Nuclear-Structure Studies of Co^{55} and Co^{57} by Means of the $Fe^{54,56}(He^3,d)$ Reaction*

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A high-resolution study of the $Fe^{54,56}(He^3,d)Co^{55,57}$ reactions at 16.5-MeV bombarding energy was performed. Twenty-five states of Co^{55} and forty-one states of Co^{57} below 8-MeV excitation energy were identified. The angular distribution of deuterons at forward angles was measured, and with the aid of distorted-wave Born-approximation predictions, values of angular momentum transfers and spectroscopic factors were evaluated for the more intense transitions. Analog states to some of the low-lying states in Fe^{55} and Fe^{57} were identified and Coulomb displacement energies of 9.00 ± 0.03 and 8.90 ± 0.03 MeV were determined for the Co^{55}-Fe^{55} and Co^{57}-Fe^{57} pairs, respectively. The location of $1f_{7/2}$, $2p_{3/2}$, and $2p_{1/2}$ single-particle proton states by means of the "centroid method" is discussed and evaluated for the case of Co^{55}.

INTRODUCTION

AT suitable bombarding energies the (He^3,d) reaction is essentially a stripping reaction in which a proton is transferred from the He^3 projectile into the target nucleus. It resembles the well-known (d,p) stripping reaction in which a neutron is the transferred particle. The similarity between the two types of stripping reactions permits the use of similar techniques for data collection and analysis. Thus, the (He^3,d) reaction may be used to extract values of angular-momentum transfers and spectroscopic factors, and also to provide information on the location of the single-particle proton states and the manner in which they are filling.

In addition, the (He^3,d) reaction is capable of exciting states which are analogs of states that can be obtained by the (d,p) reaction on the same target nucleus. In isotopes with small neutron excess these analog states occur at a rather low excitation energy and they share an appreciable part of the total single-particle transition intensity. In many cases these analog states are bound and, therefore, not accessible to proton resonance scattering studies, and the (He^3,d) reaction is the most convenient reaction by which they can be studied.

Several recent experimental studies of the (He^3,d) reactions on medium weight nuclei have demonstrated the usefulness of this reaction for nuclear-structure studies.[1,2] But, because of either low beam intensity or inadequate energy resolution, only nuclei with closed-shell configurations of protons or neutrons were used as targets. For these cases the level densities at low excitation energies of the final nucleus are rather low and only a few states share the total transition strength. In the present study, levels in Co^{55} and Co^{57} were studied with high resolution up to an excitation energy of 7–8 MeV using the $Fe^{54}(He^3,d)Co^{55}$ and $Fe^{56}(He^3,d)$-Co^{57} reactions.

EXPERIMENTAL PROCEDURE

The experiment was performed with 16.5-MeV He^3 ions from the University of Pennsylvania Tandem Accelerator. Deuterons from the reactions were recorded in nuclear emulsion plates in the focal plane of a broad-range magnetic spectrograph of the Browne-Buechner type. Ilford Nuclear Research plates type K2, 50-μ thick were used for the measurements. The emulsion was covered with a suitable Mylar absorber to stop all reaction products other than protons and deuterons. Mylar was chosen so that index marks, which serve for calibration of distances along the plate, could be photographed onto the plates after the plateholder had been completely loaded. The high-energy proton groups that start to appear at positions corresponding to excitation energies of 4–5 MeV in the deuteron spectrum were easily discriminated from the deuterons, because their tracks in the photographic emulsion are rather light compared to the dense deuteron tracks.

The (He^3,d) reactions were performed in two steps. First, exposures were taken with relatively thin targets ($\sim$75 μg/cm^2) at 10° and 25° with charge collection of 1000 μC. This was done in order to obtain good energy calibration. A complete angular distribution of the deuterons was then taken with $\sim$200 μg/cm^2 thick targets. Angular distributions were recorded over the range 6° to 70° for Fe^{54}. Since most of the spectroscopic information can be extracted from the region of small angles, the angular distributions were extended only to 40° for Fe^{56}. Deuteron groups originating from carbon and oxygen contaminants were easily identified, and because of their large energy shift with angle they usually do not interfere at more than a single angle with any deuteron group originating from a reaction on an iron isotope.

Target thicknesses were measured by recording 9-MeV He^3 particles elastically scattered through 25°. The elastic scattering was determined to be pure Rutherford scattering for this experimental setup and

* Supported by the National Science Foundation.

[1] A. G. Blair, Argonne National Laboratory Report No. 6878, 1964, p. 115 (unpublished); A. G. Blair, Phys. Rev. **140**, B648 (1965); J. R. Erskine, A. Marinov, and J. P. Schiffer, *ibid.* **142**, 633 (1966); J. J. Schwartz and W. P. Alford, *ibid.* **149**, 820 (1966).
[2] D. D. Armstrong and A. G. Blair, Phys. Rev. **140**, B1226 (1965).

then the theoretically calculated absolute cross sections were used to obtain the target thickness.

DWBA ANALYSIS

Distorted-wave Born-approximation (DWBA) calculations for the $Fe^{54}(He^3,d)Co^{55}$ reaction were carried out by Dr. R. H. Bassel at Oak Ridge National Laboratory. The Saxon-Woods potential was used for the bound state as well as for ingoing and outgoing channels. The potential included an l-s coupling term for the bound state but none for the He^3 or deuteron elastic scattering. Calculations were made for Q values of 4, 2, 0, -2, and -4 MeV for $2p_{3/2}$, $2p_{1/2}$, $1f_{7/2}$, $1f_{5/2}$, and $1g_{9/2}$ proton capture.

