

ONE AND TWO-NEUTRON PICK-UP REACTIONS
IN THE f-p SHELL

by

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PREFACE AND ACKNOWLEDGEMENTS

This thesis describes work on (d,t) and (p,t) reactions on Cr, Zn and Se nuclei from the (f,p) shell. The work was carried out with the E.N. tandem and the cyclograaff facilities of the Department of Nuclear Physics at the Australian National University and was under the supervision of Dr. Jan Nurzynski.

The experiment on the (d,t) reaction described in Chapter 4 was proposed by the author. The data reduction and analysis were performed by the author with advice in the theoretical aspects by Dr. J. Nurzynski.

The (p,t) reaction on the two Se isotopes described in Chapter 5 was suggested by Dr. Nurzynski. The data reduction and analysis were performed by the author under the supervision of Dr. Dennis Gebbie.

The particle identifier described in Appendix II was built for the first time in the Department of Nuclear Physics at the Australian National University by Dr. Brian England from the University of Birmingham. Another four particle identifiers of the same type were built by the author and were used during the measurements reported in this thesis.

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M. Borsaru, L. Barbopoulos, D.W. Gebbie, C.L. Hollas,
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18 (1973) 1408.

The author also participated in other experiments, the results of which were published in different publications.

No part of this thesis has been submitted for a degree at any other university.

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CHAPTER 1

INTRODUCTION

Detailed information about the structure of ground and excited states of nuclei can be obtained from nuclear reactions induced by monoenergetic charged particle beams.

One-nucleon transfer reactions have proved to be a powerful tool in determining the single particle structure of nuclear levels. Stripping and pick-up reactions leading to the same final nuclear states are complementary reactions. Stripping reactions are used to study particle states while pick-up reactions study hole states. Spectroscopic factors which are directly related to the spreading of the single particle strength over the final nuclear states can be extracted by comparing the experimental angular distributions with calculations employing the distorted waves Born approximation. From the spectroscopic factors filling coefficients can be calculated which yield information on the magnitude of the single particle components in the nuclear wave functions. However no information about the relative phases of the different components can be obtained from direct single-nucleon transfer reactions since the transition strength is given by an incoherent sum of the individual transition intensities from each orbit participating in the reaction.

On the other hand, the cross-section for two-nucleon transfer reactions is given by a coherent sum over all configurations appearing in the nuclear wave functions. Thus a two-nucleon transfer reaction is expected to be sensitive to both the magnitudes and phases of the various components of the wave functions and analysis of such data could in principle be used as a test for the accuracy of the different wave functions. However in practice because of the inadequacies in the DWBA

procedure for two-nucleon transfer reactions this has rarely turned out to be the case.

The two-neutron transfer reactions (p,t) or (t,p) are of particular importance in studying dynamical aspects of pairing correlations. It is well established that pairing correlations acting in the $T = 1$ isospin channel play a fundamental role in the structure of nuclei [Bè 69]. The angular distributions for $L = 0$ transitions in (p,t) reactions display a distinct and characteristic diffraction pattern and are easily identified. These transitions which involve the transfer of a pair of neutrons in an $L = 0$, $S = 0$ and $T = 1$ state, are very suitable for studying neutron pair correlations.

In the present work the (d,t) reaction on ^{54}Cr and $^{67,68}\text{Zn}$ nuclei was studied at 12 MeV deuteron energy and the (p,t) reaction on $^{76,78}\text{Se}$ was carried out at a proton energy of 33 MeV. The nuclei ^{54}Cr , ^{67}Zn , ^{68}Zn , ^{76}Se , ^{78}Se have 2, 9, 10, 14 and 16 valence neutrons respectively outside the $N = 28$ closed neutron shell. These neutrons occupy the shell model orbits shown in Fig. 1.1 above the $N = 28$ closed shell and are expected to be the ones taking part in both the one and two-neutron pick-up reactions.

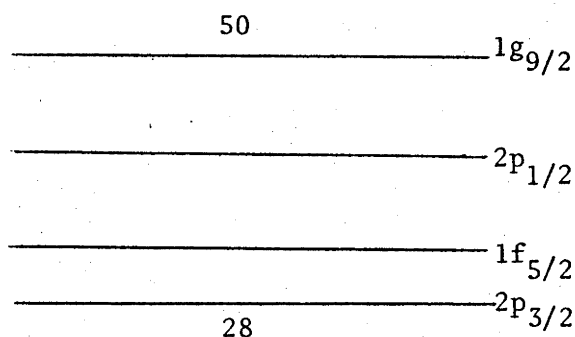


Fig. 1.1. The sub-shells occupied by the valence neutrons for the nuclei studied.

It is now well established that the angular distributions measured in single-neutron transfer reactions on spin zero targets can depend not only on the orbital angular momentum of the transferred neutron but also

on its total angular momentum j . A number of measurements, particularly on f - p shell nuclei, have shown that in (p,d) and (d,p) reactions systematic and consistent differences exist between the angular distributions for the two possible values of j . However for the (d,t) reaction only one detailed examination of any such j -dependence has been made.

Fulmer and Daehnick [Fu 64] have investigated several $\ell = 1$ transitions in ^{55}Fe and $^{59,63}\text{Ni}$ using the (d,t) reaction and observed deep minima at backward angles for $j = 1/2$ similar to those seen in (d,p) reactions. They also observed a slight indication of some forward angle differences for two $\ell = 3$ transitions in ^{59}Ni but in this case the data were not extended beyond about 60° . A difference in the angular distributions for the ground state ($j = 3/2$) and 0.57 MeV ($j = 1/2$) level in ^{53}Cr was reported from the (d,t) measurements of Fitz et al. [Ft 67]. Their distributions are however not typical of either those of Fulmer and Daehnick or of those from (d,p) or (p,d) work. They also report on three $\ell = 3$ transitions for which no differences were seen. No attempt was made in either (d,t) study to fit the observed j -dependence. In $\ell = 3$ transitions no satisfactory fits have yet been obtained from any reaction.

Spectroscopic information on the Zn isotopes has come from many sources. However since no ^{65}Zn target is available single-neutron transfer reactions to ^{66}Zn have been restricted to only one (p,d) reaction [Mc 66], and while final states in ^{67}Zn have been extensively studied in (d,p) work [Li 63, Eh 67] (p,d) measurements [Mc 66] have been made only to about 1 MeV excitation. The only previous (d,t) work on these isotopes was two studies; one of a few low-lying states using the Butler theory [Ze 60] and the second of a few states in three isotopes from a reaction on a natural Zn target.

The present (d,t) measurements were made with the purpose of

providing additional spectroscopic information on $^{66,67}\text{Zn}$ with the (d,t) reaction and at the same time of extending the systematics on (d,t) j-dependence to additional nuclei. In view of the data of Fitz on ^{53}Cr a possible j-dependence in this nucleus was also re-examined. The ^{53}Cr nucleus should a-priori be a good candidate for j-dependence measurements because the well known low-lying states are populated by both $\ell = 1, 3$ transitions and contain spins of both $j = \ell \pm 1/2$.

Also since no previous attempt was made to fit (d,t) j-dependence, it was proposed in the present work to make detailed DWBA calculations following successful attempts that had been made in (p,d) and (d,p) reactions.

There is a lack of information about the nuclear structure of the selenium isotopes both regarding spins and parities and also of energy levels in some of these nuclei. Also very little has been done in the way of calculations in this region because of the lack of available experimental data and difficulties arising from the large number of valence neutrons involved. The (p,t) reaction is very selective and only natural parity states can be excited if the reaction proceeds through a single step process.

The present (p,t) reactions on ^{76}Se and ^{78}Se nuclei were performed in order to obtain more information on the energy levels of ^{74}Se and ^{76}Se . The levels of ^{76}Se have been studied previously with β -decay, inelastic scattering and (HI,x γ) reactions. The only previous transfer reaction measurement was the $^{77}\text{Se}(\text{d,t})^{76}\text{Se}$ reaction of Lin et al. [Li 65b]. Information on the energy levels of ^{74}Se exists only from studies of β -decay and (HI,x γ) reactions. No information exists from inelastic scattering or transfer reactions.

The DWBA theory has been used with mixed success in the analysis of angular distributions from (p,t) reactions. An extensive study by

Baer et al. [Ba 73] on DWBA predictions for the (p,t) reaction on the even-A titanium isotopes found that only $L = 0$ transitions could be reliably assigned. It has also been found [Ya 72, Co 72b] that angular distributions for the (p,t) reaction leading to the first excited 2^+ states of vibrational nuclei display a pattern which cannot be accounted for by DWBA calculations. Yagi et al. [Ya 72] and Udagawa [Ud 74] have shown that coupled-channel-Born-approximation (CCBA) calculations can better reproduce this shape. The selenium isotopes also display characteristics of vibrational nuclei so that another aim of the present study was to test the reliability of DWBA for spin assignments in the (p,t) reaction in this mass region.

Chapter 2 presents the optical model concepts and the DWBA theory. The optical model is presented quite extensively because of its importance in the DWBA calculations. The experimental techniques used in the present work together with the data reduction are discussed in Chapter 3. Chapter 4 presents the results from the (d,t) reaction on ^{54}Cr , $^{67,68}\text{Zn}$ nuclei. The j -dependence observed for $\ell = 3$ transitions in ^{53}Cr and $\ell = 1$ transitions in ^{53}Cr and ^{67}Zn together with the DWBA calculations are thoroughly discussed. The chapter includes a discussion of the spectroscopic factors extracted from the $^{67,68}\text{Zn}(d,t)$ reactions. Filling coefficients and centre of gravity energies extracted from the $^{68}\text{Zn}(d,t)$ reaction are compared with calculations employing the pairing theory developed by Kisslinger and Sorensen [Ki 60]. The results from the (p,t) work are presented in Chapter 5 and the different sets of optical model parameters tried in the analysis of the angular distributions are compared. Enhancement coefficients were extracted by comparing the angular distributions with the DWBA calculations. Conclusions and a summary of both (d,t) and (p,t) work are given in Chapter 6.

CHAPTER 2

THE DWBA THEORY

2.1 OPTICAL MODEL OF ELASTIC SCATTERING

2.1.1. The Compound Nucleus and Direct Contributions in Nuclear Reactions

An exact treatment of nuclear reactions is impossible at present because of the complexity of the problem. As in the case of nuclear structure different models were proposed. The first, the compound nucleus model suggested by Bohr in 1936 [Bo 36], was based on the short range character and the strong nature of nuclear forces. According to this model the incident particle is absorbed by the target nucleus and forms a compound system which forgets the way it was formed. The compound nucleus is in an excited state, the energy of the incident particle being shared among all the other nucleons. The second step of this reaction mechanism will be the decay into the final products. Because of the complexity of the compound process many degrees of freedom are involved and the mean life of the state is long; or in other words the width of the level is narrow. The lifetime of the compound nucleus is of the order of 10^{-16} s.

The compound nucleus mechanism successfully explained the sharp resonances observed when the nucleus is bombarded by either charged or uncharged particles. This model was well established when a new kind of resonance was discovered. These were giant resonances having cross-sections with a broad peak of width of the order of 1 MeV which varied with the energy and the mass number. These were observed with both slow [Fo 50] and fast [Ba 52, Mi 52] neutrons and could not be explained by the compound nucleus model.

It was also known that the elastic scattering cross-sections,

when measured with lower resolution, varied smoothly with energy and mass number. This averaged behaviour of the cross-sections led theoreticians to represent the nucleon-nucleus interaction by a two body potential between the nucleon and the nucleus as a whole, and so the optical model was created. The form of this potential can be determined either theoretically by summing all the nucleon-nucleon interactions or phenomenologically by fitting experimental data with different potentials and choosing the one which gives the best fit. The optical model could account for the giant resonances and has a large range of application in nuclear physics.

Another reaction mechanism is the direct interaction, defined as a process which involves a small number of degrees of freedom. In this type of interaction the incoming particle interacts with only a few target nucleons. The time of interaction in this case is very short, of the order of 10^{-22} s.

For light target nuclei at low energies where the levels are well separated and have narrow partial widths, the number of open channels for the decay of the compound nucleus is small. At higher energies and heavier nuclei the level density and partial widths increase and more channels open up, so that the nucleus will spend less time as a compound system. Consequently it can be argued qualitatively that at low energies the compound nucleus process is more likely to occur, whereas the direct reaction mechanism is dominant at higher energies.

For a particular energy both mechanisms must be considered. When an elastic scattering angular distribution is analysed using the optical model the compound nucleus component must be subtracted before the optical analysis begins [Ho 67]. When the number of open channels is large the compound nucleus cross-section can be calculated by the statistical theory of Hauser and Feshbach [Ha 52] modified by the width fluctuation

correction [La 57, Mo 64]. If the compound nucleus cross-section is negligible an optical model analysis only is satisfactory.

2.1.2 The Optical Potential

The optical potential is written in terms of real and imaginary components. The real part explains the elastic scattering while the imaginary part is introduced in order to account for the non-elastic processes. This potential does not make any differentiation among the inelastic processes and its effect is only to absorb particles from the incident beam. The name optical potential comes from the analogy with the refraction and absorption of light by a medium with a complex refractive index. The real and imaginary parts are expressed as products of potential depths V_0 , W and normalised radial form factors and can be written as

$$U = V_0 f(r) + iWg(r). \quad (2.1)$$

The form factor $f(r)$ has to represent the net effect of nuclear forces. In order to reproduce the saturation and short range nature of nuclear forces $f(r)$ can be assumed to have a constant value inside the nucleus and to fall rapidly to zero with increasing r in the vicinity of the nuclear surface. The Woods-Saxon function [Wo 54] accounts for these features and is usually written as

$$f(r) = \frac{1}{1 + \exp\left(\frac{r-r_0 A^{1/3}}{a}\right)} \quad (2.2)$$

where r_0 and a are the nuclear radius parameter and the surface diffuseness parameter respectively.

