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States of ^{55}Co via the ^{58}Ni(p, α)^{55}Co reaction*

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α particles from the ^{58}Ni(p,α)^{55}Co reaction were analyzed with a 100-cm modified broad-range magnetic spectrograph. Data were taken at nominal bombarding energies from 12 to 16 MeV and at the observation angles of 60, 90, and 120°. 90 levels have been identified in ^{55}Co in the region of excitation from the ground state to 6.6 MeV. Below 3 MeV, a new level at 2.9785 MeV has been observed and the existence of two levels at 2.9238 and 2.9428 MeV has been further verified. 47 previously unreported levels have been observed and uncertainties in excitation energies have been reduced in many cases by as much as a factor of 6 or more. The possibility of a 33-fold degeneracy in the 1160-keV γ-ray transition and a 25-fold degeneracy in the 1600-keV γ-ray transition which are seen in (p,γ) is discussed.

[NUCLEAR REACTIONS ^{58}Ni(p, α), E=12–16 MeV; ^{55}Co levels deduced. Enriched targets. θ=60–120°.]

INTRODUCTION

In the simplest form the shell-model configuration of ^{55}Co is a single proton hole in the doubly closed $f_{7/2}$ shell. This expected simplicity has encouraged many recent investigations of the level structure using single-particle transfer reactions.[1-7] Much of the emphasis of the work has been to locate and identify the single-particle states and $T=\frac{3}{2}$ analog states. The precision quoted for the excitation energies measured in many of these experiments however, has been rather low, between 10 and 30 keV even for the low-lying states. In a recent measurement of the ^{54}Fe(^{3}He, $d\gamma$) reaction Shoup, Fox, and Brown[5] quote an uncertainty of ±20 keV for all levels. A comparison with the ^{54}Fe(d,n) studies of Hagen, Janetzki, and Maier,[6] who also quote a precision of ±20 keV for all excitation energies, reveals discrepancies in the positions and even the number of levels seen in the two reactions. Martin *et al.*[8] who quote uncertainties of ±1 to ±2 keV for levels seen in their study of the ^{54}Fe(p,γ) reaction, report a level at 2.918 MeV which had not previously been published and thus confirm earlier speculation of the existence of a 20-keV doublet near this energy but do not indicate having observed the 5-keV doublet at 3.866 MeV reported by Shoup, Fox, and Brown.[5] Since the spacing of the new doublet is 20 keV it is not clear why this was also not resolved by Shoup and coworkers. The purpose of the present work is to provide more experimental information about levels in ^{55}Co in an attempt to resolve some of the apparent discrepancies and to provide accurate excitation energies in the region from the ground state to about 6.5 MeV. We have chosen a (p, α) reaction for study as this reaction should populate more levels than those observed in the single-particle transfer reactions. The results of our study of the ^{58}Ni(p, α)^{55}Co reaction are discussed and presented below.

EXPERIMENTAL

Isotopically enriched ^{58}Ni targets were prepared by vacuum deposition of 99.9% pure ^{58}Ni onto 20-μg/cm^2 carbon foil backings. Several targets were used during the course of the experiment, all approximately 11 keV thick to 11-MeV α particles. Proton beams were produced with the University of Notre Dame FN tandem Van de Graaff accelerator with the nominal bombarding energy being determined by magnetic analysis. The reaction products were momentum analyzed with our 100-cm modified broad-range magnetic spectrograph[9] and nuclear track plates were used as particle detectors. Typical charge collection varied from 30 000 to 100 000 μC except for the 12-MeV, 90° run which had 8000 μC. In order to keep the inelastic proton spectrum from obscuring the α-particle spectrum and also to permit positive α-particle identification, 50-μm Ilford KO nuclear track plates were used to record most of the data as these plates are quite insensitive to protons. Data were taken at the observation angles of 60, 90, and 120° at nominal bombarding energies ranging from 12 to 16 MeV. In the ^{58}Ni(p, α) reaction the Coulomb barrier height for the outgoing α particle is approximately 10.3 MeV. The effect of the Coulomb barrier on two 90° α-particle spectra taken at 12- and 16-MeV bombarding energy, respectively, is dramatically shown in Fig. 1 and Fig. 2. In the 12-MeV spectrum only a few states are strongly populated whereas in the 16-MeV spectrum some 90 states have been identified.

In both figures contaminants have been labeled with the symbol of the residual nucleus and its excitation energy. Since most runs were very long, great care has been taken to identify contaminants and in kinematic identification of ^{55}Co α-particle groups. The ^{55}Co levels are labeled with a group number given in Table I. The double or triple peaking of α-particle groups from ^{16}O and ^{13}C is due to the presence of these elements on the front of the target and in the carbon foil backing.