It was found that the spin-orbit term introduces a $\sim$10% difference between the predicted transition intensities to the $2p_{3/2}$ and $2p_{1/2}$ states, and $\sim$20% for the $1f_{7/2}$ and $1f_{5/2}$ case (Fig. 1). In both cases the predicted cross section for the $j=l+s$ case is larger than that of the $j=l-s$ case. The change of the radial cutoff from the value of 4.2 fm to zero had a negligible effect on the shape of the angular distributions and on the predicted value of the peak cross section.

For a (He^3,d) reaction on a nucleus with spin-zero ground state, the relation between the experimental cross section and the DWBA prediction is given by[3]

$$\sigma_{\text{exp}}=4.4(2J+1)C^2S\sigma_{\text{DWBA}}, \tag{1}$$

from which the transition strength $(2J+1)C^2S$ can be readily evaluated. The quantity J is the spin of the final state; S is the spectroscopic factor; C is an isotopic spin Clebsch-Gordan coefficient which takes into account the fact that states of the same J but different isospin T, which share the total transition intensity, can be excited in the (He^3,d) reaction. Formulas for C^2S are given by French and Macfarlane.[4] For Q values more negative than -5.5 MeV, which corresponds to the breakup energy of the He^3 projectile, no DWBA calculations are available.

The theoretical cross sections for $l=3$ and $l=4$ cases can be readily extrapolated from the calculated values because the peak cross section obeys the simple relation

$$\sigma_{\max}=\sigma_0 K^{-Q}; \quad \begin{matrix} K=1.79 & \text{for} & l=3, \\ K=1.38 & \text{for} & l=4, \end{matrix} \tag{2}$$

where Q is the reaction energy. For the $l=1$ cases, such simple relation was not found (see Fig. 1). Therefore, no extrapolations were made for the $l=1$ case.

$Fe^{54}(He^3,d)Co^{55}$ RESULTS

A deuteron spectrum obtained with 20-keV resolution from the $Fe^{54}(He^3,d)Co^{55}$ reaction at 25° is presented in Fig. 2. Twenty-five states up to the excitation energy of $\sim$7.2 MeV were populated in this reaction and their excitation energies are listed in Table I. This table lists also in consecutive columns the values of the transferred angular momentum and total cross sections for the various transitions as extracted from the first peak of the angular distribution. The transition strengths $(2J+1)C^2S$ evaluated using Eq. (1) are given in column 5. The last column presents the assumed J^π values for the final states that were used in subsequent calculations.

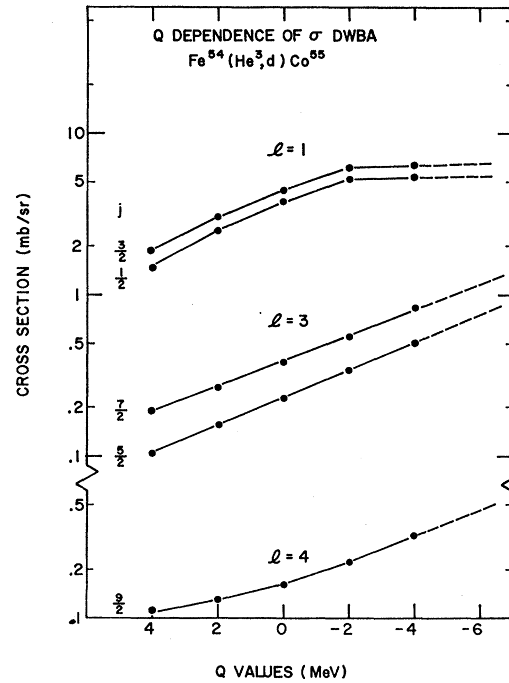

FIG. 1. Q dependence of the DWBA predicted cross section, taken at the first maximum of the angular distribution.

$l=3$ Transitions (Fig. 3)

The transition leading to the $\frac{7}{2}^-$ ground state of Co^{55} is the only unambiguous $l=3$ transition leading to a low-lying state in the final nucleus and it takes almost the total transition strength for proton capture in the $1f_{7/2}$ orbit. No other $l=3$ transitions which might lead to spin-$\frac{5}{2}$ states were observed up to excitation energy of 5 MeV. This finding may indicate any of the following: Either the $f_{7/2}$-$f_{5/2}$ energy splitting is greater than 5 MeV, or spin-$\frac{5}{2}$ states happen to be close-lying doublets with other states which are strongly excited by an $l=1$ angular momentum transfer, or the intensity for transitions leading to spin-$\frac{5}{2}$ states is distributed among many weak states, thus making their identification impossible.

Armstrong and Blair[2] claim that the two states at 3.327 MeV and the 4.185-MeV excitation are, in effect, unresolved doublets, because the angular distributions of the deuterons leading to them can be fitted by $l=1+3$ mixtures. Despite our better resolution, no doublet structure was observed for these states within 20 keV.

[3] R. H. Bassel, Phys. Rev. **149**, 791 (1966).
[4] J. B. French and M. H. Macfarlane, Nucl. Phys. **26**, 168 (1961).

