Energy Levels of Fe^{59} from the $Fe^{58}(d,p)Fe^{59}$ Reaction*

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The angular distributions of the protons from the $Fe^{58}(d,p)Fe^{59}$ reaction leading to eight states of Fe^{59} have been measured with 10-MeV deuterons at the Argonne tandem accelerator. Data were taken from 15° to 165°. Absolute cross sections were obtained by comparing the 7-MeV deuterons elastically scattered at 20° with the ground-state protons from the (d,p) reaction at $E_d=10$ MeV. Values of the orbital-angular-momentum transfer and spectroscopic factors were obtained by comparing the measured cross sections at the forward peaks with those calculated by means of the distorted-wave Born approximation. Spins were assigned by use of the empirical J-dependence rules. The assignments $E_{exc}(l,J,S)$ resulting from the present work are ground state $(1,\frac{3}{2},0.45)$; 0.287 MeV $(1,\frac{1}{2},0.22)$; 0.470 MeV $(3,\frac{5}{2},0.54)$; 0.728 MeV $(1,\frac{3}{2},0.20)$; 1.026 MeV $([3],[\frac{7}{2}],0.08)$; 1.214 MeV $(1,\frac{1}{2},0.81)$; 1.572 MeV $(4,\frac{9}{2},1.07)$; and 1.749 MeV $(2,\frac{5}{2},[\frac{3}{2}],3.59/(2J+1))$.

INTRODUCTION

THE Q value of the $Fe^{58}(d,p)Fe^{59}$ reaction and the energies of excited states in Fe^{59} have been accurately measured by Sperduto and Buechner.[1] Previous work on (d,p) angular distributions from the levels in Fe^{59} has been discussed briefly in a recent paper of Lee and Schiffer,[2] which contains a general discussion of spin assignments of levels in the $2p$ shell. These assignments are based on the empirically established J dependence in (d,p) angular distributions and are compared with available nuclear-structure calculations. The present work reports detailed measurement of the absolute cross sections for the (d,p) reactions for the ground state and seven excited states of Fe^{59}. The bombarding energy $E_d=10$ MeV was chosen because previous work[3] had shown that the J-dependent effects on the (d,p) angular distributions are somewhat more pronounced at this energy than at 8 or 12 MeV. From the present absolute cross sections and the distorted-wave Born-approximation (DWBA) analysis discussed below, spectroscopic factors for eight of the states of Fe^{59} have been obtained.

EXPERIMENTAL METHOD

The angular distributions were measured at $7\frac{1}{2}$° and 5° intervals from 15° to 165° in the laboratory, with two additonal points at $132\frac{1}{2}$° and $137\frac{1}{2}$°. The Argonne tandem accelerator was the source of the 10-MeV deuterons. The silicon surface-barrier detector discussed below was used as the proton detector for the data taken at angles of 25° to 165°. A silicon dE/dx detector was used in front of the proton detector to help discriminate against elastically scattered deuterons in a run covering angles from 15° to 40°. Finally, a run was made with the Argonne magnetic spectrograph[4] at angles of 7.5°, 15°, 20°, 25°, and 35°. In all the above cases, a monitor counter at 90° was used to normalize the various runs.

The absolute (d,p) cross sections were obtained in another measurement with the magnetic spectrograph. In this experiment, the yield of 7-MeV deuterons elastically scattered at a laboratory angle of 20° was compared to that of the ground-state proton group emitted at 20° in the (d,p) reaction induced by 10-MeV deuterons. A monitor counter was used to establish the fraction of the integrator cycle over which the deuteron elastic-scattering measurement was made.

The detector used in the proton angular-distribution measurements described above was a high-resistivity (nominal resistivity 20 000 Ω-cm) silicon surface-barrier counter whose inversion layer was formed by a boiling-water technique.[5] It was operated at a reverse bias of 700 V; at this bias the measured energy resolution width for 17-MeV protons was 29 keV. In the present work, owing to the thickness of the Fe^{58} target, the energy resolution width for the ground-state proton group was 44 keV. The detector has been operated for more than 200 h at the Argonne tandem, and its noise and leakage current have remained substantially unchanged over a period of more than two years. The detector was cooled and electrostatically shielded by means of an aluminum cylinder which was attached to a thermoelectric unit[6] whose power input was 25 W. Tap water to cool the heat sink of the cooler was introduced into the scattering chamber through a cylinder fitted with an O ring to allow easy changing of the detector angle. At a reverse bias of 700 V, the detector leakage current was 0.05 μA.