RESULTS AND DISCUSSION

The results of the present work are presented in Table I. The number of runs from which values were obtained and averaged is given in column 2. The standard deviation of the mean is given in column 5. In the nine runs presented here, separation energies have been measured with respect to the ground state. In three of the runs only the separation between the ground state and first excited state was measured. The separation energies measured in this experiment are quite insensitive to the input energy and the resulting excitation energies depend mainly on the measured energy differences of the α-particle groups. The input energy for each run was determined from the position of the ground-state group on the plates and the ground-state Q value. In the 1971 Mass Tables[10] the ground-state Q value is given as -1.3583 ± 0.0039 MeV. We have recently remeasured this Q value[11] and found it to be in error by 17.3 keV. The excitation energies given here have been calculated using our value of -1.3410 ± 0.0029 MeV for the ground-state Q value. The resulting change in excitation energies with the change in Q_0 is rather small, only about 0.1 keV. In column 4 of Table I, we list the internal errors of each measurement as calculated according to the standard procedures described in Ref. 12. These include estimates of uncertainties in the following quantities: the position of a group on the plate, beam-spot position, reaction angle, input energy, spectrograph field, and spectrograph calibration curve.

We have observed several close-lying doublets in ^{55}Co. Though groups 4 and 5, 11 and 12, 16 and 17, 19 and 20, and 29 and 30 many not appear well resolved in Fig. 2, they can easily be unfolded by using the group shape of an isolated group. The large dispersion of the new spectrograph has been a great aid in this analysis. The relative change in yields to the various states with bombarding energy and angle also helps in resolving levels. Groups 4 and 5, though not very well resolved in the 16-MeV, 90° spectrum (Fig. 2), are well resolved in the 16-MeV, 120° spectrum (See Fig. 3). The target was approximately the same in the two runs. The 90° run was taken for a charge collection of 40 000 μC and the 120° run for 100 000 μC.

A comparison with other work is presented in Table I. Below 3 MeV, group 4 at 2.9238 MeV which has only recently been resolved by Martin *et al.*[8] is well populated in the (p, α) reaction. Group 6 at 2.9785 MeV, however, has never previously been published. The existence of these two levels below 3 MeV must certainly affect some of

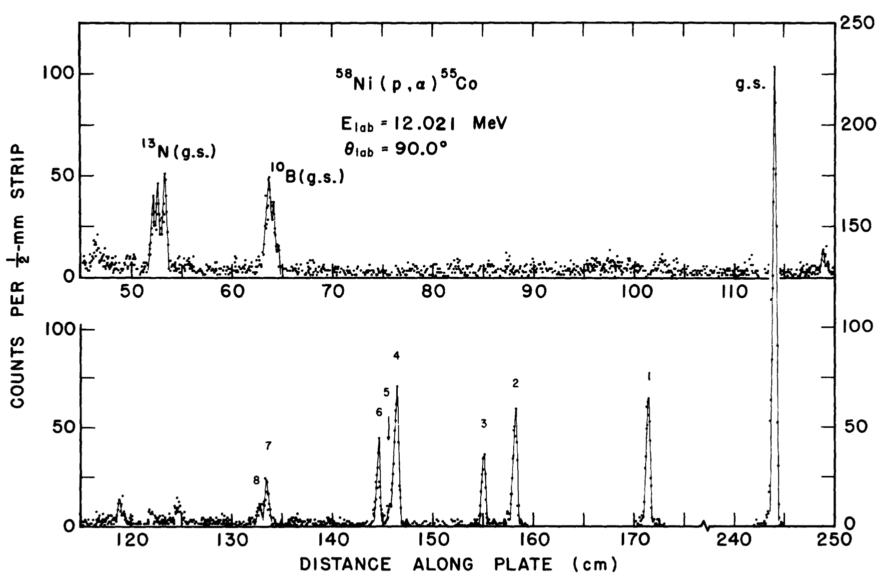

FIG. 1. Spectrum of α particles recorded with the 100-cm modified broad-range spectrograph. Note the few ^{55}Co states excited at this bombarding energy. Note the break in the distance scale to allow the g.s. to be shown.

the previous γ-ray studies of ^{55}Co. The level at 3.5670 MeV also has not previously been published and above 4 MeV some 43 new states have been identified. The level given at 3.682 ± 0.005 MeV in the Nuclear Data Sheet[13] is not observed by us nor with many of the other reactions listed. Evidence for this level appears to come primarily from the ^{54}Fe(p,γ) decay studies of Erlandsson.[14]

Comparison of the excitation energies measured in the present work with other work is made somewhat difficult by the poor precision in many of these experiments. In view of the much larger number of levels observed in the present experiment, the correspondence to previously reported levels is not always clear. In placing levels from earlier reaction data in Table I we have placed the level on the same line as the closest level from our results although we often have several levels within the uncertainties stated in previous work. In particular we see several levels in the vicinity of the analog states reported by Shoup, Fox, and Brown[5] at 4.720 ± 0.020, 5.165 ± 0.020, and 5.737 ± 0.020 MeV and by Rosner and Holbrow[1] at 4.755 MeV, 5.188, and 5.765 MeV (errors 10–30 keV). Since the (p, α) reaction is non selective and since we see so many more levels in this region we cannot determine which of our states correspond to the analog states. More accurate (^{3}He, d) data would be required to resolve this point. Though the number of levels seen in the (^{3}He, d), (^{3}He, $d\gamma$), and (d,n) reaction differs, we observe almost all the levels seen by each. Possible exceptions are levels seen at 3.98 and 4.39 MeV in the (d,n) work of Hagen, Janetzki, and Maier[6] and the 5-keV doublet at 3.8630 MeV ob-

