Pramāna, Vol. 13, No. 3, September 1979, pp. 269-280, © printed in India

Analysis of two neutron (proton) transfer reaction data in the Zr-region

S HAQ and Y K GAMBHIR
Department of Physics, Indian Institute of Technology, Bombay 400 076

MS received 15 February 1979; revised 4 July 1979

Abstract. The spectroscopic amplitudes, form factors, angular distributions and total cross-sections for two nucleon transfer reactions in Zr-region in the zero range distorted wave Born approximation are calculated using consistent set of shell model wave functions. A single normalisation factor gives a good fit to all the two neutron transfer reaction data whereas the corresponding fit for the two-proton transfer reaction data is less satisfactory.

Keywords. Nuclear reactions; shell model wave functions; zero range DWBA; spectroscopic amplitudes; form factors; angular distributions; total cross-sections.

1. Introduction

In recent years a number of papers on two-nucleon transfer reactions in the Zr-region, have appeared. These also contain the zero range distorted wave Born approximation (DWBA) analysis of the data using mostly pure or phenomenological shell model wave functions for the transferred pair of neutrons (protons) and sometimes over-simplified shell nodel wave functions for the target and the residual nuclei. The (p, t) reaction data ($E_p=38$ MeV) and its analysis for Zr-isotopes using pure $(2d_{5/2})^2$ shell model configuration of the transferred pair of neutrons were reported by Ball *et al* (1971). This revealed the necessity of using mixed configurations for the transferred neutrons. Flynn *et al* (1974) and Casten *et al* (1972) analysed the (t, p) reaction ($E_t=20$ MeV) data for the Zr-isotopes using the phenomenological shell model neutron wave functions of Ball and Bhatt (unpublished, quoted in Flynn *et al* 1974) with a reasonable success. The results of the shell model calculations for ^{90}Zr and ^{92}Zr were used in the analysis of ^{90}Zr (t, p) ^{92}Zr reaction ($E_t=11\cdot85$ MeV) by Ipson *et al* (1975). The analysis predicted right order of magnitudes of the experimental results. Recently, ^{88}Sr (t, p) ^{90}Sr reaction ($E_t=20$ MeV) and its analysis have been published by Flynn *et al* (1976). For the first few positive parity states of ^{90}Sr the analysis used a pure $(2d_{5/2})^2$ configuration for the transferred neutrons. The experimental and the calculated maximum differential cross-sections $(\sigma(\theta))$ were compared and their ratio ranged from 2·2 to 3·0. The angular distributions from 0° to 40° for $(^3\text{He}, n)$ reactions ($E_{^3\text{He}}=25\cdot4$ MeV) on target of ^{88}Sr, ^{90,92,94}Zr, ^{92,94,96,100}Mo and ^{102}Ru were measured by Fielding *et al* (1976). These authors also reported the zero range DWBA analysis for these reactions, using pure $(2p_{1/2})^2$, pure $(1g_{9/2})^2$ and a mixed $[0\cdot68\ (2p_{1/2})^2+0\cdot68\ (1g_{9/2})^2+0\cdot23\ (2p_{3/2})^2+0\cdot23\ (1f_{5/2})^2]$ shell model configurations for the transferred pair of protons and four different sets of optical model parameters for ^{3}He.

On the theoretical front, the shell model with ^{88}Sr ($N=50, Z=38$) as an inert core, is expected to be a good description in this region. The well-known problem of dimensionality of the configuration space in the shell model compels the restriction of the number of single particle (sp) states to be included in the model space. For a given choice of the model space the shell model results are sensitive to the input information, namely the sp energies and the two-body matrix elements. Therefore, the most reliable results are expected to be those of the phenomenological analysis in which the input parameters are adjusted by the least squares fit to the experimental (level energies and sometimes transition rates) data. Such phenomenological analyses have been reported in this region (Gloeckner *et al* 1972; Gloeckner and Serduke 1974; Serduke *et al* 1975; Gloeckner 1975; Gross and Frenkel 1976). The motivation of the present work is to test the compatibility of these phenomenological shell model wave functions with the related two-neutron (proton) transfer reactions. This is all the more important in view of the fact that the earlier analyses used: (a) pure or phenomenological set of shell model wave functions for the transferred pair of nucleons and sometimes over-simplified shell model wave functions for the target and the residual nuclei and (b) different sets of optical model parameters and even different bound state geometry although the nuclei involved in these reactions have nearly the same mass number A. In contrast we use:

(i) A consistent set of complete shell model structure wave functions generated by a single phenomenological interaction, for the target and the residual nuclei.
(ii) Two sets of optical model parameters (a) borrowed from the earlier published work, and (b) a single energy-dependent optical potential and the same bound state geometry of the Woods-Saxon potential.

The results obtained with both the sets of the optical model parameters are similar and both reproduce reasonably well all the observed (p, t), (t, p) reaction data. In (^{3}He, n) reactions the results with the second (ii) set of optical parameters mentioned above are consistently smaller.

