PHYSICAL REVIEW C VOLUME 13, NUMBER 6 JUNE 1976

Energy levels of ^{57,59,61}Co using the ^{60,62,64}Ni(p, α) reaction and level densities of cobalt isotopes*

J. F. Mateja, J. A. Bieszk, J. T. Meek,[†] J. D. Goss,[‡] A. A. Rollefson,[§] P. L. Jolivette, and C. P. Browne
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556
(Received 28 August 1975; revised manuscript received 23 March 1976)

α particles from the $^{60,\ 62,\ 64}$Ni(p,α) reactions were analyzed with the Notre Dame modified 100 cm broad-range magnetic spectrograph. Data were taken at bombarding energies of 13 to 16 MeV and at observation angles of 16 to 140°. Approximately 125 new levels were observed and uncertainties in excitation energies average 1.3 keV. Systematics of the (p,α) reaction on the cobalt isotopes have been used to discuss spin assignments to several states in ^{61}Co. Level densities and energy spacings are calculated for all the cobalt isotopes from $A = 55$ to $A = 61$.

[NUCLEAR REACTIONS ^{60,62,64}Ni(p, α), E=13–16 MeV θ=16–140°, enriched targets. ^{57,59,61}Co levels deduced. High-spin state postulated using (p, α) reaction systematics. Level densities deduced $^{55-61}$Co.]

I. INTRODUCTION

The cobalt nuclei are of theoretical interest since they lack only one proton in the $f_{7/2}$ proton subshell while as A increases the neutron number passes through the closure of the $f_{7/2}$ neutron subshell. Shell-model[1,2] and several unified-model calculations[3-6] have been performed on the cobalt nuclei in order to understand their structure. Much experimental work has been done, and the level schemes of ^{57,59}Co are well known at least up to 3 MeV excitation. The unified-model calculations are in good agreement up to perhaps 2 MeV; however, the shell-model results have in general not been successful. In the case of ^{61}Co the level structure is less well known and this has hampered comparison of theoretical calculations with experimental results. The present work was undertaken as a systematic survey of the levels of the odd mass cobalt isotopes with the aim of providing as complete and accurate level schemes as possible in order to define the level structures of the odd A isotopes in a consistent manner. We then use these results and others to examine the level density and energy spacing as a function of neutron number.

The (p, α) reaction has been found generally to excite almost all the states and hence this reaction was used not only to reexamine the well known ^{57}Co and ^{59}Co isotopes but also the relatively unknown ^{61}Co. With the Notre Dame 100-cm modified broad-range spectrograph the resolution is higher than that previously used in charged particle measurements and considerably improved accuracy is achieved. We observed approximately 125 new levels and have removed most of the discrepancies left by earlier investigators. Level schemes more nearly complete than those previously published are given for excitations up to 5 MeV for ^{57}Co and ^{59}Co and up to 4 MeV for ^{61}Co. Secondly, by using the systematics of the (p, α) reaction we suggest that a level previously thought to be one of the missing low-lying high-spin states in ^{61}Co cannot have this high spin. A previously assumed doublet was resolved into a triplet, thus making the level at 1.6645 MeV a new level which appears to be a more likely candidate for this high-spin state.

Finally, both the level density and energy level spacing for the cobalt isotopes were determined. In making these calculations we included the ^{55}Co and ^{60}Co isotopes which we had investigated earlier[7,8] and the ^{56}Co and ^{58}Co isotopes measured by Schneider and Daehnick.[9] The inclusion of the ^{55}Co results dramatically demonstrates the closure of the $f_{7/2}$ neutron subshell at this isotope.

II. EXPERIMENTAL

The various nickel targets were prepared by vacuum depositions of ^{60}Ni, ^{62}Ni, or ^{64}Ni onto commercially prepared carbon foils. The isotopic enrichment of each target was approximately 98% and the target thickness ranged from 10–30 μg/cm^2.

Proton beams of 13–16 MeV were produced with the Notre Dame FN tandem accelerator. Nominal beam energies were determined by magnetic analysis. The reaction products were momentum analyzed with the Notre Dame 100 cm magnetic spectrograph using 50-μ KO Ilford nuclear track plates as detectors. The emulsion of these plates is insensitive to protons and thus eliminates the background from proton scattering. We deduced

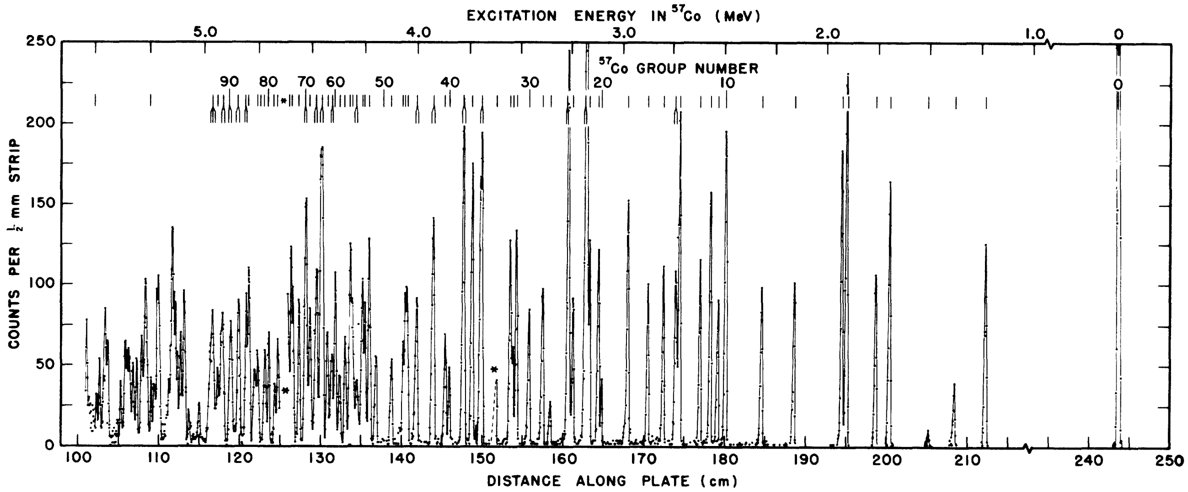

FIG. 1. A typical spectrum from the ^{60}Ni(p, α)^{57}Co reaction. The bombarding energy was 14 MeV and the observation angle 60°. The bottom scale gives the position on the plate and the top scale gives the excitation energy in ^{57}Co. A schematic spectrum is shown labeled with the group number. Group numbers correspond to those in Table I. No analysis was attempted beyond group 96. Asterisks indicate the ends of plates where tracks were not recorded.

α-particle energies from the measured positions of the particle groups on the plates, using our standard procedure with magnetic field cycling.[10] The spectrograph calibration is based on the energies of α particles from ^{210}Po and ^{212}Po and uncertainties in energies for a given run are generally 2 to 3 keV. The proton bombarding energies for the (p, α) reactions were calculated from the positions of the ground state group using Q values reported by Jolivette *et al.*[10] The calculated excitation energy of a particular state depends mainly on the measured energy difference between the corresponding group and the ground state group. With this procedure the energy is quite insensitive to uncertainties in input energy, angle of observation, beam spot position, and target stopping. The uncertainties in the final results are of the order of 1 keV. To positively identify groups with the particular residual nucleus being studied, various observation angles were used to assure that the kinematic energy shift of the group was correct. Observation angles were 60 and 90° for the

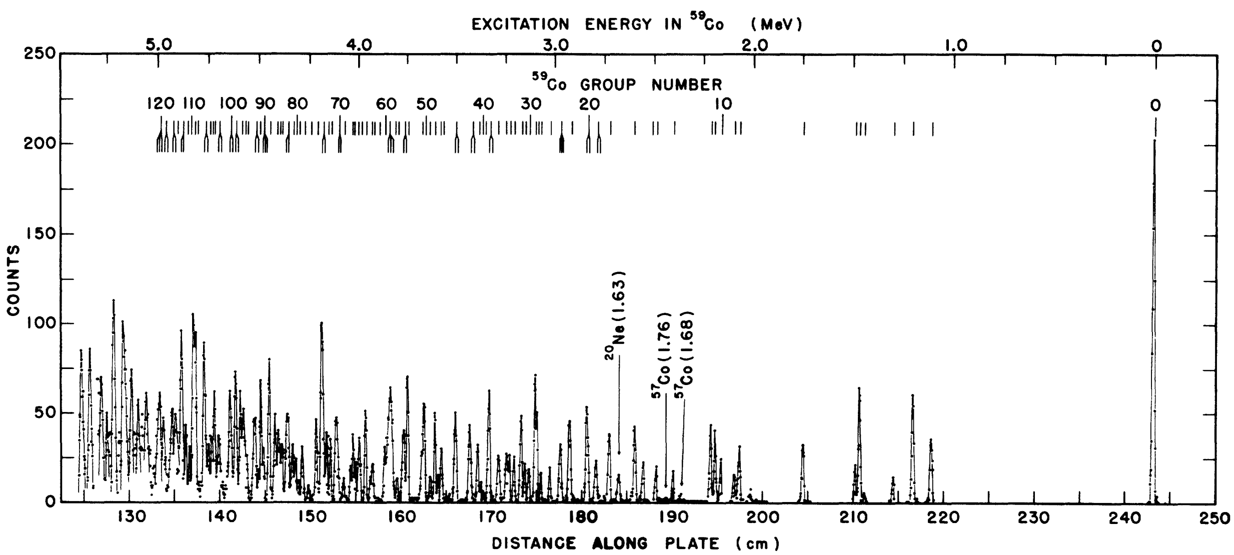

FIG. 2. A typical spectrum from the ^{62}Ni(p, α)^{59}Co reaction. The bombarding energy was 16 MeV and the observation angle 120°. Group numbers correspond to those in Table II. Contaminant groups are labeled with the symbol and excitation energy of the residual nucleus. No analysis was attempted beyond group 121.

