NEUTRON PICKUP STRENGTH FROM ^{56}Fe$(\boldsymbol{p},\boldsymbol{d})^{55}$Fe REACTION AT 28 MeV INCIDENT PROTON ENERGY

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Differential cross-sections for the ^{56}Fe$(p,d)^{55}$Fe reaction have been measured at 28 MeV proton energy using 15 UD Pelletron accelerator at Nuclear Science Centre, New Delhi. The data has been analysed using the zero range Distorted Wave Born Approximation (DWBA) using the standard Woods–Saxon optical model potential and the non local range corrections. The spectroscopic factors for the $5/2^-$ (2.144 MeV), $1/2^+$ (4.450 MeV), $3/2^+$ (4.825 MeV) and $5/2^-$ (7.610 MeV) excited states have been newly measured.

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1. Introduction

The nucleus ^{55}Fe can be described as a single neutron outside and two proton holes in the doubly closed $1f_{7/2}$ shell. There are two approaches reported in the literature [1–4] to describe this nucleus. In the first approach the shell model calculations consider ^{48}Ca as an inert core and the effective p–p and p–n interactions are used to describe the different configuration out side this core. While the second approach is the intermediate coupling model which considers the coupling of an odd nucleon to the neighbouring even-even core which is either in the ground or in the excited state. Carola and Ohnuma [4] have compared the electromagnetic transition strength with the intermediate coupling model which is simple in nature and have found a good agreement with the experimental observations except the static electric quadrupole moments which most of the models failed to reproduce. Ohnuma [3] has also calculated the energy levels of the nuclei by the shell model with the configuration mixing. The simple effective n–p interaction had the radial Gaussian dependance and has been taken to fit the experimental data on the energy levels of ^{56}Co and ^{50}Sc. He has calculated the energy level spectrum and the spectroscopic factors which were found to be in a reasonable agreement for the lower energy spectrum *i.e.* ≤ 2 MeV.

In ^{55}Fe nucleus very little work has been done to study the spectroscopic factors from pickup reactions which provide a quantitative appraisal of the shell model and the intermediate coupling model. In the present work the (p,d) reaction has been used to study the spectroscopic factors which are reliably deduced from the simple reaction mechanism *i.e.* direct pick-up of one neutron from the target and the appropriate use of the Distorted Wave Born Approximation (DWBA). Earlier workers [5–11] have studied the ^{56}Fe$(p,d)^{55}$Fe reaction but the results on the spectroscopic factors differ considerably from each other. Further, these factors have been measured only for some prominent transitions. The present experiment was aimed to remove the existing ambiguity and to measure the spectroscopic factors for the weak transitions for which no data is available in the literature. A complete knowledge of the spectroscopic factors shall provide a better tool for understanding the structure of this nucleus.

2. Experimental set-up

The ^{56}Fe$(p,d)^{55}$Fe reaction was studied using the 28.0 MeV proton beam from the 15UD Pelletron at Nuclear Science Centre, New Delhi. A self supporting 850 $\mu g/\mathrm{cm}^2$ thick metal foil of natural iron (91.8% ^{56}Fe) was used as the target. The charged particle telescopes consist of E (5 mm) and ΔE (300 μm) silicon detectors. The angular distributions of deuterons were measured in the angular range from 28.5° to 65° in steps of 2.5°. The overall energy resolution was about 50 keV. A typical deuteron spectrum is shown in Fig. 1.

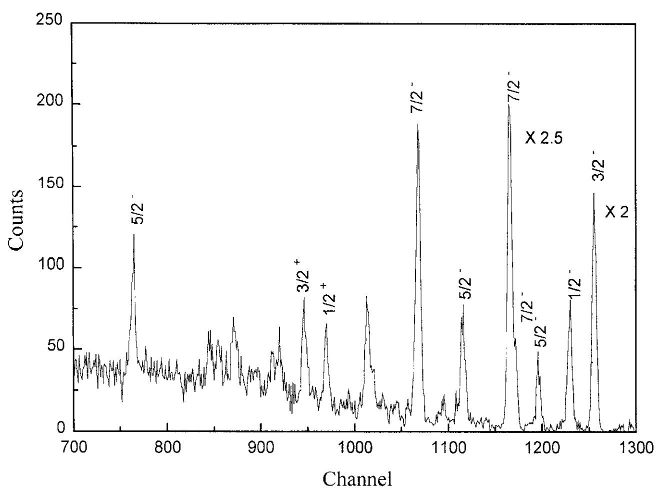

Fig. 1. The energy spectrum of deuterons from ^{56}Fe$(p,d)^{55}$Fe at $\theta = 63.5°$.