2. Calculation

The structure information for the nuclei under consideration, is obtained in the framework of shell model using ^{88}Sr as an inert core. The valence protons have been confined to $2p_{1/2}$ and $1g_{9/2}$ shell model orbitals while the valence neutrons have been restricted to $2d_{5/2}$ and $3s_{1/2}$ sp states. The phenomenological set of proton-proton effective matrix elements along with sp energies of $2p_{1/2}$ and $1g_{9/2}$ states, used here are taken from the earlier shell model analysis reported by Gloeckner and Serduke (1974). These eleven parameters were obtained by the least squares fit to the 45 observed energy levels of $N=50$ nuclei. The neutron-neutron and the neutron-proton matrix elements along with the energies of sp neutron states are also taken from the earlier phenomenological shell model analysis (Gloeckner 1975) of the Zr and Nb isotopes. The shell model wave functions are then obtained by diagonalising the relevant hamiltonian.

The structure information needed in the DWBA analysis, enters only through the spectroscopic amplitudes. The partial spectroscopic amplitude ($S_J\,(j_a j_b)$) is defined (apart from a phase and a multiplicative factor) as an overlap between the state ($\psi_{J_f\,M_f}$) of a given spin and parity of residual (target) nucleus and the state obtained by coupling the wave function ($\mathscr{A}_J^\dagger\,(j_a j_b)$) of the transferred pair of nucleons to the state ($\psi_{J_i\,M_i}$) of the target (residual) nucleus. Explicitly

$$S_J\,(j_a j_b) = \langle \psi_{J_f\,M_f}\,(A+2)\,|\,(\mathscr{A}_J^\dagger\,(j_a j_b) \otimes \psi_{J_i}\,(A))^{J_f}_{M_f} \rangle. \tag{1}$$

Using the explicit shell model expressions for $\psi_{J_i\,M_i}(A)$ and $\psi_{J_f\,M_f}(A+2)$ all the relevant $S_J(j_a j_b)$ (equation (1)) can easily be computed. The DWBA expressions (Broglia *et al* 1972) for the form factors, angular distributions $\sigma\,(\theta)$ and total cross-sections σ involve, in addition to $S_J(j_a j_b)$, the bound state wave functions of the transferred nucleons and the distorted wave functions of the projectile and the outgoing particles. The single nucleon bound state wave functions are generated from the Woods-Saxon well including the Thomas form of the spin orbit term. If the nucleon is a proton, a Coulomb potential of a uniform charge distribution of appropriate radius and total charge is added. The strength of the well is adjusted so that the calculated eigenvalue is, approximately, half of the two-nucleon separation energy taken to be ($|Q|+8{\cdot}48$) MeV for the two-neutron transfer and ($|Q|+7{\cdot}718$) MeV for the two-proton transfer reactions (Q being the Q value of the reaction). The remaining parameters of the Woods-Saxon potential are taken from published work. These parameters for the specific cases are listed in table 1. The distorted waves for the projectile and the outgoing particles are generated through the optical model potential $V(r)$, written as

$$\begin{aligned} V(r) = -\, & V_0\{1+\exp\,[(r-R)/a_0]\}^{-1} - i[W'\{1+\exp\,[(r-R')/a'_0]\}^{-1} \\ & + 4W''\,[\exp\,\{(r-R'')/a''_0\}] \times [(1+\exp\,\{(r-R'')/a''_0\}]^{-2}]. \end{aligned} \tag{2}$$

Here, $R=r_0\,A^{1/3}$, $R'=r'_0\,A^{1/3}$, $R''=r''_0\,A^{1/3}$ and A is the mass of the heavy particle in the scattering channel. The optical model parameters available in the earlier published papers are used in the first set of calculation. However for the (^{3}He, n) reactions, the $B1$ set of optical model parameters of Becchetti *et al* (1972) for ^{3}He is used and we omit the spin orbit term for the neutron optical model parameters of Becchetti and Greenless (1969). The analysis of (^{3}He, n) reactions reveals that the results are sensitive to the neutron optical model parameters and the results obtained by using the equivalent local potential of Wilmore and Hodgson (1964) for the neutron do not even reproduce the qualitative features of the angular distributions. Therefore these will not be presented here.

In the second set of calculations for (p,t) and (t,p) reactions, we use a single set of bound state parameters ($r=1{\cdot}25$, $a=0{\cdot}65$) and an energy-dependent optical model parameters for protons of Perey (1963) and for tritons ($E=20$ MeV) of Flynn *et al* (1969). In the second set of calculation for the (^{3}He, n) reactions we have used the same optical model parameters (set 1) but a fixed bound state geometry ($r=1{\cdot}25$, $a=0{\cdot}65$) consistent with the corresponding (p, t), (t, p) case. These are also given (in parantheses) in table 1.