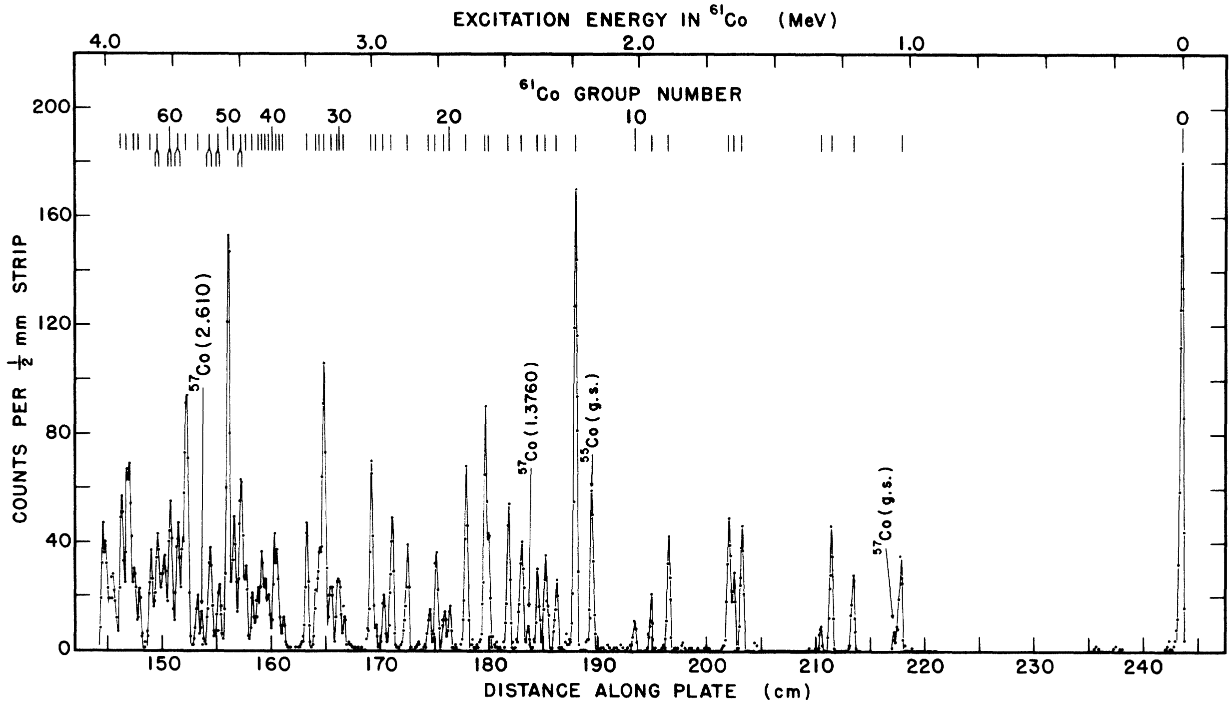

FIG. 3. A typical spectrum from the ^{64}Ni(p, α)^{61}Co reaction. The bombarding energy was 14 MeV and the observation angle 140°. Group numbers correspond to those in Table III. Contaminant groups are labeled with the symbol and excitation energy of the residual nucleus. The analysis was terminated at group 69.

^{57}Co study, 60, 90, and 120° for the ^{59}Co investigation, and 16, 30, 60, 90, 120, and 140° for the ^{61}Co work. Typical spectra for ^{57}Co, ^{59}Co, and ^{61}Co are shown in Figs. 1, 2, and 3, respectively. The full width at half maximum varied from 10 to 14 keV and typical charge collections were 45 to 95 mC.

In addition to the ^{58}Ni(p, α) data, two sets of data on ^{57}Co were obtained while measuring the Q value of the ^{54}Fe(α,p) ^{57}Co reaction. These targets were also prepared by vacuum evaporation of 96.81% isotopically enriched ^{54}Fe onto 20-μg/cm^2 thick carbon foils. The reaction products were also momentum analyzed with the 100-cm spectrograph. Data were taken at 13 and 14 MeV bombarding energies and at an observation angle of 90°.

III. RESULTS

A. ^{57}Co

Energy levels found in this study are compared in Table I with those previous results which have quoted errors of generally less than 10 keV. The known spin and parity assignments given in column 5 are taken from Refs. 11-18. Ninety-six levels, one a possible doublet, have been identified below 4.97-MeV excitation energy. Many measurements have been made on this isotope and the low-lying levels are well known. The present results confirm the level scheme given in the tabulation[11] up to 2.61 MeV and the more recent ^{57}Fe(p,$n\gamma$)^{57}Co measurements[13] up to 3.26 MeV. The next 12 levels above this energy have been seen in one or more earlier measurements. The first new level comes at 3.7696 MeV and in all we find 36 levels that were not previously reported. The most accurate earlier work is the ^{54}Fe(α,$p\gamma$)^{57}Co measurement of Dayras *et al.*[14] The average difference between these 22 excitation energies and ours is −0.19 keV with a standard deviation of the mean of 0.25 keV. The ^{57}Fe(p,$n\gamma$)^{57}Co results[13] generally agree much better than the ± 3 keV stated uncertainties. Many of the ^{56}Fe(p,γ)^{57}Co results[15] agree, but the values for states 10, 11, 13, 32, and especially 30, are well outside the stated errors.

Considerable controversy has arisen about the existence of a doublet around 1.75 MeV excitation. A level near 1.75 MeV was given a spin assignment of $\frac{5}{2}^-$ by Lingeman and co-workers[19] in their β-decay work and by August, Gossett and Treado[20] using the ^{56}Fe(p,γ) reaction. This assignment, however, was in disagreement with the $\frac{3}{2}^-$ assignment of Blair and Armstrong[21] who used the ^{58}Ni-

TABLE I. Excitation energies of ^{57}Co from the present work, tabulated summary, and some previous experiments.

Group number	Present work Number of runs	Present work Excitation energy (MeV)	Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 11) (MeV ± keV)	^{60}Ni(p,α) (Ref. 12) (MeV ± keV)	^{57}Fe($p,n\gamma$) (Ref. 13) (MeV ± keV)	^{54}Fe($\alpha,p\gamma$) (Ref. 14) (MeV ± keV)	^{56}Fe(p,γ) (Ref. 15) (MeV ± keV)	^{57}Ni$^{\beta^-}\to^{57}$Co (Ref. 16) (MeV ± keV)	^{56}Fe(^{3}He,d) (^{3}He,$d\gamma$) (Ref. 17) (MeV ± keV)
0	8	g.s.		$\frac{7}{2}^-$	g.s.	g.s.	g.s.	g.s.	g.s.	g.s.	g.s.
1	8	1.2239	0.7	$\frac{9}{2}^-$	1.2235 ± 4	1.222 ± 4	1.2236 ± 3	1.2237 ± 0.3	1.2240 ± 0.3	1.2235 ± 0.4	
2	8	1.3769	0.7	$\frac{3}{2}^-$	1.3779 ± 1	1.375 ± 4	1.3773 ± 3	1.3775 ± 0.3	1.3781 ± 0.3	1.3776 ± 0.2	1.379 ± 10
3	8	1.5043	0.7	$\frac{1}{2}^-$	1.5050 ± 2	1.502 ± 4	1.504 ± 3	1.5047 ± 0.3	1.5053 ± 0.4	1.5047 ± 0.2	1.507 ± 10
4	8	1.6898	0.7	$\frac{11}{2}^-$	1.681 ± 10	1.687 ± 4	1.6898 ± 3	1.6894 ± 0.3			
5	8	1.7573	0.7	$\frac{3}{2}^-$	1.7577 ± 1	1.754 ± 4	1.7474 ± 3	1.7572 ± 0.3	1.7575 ± 0.3	1.7576 ± 0.2	1.758 ± 10
6	8	1.8972	0.7	$\frac{7}{2}^-$	1.8965 ± 4	1.894 ± 7	1.8976 ± 3	1.8969 ± 0.3	1.8964 ± 0.3	1.8965 ± 0.4	1.898 ± 15
7	8	1.9192	0.7	$\frac{5}{2}^-$	1.9201 ± 7	1.917 ± 7	1.9197 ± 3	1.9196 ± 0.3	1.9195 ± 0.3	1.9195 ± 0.2	
8	8	2.1330	0.8	$\frac{5}{2}^-$	2.1329 ± 3	2.127 ± 7	2.133 ± 3	2.1336 ± 0.3	2.1320 ± 1.0	2.1329 ± 0.3	2.135 ± 10
9	8	2.3110	0.8	$\frac{7}{2}^-$	2.305 ± 10	2.307 ± 7	2.311 ± 3	2.3113 ± 0.4			2.314 ± 10
10	8	2.4846	0.8	$\frac{11}{2}^-$	2.485 ± 10	2.481 ± 7	2.486 ± 3	2.4858 ± 0.4	2.4790 ± 1		
11	8	2.5233	0.8	$\geq\frac{13}{2}$	2.511 ± 10	2.520 ± 7	2.523 ± 3	2.5236 ± 0.5	2.5140 ± 1		
12	8	2.5592	0.8	$\geq\frac{11}{2}$	2.550 ± 10	2.559 ± 7	2.555 ± 3	2.5596 ± 0.4			
13	8	2.6108	0.9	$\frac{7}{2}^-$	2.600 ± 10	2.608 ± 7	2.612 ± 3	2.6111 ± 0.5	2.6145 ± 1		
14	8	2.7230	0.9			2.727 ± 7	2.722 ± 3	2.7230 ± 0.6			
15	8	2.7322	1.0	$\frac{3}{2}^-,\frac{5}{2}^-$	2.7306 ± 2		2.731 ± 3	2.7303 ± 0.5	2.7336 ± 2	2.7306 ± 0.2	
16	8	2.7440	1.0				2.744 ± 3	2.7433 ± 0.6			
17	6	2.8035	0.9	$\frac{3}{2}^-,\frac{5}{2}^-$	2.8040 ± 3	2.803 ± 7	2.805 ± 3	2.8026 ± 0.6		2.8039 ± 0.2	
18	8	2.8788	0.9	$\frac{3}{2}^-$	2.875 ± 10	2.880 ± 7	2.879 ± 3	2.8794 ± 0.6			2.883 ± 10
19	7	2.9779	1.0	$\frac{1}{2}^+$	2.9812 ± 5	2.797 ± 7	2.979 ± 3	2.9809 ± 0.6			2.979 ± 10
20	7	3.1068	1.0	($\leq\frac{5}{2}^-$)	3.1085 ± 4	3.111 ± 7	3.107 ± 3	3.1098 ± 0.7		3.1082 ± 0.5	3.112 ± 10
21	8	2.1214	0.9				3.121 ± 3				
22	5	3.1649	1.1				3.165 ± 3				
23	5	3.1765	1.1	($\frac{5}{2}^-$)	3.1770 ± 2		3.177 ± 3	3.1756 ± 0.7		3.1769 ± 0.3	3.175 ± 10
24	5	3.1841	1.2			3.182 ± 7	3.186 ± 3				