3. Optical model calculation

The data analysis was performed with a 13-parameter optical model potential including a complex central potential of the Woods–Saxon shape and its derivative, a spin-orbit term of Thomas form and a Coulomb term as given below

$$V(r) = -V_R f(r, r_r, a_r) - iW_s f(r, r_s, a_s) + i4a_i W_D . \frac{d}{dr} f(r, r_D, a_D)$$

$$+V_{LS} \left(\frac{\hbar}{m_p c}\right)^2 (L.S) \frac{1}{r} \cdot \frac{d}{dr} f(r, r_{LS}, a_{LS}) + V_{\mathrm{Coul}} ,$$

where the Woods–Saxon well $f(r, r_0, a_0)$ is given by

$$f(r, r_0, a_0) = \left[1 + \exp\left(\frac{r - r_0 A^{1/3}}{a_0}\right)\right]^{-1} ,$$

where A is the target mass number. The Coulomb term is taken as the potential for a unifrom charged sphere of radius $R_{\mathrm{c}} = r_{\mathrm{c}} A^{1/3}$.

3.1. Proton optical model parameters

The angular distributions of elastically scattered protons from ^{56}Fe were measured to obtain the proton optical model parameters for entrance channel. The starting parameters to fit the proton elastic scattering data were taken from Perey and Perey [12] and were tuned to obtain the final optical model parameters. These final optical model parameters are given in Table I which are used for the entrance channel in the DWBA analysis.

3.2. Deuteron optical model parameters

The optical model parameters for deuterons were taken from the global set of Daehnick *et al.* [13]. We modified these parameters slightly to get the best fit of the deuterons angular distribution from the ground state of ^{55}Fe. These modified parameters (Table I) were used for the DWBA analysis for all the excited states. The neutron potential used for this analysis are also tabulated in Table I.

TABLE I

Potential	Depth (MeV)	Radius (r_0) (fm)	Diffusness (a_0) (fm)
Proton optical model potential parameters			
Real	42.2	1.14	0.79
Volume Imaginary	8.1	1.37	0.52
Surface Imaginary	1.5	1.37	0.52
Real Spin–Orbit	6.6	0.96	0.67
Coulomb	—	1.11	—
Deuteron Optical Model Potential Parameters			
Potential	Depth (MeV)	Radius (a_0) (fm)	Diffuseness (a_0) (fm)
Real	106.0	1.12	0.90
Volume Imaginary	0.0	—	—
Surface Imaginary	65.0	1.38	0.74
Real Spin-Orbit	13.0	0.90	1.18
Neutron Optical Model Potential Parameters			
Potential	Depth (MeV)	Radius (fm)	Diffuseness (a) (fm)
Real	varied	1.14	0.79
Spin- Orbit	Factor multiplying the Thomas term (25.0)	—	—

4. Distorted wave analysis

Zero range DWBA calculations with finite range parameter R equal to 0.621 with nonlocal range corrections were performed for all the observed transitions employing the computer code DWUCK4. The non locality correction B=0.85 fm^2 for the protons and β=0.54 fm^2 for the deuterons were applied. The target form factors were generated by employing the well depth method. The depth of the Woods–Saxon potential is adjusted until the separation energy of the picked-up particle from the specified orbital is matched. The spectroscopic factor S was extracted using the relation

$$\left(\frac{d\sigma}{d\omega}\right)_{\rm Exp} = 2.3C^2S\left(\frac{d\sigma}{d\omega}\right)_{\rm DWBA},$$

C is the isospin Clebsch–Gordon coefficient and the factor 2.3 is the normalisation constant due to the finite range effects, calculated by Bassel *et al.* [14] for the (p,d) reactions using the Hulthen wave functions for the internal structure of the deuteron.

5. Results and discussion

The transitions corresponding to ten exited states were observed in the present experiment. We calculated the neutron pick-up strength from the $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$, $1f_{7/2}$, $2s_{1/2}$ and $1d_{3/2}$ orbitals. The DWBA predictions for transitions involving $2p_{3/2}$ and $2p_{1/2}$ transfers are shown in Fig. 2. It is clear from the figure that the differential cross-sections for the $3/2^-$ (0.0 MeV) and the $1/2^-$ (0.411 MeV) states are reasonably well reproduced. The DWBA calculations involving $1f_{7/2}$ transfers are shown in Fig. 3. The

