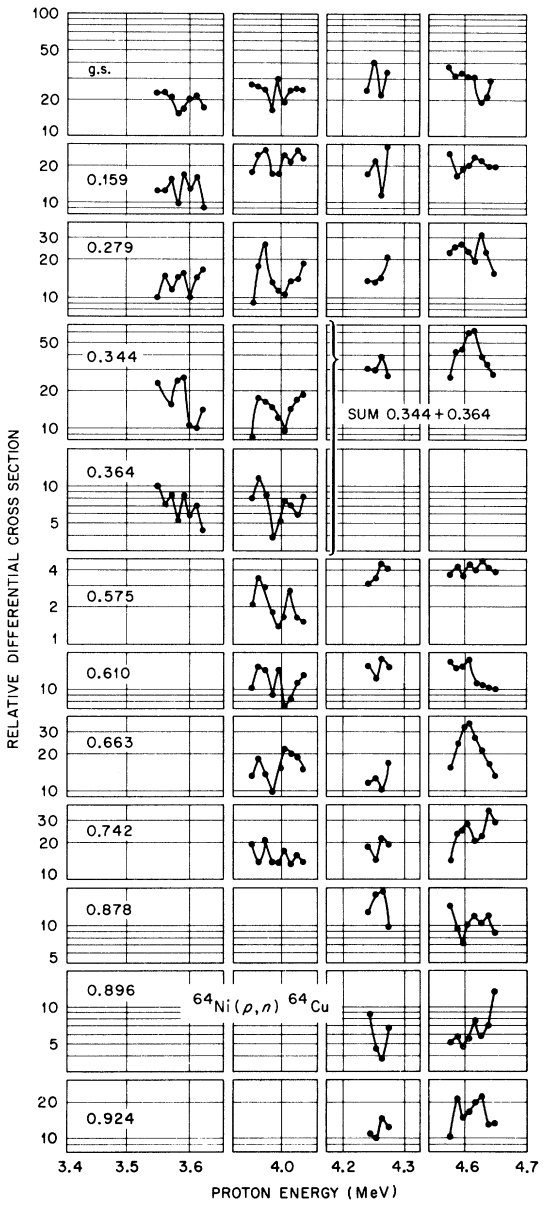

FIG. 6. Partial excitation functions for some of the yields to the levels in the residual nucleus of the reaction ^{64}Ni$(p,n)^{64}$Cu. Each state is labeled with excitation energy in keV.

correction. The inclusion of fluctuations make little difference in the predicted ratios of cross sections.

We must also decide how many exit channels to include in the Hauser-Feshbach calculations. We initially included a number of exit proton channels but they were found to have very little effect on the neutron channel cross-section ratios and were eliminated for most of the calculations. The neutron exit channels leading to higher excited states in the residual nucleus have unknown spin-parity characteristics. We arbitrarily assume a statistical mixture of spin-parity assignments. Altering these assignments produces rather negligible differences on cross-section ratios for the lower-lying states of the residual nucleus. Of course, the energies of states were not assumed but were taken from our previously described work on the spectroscopy of the states.

The ground states of ^{64}Cu, ^{67}Ga, and ^{68}Ga have known spin-parity assignments, viz., 1^+, $\frac{3}{2}^-$, and 1^+, respectively. We therefore compare experimental and theoretical ratios of excited state cross sections with ground-state cross sections. To illustrate the possibilities for spin-parity assignments from the (p,n) reaction we present three representative cases in Fig. 9. For example, we

