PHYSICAL REVIEW C VOLUME 5, NUMBER 5 MAY 1972

Study of ^{57}Co with the ^{56}Fe(^{3}He, d) and ^{56}Fe(^{3}He, $d\gamma$) Reactions*

G. Hardie
Western Michigan University, Kalamazoo, Michigan 49001, and Argonne National Laboratory, Argonne, Illinois 60439

and

T. H. Braid, L. Meyer-Schützmeister, and J. W. Smith†
Argonne National Laboratory, Argonne, Illinois 60439
(Received 20 December 1971)

About 65 levels in ^{57}Co were populated by the ^{56}Fe(^{3}He, d) reaction. The angular distributions of deuterons leading to many of these states were obtained with a split-pole magnetic spectrograph. In many cases, comparison of these angular distributions with distorted-wave Born-approximation calculations permitted both the determination of the angular momentum of the transferred proton and the transition strength. These results are compared with previous work. Coincidences between deuterons and γ rays from the ^{56}Fe(^{3}He, $d\gamma$) reaction were also studied to obtain the γ decay of some levels in ^{57}Co. The possibility of pairs of closely spaced levels, which has been suggested as an explanation for the discrepancies in some spin and parity assignments, is also investigated. Theoretical calculations are briefly compared with some of the existing experimental results on excited states in ^{57}Co. Finally, the question of which states in ^{57}Co are analogs of low-lying states in ^{57}Fe is discussed.

I. INTRODUCTION

Theoretical calculations have less successfully accounted for the measured properties of the energy levels of ^{57}Co than for those of other nuclei in this mass region. In our study of ^{58}Co, using the reaction ^{56}Fe(^{3}He, $p\gamma$)^{58}Co,[1] we also simultaneously studied coincident deuterons and γ rays coming from the reaction ^{56}Fe(^{3}He, $d\gamma$)^{57}Co. Because of the interest in ^{57}Co, we attempted to obtain additional information by analyzing these data and supplementing them with angular distributions of deuterons from the reaction ^{56}Fe(^{3}He, d)^{57}Co.

From a study of the deuteron spectra we were able to determine previously unreported energy levels in ^{57}Co. Also, the present work provides additional evidence regarding the possibility of sets of closely spaced energy levels. Such sets of levels have been postulated to explain conflicting spin and parity assignments. A comparison of the deuteron angular distributions with those calculated by use of the distorted-wave Born approximation (DWBA) permitted the assignment of the angular momentum of the transferred proton for a number of states and so determined the parity of these states and limited their spins to two possible values. Transition strengths were also obtained from the DWBA calculations. The angular momentum transfers obtained in the present study generally agree with those obtained by Rosner and Holbrow[2] in an earlier study using the (^{3}He, d) reaction, but the transition strengths are much smaller than theirs. This discrepancy, and its effect on spin assignments, is discussed.

Isobaric analogs of low-lying levels in ^{57}Fe are expected at excitation energies above 7 MeV. This region has been studied with both the (^{3}He, d) and (p, γ) reactions. Results obtained in these studies are compared, and we suggest that the analog states have not yet been positively identified.

Finally, the spins, parities, and positions of the experimentally determined energy levels are briefly compared with the results of a shell-model calculation by Gatrousis *et al.*[3] and a unified-model calculation by Satpathy and Gujrathi.[4]

II. SPECTROGRAPH MEASUREMENTS

Deuterons from the reaction ^{56}Fe(^{3}He, d)^{57}Co were detected in the split-pole magnetic spectrograph[5] at the Argonne model FN tandem Van de Graaff accelerator. A 22-MeV ^{3}He^{++} beam was directed onto an ^{56}Fe target placed at the center of the scattering chamber of the spectrograph. The deuterons were detected with 50-μm-thick Kodak NTB emulsions covered with acetate foils of thicknesses selected to maximize visibility of the deuteron tracks and to stop the elastically scattered particles.

To prepare the target, Fe enriched to over 99% in ^{56}Fe was evaporated onto a 30-μg/cm^2 carbon backing. The elastic scattering of 8-MeV ^{3}He^{++}

ions was observed at laboratory angles of 12, 17, and 22°. With the assumption of pure Rutherford scattering, the target thickness was determined to be 100 ± 15 μg/cm^2.

A spectrum of the deuterons emerging at an angle of 7° to the incident beam direction is given in Fig. 1. The resolution (full width at half maximum) is 20 keV. The numbers above the peaks label the ^{57}Co states clearly seen at this angle, and the corresponding excitation energies are given in Table. I. Excitation energies obtained by other workers are also given in this table. Up to 3.3 MeV our results agree to better than ±5 keV with the accurate measurements of Gatrousis *et al.*[3] and of Dayras *et al.*[6] Our value for the excitation energy of level No. 14 is 11 keV higher than the value given by Dayras *et al.*[6] The present results agree to within ±20 keV with the excitation energies obtained by Rosner and Holbrow,[2] except for levels 17, 18, and 37, for which the differences are slightly greater than 20 keV.

A study of the spectrum of protons from the ^{54}Fe(α, p) reaction led Bouchard and Čujec[7] to conclude that there are probably two levels close together at an excitation energy of about 1.747 MeV. As they pointed out, this could account for the discrepancy regarding the spin assignment for this level. On the one hand, the β-decay studies of Piluso, Wells, and McDaniels[8] and Lingeman *et al.*[9] agreed, yielding $J^\pi = \frac{5}{2}^-$, as did the ^{56}Fe($p, \gamma\gamma$) experiment of August, Gossett, and Treado.[10] On the other hand, the ^{58}Ni(t, α) experiment of Blair and Armstrong[11] and the (^{3}He, d) experiment of Rosner and Holbrow[2] yielded $J^\pi = \frac{3}{2}^-$. However, later experiments cast doubt on the presence of two levels around 1.75 MeV. In particular, the β-decay work of Gatrousis *et al.*[3] conflicts with the earlier β-decay studies by assigning $J^\pi = \frac{3}{2}^-$ to a level at 1.7576 MeV. Also, later studies[6,12] of the (α, p) reaction showed no evidence for two levels in this excitation region. A study of the deuteron spectra obtained in the present experiment permits us to conclude that if there are two levels around 1.76 MeV, and if the (^{3}He, d) reaction populates them both with about equal probability, then they are separated by less than 10 keV.

Bouchard and Čujec[7] also concluded that the level at 2.13 MeV is actually two closely spaced levels. This could partially account for the variety of spin and parity assignments to a level around 2.13 MeV: $\frac{5}{2}^+$ by August, Gossett, and Treado,[10] $\frac{3}{2}^+$ by Blair and Armstrong,[11] and $\frac{5}{2}^-$ by Rosner and Holbrow.[2] Further, Burton and McIntyre[13] and O'Brien and Coote[14] support the possibility of two levels in this excitation region. However, the more recent (α, p) work of Dayras *et al.*[6] and Coop, Graham, and Titterton[15] does not support this possibility. Again, in the present experiment, if two levels exist in this energy region, and if both are excited with about equal probability by the (^{3}He, d) reaction, then they are separated by less than 10 keV. These excitation regions will be discussed further in Sec. III.

