$^{56}Fe(d,n)^{57}Co$ reaction and ^{57}Co levels

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The $^{56}Fe(d,n)$ reaction has been studied at 6.0, 8.0, and 10.0 MeV deuteron bombarding energies. The neutron spectrum was determined with the time-of-flight method and the overall time resolution was about 2 ns. Targets with natural and enriched abundances of ^{56}Fe were used. Angular distributions of neutrons leading to states in ^{57}Co were measured between 20° and 100°. The measured cross sections were analyzed in the framework of the distorted-wave Born approximation theory to deduce l_p values and proton transition strengths. For the lowest bombarding energy the compound-nucleus mechanism was also taken into account. The experimental results were compared with the corresponding data from $(^3He, d)$ reactions and other (d,n) studies and with existing theoretical calculations of proton strengths in ^{57}Co.

[NUCLEAR REACTIONS $^{56}Fe(d,n)$, E_d = 6.0, 8.0, and 10.0 MeV; measured $\sigma(E_n, \theta)$. ^{57}Co deduced l, j, π, and S. Natural and enriched targets.]

I. INTRODUCTION

A considerable amount of experimental and theoretical work has been devoted to the study of ^{57}Co, and the characteristics of most of the low-lying levels are now well known. These level properties have been studied by the β decay of ^{57}Ni,[1-3] γ-γ,[4] and particle-γ angular correlations[5-7] and by lifetime measurements.[7-8] The spectroscopic factors for some of the levels have been obtained either with stripping[9-12] or pickup reactions.[13-16]

The $^{56}Fe(^3He, d)^{57}Co$ reaction has been studied by Rosner and Holbrow[9] and by Hardie *et al.*[12]; the transition strengths obtained by these authors are in serious disagreement. These transition strengths have also been deduced from the $^{56}Fe(d, n)$ reaction studied by Okorokov *et al.*[10] and by Couch.[11] The (d,n) results by Couch are in rather good agreement with the $(^3He, d)$ results of Rosner *et al.*

In order to clarify a situation where two experiments agree with each other but disagree with two others, we have remeasured the angular distributions of the $^{56}Fe(d, n)$ reaction at three deuteron bombarding energies. Special attention has been paid to obtain accurate cross sections.

The present results are more complete and supersede those presented earlier.[17]

II. EXPERIMENTAL METHOD

Angular distributions of emitted neutrons were measured using the pulsed beam time-of-flight technique at three different incident energies: 6, 8, and 10 MeV. The burst width of the pulsed deuteron beam of the Bruyères-le-Châtel Tandem Van de Graaff accelerator was 1.2 ns, with a repetition rate of 1.25 MHz and an average current of 0.8 μA on the target. The neutron spectrometer used is described in detail elsewhere.[18] Neutrons were detected with five shielded 10 cm× 2.54 cm NE 213 scintillators located at 18.4 m from the target for each angle of measurement. The target thicknesses were obtained by measuring the elastic scattering of 2 MeV protons at 70° and 120° and assuming the scattering to be pure Rutherford. The thicknesses were also checked by weighing and both results were found to be in good agreement. Different target thicknesses were used: 470 ± 30 μg/cm^2 at E_d = 6 MeV, 870 ± 50 μg/cm^2 at E_d = 8 MeV, and 1000 ± 60 μg/cm^2 at E_d = 10 MeV. The two first targets contained natural Fe (91.7% ^{56}Fe and 5.8% ^{54}Fe) and the third one (supplied by the Oak Ridge National Laboratory) was enriched in ^{56}Fe(99.93%). The target thicknesses corresponded to energy spreads of 31, 48, and 47 keV, respectively, in the incident beam. Angular distribution measurements were taken in 5° steps from 20° to 100° at E_d = 6 and 10 MeV, and from 20° to 85° at E_d = 8 MeV. Absolute detection efficiencies were calculated with the Monte-Carlo code 05S of Textor and Verbinsky,[19] the results of which were checked by using the associated particle method with the $^2H(d, n)^3He$ and $^3H(d, n)^4He$ reactions. The agreement between measured and calculated efficiencies was found to be well within the experimental error. The yields of neutron groups were corrected for absorption in the wall of the scattering chamber and in the air along the flight path.

III. DATA ANALYSIS

The first studies of ^{57}Co have shown that even at low excitation energies the level density in this nucleus is very high. Accurate charged particle measurements with high resolution magnetic spectrographs have reported 96 levels below 5 MeV excitation energy,[20–22] and the recent $^{60}Ni(p,\alpha)$ results obtained by Bieszk *et al.*[22] were in very good agreement with the energies deduced from γ transitions in the $^{54}Fe(\alpha,p\gamma)$[7,8] and $^{57}Fe(p,n\gamma)$[23] reactions, at least for the levels below 3 MeV. The ^{57}Co level energies used in the present work are those obtained by Bieszk *et al.*[22]

At $E_d = 6$ MeV, the over-all experimental time resolution was about 2 ns, corresponding to an energy resolution of about 100 keV for the ground state transition, and of 40 keV for states of approximately 4.5 MeV in excitation. A typical time-of-flight spectrum is shown in Fig. 1. This resolution permitted almost all the known levels below 3 MeV to be resolved. The analysis method described in Ref. 24 was used to determine the peak areas of unresolved multiplets. Contaminant peaks from the $^{54}Fe(d,n)$ reaction were also subtracted. The peak analysis was stopped at an excitation energy of 4.4 MeV because of background subtraction difficulties.