A collimator $\frac{1}{8}$ in. in diameter and 8 cm from the target was used to define the particle beam entering the detector. Without a magnetic field to deflect electrons away from the collimator, the energy resolution of the system was found to vary with the deuteron beam current. A sufficient deflecting field was produced by a

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[5] E. D. Klema, Nucl. Instr. Methods **26**, 205 (1964).
[6] Manufactured by Jepson Thermoelectrics, Inc., Chicago, Illinois.

small permanent magnet placed directly in front of the collimator. It was also necessary that the bias on the surface-barrier detector be introduced by means of a wire held at a high negative voltage with respect to ground. When a positive high-voltage lead was used, even a well-shielded one, stray electrons were collected on it and the energy resolution was seriously degraded.

EXPERIMENTAL RESULTS

Figure 1 shows the measured angular distributions for the ground state of Fe^{59} and for the excited states at 0.287, 0.470, 0.728, 1.026, 1.214, 1.572, and 1.749 MeV. In nearly all cases, the statistical errors are smaller than the sizes of the circles; in those cases in which this is not true, the errors are indicated by the vertical lines. The solid curves represent the cross sections calculated with the DWBA as discussed below.

The absolute cross section for the deuteron elastic scattering was calculated by means of the ABACUS program.[7] This calculation provided a small correction; the elastic scattering is 4% less than Coulomb scattering at $\theta=20°$ and $E_d=7$ MeV. Comparison of the deuteron

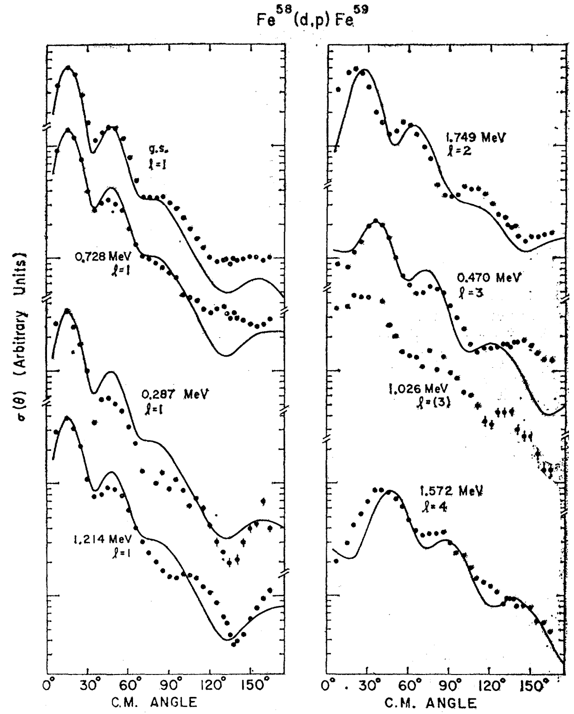

FIG. 1. Angular distributions from the $Fe^{58}(d,p)Fe^{59}$ reaction. The circles show the measured distributions for reactions to the indicated final states; the solid lines represent the DWBA calculations discussed in the text. The data are displaced vertically to facilitate comparison.

elastic-scattering group with the ground-state proton group obtained during the last experimental run provided the factor required to convert the measured counts to absolute cross sections. The data points in Fig. 1 are plotted in arbitrary units to facilitate comparison. The measured absolute cross sections (mb/sr) are given in Table I. The absolute accuracy of the cross sections is believed to be about ±10%.

TABLE I. Measured absolute cross sections for the $Fe^{58}(d,p)Fe^{59}$ reaction to the indicated states, for $E_d=10$ MeV. The cross sections, given in millibarns/steradian, are believed to be accurate to ±10%.

