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THE ^{56}Fe (d, n) ^{57}Co REACTIONS AND ^{57}Co LEVELS[1]

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The (d, n) reaction on a natural Fe target has been studied at 6.0 and 8.0 MeV deuteron bombarding energies using the neutron time-of-flight technique with an overall time resolution of 2 ns. 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 *DWBA* theory to deduce l_p values and proton spectroscopic factors. For the lowest bombarding energy the compound nucleus mechanism was taken into account. The results are compared with the corresponding data from (^{3}He, d) and other (d, n) studies.

A considerable amount of experimental [1—9] and theoretical [10—13] works have been devoted to the study of ^{57}Co levels. Level properties have been studied with nucleon transfer reactions [1—5] and γ-ray decay experiments [6—9]. Assignments of spin and parity (J^π) have been made [6—9] and lifetimes measured [8—9] for several levels below the 3 MeV excitation energy. Single particle amplitudes are determined directly from nucleon spectroscopic factors. The spectroscopic factors have thus been obtained from transfer reaction studies for comparison with theoretical estimates [11]. However, severe discrepancies exist between previous (d, n) studies [2—4] and also between previous (^{3}He, d) studies [1—5]. In order to attempt clarification of the transfer amplitudes, we have completed a new study of the differential cross section of the ^{56}Fe(d, n)^{57}Co reactions.

The angular distributions were measured using pulsed beam time-of-flight techniques and at two incident energies, 6 and 8 MeV. In this experiment, the pulsed deuteron beam of the Bruyères-le-Châtel tandem Van de Graaff had a burst width of 1.5 ns, a repetition rate of 1.25 MHz, and an average current of ~0.8 μA. Neutrons were detected with five 10 cm × 2.54 cm shielded *NE* 213 scintillators located at 18.4 m from the target. The overall time resolution was about 2 ns (see Fig. 1).

Absolute detection efficiences were calculated with the Monte-Carlo code of Textor and Verbinski [14]. The results of this code have been carefully tested in a separate set of measurements of detector efficiencies for these detectors [15]. The entire experimental system is described in detail in Ref. [15].

Angular distribution measurements were taken at 6 and 8 MeV incident energies, in 5° steps from 20° to 100°. Two different natural Fe target thicknesses were used: 470 μg/cm² at 6 MeV and 870 μg/cm² at 8 MeV.

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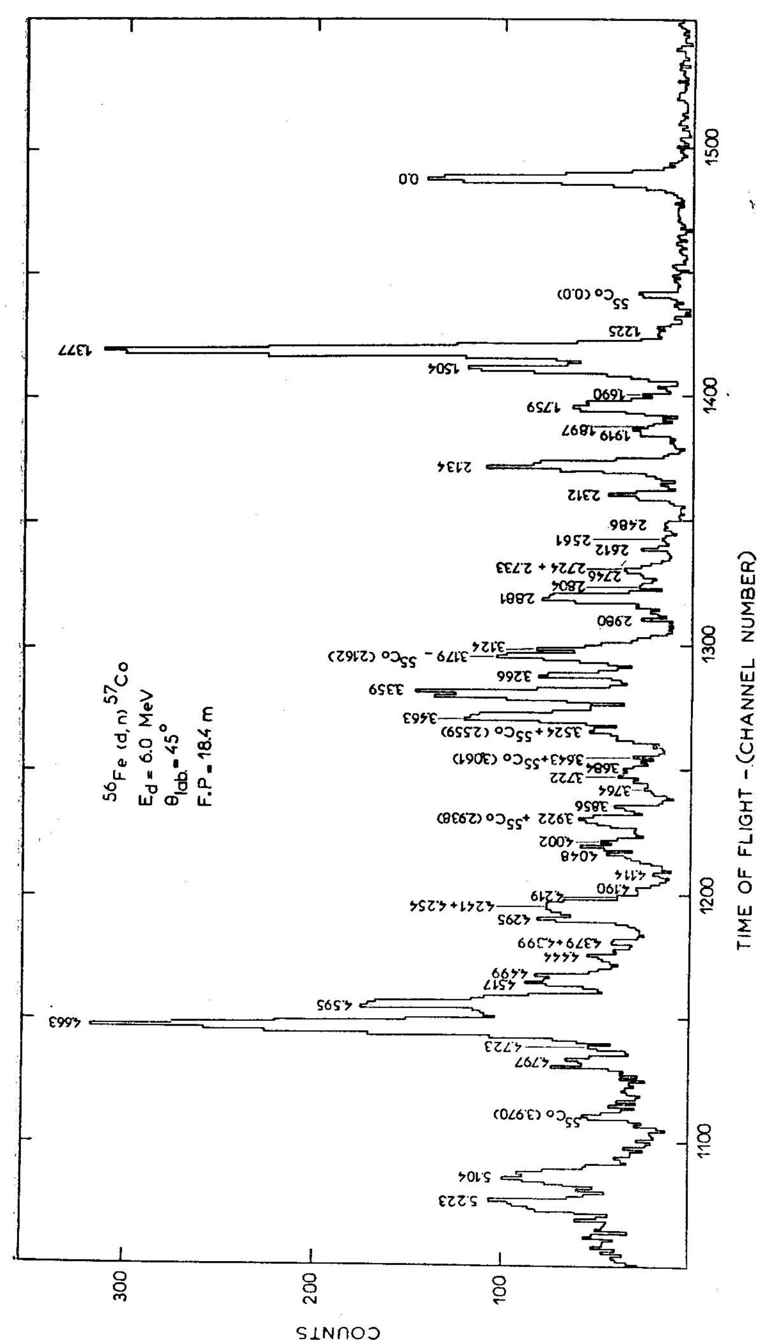