One should note that at this incident energy the compound-nucleus contribution to the (d,n) reaction mechanism is not negligible. The theoretical cross section should thus be expressed as an incoherent superposition of direct reaction (DR) and compound-nucleus (CN) cross sections:

$$\left(\frac{d\sigma}{d\Omega}\right)=\left(\frac{d\sigma}{d\Omega}\right)_{DR}+R\left(\frac{d\sigma}{d\Omega}\right)_{CN}, \qquad (1)$$

where the reduction factor R, treated as an empirical normalization factor, takes into account the channels which absorb the incident flux but which are not explicitly included in the CN calculations of cross sections, e.g., all of the direct reaction cross sections, as well as the cross sections to unobserved levels. The compound-nucleus cross sections were calculated in the Wolfenstein-Hauser-Feshbach (WHF) formalism using the code MANDY.[25] The transmission coefficients used by the program MANDY were calculated with the code MAGALI[26] for all open channels for which final spins were known. The reduction factor R was then determined by matching the calculated cross sections to those experimental ones which did not contain any discernible direct components. These were the cross sections to the levels at 1.225, 1.690, 2.486, 2.561, 2.612, and 2.804 MeV for which the spin values are well known. The results are seen on Fig. 2 and show that a single

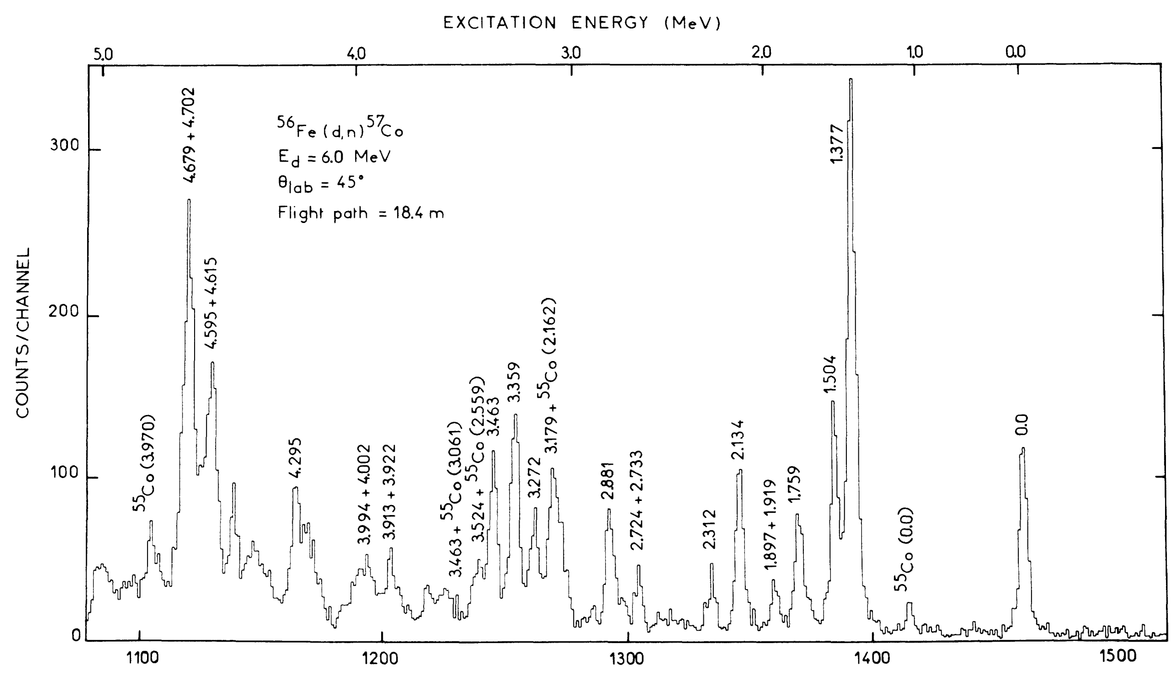

FIG. 1. Neutron time-of-flight spectrum for the $^{56}Fe(d,n)^{57}Co$ reaction taken at a laboratory angle of 45° with a flight path of 18.4 m for an incident deuteron energy of 6 MeV. Only some of the ^{57}Co level excitation energies are shown. States of ^{55}Co are also excited through the $^{54}Fe(d,n)^{55}Co$ reaction, since the target is made out of natural Fe.