Table 1. Optical model parameters used in the DBWA calculation. (Number in paranthesis correspond to second set of calculations)

Reactions and bombarding energies	Bound state parameters			Optical model parameters						
				Real			Imaginary			
	r (fm)	a (fm)	Incoming and outgoing particles	V(MeV)	r_0(fm)	a_0(fm)	W'(MeV)	W''(MeV)	$r'_0=r''_0$ (fm)	$a'_0=a''_0$ (fm)
^{92}Zr(p, t) ^{90}Zr	1·25	0·65	p^{a}	54·3 (39·47)	1·12 (1·25)	0·78 (0·65)	5·66 (0·0)	3·86 (13·5)	1·32 (1·25)	0·601 (0·47)
E_p=38 MeV			t^{a}	170·1 (166·7)	1·15 (1·16)	0·739 (0·752)	19·0 (24·35)	0·0 (0·0)	1·515 (1·498)	0·758 (0·817)
^{90}Zr(t, p) ^{92}Zr	1·25	0·65	t^{b}	171·3 (166·7)	1·16 (1·16)	0·735 (0·752)	16·8 (24·35)	0·0 (0·0)	1·48 (1·498)	0·885 (0·817)
E_t=20 MeV			p^{b}	48·4 (45·324)	1·25 (1·25)	0·65 (0·65)	0·0 (0·0)	15·4 (13·55)	1·25 (1·25)	0·47 (0·47)
^{88}Sr(t, p) ^{90}Sr	1·27	0·67	t^{c}	166·7	1·16	0·752	23·3	0·0	1·498	0·817
E_t=20 MeV	(1·25)	(0·65)	p^{c}	50·0 (46·748)	1·25 (1·25)	0·65 (0·65)	0·0 (0·0)	13·55 (13·55)	1·25 (1·25)	0·47 (0·47)
^{88}Sr(^{3}He, n) ^{90}Zr	1·28	0·76	^{3}He^{d}	154·09	1·20	0·72	38·07	0·0	1·43	0·84
$E_{^{3}\mathrm{He}}$=25·4 MeV	(1·25)	(0·65)	n^{e}	43·03	1·17	0·75	5·69	3·38	1·26	0·58
^{90}Zr(^{3}He; n) ^{92}Mo	1·28	0·76	^{3}He^{d}	152·9	1·20	0·72	37·10	0·0	1·43	0·84
$E_{^{3}\mathrm{He}}$=25·4 MeV	(1·25)	(0·65)	n^{e}	44·52	1·17	0·75	5·10	4·38	1·26	0·58

[a] Ball *et al* (1972) [b] Flynn *et al* (1974) [c] Flynn *et al* (1976) [d] Set B1 of Becchetti *et al* (1972) [e] Becchetti and Greenless (1969)

The orbital parts of the triton and ^{3}He internal wave functions are taken to be of Gaussian shape with size parameters adjusted so as to reproduce the respective measured mean square radii. The integral appearing in the expression of the form factor, is evaluated using the technique of Bayman and Kallio (1967). These form factors are then used to calculate the angular distributions and the total cross-sections. All the zero range DWBA calculations are performed with the Bayman's two-particle transfer code TWOPAR.

3. Results and discussion

3·1 *Two neutron transfer reactions*

In the present analysis the full shell model wave functions for ^{90}Sr, ^{90}Zr and ^{92}Zr with respect to ^{88}Sr inert core are used to calculate the partial spectroscopic amplitudes through equation (1). Using these amplitudes, the zero range DWBA form factors, the differential cross-sections and the total cross-sections are calculated. A single normalisation factor 310, consistent with the earlier work, is used for quantitative comparison with the experimental data and with the earlier analysis.

The calculated and experimental (Ball *et al* 1971) angular distribution for ^{92}Zr(p, t) ^{90}Zr$_{gs}$ is plotted in figure 1. It is clear that for both sets of calculations the shape and even the relative magnitudes of the maxima and minima are well reproduced, while the exact positions of the maxima and minima are shifted by a few degrees to the right. However, such shifts can be corrected (Bayman and Hintz 1968) by introducing lower cut-off in the DWBA integral and sometimes by readjusting the optical model