It is not easy to find an expression for the form of $g(r)$ from simple considerations. It can however be argued that at low energies the absorption is more likely to occur in the region of the nuclear

surface where the nucleons are less strongly bound. Inside the nucleus, collisions are limited by the exclusion principle and therefore absorption is less probable. At higher energies the absorption in the interior of the nucleus becomes important. These simple considerations suggest that at low energies the absorption is peaked in the region of the nuclear surface and is spread throughout the nucleus at higher energies. The volume absorption is represented by the Woods-Saxon form while the surface absorption is represented either by a Gaussian form or the first radial derivative of the Woods-Saxon function.

2.1.3 Spin Dependent Terms in the Optical Potential

It is well known that the nucleon-nucleon interaction contains spin-orbit and tensor components. It is therefore expected that such components should be included in the optical potential. Satchler [Sa 60] has shown that it is possible to construct one vector and three tensor independent interactions with the vectors $\vec{r}$, $\vec{p}$, $\vec{\ell}$ and $\vec{s}$ which represent the position, the momentum, the orbital angular momentum and the spin of the incident particle respectively. It has been found that components which can be constructed by using in addition the target spin $\vec{I}$ have little effect on elastic scattering and can be neglected. The tensor components are zero for spin 1/2 projectiles but exist for the spin 1 deuteron. While information about the tensor components in the optical potential are obtained from experiments with tensor polarized deuterons, more information is needed about their presence in the optical potential.

The spin-orbit term, or vector interaction component proportional to $\vec{\ell} \cdot \vec{s}$, was first introduced in the optical potential by Fermi [Fe 54] using the analogy with the Thomas term for atoms. The spin-orbit term is of the form

$$V_s(r) = V_s \frac{\hbar^2}{\pi} \left(\frac{1}{r} \right) \cdot \frac{df(r)}{dr} \vec{\ell} \cdot \vec{\sigma} \quad (2.3)$$

where λ_π is the reduced pion Compton wavelength and $\vec{\sigma}$ is the Pauli spin operator. Simple considerations point to the conclusion that the spin-orbit term for nuclear interactions is peaked at the surface of the nucleus. The spin-orbit interaction must be introduced in order to explain nuclear polarization.

2.1.4 The Optical Model for Composite Projectiles - The Deuteron Case

It was found that the optical model as presented above can account for the scattering of composite particles by nuclei. In the case of the deuteron, the neutron and proton are loosely bound and the separation between them is relatively large. However the internal structure has little effect on deuteron elastic scattering which can be well described by a simple optical model [Ho 66].

The deuteron-nucleus potential can be estimated as the sum of the neutron and proton optical potentials at half the deuteron energy [Ho 71]. Since the deuteron is a weakly bound charged particle deuteron break-up is likely to occur. This is equivalent to absorption of particles from the incident beam and the imaginary part of the potential must be larger than that expected from only nucleon scattering considerations. The real part of the deuteron potential is smaller in magnitude and the diffuseness larger than for the nucleon case because of the finite size of the deuteron.

The contribution of deuteron break-up to the deuteron optical potential from deuteron induced reactions has been studied extensively in the last few years. Johnson and Soper [Jo 70] derived a set of coupled equations for the elastic scattering and break-up wave functions and Bencze and Szentpétery obtained an explicit expression for the break-up correction to the deuteron potential [Be 69b].

2.1.5. Method of Analysis.

An optical model analysis of the elastic scattering angular distributions consists of a variation of the optical model parameters until a minimum value is obtained for the quantity

$$\chi^2 = \frac{1}{N} \sum_{i=1, N} \left(\frac{\sigma_e - \sigma_t}{\Delta\sigma_e} \right)^2 \quad (2.4)$$

where σ_t and σ_e are the calculated and experimental cross-sections for a given angle, $\Delta\sigma_e$ is the absolute experimental error and N is the number of experimental points. Polarization and reaction cross-section data can also be analysed together with the elastic scattering.

Angular distributions and polarizations can be calculated by solving the Schrödinger equation numerically using a phenomenological optical potential. The Schrödinger equation is written in the form

$$\left\{ -\frac{\hbar^2}{2\mu} \nabla^2 + U(r) \right\} \psi = E\psi \quad (2.5)$$

where

$$U(r) = V_c(r) + V_o f(r) + iWg(r) + V_s h(r) \vec{l} \cdot \vec{s} . \quad (2.6)$$

In eq.(2.6) V_c is the Coulomb potential due to a uniformly charged sphere and must be included for charged projectiles. The other terms in the optical potential are the real, imaginary and spin-orbit terms respectively. The method of solving eq.(2.5) as well as expressions for cross-sections and polarizations can be found in many papers [Bu 60, Sa 60, Ho 66, Ro 67].

2.2 THE DISTORTED WAVES THEORY

2.2.1. The Direct Interaction in Nuclear Reactions

While the compound nucleus process plays an important part in nuclear reactions induced by low energy particles, its contribution to

our knowledge of nuclear structure has been small. It is through the much simpler direct reaction mechanism that more significant advances have been made. Much of the work done in the direct reaction field has involved the use of the one or multi-nucleon transfer reactions.

The information obtained from one-nucleon transfer work is different from that obtained from multi-nucleon transfer reactions. Different modes of nuclear excitation can be induced by different kinds of nuclear reactions. Collective modes are usually excited by inelastic scattering or certain types of two-nucleon transfer processes, while single particle modes are excited by one-nucleon transfer reactions. The cross-sections for transfer reactions are sensitive to the orbital angular momentum of the transferred nucleons and those for the multi-nucleon case can be sensitive to the relative phases of the wave functions of the transferred particles. Multi-nucleon transfer reactions can also excite states of higher spin than can the one-nucleon transfer reactions.

The first direct reaction theory was the plane wave theory developed by Butler [Bu 51] and applied to (d,p) stripping reactions. In this theory the distortion of the wave functions of the incident deuteron and the outgoing proton by the Coulomb and nuclear fields is neglected. The deuteron and proton wave functions are represented by plane waves of the form $\exp(i \vec{k}_d \cdot \vec{r}_d)$ and $\exp(-i \vec{k}_p \cdot \vec{r}_p)$ respectively. This theory was good enough to predict the first and perhaps the second maximum in the (d,p) angular distributions, but could not fit them accurately and failed completely to predict the absolute cross-sections.

The distorted waves Born approximation (DWBA) replaces the plane waves by waves which are distorted by optical model potentials in both the entrance and exit channels. This theory gives fairly good fits to angular distributions and can predict absolute cross-sections especially for the case of one-nucleon transfer reactions. The theory has been presented by many authors [Au 63, Gl 63, Ba 66b, Sa 66, Fr 69].

2.2.2. The Mathematical Formalism of the Distorted Waves Born Approximation Theory

The discussion of the DWBA formalism will be confined to one and two-nucleon stripping reactions of the type $A(a,b)B$ where the incoming particle a is composed of the transferred particle x plus outgoing particle b as shown in Fig. 2.1.

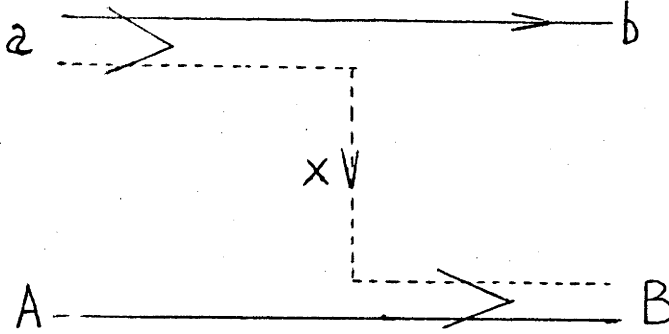


Fig. 2.1. The diagrammatic presentation of the stripping reaction.

The total Hamiltonian for this reaction is

$$H = H_{\alpha} + K_{\alpha} + U_{\alpha} = H_{\beta} + K_{\beta} + U_{\beta} \quad (2.7)$$

where $\alpha(a,A)$ and $\beta(b,B)$ represent the initial and final channels, $H_{\alpha} = H_a + H_A$ and $H_{\beta} = H_b + H_B$ are internal Hamiltonians for the participant channels α and β , K_{α} , K_{β} are the kinetic energy operators in channels α and β and U_{α} , U_{β} are the interaction operators between a and A and b and B respectively. The total wave function ψ for the interacting system satisfies the Schrödinger equation with total Hamiltonian H and total energy E given by

$$H\psi = E\psi \quad (2.8)$$

The initial wave functions $\phi_{\alpha}(\xi_{\alpha}) = \phi_a(\xi_a)\phi_A(\xi_A)$ are solutions of the Schrödinger equation

$$H_{\alpha}\phi_{\alpha} = (E - E_{\alpha})\phi_{\alpha} \quad (2.9)$$

where ξ_α are internal coordinates of the projectile a and target A , $E_\alpha = (\hbar^2/2\mu_a)k_a^2$ is the relative kinetic energy of (a,A) and k_a and μ_a are the channel wave number and the reduced mass in channel α . The expression for the differential cross-section can be derived from the general theory of scattering as

$$\frac{d\sigma}{d\Omega} = \frac{\mu_a \mu_b}{(2\pi\hbar^2)^2} \frac{k_b}{k_a} \sum_{Av} |T_{\alpha\beta}|^2 \quad (2.10)$$

where $\sum_{Av}$ represents a sum over final and an average over initial spin projections and $T_{\alpha\beta}$ is the reaction amplitude which is given by

$$T_{\alpha\beta} = \langle \ell^{i\vec{k}_b \cdot \vec{r}_\beta} \phi_\beta | U_\beta | \psi_\alpha^{(+)} \rangle . \quad (2.11)$$

In this expression $\psi_\alpha^{(+)}$ is the total wave function satisfying eq.(2.8). By separating from the full interaction operator $U_\beta(\xi_\beta, \vec{r}_\beta)$ an average interaction $\bar{U}_\beta(\vec{r}_\beta)$ independent of the internal coordinates such that

$$U_\beta(\xi_\beta, \vec{r}_\beta) = \bar{U}_\beta(\vec{r}_\beta) + u_\beta(\xi_\beta, \vec{r}_\beta) , \quad (2.12)$$

and making use of the Gell-Mann-Goldberger relation [Ge 53] the reaction amplitude becomes

$$\begin{aligned} T_{\alpha\beta} = & \langle \chi_\beta^{(-)} \phi_\beta | \bar{U}_\beta | \phi_\alpha \ell^{i\vec{k}_a \cdot \vec{r}_\alpha} \rangle + \\ & + \langle \chi_\beta^{(-)} \phi_\beta | u_\beta | \psi_\alpha^{(+)} \rangle . \end{aligned} \quad (2.13)$$

Here $\bar{U}_\beta(\vec{r}_\beta)$ is represented by the optical potential discussed earlier and $\chi_\beta^{(+)}$ are waves distorted by the optical potential. The distorted waves are solutions of the equation

$$(K_\beta + \bar{U}_\beta) \chi_\beta^{(+)} = E_\beta \chi_\beta^{(+)} \quad (2.14)$$

with outgoing wave boundary conditions and describe the elastic scattering

of (b,B) by the potential $\bar{U}_\beta$. The time-reversed scattering wave functions $\chi^{(-)}$ are defined as

$$\chi^{(-)}(\vec{k}, \vec{r}) = [\chi^{(+)}(-\vec{k}, \vec{r})]^* . \quad (2.15)$$

The first term in the reaction amplitude shown in eq.(2.13) describes the elastic scattering while the second term describes the reaction $A(a,b)B$ and is denoted by T_{ab} . The differential cross-section is given by eq.(2.10) with T_{ab} substituted for the reaction amplitude. A few approximations must be made in order to calculate the reaction amplitude T_{ab} .

(a) The Distorted Waves Born Approximation

The DWBA approximation assumes that the total wave function $\psi_\alpha^{(+)}$ can be approximated by

$$\psi_\alpha^{(+)} \rightarrow \phi_\alpha(\xi_\alpha) \chi_\alpha^{(+)}(\vec{k}_\alpha, \vec{r}_\alpha) . \quad (2.16)$$

In contrast to the plane waves Born approximation, the DWBA takes into account the distortion of the incident and exit particle waves by the optical potential. After this approximation the reaction amplitude becomes

$$T_{ab} = \langle \chi_\beta^{(-)}(\vec{k}_\beta, \vec{r}_\beta) \phi_\beta(\xi_\beta) | u_\beta(\xi_\beta, \vec{r}_\beta) | \phi_\alpha(\xi_\alpha) \chi_\alpha^{(+)}(\vec{k}_\alpha, \vec{r}_\alpha) \rangle . \quad (2.17)$$

For stripping reactions where $a = b + x$ and $B = A + x$ (see Fig. 2.1) the full interaction in the final state is

$$U_\beta = V_{bx} + V_{bA} \quad (2.18)$$

$$\text{or} \quad u_\beta = U_\beta - \bar{U}_\beta = V_{bx} + (V_{bA} - \bar{U}_{bB}) . \quad (2.19)$$

In eq.(2.19) $\bar{U}_{bB}$ is the optical potential which distorts the waves in the exit channel so that $\bar{U}_{bB} = \bar{U}_\beta$.

(b) The Stripping Approximation

In this approximation the target nucleus A is assumed to be an inert core whose configuration does not change during the transfer process. In other words $V_{bA} \approx \bar{U}_{bA} \approx \bar{U}_{bB}$. If the internal wave functions ϕ_α and ϕ_β are now written explicitly as $\phi_\alpha = \phi_a \phi_A$ and $\phi_\beta = \phi_b \phi_B$, the transition amplitude in eq.(2.17) becomes

$$T_{ab} = J \int d\vec{r}_a \int d\vec{r}_b \chi_b^{(-)*}(\vec{k}_b, \vec{r}_b) \langle \phi_b \phi_B | V_{bx} | \phi_A \phi_a \rangle \chi_a^{(+)}(\vec{k}_a, \vec{r}_a) . \quad (2.20)$$

In eq.(2.20) the structure effects are separated from kinematic effects. Here J is the Jacobian of the transformation from the channel coordinates $\vec{r}_\alpha = \vec{r}_{xA}$, $\vec{r}_\beta = \vec{r}_{bX}$ to the relative coordinates $\vec{r}_a$, $\vec{r}_b$ shown in Fig. 2.2.