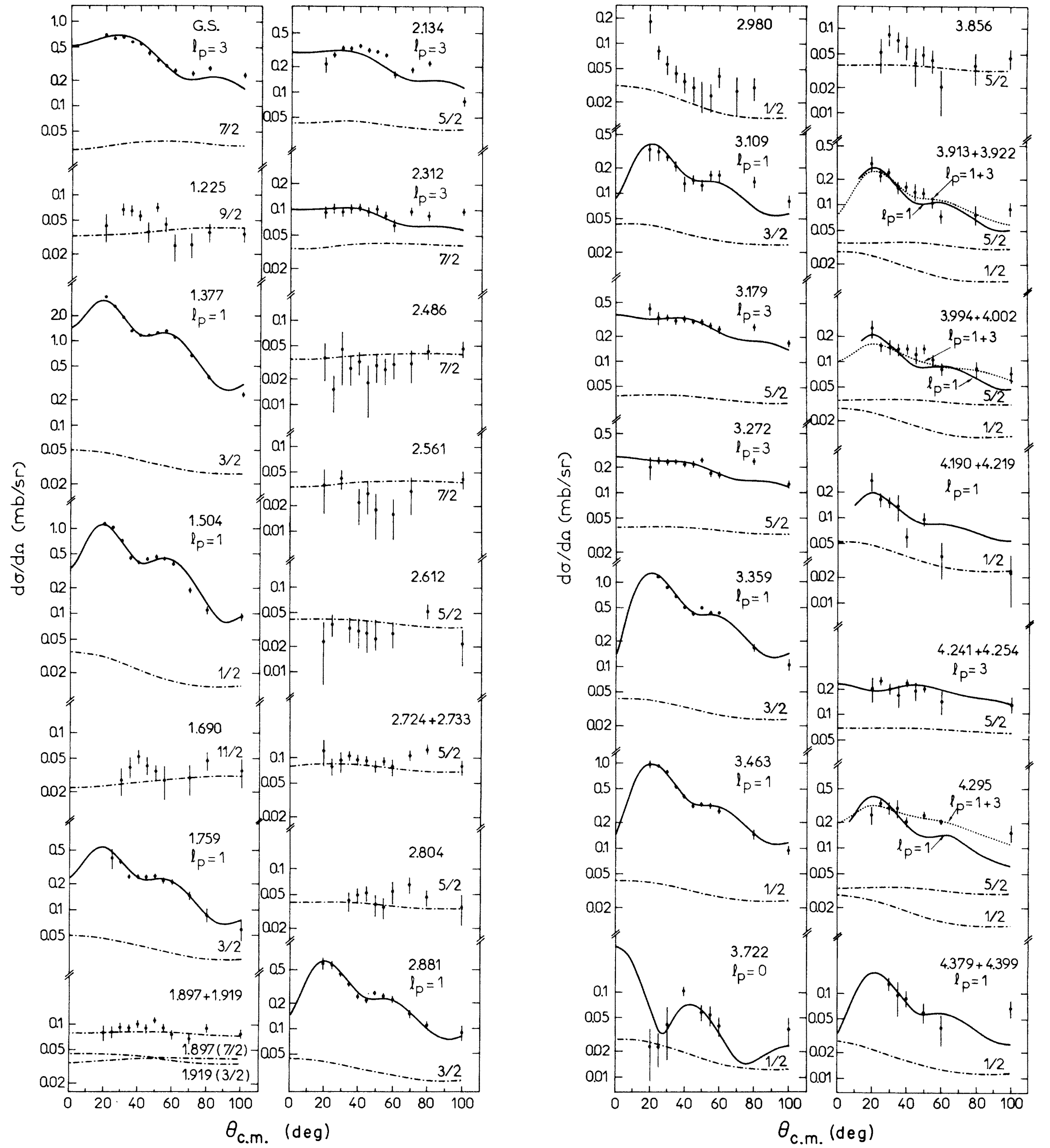

FIG. 2. Angular distributions of neutrons from the $^{56}Fe(d,n)$ reaction for a deuteron energy of 6 MeV. The dot-dashed line represents the compound-nucleus contribution calculated with the WHF formalism. The solid lines are the incoherent sums of the WHF and DWBA predictions. The l_p values and the excitation energies are indicated for each case. The vertical bars represent statistical errors.

normalization factor R gives an excellent fit for other levels. Thus for all transitions the compound-nucleus cross sections were multiplied by an average reduction factor $R = 0.03$, and this contribution was then subtracted from experimental angular distributions. At $E_d = 8$ and 10 MeV no compound-nucleus contribution was observed.

The angular distributions were analyzed in the framework of the DWBA theory with the code DWUCK.[27] The deuteron potential parameters were taken from the global study of Perey[28] taking into account the energy dependence of the real and imaginary parts of the potentials. The neutron parameters were those proposed by Wilmore and

Hodgson.[29] The optical-model parameters used in the distorted-wave Born approximation (DWBA) analysis are given in Table I. The DWBA calculations were corrected for the nonlocality of the potentials and for the finite range of the neutron-proton interaction with the value $r = 0.62$ fm, where r is the range of the interaction.[30]

IV. ANGULAR MOMENTUM TRANSFER AND SPIN-PARITY ASSIGNMENTS

The measured angular distributions are shown in Figs. 2 and 3, corresponding to the incident energies of 6 and 10 MeV, respectively.

A. $l_p = 3$ transitions

The angular distributions for the ground, 2.134, 2.312, 3.179, and 3.272 MeV states and the doublets at 4.241-4.254 MeV and 4.772-4.797 MeV are well fitted by DWBA curves with $l_p = 3$. The same momentum transfer value was deduced from the $^{56}Fe(^3He, d)$ measurements.[9,12] According to the shell model the ground state of ^{57}Co has the $1f_{7/2}{}^{-1}$ proton configuration and the spin and parity $J^\pi = \frac{7}{2}^-$ have been confirmed by many experimental studies.[1,3,9,12]

1. 2.134 MeV level

The angular distribution for the 2.134 MeV level measured at $E_d = 8$ MeV is well fitted by a DWBA curve for $l_p = 3$. The fit is very good also at $E_d = 10$ MeV, but at 6 MeV the fit would be inconclusive. The 10 MeV fit is shown in Fig. 3. The value deduced from the $^{58}Ni(t, \alpha)$ reaction is $l_p = 2$, in disagreement with the results of the $^{56}Fe(^3He, d)$ and $^{56}Fe(d, n)$ reactions. From triple angular correlation measurements using the $^{56}Fe(p, \gamma\gamma)$ reaction, Gossett, and Treado[4] proposed $J^\pi = \frac{5}{2}^+$ for that level, but recent p-γ angular correlations[6,7] and lifetime measurements[7] assign $J^\pi = \frac{5}{2}^-$ for the 2.314 MeV level, which is consistent with our results.

2. 2.312 MeV level

The 2.312 MeV level was observed in this work and in the $^{58}Ni(d, ^3He)$ reaction.[16] Both measurements are consistent with $l_p = 3$. Out of the two possible spins $J = \frac{5}{2}$ or $\frac{7}{2}$ the first one has to be rejected from considering the intensity of the γ transition between the 2.312 and 1.225 MeV levels.[7] Thus the spin and parity of the 2.312 MeV level should be $\frac{7}{2}^-$. The $l_p = 4$ value proposed by Couch from his (d, n) study is in disagreement with our results.