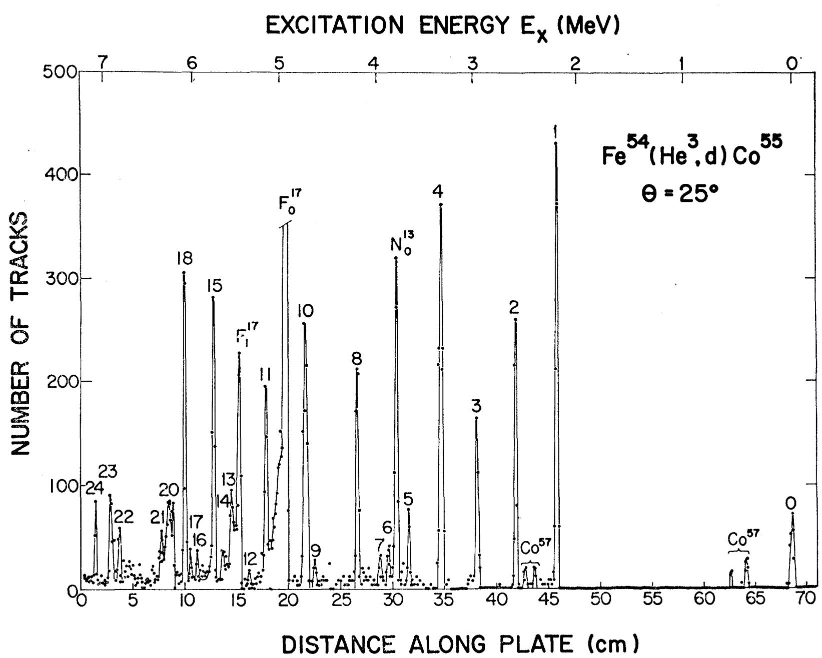

FIG. 2. Deuteron spectrum of the $Fe^{54}(He^3,d)Co^{55}$ reaction.

The only other clear $l=3$ transition proceeds to a state at 5.765-MeV excitation energy which is identified as the analog of the 0.935-MeV state in Fe^{55}.

TABLE I. Summary of experimental results obtained in the $Fe^{54}(He^3,d)Co^{55}$ reaction.

Level	Excitation energy (MeV)[a]	l	σ_{ex} (mb/sr)	$(2J+1)C^2S$	Assumed J^π
0	g.s.	3	0.55	1.68	$\frac{7}{2}^-$
1	2.162	1	9.90	1.68	$\frac{3}{2}^-$
2	2.559	1	6.13	1.04	$\frac{3}{2}^-$
3	2.938	1	2.79	0.76	$\frac{3}{2}^-$
4	3.327	(1)	3.47	0.68	$\frac{1}{2}^-$
5	3.657	1	1.33	0.26	$\frac{1}{2}^-$
6	3.870	...	<0.20		
7	3.970	...	<0.20		
8	4.185	(1)	2.30	0.46	$\frac{1}{2}^-$
9	4.650	...	<0.20		
10	4.755	1	6.19	0.92	$\frac{3}{2}^{-b}$
11	5.188	(1)	2.40	0.48	$\frac{1}{2}^{-b}$
12	5.382	...	<0.20		
13	5.566	(1)	1.47	0.30	$\frac{1}{2}^-$
14	5.670	...	<0.20		
15	5.765	3	1.35	1.56	$\frac{5}{2}^{-b}$
16	5.955	...	<0.20		
17	6.037	...	<0.20		
18	6.080	4	1.49	5.00	$\frac{9}{2}^+$
19	6.215	...	<0.20		
20	6.277	...	0.20[c]		
21	6.342	...	<0.20		
22	6.850	...	<0.20		$(\frac{1}{2})^b$
23	6.928	...	0.22[c]		$(\frac{5}{2})^b$
24	7.108	...	0.23[c]		

[a] The uncertainty in excitation energy varies between 10 and 30 keV depending on the intensity of the transition.
[b] Analog states.
[c] Cross sections taken at 25°.

$l=1$ Transitions (Fig. 4)

$l=1$ transitions observed in the $Fe^{54}(He^3,d)$ reaction lead to states with spins of either $\frac{3}{2}$ or $\frac{1}{2}$ in Co^{55}. It is known[5] that for the Fe-Ni region the width of the distribution of spin-$\frac{1}{2}$ and $\frac{3}{2}$ states is at least as wide as

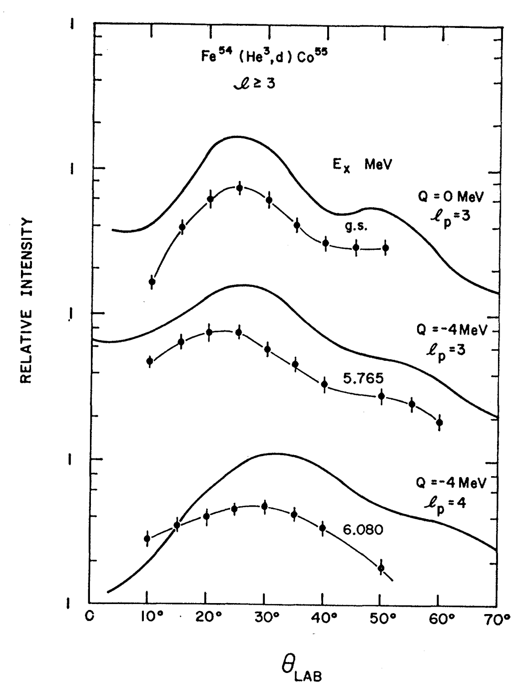

FIG. 3. Angular distributions of deuterons for $l_p \geq 3$ transitions in the $Fe^{54}(He^3,d)Co^{55}$ reaction. The heavy lines are DWBA predictions.