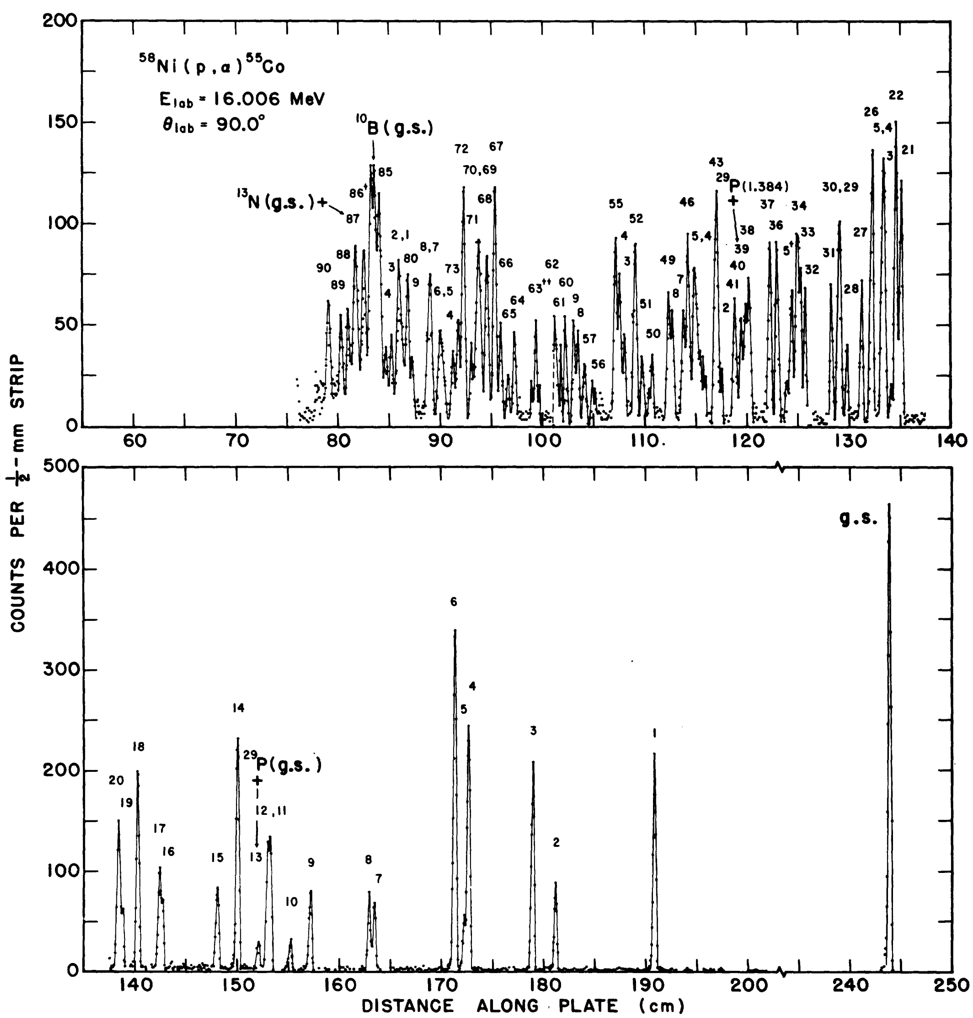

FIG. 2. Spectrum of α particles from 16-MeV bombardment. Compare with Fig. 1 to see the dramatic increase in the number of ^{55}Co states excited. Levels marked with † are possible doublets. The level marked with †† is a possible triplet.

TABLE I. Excitation energies of ^{55}Co from measurements with the ^{58}Ni(p,α)^{55}Co reaction and tabulation of previous work. Correspondence between present levels and previous work is not always clear. See text.