3. 3.179 MeV level

The present work restricts the spin of the 3.179 MeV level to the values $\frac{5}{2}$ and $\frac{7}{2}$. However, the log*ft* value corresponding to the feeding of the level through the β decay of ^{57}Ni limits the spin value to $J \leq \frac{5}{2}$. Therefore, we believe that the spin and parity of this level is now established as $\frac{5}{2}^-$.

4. 3.272 MeV level

The sum rule of transition strengths to a single particle state gives the limit value of 2.0 for the $1f_{7/2}$ state. Almost all of this strength is contained in the transition to the ground state, and a small part in the transition to the 2.312 MeV level. Thus all the transitions to higher levels having $l_p = 3$ should be assumed as proceeding through a transfer into the $1f_{5/2}$ subshell. Therefore the spin of the 3.272 MeV level is likely to be $J^\pi = \frac{5}{2}^-$.

5. 4.241-4.254 and 4.772-4.797 doublets

A strong transition with $l_p = 3$ was observed by Rosner and Holbrow and by Hardie *et al.*[12] corresponding to a level at 4.250 MeV. With the energy resolution obtained in the present work, it is impossible to separate the two levels at 4.241

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

	V_o (MeV)	r_o (fm)	a_o (fm)	W_D (MeV)	r_D (fm)	a_D (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_c (fm)	β (fm)
d [a]	b	1.175	0.821	c	1.366	0.688	7.5	1.175	0.821	1.30	0.54
n [d]	e	1.290	0.66	f	1.250	0.48	7.0	1.30	0.66		0.85
p	g	1.25	0.65				$\lambda = 25$			1.25	0.85

[a] Reference 28.
[b] $V_o = 94.61 - 0.22E$.
[c] $W_D = 14.4 \pm 0.24E$.
[d] Reference 29.
[e] $V_o = 47.01 - 0.267E - 0.0018E^2$.
[f] $W_D = 9.52 - 0.053E$.
[g] Searched by DWUCK. β is the nonlocality range parameter.

and 4.254 MeV. The angular distribution for the sum of transitions to these two levels is fitted with an $l_p = 3$ DWBA curve (Fig. 2), but other l_p values cannot be excluded. Another doublet at 4.772-4.797 MeV displays also an angular distribution characterized by an $l_p = 3$ momentum transfer. A level was identified by Hardie *et al.* at 4.800 ± 0.020 MeV, but no other information was given.

B. $l_p = 1$ transitions

The angular distributions for the 1.377, 1.504, 1.759, 2.881, 3.109, 3.359, and 3.463 MeV levels are well fitted with $l_p = 1$ DWBA curves, as shown in Fig. 2 and particularly in Fig. 3.

1. 1.377 and 1.504 MeV levels

These levels were studied by the ^{56}Fe(^{3}He, *d*), ^{56}Fe(*d*, *n*), and ^{58}Ni(*d*, ^{3}He) reactions which all gave the same $l_p = 1$ value. Out of the two possible spin values for these levels the β-γ angular correlations[2] give a definite assignment $J^\pi = \frac{3}{2}^-$ for the 1.377 MeV level and $J^\pi = \frac{1}{2}^-$ for the level at 1.504 MeV.

2. 1.759 MeV level

The 1.759 MeV level is also populated by the ^{56}Fe(^{3}He, *d*) and ^{58}Ni(*t*, α) reactions with $l_p = 1$; the assignment $J^\pi = \frac{3}{2}^-$ was deduced from γ angular distributions in the ^{56}Fe(*p*, γ) reaction for many resonance energies.[5]

3. 2.881 MeV level

Several authors[6,7] have observed a strong γ transition between the 2.881 MeV level and the ground state; as an *M*3 transition is unlikely, a $J^\pi = \frac{3}{2}^-$ can be assigned to this level.

4. 3.109, 3.359, and 3.463 MeV levels

The 3.109 MeV level was also observed by Hardie *et al.*[12] with $l_p = 1$, in agreement with our results. The transition to the 3.359 MeV level, observed here with $l_p = 1$, is in agreement with the ^{56}Fe(^{3}He, *d*) results but in disagreement with the value $l_p = 3$ deduced from the ^{58}Ni(*t*, α) reaction.[15] The angular distribution for the 3.463 MeV level was also observed for the ^{56}Fe(^{3}He, *d*)[9,12] and ^{56}Fe(*d*, *n*)[11] reactions with $l_p = 1$, in agreement with our results. The γ decay of the 3.109, 3.359, and 3.463 MeV levels has not been studied and the assignments $J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$ remain possible for the two levels.

5. 3.913 and 3.922 MeV doublet

The angular distribution for this doublet is well reproduced by an $l_p = 1$ DWBA curve (Figs. 2 and