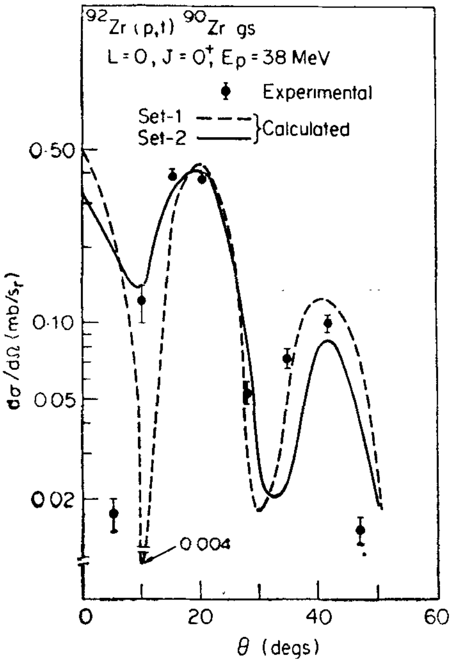
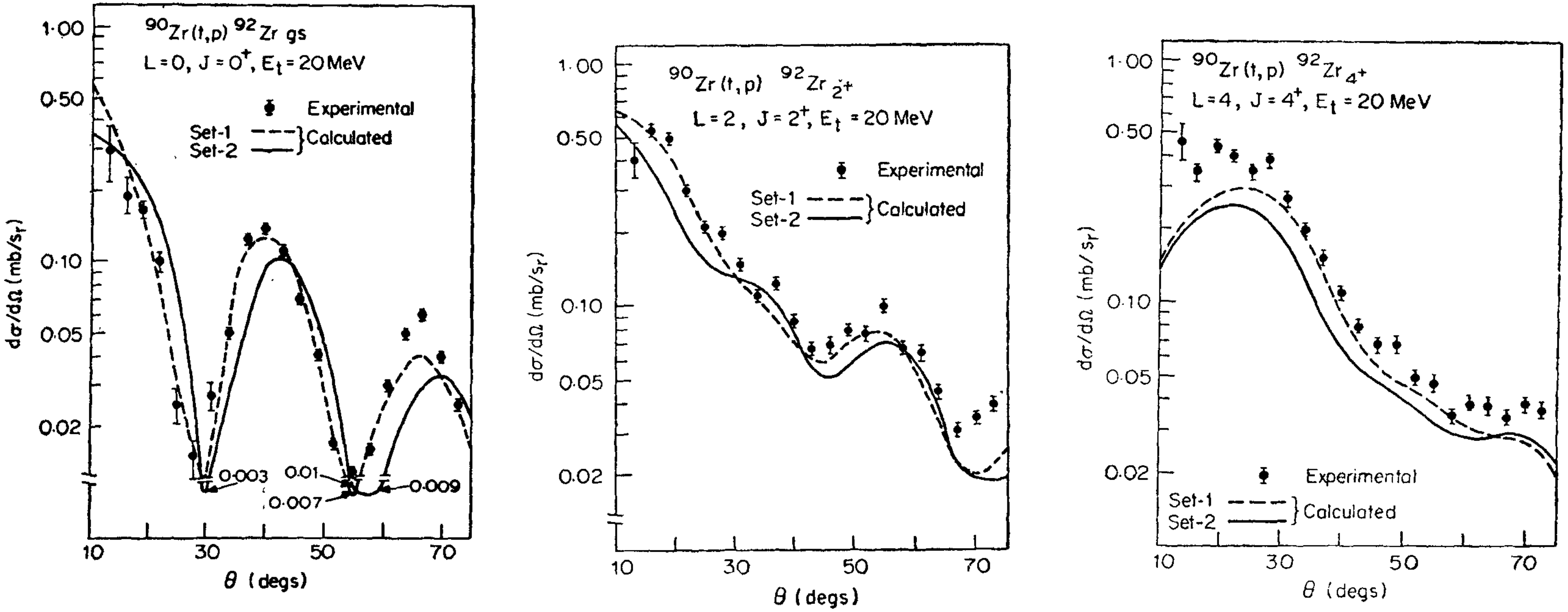
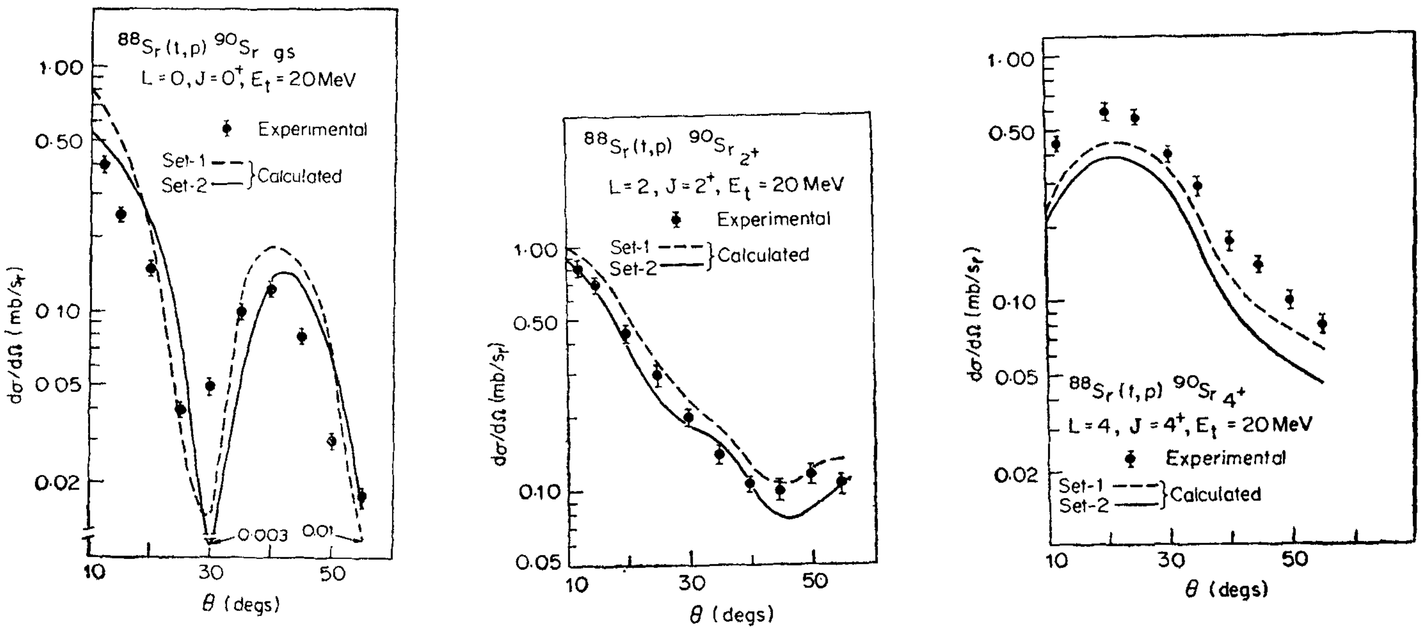