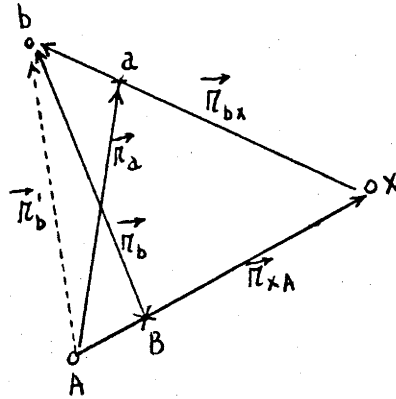


Fig. 2.2. Co-ordinates of the stripping reaction $A(a,b)B$ with $a = b + x$ and $B = A + x$.

2.2.3. One-Nucleon Transfer Reactions

The notations $\vec{r} \equiv \vec{r}_{xA}$ and $\vec{\rho} = \vec{r}_{bX}$ are used for the channel coordinates. In treating stripping reactions the wave function of the final nucleus B can be written as the wave function of the core A plus

that of the transferred nucleon such that

$$\begin{aligned} \phi_B &= \phi_{J_B T_B}^{M_B T_{zB}}(\xi_A, \sigma\tau, \vec{r}) = \sum_{n\ell j} (J_A, n\ell j | J_B) (T_A, 1/2 | T_B) \\ &\times \left[\psi_{n\ell j 1/2}(\sigma\tau, \vec{r}) \phi_{J_A T_A}(\xi_A) \right]_{J_B T_B}^{M_B T_{zB}} \end{aligned} \quad (2.21)$$

where (|) are single particle coefficients of fractional parentage (c.f.p) [Am 63] and the bracket [] means spin and isospin coupling. The captured nucleon wave function is now separated into spin-isospin, orbital and radial parts such that

$$\psi_{n\ell j 1/2}^{m_j t_z}(\sigma\tau, \vec{r}) = U_{n\ell}(r) \left[i^\ell Y_\ell(\hat{r}) \phi_{1/2 1/2}(\sigma\tau) \right]_{j 1/2}^{m_j t_z}. \quad (2.22)$$

If the assumption is made that particle b and the nucleon that form incoming particle a are in an S-state of relative motion, the wave function of particle a can be written as

$$\begin{aligned} \phi_a &\equiv \phi_{j_a t_a}^{m_a t_{za}}(\xi_b, \sigma\tau, \vec{\rho}) = (j_b, 1/2 | j_a) (t_b, 1/2 | t_a) \theta_a(\vec{\rho}) \\ &\times \left[\phi_{j_b t_b}(\xi_b) \cdot \phi_{1/2 1/2}(\sigma\tau) \right]_{j_a t_a}^{m_a t_{za}} \end{aligned} \quad (2.23)$$

where $\theta_a(\rho)$ is the radial wave function of particle a. Now by inserting eqs.(2.21), (2.22) and (2.23) into eq.(2.20), assuming the interaction V_{bx} is a scalar in ρ so that $V_{bx} = V(\rho)$, and integrating over ξ_A , ξ_b and summing over σ and τ , T_{ab} can be written

$$\begin{aligned} T_{ab} &= \sum_{n\ell j} \sum_{m m_s} \langle J_A M_A, j m_j | J_B M_B \rangle \langle \ell m, 1/2 m_s | j m_j \rangle \\ &\langle j_b m_b, 1/2 m_s | j_a m_a \rangle \left(\frac{a}{2} \right)^{1/2} (2\ell+1)^{1/2} C_T S_{n\ell j}^{1/2} B_{n\ell}^m. \end{aligned} \quad (2.24)$$

Here

$$B_{n\ell}^m(\vec{k}_b, \vec{k}_a) = (2\ell+1)^{-1/2} \int d\vec{r} \int d\rho \chi_b^{(-)*}(\vec{k}_b, \vec{r}_b) U_{n\ell}^*(r) [i^\ell Y_\ell^m(\hat{r})]^* \\ \times V(\rho) \theta_a(\rho) \chi_a^{(+)}(\vec{k}_a, \vec{r}_a) , \quad (2.25)$$

$$\text{with } \vec{r}_b = \vec{\rho} + (A/B)\vec{r} , \quad \vec{r}_a = \vec{r} + (b/a)\vec{\rho} , \quad (2.26)$$

$$S_{n\ell j}^{1/2} = (A+1)^{1/2} (J_{A, n\ell j} | J_B) (T_{A, 1/2} | T_B) \quad (2.27)$$

$$\text{and } C_T = \langle T_{A, 1/2} T_{zA} | T_{B, 1/2} T_{zB} \rangle . \quad (2.28)$$

The factor $[a(A+1)]^{1/2}$ in eq.(2.24) arises from antisymmetrization of the target A and projectile a wave functions. The factor $1/\sqrt{2}$ is the product $(j_b, 1/2 | j_a) \cdot (t_b, 1/2 | t_a) \cdot \langle t_b t_{zb}, 1/2 t_z | t_a t_{za} \rangle$ for projectiles of mass number $a \leq 4$.

The reaction cross-section can now be obtained by introducing the expression for T_{ab} given by eq.(2.24) into eq.(2.10). It is found that the differential cross-section is proportional to

$$\sum_{\ell j m} \left| \sum_n S_{n\ell j}^{1/2} B_{n\ell}^m \right|^2 \quad (2.29)$$

i.e. incoherent with respect to the orbital and total angular momentum quantum numbers and coherent with respect to the principal quantum number n of the captured nucleon. Assuming only a single value for n , the differential cross-section becomes

$$\frac{d\sigma}{d\Omega} = \sum_{\ell} S_{\ell} \sigma_{\ell}(\theta) \quad (2.30)$$

$$\text{with } \sigma_{\ell}(\theta) = \frac{\mu_a \mu_b}{(2\pi\hbar^2)^2} \cdot \frac{k_b}{k_a} \cdot \frac{2J_B+1}{2J_A+1} \cdot \frac{a}{4} C_T^2 \sum_m |B_{\ell}^m|^2 \quad (2.31)$$

and

$$S_{\ell} = \sum_j S_{\ell j} \quad (2.32)$$

For a given orbital angular momentum ℓ of the transferred nucleon, the differential cross-section given in eq.(2.30) is proportional to a shape or geometric factor $\sigma_{\ell}(\theta)$ independent of nuclear structure and a factor proportional to the square of the single particle c.f.p. The quantity S_{ℓ} is called the spectroscopic factor and contains all the information about the nuclear structure.

The spectroscopic factor can be extracted by comparing the experimental absolute cross-section $d\sigma/d\Omega$ with the angular distribution $\sigma_{\ell}(\theta)$ calculated by the DWBA in which pure single particle states are assumed. For a spin zero target like ^{54}Cr or ^{68}Zn only one single ℓ transfer must be considered. If the target does not have zero spin as in the case of ^{67}Zn , more than one ℓ could contribute. In this case a good approximation is to consider only one ℓ value since the cross-section usually decreases rapidly as ℓ increases.

The expression (2.27) which expresses the spectroscopic factor can be written also [Gl 63] as

$$S_{\ell}^{1/2}(n\ell j) = (A+1)^{1/2} \int \phi_{J_B}^{M_B^*} \psi_{J_B} d(A+1) \quad (2.33)$$

where $d(A+1)$ means integration over the $A + 1$ nucleons in the final nucleus. In eq.(2.33) ψ_{J_B} is the total wave function for the final nuclear state which can be expanded on a basis consisting of the target plus the stripped nucleon in a single particle state

$$\psi_{J_B} = \sum_{\ell j J_A} \beta_{j\ell} (J_A J_B) \phi_{(J_A j \ell) J_B} \quad (2.34)$$

The function $\phi_{J_B}^{M_B}$ can be constructed as it was shown before by coupling

the stripped nucleon in the state $\psi_{\ell j}$ to the target wave function with angular momentum J_A

$$\phi_{(J_A j \ell) J_B}^{M_B} = \sum (J_A^{M_A} j m_j | J_B^{M_B}) \phi_{J_A}^{M_A} \psi_{\ell j}^{m_j} \quad (2.35)$$

It is clearly seen from eq.(2.33) that the spectroscopic factor is given by an overlap integral which includes passive nucleons which are not involved in the reaction.

For a pick-up reaction $B(b,a)A$ the cross-section is related to the corresponding stripping reaction $A(a,b)B$ by the principle of detailed balance which gives

$$\frac{d\sigma}{d\Omega} \{B(b,a)A\} = \frac{k_a^2}{k_b^2} \frac{2 s_b + 1}{2 s_a + 1} \frac{2 J_A + 1}{2 J_B + 1} \frac{d\sigma}{d\Omega} \{A(a,b)B\} \quad (2.36)$$

2.2.4. Two-Nucleon Transfer Reactions

The cross-section for a two-nucleon pick-up reaction is related to the inverse stripping reaction by eq.(2.36). The cross-section for a two-nucleon stripping reaction is derived in Appendix I and is given by

$$\frac{d\sigma}{d\Omega} = \frac{\mu_a \mu_b}{(2\pi\hbar^2)^2} \frac{k_b}{k_a} \frac{2 J_B + 1}{2 J_A + 1} \sum_{LSJTM} (C_T b_{ST})^2 \left| \sum_N G_{NLSJT} B_{NL}^M \right|^2 \quad (2.37)$$

where all the quantities are defined in Appendix I. It can be seen from eq.(2.37) that the cross-section for a two particle transfer reaction is incoherent with respect to L, S, J, T and M but coherent with respect to the radial quantum number N . Since the centre-of-mass motion of a pair of nucleons is described by more than one radial state it is not possible to write the cross-section of a two-nucleon transfer reaction as a product of a structure factor and a kinematic factor.

2.3 SELECTION RULES IN ONE AND TWO-NUCLEON TRANSFER REACTIONS

2.3.1. Selection Rules for One-Nucleon Transfer Reactions

For a one-nucleon transfer reaction $A(a,b)B$, the conservation of angular momentum and parity can be expressed as

$$\vec{J}_B = \vec{J}_A + \vec{j} \quad \text{and} \quad \Delta\pi = \pi_B \cdot \pi_A = (-)^{\ell} \quad (2.38)$$

where π_A and π_B are the parities of the target and residual nucleus respectively, and all the other quantities were defined earlier. The relation in eq. (2.38) restricts the value of the transferred j value to

$$|J_B - J_A| \leq j \leq J_A + J_B \quad (2.39)$$

For a specific ℓ , the total angular momentum j of the transferred nucleon is given by $j = \ell \pm \frac{1}{2}$. For an even-even target nucleus the spin and parity of the final state is

$$J_B = j \quad \text{and} \quad \pi_B = (-)^{\ell} \quad (2.40)$$

The orbital angular momentum ℓ of the transferred particle can be determined in general from the shape of the angular distributions. The ambiguity in the value of j can be resolved for some ℓ values by experiments with polarized beams, for example (d,p) and (d,t) reactions with polarized deuterons. Another way of assigning j values for states excited in one-nucleon transfer reactions is from the so called j -dependence effect. This effect noticed in (d,p), (p,d), (d,t) and other reactions is a useful tool in nuclear spectroscopy. More about this effect will be discussed in Chapter 4.

2.3.2. Selection Rules in (p,t) Reactions

Some useful selection rules can be found for two-nucleon transfer

reactions, in particular for (p,t) reactions, from the conservation of angular momentum. If j_1, l_1, s_1, t_1 and j_2, l_2, s_2, t_2 are the total angular momenta, orbital angular momenta, spins and isospins of the two transferred nucleons then the total transferred angular momentum, orbital angular momentum, spin and isospin are given by

$$\vec{J} = \vec{j}_1 + \vec{j}_2 = \vec{L} + \vec{S}, \quad \vec{L} = \vec{l}_1 + \vec{l}_2 \quad (2.41)$$

and $\vec{S} = \vec{s}_1 + \vec{s}_2 (= 0 \text{ or } 1), \quad \vec{T} = \vec{t}_1 + \vec{t}_2 (= 0 \text{ or } 1). \quad (2.42)$

The conservation of angular momentum gives the following relation between the angular momenta $\vec{J}_A$ of the target nucleus and $\vec{J}_B$ of the residual nucleus:

$$\vec{J}_B = \vec{J}_A + \vec{L} + \vec{S} = \vec{J}_A + \vec{J} \quad (2.43)$$

where $|J_A - J_B| \leq J \leq J_A + J_B. \quad (2.44)$

If target spin $J_A = 0$ then

$$J_B = L \pm 1 \text{ for } S = 1 \text{ or } J_B = L \text{ for } S = 0. \quad (2.45)$$

The isospin selection rule gives

$$|T_A - T_B| \leq T \leq T_A + T_B \quad (2.46)$$

where T_A, T_B and T are the isospins of the target, residual nuclear states and transferred neutron pair respectively.

The seniority selection rule is

$$\Delta v = 0, \pm 2 \quad (2.47)$$

because only a maximum of two pairs can be broken in a two-nucleon transfer reaction.

The approximate assumption can be made that the wave function of the transferred pair is spatially symmetric. This assumption is based on the fact that the neutrons in the triton spend about 95 per cent of their time in an S state [B1 62]. Since the total wave function of the transferred pair must be antisymmetric, then the product of the spin and isospin wave functions must also be antisymmetric. This implies that

$$S + T = 1 \quad (2.48)$$

where for two-neutron transfer reactions, $T = 1$ and $S = 0$. The conservation of parity is fulfilled if

$$\Delta\pi = \pi_A \cdot \pi_B = (-)^L = (-)^{\ell_1 + \ell_2} \quad (2.49)$$

where π_A and π_B are the parities of the target and residual nucleus respectively. The orbital angular momentum of the transferred pair can be written as a sum of the angular momentum $\vec{\Lambda}$ of the centre-of-mass of the pair and the relative angular momentum $\vec{\lambda}$ such that

$$\vec{L} = \vec{\Lambda} + \vec{\lambda} \quad (2.50)$$

For a spatially symmetric wave function for the pair λ must be even, so that

$$\Delta\pi = (-)^L = (-)^{\Lambda} \quad (2.51)$$

For a (p,t) reaction $S = 0$ and therefore $J = L$. In this case

$$|J_A - J_B| \leq L \leq J_A + J_B \quad (2.52)$$

For an even-even target $J_A = 0$, so that $J_B = L$ and the possible final states must have angular momentum and parity $0^+, 1^-, 2^+, 3^-, 4^+, 5^- \dots$. These are called "natural parity" states and are the only states that can be excited in a (p,t) reaction. The states $0^-, 1^+, 2^-, 3^+, 4^- \dots$ are

called "unnatural parity states" and can not be excited by first order processes in a (p,t) reaction.