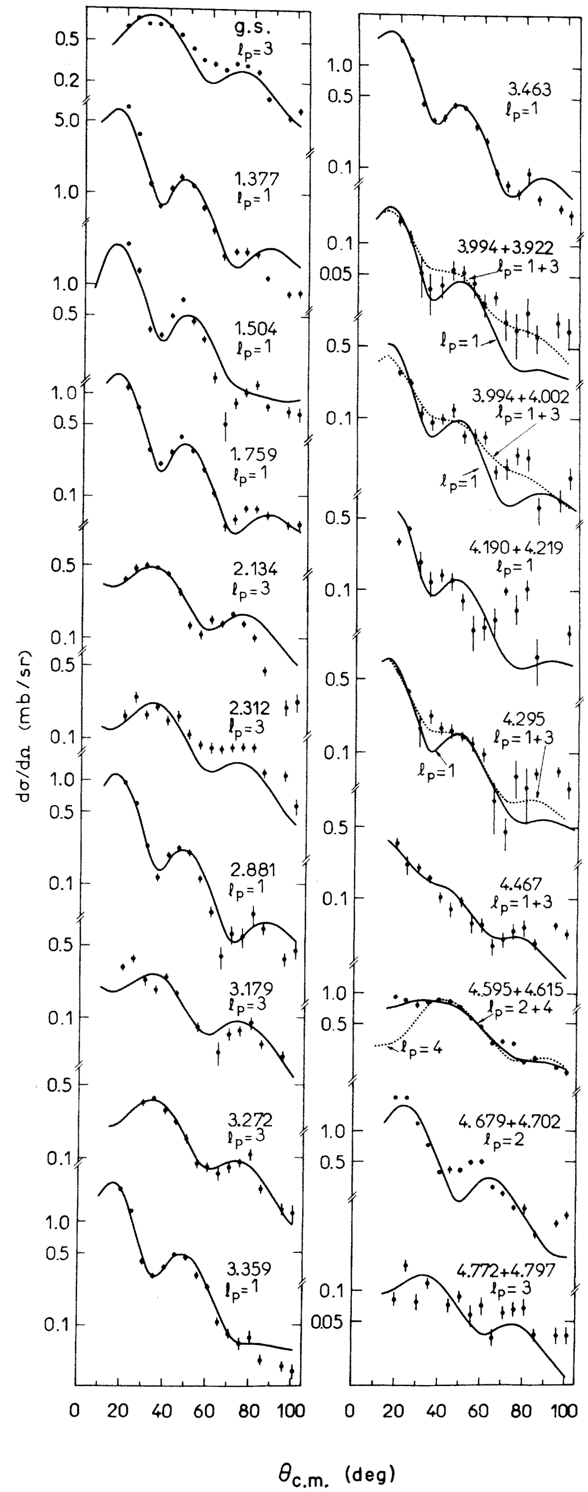

FIG. 3. Neutron angular distributions for a deuteron energy of 10 MeV compared with the DWBA predictions (solid lines).

3). At 10 MeV the angular distribution can also be fitted to a sum of $l_p = 1$ and $l_p = 3$ DWBA curves and the agreement is better for large angles. This doublet is rather strongly populated by the (d,n) reaction. A level at 3.920 MeV was observed by Hardie *et al.* but no l_p assignment was given. This level is also populated by the ^{58}Ni(t, α) reaction, but with an $l_p = 2$ momentum transfer,[15] in disagreement with the present work.

6. 3.994 and 4.002 MeV doublet

At $E_d = 6$ and 10 MeV, the angular distribution for the doublet at 3.994 and 4.002 MeV is well fitted by an $l_p = 1$ DWBA curve. However, the fit is better for a sum of $l_p = 1$ and $l_p = 3$ DWBA curves (Figs. 2 and 3). This last result was obtained by Couch[11] for a group corresponding to levels near 3.997 MeV. The transition to a 4.002 MeV level was studied by Rosner and Holbrow and by Hardie *et al.* and was characterized by an $l_p = 1$ transfer by the latter.

7. 4.190 and 4.219 MeV doublet

The angular distribution leading to this doublet is well fitted with an $l_p = 1$ DWBA curve at $E_d = 6$ MeV; the same l_p value does not lead to such a good agreement at $E_d = 10$ MeV. Hardie *et al.*[12] have observed a level at 4.197 MeV populated in the ^{56}Fe(^{3}He, d) reaction with an $l_p = 1$ momentum transfer.

8. 4.295 MeV level

The angular distribution for the 4.295 MeV level, strongly excited in the (d,n) reaction, is well fitted by an $l_p = 1$ curve at $E_d = 10$ MeV. However, no transfer momentum can be assigned to the angular distribution obtained for the 6 MeV deuteron bombarding energy. This level was also observed by Hardie *et al.* and the corresponding angular distribution was tentatively characterized by an $l_p = 1$ momentum transfer.

9. 4.379 and 4.399 MeV doublet

The angular distribution for this doublet is well fitted with an $l_p = 1$ DWBA curve. These levels were not observed previously in the ^{56}Fe(^{3}He, d) reaction studies.

10. 4.467 MeV level

A level at 4.467 MeV is strongly excited by the (d, n) reaction and the corresponding angular distribution is well reproduced by an $l_p = 1 + 3$ DWBA curve.

C. Other transitions

A transition to a level at 3.722 MeV is observed at $E_d = 6$ MeV, and the corresponding angular distribution was tentatively fitted with an $l_p = 0$ DWBA curve. A level was observed at 3.703 MeV by Rosner and Holbrow and at 3.728 MeV by Hardie *et al.*,[12] but no momentum transfer was deduced from their angular distributions.

Two strong transitions appear in the time-of-flight spectra corresponding to levels with an excitation energy between 4.5 and 5.0 MeV. The first one is probably the transition to an unresolved doublet at 4.595 and 4.615 MeV. The angular distribution is well reproduced by a mixture of $l_p = 2$ and $l_p = 4$ DWBA curves (Fig. 3). The $l_p = 4$ DWBA curve is also drawn for comparison. For the $l_p = 2$ momentum transfer component, the transition strengths were extracted both for assumed $2d_{5/2}$ particles and $1d_{3/2}$ hole states, since the particle character of the level is unknown. These two levels were also observed by Hardie *et al.*[12] but no assignment of the angular momentum transfer is given. A 4.605 MeV level (mean energy of the doublet) was reported by Rosner and Holbrow and the corresponding angular distribution is characterized by an $l_p = 4$ momentum transfer, in agreement with the results of Couch.[11]

The second strong transition corresponds to the doublet at 4.679 and 4.702 MeV. The best fit is obtained with an $l_p = 2$ DWBA curve (Fig. 3) in agreement with the results of Rosner and Holbrow[9] and Couch.[11]

V. TRANSITION STRENGTHS

The transition strengths deduced from the ^{56}Fe-(d, n) and ^{56}Fe(^{3}He, d) reaction studies are reported in Table II, with a precision of about 30% for our results. If the spin of the final state is unknown, the two possible values of the strength G_{lj} are given. These strengths are related to the spectroscopic factor S through $G_{lj} = [(2J_f + 1)/(2J_i + 1)]C^2S$, in which J_i and J_f represent the spins of the initial and final states, respectively, and C is the isobaric Clebsch-Gordan coupling coefficient. If two l_p values are used for the fit of an angular distribution, the transition strengths are calculated for the most probable spins according to the shell model. Our results for the three deuteron energies are reported in columns 4, 5, and 6. These results are mutually consistent. In column 7 the average of the three G values is reported for an easy comparison with other results.