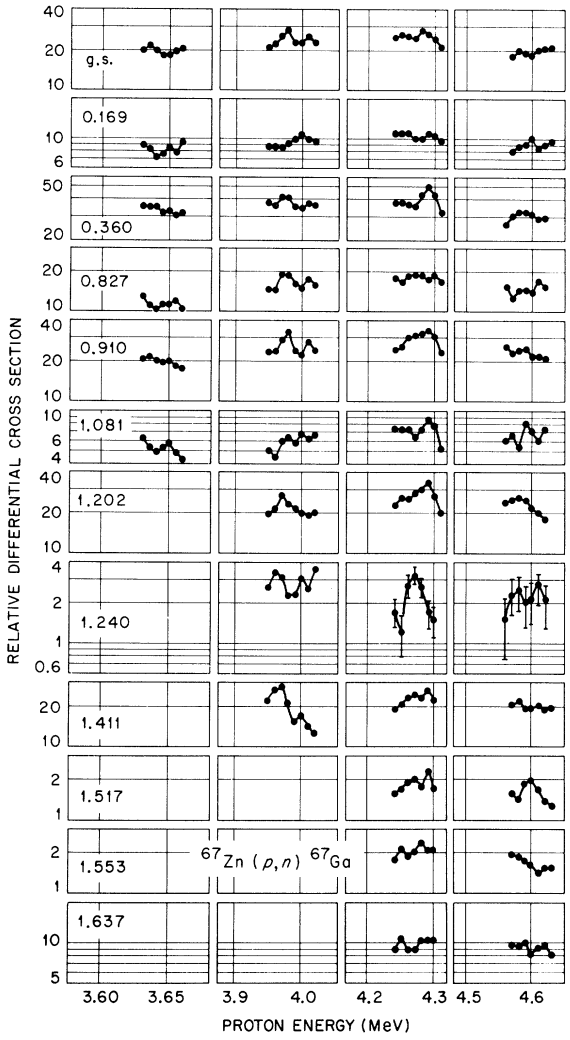

FIG. 7. Partial excitation functions for yields to the residual nucleus in the ^{67}Zn$(p,n)^{67}$Ga reaction.

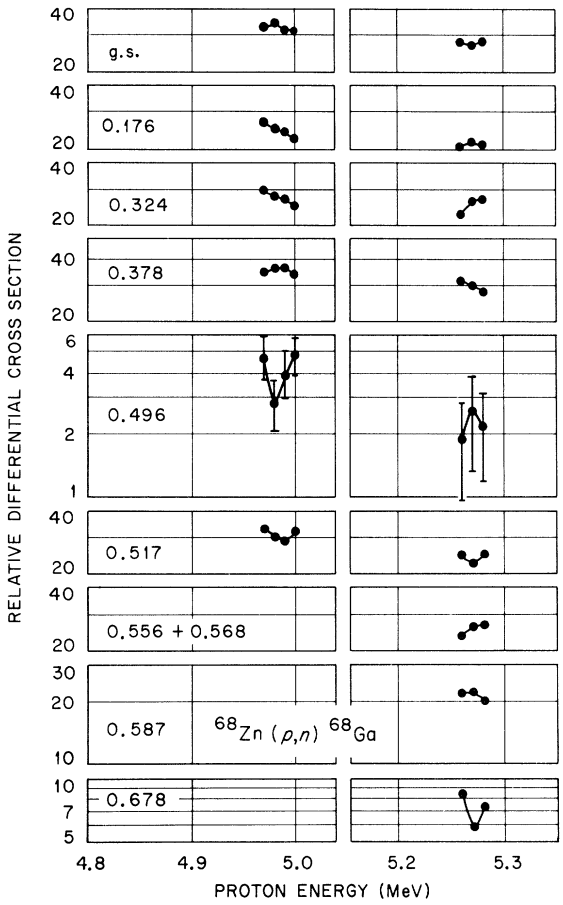

FIG. 8. Partial excitation functions for yields to the residual nucleus in the ^{68}Zn$(p,n)^{68}$Ga reaction.

calculated the expected cross for the 0.168-MeV state in ^{67}Ga for a series of possible spin-parity assignments for a proton bombarding energy of 4.28 MeV. Similar cases are shown for the 0.344-MeV state in ^{64}Cu and the 0.176-MeV state in ^{68}Ga. From a study of Fig. 9 it is evident that one will extract more useful information about spins than about parities. Even the spin assignment information may sometimes be ambiguous. For example in the ^{68}Ga case given in Fig. 9, the cross sections for 0^+ and 3^+ assignments are nearly the same. On the other hand, the expected cross sections for spin 4^+ or 4^- are rather different from those for any other possible spin assignment.