Fig. 1. Part of the ^{56}Fe(d, n)^{57}Co neutron time-of-flight spectrum, taken at a laboratory angle of 45° and with a flight path of 18.4 m, showing the low-lying levels of ^{57}Co up to an excitation energy of 5.5 MeV.

At a 6 MeV incident energy, the compound nucleus part of the reaction cross section is not negligible. The theoretical cross section is there expressed as an incoherent sum of direct reaction and compound nucleus components:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{D.I.} + R\left(\frac{d\sigma}{d\Omega}\right)_{C.N.}, \qquad (1)$$

where the reduction factor R takes account of the incident flux going into the direct non-elastic reaction channels. The statistical model of the Wolfenstein-Hauser-Feshbach (*WHF*) calculations were performed using a modified version of the code *MANDY* [16]. The code was modified to be used with incident particles of spins different than $\frac{1}{2}$.

The compound nucleus part was subtracted from measured differential cross sections, and the remainder was compared to the *DWBA* results calculated with the code *DWUCK* [17]. Since neither deuteron nor neutron scattering was studied in this experiment, the potential parameters for the *DWBA* calculations were taken from the literature [18—19], and the parameters used are presented in Table 1. All the calculations included the usual corrections for the non-locality of the potentials [20] and the finite range of the n-p interaction which is here given the value 0.62 fm [21]. It is important to note here that at an 8 MeV incident energy, the compound nucleus contribution to the cross sections could be ignored: the analysis there consisted simply of comparing the measurements and the *DWBA* calculations.

Table 1

Optical model parameters used in *DWBA* analysis

Particle	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W_i (MeV)	r_i (fm)	a_i (fm)	V_{so} (fm)	a_{so} (fm)	r_{so} (fm)	r_c (fm)	β (fm)
d[a]	85.50	1.175	0.821	17.84	1.366	0.688	7.5	1.175	0.821	1.30	0.54
n[b]	c)	1.290	0.66	d)	1.250	0.48	7.0	1.30	0.66		0.85
p		1.25	0.65				$\lambda = 25$			1.25	0.85

a) Ref. [18]
b) Ref. [19]
c) $V_0 = 47.01 - 0.267\,E - 0.0018\,E^2$
d) $W_i = 9.52 - 0.053\,E$

When doublets were not resolved, they were summed as one group and the transition strengths extracted by fitting the observed cross-sections with the relation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = (2J_1 + 1)C^2S_{l_1j_1}\left(\frac{d\sigma}{d\Omega}\right)_{DI} + (2J_2 + 1)C^2S_{l_2j_2}\left(\frac{d\sigma}{d\Omega}\right)_{DI} \qquad (2)$$

At a 6 MeV incident energy the compound nucleus contributions from both levels were subtracted before fitting the remainder to equation (2).

The transition strengths $G_{l_j} = C^2S_{l_j}\frac{2J_f + 1}{2J_i + 1}$ deduced from the analysis are listed in Table 2 and compared with previous (^{3}He, d) and (d, n) reaction results. When two final values are possible, strengths are computed for both.