The values obtained in the 10 MeV (d, n) study by Couch[11] are reported in column 8; they are, in general, larger than ours. As the experimental cross sections were rather equal in both cases, this discrepancy should come from the DWBA calculations. With the optical parameters for the deuteron channel being the same in both analyses,

TABLE II. Comparison of transition strengths for ^{57}Co states populated with (d,n) and $(^{3}\mathrm{He},d)$ reactions.

E_x (MeV)	l_p	nlj	(d,n) [a] 6 MeV	(d,n) [a] 8 MeV	(d,n) [a] 10 MeV	b	G_{lj} (d,n) [c] 10 MeV	d	(d,n) [e] 11.7 MeV	$(^{3}\mathrm{He},d)$ [f] 16.5 MeV	$(^{3}\mathrm{He},d)$ [g] 22 MeV
0.00	3	$1f_{7/2}$	1.95	1.83	1.93	1.90	2.88	1.84	5.20	1.80	0.89
1.377	1	$2p_{3/2}$	1.16	0.94	1.11	1.07	1.73	1.11	1.68	1.80	0.52
1.504	1	$2p_{1/2}$	0.56	0.36	0.44	0.45	0.63	0.40	0.76	0.72	0.35
1.759	1	$2p_{3/2}$	0.18	0.19	0.24	0.20	0.25	0.16		0.30	0.13
2.134	3	$1f_{5/2}$	1.19	1.13	1.23	1.18	2.22	1.42		2.00	1.20
2.312	3	$1f_{7/2}$	0.28	0.37	0.39	0.35	(0.79)	(0.51)		0.70	0.20
2.881	1	$2p_{3/2}$	0.16	0.12	0.15	0.14	0.26	0.17	0.48	0.39	0.11
3.109	1	$2p_{1/2}$	0.10	0.09		0.09					0.02
		$2p_{3/2}$	0.08	0.09		0.09					
3.179	3	$1f_{5/2}$	1.19	0.73	0.61	0.84				0.84	0.55
3.272	3	$1f_{5/2}$	1.28	0.74	0.80	0.94	1.14	0.73		1.62	0.65
		$1f_{7/2}$	0.54	0.52	0.60	0.55					0.44
3.359	1	$2p_{1/2}$	0.32	0.25	0.32	0.30	0.46	0.29	0.88	0.56	0.16
		$2p_{3/2}$	0.27	0.23	0.30	0.27					
3.463	1	$2p_{1/2}$	0.25	0.23	0.27	0.25	0.39	0.25		0.38	0.14
		$2p_{3/2}$	0.21	0.21	0.26	0.23					
3.722	(0)	$2s_{1/2}$	0.02			0.02			0.10		
3.913 + 3.922	1	$2p_{1/2}$	0.05		0.03	0.04					
		$2p_{3/2}$	0.05		0.03	0.04					
3.994 + 4.002	1 + 3	$2p_{1/2}$	0.02		0.03	0.03	0.04	0.03			
		$1f_{5/2}$	0.23		0.12	0.17	0.30	0.19			
	1	$1p_{1/2}$	0.04		0.06	0.05					0.03
		$1p_{3/2}$	0.03		0.05	0.05					
4.190 + 4.219	1	$2p_{1/2}$	0.03		(0.08)						0.02
		$2p_{3/2}$	0.01		(0.07)						
4.241 + 4.254	3	$1f_{5/2}$	0.56			0.56				0.70	0.26
		$1f_{7/2}$	0.41			0.41					
4.295	1 + 3	$2p_{1/2}$	0.03		0.08	0.06					0.02
		$1f_{5/2}$	0.57		0.07	(0.32)					
	1	$2p_{1/2}$	0.07		0.08	0.08					
		$2p_{3/2}$	0.06		0.08	0.07					
4.379 + 4.399	1	$2p_{1/2}$	0.03			0.03					
		$2p_{3/2}$	0.02			0.02					
4.467	1 + 3	$2p_{1/2}$			0.03	0.03					
		$1f_{5/2}$			0.23	0.23					
4.595 + 4.615	2 + 4	$1d_{3/2}$			0.31	0.31					
		$1g_{9/2}$			2.00	2.00					
		$2d_{5/2}$			0.09	0.09					
		$1g_{9/2}$			1.93	1.93	3.81	2.44		4.8	
4.679 + 4.702	2	$1d_{3/2}$			1.08	1.08					0.15
		$2d_{5/2}$			0.30	0.30	0.53	0.34			
4.772 + 4.797	3	$1f_{5/2}$			0.28	0.28					
		$1f_{7/2}$			0.23	0.23					

[a] Present work.
[b] Mean value of the transition strengths obtained at the three deuteron bombarding energies.
[c] Reference 11.
[d] Transition strengths obtained in Ref. 11 and corrected as explained in the text.
[e] Reference 10.
[f] Reference 9.
[g] Reference 12.

we used the Wilmore-Hogdson parameters to describe the neutron channels, while Couch used the Bechetti ones. These different sets of parameters should give only a small difference for the calculated cross sections. In both cases the DWBA calculations were corrected for the nonlocality of the potentials in both incoming and outgoing channels and for the finite range of the neutron-proton interaction. However, in the present work, the nonlocality correction was also used for the bound state wave function of the transferred proton, while Couch did not use this form factor. Thus his calculated cross sections are larger by about 25% than ours. Moreover, the normalization constant used by Couch was $N=1.65$, while ours had the value $N=1.53$. The transition strengths obtained by Couch and corrected for these differences (diminished by 36%) are listed in column 9. The agreement between these new values and our results is very good. The transition strengths obtained by Okorokov *et al.*[10] from the ^{56}Fe(d,n) reaction at 11.7 MeV are listed in column 10; these values are in serious disagreement with our and Couch's[11] results. It is likely that the experimental resolution in this experiment did not allow these authors to resolve individual levels well except for the ground state transition. Thus, the reported transition strengths for some levels may result from the effect of more than one level per neutron group observed.