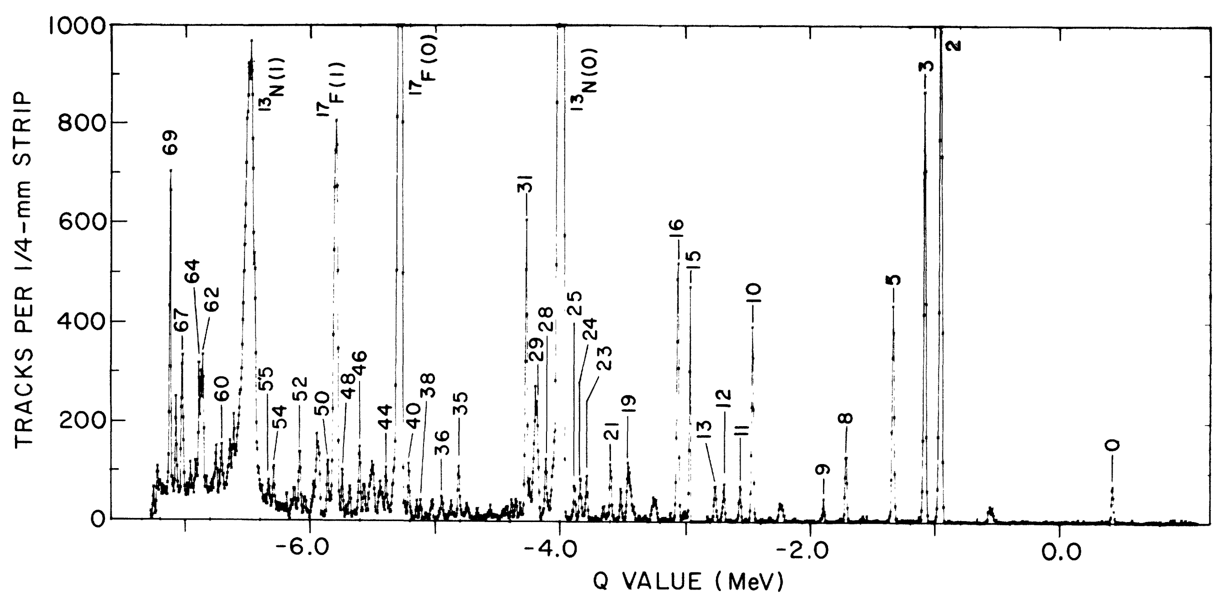

FIG. 1. Deuteron yield of the reaction ^{56}Fe(^{3}He, d)^{57}Co as a function of Q value. The spectrum was obtained with the split-pole magnetic spectrograph at an angle of 7° to the incident 22-MeV ^{3}He^{++} beam. The deuteron groups are numbered, and the corresponding excitation energies in ^{57}Co are listed in Table I. Nuclei reached by the (^{3}He, d) reactions on impurities are labeled, the number in parentheses giving the state excited.

III. DWBA ANALYSIS AND RESULTS

To obtain orbital angular momenta for the stripped protons, angular distributions were generated by use of the DWBA program JULIE [16] and these were compared with the experimental angular distributions. The optical potential used in the analysis is given by

$$V(r) = V_C(r, r_c) - Uf(r, r_u, a_u) - iW_v f(r, r_I, a_I) + iW_s(d/dr)f(r, r_I, a_I),$$

in which r represents the particle-nucleus separation and $V_C(r, r_c)$ represents the Coulomb potential due to a uniformly charged sphere of radius $r_c A^{1/3}$. Potential strengths for the volume real, volume imaginary, and surface imaginary terms are given by U, W_v, and W_s, respectively. The symbol f represents the usual Woods-Saxon form factor

$$f = \{1 + \exp[(r - r'A^{1/3})/a']\}^{-1},$$

in which r', a' are either r_u, a_u or r_I, a_I.

The parameters used in the incoming and outgoing channels, taken from the work of Dorenbusch, Rapaport, and Belote,[17] are given in Table II. For the bound proton, a radius parameter of 1.20 fm and a diffuseness parameter of 0.65 fm were used, and the depth of the real potential well was adjusted to give the transferred proton a binding energy of $E_B = Q(^3\text{He}, d) + 5.49$ MeV. A radial cutoff was not used nor were finite-range parameters included. In Figs. 2 and 3, the experimental

TABLE I. Excitation energies (MeV) in ^{57}Co.

Level No.	^{56}Fe(^{3}He, d) Present	^{56}Fe(^{3}He, d) Ref. 2	β decay Ref. 3	^{54}Fe($\alpha, p\gamma$) Ref. 6	Level No.	^{56}Fe(^{3}He, d) Present	^{56}Fe(^{3}He, d) Ref. 2
0	0.000				36	5.370 ± 0.020	5.367
1			1.2235	1.2237	37	5.425 ± 0.020	5.448
2	1.379 ± 0.010	1.379	1.3776	1.3775	38	5.528 ± 0.020	5.537
3	1.507 ± 0.010	1.506	1.5047	1.5047	39	5.559 ± 0.020	
4				1.6894	40	5.621 ± 0.020	5.635
5	1.758 ± 0.010	1.763	1.7576	1.7572	41	5.653 ± 0.020	
6	1.898 ± 0.015		1.8965	1.8969	42	5.693 ± 0.020	
7			1.9195	1.9196	43	5.743 ± 0.020	
8	2.135 ± 0.010	2.129	2.1329	2.1336	44	5.799 ± 0.020	5.798
9	2.314 ± 0.010	2.309		2.3113	45	5.976 ± 0.020	
10	2.883 ± 0.010	2.880		2.8794	46	6.013 ± 0.020	6.023
11	2.979 ± 0.010	2.978		2.9809	47	6.093 ± 0.020	6.103
12	3.112 ± 0.010		3.1082	3.1087	48	6.153 ± 0.020	6.159
13	3.175 ± 0.010	3.176	3.1769	3.1756	49	6.184 ± 0.020	
14	3.273 ± 0.015	3.259		3.2624	50	6.268 ± 0.020	6.277
15	3.369 ± 0.015	3.355			51	6.344 ± 0.020	6.358
16	3.467 ± 0.015	3.456			52	6.492 ± 0.020	6.505
17	3.681 ± 0.020	3.651			53	6.594 ± 0.020	
18	3.728 ± 0.020	3.703			54	6.699 ± 0.020	
19	3.862 ± 0.020				55	6.739 ± 0.020	
20	3.921 ± 0.020				56	6.768 ± 0.020	
21	4.002 ± 0.015	4.003			57	6.848 ± 0.020	
22	4.064 ± 0.020				58	6.885 ± 0.020	6.899
23	4.197 ± 0.015	4.195			59	7.020 ± 0.020	7.030
24	4.251 ± 0.015	4.248			60	7.115 ± 0.020	7.130
25	4.295 ± 0.015				61	7.162 ± 0.020	
26	4.454 ± 0.020				62	7.265 ± 0.020	7.275
27	4.500 ± 0.020				63	7.281 ± 0.020	
28	4.525 ± 0.015	4.524			64	7.296 ± 0.020	
29	4.595 ± 0.020	4.605			65	7.324 ± 0.020	
30	4.615 ± 0.020				66	7.367 ± 0.020	
31	4.685 ± 0.015	4.689			67	7.432 ± 0.020	7.438
32	4.730 ± 0.020				68	7.480 ± 0.020	
33	4.800 ± 0.020				69	7.528 ± 0.020	
34		4.981					
35	5.223 ± 0.015	5.232					

angular distributions for some of the levels are compared with those obtained by using JULIE. For the angular distributions shown at the left in Fig. 2, the angular momentum of the transferred proton is assigned $l=3$, while for those on the right the assignment is $l=1$. The angular distributions on the left in Fig. 3 are assigned the momentum transfer $l=0$, but no definite l is assigned for those on the right.

Transition strengths G were calculated by use of the relationship $(d\sigma/d\Omega)_{\text{EXP}}=4.42G(d\sigma/d\Omega)_{\text{JULIE}}$. The transition strength is related to the spectroscopic factor S through $G=[(2J_f+1)/(2J_i+1)]C^2S$, in which J_i and J_f represent the respective spins of the initial and final nuclei, and C^2 is the isospin Clebsch-Gordan coupling coefficient. For the $l=1$ and $l=3$ transitions, G was calculated at the first maximum, while for the $l=0$ transitions the calculations were done at the second maximum, since the first maximum is at 0° for this latter case. Because of uncertainties in the experimentally determined cross sections and in the parameters used in the DWBA analysis, transition strengths are uncertain to about 50%. The present values for the peak cross sections, l values, and transition strengths are given in Table III, as are those of Rosner and Holbrow,[2] who studied the reaction ^{56}Fe(^{3}He, d)^{57}Co at a bombarding energy of 16.5 MeV.