TABLE I. *(Continued)*.

Group number	Present work: Number of runs	Present work: Excitation energy (MeV)	Error (keV)	$J^{\pi\,a}$	Nuclear data sheets (Ref. 11) (MeV ± keV)	^{60}Ni(p, α) (Ref. 12) (MeV ± keV)	^{57}Fe(p, $n\gamma$) (Ref. 13) (MeV ± keV)	^{54}Fe(α, $p\gamma$) (Ref. 14) (MeV ± keV)	^{56}Fe(p, γ) (Ref. 15) (MeV ± keV)	^{57}Ni$^{\beta^-}\to{}^{57}$Co (Ref. 16) (MeV ± keV)	^{56}Fe(^{3}He, d) (^{3}He, $d\gamma$) (Ref. 17) (MeV ± keV)
25	8	3.2463	1.0	$(\frac{5}{2})$	3.255 ± 10		3.247 ± 3				
26	7	3.2640	1.0				3.265 ± 3	3.2624 ± 0.7			
27	7	3.2722	1.1			3.271 ± 10			3.2698 ± 2		3.272 ± 15
28	8	3.3566	1.0	$\frac{1}{2}^-, \frac{3}{2}^-$	3.349 ± 10		3.357 ± 10				3.369 ± 15
29	8	3.3937	1.0	$(\frac{7}{2})$	3.380 ± 15						
30	8	3.4605	1.0	$\frac{1}{2}^-, \frac{3}{2}^-$	3.446 ± 10		3.461 ± 10		3.4311 ± 2		3.467 ± 15
31	8	3.5219	1.0				3.520 ± 10				
32	8	3.5404	1.0	$(\frac{3}{2})^+$	3.536 ± 10		3.540 ± 10		3.5360 ± 2		
33	7	3.5532	1.1				3.554 ± 10				
34	7	3.6223	1.1		3.613 ± 10						
35	8	3.6715	1.0		3.657 ± 10		3.665 ± 10				
36	8	3.6813	1.1	$(\frac{7}{2})$	3.694 ± 10		3.673 ± 10				3.681 ± 20
37	8	3.7196	1.1								3.728 ± 20
38	6	3.7620	1.1		3.760 ± 10		3.757 ± 10				
39	6	3.7696	1.3								
40	7	3.8337	1.1		3.834 ± 10						
41	7	3.8541	1.1				3.855 ± 10		3.8507 ± 2		3.862 ± 20
42	6	3.9092	1.2		3.901 ± 10						
43	5	3.9182	1.4								3.921 ± 20
44	6	3.9908	1.2		3.973 ± 10		3.990 ± 10		3.9890 ± 1		
45	4	3.9994	1.6		4.003 ± 30						4.002 ± 15
46	6	4.0365	1.2		4.033 ± 10		4.038 ± 10				
47	6	4.0461	1.3								
48	6	4.0575	1.4								4.064 ± 20
49	8	4.1112	1.1								

TABLE I. *(Continued)*.

Group number	Present work Number of runs	Excitation energy (MeV)	Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 11) (MeV ± keV)	$^{60}Ni(p, \alpha)$ (Ref. 12) (MeV ± keV)	$^{57}Fe(p, n\gamma)$ (Ref. 13) (MeV ± keV)	$^{54}Fe(\alpha, p\gamma)$ (Ref. 14) (MeV ± keV)	$^{56}Fe(p, \gamma)$ (Ref. 15) (MeV ± keV)	$^{57}Ni \xrightarrow{\beta^-} {}^{57}Co$ (Ref. 16) (MeV ± keV)	$^{56}Fe(^3He, d)$ (Ref. 17) (MeV ± keV)
50	8	4.1869	1.2		4.195 ± 30						4.197 ± 15
51	8	4.2168	1.2								
52	8	4.2375	1.2				4.237 ± 10				
53	8	4.2508	1.2		4.248 ± 20						4.251 ± 15
54	6	4.2716	1.3								
55	7	4.2841	1.3								
56	7	4.2969	1.3								4.295 ± 15
57	7	4.3080	1.3								
58	8	4.3295	1.2								
59	7	4.3568	1.2								
60	8	4.3765	1.2								
61	8	4.3913	1.3								
62	5	4.3987	1.4								
63	8	4.4162	1.2								
64	8	4.4381	1.2								
65	8	4.4479	1.3								4.454 ± 20
66	8	4.4656	1.2								
67	7	4.4751	2.0								
68	8	4.4968	1.2								4.500 ± 20
69	8	4.5114	1.5								
70	7	4.5199	1.4		4.524 ± 20						4.525 ± 15
71	8	4.5501	1.2								
72	8	4.5758	1.8								
73	8	4.5873	1.5								4.595 ± 20
74	6	4.5973	2.5								4.595 ± 20

TABLE I. (*Continued*).

Group number	Present work: Number of runs	Present work: Excitation energy (MeV)	Present work: Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 11) (MeV ± keV)	^{60}Ni(p, α) (Ref. 12) (MeV ± keV)	^{57}Fe(p, $n\gamma$) (Ref. 13) (MeV ± keV)	^{54}Fe(α, $p\gamma$) (Ref. 14) (MeV ± keV)	^{56}Fe(p, γ) (Ref. 15) (MeV ± keV)	^{57}Ni$^{\beta^-}$ → ^{57}Co (Ref. 16) (MeV ± keV)	^{56}Fe(^{3}He, d) (^{3}He, $d\gamma$) (Ref. 17) (MeV ± keV)
75	5	4.6084	2.3		4.605 ± 20						
76	6	4.6195	1.4								4.615 ± 20
77	7	4.6449	1.3								
78	8	4.6592	1.3								
79	7	4.6745	1.4								
80	8	4.7006	1.3		4.689 ± 20						4.685 ± 15
81	8	4.7195	1.3								4.730 ± 20
82	8	4.7527	1.3								
83	8	4.7619	1.4								
84	6	4.7721	1.5								
85	7	4.7934	1.3								
86 [b]	7	4.8052	1.7								4.800 ± 20
87	6	4.8420	1.4								
88	4	4.8528	1.7								
89	7	4.8716	1.4								
90	7	4.8809	1.4								
91	8	4.9114	1.3								
92	8	4.9219	1.4								
93	7	4.9337	1.5								
94	6	4.9481	1.5								
95	7	4.9596	1.4								
96	7	4.9710	1.5		4.981 ± 30						

[a] Spin and parity assignments are taken from Refs. 11–18.
[b] Possible doublet.

$(t,\alpha)^{57}$Co reaction and of Rosner and Holbrow[22] in their ^{56}Fe(^{3}He,d)^{57}Co study. Bouchard and Čujec[23] concluded from their ^{54}Fe(α,p)^{57}Co work that a doublet may exist in this region, thus accounting for the spin discrepancies.

Recent ($\alpha,p\gamma$) work,[14] however, has given no indication of a doublet in this area. We concur with these findings. If a doublet does exist, and if we assume two equally populated states, then their separation must be less than our 4-keV resolving power. Further agreement with our findings appears in the more recent β-decay work of Gatrousis and co-workers[16] who assigned a spin of $\frac{3}{2}^-$ to a state at 1.757 MeV, and the work of Hardie *et al.*[17] whose study placed an upper limit of 10 keV for any possible doublet separation.

The next major region of controversy occurred around 2.13 MeV. A doublet in this region would partially explain the spin assignments of $\frac{5}{2}^+$ by August's ^{56}Fe(p,γ)^{57}Co study,[20] $\frac{3}{2}^+$ by Blair and Armstrong's[21] ^{58}Ni(t,α)^{57}Co work, and $\frac{5}{2}^-$ by Rosner and Holbrow's[22] ^{56}Fe(^{3}He,d)^{57}Co experiment. The investigations of Burton and McIntyre[24] and O'Brien and Coote[15] supported the possibility of a doublet. However, Dayras and co-workers[14] and other investigators found no evidence for two levels. If a doublet exists, our investigation indicates that the level separation would be less than 4 keV.