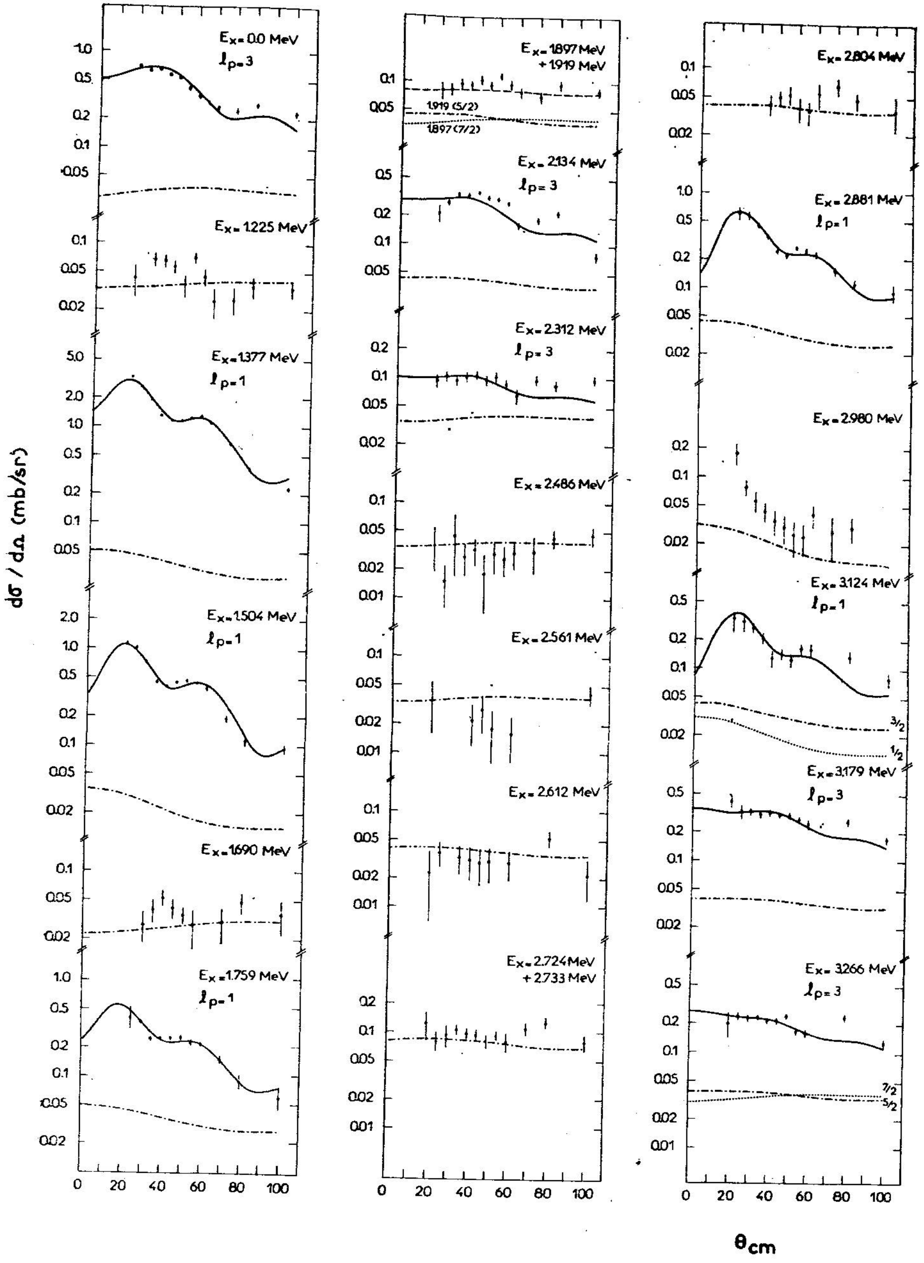
The measured angular distributions together with the Hauser-Feshbach and *DWBA* predictions are shown in Fig. 2 for an incident deuteron energy of 6.0 MeV. All the transition strength of the $f\frac{7}{2}$ state is contained in the transitions to the ground and the

Table 2

Comparison of transition strengths between the (d, n) and (^{3}He, d) measurements Where two spin values are possible, transition strengths are calculated for both.