These selection rules resulting from the conservation of angular momentum and parity are useful to extract spectroscopic information from (p,t) reaction data. They are useful in conjunction with spin and parity assignments from γ -ray work where very often the spin is not unambiguously assigned.

2.4 SUMMARY OF APPROXIMATIONS USED IN DIRECT REACTION THEORY

A few approximations were made in the DWBA theory in order to be able to write the expression for the reaction cross-section. A few of the main approximations used are now outlined.

- a) Interference from compound nucleus formation is neglected. Compound nucleus effects are only taken into account by the imaginary parts of the optical potentials. It is expected that this approximation will give better results at higher bombarding energies.
- b) In the stripping approximation any core excitation of the nucleus A is neglected. This approximation is most suitable for target nuclei at or near closed shells and less suitable for other nuclei, especially those with high degrees of deformation.
- c) For deuteron induced reactions, the assumption that the neutron and proton are in an S-state of relative motion within the deuteron neglects the D state component in the deuteron wave function. DWBA calculations including the D state in the deuteron wave functions have not shown any significant effect on the differential cross-sections of the (d,p) and (p,d) reactions [Jo 67, De 72].
- d) The interaction V_{bx} was assumed central and spin-independent.
- e) In the earlier versions of the DWBA theory for (d,p) stripping reactions, the product of the neutron-proton interaction $V(\rho)$ and the

deuteron internal wave function $\theta_a(\rho)$ was approximated by a zero-range term. With the more explicit notation in the deuteron case, $V(\rho) = V_{pn}(\vec{r}_{pn})$ and $\theta_a(\rho) = \phi_d(\vec{r}_{pn})$, the zero-range approximation can be written as

$$V_{pn}(\vec{r}_{pn}) \phi_d(\vec{r}_{pn}) = V_o \delta(\vec{r}_{pn}) \quad (2.53)$$

where $\vec{r}_{pn} = \vec{r}_p - \vec{r}_n$ and the potential V_o is given by

$$V_o = \int \phi_d(\vec{r}_{pn}) V_{pn}(\vec{r}_{pn}) d\vec{r}_{pn} \quad (2.54)$$

The zero-range approximation reduces a six-dimensional integral to a three-dimensional one.

An improvement in the zero-range approximation is obtained by considering finite-range effects. One way of doing this is to express the product $V_{pn}\phi$ as a finite-range Gaussian interaction of range r_G given by

$$V_{pn}(\vec{r}_{pn}) \phi(\vec{r}_{pn}) = V_G \exp\left(-\frac{|\vec{r}_{pn}|^2}{r_G^2}\right) \quad (2.55)$$

where V_G is given by an inversion similar to eq.(2.54). If the Gaussian function is replaced by $\frac{\beta^2}{4\pi} \frac{e^{-\beta r}}{r}$ and if ϕ is assumed to have the Hulthén form

$$\phi_d(r_{pn}) = \left[\frac{\alpha\beta(\alpha+\beta)}{2\pi(\alpha-\beta)^2} \right]^{1/2} \left(e^{-\alpha r_{pn}} - e^{-\beta r_{pn}} \right) / r_{pn} \quad (2.56)$$

then

$$V_G^2 = \frac{8\pi B_d^2}{\alpha^3} \left(\frac{\alpha+\beta}{\beta} \right)^3 \quad (2.57)$$

For $\beta \approx 7\alpha$, $V_G^2 = 1.56 \cdot 10^4 \text{ MeV}^2 \cdot \text{fm}^3$. Austern et al. [Au 64] have shown that by using these finite-range corrections the cross-sections have similar shape to those given by zero-range calculations but the magnitudes differ by about 20 per cent.

For a (t,d) reaction, the zero-range approximation is given by

$$V(\vec{Y}) = V_0 \delta(\vec{r}_n - \vec{r}_d) \quad (2.58)$$

where the effective interaction in this case is that between the outgoing deuteron and the transferred neutron.

f) For deuteron induced reactions the probability of deuteron break-up was neglected.

g) Non-locality effects should be included in a realistic interaction. It was found that the nucleon-nucleus potential is non-local when it is calculated from the nucleon-nucleon potential using the techniques of the many body theory. This means that the term $V(\vec{r}) \psi(\vec{r})$ in the optical model equation must be replaced by

$$\int V(\vec{r}, \vec{r}') \psi(\vec{r}') d\vec{r}' \quad (2.59)$$

where $V(\vec{r}, \vec{r}')$ is the non-local potential and the integration takes place over all space. The potential $V(\vec{r}, \vec{r}')$ is symmetric in $\vec{r}$ and $\vec{r}'$ and can be represented phenomenologically by

$$V(\vec{r}, \vec{r}') = V\left\{\frac{1}{2}(\vec{r} + \vec{r}')\right\} \frac{1}{\pi^{3/2} \beta^3} \exp\left\{-\left(\frac{\vec{r} - \vec{r}'}{\beta}\right)^2\right\}, \quad (2.60)$$

where β is a measure of the range of the non-locality. The optical model equation for a non-local potential is written as an integro-differential equation of the form

$$\{\nabla^2 + V_L(\vec{r}) - V_C(\vec{r}) + E\} \psi(\vec{r}) + \int V(\vec{r}, \vec{r}') \psi(\vec{r}') d\vec{r}' = 0 \quad (2.61)$$

where $V_L(\vec{r})$ is the local potential and the second term is the non-local correction. It can be shown [Ho 71, pg.150] that eq.(2.59) can be expanded in the form

$$\int V(\vec{r}, \vec{r}') \psi(\vec{r}') d\vec{r}' = V_0(\vec{r}) + V_2(\vec{r}) p^2 + \dots \quad (2.62)$$

where p is the momentum of the incident particle. Neglecting higher order terms, eq.(2.62) shows a simple linear dependence on the energy of the incident particle. The effect of the non-local potential is to decrease the role played by the nuclear interior in favour of the nuclear surface.

CHAPTER 3

EXPERIMENTAL TECHNIQUES AND ABSOLUTE CROSS-SECTION MEASUREMENTS

The (d,t) measurements on ^{54}Cr , $^{67,68}\text{Zn}$ and the (p,t) work on $^{76,78}\text{Se}$ were carried out using the A.N.U. EN tandem accelerator together with the recently installed cyclograaff facility.

3.1 BEAMS

A deuteron beam of 12 MeV energy was obtained from the A.N.U. EN tandem Van de Graaff accelerator. After being bent by a 90° analysing magnet, the beam was deflected 25° by a switching magnet and then focussed with an electromagnetic steering quadrupole lens into a 51 cm diameter scattering chamber. The energy resolution of the deuteron beam was estimated to be ≤ 5 keV from previous observations of very narrow resonances [Op 74]. The intensity of the deuteron beam on the target was varied between 15 nA and 350 nA; the intensity being lowered for measurements at forward angles to minimise counting rate effects such as pile-up from the elastically scattered deuterons.

For the (p,t) measurements, a proton beam of 33 MeV energy was obtained from the A.N.U. cyclograaff facility, by injecting a 26 MeV negatively charged H^- beam from the CNI-30 cyclotron into the EN tandem. The spread in energy of the proton beam was previously estimated to be ≤ 30 keV [Op 74]. The intensity of the proton beam on the target was varied between 5 nA and 60 nA.

For the (d,t) measurements, the beam current was collected in a Faraday cup of 6.3 cm diameter and 21 cm length placed at 106 cm from the target. The Faraday cup was provided with permanent magnets at its entrance to prevent both the escape of electrons out of the cup and also

to prevent electrons knocked out of the target by the beam from entering the cup. The Faraday cup used for the collection of the 33 MeV energy proton beam was 178 cm in length, 7.6 cm in diameter and placed at 189 cm from the target. The beam current from the Faraday cup was integrated by an ORTEC 439 current digitizer.

3.2 SCATTERING CHAMBER

Figure 3.1 shows a general view of the 51 cm scattering chamber used for the present experiments. The deuteron and the proton beams entered the chamber through a collimator consisting of discs with circular apertures of 1.5 mm, 2.3 mm, 1.5 mm and 3.0 mm diameter respectively. The discs were 0.5 mm thick tantalum for the 12 MeV deuteron beam and 6.0 mm thick carbon for the 33 MeV proton beam. The distance between the first aperture (1.5 mm) and the target was 47.5 cm. The beam spot on the target was less than 2 mm in diameter, as shown by the beam marks on the irradiated targets.

Detector solid angles were defined by the use of apertures mounted in multi-purpose "detector blocks". For the (d,t) measurements, circular apertures of 4.5 mm diameter made from 0.6 mm thick brass were used. For the (p,t) measurements three layers of 0.8 mm thick tantalum, each with a 2 mm $\times$ 5 mm rectangular slit, formed the aperture. The detector blocks were secured at a fixed radius on the lower rotating table of the scattering chamber in a machined annular groove. For the $^{54}\text{Cr}(\text{d},\text{t})^{53}\text{Cr}$ measurement the defining aperture was at a radius of 18.10 cm from the target. For the other measurements the radius was 10.48 cm. The maximum angular spread for the apertures and radii described above, calculated using the assumption of a beam spot on target of 2 mm diameter was $\approx \pm 0.8^\circ$ in the case of the $^{54}\text{Cr}(\text{d},\text{t})^{53}\text{Cr}$ reaction, $\approx \pm 1.4^\circ$ for the $^{67,68}\text{Zn}(\text{d},\text{t})^{66,67}\text{Zn}$ reactions and $\approx \pm 0.9^\circ$ for the $^{76,78}\text{Se}(\text{p},\text{t})^{74,76}\text{Se}$ reactions.

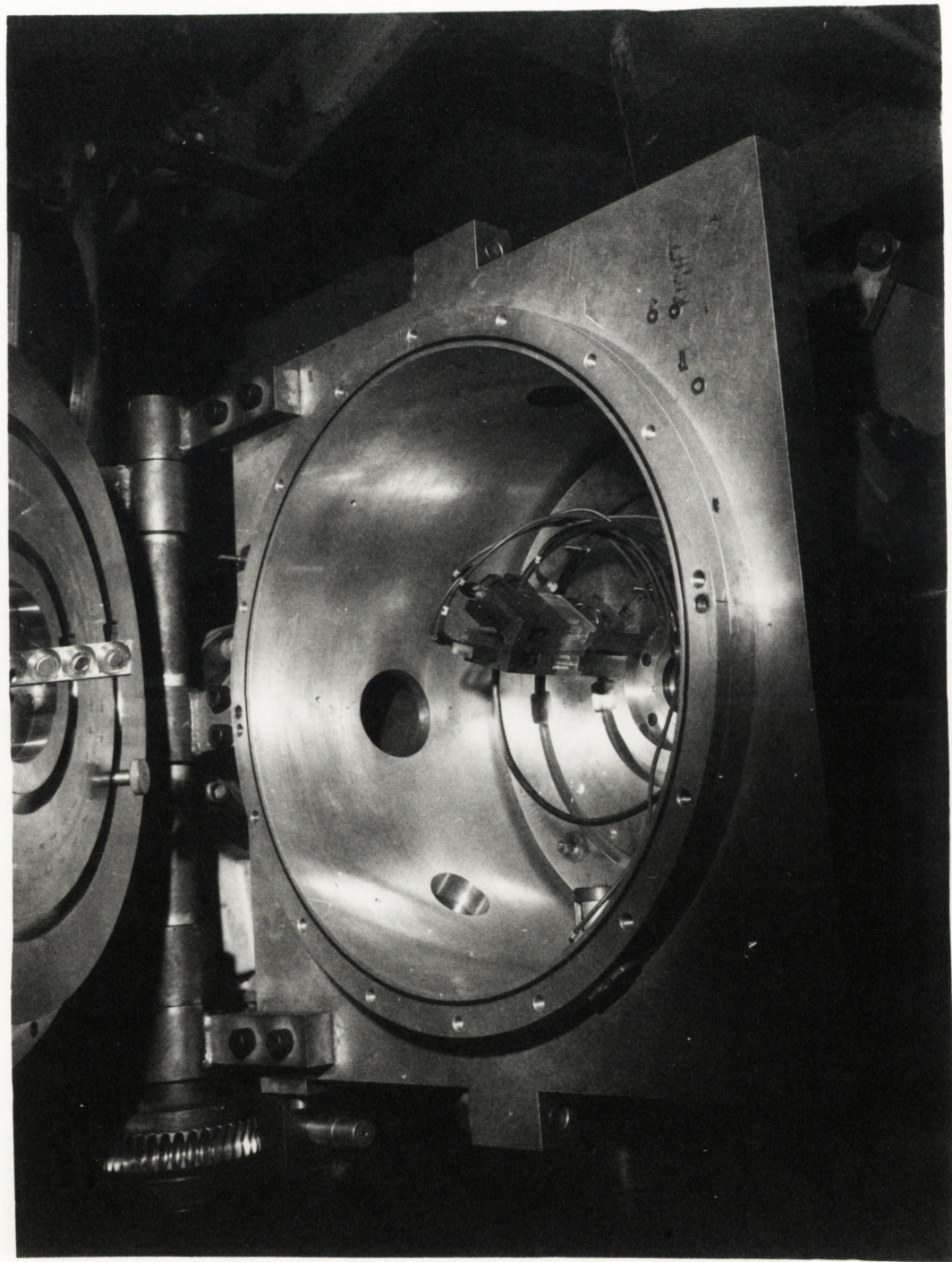


Fig. 3.1. General view of the scattering chamber and detector mounting blocks used in the present experiments.

The detector block also held permanent magnets capable of producing magnetic fields of about 450 oersteds. This magnetic field was strong enough to prevent electrons knocked out of the target by the beam from reaching the detector which was mounted on the detector block behind the defining aperture.