As Table III shows, there are large systematic discrepancies between the transition strengths obtained in the present work (done with 22-MeV ^{3}He particles) and those of Rosner and Holbrow[2] (obtained with 16.5-MeV ^{3}He particles). Calculations with JULIE indicate that in going from 16.5 to 22 MeV, the peak cross sections should rise by about a factor of 2. For states below 4 MeV, however, the cross sections determined in the present experiment are either lower than or comparable to those determined by Rosner and Holbrow,[2] with the exception of that for the 2.979-MeV state. It might be objected that for an incident energy as high as 22 MeV, the DWBA calculations cannot be compared with the experimental cross sections to extract transition strengths because of the possibility of deuteron or ^{3}He breakup. However, when the reaction ^{49}Ti(^{3}He, d)^{50}V was used to check this possibility[18] by comparing the ratio of the experimental cross sections at energies of 15.0 and 22 MeV with the corresponding ratio generated by a

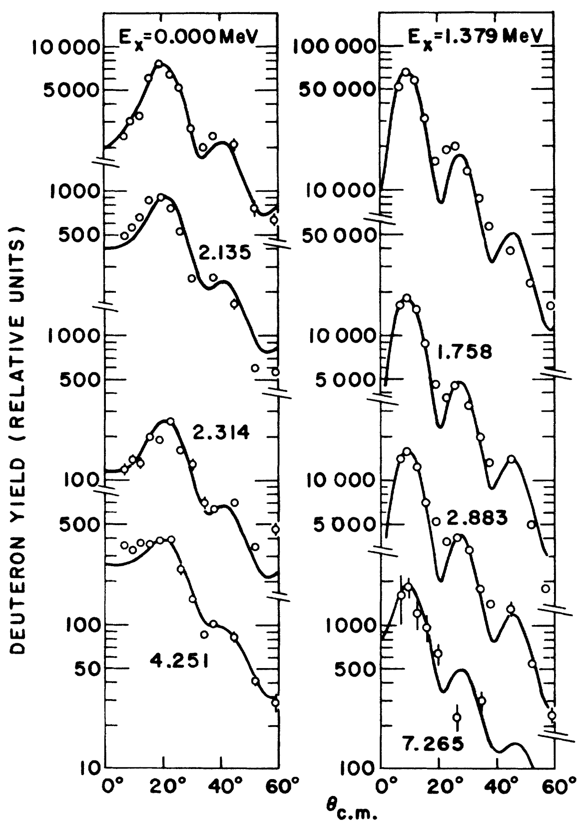

FIG. 2. Angular distributions of deuterons from the ^{56}Fe(^{3}He, d) reaction. On the left side are transitions in which the stripped proton transfers three units of orbital angular momentum, while on the right side are those involving a transfer of one unit of angular momentum. The solid lines are DWBA predictions.

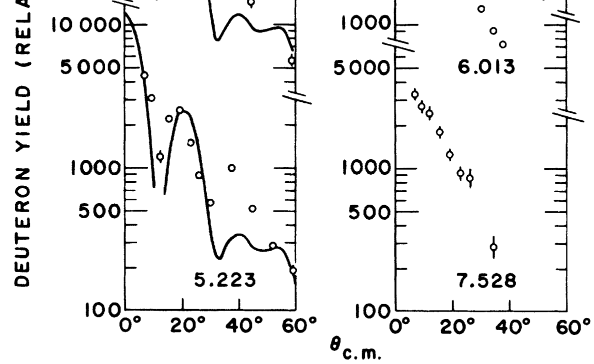

FIG. 3. Angular distributions of deuterons from the ^{56}Fe(^{3}He, d) reaction. On the left side are transitions in which the stripped proton transfers no orbital angular momentum, while on the right side are transitions for which an angular momentum transfer has not been assigned. The solid lines are DWBA predictions.

TABLE II. Optical-model parameters used in the DWBA analysis.

Particle	U (MeV)	W_v (MeV)	r_u (fm)	a_u (fm)	W_s (MeV)	r_I (fm)	a_I (fm)	r_c (fm)
^{3}He	167.9	16.79	1.07	0.775	0.0	1.611	0.60	1.40
d	112.0	0.00	1.00	0.90	72.0	1.55	0.47	1.30

DWBA code,[19] they were found to agree to within 20%. Thus the most likely explanation for the discrepancy between the transition strengths we obtained and those of Rosner and Holbrow[2] is that the cross sections we measured are too low, or their measurements are too high, or both.

Since the transition strengths obtained in the present experiment differ markedly from those of Rosner and Holbrow,[2] different conclusions will be drawn. According to these authors, the strength of the transition to the $J^\pi = \frac{7}{2}^-$ ground state is almost the sum-rule limit. Because of this, they assigned $J^\pi = \frac{5}{2}^-$ to states, populated by $l=3$, at the excitation energies of 2.135, 2.314, 3.175, 3.273, and 4.251 MeV. But the 2.314-MeV state is almost certainly $\frac{7}{2}^-$, as shown by several experiments. First, it is populated in the (t, α) proton pickup reaction[11] and a $\frac{5}{2}^-$ assignment would imply that the wave function for the ground state of ^{58}Ni contains an appreciable component with two protons in the $1f_{5/2}$ shell, an unlikely possibility. Second, if it were $\frac{5}{2}^-$ it is difficult to understand why it is not populated in the β decay of ^{57}Ni. Third, provided the assignment of $\frac{9}{2}^-$ to the 1.222-MeV state is accepted, proton-γ correlation experiments[6,15] give an assignment of $\frac{7}{2}^-$ to the state at 2.314 MeV. Finally, this assignment is supported by lifetime measurements.[6,13] Hence it is clear that the transition strengths given by Rosner and Holbrow[2] are overestimates, since an assignment of $J^\pi = \frac{7}{2}^-$ to the 2.314-MeV state results in a violation of the sum rule if their transition strengths are used.

As discussed earlier, spins and parities $\frac{5}{2}^-$, $\frac{5}{2}^+$, and $(\frac{3}{2}^+)$ have been assigned to the 2.135-MeV state. To partially resolve this discrepancy, the possibility of two closely spaced energy levels was raised. However, if two levels exist and if both are excited by the (^{3}He, d) reaction, then they are separated by less than 10 keV. This possibility can be explored by studying the angular distribution. Suppose two states, one $\frac{5}{2}^-$ or $\frac{7}{2}^-$ and the other $\frac{3}{2}^+$ or $\frac{5}{2}^+$, are within 10 keV and about equally populated. The observed deuteron angular distribution would be the sum of two angular distributions, one with $l=3$ and the other with $l=2$. However, the observed angular distribution is fitted very well by a DWBA calculation assuming $l=3$. It is true that the first maximum is a few degrees lower than predicted by the calculations, but the same shift can be seen for the ground-state transition (also $l=3$) and is most likely due to the choice of optical-model parameters. Hence the present experiment supports a single state at 2.135 MeV, with $J^\pi = \frac{5}{2}^-$ or $\frac{7}{2}^-$. Most likely the tentative assignment of $\frac{3}{2}^+$ by Blair and Armstrong[11] and the assignment of $\frac{5}{2}^+$ by August, Gosset, and Treado[10] are in error. The recent $(\alpha, p\gamma)$ work of Dayras *et al.*[6] and Coop, Graham, and Titterton[15] establish the J^π of this level as $\frac{5}{2}^-$, in agreement with this earlier assignment by Rosner and Holbrow.[2]

The assignment of $\frac{5}{2}^-$ by Rosner and Holbrow[2] to the 3.175-MeV state is also correct, because β-decay studies[3,9] limit the spin of this state to $J \leq \frac{5}{2}$. Both the present work and that of Rosner and Holbrow[2] yield $l=3$ for the transitions populating the states at 3.273 and 4.251 MeV, so they must have negative parity and spins of $\frac{5}{2}$ or $\frac{7}{2}$.

Now consider the $l=1$ transitions. The angular distribution of the deuterons leading to the 1.758-MeV state is fitted very well by a DWBA calculation assuming $l=1$ for the transferred proton. Earlier the possibility of two closely spaced levels near this energy, one with $J^\pi = \frac{3}{2}^-$ and the other with $J^\pi = \frac{5}{2}^-$, had been considered. If this were so, the experimentally determined angular distribution should be a composite of $l=1$ and $l=3$ distributions. Hence we can conclude that if there are two levels near 1.76 MeV, the (^{3}He, d) reaction with 22-MeV ^{3}He particles excites only the one with $J = \frac{1}{2}^-$ or $\frac{3}{2}^-$. The $(\alpha, p\gamma)$ studies of Coop, Graham, and Titterton[15] also show only a single level in this energy region and establish its spin and parity as $\frac{3}{2}^-$.