A. Spins of ^{64}Cu Levels

The comparison of observed cross-section ratios (excited state to ground state) to calculated cross sections for different possible spin assignments to the excited state is shown in Fig. 10. Extensive information on the spin-parity assignments of levels in ^{64}Cu is available from the (d,p) and (d,α) experiments of Park and Daehnick[8] and from the (n,γ) work of Shera and Bolotin.[7] In Table VI we compare our information on spins with the previous information. Generally speaking the agreement is quite satisfactory. All the experimental evidence indicates that the 159-, 279-, and 344-keV states are 2^+. There is also agreement that the 364- and 575-keV states are, respectively, 3^+ and 4^+. If the 3^+ assignment for the 364-keV state is correct, then we find the best spin for the 344-keV state to be 2^+, which agrees with the (d,p) and (d,α) work and also the (n,γ) conjecture of 1^+ or 2^+. For the 610-keV level, we find 0^+ most likely, although 2^+ is also possible and would agree with the other work. A 1^+ assignment seems very likely for the 663-keV level, in harmony with 1^+ or 2^+ suggested in the (n,γ) paper, and also the (d,p) val-

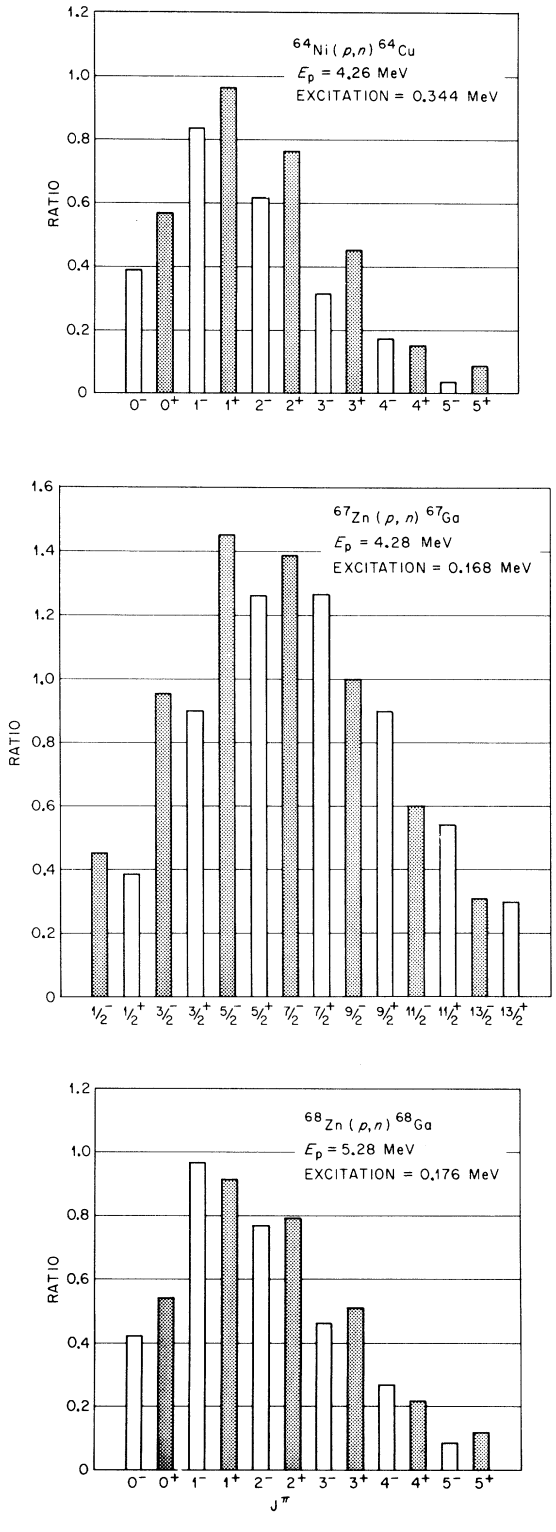

FIG. 9. Theoretical predictions, using the Hauser-Feshbach formalism, for the cross-section ratios of selected excited states to the ground state. Proton energies are typical of those used for the reactions on the three nuclei.