For the first time in a charged particle spectrum a triplet was observed at 2.7230, 2.7322, and 2.7440 MeV. Previously this triplet had been reported as a possible doublet by Coop and co-workers[12] using the (p,α) reaction. Burton and McIntyre[24] and other investigators saw only one level at 2.731 MeV that decayed to the ground state. However, in the ^{54}Fe($\alpha,p\gamma$) study of Dayras and co-workers[14] a triplet was reported from observation of γ rays. This triplet level scheme around 2.7 MeV was also deduced by Pietrzyk and co-workers[13] using the ^{57}Fe($p,n\gamma$) reaction. Our observation of this triplet supports the decay scheme proposed by Dayras and co-workers[14] and Pietryzk and co-workers.[13]

Levels at 3.11, 3.18, and 3.27 MeV found in previous (p,α) work[12] have been resolved into multiplets. The new states have energies of 3.1068 and 3.1214, 3.1765, and 3.1841, and 3.2640 and 3.2722 MeV. In the ($p,n\gamma$) work[13] the first two pairs were seen but only one member of the upper pair was seen. Only the other member of this pair was found in the ^{56}Fe(p,γ) work[15] and the (^{3}He,d) work.[17]

Leslie and co-workers[25] and O'Brien and Coote[15] [both using the ^{56}Fe(p,γ) reaction] saw a level at approximately 3.993 MeV that decays to the ground state. Hardie and co-workers[17] have seen a level at 4.002 MeV that they believe may be the same level although no evidence for a ground state decay was observed. Our study showed levels at both 3.9908 and 3.9994 MeV, removing the apparent discrepancy in the two measurements. Above 4 MeV, the number of levels populated is very large and, as only an occasional one was seen in other works, an exact comparison is difficult.

B. ^{59}Co

The levels observed in ^{59}Co are compared in the Table II with those previously reported.[26-29] The level scheme was well known up to 2.7 MeV although the excitation energies were not as accurately known as those of ^{57}Co. Using the (p,α) reaction we find all levels reported by previous investigators with the exception of a state at 2.720 MeV. In addition, four new levels below 3.5 MeV have been observed. Between 3.5 and 4 MeV most levels had been seen only in (p,p') studies. We confirmed these and added three new ones. Between 4 and 5 MeV approximately 50 new levels are added to the ^{59}Co structure. The present work then has extended the level scheme to 5 MeV and reduced uncertainties to the order of 1 to 2 keV over this range. Previously they were 5 to 8 keV.

In the present work, the doublet suggested by Coop and co-workers[12] at 2.822 MeV has been resolved into states at 2.8202 and 2.8291 MeV. Swann however, using ^{59}Co(γ,γ) has reported[27] a single level at 2.825 ± 0.001 MeV. A triplet at this energy might explain the situation; however, we saw no evidence of a triplet. Other new states below 3.5 MeV have energies of 3.3509 and 3.4981 MeV. Above 3.5 MeV, we saw all the levels reported in the last Nuclear Data Sheets compilation plus approximately 53 new levels.

C. ^{61}Co

This nucleus was not nearly so well known[30] as the ^{57}Co and ^{59}Co isotopes. Prior to this investigation, comparison between energy level schemes reported by different investigators was quite difficult. A survey of the publications on ^{61}Co produced only two sets of data in which level positions are given to better than 10 keV.[13,30] Those studies terminated at about 3 MeV in excitation. Since uncertainties given by other authors[21,31] were as large as 30 keV, the level reported by one author may fall well within the errors of several levels reported by another investigator.

Table III presents our results. Sixty-eight levels were identified up to 4 MeV and of these approximately 30 had not been reported before. Doubt is cast on the existence of two previously reported low-lying levels at 1.272 and 1.425 MeV (see Sec. III D). The table also shows some pre-

TABLE II. Excitation energies of ^{59}Co from the present work, tabulated survey, and some previous experiments.

Group number	Present work: Number of runs	Present work: Excitation energy (MeV)	Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 26) (MeV ± keV)	$^{62}Ni(p,\alpha)$ (Ref. 12) (MeV ± keV)	$^{59}Co(\gamma,\gamma)$ (Ref. 27) (MeV ± keV)	$^{59}Co(p,p')$ (Ref. 28) (MeV ± keV)	$^{59}Co(p,p')$ (Ref. 29) (MeV ± keV)	$^{60}Ni(t,\alpha)$ (Ref. 21) (MeV ± keV)
0	4	g.s.	g.s.	$\frac{7}{2}^-$	g.s.	g.s.	g.s.	g.s.		g.s.
1	4	1.0990	1.1	$\frac{3}{2}^-$	1.09927 ± 0.08	1.100 ± 4	1.0987 ± 0.5	1.097 ± 5		1.093 ± 15
2	4	1.1914	0.9	$\frac{9}{2}^-$	1.190 ± 3	1.190 ± 4	1.1896 ± 0.5	1.189 ± 5		1.188 ± 15
3	4	1.2911	1.1	$\frac{3}{2}^-$	1.29154 ± 0.08	1.291 ± 4		1.289 ± 5		1.290 ± 15
4	2	1.4349	1.8	$(\frac{1}{2}^-)$	1.43403 ± 0.09	1.434 ± 4		1.432 ± 5		
5	4	1.4593	0.9	$\frac{11}{2}^-$	1.460 ± 1	1.463 ± 4	1.4588 ± 0.3	1.458 ± 5		1.460 ± 15
6	4	1.4818	1.1	$\frac{5}{2}^{+-}$	1.481 ± 3	1.482 ± 4	1.4804 ± 0.3	1.479 ± 8		
7	4	1.7450	1.0	$\frac{7}{2}^-$	1.744 ± 2	1.744 ± 4	1.745 ± 1	1.743 ± 5	1.745 ± 5	1.738 ± 15
8	4	2.0616	1.0	$(\frac{7}{2}^-)$	2.062 ± 3	2.059 ± 7		2.061 ± 5	2.065 ± 5	2.057 ± 20
9	4	2.0870	1.1	$(\frac{5}{2}^-)$	2.087 ± 3	2.085 ± 7		2.086 ± 5	2.088 ± 5	
10	4	2.1536	1.0		2.153 ± 3	2.146 ± 7		2.152 ± 5	2.157 ± 5	
11	4	2.1835	1.0	$(\frac{5}{2}^-, \frac{7}{2}^-)$	2.183 ± 3	2.183 ± 7		2.183 ± 5	2.187 ± 5	2.191 ± 20
12	4	2.2051	1.0		2.206 ± 4	2.201 ± 7		2.205 ± 5	2.207 ± 5	
13	5	2.3945	0.9		2.397 ± 3	2.394 ± 7		2.397 ± 6	2.396 ± 5	
14	5	2.4784	1.0		2.479 ± 4	2.476 ± 7	2.479 ± 1	2.477 ± 6	2.480 ± 5	
15	5	2.5427	1.0		2.541 ± 4	2.537 ± 7		2.540 ± 6	2.542 ± 5	
16	5	2.5849	1.0		2.585 ± 4	2.581 ± 7		2.585 ± 6	2.585 ± 5	2.585 ± 20
17	4	2.7134	1.1	$\frac{1}{2}^+$	2.712 ± 5	2.711 ± 10		2.711 ± 6	2.714 ± 10	2.715 ± 20
					2.720 ± 10				2.720 ± 10	
18	3	2.7699	1.4		2.770 ± 5	2.771 ± 10		2.770 ± 6	2.769 ± 70	
19	4	2.7801	1.2		2.781 ± 5		2.783 ± 1	2.781 ± 6	2.782 ± 7	
20	4	2.8202	1.2	$(\frac{3}{2}^-)$	2.822 ± 4	2.822 ± 10	2.825 ± 1	2.822 ± 6	2.821 ± 6	2.818 ± 25
21	3	2.8291	1.3							
22	4	2.9140	1.2		2.913 ± 4	2.911 ± 10		2.911 ± 6	2.914 ± 5	
23	5	2.9563	1.1		2.957 ± 4	2.953 ± 10		2.955 ± 6	2.958 ± 5	
24	4	2.9651	1.2		2.967 ± 7	2.966 ± 10	2.966 ± 1	2.964 ± 9		2.961 ± 25
25	3	2.9770	1.3						2.973 ± 12	
26	3	3.0159	1.2			3.012 ± 10		3.015 ± 6	3.016 ± 5	
27	4	3.0614	1.2			3.058 ± 10		3.058 ± 6	3.061 ± 5	
28	3	3.0823	1.2					3.081 ± 9	3.082 ± 5	
29	4	3.0906	1.2						3.090 ± 12	
30	4	3.1231	1.2					(3.120 ± 10)	3.123 ± 7	
31	4	3.1423	1.2		3.143 ± 6			(3.148 ± 10)	3.140 ± 7	

TABLE II. *(Continued)*.