Established $\frac{3}{2}^-$ states include those at 1.379 and 1.758 MeV, while the 1.507-MeV state is known to have $J^\pi = \frac{1}{2}^-$ (as can be seen from the references and discussion given by Coop, Graham, and Titterton[15]). The 2.883-MeV state has been assigned $J^\pi = \frac{1}{2}^-$ by Rosner and Holbrow.[2] However, both in the present work (as will be discussed shortly) and in that of Burton and McIntyre[13] and Dayras *et al.*,[6] a strong γ-ray branch is observed to the ground state from this level. Since it is very unlikely that such an $M3$ transition would compete strongly with $E2$ transitions, the 2.883-MeV state is also very likely $\frac{3}{2}^-$. The sum of the transition strengths to these three states, according to the present measurements and calculations, is 0.76 – well below the limit of 3.6 for $T_<$ states with $J^\pi = \frac{3}{2}^-$. If one arbitrarily assumes that all the $l = 1$ proton transfers (except that to the known $\frac{1}{2}^-$ state at 1.507 MeV) observed in the present experiment lead to $\frac{3}{2}^-$ states, then the sum of the strengths is still less than half the limit. Although the sum-rule limit of 3.6 may be somewhat high because it is based on an oversimplified shell model for the ground state of ^{56}Fe, it is unlikely that a more realistic shell model would reduce the limit by a factor of 2. Hence, either: (a) about half of the $2p_{3/2}$ strength resides in transitions to levels not observed in the present experiment; or (b) the transition strengths obtained in the present experiment are somewhat low and the actual strengths lie somewhere between those we have

TABLE III. Summary of maximum differential cross sections, l values, and transition strengths.

Excitation energy (MeV)	$(d\sigma/d\Omega)_{EXP}$ Present (mb/sr)	Ref. 2 (mb/sr)	l value Present	Ref. 2	$(2J_f+1)C^2S$ Present	Ref. 2	Assumed J^π
0.000	0.711	0.62	3	3	0.89	1.80	$\frac{7}{2}^-$
1.379	6.11	10.40	1	1	0.52	1.80	$\frac{3}{2}^-$
1.507	3.67	4.20	1	1	0.35	0.72	$\frac{1}{2}^-$
1.758	1.69	1.80	1	1	0.13	0.30	$\frac{3}{2}^-$
2.135	0.836	0.61	3	3	1.2	2.00	$\frac{5}{2}^-$
2.314	0.239	0.21	3	3	0.20		$\frac{7}{2}^-$
						0.70	$\frac{5}{2}^-$
2.883	1.51	1.90	1	1	0.11		$\frac{3}{2}^-$
						0.39	$\frac{1}{2}^-$
2.979	0.229 [a]	<0.10	0				$\frac{1}{2}^+$
3.112	0.247		1		0.019 [b]		
3.175	0.485	0.31	3	3	0.55	0.84	$\frac{5}{2}^-$
3.273	0.658	0.60	3	3	0.65	1.62	$\frac{5}{2}^-$
					0.44		$\frac{7}{2}^-$
3.369	2.15	2.80	1	1	0.16 [b]		
						0.56	$\frac{1}{2}^-$
3.467	1.94	1.90	1	1	0.14 [b]		
						0.38	$\frac{1}{2}^-$
4.002	0.420	0.23	(1)		0.029 [b]		
4.064	0.128		(1)		0.009 [b]		
4.197	0.364	<0.10	1		0.024 [b]		
4.251	0.366	0.28	3	3	0.26 [b]		
						0.70	$\frac{5}{2}^-$
4.295	0.301		(1)		0.020 [b]		
4.525		1.53		(1)			
4.685	2.30	1.84	(1)	(2)	0.15 [b]		
5.223	0.409 [a]	0.24	0		0.027		$\frac{1}{2}^+$
5.621	0.42	0.20	1	(1)			
6.011	0.553	<0.10					
7.265	1.23	0.57	1	1		(0.12)	

[a] Calculated at 18.5° (second maximum).

[b] The average of the two values corresponding to the two possible spin assignments.

reported and those reported by Rosner and Holbrow.[2] States that lie above 3 MeV and are excited by an $l=1$ proton transfer have either $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$, but a more definite assignment will require further experimental work. The distribution of the $l=1$ and $l=3$ transition strengths among the energy levels is summarized graphically in Fig. 4.

The states at 2.979 and 5.233 MeV are excited by $l=0$ proton transfers and hence have $J^\pi=\frac{1}{2}^+$. The nature of these states will be discussed in Sec. VI.

Rosner and Holbrow[2] tentatively assigned $l=4$ to a state at 4.605 MeV. However, in this energy region, the present work (Table I) shows two levels separated by about 20 keV. If these two states are populated by protons captured with different l values, the composite angular distribution may look somewhat like that produced by an $l=4$ proton transfer. In the present experiment the two levels were not resolved very well, and at some angles were obscured by a contaminant, so l values could not be assigned.

IV. DEUTERON-γ-COINCIDENCE MEASUREMENTS

In the deuteron-γ-coincidence study a target about 1 mg/cm^2 thick, enriched to over 99% in ^{56}Fe, was bombarded with 13-MeV ^{3}He^{++} ions obtained from the Argonne FN tandem Van de Graaff accelerator. Deuterons emerging in the forward direction were detected by a system consisting of two surface-barrier detectors in tandem (total thickness =4000 μm) connected to the two inputs of a single preamplifier. This large detector thickness was not necessary to stop the deuterons, but it was necessary to stop the protons for the proton-γ coincidences which were recorded simultaneously. The detector system accepted particles in the range from −10 to +10° relative to the incident beam direction. To prevent the incident beam from striking the detector system, a 100-mg/cm^2 gold foil was placed between the target and detecting system.

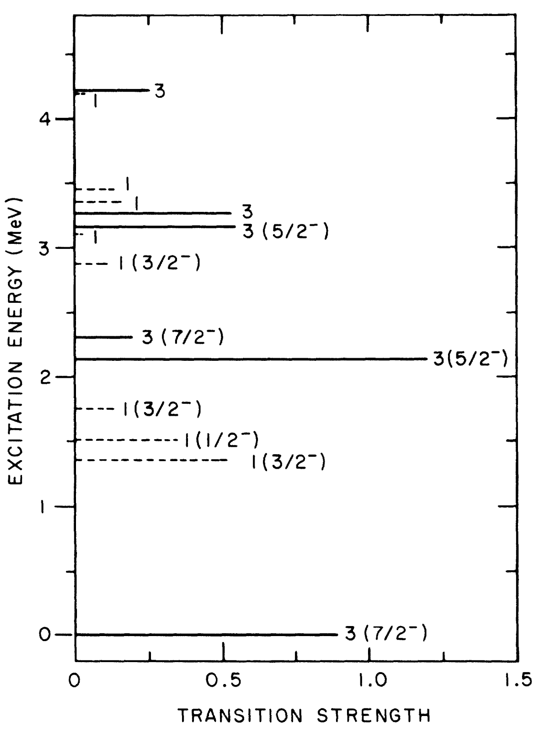

FIG. 4. Transition strengths as a function of excitation energy for $l=1$ (dashed lines) and $l=3$ (solid lines) proton transfers. Known J^π assignments are given in parentheses.

The spectrum of particles in coincidence with all γ rays is shown in Fig. 5. Particles above channel No. 350 are all protons from the ^{56}Fe(^{3}He,$p\gamma$) and ^{12}C(^{3}He,$p\gamma$) reactions. The peak around channel number 280, labeled KOP (knock-on protons), is due to protons ejected from the target by the incident ^{3}He^{++} beam. Deuteron peaks corresponding to the excitation of levels in ^{57}Co are indicated by the numbers used in Table I. Below a channel number of about 300, a contribution from the reaction ^{56}Fe(^{3}He, $np\gamma$)^{57}Co gives a background that increases with decreasing channel number.