Center-of-mass angle (deg)	Reaction to final state at E_{exc} (MeV)							
	0.000	0.287	0.470	0.728	1.026	1.214	1.572	1.749
7.7	5.10	1.53	0.48	2.48	0.218	6.08	0.43	3.06
15.3	7.29	1.98	0.46	3.75	0.230	8.05	0.63	4.36
20.4	6.39	1.46	0.61	3.21	0.290	6.60	0.90	4.67
25.5	4.15	1.02	0.75	2.07	0.279	4.59	1.14	4.26
30.6	2.31	0.59	1.04	1.07	0.279	2.33	1.43	3.29
35.7	1.63	0.20	1.15	0.72		1.62	1.83	1.93
40.7	1.91	0.33	1.07	0.85	0.256	1.69	1.85	1.57
45.8	2.12	0.34	0.82	0.90	0.159	1.94	1.78	1.24
50.9	2.11	0.30	0.54	0.84	0.127	1.90	1.55	1.30
55.9	1.69	0.26	0.38	0.73	0.093	1.64	1.32	1.54
61.0	1.16	0.19	0.32	0.50	0.084	1.24	1.01	1.48
66.1	0.72	0.134	0.27	0.36	0.081	0.85	0.82	1.24
71.1	0.51	0.075	0.27	0.28	0.067	0.63	0.74	0.94
76.1	0.50		0.30	0.27	0.092	0.52	0.76	0.75
81.1	0.50	0.059	0.29	0.24	0.064	0.42	0.76	0.44
86.2	0.51	0.073	0.26	0.23	0.082	0.35	0.78	0.35
91.2	0.46	0.052	0.20	0.20	0.059	0.32	0.63	0.34
96.2	0.40	0.064	0.160	0.183	0.053	0.30	0.52	0.35
101.1	0.33	0.051	0.127	0.126	0.040	0.33	0.49	0.42
106.1	0.27	0.037	0.092	0.120	0.038	0.32	0.38	0.39
111.1	0.21	0.043	0.079	0.111	0.030	0.30	0.30	0.40
116.1	0.182	0.035	0.086	0.092	0.022	0.26	0.28	0.36
121.0	0.147	0.025	0.084	0.088	0.020	0.22	0.26	0.29
126.0	0.134	0.018	0.087	0.094	0.026	0.181	0.23	0.24
130.9	0.138	0.014	0.093	0.098	0.026	0.137	0.179	0.22
133.4	0.141		0.092	0.085		0.120	0.200	0.191
135.8	0.130	0.012	0.087	0.077	0.027	0.094	0.200	0.181
138.3	0.144		0.096	0.087		0.077	0.197	0.183
140.7	0.138	0.013	0.097	0.077	0.018	0.083	0.173	0.151
145.7	0.143	0.017	0.101	0.075	0.016	0.095	0.173	0.135
150.6	0.148	0.023	0.091	0.069	0.016	0.131	0.167	0.149
155.5	0.150	0.026	0.077	0.066	0.011	0.165	0.126	0.150
160.4	0.137	0.040	0.068	0.069	0.008	0.20	0.122	0.154
165.3	0.148	0.023	0.065	0.076	0.008	0.24	0.102	0.160

ANALYSIS

The computer code JULIE was used[8] to calculate the theoretical single-particle (d,p) cross sections for the excitation of the various energy levels observed in the present work. A surface-derivative imaginary potential was used. Table II gives the values used for the various parameters. The parameters listed in Table II were also used in the ABACUS calculation discussed above. The lower radial cutoff used in the JULIE calculations was $R=5.0$ F. The spectroscopic factors of the various levels were found by taking the ratios of the experimental to the calculated cross sections at the forward peaks.

Table III gives the results of the present work. It lists the energies of the levels, the measured absolute peak (d,p) cross sections, the calculated peak cross

[7] We are indebted to E. Auerbach for the ABACUS program.

[8] We are indebted to R. Drisko, G. R. Satchler, and R. Bassel for the JULIE program.

TABLE II. Parameters used in JULIE calculations described in the text

		Incident deuteron[a]	Outgoing proton[b]	Transferred neutron
V	(MeV)	74.2	54.4	
r_0	(F)	1.26	1.25	1.25
r_c	(F)	1.20	1.25	1.25
a	(F)	0.794	0.65	0.65
r_0'	(F)	1.528	1.25	
a'	(F)	0.557	0.47	
W'[c]	(MeV)	19.9	13.0	

[a] Parameters obtained by G. R. Satchler (private communication) by fitting the elastic deuteron scattering from Fe^{54} [L. L. Lee, Jr., and J. P. Schiffer (to be published)].
[b] Parameters obtained from F. G. Perey [Phys. Rev. 131, 745 (1963)].
[c] W' as used in the JULIE program is defined as 4 times the number given in the table (79.5 MeV for deuterons and 52 MeV for protons).

sections, the spectroscopic factors, and the assignments of l and J.