Group number	Present work: Number of runs	Present work: Excitation energy (MeV)	Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 26) (MeV ± keV)	^{62}Ni(p, α) (Ref. 12) (MeV ± keV)	^{59}Co(γ, γ) (Ref. 27) (MeV ± keV)	^{59}Co(p, p') (Ref. 28) (MeV ± keV)	^{59}Co(p, p') (Ref. 29) (MeV ± keV)	^{60}Ni(t, α) (Ref. 21) (MeV ± keV)
31	4	3.1423	1.2		3.143 ± 6			(3.148 ± 10)	3.140 ± 7	
32	4	3.1621	1.2	$\frac{3}{2}^+, \frac{5}{2}^+$	3.160 ± 4			3.159 ± 8	3.161 ± 5	3.166 ± 25
33	4	3.1936	1.2					3.192 ± 8	3.195 ± 5	
34	5	3.2226	1.1					3.222 ± 8	3.224 ± 5	
35	5	3.2364	1.1					3.233 ± 8	3.235 ± 5	
36	5	3.2754	1.1					3.273 ± 8	3.275 ± 5	
37	5	3.3221	1.1					3.323 ± 8	3.326 ± 5	
38	4	3.3307	1.4				3.328 ± 2			
39	5	3.3509	1.3							
40	5	3.3660	1.2							
41	5	3.3823	1.1					3.379 ± 8	3.383 ± 6	
42	4	3.4160	1.2					3.412 ± 8	3.416 ± 5	
43	3	3.4237	1.6						3.425 ± 10	
44	5	3.4916	1.1					3.490 ± 8	3.492 ± 5	
45	4	3.4981	1.3							
46	4	3.5650	1.3					(3.560 ± 10)	3.565 ± 5	
47	5	3.5801	1.2						3.582 ± 8	
48	5	3.5995	1.1					3.602 ± 8	3.600 ± 5	
49	4	3.6219	1.3				3.625 ± 2		3.620 ± 10	
50	4	3.6528	1.3					(3.654 ± 10)	3.655 ± 5	
51	4	3.6655	1.6				3.667 ± 2		3.666 ± 7	
52	5	3.7371	1.1						3.741 ± 5	
53	5	3.7574	1.2						3.760 ± 5	
54	5	3.7690	1.4						3.765 ± 5	
55	3	3.7919	1.6						3.797 ± 5	
56	4	3.8075	1.3						3.812 ± 5	
57	5	3.8209	1.2						3.819 ± 8	
58	5	3.8321	1.2						3.830 ± 8	
59	4	3.8428	1.5						3.845 ± 8	
60	4	3.8548	1.3						3.857 ± 8	
61	3	3.8886	1.6							
62	4	3.9152	1.4						3.917 ± 10	
63	4	3.9263	1.7						3.925 ± 10	
64	4	3.9494	1.3				3.954 ± 3		3.950 ± 5	
65	4	3.9817	1.4						3.986 ± 8	
66	4	4.0000	2.5						4.000 ± 12	
67	4	4.0141	1.3						4.015 ± 8	

TABLE II. *(Continued)*.

Group number	Present work Number of runs	Excitation energy (MeV)	Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 26) (MeV± keV)	$^{62}Ni(p, \alpha)$ (Ref. 12) (MeV± keV)	$^{59}Co(\gamma,\gamma)$ (Ref. 27) (MeV± keV)	$^{59}Co(p,p')$ (Ref. 28) (MeV± keV)	$^{59}Co(p,p')$ (Ref. 29) (MeV± keV)	$^{60}Ni(t, \alpha)$ (Ref. 21) (MeV± keV)
68	4	4.0262	1.7						4.030 ± 8	
69	4	4.0606	1.3							
70	4	(4.0880	2.7)							
71	4	4.0996	1.5							
72	3	4.1288	2.3							
73	3	4.1518	1.5							
74	4	4.1697	1.4							
75	3	4.1779	2.8							
76	4	4.1955	1.4							
77	3	4.2357	1.5							
78	3	4.2672	1.6							
79	4	4.2910	1.4							
80	4	4.3074	1.4				4.303 ± 3			
81	4	4.3209	1.4							
82	4	4.3476	1.4							
83	2	(4.3569	2.0)							
84	3	4.3775	1.6							
85	4	4.3907	1.5							
86	4	4.4068	1.4							
87	4	4.4385	1.4							
88	2	(4.4577	1.9)							
89	4	4.4667	1.4				4.467 ± 3			
90	4	4.4800	1.4							
91	4	4.4910	1.7							
92	4	4.5068	1.5							
93	4	4.5169	1.6							
94	4	4.5522	1.5							
95	4	4.5663	1.5							
96	4	4.5813	1.5							
97	4	4.6063	1.5							
98	3	4.6168	1.7							
99	4	4.6327	1.5							
100	4	4.6429	1.7							
101	3	4.6882	1.6							
102	3	4.6995	1.8							
103	4	4.7150	1.5							
104	3	4.7306	1.7							

TABLE II. *(Continued).*

Group number	Present work Number of runs	Present work Excitation energy (MeV)	Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 26) (MeV± keV)	$^{62}Ni(p, \alpha)$ (Ref. 12) (MeV± keV)	$^{59}Co(\gamma, \gamma)$ (Ref. 27) (MeV± keV)	$^{59}Co(p, p')$ (Ref. 28) (MeV± keV)	$^{59}Co(p, p')$ (Ref. 29) (MeV± keV)	$^{60}Ni(t, \alpha)$ (Ref. 21) (MeV± keV)
105	2	(4.7432	1.9)							
106	3	4.7602	1.6							
107	4	4.7679	1.5							
108	4	4.8064	1.5							
109	4	4.8180	1.7							
110	3	4.8363	1.7							
111	4	4.8557	1.5							
112	4	4.8770	1.5							
113	4	4.8905	1.6							
114	4	4.9062	1.5							
115	3	4.9172	1.7							
116	3	4.9279	1.8							
117	3	4.9592	1.6							
118	3	4.9691	1.7							
119	3	4.9831	1.7							
120	3	4.9909	1.7							
121	3	5.0018	2.6							

[a] Spin and parity assignments are taken from Refs. 12, 21, 26, and 27.

vious results and it can be seen that the present results agree well with those of Coop and co-workers,[12] who used the same reaction at bombarding energies of 9.5 to 10.5 MeV. We find seven more levels below 3 MeV, however. The average difference in excitation energies for the 22 states seen in both experiments is 1.2 ± 0.5 keV even though the uncertainties quoted on the earlier work range from 4 to 10 keV compared to the present 0.6 to 1.6 keV. The recent ^{61}Fe decay work of Bron, Jongsma, and Verhul[30] is also in excellent agreement with our results with an average difference in excitation energy for 22 levels of -0.34 ± 0.30 keV.

Many states below 3 MeV have now been confirmed by this investigation and several new levels have been observed. Levels at 2.7801 and 2.9529 MeV had not been seen in previous works. A state that had been observed as a singlet at 2.568 ± 0.025 MeV in the Hudson and Glover[31] (t,p) reaction and at 2.563 ± 0.010 MeV by Coop *et al.*[12] has been resolved into a doublet of 2.5586 MeV and 2.5716 MeV. There now exists some question as to which member of the 2.568-MeV pair the tentative $\frac{3}{2}^+$ spin assignment belongs.

Above 3 MeV approximately 27 new levels are reported. Several levels, previously reported (at 3.220, 3.394, 3.450, and 3.713 MeV) and given spin assignments by Hudson and Glover,[31] have been resolved into doublets and triplets.

D. Comparisons of level structures

The odd A cobalt isotopes have been studied theoretically by several investigators.[1-6] One of the major successes of these calculations is the prediction of two low-lying high-spin states, $\frac{9}{2}^-$ and $\frac{11}{2}^-$, for the odd A cobalt isotopes. These two states have been experimentally established for both ^{57}Co and ^{59}Co, but have not been identified in ^{61}CO. The calculations predict that in ^{61}Co these two states lie between 1 and 1.6 MeV. Of the previously reported levels in ^{61}Co, only a doublet at 1.272-1.287 MeV, observed in the (t,α) work of Hudson and Glover,[31] and the 1.425-MeV state reported in the β-decay study of Gujrathi and Mukherjee,[33] have not been given at least tentative spin assignments and therefore would seem to be candidates for the $\frac{9}{2}$ and $\frac{11}{2}$ states. It appears that the 1.425-MeV state does not exist since it has been seen neither in the recent β-decay study of Bron and co-workers[30] nor in this investigation.

Furthermore, in the present work only a single level at 1.2856 MeV has been observed. The doublet, which was weakly populated in the (t,α) study of Hudson and Glover,[31] was not observed in the earlier (t,α) work by Blair and Armstrong.[21] However, these authors failed to identify other weakly populated levels. A further (t,α) investigation would be useful in resolving the question of the existence of this state. If this doublet does exist, both members probably cannot be high-spin states. This statement is based on the observation that in our ^{57}Co and ^{59}Co studies using the (p,α) reaction, the $\frac{9}{2}$ and $\frac{11}{2}$ states (group numbers 1 and 4 in Fig. 1 and 2 and 5 in Fig. 2) are among the most strongly populated of the low-lying levels. The fact that the 1.272-MeV member of the Hudson and Glover[31] doublet was not populated in our (p,α) work suggests that this can neither be the $\frac{9}{2}$ nor $\frac{11}{2}$ state.

This would leave only the 1.2856-MeV state as a possible candidate for one of the two missing high-spin states. The resolution by this investigation of the 1.650-MeV doublet into a triplet with energies of 1.6193, 1.6460, and 1.6645 MeV, provides a candidate for the other missing level. An absence of β feeding to a level at 1.6645 MeV in the recent work of Bron and co-workers[30] makes probable a spin assignment of $\geq\frac{7}{2}$. Furthermore, the fact that in our (p,α) work this level (group number 7 in Fig. 3) was one of the most strongly populated low-lying levels is consistent with a high-spin assignment. Any levels found much higher in excitation energy would be so far from the theoretically predicted states that they could not seriously be considered as candidates for the missing $\frac{9}{2}$ and $\frac{11}{2}$ states. Thus it appears that the 1.2856- and 1.6645-MeV levels are the best candidates for these low-lying high-spin states in ^{61}Co.

Figure 4 displays the levels of ^{57,59,61}Co observed in the present work. The levels of ^{55}Co up to 5 MeV are taken from previous work of this laboratory[7] using the same reaction. Shorter lines indicate levels previously known. Dashed lines represent previously reported states not seen in this work. The rapid increase in level density as the neutron number increases from the closed shell at ^{55}Co is striking. This is discussed below. Lines connecting the first eight levels in ^{57,59,61}Co are labeled with the J^π of the levels. Our suggestion that the state at 1.6645 MeV is the missing $\frac{11}{2}^-$ state is incorporated in the drawing. The observed set of J^π values for the first eight states of ^{57,59,61}Co as well as the approximate excitation energies are correctly predicted by the unified vibrational model.[4,6] This model may not be applicable to ^{55}Co. At present there is too little experimental information on the J^π values of ^{55}Co to attempt a comparison with the other isotopes.