A lithium-drifted germanium detector of 28-cm^3 active volume, located approximately 6.25 cm from the target and at 100° to the incident beam direction, was used to obtain the γ-ray spectrum. The energy dependence of the detector efficiency was measured in a previous experiment.[20] In the present experiment the radioactive isotopes ^{60}Co, ^{137}Cs, and ThC'' were used for energy calibration. Also, γ rays from the decay of several states in ^{14}N produced in the ^{12}C(^{3}He,$p\gamma$) reaction were recorded in coincidence with the protons populating the states. Since the cross section for this reaction is large at 13 MeV, good statistics could be obtained quickly.

The method of collecting and recording particle-γ coincidences and the details of the electronic arrangement are given elsewhere.[18]

V. γ DECAYS

To deduce the decay scheme for levels in ^{57}Co, we studied the γ rays in coincidence with deuteron groups leading to states in this nucleus. However, the detector arrangement did not distinguish between these deuterons and the protons from the ^{56}Fe(^{3}He, $np\gamma$) reaction, which were also in coincidence with γ rays from the decay of ^{57}Co. To avoid misinterpretation, the particle energy range was divided into a large number of small groups. Then the spectrum of γ rays in coincidence with each group was obtained. Finally, the intensities of the γ rays suspected of being associated with the decay of a particular level were plotted as a function of the average energy of each group. This was done to ensure that the intensity increased above the "background" value (due to the proton-γ coincidences) in the energy region corresponding to deuterons exciting that particular state.

Because γ-ray angular distributions were not taken, branching ratios could not be assigned. Figure 6 shows the decay scheme obtained in the present work. In most cases the present results agree with those reported earlier. A very complete decay scheme for levels below 3.3 MeV is given by Dayras *et al.*[6] However, the latter disagree with Burton and McIntyre[13] on the decay of the 2.883-MeV level. In agreement with Dayras *et al.*,[6] we observe strong branches to the ground state and to the 1.758- and 1.920-MeV states. Burton and McIntyre[13] do not observe a transition to the 1.920-MeV state, but report a branch to the 1.378-MeV state. No evidence for the latter transition was found in the present experiment, although we would not see less than a 20% branch. Of course a highly anisotropic distribution with a minimum around 100° would cause us to miss a somewhat larger branch.

The γ decay of some of the low-lying levels has also been determined previously[6, 21] in studies using the reaction ^{56}Fe(p, γ)^{57}Co. According to Leslie *et al.*,[21] the 2.984-MeV state decays to the 1.897-MeV state, while both the present work and that of Dayras *et al.*[6] show only a decay to the 1.758-MeV state. According to both the present investigation and that of Leslie *et al.*,[21] the 3.369-MeV state (the 3.3570-MeV state of Ref. 21) decays to the 1.378-MeV state. Both Leslie *et al.*[21] and O'Brien and Coote[14] indicate that a level with an energy of about 3.993 MeV decays mainly to the ground state. The 4.002-MeV state investigated in the present study may be the same level. We see no evidence for a ground-state decay, but some evidence for a decay to the 1.507-MeV state.

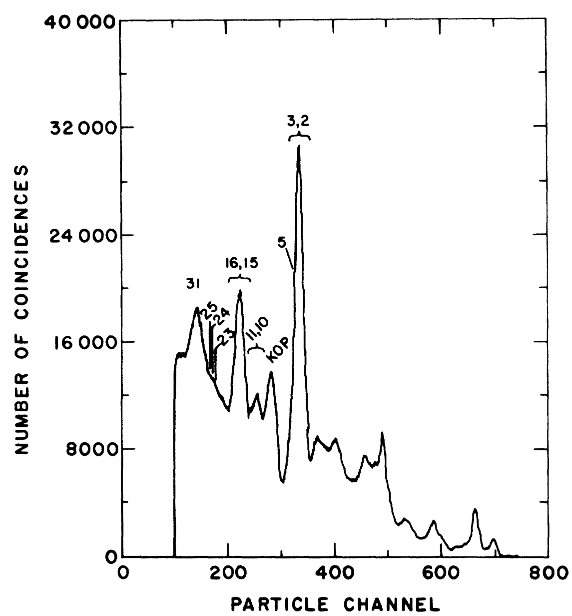

FIG. 5. The number of particles in coincidence with all the γ rays detected when a 13-MeV ^{3}He^{++} beam strikes an ^{56}Fe target. The particle detector was at 0° to the incident beam direction and the γ-ray detector was at 100°. The numbers above the peaks label deuteron groups leaving ^{57}Co in excited states; their excitation energies are given in Table I. The peaks above channel number 350 are due either to impurities or to protons from the ^{56}Fe(^{3}He, $p\gamma$) reaction.

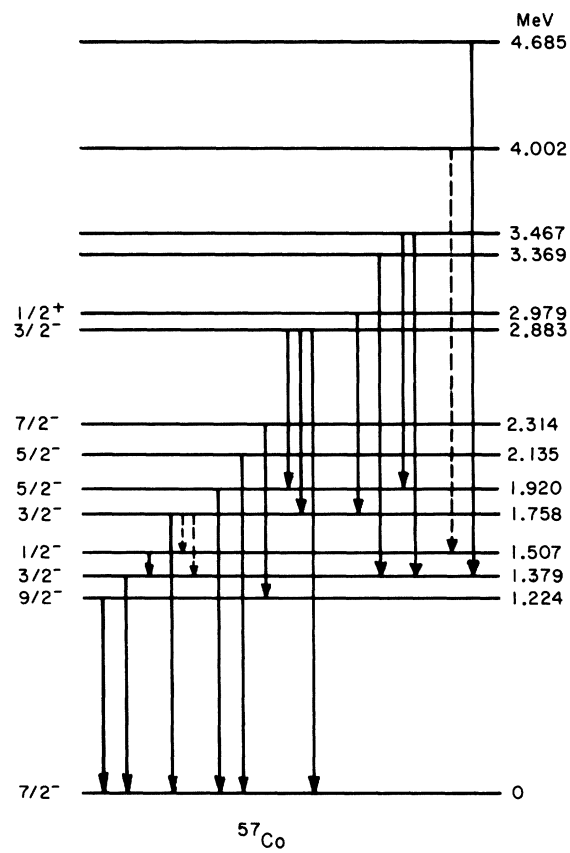

FIG. 6. Decay scheme for ^{57}Co levels deduced from the present study of the ^{56}Fe(^{3}He, $d\gamma$) reaction. Uncertain transitions are indicated by dashed lines. All energies, except for the 1.224- and 1.920-MeV states, are from the present spectrograph study of the ^{56}Fe(^{3}He, d) reaction.

VI. DISCUSSION

Figure 7 summarizes the spins, parities, and γ-ray decays of levels in ^{57}Co up to an excitation energy of 4.7 MeV. All definitely established energy levels below an excitation energy of 3.5 MeV are shown in this figure. At present there is insufficient evidence to justify the inclusion of two additional levels, one postulated to be near 1.75 MeV and the other near 2.13 MeV. A level above $E_x = 3.35$ MeV is included only if something in addition to its excitation energy is known. A more complete list of levels with energies above 3.5 MeV is included in Table I. For the 2.879- and 2.981-MeV states, the decay scheme shown in Fig. 7 is the one deduced both by Dayras *et al.*[6] and in the present work, but Burton and McIntyre[13] present a somewhat different decay scheme for the 2.879-MeV state, while Leslie *et al.*[21] give a different mode for the 2.981-MeV state. The transition from the 3.993-MeV state to the ground state was observed by both O'Brien and Coote[14] and Leslie *et al.*[21] Also, for this state, Leslie *et al.*[21] report a branch to the 1.7572-MeV state and we see some evidence for a branch to the 1.507-MeV state.