Columns 11 and 12 list the transition strengths deduced from the ^{56}Fe(^{3}He, d) reaction analyzed by Rosner and Holbrow[9] and by Hardie *et al.*.[12] Rosner's values for the 2.312 and 2.881 MeV levels have been obtained assuming the spin values to be $\frac{5}{2}$ and $\frac{1}{2}$, respectively, which are presently known to be incorrect. Thus the transition strengths corresponding to these two levels can not be compared to the other results. However, the agreement between the results of Rosner and Holbrow and those deduced from the ^{56}Fe(d,n) reaction is generally good. On the other hand, the transition strengths obtained by Hardie *et al.*[12] are smaller by nearly a factor of 2 than all the other results.

A. Sum rules

In reactions involving the addition of a proton, the two isobaric states with $T=T_z\pm\frac{1}{2}$ can be populated. In this case the sum rule for each of the two isobaric spin states is given by[31]

$$\sum G_{lj}(T_<)=\langle\pi\rangle_{lj}-\frac{1}{(N-Z+1)}\langle\nu\rangle_{lj} \qquad (2)$$

and

$$\sum G_{lj}(T_>)=\frac{1}{(N-Z+1)}\langle\nu\rangle_{lj}\,, \qquad (3)$$

where $\langle\pi\rangle_{lj}$ and $\langle\nu\rangle_{lj}$ are the numbers of proton and neutron holes in the nlj subshell for the target nucleus having N neutrons and Z protons. The transition strength sums for the $T_<$ states and for the $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ particle states are reported in Table III together with the results of Couch,[11] Rosner and Holbrow,[9] and Hardie *et al.*,[12] and are compared with the theoretical limits predicted by the single-particle shell model. The transition strength sum to the ground and 2.312 MeV states is larger than the theoretical value but is within the 30% error on the determined strengths. As all the strength of the $f_{7/2}$ state is contained in the transitions to these levels, the transitions to higher levels characterized by an $l_p=3$ momentum transfer can be supposed to go to the $f_{5/2}$ subshell. To calculate the transition strength sums and the proton state mean energies as defined below, the values of column 7 were used with the assumption that levels below 3.5 MeV and populated by an $l_p=1$ transfer momentum have the spin $J=\frac{3}{2}$, and higher levels have the spin $J=\frac{1}{2}$. However, as the $p_{1/2}$ and $p_{3/2}$ proton states distributions overlap partially, the above assumption is rather arbitrary.

It appears from Table III that about 40% of the $p_{3/2}$ state strength was not observed in our exper-

TABLE III. Summed spectroscopic strengths and centroids for proton states in ^{57}Co.

		$\sum G\ (T_<)$				ϵ_{lj} (MeV)		
Subshell	Theory	(d,n) [a]	(d,n) [b]	(^{3}He, d) [c]	(^{3}He, d) [d]	(d,n) [a]	(^{3}He, d) [c]	(^{3}He, d) [d]
$f_{7/2}$	2.00	2.25	2.88	1.80	1.09	0.36	0.0	0.42
$p_{3/2}$	3.60	2.00	2.58	2.10	1.06	2.11	1.43	1.19
$p_{1/2}$	1.60	0.69	1.13	2.05	0.65	2.44	2.63	2.39
$f_{5/2}$	4.80	4.32	3.66	5.86	2.66	3.28	2.87	2.83

[a] Present work.
[b] Reference 11.
[c] Reference 9.
[d] Reference 12.

iment, as well as 60% of the $p_{1/2}$ state. A fraction of this unobserved strength may be contained in transitions too small to be seen or in transitions to levels with an excitation energy higher than 4.8 MeV. A large part of the transition strength to the $f_{5/2}$ state has been observed in the present work. This may be understood by recalling that the spreading width of the $f_{5/2}$ single particle state is smaller than that of the $p_{1/2}$ and $p_{3/2}$ states, due to the effect of the angular momentum barrier.

The centroid energies of proton particle states defined by

$$\epsilon_{lj} = \sum E_{lj} G_{lj} \Big/ \sum G_{lj} \,, \tag{4}$$

where the sums extend over all states with the same J^π, are also reported in Table III.

A better knowledge of the spin of levels populated by the one-proton transfer reactions and of the corresponding transition strengths should be necessary for a more accurate determination of the proton state centroid energies and spreading widths.