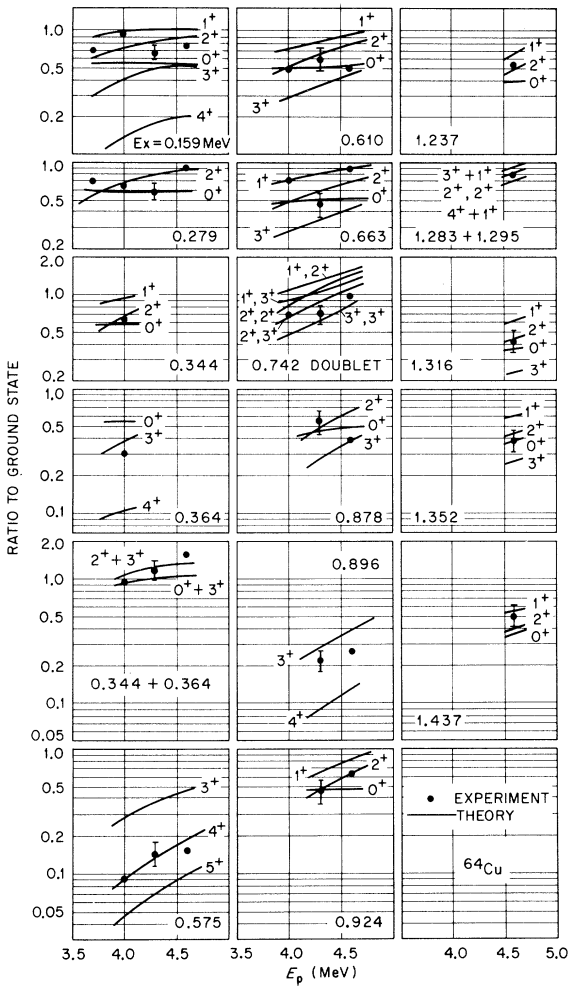

FIG. 10. Comparison of experimental and theoretical cross-section ratios of excited state to ground state for ^{64}Ni$(p,n)^{64}$Cu. Each case is labeled with spin, parity, and excitation energy (MeV). The experimental points typically represent averages for about eight closely spaced (10 keV) proton energies. The points shown with error bars are of poorer quality than the other points.

ues, but in disagreement with 3^+ suggested by the l transfer of 4 in the (d,α) work. Our next most likely assignment is 2^+. A 3^+ assignment would require cross sections about a factor of 2 less than those observed and is thus improbable from our work. The unresolved doublet at 742 keV could only be tested for a pair of spins. A 1^+ assignment for either state would require the companion state to have a spin of 4 or larger. A 2^+ and 3^+ combination seemed best, and agrees with the other work. The 0^+ and 3^+ assignments we obtained for the 878- and 896-keV levels are in general agreement with the other work. The 924-keV level assignment of 2^+ agrees with the (n,γ) and (d,p) work.

TABLE VI. A summary of J^π assignments to the energy levels of ^{64}Cu.

Level number	Excitation energy (keV)	Present experiment	J^π (d,p) (Ref. 8)	(d,α) (Ref. 7)
1	0	1^+ [a]	1^+	1^+
2	159	2 (1,0)	2^+	(2^+)
3	279	2 (1,0)	2^+	2^+
4	344	2 (0)	2^+	$(1^+,2^+)$
5	364	3	3^+	(3^+)
6	575	4	4^+	(4^+)
7	610	0 (2)	2^+ (1^+)	$(1^+,2^+)$
8	663	1 (2)	3^+	$(1^+,2^+)$
9	742 [b]	(3,2) [c]	$(2^+,3^+)$	$(2^+,3^+)$
10			$(1^+,2^+,3^+)$	$(1^+,2^+,3^+)$
11	878	0 (3)	0^+ $(1^+,2^+)$	$(0^+,1^+,2^+)$
12	896	3	3^+	(2^+)
13	924	2 (0,1)	1^+	$(1^+,2^+)$
14	1237	2 (1,0)	2^+ (1^+)	
15	1283	(3,4)		
16	1295	1	1^+	
17	1316	2,0 (3,1)		
18	1352	0,2 (3)	3^+	
19	1437	1 (2,0)	1^+	

[a] Known ground state J^π.
[b] Unresolved doublet.
[c] Results compatible with spin assignments 2 and 3 for doublet.

We take the remaining assignments from cross sections averaged at only one energy, and the values are somewhat less certain. The 1237-, 1295-, and 1437-keV levels are labeled, respectively, 2^+, 1^+, and 1^+ as in the (d,p) and (d,α) work. A weak level at 1283 keV appears to be either 3^+ or 4^+. The two states at 1316 and 1352 keV are assigned either 2^+ or 0^+. The (d,p) and (d,α) work assigned the somewhat less likely (in our work) 3^+ assignment to the 1352-keV level.