[5] D. S. Gemmell, L. L. Lee, Jr., A. Marinov, and J. P. Schiffer, Phys. Rev. **144**, 923 (1966).

the energy difference between the $p_{3/2}$ and $p_{1/2}$ subshells. This fact and the lack of other criteria for distinguishing between $\frac{3}{2}$ and $\frac{1}{2}$ spins make spin assignments somewhat difficult. The large transition strength to the states at 2.162- and 2.559-MeV excitation energy strongly indicates that they have spin $J=\frac{3}{2}$, because the total transition strength to all $\frac{1}{2}^-$ states can be no greater than 1.33. If the assignment of $\frac{3}{2}^-$ to these states is correct, sum-rule arguments imply most of the remaining $l=1$ states with $T=\frac{1}{2}$ must have $J^\pi=\frac{1}{2}^-$.

The sum of all observed transition strengths should equal the total number of proton holes which is 8 for the $f_{7/2}$, $p_{3/2}$, and $p_{1/2}$ orbits in Fe^{54}. This number is to be compared to the experimental sum 8.26. The close agreement supports the value 4.4 used by Bassel[3] for the normalization of the DWBA calculation for the (He^3,d) reaction. Unfortunately, this sum depends only slightly on $l=3$ mixtures in transitions characterized by $l=1$ angular-momentum transfers because the transition strengths were extracted from the first maximum of the angular distribution ($\sim 10°$ in this case) where the contribution from $l=3$ transitions is expected to be rather small.

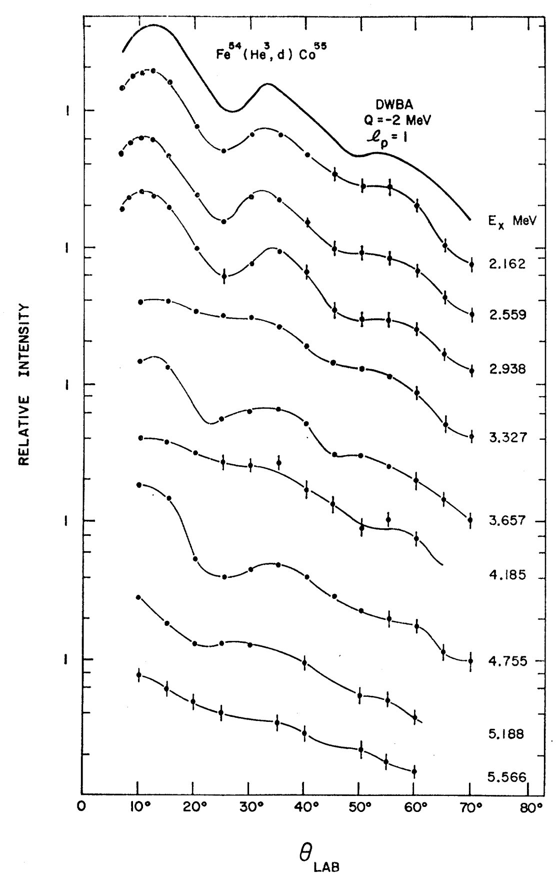

FIG. 4. Angular distributions of deuterons for $l_p=1$ transitions in the $Fe^{54}(He^3,d)Co^{55}$ reaction. The heavy line on top represents a typical DWBA prediction for $l_p=1$ angular-momentum transfer.

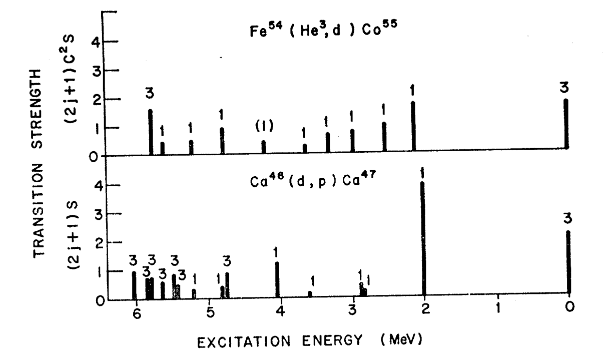

FIG. 5. Comparison of transition strengths for the $Fe^{54}(He^3,d)$-Co^{55} and $Ca^{46}(d,p)Ca^{47}$ reaction, leading to final states in nuclei which have closed-shell plus one-hole configurations.

$l=4$ Transition (Fig. 5)

Only one $l=4$ transition, leading to the 6.080-MeV state, was identified, taking 50% of the total transition strength to the $1g_{9/2}$ states.

States 6, 7, 9, 12, and 14, for which l values could not be assigned, will contribute less than 0.2 to the transition strength if they are $l=1$ transitions and less than 1.2 if they are $l=3$ transitions, leading to $\frac{5}{2}^-$ states.

A comparison between the $Fe^{54}(He^3,d)Co^{55}$ and Ca^{46}-$(d,p)Ca^{47}$ reactions[6] is schematically given in Fig. 5. Co^{55} has a single proton hole in the $f_{7/2}$ shell and a closed-shell $N=28$ configuration, whereas Ca^{47} has a single neutron hole in the $f_{7/2}$ shell with a closed shell $Z=20$ configuration. Assuming charge independence of nuclear forces and inert cores, Co^{55} and Ca^{47} should have rather similar level structures. In fact, a similar energy gap of ~ 2 MeV exists in both nuclei between the $\frac{7}{2}^-$ ground state and the first excited $\frac{3}{2}^-$ state. Also, most of the $l=1$ transitions are found to lead to states at similar excitation energies. It is interesting to note that for the Ca^{47} isotope with the $Z=20$ closed shell, a single state at the excitation energy of 2.017 MeV takes most of the strength of transitions leading to spin $\frac{3}{2}$ states. On the other hand, for Co^{55} with the $N=28$ closed shell which is assumed to present a more inert configuration, at least two low-lying states of similar intensity need to have the $\frac{3}{2}$ spin assignment in order to exhaust the full transition strength.