Figure 1. The calculated and experimental (Ball *et al* 1971) angular distribution for ^{92}Zr(p,t)^{90}Zr gs.



(a) (b) (c)

Figure 2. The calculated and experimental (Flynn *et al* 1974) angular distributions for ^{90}Zr$(t,p)^{92}$Zr$_{J^\pi}$. **a.** $J^\pi = 0^+$ (gs) **b.** $J^\pi = 2^+$ and **c.** $J^\pi = 4^+$.



(a) (b) (c)

Figure 3. The calculated and the experimental (Flynn *et al* 1976) angular distributions for $^{88}Sr(t,p)^{90}Sr_{J^\pi}$. a. $J^\pi = 0^+$ (gs) b. $J^\pi = 2^+$ and c. $J^\pi = 4^+$.

parametres. We have not attempted here to rectify the shift. The calculated total cross-section with the shell model wave functions of ^{92}Zr in both the cases is approximately 1·6 times the total cross-section obtained by using pure $(2d_{5/2})^2$ configuration for the transferred neutrons. It should be noted that this number (1·6) is exactly equal to the enhancement factor (ϵ) obtained by Ball *et al* (1971) using pure $(2d_{5/2})^2$ configuration for the transferred pair of neutrons. This, therefore, implies that the shell model ground state wave function of ^{92}Zr in the zero range DWBA, exactly reproduces the observed total cross-section for $^{92}\mathrm{Zr}(p, t)\,^{90}\mathrm{Zr}_{\mathrm{gs}}$ reaction.

The angular distributions for $^{90}\mathrm{Zr}(t, p)\,^{92}\mathrm{Zr}_{J\pi}$ ($J^{\pi}=0^+$ (gs), 2^+, 4^+) are displayed in figures 2a, 2b and 2c and for $^{88}\mathrm{Sr}(t, p)\,^{90}\mathrm{Sr}_{J\pi}$($J^{\pi}=0^+$(gs), 2^+,4^+) in figures 3a, 3b and 3c. The figures also contain the corresponding experimental (Flynn *et al* 1974, 1976) results. These figures reveal that the shape and the positions as well as the relative magnitudes of the various maxima and minima are well reproduced. However, for $^{88}\mathrm{Sr}(t, p)^{90}\mathrm{Sr}_{4^+}$ reaction, while the shape is reproduced, the theoretical differential cross-sections are slightly off by a constant factor. This may be attributed to the inadequacy of the truncated space considered for the transferred neutrons, as in this case ($J^{\pi}=4^+$) only $(2d_{5/2})^2$ configuration can contribute to the reaction. The same remarks should also apply for the $^{90}\mathrm{Zr}(t, p)\,^{92}\mathrm{Zr}_{4^+}$ reaction.

The ratios of the calculated total cross-sections for $^{90}\mathrm{Zr}(t, p)\,^{92}\mathrm{Zr}_{J\pi}$ reaction are arranged in table 2, so that the results are free from the normalisation factor. The results of the set 2 calculations are shown in the parentheses. The table which also includes for comparison the corresponding experimental and calculated results of Flynn *et al* (1974) demonstrates a satisfactory agreement between the experimental and the corresponding DWBA cross-sections. Unfortunately, direct data for the

Table 2. Ratios of the total cross-sections (σ) of $^{90}\mathrm{Zr}(t,p)$, $^{92}\mathrm{Zr}_{J\pi}$ reactions for the lowest states.

	Expt. (Flynn *et al* 1974)	Theory (Flynn *et al* 1974)	Calculated
$\sigma_{2^+}/\sigma_{0^+}$ (gs)	1·70	1·76	1·69 (1·56)
$\sigma_{4^+}/\sigma_{0^+}$ (gs)	1·41	1·57	1·45 (1·26)
$\sigma_{2^+}/\sigma_{4^+}$	1·21	1·12	1·16 (1.24)