B. Spins of ^{67}Ga Levels

The Hauser-Feshbach cross-section ratios are compared with experimental values in Fig. 11. For this nucleus several predictions were ambiguous at lower excitation energies, notably the pairs $\frac{5}{2}^-$, $\frac{7}{2}^-$, and $\frac{3}{2}^-$, $\frac{9}{2}^-$. We found the first excited state to be an unambiguous $\frac{1}{2}^-$. The states at 360 and 910 keV were consistent with the $\frac{5}{2}^-$ or $\frac{7}{2}^-$. The 827-keV level best matched $\frac{3}{2}^-$ or $\frac{9}{2}^-$. Another more obvious assignment was $\frac{1}{2}^-$ at 1081 keV. Table VII shows these predictions are consistent with the (d,n) work of Couch *et al.*[18] and also the ^{67}Ge decay work of Zoller,[9] except for the latter's tentative assignment of $\frac{3}{2}^-$ to the 910-keV level. Following another $\frac{5}{2}^-$ or $\frac{7}{2}^-$ state at 1202 keV, which is consistent with the other work, we see a weak level at 1240 keV, with cross sections closely fitting a predicted $\frac{13}{2}^-$. Three stronger states appear at 1411, 1517, and 1553 keV with a $\frac{5}{2}^-$ or $\frac{7}{2}^-$ assignment. The first three had no assignments in the other papers, and the last agrees with the ^{67}Ge decay and is consistent with the (d,n) label of $\frac{5}{2}^-$. For the 1637-keV state, the $\frac{9}{2}^-$ and $\frac{3}{2}^-$ predictions are better separated. This level and another level at 1808 keV appear to be $\frac{3}{2}^-$, with $\frac{9}{2}^-$ somewhat less likely. Both of these possible spins for the 1808-keV state disagree with the (d,n) $\frac{1}{2}^-$ or $\frac{5}{2}^-$ assignments. However, the assignments of that work are based largely on shell-model systematics. We saw another very weak state at 1735 keV, which required an assignment as high as $\frac{15}{2}^-$ or $\frac{17}{2}^-$. Two states at 1974 and 2037 keV are best fitted by a $\frac{5}{2}^-$ or $\frac{7}{2}^-$ assignment. A single energy average yielded spins of $\frac{3}{2}^-$ or $\frac{9}{2}^-$ for the remaining two states at 2069 and 2120 keV. The last four assignments are new.

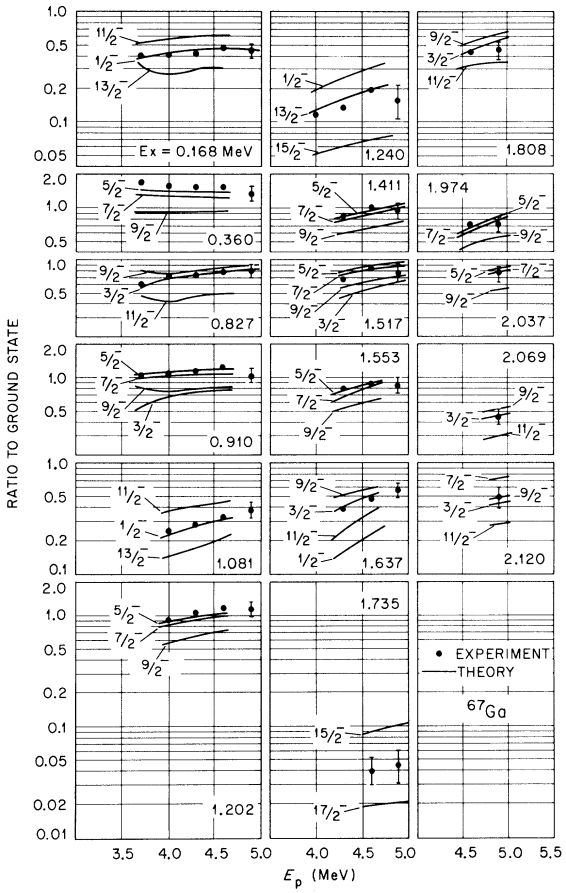

FIG. 11. Comparison of experimental and theoretical cross-section ratios for ^{67}Zn$(p,n)^{67}$Ga.

C. Spins of ^{68}Ga Levels

The cross-section ratios for ten excited states are compared with theory in Fig. 12. Table VIII shows that the assignment for six states are in

TABLE VII. A summary of J^π assignments to the energy levels of ^{67}Ga.