The first $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states are also labeled and connected in Fig. 4. These are presumed to be hole states. Hudson and Glover[31] note that the (p,α) reaction tends to favor population of high

TABLE III. Excitation energies of ^{61}Co from the present work, tabulated summary, and some previous experiments.

Group number	Present work: Number of runs	Present work: Excitation energy (MeV)	Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 32) (MeV ± keV)	^{64}Ni(p, α) (Ref. 12) (MeV ± keV)	^{61}Fe(β) (Ref. 30) (MeV ± keV)	^{59}Co(t, p) (Ref. 31) (MeV ± keV)	^{62}Ni(t, α) (Ref. 31) (MeV ± keV)
0	8	g.s.	g.s.	$\frac{7}{2}^-$	g.s.	g.s.		g.s.	g.s.
1	8	1.0282	0.6	$\frac{3}{2}^-$	1.025 ± 1	1.029 ± 4.0	1.027 42 ± 0.11	1.026	1.031 ± 15
2	7	1.2061	0.8	$\frac{3}{2}^-, \frac{5}{2}^-$	1.204 ± 1	1.206 ± 4.0	1.205 06 ± 0.09	1.213 ± 15	1.210 ± 25
									1.272 ± 25
3	8	1.2856	0.9			1.287 ± 4.0	1.2857 ± 0.3	1.286 ± 15	1.287 ± 25
4	3	1.3232	1.3	$(\frac{1}{2}^-)$	1.324 ± 2	1.325 ± 4.0	1.325 36 ± 0.07		1.338 ± 25
					1.425				
5	8	1.6193	0.7	$\frac{7}{2}^-$		1.623 ± 7.0	1.6189 ± 0.2	1.620 ± 15	1.635 ± 25
6	7	1.6460	0.7	$(\frac{3}{2})^-, \frac{5}{2}^-$	1.632 ± 10		1.645 88 ± 0.13		
7	8	1.6645	0.7		1.674 ± 15	1.655 ± 7.0		1.660 ± 15	1.682 ± 25
8	8	1.8893	0.7		1.893 ± 15	1.887 ± 7.0	1.8890 ± 0.4		1.903 ± 25
9	8	1.9533	0.8	$\frac{3}{2}^-$	1.971 ± 12	1.953 ± 7.0	1.953 10 ± 0.15		1.971 ± 25
10	8	2.0144	1.1	$\frac{3}{2}, \frac{5}{2}$		2.015 ± 7.0	2.0115 ± 0.2		
11	8	2.2319	0.9	$\frac{1}{2}^+$	2.248 ± 17	2.230 ± 7.0	2.2309 ± 0.3	2.239 ± 20	2.258 ± 25
12	8	2.3037	0.8	$\frac{3}{2}^-, \frac{5}{2}^-$		2.302 ± 7.0	2.3029 ± 0.2	2.313 ± 20	
13	8	2.3455	0.8			2.343 ± 7.0		2.348 ± 20	2.368 ± 25
14	4	2.3738	1.1					2.386 ± 20	
15	8	2.4322	0.9			2.433 ± 7.0	2.4315 ± 0.3	2.436 ± 25	2.459 ± 59
16	6	2.4839	1.0	$\frac{3}{2}, \frac{5}{2}$		2.486 ± 7.0	2.4844 ± 0.4		
17	8	2.5586	0.8	$\frac{3}{2}^+$		2.563 ± 10.0			
18	8	2.5716	0.9		2.575 ± 20			2.568 ± 25	
19	8	2.6423	0.8			2.639 ± 10.0		2.639 ± 25	
20	4	2.7067	1.1			2.705 ± 10.0			
21	7	2.7265	1.0	$\frac{1}{2}$ to $\frac{5}{2}$	2.720 ± 30			2.728 ± 25	
22	4	2.7565	1.6	$\frac{3}{2}^-, \frac{5}{2}^-$		2.751 ± 10.0	2.7544 ± 0.4	2.765 ± 25	
23	8	2.7801	1.0						
24	4	2.8671	1.1	$\frac{5}{2}^-$	2893 ± 25	2.864 ± 10.0	2.8643 ± 0.2	2.882 ± 25	2.895 ± 25
25	7	2.9222	1.0	$\frac{3}{2}, \frac{5}{2}$		2.920 ± 10.0	2.9200 ± 0.5		
26	7	2.9529	1.0						
27	7	2.9799	1.0					2.975 ± 25	
28	8	2.9984	0.9	$\frac{5}{2}^-$	3.022 ± 25	2.996 ± 10.0	3.0003 ± 0.5	3.017 ± 25	3.028 ± 25
29	4	3.1024	1.6			3.103 ± 10.0	3.1044 ± 0.5		
30	4	3.1167	1.1						
31	5	3.1263	1.1						
32	5	3.1517	1.1		3.159 ± 25			3.151 ± 25	3.163 ± 25
33	8	3.1760	0.9						
34	6	3.1903	1.2	$\frac{3}{2}, \frac{5}{2}$			3.1910 ± 0.6		
35	7	3.2039	1.0	$\frac{3}{2}, \frac{5}{2}$	3.215 ± 25		3.2045 ± 0.3	3.220 ± 25	3.208 ± 25
36	6	3.2398	1.1	$\frac{3}{2}, \frac{5}{2}$			3.2391 ± 0.6		
37	5	3.3494	1.1						
38	5	3.3570	1.3						
39	5	3.3644	1.3	$\frac{3}{2}^-, \frac{5}{2}^-$			3.3649 ± 0.7		
40	6	3.3843	1.1						
41	7	3.3969	1.2		3.395 ± 30			3.394 ± 25	3.396 ± 25
42	8	3.4097	1.1						

TABLE III. *(Continued)*.

Group number	Number of runs	Excitation energy (MeV)	Error (keV)	J^{π} [a]	Nuclear data sheets (Ref. 32) (MeV± keV)	^{64}Ni(p, α) (Ref. 12) (MeV± keV)	^{61}Fe(β) (Ref. 30) (MeV± keV)	^{59}Co(t,p) (Ref. 31) (MeV± keV)	^{62}Ni(t, α) (Ref. 31) (MeV± keV)
43	8	3.4284	1.1						
44	7	3.4451	1.2					3.450 ± 25	
45	7	3.4708	1.0	($\frac{5}{2}^-$, $\frac{7}{2}^-$)	3.470 ± 30				3.467 ± 25
46	8	3.4848	1.1						
47	4	3.4925	1.4						
48	7	3.5136	1.1					3.515 ± 25	
49	8	3.5356	1.0						
50	4	3.5647	1.3						
51	6	3.5753	1.3	($\frac{3}{2}^+$, $\frac{5}{2}^+$)	3.573 ± 30			3.578 ± 25	3.585 ± 25
52	3	(3.5996	1.4)						
53	5	3.6094	1.3						
54	7	3.6540	1.1					3.653 ± 25	3.664 ± 25
55	8	3.6915	1.0						
56	4	3.7002	1.5						
57	4	3.7278	1.5					3.713 ± 25	
58	5	3.7526	1.2					3.746 ± 25	
59	3	(3.7582	1.5)	($\frac{5}{2}^-$, $\frac{7}{2}^-$)	3.766 ± 35				
60	7	3.7753	1.1						3.782 ± 30
61	4	3.8063	1.3						
62	4	3.8146	1.5						
63	5	3.8273	1.4						
64	7	3.8711	1.2	$\frac{3}{2}^+$, $\frac{5}{2}^+$	3.854 ± 35			3.870 ± 25	3.869 ± 30
65	6	3.8898	1.3						
66	7	3.9056	1.2						
67	6	3.9157	1.2						
68	6	3.9244	1.3						
69	7	3.9371	1.2	($\frac{5}{2}^-$, $\frac{7}{2}^-$)	3.975 ± 35			3.965 ± 25	3.970 ± 30

[a] Spin and parity assignments are taken from Refs. 12, 30, and 32.

spins, and that in earlier work the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ hole states are among the most weakly populated levels in the entire ^{57}Co and ^{59}Co spectra. This would be consistent with a compound nucleus mechanism. In most of our spectra we find the $\frac{1}{2}^+$ states to be strongly excited with (p, α), especially at forward angles. Thus we conclude that they are excited by a direct mechanism. The $\frac{3}{2}^+$ states are strongly excited under some reaction conditions.

IV. LEVEL DENSITIES AND LEVEL SPACINGS

In order to obtain information relating to the neutron shell closure at $N = 28$ and to determine the number of levels missed due to the finite resolution inherent in these measurements, level density and level spacing calculations were performed. In addition to the data on ^{57}Co, ^{59}Co, and ^{61}Co we have included previous results[7] from this laboratory on ^{55}Co as well as recent results from the ^{59}Co(d,p)^{60}Co reaction,[8] and also the results of Schneider and Daehnick[9] on the ^{58}Ni(d, α)^{56}Co and ^{60}Ni(d, α)^{58}Co reactions.

The procedure for extracting level density parameters is described in detail by Tee and Aspinall.[34] This method is summarized here.

The excitation energy corrected for pairing effects is;

$$U = E_x + 0.5\epsilon\Delta ,$$

where E_x is the measured excitation energy, ϵ is the number of unpaired particles, and Δ is the pairing energy, taken to be $\Delta = 3.36(1 - A/400)$ where A is the mass number.