Group number	Present work: Number of runs	Present work: Excitation energy (MeV ± keV)	σ_m (keV)	Nuclear Data Sheets (Ref. 13) (MeV ± keV)	(^{3}He,d) (Ref. 1) (MeV ± 10–30 keV)	(^{3}He,$d\gamma$) (Ref. 5) (MeV ± keV)	(d,n) (Ref. 6) (MeV ± keV)	(p,γ) (Ref. 8) (MeV ± keV)	(p,γ) (Ref. 15) (MeV ± keV)	(p,γ) (Ref. 14) (MeV ± keV)
0	9	g.s.		g.s.	g.s.	g.s.	g.s.	g.s.	g.s.	g.s.
1	9	2.1686 ± 1.7	0.2	2.168 ± 3	2.162	2.162 ± 20	2.16 ± 20	2.166 ± 1	2.17 ± 20	2.168 ± 3
2	5	2.5695 ± 2.1	0.2	2.564 ± 3	2.559	2.560 ± 20	2.56 ± 20	2.565 ± 1	2.57 ± 20	2.564 ± 3
3	6	2.6634 ± 2.1	0.3	2.661 ± 3		2.656 ± 20	2.7 ± 20	2.660 ± 1	2.66 ± 20	2.661 ± 3
4	6	2.9238 ± 2.2	0.3					2.918 ± 1		
5	6	2.9428 ± 2.2	0.4	2.932 ± 10	2.938	2.930 ± 20	2.94 ± 20	2.938 ± 1	2.95 ± 20	
6	6	2.9785 ± 2.2	0.3							
7	6	3.3070 ± 2.3	0.5	3.301 ± 10		3.318 ± 20		3.302 ± 1		
8	5	3.3272 ± 2.4	0.6	3.321 ± 5	3.327	3.335 ± 20	3.33 ± 20	3.324 ± 2	3.31 ± 20	3.321 ± 5
9	6	3.5670 ± 2.4	0.8							
10	5	3.6468 ± 2.6	0.5		3.657	3.635 ± 20	3.66 ± 20			
				3.682 ± 5						3.682 ± 5
11	4	3.7298 ± 2.7	0.5	3.726 ± 5			3.72 ± 20	3.725 ± 1		3.726 ± 5
12	5	3.7411 ± 2.6	0.8							
13	5	3.7784 ± 2.6	0.7							
14	5	3.8630 ± 2.6	0.5	3.867 ± 5	3.870	3.866 ± 20	3.87 ± 20	3.860 ± 1		3.867 ± 5
						3.871 ± 20				
15	5	3.9465 ± 2.7	0.7	3.970 ± 30	3.970	3.933 ± 20	3.98 ± 20			
16	5	4.1700 ± 2.8	0.7			4.155 ± 20		4.164 ± 2		
17	5	4.1828 ± 2.8	0.9	4.178 ± 5	4.185	4.170 ± 20	4.19 ± 20	4.176 ± 2		4.175 ± 5
18	5	4.2695 ± 2.8	0.6				4.29 ± 20			
19	5	4.3324 ± 2.8	0.5							
20	5	4.3465 ± 2.8	0.7							
							4.39 ± 20			
21	5	4.4789 ± 2.9	0.7							
22	5	4.4983 ± 2.9	1.3				4.50 ± 20			
23	4	4.5215 ± 3.0	0.8							
24	5	4.5441 ± 2.9	1.1							
25	5	4.5545 ± 2.9	1.6							
26	5	4.5929 ± 3.0	0.8				4.58 ± 20			
27	5	4.6335 ± 3.0	1.7	4.650 ± 30	4.650		4.65 ± 20			
28	3	4.6941 ± 3.3	1.0							
29	5	4.7208 ± 3.1	1.2			4.720 ± 20		4.722 ± 2		
30	3(4)	4.7291 ± 3.4	2.5							
31	4(5)	4.7521 ± 3.2	2.0	4.755 ± 20	4.755		4.75 ± 20			

TABLE I (*Continued*)

Group number	Present work Number of runs	Present work Excitation energy (MeV ± keV)	σ_m (keV)	Nuclear Data Sheets (Ref. 13) (MeV ± keV)	(^{3}He,d) (Ref. 1) (MeV ± 10–30 keV)	(^{3}He,$d\gamma$) (Ref. 5) (MeV ± keV)	(d,n) (Ref. 6) (MeV ± keV)	(p,γ) (Ref. 8) (MeV ± keV)	(p,γ) (Ref. 15) (MeV ± keV)	(p,γ) (Ref. 14) (MeV ± keV)
32	5	4.8554 ± 3.1	1.4							
33	5	4.8742 ± 3.1	1.2							
34	5	4.8866 ± 3.1	0.9							
35 [c]	5	4.9076 ± 3.1	0.9							
	2(3)	(4.924)					4.94 ± 20			
36	5	4.9662 ± 3.1	1.6							
37	5	4.9919 ± 3.1	1.2						5.00 ± 50	
38	5	5.0692 ± 3.2	1.8				5.05 ± 20			
39	4(5)	5.0867 ± 3.3	1.9							
40	5	5.1030 ± 3.2	1.5							
41	5	5.1249 ± 3.2	1.2							
42	5	5.1782 ± 3.2	2.1			5.165 ± 20				
43	5	5.1946 ± 3.2	1.3	5.188 ± 20	5.188					
44	5	5.2634 ± 3.3	1.9							
45	5	5.2747 ± 3.3	1.0							
46	5	5.2981 ± 3.3	1.3							
47	3(5)	5.3155 ± 3.6	1.0							
48	4	5.3572 ± 3.4	1.0							
49	4	5.3724 ± 3.5	1.6	5.382 ± 30	5.382		5.38 ± 20			
50	3(4)	5.4348 ± 3.7	1.1							
51	5	5.4676 ± 3.4	0.8				5.48 ± 20			
52	4	5.4923 ± 3.5	1.0							
53	5	5.5346 ± 3.4	0.9							
54	4(5)	5.5496 ± 3.5	0.9							
55	5	5.5653 ± 3.4	1.0	5.566 ± 30	5.566		5.56 ± 20			
56	4	5.6503 ± 3.6	1.3				5.64 ± 20			
57	5	5.6814 ± 3.5	1.2	5.670 ± 30	5.670		5.67 ± 20			
58	4	5.7061 ± 3.6	1.9							
59	5	5.7219 ± 3.5	1.2			5.737 ± 20				
60	5	5.7516 ± 3.5	1.1			5.758 ± 20	5.76 ± 20			
61	4(5)	5.7723 ± 3.6	1.3	5.765 ± 20	5.765					
62	5	5.7899 ± 3.5	0.9							
	1(2)	(5.854)								
63 [a]	2(3)	(5.864)								
	2(3)	(5.880)								
64	5	5.9411 ± 3.6	0.7				5.91 ± 20			
65	4(5)	5.9666 ± 3.7	1.6	5.955 ± 30	5.955		5.96 ± 20			