Level number	Excitation energy (keV)	J^π Present experiment	J^π (d,n) (Ref. 18)	J^π ^{67}Ge decay (Ref. 9)
1	0	$\frac{3}{2}^-$ [a]	$\frac{3}{2}^-$	$\frac{3}{2}^-$
2	168	$\frac{1}{2}$	$(\frac{1}{2}^-)$	$\frac{1}{2}^-$
3	360	$\frac{5}{2}, \frac{7}{2}$	$(\frac{5}{2}^-)$	$\frac{5}{2}^-$
4	827	$\frac{3}{2}, \frac{9}{2}$	$(\frac{3}{2}^-)$	$(\frac{3}{2}^-)$
5	910	$\frac{5}{2}, \frac{7}{2}$		$(\frac{3}{2}^-)$
6	1081	$\frac{1}{2}$	$(\frac{1}{2}^-)$	$(\frac{1}{2}^-)$
7	1202	$\frac{5}{2}, \frac{7}{2}$	$(\frac{7}{2}^-)$	$(\frac{5}{2}^-, \frac{7}{2}^-)$
8	1240	$\frac{13}{2}$		
9	1411	$\frac{5}{2}, \frac{7}{2}$		
10	1517	$\frac{7}{2}, \frac{5}{2}(\frac{9}{2})$		
11	1553	$\frac{5}{2}, \frac{7}{2}(\frac{9}{2})$	$(\frac{5}{2}^-)$	$(\frac{5}{2}^-, \frac{7}{2}^-)$
12	1637	$\frac{3}{2}(\frac{9}{2})$		
13	1735	$\frac{15}{2}, \frac{17}{2}$		
14	1808	$\frac{3}{2}(\frac{9}{2}, \frac{11}{2})$	$(\frac{1}{2}^-, \frac{5}{2}^-)$	
15	1974	$\frac{7}{2}, \frac{5}{2}$		
16	2037	$\frac{5}{2}, \frac{7}{2}(\frac{9}{2})$		
17	2069	$\frac{3}{2}, \frac{9}{2}(\frac{11}{2})$		
18	2120	$\frac{3}{2}, \frac{9}{2}(\frac{7}{2}, \frac{11}{2})$		

[a] Known ground state J^π.

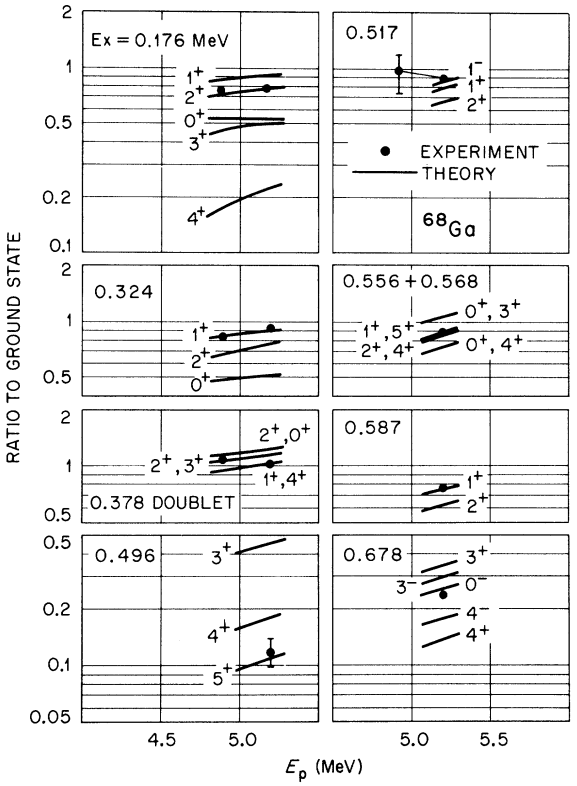

FIG. 12. Comparison of experimental and theoretical cross-section ratios for ^{68}Zn$(p,n)^{68}$Ga.

TABLE VIII. A summary of J^π assignments to the energy levels of ^{68}Ga.

Level number	Excitation energy (keV)	J^π Present experiment	J^π Summary (Ref. 11)	J^π (p,n) (Ref. 12)
1	0	1^+ [a]	1^+	1^+
2	176	2 (1)	$2^{(+)}$	2^+
3	324	1 (2)	$1^{(+)}, 2^{(+)}$	1^+
4	378 [b]	2 + 3 [c]	$2^{(+)}$	2^+
5			$3^{(+)}$	
6	496	5 (4)		
7	517	1 (2)		(1^-)
8	556	(4)		(2^+)
9	568 [b]	(2)		
10	587	1 (2)		(1^-)
11	678	0 (3,4)		

[a] Known ground state J^π.