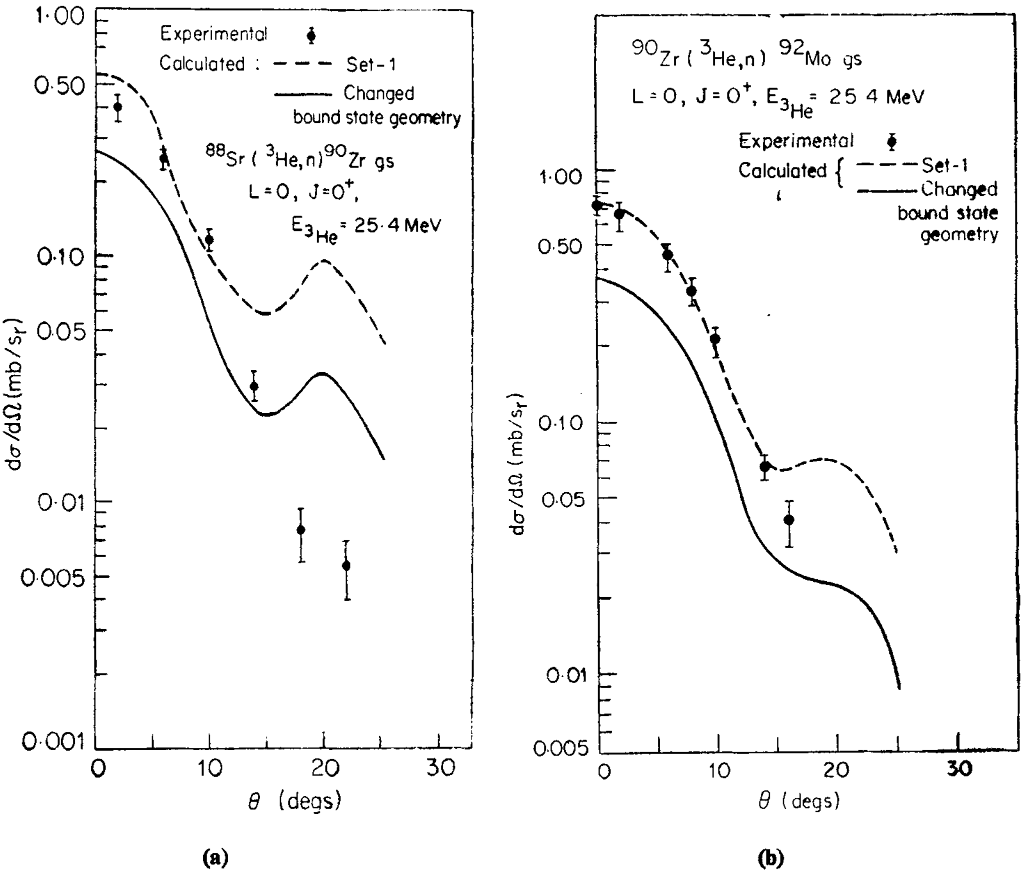
Table 3. Ratios of the experimental to calculated summed cross-sections (10°—55°) of $^{88}\mathrm{Sr}(t,p)^{90}\mathrm{Sr}_{J\pi}$ reaction.

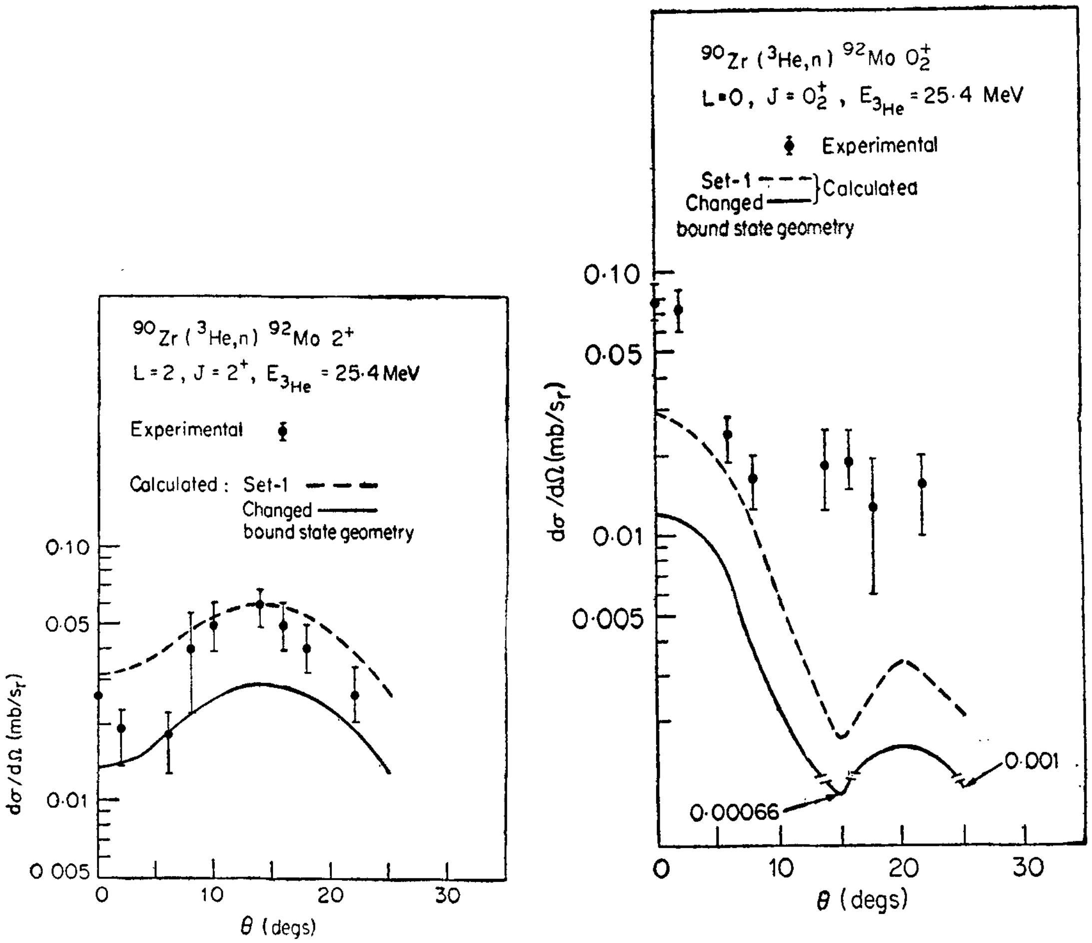
$J\pi$	Summed ($\sigma_{\mathrm{expt.}}$*/$\sigma_{\mathrm{calculated}}$)
0+ (gs)	0·72 (0·88)
2+	0·85 (1·09)
4+	1·37 (1·67)