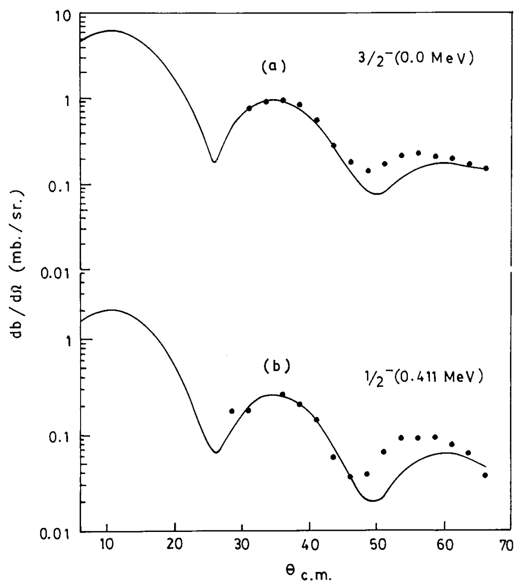

Fig. 2. The experimental differential cross-sections for (a) $3/2^-$ (0.0 MeV) and (b) $1/2^-$ (0.411 MeV) states.

first $7/2^-$ state (1.316 MeV) is weakly excited in comparison to the second $7/2^-$ (1.408 MeV) state therefore, the transition to the first excited state may have a considerable two steps transition probability while the second excited state is mainly reached by a one step transition. This is also confirmed by Vennink and Glaudmans by the shell model calculations [15]. The spectroscopic strength for the third $7/2^-$ state (2.938 MeV) is 1.39 which is also strongly excited therefore, seems to be a one step transition. The relative strength of the second $7/2^-$ (1.408 MeV) state to the first $7/2^-$ (1.316 MeV) excited state is about 4.8 which lies close to the value of 4.4 measured by Majumdar *et al.* [16] from the ^{56}Fe(d,t) reaction. These three $7/2^-$ states carry the 62% of the total $7/2^-$ strength as shown in Table II.

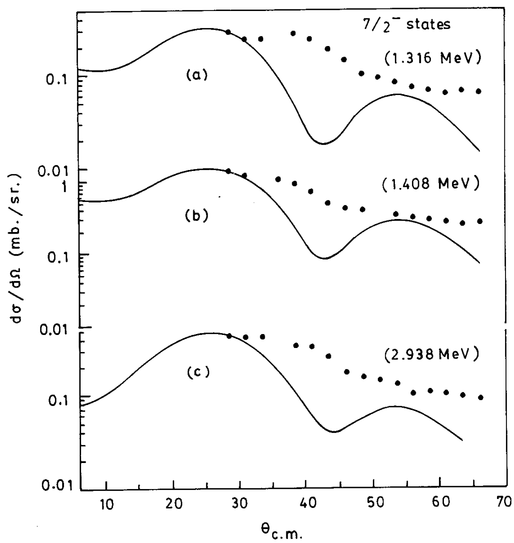

Fig. 3. The experimental differential cross-sections of deuterons for (a) $7/2^-$ (1.316 MeV), (b) $7/2^-$ (1.408 MeV) and (c) $7/2^-$ (2.938 MeV) states.

TABLE II

Comparison of the present results with earlier results.

E_x (MeV)	State	l transfer	Present work	(p,d) [10]	(d,t) [9]	(d,t) [16]	(h,α) [18]	(h,α) [19]	Theoretical KB1[10]	Theoretical SDI[10]
0.0	$3/2^-$	1	1.51(7)	0.69	1.22	0.90	0.63	0.28	1.13	0.42
0.411	$1/2^-$	1	1.03(15)	0.28	0.40	0.28	0.47	—	0.41	0.44
0.931	$5/2^-$	3	0.46(3)	0.33	0.70	0.40	0.43	0.37	0.18	0.84
1.316	$7/2^-$	3	0.62(4)	0.41	—	0.73	0.62	—	0.35	0.04
1.408	$7/2^-$	3	2.96(12)	2.41	—	2.91	4.68	—	2.66	3.72
2.144	$5/2^-$	3	0.43(6)	—	—	—	—	—	—	—
2.938	$7/2^-$	3	1.39(7)	0.87	—	—	1.21	0.73	0.54	0.41
4.450	$1/2^+$	0	1.93(39)	—	—	—	—	—	—	—
4.825	$3/2^+$	2	3.55(64)	—	—	—	—	—	—	—
7.610	$5/2^-$	3	1.61(21)	—	—	—	—	—	—	—

The spectroscopic strengths for the $5/2^-$ states were calculated considering these due to one nucleon transfer from the $1f_{5/2}$ orbitals. The spectroscopic strength for the $5/2^-$ (0.931 MeV) state was found to be in a good agreement with the values obtained earlier by Zaman *et al.* [17,18]. The spectroscopic strength for the $5/2^-$ states at 2.144 MeV and 7.610 MeV have been newly measured. We found 41% of the total $5/2^-$ strength distributed among these three states. The remainder is probably spread over a large number of weakly excited states. The comparison of the experimental data with the theoretical angular distributions for these states is shown in Fig. 4.