The detector blocks were clamped to a copper coil which was cooled by a freon expansion refrigerator mounted underneath the scattering chamber. With this apparatus the detectors were cooled to -25°C .

3.3 DETECTOR TELESCOPE ASSEMBLIES

The detector telescope assemblies used during the present experiments consisted of pairs of ΔE and E silicon surface barrier detectors manufactured in the laboratory [En 70a]. The particles of interest passed through the ΔE transmission detector and were stopped in the E detector. Care was taken in selecting and using the ΔE detectors. For good mass resolution, the lowest energy particles of interest should not lose more than 80% of their energy in the ΔE detector [En 70b]. The ΔE detectors used for the (d,t) measurements were 100 μm and 40 μm thick and ΔE detectors 500 μm thick were used for the (p,t) measurements. The E detectors were 2 mm thick.

To insure that the ΔE detector was fully depleted a bias voltage at least 10% higher than required for total depletion of the detector was applied. This compensated for any change in voltage across the detector due to leakage current fluctuations with time and temperature.

An 0.5 mm thick brass disc with a hole larger than the defining aperture was placed between the ΔE and the E detector of each telescope. By using silicon vacuum grease a Ra α source was attached each side of the disc illuminating the gold surface of the ΔE and E detector. The α source produced known energy signals of 6.05 MeV and 8.78 MeV

so that the gains of the amplifier systems of the ΔE and E detectors could be accurately matched. Three detector telescopes were used simultaneously for the (d,t) measurements and two in the (p,t) work. Spectra from the (p,d) as well as the (p,t) reactions on selenium were accumulated simultaneously and filled the data acquisition area of the computer. The energy resolution achieved during the measurements was between 45-65 keV for the (d,t) reactions and between 65-80 keV for the (p,t) measurements.

3.4 TARGETS

The targets used were thin foils of thickness varying from 100 $\mu\text{g}/\text{cm}^2$ for chromium and zinc to 400 $\mu\text{g}/\text{cm}^2$ for selenium. The chromium and zinc targets were prepared by heating oxide powders of each of the isotopes studied in clean tantalum boats using an r.f. generator. The oxide is reduced by the tantalum forming the compound Ta_2O_4 and the isotope is left in a metallic form. Then by heating at a higher temperature the metal was evaporated onto either carbon or aluminium thin films of about 30 $\mu\text{g}/\text{cm}^2$ thickness. These had previously been vacuum deposited onto glass slides coated with a suitable releasing agent. The selenium targets were prepared by evaporating selenium metal onto carbon foils as described before. After evaporation the foils were floated off the glass in deionised water and picked up from the surface of the water onto aluminium target frames. Since for the same thickness the aluminium foils are stronger than the carbon, aluminium backing was used instead of carbon for the ^{67}Zn and ^{68}Zn targets. A set of ^{67}Zn targets of about 150 $\mu\text{g}/\text{cm}^2$ thickness, having carbon backings of about 30 $\mu\text{g}/\text{cm}^2$, were very fragile and broke easily. The selenium targets had a carbon layer on each side to prevent the sublimation of selenium on bombardment with 33 MeV protons, an effect known to be very important for low energy

protons. The degradation of selenium targets prepared in this way was checked during the experiments and found to be undetectable for beam currents below 60 nA.

In both the (d,t) and (p,t) reactions, because of the large difference in Q values, the tritons from reactions involving carbon and aluminium were well separated in energy from those from the nuclei of interest. Table 3.1 presents the Q values for the (d,t) and (p,t) reactions on the nuclei involved in the present work [Go 72].

TABLE 3.1

The Q values for the (d,t) and (p,t) reactions on the nuclei involved in the present work.

Nucleus	Q value (MeV) (d,t)	Q value (MeV) (p,t)
^{54}Cr	- 3.463	
^{67}Zn	- 0.796	
^{68}Zn	- 3.942	
^{76}Se		-10.702
^{78}Se		- 9.433
^{12}C	-12.464	-23.364
^{27}Al	- 6.800	-15.944

The isotopic composition of the target materials as given by the supplier[†] is shown in the table 3.2.

[†] Oak Ridge National Laboratory, Tennessee, U.S.A.

TABLE 3.2

The isotopic composition of the target materials

Target	Isotopic Composition (%)					
^{67}Zn	^{64}Zn 6.10	^{66}Zn 13.71	^{67}Zn 58.46	^{68}Zn 21.61	^{70}Zn 0.11	
^{68}Zn	^{64}Zn 0.66	^{66}Zn 0.57	^{67}Zn 0.30	^{68}Zn 98.46		
^{54}Cr	^{50}Cr 0.25	^{52}Cr 6.96	^{53}Cr 2.18	^{54}Cr 90.6		
^{76}Se	^{74}Se < 0.2	^{76}Se 86.1	^{77}Se 2.0	^{78}Se 4.4	^{80}Se 5.9	^{82}Se 1.6
^{78}Se	^{74}Se < 0.1	^{76}Se 0.44	^{77}Se 0.98	^{78}Se 96.02	^{80}Se 2.34	^{82}Se 0.21

3.5 ELECTRONICS

Particle identification techniques were used to separate the tritons from the other particles emerging from the different nuclear reactions occurring when the targets were bombarded by deuterons or protons. Block diagrams of the electronics used for the (d,t) and (p,t) experiments are presented in Figs. 3.2, 3.3 respectively. More details about the techniques used and the functions of the particle identifier employed in these electronic schemes are given in Appendix II.

For the (d,t) measurements, the output pulses from the ΔE and E detectors were amplified by charge sensitive preamplifiers and then fed into linear amplifiers where RC shaping was used with integration and differentiation time constants of 0.5 μs . The unipolar pulses from both linear amplifiers were then summed in a summing amplifier and the total energy pulse $E_{tot} = E + \Delta E$, as well as the ΔE unipolar pulse were fed into the particle identifier set on the F_1 function. The ΔE and E symbols are used to denote pulses coming from the ΔE and E detectors respectively.

The output pulses from the particle identifier, representing the mass spectrum, were fed into a timing single channel analyser (TSCA). The threshold levels of the TSCA were set so that only the triton pulses were allowed to pass through to a linear gate and slow coincidence unit. The unipolar total energy pulse was fed into the linear gate after being delayed such that the gate opened only for total energy pulses corresponding to the tritons.

The unipolar output pulses from the linear gates for all three telescopes were fed into a mixer and routing box. The mixed unipolar pulses were then fed into an analogue to digital converter which is interfaced to the IBM 1800 computer. The total energy pulses were then separated according to their associated routing signals and stored in

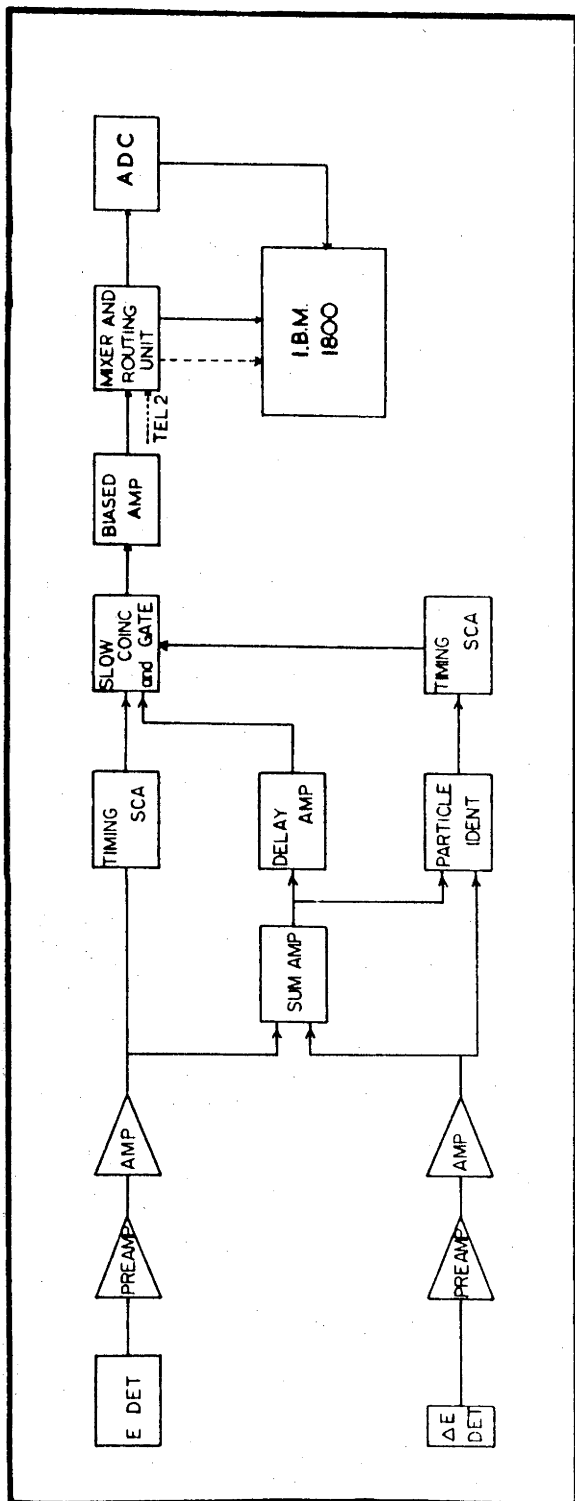


Fig. 3.2. The electronic scheme used for the (d,t) experiment.

PREAMP-----Preamplifier, ORTEC 109A.
 AMP-----Linear Amplifier, ORTEC 410.
 TIMING SCA-----Timing Single Channel Analyser, ORTEC 420.
 PARTICLE IDENT-----Particle Identifier, ANU.
 SUM AMP-----Summing Amplifier, ANU.
 DELAY AMP-----Delay Amplifier, ORTEC 427.
 SLOW COINC and GATE-----Linear Gate and Slow Coincidence, ORTEC 409.
 BIASED AMP-----Biased Amplifier, ORTEC 408.
 ADC-----Analogue to Digital Converter, Nuclear Data Inc.

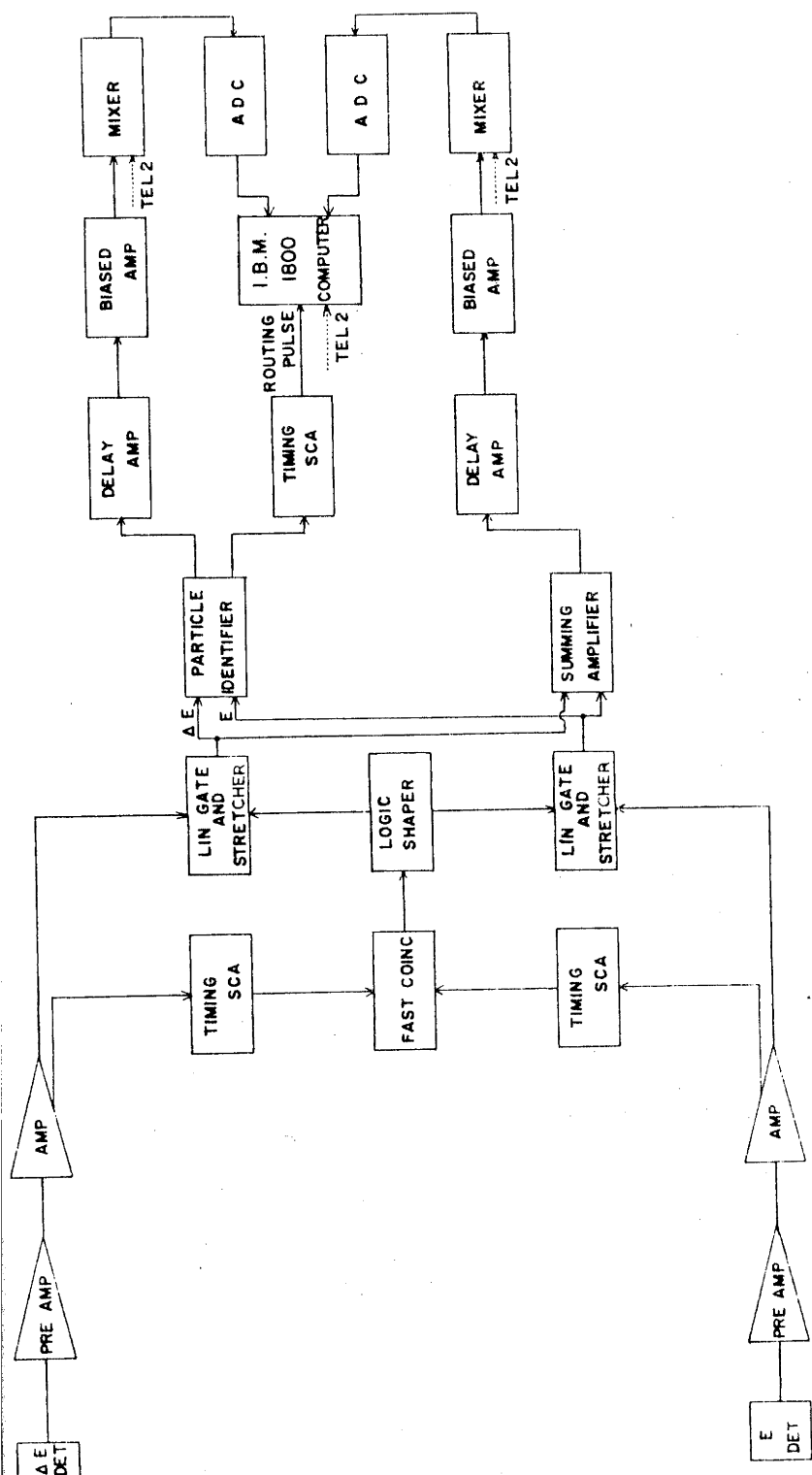


Fig. 3.3. The electronic scheme used for the (p,t) experiment.