VI. COMPARISON WITH NUCLEAR MODELS

The transfer reaction ^{56}Fe(d,n) displays the one-particle character of the levels of ^{57}Co. For example, the ground state ($\frac{7}{2}^-$), the 1.377 ($\frac{3}{2}^-$), 1.504 ($\frac{1}{2}^-$), and 2.134 ($\frac{5}{2}^-$) MeV levels are strongly excited in reactions involving one-proton transfer. These states may be considered as one-particle states resulting from the addition of one proton in, respectively, the $1f_{7/2}$, $2p_{3/2}$, $2p_{1/2}$ and $1f_{5/2}$ subshells to a core of ^{56}Fe in its ground state. On the other hand, the 1.225 ($\frac{9}{2}^-$), 1.690 ($\frac{11}{2}^-$), 1.759 ($\frac{3}{2}^-$), 1.897 ($\frac{7}{2}^-$), and 1.919 ($\frac{5}{2}^-$) MeV levels are rather weakly excited by the (d,n) reaction. The $B(E2)$ strengths for these levels are larger than the single-particle estimates[6,7] showing their collective character. The mean energy of this five-level multiplet lies at 1.65 MeV while the first 2^+ level in ^{58}Ni has an excitation energy of 1.45 MeV. In the framework of the intermediate coupling model, these levels may be interpreted as the coupling of one $(1f_{7/2})^{-1}$ proton hole to the quadrupole vibrations of ^{58}Ni. Moreover, these collective levels are spread over an energy range of 0.7 MeV, indicating that the coupling is moderately strong. The ^{57}Co nucleus is a good test nucleus for comparison with different models, as it seems to have levels which exhibit two different types of character.

In a shell-model calculation for nuclei near ^{57}Co, Vervier[32] considers that protons and neutrons beyond the $Z=20$ and $N=28$ shells fill the $1f_{7/2}$ and $2p_{3/2}$ orbits, respectively; the nucleon-nucleon interaction is introduced indirectly by smoothing experimental data. Similarly, McGrory[33] placed the two valence neutrons of ^{57}Co in the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ orbits, obtaining a relatively better agreement with experiment. No spin $\frac{1}{2}^-$ or $\frac{3}{2}^-$ levels, however, appear below 2.5 MeV in any of the two calculations. A recent calculation made by Gatrousis *et al.*[3] with an inert core of ^{40}Ca and with the 17 extra nucleons distributed into the $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ orbits with two or three nucleons in the three upper orbits reproduced the experimental scheme rather well, although some levels are ordered incorrectly and a second $\frac{9}{2}^-$ level appears below 2 MeV. A new calculation[34] performed with a ^{48}Ca core did not show much improvement. The theoretical transition strengths for $\frac{7}{2}^-$ levels are given in Table IV and compared with experimental values. The agreement is good only for the ground state. Thus it appears that present shell-model calculations do not successfully reproduce the experimental level sequence and transition strengths of ^{57}Co.

Using the unified model, Satpathy and Gujrathi[35] limit the proton holes to the $1f_{7/2}{}^{-1}$, $1d_{3/2}{}^{-1}$, and $2s_{1/2}{}^{-1}$ orbits. The agreement between the theoretical and experimental level schemes is relatively good. Using the same model and supposing that the quadrupole vibrations of the core are coupled to the proton configurations $(1f_{7/2}{}^{-2}2p_{3/2})$, $(1f_{7/2}{}^{-2}1f_{5/2})$, and $(1f_{7/2}{}^{-2}2p_{1/2})$, Gomez[36] calculates the level scheme to find that the calculated first $\frac{3}{2}^-$ level is too low in energy. The transition strengths calculated by Gomez for reactions involving one-proton transfer are reported in Table IV. The calculations were made for two values of the model parameters (energies of

TABLE IV. Comparison of experimental (d,n) and theoretical transition strengths for one-proton transfer reaction on ^{56}Fe.

E_x (MeV)	J_{exp}	G_{exp} (d,n) [a]	Theoretical values Horie [b]	Gomez I [c]	Gomez II [c]
0.0	$\frac{7}{2}^-$	1.90	1.98	1.41	1.41
1.377	$\frac{3}{2}^-$	1.07		1.90	1.60
1.504	$\frac{1}{2}^-$	0.45		0.75	0.96
1.759	$\frac{3}{2}^-$	0.20		0.86	1.09
2.134	$\frac{5}{2}^-$	1.18		3.23	3.58
2.312	$\frac{7}{2}^-$	0.35	0.0	0.95	0.56
2.881	$\frac{3}{2}^-$	0.14		0.43	0.32

[a] Present work.
[b] Reference 34.
[c] Reference 36.

particle states). The agreement with experiment may be considered as good except for the 1.759 and 2.134 MeV levels. However, calculations with several particle and several phonon states[37] do not well reproduce the low-lying level properties. Stewart, Castel, and Singh[38] have presented a new version of the intermediate coupling model based on description of the phonon states using the anharmonic scheme; pairing effects are not ignored and quasiparticle states have been introduced. The correspondence between experimental and calculated excitation energies is excellent for excitation energies below 2.5 MeV and the electromagnetic strengths are well reproduced. Unfortunately, no transition strength G_{lj} was calculated. The model predicts the existence of $\frac{13}{2}^-$ and $\frac{15}{2}^-$ levels between 2 and 3 MeV but they have not been observed experimentally.

CONCLUSION

The ^{56}Fe(d, n)^{57}Co reaction has been studied at three deuteron bombarding energies: 6, 8, and 10 MeV. The experiment and subsequent DWBA analysis were undertaken to resolve the serious discrepancies which remained from several previous one-proton transfer reaction studies on ^{56}Fe, and also to clarify the relationship between transition strengths obtained from (d, n) and $(^3$He$, d)$ reactions.

Angular distributions were obtained for 13 well resolved levels. The proton transfer transition strengths obtained here are in good agreement with those from the $(^3$He$, d)$ study of Rosner and Holbrow,[9] and for some levels with the (d, n) transition strengths obtained by Couch.[11] The results of Hardie *et al.* and of Okorokov *et al.* disagree with the present results. A comparison of the measured proton transition strengths with those calculated for several models of ^{57}Co has been made. Present shell-model calculations completely fail to reproduce these transition strengths, as do intermediate coupling model calculations based on an ^{56}Fe core. On the other hand, intermediate coupling model calculations with a ^{58}Ni core give a reasonably good account of the results.

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