The results obtained in the present study, in which the ^{57}Co was excited in the (^{3}He, *d*) stripping reaction, agree quite well with the results[11] of the (*t*, α) pickup reaction leading to states in ^{57}Co. Table IV compares some of the results for levels excited in these two reactions. Although the assignments in the (*t*, α) study were made tentatively, disagreements occur only for the states at 2.135 and 3.369 MeV. As discussed earlier, the 2.135-MeV state is almost certainly $\frac{5}{2}^-$. Since Blair and Armstrong's[11] assignment of $l=3$ for the 3.354-MeV state is uncertain, since Rosner and Holbrow[2] agree with our assignment of $l=1$, and since the experimental angular distribution (Fig. 2) obtained in our work is fitted very well by a DWBA calculation assuming $l=1$, an assignment of $\frac{1}{2}^-$ or $\frac{3}{2}^-$ is to be preferred over $\frac{7}{2}^-$ for this state. In the present experiment, the 1.379-MeV state is populated strongly, the proton being captured in the $2p_{3/2}$ shell. Also the 2.135-MeV state is strongly populated, the proton being captured in the $1f_{5/2}$ shell. Since these states are also seen with a good direct-interaction pattern in the (*t*, α) proton pickup reaction, the ^{58}Ni ground-state wave function must include terms with particles in the $2p_{3/2}$ and $1f_{5/2}$ shells. On the other hand, the 1.507-MeV state, which is formed by placing a proton in the $2p_{1/2}$ shell, is not seen in the (*t*, α) work. Hence the wave function for the ground state of ^{58}Ni does not include a large term with particles in the $2p_{1/2}$ shell.

Work with the (*t*, α) reaction[11] located the $2s_{1/2}$ hole state at 2.970 MeV and the $2d_{3/2}$ hole state at 3.539 MeV. Since the former state is populated in the (^{3}He, *d*) reaction but the latter state is not, the ^{56}Fe ground-state wave function must contain

TABLE IV. Comparison of the experimental results obtained with the proton pickup and proton stripping reactions, both leading to states in ^{57}Co.

Reaction ^{56}Fe(^{3}He, d)^{57}Co[a] Excitation energy (MeV)	l	Assumed J^π	$(2J_f+1)C^2S$	C^2S	Reaction ^{58}Ni(t, α)^{57}Co[b] Excitation energy (MeV)	l	Assumed J^π	C^2S
0.000	3	$\frac{7}{2}^-$	0.89	0.11	0.000	3	$\frac{7}{2}^-$	5.36
1.379	1	$\frac{3}{2}^-$	0.52	0.13	1.369	1	$\frac{3}{2}^-$	0.06
1.507	1	$\frac{1}{2}^-$	0.35	0.17				
1.758	1	$\frac{3}{2}^-$	0.13	0.03	1.747	1	$\frac{3}{2}^-$	0.19
2.135	3	$\frac{5}{2}^-$	1.2	0.20	2.130	(2)	$\frac{3}{2}^+$	0.10
2.314	3	$\frac{7}{2}^-$	0.20	0.025	2.302	3	$\frac{7}{2}^-$	0.20
2.979	0	$\frac{1}{2}^+$			2.970	0	$\frac{1}{2}^+$	1.31
3.273	3	$\frac{7}{2}^-$	0.44	0.055	3.259	(3)	($\frac{7}{2}^-$)	0.14
		$\frac{5}{2}^-$	0.65	0.11				
3.369	1		0.16[c]		3.354	(3)	($\frac{7}{2}^-$)	0.11
					3.539	2	$\frac{3}{2}^+$	2.33

[a] Present work.
[b] Reference 11.
[c] The average of the two values corresponding to the two possible spin assignments.

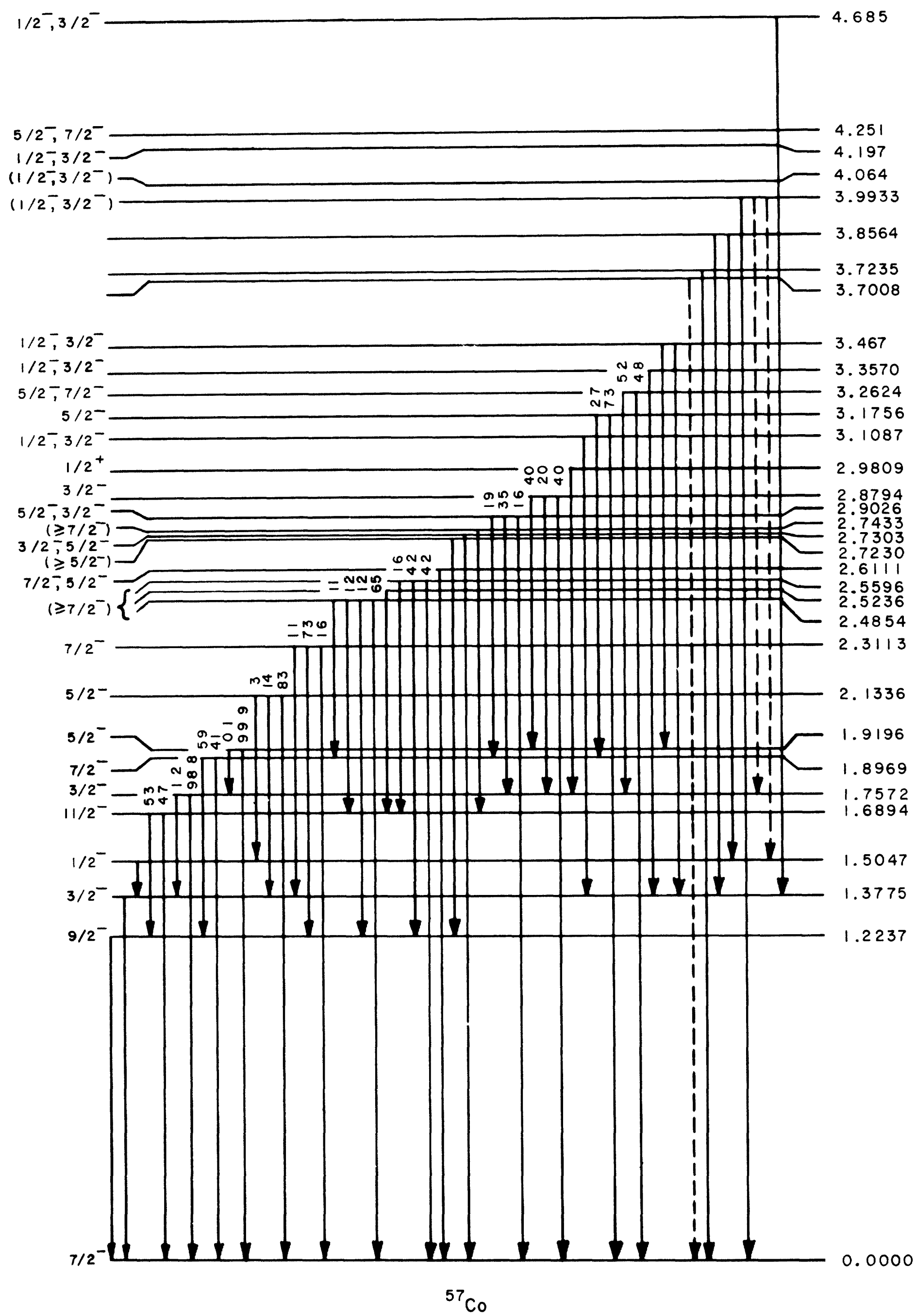

FIG. 7. A summary of the energies, spins, parities, and γ-ray decays for ^{57}Co states below 5.7 MeV. The excitation energies are given in MeV. Dashed lines indicate transitions that are somewhat uncertain. The information shown is from Dayras *et al.* (Ref. 6), Gatrousis *et al.* (Ref. 3), O'Brien and Coote (Ref. 14), and Leslie *et al.* (Ref. 21), as well as from the present work.

a term involving holes in the $2s_{1/2}$ shell, but no appreciable term involving holes in the $2d_{3/2}$ shell. Not only the state at 2.970 MeV, but also the state at 5.233 MeV is formed by an $l=0$ proton transfer. However, this latter state is not populated in the (t, α) reaction and so may possibly be formed by transferring a proton into the $3s_{1/2}$ shell (though evidence to the contrary will be presented below).