PREAMP-----Preamplifier, ORTEC 125.
 AMP-----Amplifier, TENNELEC TC203.
 TIMING SCA-----Timing Single Channel Analyser, CANBERRA 1437.
 LIN GATE AND STRETCHER-----Linear Gate and Stretcher, CANBERRA 1454.
 LOGIC SHAPER-----Logic Shaper and Delay, CANBERRA 1455A.
 DELAY AMP-----Delay Amplifier, CANBERRA 1457.
 SUMMING AMPLIFIER-----Summing Amplifier, ANU.
 PARTICLE IDENTIFIER-----Particle Identifier, ANU.
 BIASED AMP-----Biased Amplifier, ORTEC 408A.
 TIMING SCA-----Timing Single Channel Analyser, CANBERRA 1437.
 FAST COINC-----Fast Coincidence, ORTEC 414.
 ADC-----Analogue to Digital Converter, Nuclear Data Inc.

different memory location in the computer.

For the (p,t) measurements the electronic scheme was modified as shown in Fig. 3.3 to enable simultaneous collection of deuteron and triton spectra and to accommodate the larger dynamic range of particles passing through the detectors. The bipolar pulses from the amplifiers corresponding to the ΔE and E detectors were fed into two single channel analysers. By setting proper threshold levels on the TSCA the lower energy part of the deuteron and triton spectra presented to the particle identifier was cut off. The elastic and most of the inelastically scattered protons were not stopped in the E detectors which were too thin for the proton energy used during the experiments. Most of the proton pulses recorded were removed by the same windows set on the single channel analysers. This helped to greatly decrease the count rate in the particle identifier. By thus reducing the dynamic range of the particles of interest and eliminating the pulses corresponding to the unwanted protons, the resolution of the mass spectrum produced by the particle identifier is greatly improved [En 71].

Another modification introduced in the electronic scheme used in the (p,t) experiment was the replacement of the slow coincidence unit with a fast unit. The fast leading edge coincidence unit reduced the coincidence resolving time from a few μs to the order of 35 ns. This helped to reduce the background at the most forward angles and much improved the mass spectrum. The F_3 function of the particle identifier is more suitable for this energy range [En 71] and for this function ΔE and E pulses are required as inputs. Typical mass spectra for (d,t) and (p,t) are presented in Figs. 3.4 and 3.5 respectively. The deuteron spectra resulting from the (p,d) reaction were recorded simultaneously with the tritons by setting windows on the deuteron and triton peaks in the mass spectrum. Coincidences were required between each window and the mixed total energy spectra. The setting of the mass windows, the

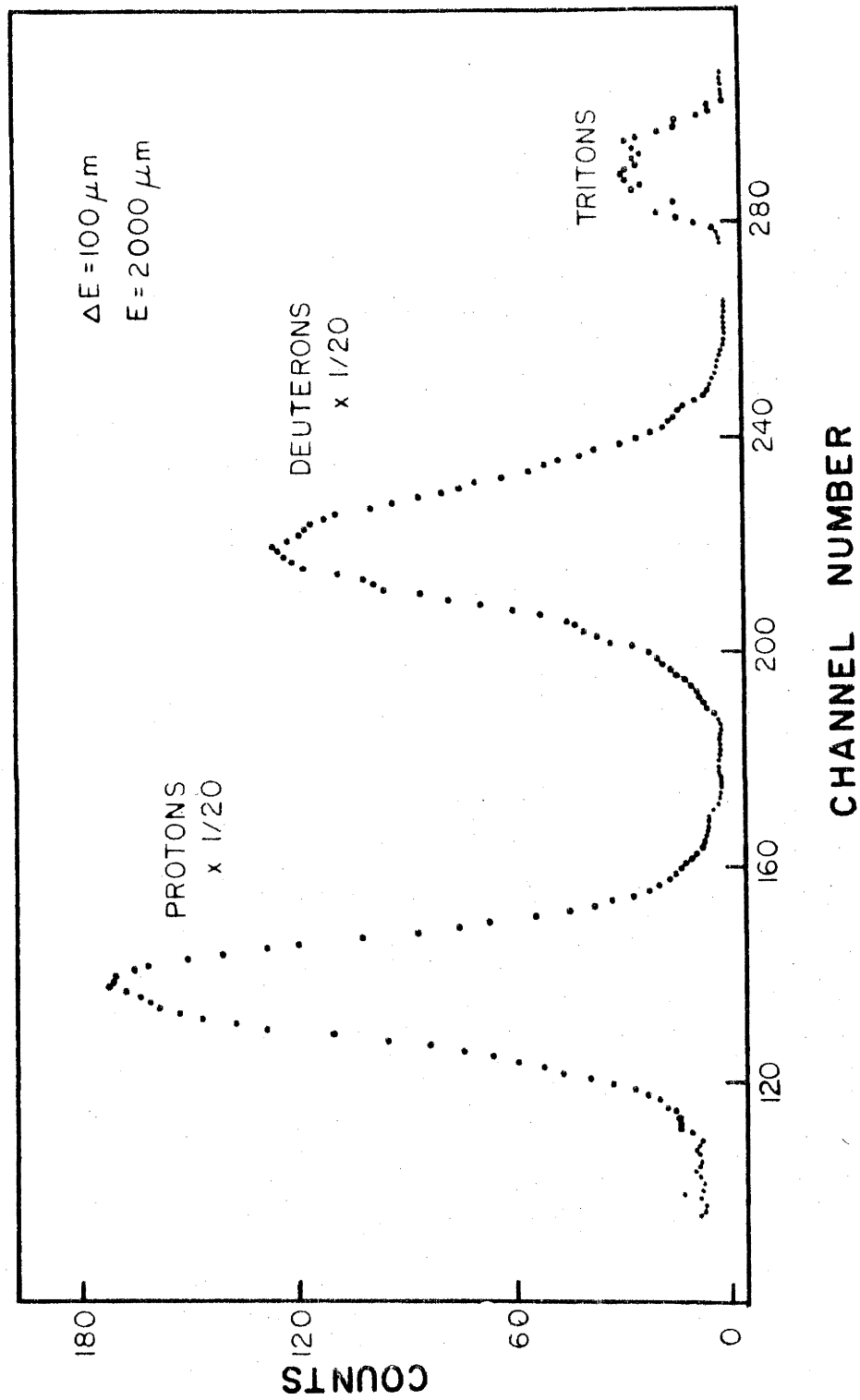


Fig. 3.4. Typical mass spectrum from the $^{54}\text{Cr}(d,t)^{53}\text{Cr}$ reaction.

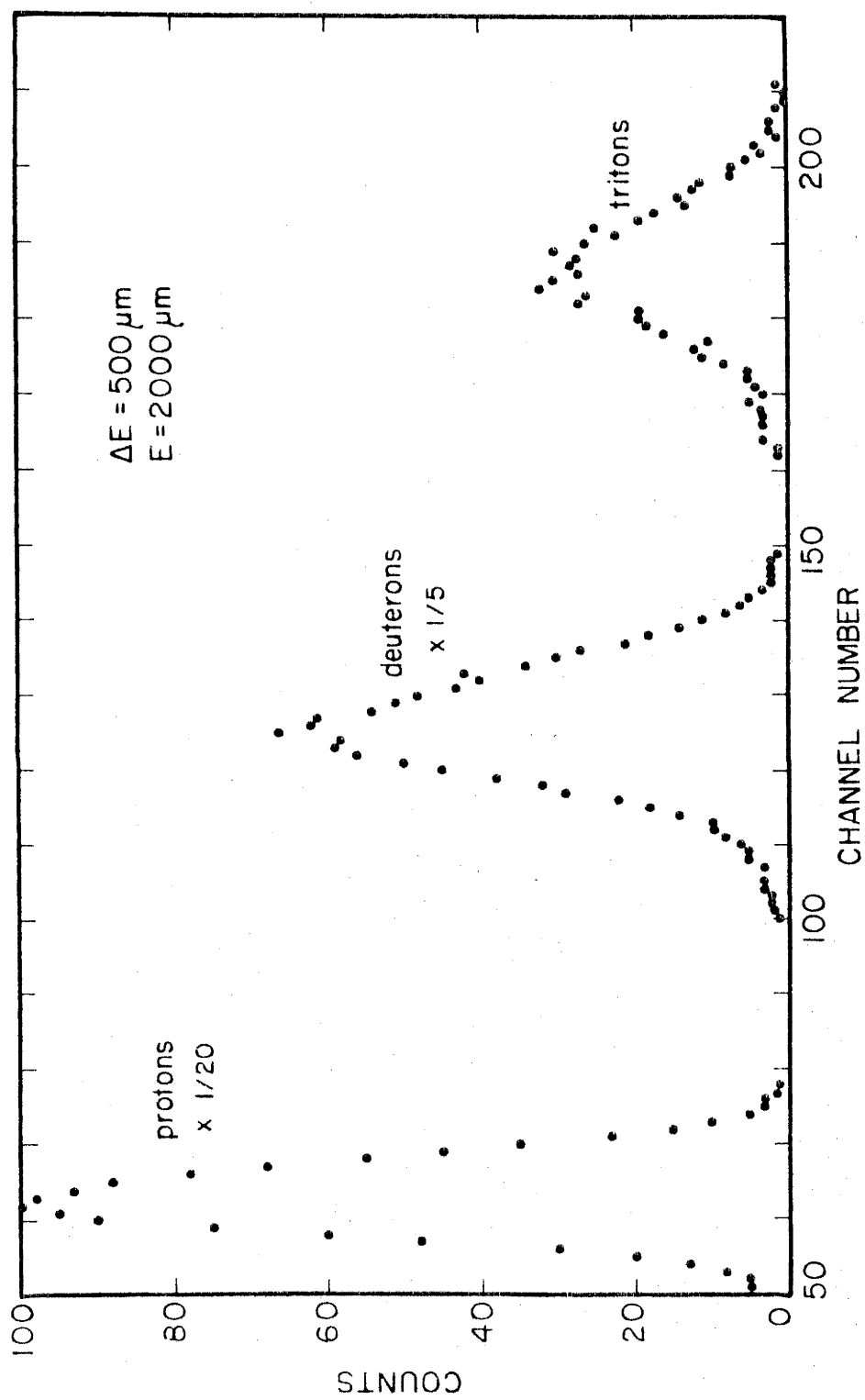


Fig. 3.5. Typical mass spectrum from the $^{78}\text{Se}(d,t)^{76}\text{Se}$ reaction.

establishment of the appropriate coincidence conditions and the subsequent routing of the deuteron and triton energy spectra for the two telescopes into different computer areas were all achieved by digital means. This was done by the data acquisition program Routed Window in the IBM 1800 computer.

The data were stored in the data acquisition area of the IBM 1800 computer and dumped into the computer buffer after each run. When the buffer was full or the measurement was finished the spectra were transferred to a demountable disc pack for storage.

3.6 NORMALISATION AND MONITOR COUNTS

The spectra were normalised by using both the integrated charge and the monitor counts. The monitor detector, placed at 90° with respect to the beam, served to check against any target deterioration, target nonuniformity and any variations in the beam current integration. The monitor was especially necessary when the selenium targets were bombarded with protons. No corrections for target deterioration were found to be necessary for the beam current below at least 60 nA; the intensity was not increased above this limit during the experiments. The measured cross-sections were consistent using both normalisations.

Since more than one detector telescope was used, relative solid angles were determined by measuring cross-sections at the same angle with all telescopes.

3.7 ABSOLUTE CROSS-SECTIONS

The number of particles $N(\theta, E)$ emitted in a nuclear reaction at an angle θ is given by

$$N(E, \theta) = A(\theta) \cdot t \cdot I \cdot \sigma(E, \theta) \quad (3.1)$$

where t is the target thickness, E is the energy of the incident particles

and $I = \frac{Q}{e}$ is the number of particles passing through the target. Here Q is the total charge collected in the Faraday cup and e is the unit charge of the deuteron or proton. The quantity $A(\theta)$ is a constant including the solid angle, Avogadro's number and the density of the target. $\sigma(E, \theta)$ is the differential cross-section for the reaction. The quantities $N(\theta, E)$ and Q are measured in the experiment. For absolute cross-section measurements the product $A(\theta)t$ must also be known.

The forward angle scattering of 4.5 MeV deuterons or protons on the target nuclei used in the present experiments was assumed to be described by the Rutherford scattering cross-section $\sigma_R(E_R, \theta')$. This is given in the centre-of-mass by

$$\sigma_R(E, \theta)_{\text{C.M.}} = 1.296 \left(\frac{Z_1 Z_2}{E} \right)^2 \left(\frac{M_1 + M_2}{M_2} \right)^2 \frac{1}{\sin^4(\frac{1}{2}\theta)} \text{mb/sr} \quad (3.2)$$

where Z_1 , Z_2 , M_1 and M_2 are the charge and mass of the incident particle and target nucleus respectively.

In terms of the experimentally measured quantities the Rutherford cross-section can be written as

$$\sigma_R(E_R, \theta') = \frac{N(E_R, \theta')}{A'(\theta')t'I} \quad (3.3)$$

Comparing eqs. (3.1) and (3.3) the ratio of the cross-sections can be written as

$$\frac{\sigma(E, \theta)}{\sigma_R(E_R, \theta')} = \frac{N(E, \theta)}{N_R(E_R, \theta')} \frac{A'(\theta')t'Q'}{A(\theta)tQ} \quad (3.4)$$

If the number of counts $N(E, \theta)$ and $N_R(E_R, \theta')$ are measured for the same angle θ and with the same target and detector geometry eq. (3.4) becomes

$$\frac{\sigma(E, \theta)}{\sigma_R(E_R, \theta)} = \frac{N(E, \theta)}{N_R(E_R, \theta)} \frac{Q'}{Q} \quad (3.5)$$

In the present experiment the absolute cross-sections for the (d,t) and (p,t) reactions were determined from eq.(3.5). The number of tritons emitted at 25°, 30°, 35° and 40° from either (d,t) or (p,t) reaction was first measured for an integrated beam charge of 200 μc . Then keeping the target in the same position, the beam energy was lowered to 4.5 MeV for both deuterons and protons and the number of elastically scattered deuterons or protons were measured for the same angles using the same geometry.

Relative cross-sections were obtained by dividing the number of tritons for each state by the integrated charge or monitor counts. By dividing the relative cross-section $\frac{N(E,\theta)}{Q}$ by the absolute cross-section as determined above, a normalisation constant was extracted which was used to convert all relative cross-sections to absolute cross-sections.