A comparison between the excitation energies of $\frac{5}{2}^-$ states excited with $l=3$ angular-momentum transfer may give information about the special interaction between proton and neutrons occupying states with the same l value as discussed by Cohen.[7] In Ca^{47} all $l=3$ transitions were observed between excitation energies of 4.5 and 6 MeV. Unfortunately, no $l=3$ transitions but the one leading to the $\frac{5}{2}^-$ analog state at 5.765 MeV were clearly identified in the $Fe^{54}(He^3,d)Co^{55}$ reaction.

Armstrong and Blair[2] have assigned spins and parities of $\frac{5}{2}^-$ to states at excitation energies 3.327 and 4.185

[6] T. A. Belote, H. Y. Chen, and Ole Hansen, Phys. Rev. **142**, 624 (1966).
[7] B. L. Cohen, Phys. Rev. **127**, 597 (1962).

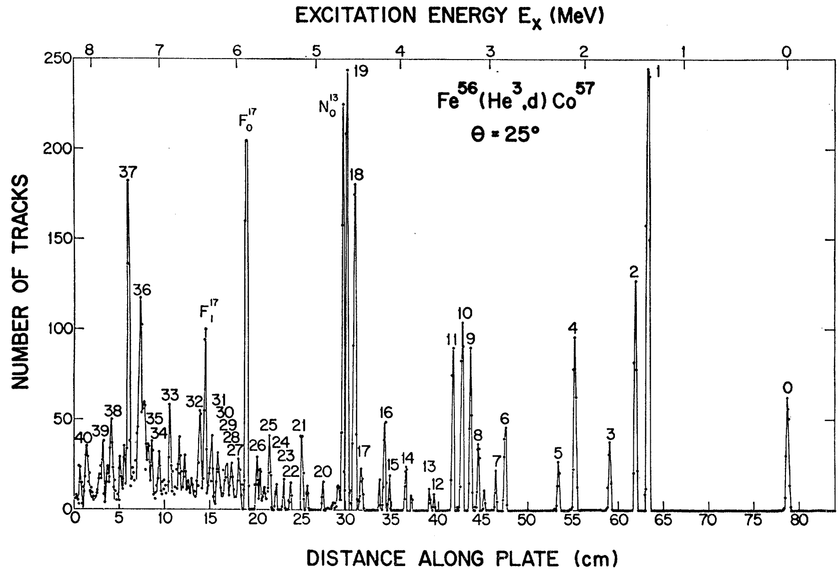

FIG. 6. Deuteron spectrum for the $Fe^{56}(He^3,d)Co^{57}$ reaction.

MeV by unfolding possible $l=1+3$ doublets. Their results support the existence of this special n-p interaction, but it is also possible that some of the weakly excited states observed in the present experiment above 4.5-MeV excitation energy are the missing $\frac{5}{2}^-$ states.

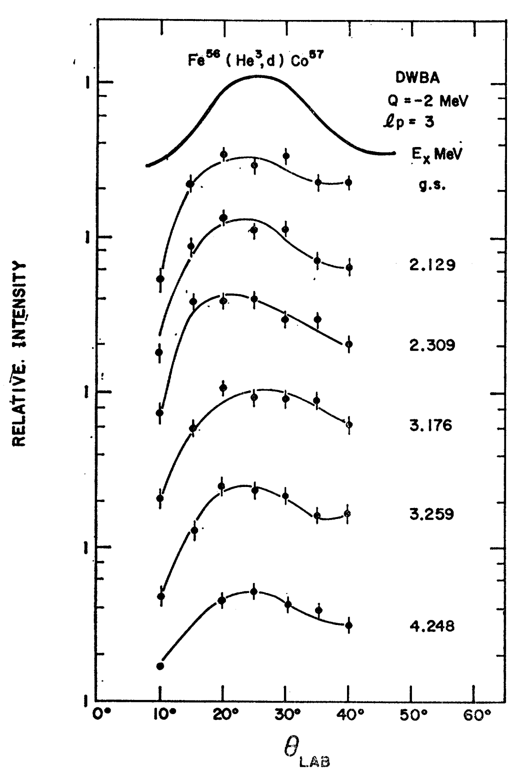

FIG. 7. Angular distributions of deuterons for $l_p=3$ angular-momentum transfer in $Fe^{56}(He^3,d)Co^{57}$ reaction. The heavy line represents a typical DWBA prediction.

$Fe^{56}(He^3,d)Co^{57}$ RESULTS

Figure 6 presents the deuteron spectrum for the $Fe^{56}(He^3,d)Co^{57}$ reaction taken at 25°. Forty-one states up to the excitation energy of 8 MeV in Co^{57} were identified. The summary of the experimental results is given in Table II. The ground state and the states at excitation energies of 1.379, 1.506, and 1.763 MeV that are populated in the β^+ decay of Ni^{57} are excited also in this study.

The 1.888-MeV state deserves special attention. It is populated in the beta decay of Ni^{57} but has a peak cross section of <0.02 mb/sr in the (He^3,d) study. If its $\frac{5}{2}^-$ spin-parity assignment[8,9] is correct, this result is difficult to understand. On the other hand, if the $\frac{7}{2}^-$ assignment suggested from the results of $Ni^{58}(t,\alpha)$ reaction[10] is the correct one, then it is difficult to see why this state is populated in the β^+ decay of Ni^{57}, whereas the $\frac{7}{2}^-$ ground state is not.