TABLE I (*Continued*)

Group number	Present work: Number of runs	Present work: Excitation energy (MeV ± keV)	σ_m (keV)	Nuclear Data Sheets (Ref. 13) (MeV ± keV)	(^{3}He,d) (Ref. 1) (MeV ± 10–30 keV)	(^{3}He,$d\gamma$) (Ref. 5) (MeV ± keV)	(d,n) (Ref. 6) (MeV ± keV)	(p,γ) (Ref. 8) (MeV ± keV)	(p,γ) (Ref. 15) (MeV ± keV)	(p,γ) (Ref. 14) (MeV ± keV)
66	5	5.9936 ± 3.6	1.0							
67	5	6.0152 ± 3.6	0.9							
68	5	6.0435 ± 3.6	1.0	6.037 ± 30	6.037		6.04 ± 20			
69	5	6.0708 ± 3.6	0.6							
70	5	6.0819 ± 3.7	0.8	6.080 ± 20	6.080		6.08 ± 20			
71	5	6.1017 ± 3.7	0.8							
72	4	6.1351 ± 3.8	1.2							
73	3(4)	6.1528 ± 4.1	1.6						6.143 ± 13[b]	6.143 ± 10[b]
74	3	6.1752 ± 4.1	1.3				6.17 ± 20			
									6.197 ± 13	6.199 ± 10
75	3(4)	6.2127 ± 4.1	0.6	6.215 ± 30	6.215		6.19 ± 20			6.203 ± 10
76	3	6.2260 ± 4.1	0.2				6.22 ± 20			
77	3	6.2585 ± 4.1	0.7							
78	3	6.2714 ± 4.1	0.8	6.277 ± 30	6.277		6.28 ± 20		6.259 ± 13	6.263 ± 10
										6.287 ± 10
79	3(4)	6.3337 ± 4.1	1.9						6.320 ± 13	6.326 ± 10
80	3	6.3494 ± 4.2	0.8	6.342 ± 30	6.342		6.34 ± 20			
81	3	6.3699 ± 4.2	1.5						6.361 ± 13	6.366 ± 10
82	3	6.3856 ± 4.2	1.9				6.39 ± 20			
83	3	6.4136 ± 4.2	0.5						6.401 ± 13	6.407 ± 10
										6.418 ± 10
84	3	6.4352 ± 4.2	1.0							
85	4	6.4557 ± 4.1	0.9							
							6.47 ± 20			
	2(3)	(6.493)								
86[c]	4	6.5176 ± 4.1	0.4						6.505 ± 13	6.509 ± 10
	2	(6.537)								
87	3	6.5505 ± 4.3	0.2				6.54 ± 20			
88	3	6.5859 ± 4.3	1.6							
89	4	6.6131 ± 4.1	1.4							
	2	(6.636)								
90	4	6.6622 ± 4.2	1.3				6.66 ± 20			
									6.665 ± 13	6.668 ± 10

[a] Possible triplet.

[b] A Q of 5057 ± 13 keV was used in Ref. 15 and a Q of 5057 ± 10 keV was used in Ref. 14. This Q value may be in error, see text. The excitation energies quoted in these references may need to be raised by as much as 7 to 10 keV.

[c] Possible doublet.

served by Shoup, Fox, and Brown.[5] There is no indication in our work that there is a doublet at this energy, however if the spacing were indeed 5 keV or less we probably would not have resolved it unless there had been favorable reaction conditions.