For the $l=1$ transitions the ratio

$$R\equiv[\bar{\sigma}_{\max}-\sigma_{\min}]/\tfrac{1}{2}(\bar{\sigma}_{\max}+\sigma_{\min})$$

was formed in the vicinity of the backward minimum at $\sim 135°$. As discussed in Ref. 2, $R>0.5$ implies $J^\pi=\frac{1}{2}$ while $R<0.5$ corresponds to $J^\pi=\frac{3}{2}^-$. The assignments to the four $l=1$ transitions seem unambiguous. For the strong $l=3$ transition at 0.470 MeV, the $J^\pi=\frac{5}{2}^-$ assignment is consistent with shell-model expectations and the behavior at backward angles also suggests this.[3] For the weak transition to the 1.026-MeV state, the $l=3$ assignment seems to be the only reasonable one. The backward-angle behavior is consistent with the J dependence for a $\frac{7}{2}^-$ state: the yield decreases by a factor of ~ 3 in the interval from 100° to 150°. For the 0.47-MeV state, however, this factor was only 1.3—precisely the difference found to characterize the $l=3$ J dependence in nearby nuclei.[3]

TABLE III. Values obtained for the measured peak cross sections for the (d,p) reaction at $E_d=10$ MeV, the spectroscopic factors, the orbital-angular-momentum transfers, the quantity R as defined in the text, and the angular momenta and parities of the listed states in Fe^{59}.

Excitation energy (MeV)	$\sigma(d,p)$ (mb/sr)	S	l	R	J
0.000	7.29	0.45	1	0.07	$\frac{3}{2}^-$
0.287	1.99	0.22	1	0.96	$\frac{1}{2}^-$
0.470	1.16	0.54	3		$\frac{5}{2}^-$
0.728	3.79	0.20	1	0.24	$\frac{3}{2}^-$
1.026	0.29	0.08	(3)		$(\frac{7}{2}^-)$
1.214	8.33	0.81	1	1.10	$\frac{1}{2}^-$
1.572	1.85	1.07	4		$\frac{9}{2}^+$
1.749	4.69	$3.59/(2J+1)$	2		$\frac{5}{2}^+, (\frac{3}{2}^+)$

DISCUSSION

The sum of spectroscopic factors for the odd-parity states is $\sum(2J+1)S=8.5$, in good agreement with the 8.0 expected from the filling of the f-p shell. On the basis of its spectroscopic factor, the $\frac{9}{2}^+$ state appears to be a single-particle state; but the $l=2$ state at 1.79 MeV clearly is not. A comparison with the level scheme of Ni^{61} indicates no particular similarity. The summed spectroscopic factors for the $Ni^{60}(d,p)Ni^{61}$ reaction[9] and in the $Ni^{60}(d,t)Ni^{59}$ reaction[10] yield a measure of the filling of the various active orbits in Ni^{60} (Table IV).

TABLE IV. Degree of filling of various single-particle orbitals in ${}_{26}Fe_{32}{}^{58}$ and ${}_{28}Ni_{32}{}^{60}$.

Orbital	$V_j^2=1-\sum S_j(d,p)$ Fe^{58a}	Fe^{58b}	Ni^{60c}	Ni^{60d}
$2p_{3/2}$	0.35	0.44	0.69	0.58
$2p_{1/2}$	0			0.30
$1f_{5/2}$	0.46	0.38	0.21	0.18

[a] Present work.
[b] From the $Fe^{58}(p,d)Fe^{57}$ reaction, Ref. 11. The $2p$ strengths were not separated but are assumed to be all $2p_{3/2}$ for the purposes of the entry in this table.
[c] Reference 9.
[d] From the $Ni^{60}(d,t)Ni^{59}$ reaction, Ref. 10.

We deduce that the neutron $1f_{5/2}$ orbit is more filled and the $2p_{3/2}$ is less filled in ${}_{26}Fe_{32}{}^{58}$ than in ${}_{28}Ni_{32}{}^{60}$, a conclusion which seems somewhat surprising in view of the fact that the $\frac{5}{2}^-$ state occurs at 69 keV in Ni^{61} and at 470 keV in Fe^{59}, the ground state being a strong $\frac{3}{2}^-$ state in both cases. Agreement with the results reported by Sherr[11] on the occupation of orbitals based on the $Fe^{58}(p,d)Fe^{57}$ reactions is reasonable. It is of interest to note that Sherr finds it necessary to use rather large normalization factors to bring spectroscopic factors into line with sum rules. This is in contrast with the present results, where the inverse reaction in the same energy range gives good absolute agreement.

ACKNOWLEDGMENT

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