To check the validity of the assumption that the low energy elastic scattering is composed of pure Rutherford scattering, the product $(A \cdot t)$ from eq.(3.1) was measured at many angles and found to be consistent.

3.8 CORRECTIONS FOR ISOTOPIC IMPURITIES

In the case of the $^{67}\text{Zn}(d,t)^{66}\text{Zn}$ reaction some of the triton peaks were obscured by impurities coming from the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ and $^{66}\text{Zn}(d,t)^{65}\text{Zn}$ reactions. Using the isotopic composition of the ^{67}Zn target (Table 3.2) and the absolute cross-sections for the states measured in the $^{68}\text{Zn}(d,t)$ reaction, corrections were made at each angle for each state in ^{66}Zn affected by these impurities. Similar corrections for the states at 4.00 and 4.10 MeV in ^{66}Zn , affected by tritons from the $^{66}\text{Zn}(d,t)^{65}\text{Zn}$ reaction, could not be made since no absolute cross-section data were available for the $^{66}\text{Zn}(d,t)$ reaction.

Corrections to $\sigma_{\text{Rutherford}}$ from isotopic impurities were also

made and then taken into account in the absolute cross-sections.

3.9 PEAK INTEGRATION

Two different programs were used to unfold the experimental spectra. The data from the (d,t) reactions were analysed with the program SKEWED which assumes a Gaussian distribution for the peak shape corresponding to monoenergetic particles. After fitting a Gaussian to each of the peaks the program then fits the following function to the entire spectrum using the least squares method [Mc 62].

$$y = \text{background} + \sum_{i=1}^N A_i \left[(2\pi)^{1/2} S_i \right]^{-1} \times \exp \left\{ -\frac{1}{2} \left[(x - \bar{x}_i) S_i^{-1} \right]^2 \right\} \quad (3.6)$$

The second term sums the i Gaussian peaks in the spectrum where A_i is the area of the i -th peak, S_i is the standard deviation (half-width at half-maximum) of the i -th peak, $\bar{x}_i$ is the mean value of the i -th peak position and N is the number of peaks.

Different types of backgrounds can be chosen; linear, exponential, Gaussian or parabolic. In the present analysis a linear background was used. The program was used to fit each peak using the same S for all peaks so that

$$y = \text{background} + \sum_{i=1}^N A_i \left[(2\pi)^{1/2} S \right]^{-1} \times \exp \left\{ -\frac{1}{2} \left[(x - \bar{x}_i) S^{-1} \right]^2 \right\} \quad (3.7)$$

Nine peaks could be fitted simultaneously by the program as long as the separation between them is adequate. When the separation was poor the program could not fit more than two or three peaks simultaneously.

To check the accuracy of the assumption of a Gaussian distribution for the peak shape, a few well separated peaks were integrated by hand and their areas compared with the areas given by the program SKEWED. The

agreement was in the limit of the statistical error.

Another program AUTOFIT [Sp 65] later became available and was used to unfold the (p,t) spectra. AUTOFIT is a spectrum decomposition program specifically designed for the analysis of spectra obtained from charged particle reactions. The program has facilities for removing backgrounds, obtaining peak areas by setting the shape of an experimental reference peak and obtaining the locations of the peaks. A fixed peak shape is used for all peaks and a maximum of 200 peaks can be fitted simultaneously. The advantage of AUTOFIT is that it does not require a complicated analytic function to describe the peak shape but uses the shape of a well separated peak from the actual spectrum to be analysed. In the present (p,t) analysis, either the peak corresponding to the 0^+ ground state or the peak corresponding to the 2^+ first excited state were used as reference peaks. The advantage of using the actual experimental peak shape in AUTOFIT is even greater when the Gaussian distribution no longer gives an adequate description of the peak shape. This often occurs after the detectors have suffered radiation damage, and recombination effects produce a tail towards the low energy side of the peaks.

Both SKEWED and AUTOFIT produced graphical and tabulated displays of the original data together with the calculated results and errors. The programs were available on the UNIVAC 1108 computer of the Australian National University. On average, 1.5 minutes were necessary to unfold 20 peaks.

3.10 ENERGY CALIBRATIONS

The well known low lying energy levels of ^{66}Zn and ^{67}Zn were used as energy calibration points in the zinc data. The energies of the previously reported levels were adopted from Nuclear Data Tables

or other work done with better energy resolution. The energies for two new levels in ^{67}Zn were graphically extracted from the ^{67}Zn calibration line. The error is estimated to be less than 25 keV.

In the case of the $^{76,78}\text{Se}(p,t)^{74,76}\text{Se}$ reactions many new states were found and their excitation energies were extracted using the code AUTOFIT. The Q values for these reactions and well known excitation energies for the low lying levels in $^{74,76}\text{Se}$ nuclei were used as calibration points in the program. Peaks from impurity selenium isotopes were also helpful at some angles. Corrections for target thickness were also taken into consideration. The error in the excitation energies is of the order of 10 keV for the strongly excited states but could be as high as 15-20 keV for the weakly excited states at high excitation.

3.11 ERRORS

The relative cross-section is calculated from the formula

$$\sigma_{\text{rel}} = \frac{T-B}{M} \equiv \frac{N}{M} \quad (3.8)$$

where T is the total number of counts in the peak of interest, B is the number of background counts, N is the net number of counts in the peak and M is the number of counts in the elastic peak in the monitor spectrum. The absolute error for the relative cross-section is given by

$$\Delta\sigma_{\text{rel}} = \frac{1}{M} \sqrt{(\Delta M)^2 + \left(\frac{N}{M}\right)^2 (\Delta N)^2} \quad (3.9)$$

where $\Delta M = \sqrt{M}$ is the statistical error in the monitor counts

and $\Delta N = \sqrt{N+2B}$ is the statistical error in the net number of counts.

When the program SKEWED was used, the error ΔN was calculated from the formula

$$\Delta N = (\Delta N)_{\text{statistical}} \sqrt{1 + \frac{\chi^2}{\nu}} \quad (3.10)$$

where ν is the number of degrees of freedom. Both χ^2 and ν are given as output by the program.

When the program AUTOFIT was used to unfold the spectra the error ΔN was calculated from the formula

$$\Delta N = (\Delta N)_{\text{statistical}} \sqrt{1 + \frac{F_{\text{Best}}}{\nu(n-\nu)}}$$

where ν is the number of peaks considered simultaneously by the program, n is the total number of channels considered and $F_{\text{Best}} = (n-\nu)\chi^2$.

All these quantities are printed out by the program.

The absolute errors consist mainly of three contributions:

1. geometrical errors in setting the scattering angle
2. errors in charge integration
3. errors introduced by the assumption of pure Rutherford scattering at forward angles for deuterons and protons of 4.5 MeV.

The scattering angle could be set to $\pm 0.2^\circ$ and an eccentric scattering geometry arising from a noncentral beam spot, provides a possible further error in the angle. The absolute error in the cross-section introduced by the geometry is estimated to be less than 4%.

The error introduced by the charge integrator is given by the manufacturer as less than 1%.

The upper limit on the error resulting from the assumption of pure Rutherford scattering is estimated to be 6%, which is supported by optical model calculations at this energy. The error bars in the figures represent relative errors from the statistics and the fitting procedure only. An error of less than 10% is estimated in the absolute value of the measured cross-sections.

CHAPTER 4

THE (d,t) REACTION ON ^{54}Cr , ^{67}Zn AND ^{68}Zn

AT 12 MeV DEUTERON ENERGY

4.1. j-DEPENDENCE IN TRANSFER REACTIONS

Transfer reactions are a useful tool in nuclear spectroscopy. The orbital angular momentum of the transferred nucleon can be uniquely determined from the shape of the angular distributions and therefore the parity of the residual state is unambiguously determined. For one-nucleon transfer reactions on spin zero target nuclei the total angular momentum J_R of the residual state is given by

$$J_R = \ell \pm 1/2 .$$

This twofold ambiguity can be resolved in some cases by the use of the j-dependence effect. Here the shape of the angular distribution depends not only on the transferred orbital angular momentum ℓ but also on the total angular momentum j of the transferred nucleon.

The first experimental evidence for j-dependence in angular distributions was reported by Lee and Schiffer for $\ell = 1$ transitions [Le 64] in (d,p) reactions. They investigated the (d,p) reaction on ^{40}Ca , ^{48}Ti , ^{54}Fe , $^{58,60,62}\text{Ni}$ at 10 MeV deuteron energy. All the $1/2^-$ states were found to exhibit a deep minimum in the angular distribution at backward angles, while none of the $3/2^-$ states showed such an effect. This j-dependence for $\ell = 1$ transitions in (d,p) has been used extensively for spin assignments [Sc 66, Ro 70]. To assign spins for 2p transitions Lee and Schiffer proposed an empirical rule in terms of the quantity

$$R = \frac{\bar{\sigma}_{\max} - \sigma_{\min}}{\frac{1}{2}(\bar{\sigma}_{\max} + \sigma_{\min})}$$

where $\sigma_{\min}$ is the differential cross-section at the 135° minimum and $\bar{\sigma}_{\max}$ is the average cross-section for the neighbouring maxima at approximately 25° either side of the minimum. For $R \leq 0.3$, $j = 3/2$ and for $R \geq 0.8$, $j = 1/2$. However, the (d,p) transition to the 1.895 MeV level in ^{51}Cr appears to violate this rule [De 69]. A spin of $j = 3/2$ has been assigned from (n, $\gamma\gamma$) correlation measurements [Ba 66a] while the j-dependence rule predicts [Al 67, Le 67, Ro 68a] either $j = 3/2$ or $j = 1/2$ depending upon the deuteron bombarding energy. This apparent violation of the empirical rule raises the question of just how reliable are spin assignments made using the j-dependence effect.

Later studies on (d,p) reactions have also shown a marked j-dependence for $\ell = 3$ transitions [Al 67, De 68, Br 71].

Scherr, Rost and Rickey [Sh 64] have studied the (p,d) reaction on elements ranging from Ti to Ni at 28 MeV proton energy and found a strong difference in the shape of the forward angle maxima for $j = 5/2^-$ and $j = 7/2^-$ for $\ell = 3$ transitions. They noticed that the peaks for the $5/2^-$ states

a) appear at a smaller angle

and b) the fall-off with increasing angle is steeper.

This type of j-dependence for $\ell = 3$ transitions in (p,d) reactions was also reported by Glashausser and Rickey [Gl 67] and Whitten Jr. [Wh 67].

In the (d,t) reaction, j-dependence has been observed by Fulmer and Daehnick [Fu 64] for $\ell = 1$ transitions at 14.7 MeV deuteron energy. The angular distributions for transitions picking up neutrons from the $2p_{3/2}$ and $2p_{1/2}$ shells are different for angles greater than 70° . The angular distribution corresponding to $j = 1/2^-$ has

- a) a deep minimum at 125°
- and b) a faster decrease in cross-section near 80° .

They also observed a slight indication of some forward angle differences for two $\ell = 3$ transitions in ^{59}Ni but in this case the data were not extended beyond about 60° .

Blair [Bl 65] has reported a j -dependence effect for $\ell = 1$ transitions in the $(^3\text{He}, \alpha)$ reaction on $^{62,64}\text{Ni}$ at 22 MeV ^3He energy. The angular distributions for the $j = 1/2^-$ and $j = 3/2^-$ states begin to differ at approximately 50° and by 90° the $p_{1/2}$ first excited state distribution is out of phase with the $p_{3/2}$ ground state distribution.

In $(^3\text{He}, \alpha)$ reactions, j -dependence has been noticed for $\ell = 1$ transitions in ^{14}N and ^{13}C by Ball and Cerny [Ba 66] and also by Stock et al. [St 67] in the even Cr isotopes. The DWBA theory was applied with some success in the latter case.

An interesting case of j -dependence is seen in (α, p) reactions [Ya 63, Le 65, Bu 72] and in the inverse (p, α) reactions [No 66, Yo 73]. It was found that the angular distributions for $j = \ell + 1/2$ are characterised by a lack of diffraction structure, in contrast to the $j = \ell - 1/2$ case which is characterised by a great deal of oscillation. DWBA calculations assuming a simple triton transfer have fitted this j -dependence [No 66, Bu 72, Yo 73] fairly well.

The j -dependence effect is not completely understood from the theoretical point of view. Standard distorted waves calculations that included spin-orbit terms in the distorted potentials successfully reproduced the j -dependence for $\ell = 1$ transitions in (α, p) and (p, α) reactions [No 66, Bu 72, Yo 73]. These calculations were also applied with some success in (d, p) reactions [Ro 68b, De 69, Se 72, Ro 70].

The simple spin dependent DWBA formalism was unable to reproduce the forward angle j -dependence for $\ell = 3$ transitions in (d, p) and (p, d)

reactions. More sophisticated approaches have been tried but not with much success. Sherr et al. [Sh 64] obtained a qualitative agreement for the forward angle j -dependence by using an effective binding energy for the $j = 5/2$ neutron of 6 MeV less than that used for the $j = 7/2$ neutron. Pinkston and Satchler [Pi 65] have criticised this simple approach on the grounds that the asymptotic form of the wave function obtained is incorrect. Instead they proposed using an increased radius for the $j = 5/2$ neutron while maintaining the correct asymptotic form. It has been shown [Gl 67] that both methods do not give a satisfactory description over a range of energies. At lower energies the effects predicted by both assumptions are almost negligible. In another attempt to describe the forward angle j -dependence, Huby and Hutton [Hu 66] have used neutron wave functions calculated under the assumption of a configuration mixed target state. They explained satisfactorily the forward angle data from the reaction $^{58}\text{Ni}(p,d)^{57}\text{Ni}$. Siemssen et al. [Si 68] measured angular distributions for $\ell = 3$ transitions leading both to single particle and configuration mixed states. The experimental data have shown a more pronounced j -dependence for the configuration mixed states.