A comparison of our results with the results of ^{54}Fe(p, γ) resonance studies requires some discussion. Maripuu[15] and Erlandsson[14] quote uncertainties of 13 and 10 keV, respectively, for the excitation energies of levels seen as resonances, though the resonance energies are reported to be known much better than this (± 1 keV by Maripuu and ± 3 by Erlandsson). The large uncertainty in excitation energy is due to the uncertainty in the value of 5.057 MeV used by both authors for the ^{54}Fe(p, γ) Q value. As mentioned earlier, we had found a 17.3-keV discrepancy in the ^{58}Ni(p, α)^{55}Co Q value. It is not clear from this measurement alone whether the mass of ^{58}Ni or ^{55}Co is in error. However, Martin *et al.*[8] have recently measured the ^{54}Fe(p, γ) Q value and obtained values of 5.064 ± 0.002 and 5.063 ± 0.002 MeV. The ^{54}Fe(p, γ) Q value as reported in the latest tabulation of Wapstra and Gove[10] is given to be 5.050 ± 0.0022 MeV. This 14-keV discrepancy in the value of Martin *et al.* from the tabulated value is in the same direction as our result if one assumes that the mass of ^{55}Co is in error. If we were to assume that the ^{54}Fe-^{58}Ni mass difference is known, we would calculate from our measurement of the ^{58}Ni(p, α) Q value, a value of 5.067 ± 0.005 MeV for the ^{54}Fe(p, γ) Q value. This value is in excellent agreement with the measurements of Martin *et al.* Thus before a meaningful comparison of excitation energies can be made, the values of Maripuu and Erlandsson should be adjusted upwards by at least 7 keV and possibly by as much as 10 keV. When the energies of Erlandsson are adjusted by 7 keV and compared with our results, we find excellent agreement. The average difference between excitation energies is about 0.8 keV. A comparison with the results of Maripuu[15] is not as good, there being an average difference in measured excitation energies of 4.7 ± 0.8 keV. If the excitation energies are adjusted by as much as 10 keV, the average difference between Erlandsson and ourselves is − 1.7 ± 1.0 keV and is 1.7 ± 0.8 keV with Maripuu. Agreement within experimental uncertainty is nevertheless good in either case.

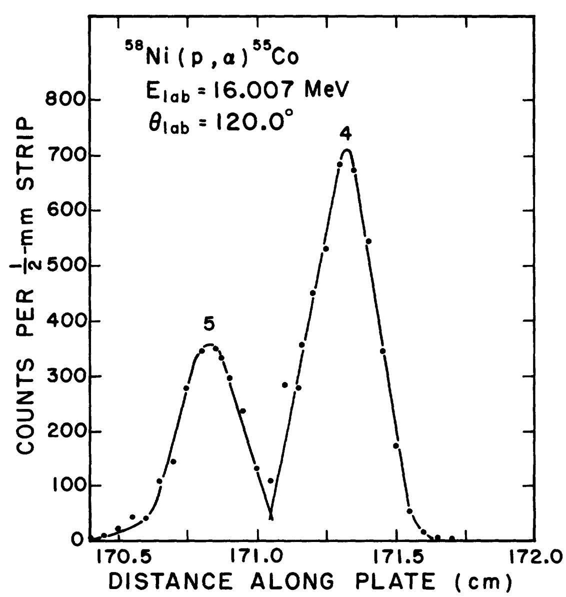

FIG. 3. Enlarged plot of two close-lying α particle groups. The energy separation is 19 keV.

A comparison of the excitation energies of the low-lying states with ^{54}Fe(p, γ) decay studies also requires some discussion. Agreement with Erlandsson[14] is again good. If we calculate the average difference between measured excitation energies we obtain a value of about 2.4 ± 1.5 keV as compared with the average uncertainty of 4 keV quoted by Erlandsson. The 4.175-MeV level has not been included in this average as it is not clear with which state to compare.

If we compare with the more accurately quoted values of Martin *et al.*,[8] there appears to be some disagreement. The average difference between our values and theirs is 4.3 ± 0.5 keV as compared to the average uncertainty of 1.3 keV quoted by Martin *et al.* and 2.4 keV quoted by us. The energy spacings between most levels, however, agree quite well. If we were to measure excitation energies with respect to the first or second excited state rather than from the ground state, and use the excitation energies of Martin *et al.* for these states, there would be fairly good agreement. We have investigated several possibilities for the cause of this apparent shift. The calibration of the spectrograph was rechecked with a Po-α source and found to be reproduceable to at least, or in many cases better than, 1/5000 in absolute energy along the entire focal surface. To check the possibility of fluctuations in the focal surface, the first excited state was measured some nine times with positions on the plates ranging from 192 to 138 cm. A standard deviation of the mean of the nine runs of 0.2 keV was obtained. The possibility of a shift due to target thickness was also investigated and found to be negligible.

As an independent check of spectrograph results in a similar experiment, we compare the results of the measurements on the ^{62}Ni(p, α)^{59}Co reaction now being performed by Mateja *et al.*[16] with the accurately quoted γ-ray results of Swann.[17] These results are given in Table II. The average differ-

TABLE II. A comparison of some results of charged-particle measurements with accurate γ-ray measurements to substantiate the spectrograph calibration.