A plot of the number of levels, $N(U)$ of excitation energy less than U, versus U is shown in Fig. 5 with logarithmic scales used for both axes. From about 4 to 6 MeV corrected excitation energy the graphs are seen to follow a nearly straight line. This line is fitted by the empirical formula

$$N(U) = KU^{p} .$$

The parameters K and p were obtained by a least

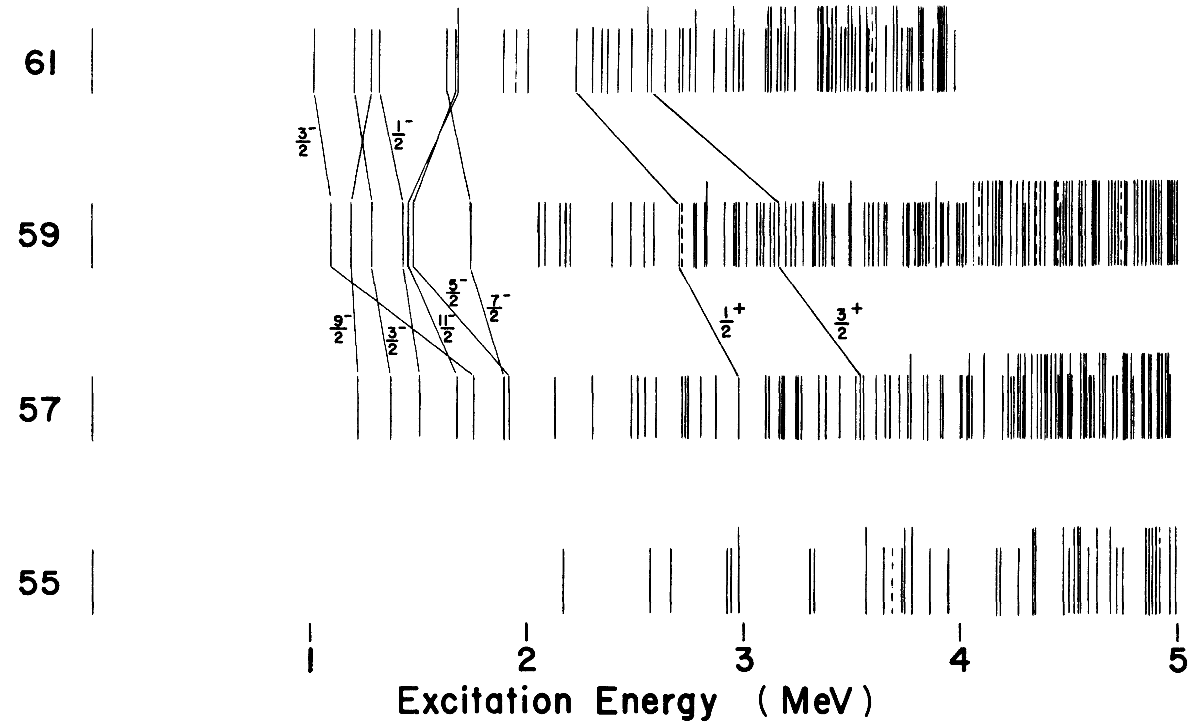

FIG. 4. Energy levels of odd A cobalt isotopes. The excitation energy is plotted horizontally and each array is labeled with the corresponding mass number on the left. Shorter lines signify that the state was known previously. Longer lines show states discovered in the present work. The increasing density as neutrons add to the closed shell at ^{55}Co is quite apparent. Suggested spin assignments and correspondence of the first seven excited states is taken mainly from Ref. 18 but the $\frac{9}{2}^-$ and $\frac{11}{2}^-$ assignments in ^{61}Co are suggested in the present work.

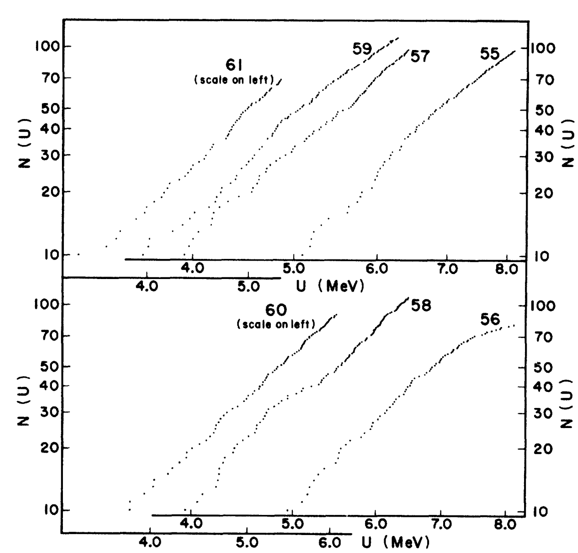

FIG. 5. Level number plotted against corrected excitation energy (logarithmic scales) for the cobalt isotopes. The results for ^{61}Co and ^{60}Co are plotted on a shifted energy scale to separate them from the adjacent isotopes.

squares fit to the data. The level density $\rho(U)$ corresponding to a given excitation energy U could be calculated from

$$\rho(U)=\frac{dN}{dU}=KpU^{(p-1)} .$$

The single particle level densities are then calculated by the method of Lang and LeCouteur[35,36] which is based on the Fermi gas model. This method gives a level density for levels of all spins and parities of

$$\rho(U)=\frac{1}{(2\pi c't)^{1/2}}P(U) ,$$

where the density of states $P(U)$ is given by

$$P(U)=\frac{\exp[2U/t-\frac{1}{8}\pi^2 ga\exp(-a/t)+1]}{12(\pi t)^{5/2}(g/6)^{3/2}}$$

and

$$U=(g/6)\pi^2t^2\left[\tfrac{1}{4}+\tfrac{3}{4}\left(1+\frac{a}{t}\right)e^{-a/t}\right]-t ,$$

where t is a nuclear temperature, g is the single particle level density, Δ is the pairing energy

TABLE IV. Level densities in the cobalt isotopes.

Isotope	$\rho(U)$ [a] (MeV^{-1})	$\rho(U)$ [b] (MeV^{-1})	g [a] (MeV^{-1})	g [b] (MeV^{-1})
^{55}Co	9.8	10.9 ± 4.7	5.73	5.93 ± 0.49
^{56}Co	11.2	12.7 ± 8.1	6.39	6.64 ± 0.94
^{57}Co	26.7	30.9 ± 6.4	7.75	8.08 ± 0.31
^{58}Co	26.6	30.9 ± 10.7	8.23	8.57 ± 0.58
^{59}Co	58.3	74.6 ± 24.8	9.59	10.20 ± 0.60
^{60}Co	34.3	39.2 ± 21.0	8.80	9.13 ± 0.94
^{61}Co	48.1	55.1 ± 12.7	9.08	9.42 ± 0.41

[a] Level densities calculated from experimental data.
[b] Level densities calculated after correction for missed levels.

previously defined, and $a = 0.437\Delta$. The quantity c' is the moment of inertia for a spherical nucleus and according to the model varies with t and thus the excitation energy as

$$c't = cte^{-a/t} + \epsilon\overline{m^2} ,$$

where ϵ is the number of unpaired particles, m is the magnetic quantum number such that

$$\overline{m^2} = 0.24A^{2/3} ,$$

and c is the rigid body moment of inertia given by

$$c = 0.146A^{2/3}g .$$

From the experimental values of $\rho(U)$ a value of g can be extracted using these relationships. The ρ values and g values calculated from the experimental data are given in the second and fourth columns, respectively, of Table IV. Corrections are discussed below.

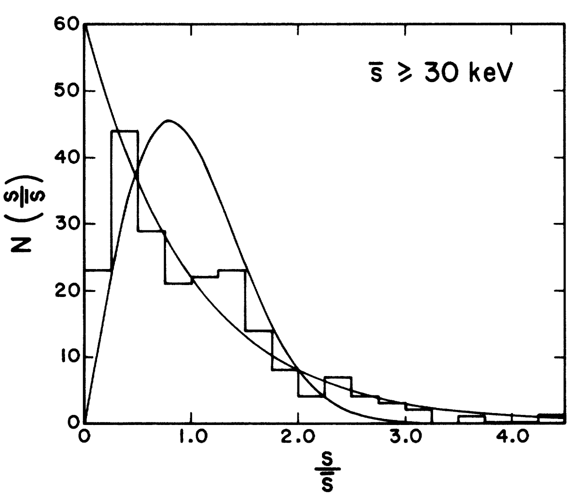

FIG. 6. Experimental spacing distribution for all levels in the cobalt isotopes for which $\bar{s} \geq 30$ keV. The two curves are for an exponential distribution and a Wigner distribution.

Additional information can be obtained concerning the spacings of nuclear energy levels in the cobalt isotopes by following the procedures described in detail by Huizenga and Katsanos.[37] The average level spacing $\bar{s}$ at a given excitation energy for any of the cobalt isotopes can be calculated from $\rho(U)$. The observed level spacings s are divided by the average level spacing and the data are sorted in units of $s/\bar{s}$ of 0.25. In order to reduce the effect of missed levels we have used only data for which $\bar{s} \geq 30$ keV. The results for the cobalt isotopes are shown in Fig. 6. The two curves shown in the figure are a normalized exponential distribution, given by

$$N(s/\bar{s}) = A\exp(-s/\bar{s}) ,$$

which is the expected distribution for levels occurring in a completely random way, and a normalized Wigner distribution

$$N(s/\bar{s}) = A'(\pi s/2\bar{s})\exp(-\pi s^2/4\bar{s}^2) ,$$

which is the expected distribution of spacings between adjacent levels of the same spin and parity. Except for the first bin, the experimental spacing distribution is in good agreement with the exponential spacing distribution and in poor agreement with a Wigner distribution. This is consistent with the predictions for levels of mixed spin and parity and in agreement with the results of Huizenga and Katsanos.[37]

The probability of missing a level because it is a member of an unresolved doublet may now be calculated as

$$\int_0^{\delta/\bar{s}} Ae^{-bx}dx \Big/ \int_0^{\infty} Ae^{-bx}dx ,$$

where $x = s/\bar{s}$, δ is the minimum observable spacing, and A and b are determined from the exponential fit to the level spacing data in Fig. 6. Resolutions (δ) of 3.5, 7.0, and 7.5 keV were used for the (d,p), (d,α), and (p,α) reactions, respectively. Note in Fig. 6 the first bin falls well below the line of the exponential. The number of levels missing in this bin is consistent with the calculated number of missed levels. This emphasizes the point that one cannot hope to find all the levels of a nucleus using only one reaction.