[b] Unresolved doublet.

[c] Results compatible with spin assignments 2 and 3 for doublet.

good agreement with (p,n) results of Egan *et al.*[12] and Rao.[11] The first two levels, at 176 and 324 keV, are given 2^+ and 1^+ as in the other work. Our spectra do not resolve a doublet at 378 keV, and the pair of spins most consistent with both our data and previous work is 2^+ and 3^+. We labeled the very weak 496-keV state 5^+. A 4^+ assignment would be slightly less probable. Levels at 517 and 587 keV appear to be 1^+ or 1^-, in agreement with the conjecture of Egan *et al.* We resolved a doublet at 556 and 568 keV in our high-resolution work, but not in the averaged data. The combined evidence indicates 4^+ and 2^+, respectively; this is based on an estimated ratio of the two peaks of about 4:1. The 678-keV level assignment is parity dependent. Positive parity would yield 3^+ or 4^+. The best fit, however, is 0^-.

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†Oak Ridge Graduate Fellow from the University of Tennessee under appointment from the Oak Ridge Associated Universities.

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Nuclear Orientation of Iron-59 in Rare-Earth Double-Nitrate Crystals*

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Anisotropic emission of 1.10- and 1.29-MeV γ rays from Fe^{59} oriented in clear single crystals of Ce-Zn and Nd-Zn nitrates cooled by adiabatic demagnetization has been studied as a function of temperature in fields of 0 and 250 Oe. From the temperature dependence of the γ anisotropy is extracted an estimate of the nuclear magnetic dipole moment of the ground state of Fe^{59} of $(1.1\pm0.2)\mu_N$. Analysis of the data in terms of the currently accepted spin sequence $\frac{3}{2}(\beta)\frac{3}{2}(\gamma)\frac{7}{2}$ for both γ rays, assuming the fraction of Fe^{59} aligned in zero field is 0.30 ± 0.03, requires either (i) the hypothesis of Fermi contributions in excess of 30% (contrary to conserved-vector-current theory) or, alternatively, (ii) enhancement factors $Q_2=5.0\pm2.6$ and 6.7 ± 2.4 for intermediate-state reorientation in the 1.10- and 1.29-MeV levels, respectively. Admixtures of $M3$ radiation of the order 1–4% may also be involved in the interpretation.

I. INTRODUCTION

The angular distribution of γ radiation from oriented radioactive nuclei provides independent information on spin assignments, β-decay matrix elements, and γ-ray multipolarities which supplements that obtained from internal-conversion coefficients, γ-γ angular correlations, and β-γ circular polarization correlations.[1] Thus, despite the relatively large number of experimental studies[2–17] of the Fe^{59} decay, the parameters assigned the two principal decay channels *via* the 1.10- and 1.29-MeV levels in Co^{59} have undergone continual evolution and modification in the past 18 years as new information became available, and so we decided to carry out an experiment to orient Fe^{59} by the method suggested by Culvahouse and Olsen.[18] This method is reviewed and the theoretical framework set up in Sec. II, after which the experimental data are presented in Sec. III and their implications discussed in Sec. IV.

II. NUCLEAR-ORIENTATION METHOD

Spin-Hamiltonian coefficients corresponding to sharp-line electron paramagnetic resonance (EPR) spectra of Fe^{3+} ions in two sites in La-Zn nitrate (LZN) and Ce-Zn nitrate (CZN) have been measured by Culvahouse and Olsen.[18] The essential feature of these data is that D, the coefficient of the second-degree axial crystal field term $D(S_z^2-\frac{35}{12})$, is negative and much larger in magnitude than either the fourth-degree term or the isotropic hfs coefficient A of Fe^{57}, just the condition discussed by Bleaney[19] for nuclear orientation described, as a result of the $M_s=\pm\frac{5}{2}$ states lying lowest, by an effective spin Hamiltonian

$$H=g'_{\parallel}\beta H_z S'_z+g'_{\perp}\beta(H_x S'_x+H_y S'_y)+A' I_z S'_z+B'(I_x S'_x+I_y S'_y)\,, \tag{1}$$

with