$l=3$ Transitions (Fig. 7)

The transition to the $\frac{7}{2}^-$ ground state of Co^{57} proceeds with an $l=3$ angular-momentum transfer and it takes almost the full transition strength of the (He^3,d) reaction to states with spin $\frac{7}{2}$. It is, therefore, reasonable to assign spin $\frac{5}{2}$ to the states at excitation energies of 2.129, 2.309, 3.176, 3.259, and 4.248 MeV. The state at excitation energy of 7.438 MeV is most probably the analog of the first excited $\frac{5}{2}^-$ state at 0.136-MeV excitation energy in Fe^{57}. It is interesting to note that where five $\frac{5}{2}^-$ states were identified in Co^{57} below 4.5-MeV excitation energy, none was clearly identified in the Co^{55} isotope in the same range of excitation energies.

[8] J. Komijn, H. L. Hagedoorn, and B. Van Nooijen, Physica **27**, 129 (1958).

[9] C. J. Piluso, D. O. Wells, and D. K. McDaniels, Nucl. Phys. **77**, 193 (1966).

[10] A. G. Blair and D. D. Armstrong, Phys. Rev. **151**, 930 (1966).

$l=1$ Transitions

The $\frac{3}{2}^-$ assignment[8] for the 1.379-MeV state is confirmed by the large value of the transition strength, namely, 1.8, observed in the present study. The $\frac{1}{2}$ and $\frac{3}{2}$ spin assignments for the 1.506- and 1.763-MeV states, respectively, are also in accord with our results for similar reasons. Recently, Piluso *et al.*[9] proposed a $\frac{5}{2}^-$ assignment to the 1.763-MeV state which is in contradiction to our results. Spin values for states at higher excitation energies obtained with an $l=1$ angular-momentum transfer cannot be assigned with certainty. To account for the total transition strength to $J=\frac{1}{2}$ and $\frac{3}{2}$ states, both spin-$\frac{3}{2}$ and $\frac{1}{2}$ values will have to be assigned to states at higher excitations. The states at 7.275- and 7.663-MeV excitation energies were identified as analogs of the $\frac{1}{2}^-$ ground state and the 0.366 MeV $\frac{3}{2}^-$ state in Fe^{57}.

$l=4$ Transition

The 4.605-MeV state appeared to be excited by an $l=4$ angular-momentum transfer. The strength for this transition is rather similar to that of the only $l=4$ transition found in the $Fe^{54}(He^3,d)$ reaction.

The sum of the experimental strengths of transitions leading to $1f_{7/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ states is 12.77, compared to the predicted value of 14. This somewhat low experimental value occurs because many states are too weakly excited to allow extraction of their transition strengths.

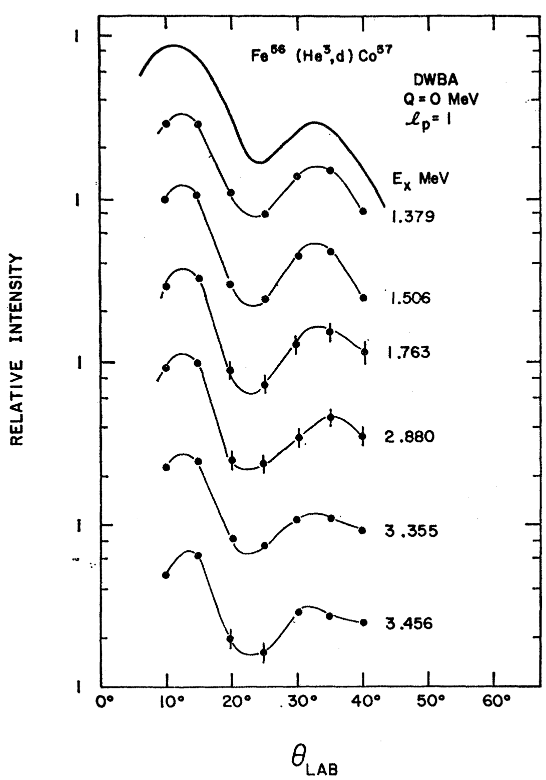

FIG. 8. $l_p=1$ transitions in the $Fe^{56}(He^3,d)Co^{57}$ reaction. The heavy line represents a typical DWBA prediction.

TABLE II. Summary of experimental results obtained in the $Fe^{56}(He^3,d)Co^{57}$ reaction. The uncertainty in excitation energy varies between 10 and 30 keV, depending on the intensity of the transition.

Level	Excitation energy (MeV)	l	σ_{ex} (mb/sr)	$(2J+1)C^2S$	Assumed J^π
0	g.s.	3	0.62	1.80	$\frac{7}{2}^-$
1	1.379	1	10.40	1.80	$\frac{3}{2}^-$
2	1.506	1	4.20	0.72	$\frac{1}{2}^-$
3	1.763	1	1.80	0.30	$\frac{3}{2}^-$
4	2.129	3	0.61	2.00	$\frac{5}{2}^-$
5	2.309	3	0.21	0.70	$\frac{5}{2}^-$
6	2.880	1	1.90	0.39	$\frac{1}{2}^-$
7	2.978	···	<0.10	···	
8	3.176	3	0.31	0.84	$\frac{5}{2}^-$
9	3.259	3	0.60	1.62	$\frac{5}{2}^-$
10	3.355	1	2.80	0.56	$\frac{1}{2}^-$
11	3.456	1	1.90	0.38	$\frac{1}{2}^-$
12	3.651	···	<0.10		
13	3.703	···	<0.10		
14	4.003	···	0.23[b]		
15	4.195	···	<0.10		
16	4.248	3	0.28	0.70	$\frac{5}{2}^-$
17	4.524	(1)	1.53		
18	4.605	(4)	1.45	4.8	$\frac{9}{2}^+$
19	4.689	(2)	1.84		
20	4.981	···	<0.10		
21	5.232	···	0.24[b]		
22	5.367	···	<0.10		
23	5.448	···	<0.10		
24	5.537	···	<0.10		
25	5.635	(1)	0.20[b]		
26	5.798	···	<0.10		
27	6.023	···	<0.10		
28	6.103	···	<0.10		
29	6.159	···	0.12[b]		
30	6.277	···	0.24[b]		
31	6.358	···	0.12[b]		
32	6.505	(3)	0.14[b]		
33	6.899	(1)	0.13[b]		
34	7.030	(1)	0.10[b]		
35	7.130	(1)	0.12[b]		
36	7.275	1	0.57	(0.12)	$\frac{1}{2}^-$[a]
37	7.438	3	0.40	(0.80)	$\frac{5}{2}^-$[a]
38	7.663	1	0.19	(0.04)	$\frac{3}{2}^-$[a]
39	7.779	···	0.10[b]		
40	7.982	···	0.10[b]		