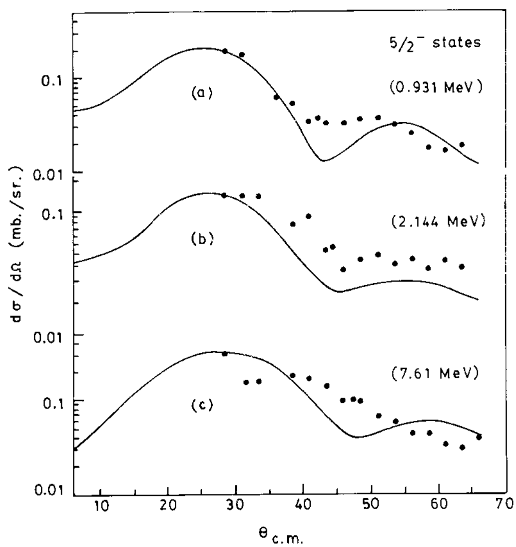

Fig. 4. The experimental differential cross-sections of deuterons for (a) $5/2^-$ (0.931 MeV), (b) $5/2^-$ (2.144 MeV) and (c) $5/2^-$ (7.61 MeV) states.

Two positive parity states $1/2^+$ (4.450) and $3/2^+$ (4.825 MeV) have also been analysed for the first time. The $1/2^+$ state was strongly excited indicating that this transition is dominated by a single step process. We got the spectroscopic strength 1.93 for this state which is about 90% of the total strength.

We considered the $3/2^+$ state as a result of one neutron pick up from $1d_{3/2}$ orbit and obtained spectroscopic strength equal to 3.55 which is nearly 88% of the total strength. The fitting of the experimental and the theoretical angular distributions for the $1/2^+$ and $3/2^+$ states are shown in Fig. 5. The present spectroscopic factors alongwith the values obtained by others are summarised in Table II. Our results for the states $5/2^-$ (0.931 MeV),

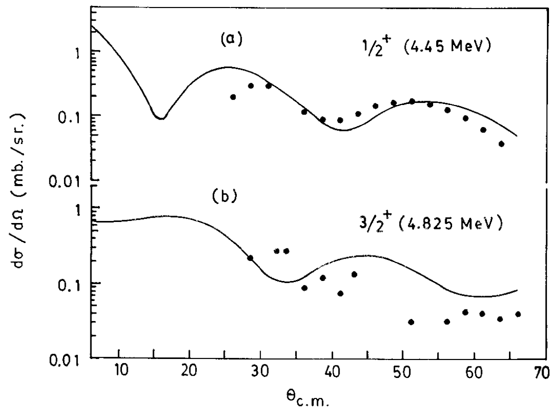

Fig. 5. The experimental differential cross-sections of deuterons for (a) $1/2^+$ (4.450 MeV) and (b) $3/2^+$ (4.825 MeV).

$7/2^-$ (1.316 MeV), $7/2^-$ (1.408 MeV) are in good agreement with the values reported earlier by Zaman *et al.* [17,18] as shown in Table II. However, our result for the $7/2^-$ (1.408 MeV) state are close to their value from (d,t) reaction [17] as compared to their value from (^{3}He,α) reaction [18]. The present spectroscopic factors (1.51) for the $3/2^-$ (0.0 MeV) state is more in agreement with the value obtained by Hosono *et al.* [9]. The experimental values are also compared with the theoretical shell model predictions using Kuo–Brown (KB1) and Surface Delta Interactions (SDI).

6. Conclusion

The spectroscopic factors for the $3/2^-$(0.0 MeV), $1/2^-$(0.411 MeV), $5/2^-$ (0.931 MeV), $7/2^-$ (1.316 MeV), $7/2^-$ (1.408 MeV), $5/2^-$(2.144 MeV), $7/2^-$ (2.938 MeV), $1/2^+$ (4.450 MeV), $3/2^+$ (4.825 MeV) and $5/2^-$ (7.610 MeV) states were extracted in the present experiment. The spectroscopic strength for the $5/2^-$ (2.144 MeV), $1/2^+$ (4.450 MeV), $3/2^+$ (4.825 MeV) and $5/2^-$ (7.610 MeV) have been reported by us for the first time. The experimental values are compared with the theoretical shell model calculations with Kuo-Brown(KB1) and SDI [10]. The agreement with theory using these interactions is very much limited. This indicates that a better theoretical interpretation including the effects of the mixing of $1f$ and $2p$ nucleons in the ground state wavefunctions as suggested by Legg and Roast [6] may be needed to describe this nucleus.

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