*obtained from angular distribution curves of Flynn *et al* (1976) total cross-sections of ^{88}Sr(t, p) ^{90}Sr$_{J^\pi}$ were not available. The summed cross-sections were calculated by using the angular distribution curves of Flynn *et al* (1976). These experimental results are given in table 3 as the ratio of the experimental to the theoretical summed cross-sections.

3.2 *Two proton transfer reactions*

For the analysis of two proton transfer (^{88}Sr(^{3}He, n) ^{90}Zr$_{gs}$, ^{90}Zr(^{3}He, n) ^{92}Mo$_{J^\pi}$, $J^\pi=0^+$ (gs), 2^+, $0_2{}^+$) reactions, the SM wave functions for ^{90}Zr and ^{92}Mo with ^{88}Sr inert core are used to calculate the partial spectroscopic amplitudes through equation (1). For the case of ^{90}Zr(^{3}He, n) ^{92}Mo$_{J^\pi}$ the calculation of $S_J(j_a j_b)$ requires the decomposition of the ^{92}Mo wave functions in terms of two protons coupled to two proton components involving two particle fractional parentage coefficients (expansion coefficients). This is simple because the states of ^{92}Mo considered here happened to be pure seniority (zero for $J=0^+$ and two for $J=2^+$) states. The angular distributions and total cross-sections are calculated using these $S_J(j_a j_b)$ and the optical model parameters of table 1. The optical model parameters used are derived from a single energy-dependent set for n from Becchetti and Greenless (1969) and for ^{3}He from Becchetti *et al* (1972) in which ($l.s$) term for n is omitted. It is found that the theoretical results reproduce the systematics of the energy dependence of $\sigma(\theta)$. The results of two-proton transfer





(c) (d)

Figure 4. The calculated angular distributions for a. ^{88}Sr (^{3}He,n)^{90} Zr gs. b. ^{90}Zr(^{3}He,n)^{92}Mo gs. c. ^{90}Zr (^{3}He, n)^{92} Mo$_{2^+}$ and d. ^{90}Zr (^{3}He, n)^{92} Mo$_{0_2^+}$ reactions. The experimental points are of Fielding *et al* (1976).

reaction are sensitive to the optical model parameters. The results obtained by using the equivalent local parameters (Wilmore and Hodgson 1964) for neutrons are consistently unsatisfactory and do not even reproduce the shape of the angular distributions, and will not be discussed further. To investigate the sensitivity of the results on the bound state geometry, we have repeated the calculations with the set 1 optical model parameters for neutrons and ^{3}He having the same bound state geometry (r=1·25, a=0·65) as for protons and tritons used in the two-neutron transfer analysis. The results ($\sigma(\theta)$, σ) obtained with this changed geometry are consistently smaller roughly by a factor of two, although the shape and the positions of maxima and minima of the angular distribution curves and the systematics of the total cross-sections are very similar to the results of set 1.

The calculated angular distributions multiplied by a single normalisation factor are shown in figures 4a–4d, for ^{88}Sr(^{3}He, n) ^{90}Zr$_{gs}$ and ^{90}Zr(^{3}He, n) ^{92}Mo ($0^+_{(gs)}$, 2^+, $0_2{}^+$) ($E_{^3He}$=25·4 MeV) reactions, respectively. The normalisation is so chosen that the DWBA angular distribution for ^{90}Zr(^{3}He,n) ^{92}Mo$_{gs}$ reproduces the maximum

Table 4. Enhancement factor ϵ ($\sigma_{\text{exp}}/\sigma_{\text{calc}}$) for ^{88}Sr (^{3}He,*n*) ^{90}Zr gs at 25·4 MeV ^{3}He energy.