[a] Analog states.
[b] Cross sections taken at 25°.

ANALOG STATES

The (He^3,d) reaction will excite both $T=\frac{1}{2}$ and $T=\frac{3}{2}$ states in Co^{55} and both $T=\frac{3}{2}$ and $T=\frac{5}{2}$ states in Co^{57}. The $T_>$ or higher isotopic spin states of each pair are analogs of states of Fe^{55} and Fe^{57}, respectively. The Coulomb force shifts these $T_>$ states in energy by an

TABLE III. Comparison of experimental results between the $Fe^{54,56}(He^3,d)Co^{55,57}$ and $Fe^{54,56}(d,p)Fe^{55,57}$ for transitions leading to analog pairs.

Analog states excited by (He^3,d) reaction Nucleus	E_x (MeV)	Energy sequence of analog states E_x (MeV)	States excited by (d,p) reaction Nucleus	E_x (MeV)	l_p	l_n	$(2J+1)C^2S$ calculated from (He^3,d) data	$(2J+1)C^2S$ predicted from (d,p) data
Co^{55}	4.76±0.02	0	Fe^{55} [a]	0	1	1	0.92	1.08
	5.19	0.43		0.417	1	1	0.48	0.40
	5.77	1.01		0.935	3	3	1.56	1.20
	6.85	2.09		2.061		1		0.13
	6.93	2.17		2.159		3		0.30
Co^{57}	7.28±0.03	0	Fe^{57} [b]	0	1	1		0.44
	7.44	0.16		0.136	(3)			
	7.66	0.38		0.366	1	1		0.20

[a] Fulmer *et al.*, Phys. Rev. **131**, 2133 (1963).
[b] Cohen *et al.*, Phys. Rev. **126**, 698 (1963).

amount ΔE_c, which is related to the excitation energy E_x by the expression

$$\Delta E_c = E_x + [Q(d,p) - Q(d,n)], \qquad (3)$$

where $Q(d,p)$ and $Q(d,n)$ are the Q values for the (d,p) and (d,n) reactions on the target nuclei.

By interpolating from Coulomb displacements measured for neighboring analog pairs, the location of the analogs of the ground states of Fe^{55} and Fe^{57} can be easily estimated. Their excitation energies are 4.755 and 7.275 MeV in Co^{55} and Co^{57}, respectively. Spectroscopic information confirmed these identifications. Higher excited analog states were identified by comparing their sequences of excitation energies with those observed in the corresponding levels excited in (d,p) reactions on the same target nuclei. In those cases where spectroscopic information was obtainable from the (He^3,d) reactions, the identifications were confirmed by comparing l values and transition strengths.[11]

It should be noted that the spectroscopic information obtainable for analog states by (He^3,d) studies is not as reliable as that which can be obtained for the corresponding states by (d,p) studies. Many of the analog states have quite negative Q values for which DWBA analysis is not reliable. Furthermore, the $T_>$ states take a rather small fraction of the total transition strength ($\frac{1}{3}$ for Co^{55} and $\gtrsim\frac{1}{5}$ for Co^{57}), so they are weakly excited even when they lie at excitation energies corresponding to Q values for which DWBA analysis may be reliably performed. Nevertheless, the correspondence of the spectroscopic information for analog pairs is quite good in most cases.

The excellent agreement between sequences of excitation energies and spectroscopic information for corresponding pairs of levels excited in (He^3,d) and (d,p) reactions is shown in Table III. A comparison between the energy sequence of the analog states and the states excited by the (d,p) reaction reveals only small deviations. Only the state at 5.77 MeV in Co^{55} which is excited with an $l=3$ angular-momentum transfer was found to lie 75-keV higher in excitation energy compared to the other analog states. A similar effect was found for the $l=3$ transition leading to the analog state at 4.32-MeV excitation energy in the $Ni^{58}(He^3,d)$ reaction.[11] The Coulomb displacement energies calculated for the Co^{55}-Fe^{55} and Co^{57}-Fe^{57} analog pairs using the excitation energies of the lowest lying analog states are tabulated in Table IV.