The number of missed levels estimated from this calculation was added to the number of observed levels. The corrected ρ values and g values are given in columns 3 and 5, respectively, of Table IV. The rather large uncertainty in ρ arises from the approximately 20% uncertainty assumed in the pairing energy. It was found that even with the resolution of 3.5 keV used for the (d,p) reaction, as many as six levels may have been missed between 2 and 3 MeV (42 observed) because of un-

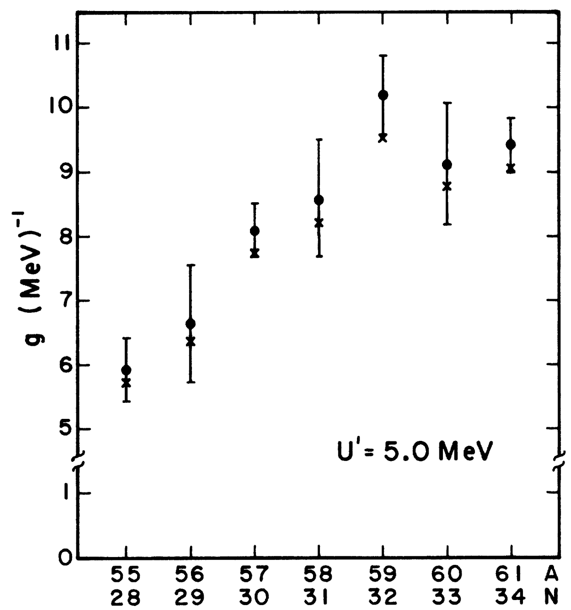

FIG. 7. Single particle level density at 5 MeV corrected excitation energy plotted against neutron number for the cobalt isotopes. The crosses show the values calculated from the observed numbers of levels. The circles show the values corrected for unresolved levels. The uncertainties shown by the error bars are dominated by the uncertainty in the pairing energy correction.

resolved multiplets in ^{60}Co. This has only a small effect on the present results, but at higher excitation energies where level densities are greater or in experiments with lower resolution it will seriously effect calculated level densities.

The single particle level densities (g) are plotted as a function of neutron number in Fig. 7. The densities without correction for missed levels are plotted with crosses, whereas the corrected values are plotted with circles. The relative insensitivity of the single particle level density on the number of missed levels is apparent. The uncertainty in the pairing correction accounts for the error bars shown on the corrected points. Other uncertainties in the measurement and calculation are negligible compared to these.

Figure 7 shows the marked decrease in level density as the $1f_{7/2}$ subshell closure at $N = 28$ (^{55}Co) is approached. This effect is similar to that observed by Tee and Aspinall for the nickel isotopes, but is more pronounced in our case since we have gone all the way to the shell closure at $N = 28$ whereas the nickel results stopped at $N = 30$. Further, our single particle level densities g may be compared with those compiled by Macgregor and Brown for a variety of nuclei and displayed in Fig. 12 of their paper on Cr isotopes.[38] Our results lie very close to a smooth curve drawn through the points from the other measurements for neutron numbers from 28 to 34. Thus single particle level densities obtained from different reactions agree rather well, and show the shell closure effect at $N = 28$.

V. SUMMARY

Approximately 125 new levels have been identified for the three cobalt nuclei: ^{57}Co, ^{59}Co, and ^{61}Co. Level schemes up to 4 MeV in the case of ^{61}Co and 5 MeV in the case of ^{57}Co and ^{59}Co were determined. Furthermore, from a study of reaction systematics, levels at 1.2856 and 1.6645 MeV have been suggested as the most likely candidates for the missing low-lying high-spin states in ^{61}Co. An exponential distribution for the energy level spacings was determined from the data. This distribution is consistent with the prediction for levels of mixed spin and parity. The closure of the neutron subshell at $N = 28$ can be observed from the plot of the single particle level densities as a function of neutron number.

We wish to thank Dr. Edgar Berners and Mr. Charles Guy for maintaining the Notre Dame accelerator and to thank our plate scanners DeLisa Darcie, Susan Hammer, Patricia Huston, Debbie Lane, Donna Smith, Patricia Murphy, and Linda Thorpe.

*Work supported by the National Science Foundation Grant No. G. P. 27456.
†Present address: Physics Department, Indiana University, Bloomington, Indiana.
‡Present address: Mesurex Corporation, Cupertino, California.
§Present address: Department of Physics, University of Arkansas, Little Rock, Arkansas.
[1]J. Vervier, Nucl. Phys. 78, 497 (1966).
[2]J. B. McGrory, Phys. Rev. 160, 915 (1967).
[3]J. M. G. Gomez, Phys. Rev. C 6, 149 (1972).
[4]L. Satpathy and S. C. Gujrathi, Nucl. Phys. A110, 400 (1968).
[5]A. Corello and V. A. Manfredi, Phys. Lett. 34B, 584 (1971).
[6]K. W. C. Stewart, B. Castel, and B. P. Singh, Phys. Rev. C 4, 2131 (1971).
[7]J. D. Goss, G. A. Huttlin, C. P. Browne, and A. A. Rollefson, Phys. Rev. C 9, 227 (1974); J. D. Goss, P. L. Jolivette, A. A. Rollefson, and C. P. Browne, *ibid.* 10, 2641 (1974).
[8]P. L. Jolivette, J. D. Goss, and C. P. Browne, Phys.

Rev. C 12, 2121 (1975).
[9]M. J. Schneider and W. W. Daehnick, Phys. Rev. C 4, 1649 (1971); 5, 1330 (1972).
[10]P. L. Jolivette, J. D. Goss, G. L. Marolt, A. A. Rollefson, and C. P. Browne, Phys. Rev. C 10, 2449 (1974).
[11]J. Rapaport, Nucl. Data B3, (Nos. 3 and 4), 103 (1970).
[12]K. L. Coop, I. G. Graham, J. M. Poate, and E. W. Titterton, Nucl. Phys. A130, 223 (1969); K. L. Coop, I. G. Graham, and E. W. Titterton, *ibid.* A149, 463 (1970).
[13]P. Pietrzyk, K. D. Buchs, E. Finckh, W. Fritsch, and B. Schreiber, Z. Phys. 262, 239 (1973).
[14]R. Dayras, M. Toulemonde, B. Čujec, B. Heusch, J. N. Mo, and I. M. Szöghy, Nucl. Phys. A173, 49 (1971).
[15]B. J. O'Brien and G. E. Coote, Nucl. Phys. A153, 593 (1970).
[16]C. Gatrousis, R. A. Meyer, L. G. Mann, and J. B. McGrory, Phys. Rev. 180, 1052 (1969).
[17]G. Hardie, T. H. Braid, L. Meyer-Schützmeister, and J. W. Smith, Phys. Rev. C 5, 1600 (1972).
[18]K. L. Coop, I. G. Graham, and E. W. Titterton, Nucl. Phys. A150, 346 (1970).
[19]E. W. A. Lingeman, J. Konijn, F. Diederix, and B. J. Meijer, Nucl. Phys. A100, 136 (1967).
[20]L. S. August, C. R. Gossett, and P. A. Treado, Phys. Rev. 142, 664 (1966).
[21]A. G. Blair and D. D. Armstrong, Phys. Rev. 151, 930 (1966).
[22]B. Rosner and C. H. Holbrow, Phys. Rev. 154, 1080 (1967).
[23]N. Bouchard and B. Čujec, Nucl. Phys. A108, 529 (1968).
[24]K. S. Burton and L. C. McIntyre, Jr., Phys. Rev. C 3, 621 (1971).
[25]J. R. Leslie, W. McLatchie, C. F. Monahan, and J. K. Thrasher, Nucl. Phys. A170, 115 (1971).
[26]J. Vervier, Nucl. Data B2, (No. 5), 1 (1968).
[27]C. P. Swann, Nucl. Phys. A172, 569 (1971).
[28]M. Mazari, A. Sperduto, and W. W. Buechner, Phys. Rev. 107, 365 (1957).
[29]A. A. Katsanos, J. R. Huizenga, and H. R. Vonach, Phys. Rev. 141, 1053 (1966).
[30]J. Bron, H. W. Jongsma, and H. Verhul, Phys. Rev. C 11, 966 (1975).
[31]F. R. Hudson and R. N. Glover, Nucl. Phys. A160, 482 (1971).
[32]J. Vervier, Nucl. Data B2, (No. 5), 81 (1968).
[33]S. C. Gujrathi and S. K. Mukherjee, Phys. Rev. 159, 909 (1967).
[34]R. G. Tee and A. Aspinall, Nucl. Phys. A98, 417 (1967).
[35]D. W. Lang and K. J. LeCouteur, Nucl. Phys. 14, 21 (1959).
[36]A. Aspinall, G. Brown, and J. G. B. Haigh, Nucl. Phys. 52, 630 (1964).
[37]J. R. Huizenga and A. A. Katsanos, Nucl. Phys. A98, 614 (1967).
[38]A. Macgregor and G. Brown, Nucl. Phys. 88, 385 (1966).