$^{62}Ni(p,\alpha)^{59}Co$ [a] Excitation energy (MeV)	$^{59}Co(\gamma,\gamma)$ [b] Excitation energy (MeV ± keV)	Δ Difference (keV)
1.1015	1.0987 ± 0.5	+2.8
1.1933	1.1896 ± 0.5	+3.7
1.4590	1.4588 ± 0.3	+0.2
1.4815	1.4804 ± 0.3	+1.1
1.7433	1.745 ± 1.0	−1.7
2.4827	2.479 ± 1.0	+3.7
2.7846	2.783 ± 1.0	+1.6
2.8250	2.825 ± 1.0	+0.0
3.3268	3.328 ± 2.0	−1.2
3.6263	3.625 ± 2.0	+1.3
	⟨uncertainty⟩ = 1.1	⟨Δ⟩ = 1.2 ± 0.6

[a] Results from four measurements.
[b] See Ref. 17.

ence in measured excitation energies is 1.2 ± 0.6 keV compared with an average uncertainty per level of 1.1 keV quoted by Swann. Thus there seems to be no systematic variation. The positions of the first excited state of ^{55}Co on the plates would correspond to the range of excitation energies in ^{59}Co from 2.2 to 3.6 MeV, and as we have seen no systematic variation here, we feel confident in our measurements.

Martin *et al.* used two Ge(Li) detectors in their study of $^{54}Fe(p,\gamma)$ one as a monitor detector placed at 90° and the other for obtaining angular distributions. It appears that the excitation energies were obtained from the 25-cm^3 monitor detector. They report that both Ge(Li) detectors were calibrated by the use of the radioactive sources ^{88}Y, ^{56}Co, ^{60}Co, ^{228}Th, and the contaminant reaction $^{19}F(p,\alpha\gamma)^{16}O$. No resolution value is reported for the monitor detector though the distribution counter resolution is given as 3.5 keV at 1.33-MeV γ-ray

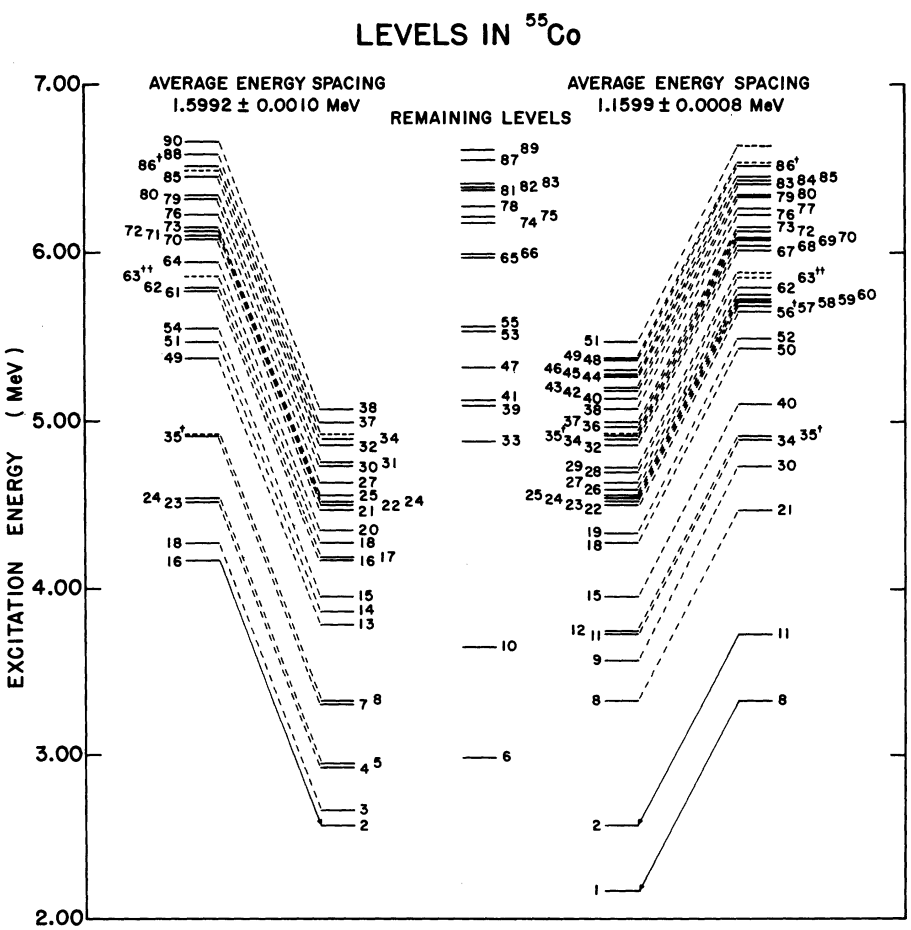

FIG. 4. Grouping of observed levels into sets of pairs having one of two spacings. The solid lines connecting states represent observed γ-ray transitions. The dashed lines represent possible transitions having the same energy within 10 keV. States not included in either of the two sets are shown in the center column.

energy. No discussion is presented as to how the uncertainty in the excitation energies was obtained or how many sets of runs were used in determining the excitation energies. Thus it is not clear where the discrepancy in our two results occurs. As the differences are only slightly outside the estimates of uncertainties it is hard to say that there is a real disagreement.