LOCATION OF SINGLE-PARTICLE PROTON STATES BY THE (He^3,d) REACTION

In the analysis of data obtained from (d,p) reactions, the "centroid method" has been very useful for locating single-particle neutron states.[12] In this method the single-particle states E_{nj} are located by the average;

$$E_{nj} = \sum_k E_j{}^k S_j{}^k / \sum_k S_j{}^k, \qquad (4)$$

where $E_j{}^k$ are the excitation energies of states with spin j excited in the (d,p) reaction and $S_j{}^k$ are the spectroscopic factors obtained for the transitions leading to them. This method is expected to locate the single-particle states accurately not only in nuclei with a single hole or a single particle outside a closed-shell configuration, but also, with the aid of an adequate theory, in many other nuclei.[13] The use of a similar averaging procedure to locate single-particle proton states E_{pj} from the (He^3,d) reaction is somewhat more complicated because this reaction excites states with different isospins which are well separated in energy.

It is possible to define three different centroids; for $T=T_z$,

$$E_{pj}{}^< = \sum_{k<} E_j{}^{k<} S_j{}^{k<} / \sum_{k<} S_j{}^{k<}, \qquad (5)$$

where $k_<$ runs only over the $T_<$ states, and for $T=T_z$

[11] B. Rosner, C. H. Holbrow, and D. J. Pullen, *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), p. 595.

[12] R. H. Fulmer, A. L. McCarthy, B. L. Cohen, and R. Middleton, Phys. Rev. **133**, B955 (1964); Baruch Rosner, *ibid.* **136**, B664 (1964).

[13] S. Yoshida, Nucl. Phys. **38**, 380 (1962).

TABLE IV. Coulomb displacement energies ΔE_c, extracted from the experimental observed excitation energies of the isobaric analog states; all energies in MeV.

Residual nucleus	Co^{55}	Co^{57}
E_x	4.76±0.02	7.28±0.03
ΔM[a]	3.46±0.01	0.84±0.01
$(n-H)$	0.78	0.78
ΔE_c	9.00±0.02	8.90±0.03

[a] Mattauch *et al.*, Nucl. Phys. **67**, 1 (1965).

TABLE V. Comparison of the location of the single-particle $f_{7/2}$, $p_{3/2}$, and $p_{1/2}$ neutron states in Ca^{47} with the single-particle proton states in Co^{55}. $E_{pj}^{<}$, $E_{pj}^{>}$, and E_{pj} are defined by Eqs. (5), (6), and (7), respectively.

Single-particle state	$E_{pj}^{<}$ (MeV)	${}_{27}Co_{28}{}^{55}$ $E_{pj}^{>}$ (MeV)	E_{pj} (MeV)	${}_{20}Ca_{27}{}^{47}$ E_{nj} (MeV)
$f_{7/2}$	0	...	...	0
$p_{3/2}$	2.44	6.28	3.72	2.25
$p_{1/2}$	4.00	8.31	5.44	3.81

+1,

$$E_{pj}^{>}=\sum_{k>} E_j^{k>}S_j^{k>}/\sum_{k>} S_j^{k>}, \qquad (6)$$

where $k_>$ runs only over the $T_>$ states, or a combined average

$$E_{pj}=\sum_k E_j^k S_j^k/\sum_k S_j^k, \qquad (7)$$

where k runs over both $T_<$ and $T_>$ states. This last average can be written

$$E_{pj}=C_<^2 E_{pj}^{<}+C_>^2 E_{pj}^{>}, \qquad (8)$$

where $C_<^2$ and $C_>^2$ are the squares of the isotopic-spin Clebsch-Gordan coefficients.[4]

The quantity $E_{pj}^{<}$ can be obtained easily because most of the states contributing to the summation in Eq. (5) occur at low excitation energies where l values, spins, and spectroscopic factors can be determined rather accurately.

The location of $E_{pj}^{>}$ is somewhat more difficult. The summation in Eq. (6) is over the $T_>$ (analog) states which usually lie at high excitation energies where the angular distributions of the deuterons from the (He^3,d) reaction lose much of the typical structure characterizing the l values. Also, values for the spectroscopic factors are only approximate, since they can be obtained only by extrapolating the DWBA calculations to very negative Q values. However, the centroid of the analog states [Eq. (6)] can be located using data from the (d,p) reaction. This is because the analog states excited in (He^3,d) reaction form a level sequence very similar to the low-lying states excited in the (d,p) reaction on the same target nucleus. The two groups of levels are separated in energy by $\Delta M=\Delta E_c-(n-H)$ where ΔE_c is the Coulomb displacement and $n-H$ is the neutron-hydrogen-atom mass difference. Therefore,

$$E_{pj}^{>}=E_a+E_{nj}, \qquad (9)$$

where E_a is the excitation energy of the ground-state analog. The transition intensities leading to corresponding analog pairs are simply related by

$$S_j^{k>}(He^3,d)=C_>^2 S_j^k(d,p). \qquad (10)$$

Table V presents the values obtained for the centroids $E_{pj}^{<}$, $E_{pj}^{>}$, and E_{pj} for spins $j=\frac{1}{2}$, $\frac{3}{2}$, and $\frac{7}{2}$ in Co^{55}. Values for $E_{pj}^{<}$ were calculated from the $Fe^{54}(He^3,d)$-Co^{55} data in Table I. The locations of the single-particle states in Fe^{55} used to evaluate $E_{pj}^{>}$ in Co^{55} were taken from the MIT data published by Gemmell *et al.*[5] The last column of Table V presents, for comparison, the locations of the single-particle states in Ca^{47} as obtained from the $Ca^{46}(d,p)Ca^{47}$ data.[6]

Good agreement between the locations of the single-particle neutron and proton states, which is expected if the nuclear interactions are charge-independent, is obtained only if the energies of the single-particle proton states are determined from the centroids $E_{pj}^{<}$ in which only $T=T_z$ states are taken in the summation.

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