Configuration	Theory (Fielding*et al* 1974)	Calculated
$(2p_{1/2})^2$	3·6	3·06 (7·8)
$(1g_{9/2})^2$	7·7	5·56 (11·6)
*$[0{\cdot}82\,(2p_{1/2})^2 - 0{\cdot}58\,(1g_{9/2})^2]$	—	2·00 (4·9)
$[0{\cdot}68\,(2p_{1/2})^2 + 0{\cdot}68\,(1g_{9/2})^2$ $+\,0{\cdot}23\,(2p_{3/2})^2 + 0{\cdot}23\,(1f_{5/2})^2]$	1·4	—

*This choice of phase is consistent with the analysis of *M*4 transition between the first excited state and the ground state of the odd—*A* $N = 50$ nuclei (Gloeckner and Serduke 1974).

experimental cross-section at 0°. This normalisation factor comes out to be almost unity in all the cases. Therefore, the calculated results without any normalisation are presented. The experimental points, also shown in the figures, are of Fielding *et al* (1976). Figures 4a–d show that for $L=0$, $J=0^+$ transfers, the agreement at small angles is good except for the excited (2·40 MeV) 0^+ state of ^{92}Mo where the calculated values roughly differ by a factor of two. Another consistent feature of $L=0$, $J=0^+$ transfer is that the calculated angular distributions predict a second maxima around 20°. The same remarks also hold for the calculated results with the changed bound state geometry. The overall agreement for the 2^+ state of ^{92}Mo is satisfactory.

Unfortunately, the experimental values of the total cross-sections were not available. We calculated the summed (2°–22°) cross-section from the experimental angular distribution curve of ^{88}Sr (^{3}He, *n*) ^{90}Zr$_{\text{gs}}$, reported by Fielding *et al* (1976). We also calculated in the zero range DWBA the summed (0°–25°) cross-section with the pure and the mixed configurations of the transferred protons. The results are given in table 4. The results of a similar analysis by Fielding *et al* (1976) with the best set of optical model parameters are also included in the table. Our optical model parameters are slightly different from the parameters of Fielding *et al* (1976) and are taken from the work of Becchetti and Greenless (1969) and Becchetti *et al* (1972) with no spin orbit term. The table reveals that the quality of the agreement between our calculated and the experimental cross-section for ^{88}Sr (^{3}He, *n*) ^{90}Zr$_{\text{gs}}$ reaction is not unsatisfactory as compared to that obtained by Fielding *et al* (1976), in spite of the fact that we do not include $(2p_{3/2})^2$ and $(1f_{5/2})^2$ extra configurations for the transferred protons. Also, our optical model parameters is not the best set and does not include the spin orbit term. The present analysis reveals that the theoretical results for the two-proton transfer reactions are sensitive to the bound state as well as to the optical model parameters and also to the structure wave functions.

In conclusion, the phenomenological set of shell model wave functions of ^{90}Zr, ^{90}Sr, ^{92}Zr and ^{92}Mo nuclei, are found to be compatible, in the zero range DWBA, with all the two-neutron transfer reaction data whereas the results for the two-proton transfer reactions are sensitive to the set of optical and bound state parameters used.

Acknowledgements

We are thankful to Dr V L Narasimham and Prof. P P Kane for their interest in this work.

References

Ball J B, Auble R L and Roos P G 1971 *Phys. Rev.* **C4** 196
Bayman B F and Hintz N M 1968 *Phys. Rev.* **172** 1113
Bayman B F and Kallio A 1967 *Phys. Rev.* **156** 1121
Becchetti F D and Greenless G W 1969 *Phys. Rev.* **182** 1190
Becchetti F D, Makofske W and Greenless G W 1972 *Nucl. Phys.* **A190** 437
Broglia R, Hansen O and Riedel C 1972 *Adv. Nucl. Phys.* **6** 287
Casten R F, Flynn E R, Hansen O and Mulligan T J 1972 *Nucl. Phys.* **A184** 357
Fielding H W, Anderson R E, Lind D A, Zafiratos C D and Alford W P 1976 *Nucl. Phys.* **A267** 1
Flynn E R, Armstrong D D, Beery J G and Blair A G 1969 *Phys. Rev.* **182** 1113
Flynn E R, Berry J G and Blair A G 1974 *Nucl. Phys.* **A218** 285
Flynn E R, Hansen O, Sherman J D, Stein N and Sunier J W 1976 *Nucl. Phys.* **A264** 253
Gloeckner D H 1975 *Nucl. Phys.* **A253** 301
Gloeckner D H, Macfarlane M H, Lawson R D and Serduke F J D 1972 *Phys. Lett.* **B40** 597
Gloeckner D H and Serduke F J D 1974 *Nucl. Phys.* **A220** 477
Gross R and Frenkel A 1976 *Nucl. Phys.* **A267** 85
Ipson S S, McLean K C, Booth W, Haigh J G B and Glover R N 1975 *Nucl. Phys.* **A253** 189
Perey F G 1963 *Phys. Rev.* **131** 745
Serduke F J D, Lawson R D and Gloeckner D H 1975 *Nucl. Phys.* **A256** 45
Wilmore D and Hodgson P E 1974 *Nucl. Phys.* **A55** 673