An intriguing facet of the ^{55}Co energy level scheme is the possibility of multiple degeneracies in the γ-ray transitions. Martin *et al.* comment that the 808-keV γ ray from the decay of the 3725-keV level to the 2918-keV level is degenerate with a γ ray from the β^+ decay of the ground state of ^{55}Co. Fishbeck *et al.*[18] have reported this γ ray to have an energy of 803.8 keV. Martin *et al.* also report that the 1158-keV γ ray observed in the (p, γ) spectrum could arise from the 3725→2565-keV transition or the 3324→2166-keV transition. Thus differences in γ-ray energies of 2 to 4 keV are too small to distinguish them as arising from different transitions.

As we observed many more levels in ^{55}Co than were previously reported, we thought it interesting to investigate the possibility of other transitions which would have this energy of 1160 keV. Of course we must choose some range of energy within which the transition is deemed to have "the same" energy. The results of a search in which ± 10 keV was chosen for the range are given in Fig. 4. The slanted solid lines on the right-hand portion of the figure indicate γ-ray transitions observed by Martin *et al.* between states 8 and 1 and 11 and 2, respectively. Other states are divided into the two right-hand groups such that the energy difference between pairs is within ± 10 keV of 1160 keV. The dotted lines indicate possible transitions which might be observed. Some 33 pairs of levels have been found which have an average spacing of 1.1599 MeV with a standard deviation of the mean of 0.8 keV. If all the levels were to decay with equal intensity the γ-ray group observed (having a 33-fold degeneracy) would have an energy of 1.1599 MeV with a full width at half maximum (FWHM) of approximately 9.8 keV. In addition 25 pairs of levels have been found which have an average spacing of 1.5992 ± 0.001 MeV which is to be compared with the 1598-keV γ ray observed by Martin *et al.* These pairs are shown on the left side of Fig. 4. One will notice immediately in Fig. 4 that almost all the lower levels observed by us have been exhausted in forming the sets of levels which have these two different spacings. Though this interesting result might tempt one to assume some special significance for these two spacings, a plot of the number of pairs of levels which have a given random separation plus or minus Δ vs the separation shows that there is nothing special about the numbers 1.160 or 1.599 MeV. Figure 5 shows plots for separations ranging from 0 to 2400 keV for three values of Δ. Even for the small uncertainty of $\Delta = 2.5$ keV there are 10 to 15 pairs of levels with any given energy difference up to about 1.5 MeV. Of course many of the transitions will occur rarely or not at all because of electromagnetic selection rules but if even a fraction of them actually do occur there will be much difficulty in interpreting the γ-ray spectrum. It is clear that for nuclei such as this with many levels, one must know the position of these levels with high accuracy before the placement of a given γ ray can be made with certainty or that one can be sure that an observed γ ray arises from a single transition. Although particle-γ or even γ-γ coincidence measurements certainly help to resolve these ambiguities, charged-particle analysis with its positive determination of level positions is much more direct. The present measurement is a good example of the high accuracy that is now attainable with this method.

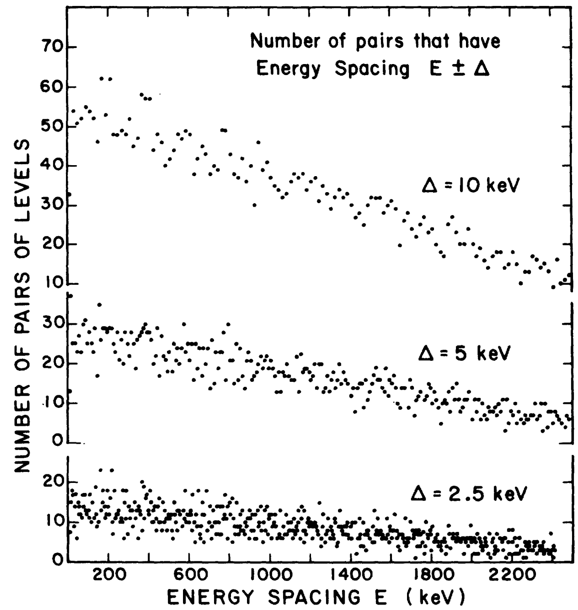

FIG. 5. Numbers of pairs of ^{55}Co states having a given energy spacing to within Δ plotted against the energy spacing for three values of Δ. All observed levels up to 6.6-MeV excitation are included.

SUMMARY

By using the ^{58}Ni(p, α)^{55}Co reaction we have identified 90 states in ^{55}Co in the region of excitation from the ground state to 6.6 MeV. 47 of these states were previously unreported. A comparison of our results with other work shows generally good agreement. A slight discrepancy in the excitation energies of the low-lying states compared to the work of Martin *et al.* has been explored. The possibility of a large degeneracy in the 1160- and 1599-keV γ-ray transitions has been discussed.

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