Certain low-lying states in ^{57}Co are presumed to be collective in nature. Coupling an $f_{7/2}$ proton hole to the first 2^+ vibrational state in ^{58}Ni will lead to states in ^{57}Co with $J^\pi = \frac{9}{2}^-, \frac{11}{2}^-, \frac{3}{2}^-, \frac{7}{2}^-$, and $\frac{5}{2}^-$. These have been identified[22] as the states at 1.224, 1.687, 1.758, 1.896, and 1.920 MeV, respectively. We would not expect a characteristic stripping pattern. This is indeed the case, except for the 1.758-MeV state, which is strongly excited and shows a good $l=1$ angular distribution.

Two rather recent calculations have attempted to reproduce the experimentally determined properties of the low-lying levels in ^{57}Co. One, a shell-model calculation by Gatrousis *et al.*,[3] assumes an inert ^{40}Ca core and particles distributed in the $1f_{7/2}$, $2p_{3/2}$, and $1f_{5/2}$ orbits. Another, by Satpathy and Gujrathi,[4] couples proton holes to the quadrupole vibrations of ^{58}Ni. Figure 8 compares the energy levels obtained in these two calculations with the experimentally determined properties of these levels. The calculations of Satpathy and Gujrathi[4] fail to give the lowest $\frac{1}{2}^-$ and $\frac{3}{2}^-$ energy levels and generally predict too few states. The calculations of Gatrousis *et al.*[3] likewise account for only one low-lying $\frac{3}{2}^-$ state, but do predict a low-lying $\frac{1}{2}^-$ state. This shell-model calculation also predicts three low-lying states that have not been seen in any experiment – namely, a second $\frac{9}{2}^-$, a second $\frac{11}{2}^-$, and a $\frac{13}{2}^-$ state. In this connection, it would be interesting to determine the spins and parities of the three states at 2.485, 2.524, and 2.560 MeV, since, as indicated in Fig. 8, their spins are known to be $\geq \frac{7}{2}$.

As discussed above, the position of the $2s_{1/2}$ hole state in ^{57}Co is known, and it is the lowest $J^\pi = \frac{1}{2}^+$ state. The experimentally determined positions (solid lines) of the first $\frac{1}{2}^+$ states in the odd-A Co isotopes decreases as the mass number increases, as is shown in Fig. 9. Since Satpathy and Gujrathi[4] include a $2s_{1/2}$ proton hole in their calculations, they predict $\frac{1}{2}^+$ states (dashed lines); and, in particular, for ^{57}Co they predict two $\frac{1}{2}^+$ states and the predicted positions agree reasonably well with the experimentally determined excitation energies. Hence the upper $\frac{1}{2}^+$ state would also seem to be a hole state. In their calculations for the (t, α) reaction, however, Satpathy and Gujrathi[4] calculate that the spectroscopic factor for the upper $\frac{1}{2}^+$ state is half that for the lower

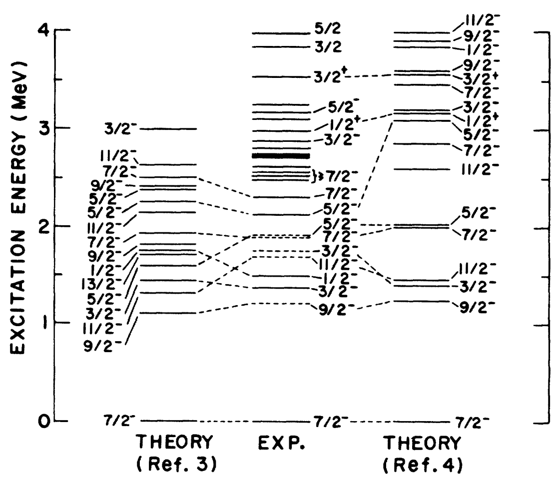

FIG. 8. Comparison between the experimentally determined properties of low-lying levels in ^{57}Co and two theoretical calculations. On the left are the results of a shell-model study by Gatrousis *et al.* (Ref. 3), while on the right are the results of a unified-model calculation by Satpathy and Gujrathi (Ref. 4). The levels shown dashed are members of a collective quintet (Ref. 22).

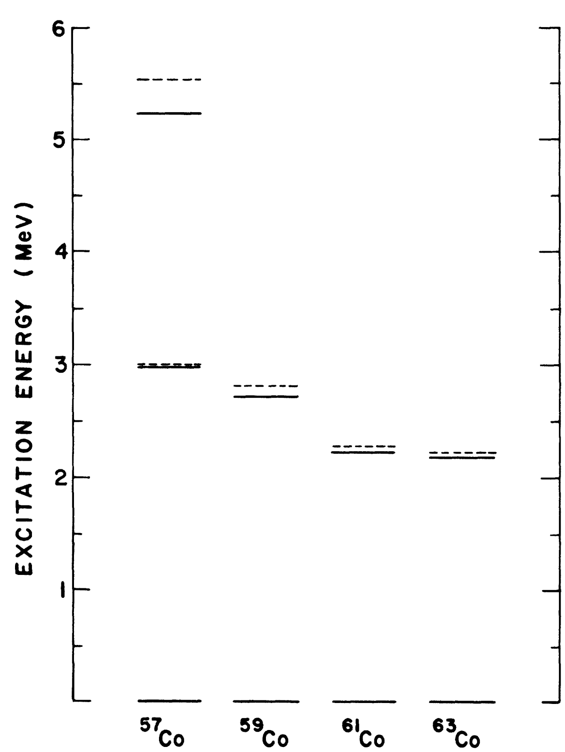

FIG. 9. Comparison of the experimentally determined energies of $s_{1/2}$ states in the Co isotopes with those given by Satpathy and Gujrathi (Ref. 4). The solid lines give the positions determined by experiments, while the dashed lines give the positions determined by the theoretical calculations.

one, so it is surprising that the higher $\frac{1}{2}^+$ state was not seen by Blair and Armstrong.[11] On the other hand, this may be a particle state as suggested above, and if so the second predicted hole state remains to be located. Of course, since the calculations of Gatrousis *et al.*[3] assumed an inert, completed ^{40}Ca core, they cannot predict even-parity states.

The energy region above 7 MeV is interesting because it contains the analogs of states in ^{57}Fe. Rosner and Holbrow[2] estimated the excitation energy of the ^{57}Co analog to the ground state of ^{57}Fe to be 7.275 MeV. Since the analog states are unbound, they can also be studied by the ^{56}Fe(p,γ) reaction. Those analog states that have significant single-particle strengths should in general be excited by the (p,γ) and (^{3}He, d) reactions. For example, if one considers the parent states in ^{57}Fe, the combined transition strength for populating the ground state ($J^\pi = \frac{1}{2}^-$) and the first excited state (0.014 MeV, $J^\pi = \frac{3}{2}^-$) by the reaction ^{56}Fe(d,p)^{57}Fe is large[23] ($C^2S = 2.2$), so we should strongly excite at least one and possibly both analogs to these states with an $l = 1$ proton transfer. In Table V, the present results for excitation energies greater than 7 MeV are compared with results from the (p,γ) reaction. Since the energies determined in the present work have an uncertainty of ±20 keV, it is difficult to be sure that the correspondences given in Table V are correct; these associations are based on the assumption that levels strongly populated in the (p,γ) work should also be populated in the present work.

Leslie *et al.*[21] claim that the analog of the first excited state ($J^\pi = \frac{3}{2}^-$) of ^{57}Fe is split and the members have different γ decay modes. It may be that some or all of the states we observe at 7.265, 7.281, 7.296, and 7.324 MeV are components of this split analog. Unfortunately, we could determine the l value ($l = 1$) for only the first of these states.