$E_x^{a)}$ (MeV)	l_p	nlj	G_{lj}					
			(d, n)[b] 6.0 MeV	(d, n)[b] 8.0 MeV	(d, n)[c] 10.0 MeV	(d, n)[d] 11.7 MeV	(^{3}He, d)[e] 16.5 MeV	(^{3}He, d)[f] 22.0 MeV
0.00	3	$1f7/2$	1.95	1.83	2.88	5.20	1.80	0.89
1.377	1	$2p3/2$	1.16	0.94	1.73	1.69	1.80	0.52
1.504	1	$2p1/2$	0.56	0.36	0.63	1.12	0.72	0.35
1.759	1	$2p3/2$	0.18	0.19	0.27		0.30	0.13
2.134	3	$1f5/2$	1.19	1.13	2.22		2.00	1.20
2.312	3	$1f5/2$	0.28	0.37	(0.79)		0.70	0.20
2.881	1	$2p3/2$	0.16	0.12	0.26	0.47	0.39	0.11
3.124	1	$2p1/2$	0.10	0.09				0.02
		$2p3/2$	0.08	0.09				
3.179	3	$1f5/2$	1.19	0.73	1.14		0.84	0.55
3.266	3	$1f5/2$	1.28	0.74			1.62	0.65
		$1f7/2$	0.54	0.52				
3.359	1	$2p1/2$	0.32	0.25	0.46	0.88	0.56	0.16
		$2p3/2$	0.27	0.23				
3.463	1	$2p1/2$	0.25	0.23	0.39		0.38	0.14
		$2p3/2$	0.21	0.21				
3.722	(0)	$2s1/2$	0.02					
3.922	1	$2p1/2$	0.04					
	+3	$1f5/2$	0.11					
4.002	1	$2p1/2$	0.02		0.04			0.03
	+3	$1f5/2$	0.23		0.30			
4.048	1	$2p1/2$	0.02					
	+3	$1f5/2$	0.12					
4.190	1	$2p1/2$	0.03					0.02
4.219		$2p3/2$	0.01					
4.241	(3)	$1f5/2$	0.56				0.70	0.26
4.254		$1f7/2$	0.41					
4.295	1	$2p1/2$	0.03					
	+3	$1f5/2$	0.57					
4.379	1	$2p1/2$	0.03					
4.399		$2p3/2$	0.02					

a) the excitation are those from Ref. [22].
b) present work.
c) ref. [4].
d) ref. [2].
e) ref. [1].
f) ref. [5].



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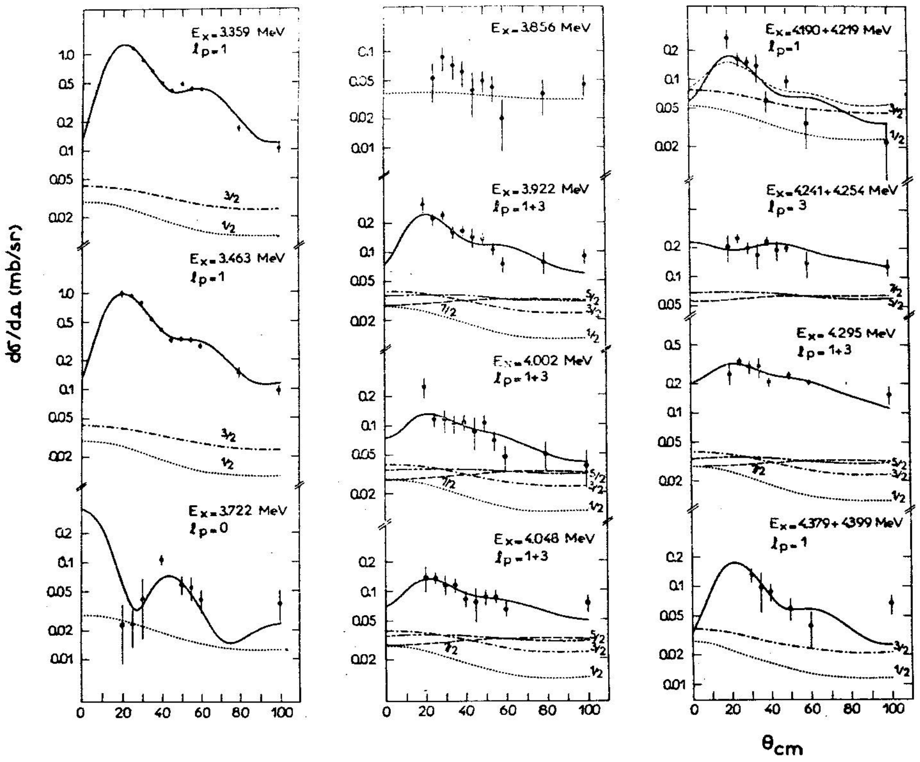

Fig. 2. Angular distributions of deuterons from the ^{56}Fe(d, n) reaction. The dashed lines represent compound nucleus contributions calculated with the *WHF* formalism. The solid lines are the incoherent sum of the *WHF* and the *DWBA* predictions. The l_p values and the excitation energies are shown.