For the position of the analog of the ground state, Rosner and Holbrow[2] give 7.275 MeV, Brändle *et al.*[24] give 7.246 ± 0.004, and O'Brien and Coote[14] give 7.2667 ± 0.001 MeV. However, Leslie *et al.*[21] calculated a proton width of about 0.7 eV for exciting the ground-state analog by the (p,γ) reaction, and hence, as they pointed out, it should only be weakly excited by this reaction and the above assignments for the energy of the ground-state analog are doubtful. On the other hand, this calculation involves the ^{56}Fe(d,p) spectroscopic factor for the ground state of ^{57}Fe, and this value can be only roughly estimated because

TABLE V. Excitation energies (MeV) obtained by the (p,γ) reaction and by the present work in an excitation region in which isobaric analog levels are expected.

Present work	August, Gossett, and Treado (Ref. 10)	O'Brien and Coote (Ref. 14)	Leslie *et al.* (Ref. 21)
7.265 ± 0.020 ($l = 1$)		7.2527 ($\frac{3}{2}^-$)	7.2551 ± 0.0029 ($\frac{3}{2}$)
			7.2673 ± 0.0020
7.281 ± 0.020		7.2667 ($\frac{1}{2}^-$)	7.2683 ± 0.0019 ($\frac{1}{2}$, $\frac{3}{2}$)
7.296 ± 0.020			7.2737 ± 0.0021 ($\frac{3}{2}$)
7.324 ± 0.020	7.320 ± 0.030		
7.367 ± 0.020	7.369 ± 0.030		
7.432 ± 0.020 ($l = 2, 3$)	7.433 ± 0.030		
	7.468 ± 0.030		
	7.474 ± 0.030		
7.480 ± 0.020	7.481 ± 0.030		
7.528 ± 0.020	7.538 ± 0.030 ($\frac{3}{2}^-$)	7.5234 ($\frac{5}{2}^+$)	
	7.610 ± 0.030 ($\frac{3}{2}^-$)		
	7.626 ± 0.030		
	7.634 ± 0.030 ($\frac{3}{2}^-$)		7.6235 ± 0.0030 ($\frac{3}{2}$, $\frac{5}{2}$)
	7.648 ± 0.030 ($\frac{5}{2}^+$)	7.6325 ($\frac{3}{2}^-$)	7.6369 ± 0.0028 ($\frac{1}{2}$, $\frac{3}{2}$)
	7.656 ± 0.030 ($\frac{3}{2}^-$)		7.6462 ± 0.0028 ($\frac{3}{2}$)
	7.662 ± 0.030		7.6527 ± 0.0028 ($\frac{3}{2}$)

the protons leading to the ground state are incompletely resolved from those leading to the first excited state. As seen in Table V, Leslie *et al.*[21] found two levels about 1 keV apart near 7.268 MeV, and as these authors pointed out, this casts some doubt on the $J=\frac{1}{2}$ assignment to the level O' Brien and Coote[14] observed at 7.2667 MeV. Hence it is an open question whether or not the analog to the ground state of ^{57}Fe has been located and whether or not is is split.

The fact that reaction ^{56}Fe$(d,p)^{57}$Fe strongly populates the second excited state ($J^\pi=\frac{5}{2}^-$) in ^{57}Fe indicates that it is largely a $1f_{5/2}$ particle state. Hence it is expected that the ^{57}Co analog of this ^{57}Fe state should be observed in the (^{3}He, d) reaction, and indeed Rosner and Holbrow[2] located this analog state at an excitation energy of 7.438 MeV. In the present experiment, a state strongly populated by protons transferring angular momentum of 2 or 3 was located at 7.432 MeV. Using the (p,γ) reaction, August, Gossett, and Treado[10] strongly populated a state at 7.433 MeV, which we presume to be the same state. However, August, Gossett, and Treado[10] point out that because of the difference in barrier transmission, f-wave capture is much less probable than p-wave capture and therefore they do not expect the strong resonances in the (p,γ) reaction to be due to f-wave capture. This argues against a $J^\pi=\frac{5}{2}^-$ assignment for the state at 7.433 MeV. However, if the reduced width for populating the analog state is an appreciable fraction of the Wigner limit, it may possibly be strongly excited by the (p,γ) reaction and the state at 7.433 MeV may in fact be this analog state. Nevertheless, the possibility remains that the state at 7.433 MeV is populated by a proton transfer with $l=2$ and hence is not the analog state. Since the parent state is of simple character, it would be somewhat surprising that we do not see the analog state – unless it is highly fragmented.

Rosner and Holbrow[2] place the analog of the third excited state ($J^\pi=\frac{3}{2}^-$) in ^{57}Fe at 7.663 MeV. According to Leslie *et al.*,[21] this analog is split, and they also associate states with $J=\frac{3}{2}$ in the region around 7.6 MeV with the third excited state in ^{57}Fe. Excitation energies above 7.53 MeV were not studied in the present experiment. It is interesting to note that a state at 7.528 MeV is strongly excited in the present experiment though it is not reported by Rosner and Holbrow.[2] This is presumably a $T_<$ state, since it does not fit into the ^{57}Fe spectrum, and its strength would indicate that is is of simple character. The angular distribution of deuterons leading to this state (Fig. 3) is rather similar to those of the bound states at 3.921 and 6.013 MeV.

Hence, work remains to be done in identifying the analog states and studying their nature. The region below the analog states is not well described by existing theoretical calculations, and it remains to be seen if more detailed shell-model or unified-model calculations will be more successful.

ACKNOWLEDGMENT

One of us (G.H.) wishes to thank the Western Michigan University Office of Research Services for partial support of this work through a faculty research grant.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†Argonne Universities Association Predoctoral Fellow, Indiana University. Present address: Ohio State University, Columbus, Ohio 43210.

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PHYSICAL REVIEW C VOLUME 5, NUMBER 5 MAY 1972

Nuclear Structure of ^{30}P and ^{34}Cl in a Unified Model*

B. P. Singh, B. Castel, and I. P. Johnstone
Physics Department, Queen's University, Kingston, Ontario, Canada

and

K. W. C. Stewart
Department of Theoretical Physics, The University, Manchester, United Kingdom
(Received 29 November 1971)

The low-lying structure of the odd-odd nuclei ^{30}P and ^{34}Cl is studied in a modified version of the vibrational unified model in which anharmonic and quasiparticle effects are included. The results are compared with recent shell-model calculations and yield satisfactory agreement with recently observed level schemes and decay rates.

I. INTRODUCTION

The second half of the $2s$-$1d$ shell provides a region where both microscopic and collective models have had considerable success in explaining the systematics of odd- and even-A nuclei. With a few exceptions, however, only the shell model has been used for investigations of odd-odd nuclei.[1,2] Since this model requires a description of states in terms of many components, the essential features of the wave functions are difficult to isolate, and therefore the physical and hence intuitive understanding is not clear. The version of the vibrational unified model which we present below is based essentially on the coupling of quasiparticles to anharmonic phonon states, and describes both the $T=0$ and $T=1$ states of an odd-odd nucleus. This model has been successfully tested for odd-A and even-even nuclei,[3] and its generalization here to odd-odd cases should provide an interesting test for its possible extension. The formalism used here in the energy-level and decay-rate calculations will be described in Sec. II, while Secs. III and IV will be devoted to the study of ^{30}P and ^{34}Cl. Finally, we shall conclude with a critical discussion of our results compared with those obtained in recent microscopic calculations.[1,2]

II. FORMALISM

The classical form of the intermediate-coupling unified model is well known and its formalism has been described already in numerous papers.[4,5] Recently this model has been modified in order to take into account the anharmonic character of the core nuclei used.[6] In addition pairing effects were considered[3] by coupling quasiparticle states to anharmonic vibrations of core nuclei. These modifications to the classical form of the unified model have indeed brought marked improvements, especially in regions where core nuclei were seen to depart markedly from the purely harmonic excitation pattern.

In the model, the total Hamiltonian is separated into four parts:

$$H = H_c + H_{\text{s.p.}} + H_{\text{int}} + H_{12}, \tag{1}$$

where $H_{\text{s.p.}}$ is the usual single-particle shell-model Hamiltonian, and H_c is the usual Hamiltonian for the core vibrations, modified to take account of the fact that the two-phonon states of angular momentum J have energy $(2+\eta_J)\hbar\omega$. Here η_J is not necessarily zero, and is defined by the observed core spectrum.