2.312 MeV levels. The transition to higher levels characterized by a $l_p = 3$ momentum transfer can be assumed to go to the $f\,\frac{5}{2}$ subshell. For the l_p particle states it was assumed that levels below 3.5 MeV had the spin $J = \frac{3}{2}$ and higher levels the spin $J = \frac{1}{2}$. The *DWBA* curves were calculated with these assumptions. Since the time separation of peaks decreases when the deuteron energy increases, yield extraction becomes more difficult at $E_d = 8.0$ MeV. Thus, at the energy fewer angular distributions were obtained. However, the results obtained at both energies are in good agreement, as it can be seen in Table 2.

In general, the *DWBA* fits to the data are quite good except for the 2.134 MeV level for which several l_p values were tried, but without success. We chose the $l_p = 3$ value because the spin was known to be $J^\pi = \frac{5}{2}^-$ from previous experiments [6–8]. The 2.980 MeV level was populated with an $l_p = 0$ transfer in the ^{56}Fe(^{3}He, d) reaction [5]. The experimental distribution is not in disagreement with such an assumption, but nothing can be deduced here because of the lack of the forward angle data.

Level assignments and comparisons between different experiments are very difficult for levels with excitation energies above 3 MeV. The level density there is quite high, as seen in a recent high resolution study of the ^{60}Ni$(p, \alpha)^{57}$Co reaction [22].

The angular momentum transfers deduced from this experiment are in agreement with those determined from earlier (d, n) and $(^3$He$, d)$ studies. The transition strengths have not been well determined in previous experiments, as noted in the introduction. For this reason, a comparison of strengths determined in the two types of transfer reactions has not been possible. Our strengths, determined by different analyses at two bombarding energies, are in agreement with each other and with those of Couch et al. [4] obtained from the same reaction at $E_d = 10$ MeV. This would seem to resolve the disagreement between the results of Couch et al. and those of Okorokov et al. [2]. Since the results of two different $(^3$He$, d)$ measurements are not in agreement, it is difficult to compare our results to those from the $(^3$He$, d)$ reactions.

REFERENCES

[1] Rosner B., Holbrow C. H., Phys. Rev. *154* (1967), 1080.
[2] Okorokov V. V., Serezhin V. M., Smotryaev V. A., Tolchenkov D. L., Trostin I. S., Cheblukov Yu. N., Sov. Journ. Nucl. Phys. *4* (1967), 697.
[3] Blair A. G., Armstrong D. D., Phys. Rev. *151* (1969), 664.
[4] Couch R. G., *Ph D dissertation*. Northwestern University, 1969, unpublished.
[5] Hardie G., Braid T. H., Meyer-Schutzmeister L., Smith J. W., Phys. Rev. *C 5* (1972), 1600.
[6] Coop K. L., Graham I. G., Titterton E. W., Nucl. Phys. *A 149* (1970), 463.
[7] O'Brien B. J., Coote G. E., Nucl. Phys. *A 153* (1970), 593.
[8] Dayras R., Toulemonde M., Cujec B., Heusch B., Mo J. N., Szoghy, Nucl. Phys. *A 173* (1971), 49.
[9] Burton K. S., Mc Intyre L. C., Phys. Rev. *C 3* (1971), 621.
[10] Mc Grory J. B., Phys. Rev. *160* (1967), 915.
[11] Satpathy L., Gujrathi S. C., Nucl. Phys. *A 110* (1968), 400.
[12] Gatrousis C., Meyer R. A., Mann L. G., Mc Grory J. B., Phys. Rev. *180* (1969), 1052.
[13] Covello A., Manfredi V. R., Phys. Lett. *34 B* (1971), 584.
[14] Textor R. E., Verbinski V. V., ORNL *4160* (1968).
[15] Adam A., Cabe J., *to be published*.
[16] Sheldon E., Strang R. M., Computer Phys. Commun. *1* (1969), 35.
[17] Kunz P. D., *The program DWUCK*. University of Colorado, unpublished.
[18] Perey C. M., Perey F. G., Nucl. Data Tables *10* (1972), 469.
[19] Wilmore D., Hodgson P. E., Nucl. Phys. *55* (1964), 673.
[20] Perey F. G., Saxon D. S., Phys. Lett. *10* (1964), 107.
[21] Bassel R. H., Phys. Rev. *149* (1966), 791.
[22] Goss J. D., *Private communication*. Notre-Dame University, Notre Dame, Indiana, USA.

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