A completely different approach for the $\ell = 3$ j -dependence was given by Johnson and Santos [Jo 67] by including in an approximate way the D-state component of the deuteron internal wave function. They were able to reproduce the $\ell = 3$ angular distributions for the reaction $^{56}\text{Fe}(p,d)^{55}\text{Fe}$. The $\ell = 0$ and $\ell = 1$ transitions were not affected. On the other hand, Delic and Robson [De 72] have shown that the inclusion of the D-state in an exact finite range DWBA calculation gives rise to a j -dependence of the cross-section for $\ell = 3$ transitions in the reaction $^{54}\text{Cr}(p,d)^{53}\text{Cr}$ at 17.5 MeV which is much smaller than is observed experimentally, thus indicating an important discrepancy. They pointed out that the j -dependence observed for $\ell = 3$ in the $^{54}\text{Cr}(p,d)$ reaction appears to arise mainly from the deuteron-nucleus spin-orbit interaction. The spin-orbit potential which they used was characterised by its "small geometry". Both

the radius and diffuseness parameters ($r_s = 0.7$ fm and $a_s = 0.4$ fm) were considerably smaller than the corresponding parameters for the central interaction. Delic and Robson [De 70] have also shown that by including the D-state of the deuteron in a finite range DWBA calculation of the angular distributions for two $\ell = 1$ transitions studied in $^{52}\text{Cr}(d,p)^{53}\text{Cr}$, the shapes of the angular distributions are insignificantly altered.

No theory can at present explain the j -dependence effect. It is well established that the spin-orbit interaction plays an important part, but it alone cannot fully explain the j -dependence for $\ell = 3$ transitions. More experimental and theoretical work must be done in order to try to fully understand this effect.

4.2 DWBA ANALYSIS

The distorted waves Born approximation was used to calculate the angular distributions measured in the ^{54}Cr , $^{67,68}\text{Zn}(d,t)$ reactions. The calculations were performed on the A.N.U. UNIVAC 1108 computer using the code DWUCK developed by Kunz [Ku 66] from the earlier code JULIE. The optical potential generating the distorted waves had the form

$$U(r) = V_c(r) - V_o f(x) + 4i W_D (df(x')/dx') + (\hbar^2/m_\pi c)^2 r^{-1} \times f(x_s) \vec{\ell} \cdot \vec{\sigma} \quad (4.1)$$

where $V_c(r)$ is the Coulomb potential due to a uniformly charged sphere of radius $1.25 A^{1/3}$,

$$f(x_i) = [1 + \exp(x_i)]^{-1} \quad (4.2)$$

$$\text{and} \quad x_i = (r - r_i A^{1/3})/a_i \quad (4.3)$$

A Thomas spin-orbit term defined by

$$V_{S.O.}(r) = -V_R \frac{V_{SOR}}{45.2} \frac{1}{r} f(x_R) \vec{\ell} \cdot \vec{s} \quad (4.4)$$

was also included in the bound state calculation. In eq.(4.4) the quantity V_R is the real well depth and V_{SOR} is the real well Thomas spin-orbit factor for the real geometry.

The numerical integration of the bound and distorted wave functions was performed using an integration step size of 0.12 fm and the same step size was used for the radial integrals. Partial wave expansions included orbital angular momenta up to $\ell = 20$. The upper cut-off on the radial integrals was 36 fm which is beyond the region of non-zero contribution. No lower cut-off on the radial integrals was used.

4.2.1 Corrections for Finite-Range and Non-Locality

The program DWUCK allows a finite-range correction factor R to be used in order to compensate for the assumption of a zero-range interaction. For a reaction of the form

$$A + t = B + d \quad (4.5)$$

where t and d denote a triton and a deuteron, the program computes the term

$$\Lambda_R(r) = \left\{ 1 + \frac{2}{\hbar^2} \frac{m_d m_n}{m_t} (R)^2 [V_t(r) - V_d(r) - V_n(r) - S_{dn}] \right\}^{-1} \quad (4.6)$$

where S_{dn} is the separation energy of the neutron from the triton, $V_{t,d,n}$ are the potentials for the corresponding particles and m_d, m_n, m_t denote the masses of the deuteron, neutron and triton. For a (d,t) reaction the parameter R is determined using a Hulthén wave function (see eq.(2.56)) so that

$$R = \frac{1}{7\alpha} = 0.845 \text{ fm} . \quad (4.7)$$

This value was used in the present calculations. The form factor is multiplied by $\Lambda_R(r)$.

Drisko and Satchler [Dr 64] have shown that the use of the finite-range corrections replaces, at least partially, the need for a lower cut-off in the radial integrals. It has the effect of damping the contributions from the nuclear interior and hence has a similar effect to that produced by a lower cut-off in the radial integration.

The non-locality correction is calculated by

$$\chi^{NL}(r) = \left[1 - \frac{\mu\beta^2}{2\hbar^2} V_O(r) \right]^{-1/2} \chi^L(r) \quad (4.8)$$

where χ^{NL} and χ^L are equivalent wave functions from the non-local and local potentials, $V_O(r)$ is the local nuclear potential and β is the range parameter of the non-locality which is determined empirically by fitting the energy dependence of the relevant optical model potential. Approximate values for β are given by Bassel [Ba 66c]. The following values have been used in the present calculations:

β	= 0.85 fm	for nucleons,
β	= 0.54 fm	for deuterons,
β	= 0.25 fm	for tritons .

4.2.2. Calculation of the Neutron Bound State Wave Function

The (d,t) reaction is a typical one-neutron pick-up reaction. The neutron bound state wave functions were obtained by adjusting the depth of the real well to give each orbit a binding energy of $-(S_n + E_x)$ where S_n is the one-neutron separation energy and E_x the excitation energy in the residual nucleus. The one-neutron separation energy S_n for the reaction $d + (A + 1) \rightarrow t + A$ is calculated as $S_n = B_{A+1} - B_A$, where B_{A+1} and B_A are total binding energies of the target nucleus $A + 1$ and residual nucleus A .

The following neutron parameters were used throughout the present DWBA calculations:

$$\begin{aligned} \text{radius parameter} \quad r_n &= 1.25 \text{ fm}, \\ \text{diffuseness} \quad a_n &= 0.65 \text{ fm}, \\ \text{Thomas spin-orbit factor} \quad V_{\text{SOR}} &= 25 . \end{aligned}$$

4.2.3. Triton Parameters

The triton parameters used for the present DWBA calculations are shown in Table 4.1. The parameters were deduced from an analysis of 20 MeV (t,t) scattering on $A \geq 40$ nuclei [Nu 74]. The depths V and W_D were adjusted using gradients of $dV/dE = -0.15$ and $dW_D/dE = -0.50$ determined from ^3He scattering [Ch 71] to match the energy of the tritons from the (d,t) reaction. A spin-orbit interaction added to the triton optical potential was found to have no significant effect. The imaginary potential was of a surface type.

4.2.4. Deuteron Parameters

The first set of deuteron optical model parameters used in the present analysis were derived from a set of energy and mass dependent formulae given by Perey and Perey [Pe 63, Nu 72] in which

$$\begin{aligned} V_O &= 81.0 - 0.22 E + 2.0(Z)/A^{1/3} \text{ MeV} , \\ r_O &= 1.15 \text{ fm} , \quad a = 0.81 \text{ fm}, \\ W_D &= 14.4 + 0.24 E \text{ MeV}, \\ \text{and} \quad r'_O &= 1.34 \text{ fm} , \quad a' = 0.68 \text{ fm} . \end{aligned} \tag{4.9}$$

These formulae have been used extensively in many stripping calculations. They are applicable below 25 MeV. The potential does not have a spin-orbit term since no polarization data were available at that time. The set of parameters corresponding to the above formulae are given in Table 4.1

TABLE 4.1

SUMMARY OF THE DEUTERON AND TRITON OPTICAL MODEL PARAMETERS USED IN THE PRESENT (d,t) WORK

Particle - set	Target	V_o (MeV)	r_o (fm)	a (fm)	W_D (MeV)	r' (fm)	a' (fm)	V_s (MeV)	r_s (fm)	a_s (fm)	Ref.	
d	D ₁	54Cr	105.0	1.05	0.85	14.0	1.43	0.71	11.0	0.84	0.46	[Gr 70, Ho 71]
d	D ₁	67,68Zn	107.3	1.05	0.85	14.0	1.41	0.73	11.0	0.84	0.46	[Gr 70, Ho 71]
d	D ₂	54Cr	82.0	1.15	0.81	17.3	1.34	0.68				[Pe 63]
d	D ₂	67,68Zn	93.0	1.15	0.81	17.3	1.34	0.68				[Pe 63]
d	D ₃	54Cr	104.4	1.10	0.69	12.4	1.25	0.84	6.25	0.90	0.60	[Ko 72]
d	D ₄	54Cr	105.3	1.05	0.86	15.4	1.42	0.69	7.0	0.75	0.50	[Ro 73]
d	D ₅	54Cr	98.9	1.07	0.83	13.4	1.41	0.70	6.0	1.07	0.83	[Fi 70]
t	T ₁	54Cr	143.0	1.23	0.72	36.9	1.15	0.85				[Nu 74]
t	T ₂	67,68Zn	150.0	1.23	0.72	32.3	1.15	0.85				[Nu 74]

as set D_2 . There has not been a recent systematic analysis of deuteron elastic scattering which covers both differential cross-sections and polarization data over a wide range of nuclei and energies.

Another set of deuteron optical model parameters was derived from the formulae obtained by Griffith et al. [Gr 70, Ho 71, pg.250] from an analysis of the polarization of 12 MeV deuterons in elastic scattering from targets ranging from Si to In. Griffith gave the following mass dependence in his formulae:

$$\begin{aligned}
 V_0 &= 90 + 2.36 Z/A^{1/3} \text{ MeV}, \\
 r_0 &= 1.05 \text{ fm}, \quad a = 0.85 \text{ fm}, \\
 W_D &= 14 \pm 2 \text{ MeV}, \\
 r'_0 &= 1.19 + 0.9 A^{-1/3} \text{ fm}, \quad a' = 0.398 + 0.082 A^{1/3} \text{ fm}, \\
 V_{so} &= 11 \pm 2 \text{ MeV}, \\
 \text{and } r_{so} &= 0.84 \text{ fm}, \quad a_{so} = 0.46 \text{ fm}.
 \end{aligned} \tag{4.}$$

This potential includes a "small geometry" spin-orbit term with the radius and diffuseness smaller than for the central term. Such a "small geometry" spin-orbit term has been found by Robson [Ro 68b] to reproduce the $\ell = 1$ j-dependence found in some transfer reactions. The deuteron parameters calculated from these formulae are given in Table 4.1 as set D_1 .

Three more sets of deuteron parameters were tried only in the case of the $^{54}\text{Cr}(d,t)^{53}\text{Cr}$ reaction. They are presented in Table 4.1 as sets D_3 , D_4 and D_5 .

The D_3 set was used by Kocher and Haeberli [Ko 72] in the analysis of vector analysing powers and cross-sections from the (d,p) reaction on ^{52}Cr at 10 MeV deuteron energy.

The D_4 set was used by Rohrig and Haeberli [Ro 73] for the study of the (d,p) reaction on ^{52}Cr using a 10 MeV tensor polarised beam.

The last set of deuteron parameters used in the $^{54}\text{Cr}(d,t)$

reaction analysis, D_5 , was derived by Fitz et al. [Ft 70] from an analysis of elastic scattering of 11.8 MeV deuterons on ^{54}Cr . No polarization data were included in this analysis.

4.3 $^{54}\text{Cr}(d,t)^{53}\text{Cr}$

4.3.1. Previous Work

The properties of levels in the ^{53}Cr nucleus have been studied by many different nuclear reactions. The first information from (d,p) reactions to levels in ^{53}Cr comes from the measurements of Elwyn and Shull [El 56]. They have studied the (d,p) reaction on ^{52}Cr and ^{53}Cr at 10 MeV deuteron energy using double proportional counter telescopes to detect the protons. Since this first (d,p) experiment on ^{52}Cr many other experiments have been reported at different energies and improved resolution [Be 60, Bo 64, An 64, Bo 65, Br 71]. The $^{52}\text{Cr}(d,p)$ reaction has also been studied with a vector polarized deuteron beam by Rohrig and Haeberli [Ro 73].

The level structure of the ^{53}Cr nucleus was investigated in the $^{54}\text{Cr}(p,d)^{53}\text{Cr}$ reaction by Whitten [Wh 67] at 17.5 MeV proton energy. He reported a j-dependence effect for both $\ell = 1$ and $\ell = 3$ transitions. The angular distribution corresponding to $1f_{5/2}$ neutron pick-up falls off faster with angle after its maximum than that corresponding to $1f_{7/2}$ neutron pick-up; the $1f_{5/2}$ transition also shows a definite second maximum at 65° which is not found in the $1f_{7/2}$ transitions.

Fitz et al. [Ft 67] have studied the $^{54}\text{Cr}(d,t)^{53}\text{Cr}$ reaction at 12 MeV deuteron energy. Spectroscopic factors were extracted for five states in ^{53}Cr and a j-dependence for $\ell = 1$ transitions was noted. No j-dependence for $\ell = 3$ transitions was seen.

In the last few years the properties of states and transitions in

^{53}Cr have been investigated rather extensively [Au 70, Gu 73].

The one neutron pick-up reactions on ^{54}Cr , such as (p,d) , $(^3\text{He},\alpha)$ or (d,t) are very suitable for studying j -dependence in both $\ell = 1$ and $\ell = 3$ transitions in ^{53}Cr . The first five states in ^{53}Cr are known to be $3/2^-$, $1/2^-$, $5/2^-$, $7/2^-$ and $7/2^-$ corresponding to energies of 0 MeV, 0.564 MeV, 1.006 MeV, 1.287 MeV and 1.539 MeV respectively.

In the present work the angular distributions of tritons from the $^{54}\text{Cr}(d,t)^{53}\text{Cr}$ reaction were remeasured at 12 MeV deuteron energy. The measurements were made from forward angles of 12.5° out to 150° in 2.5° steps in order to check more carefully the existence of j -dependence in ^{53}Cr transitions, especially for $\ell = 3$ transitions.

4.3.2a. $\ell = 1$ Transitions

The energy spectrum of the tritons at 57.0° for the five states populated in ^{53}Cr is shown in Fig. 4.1. The angular distributions for the two $\ell = 1$ and three $\ell = 3$ transitions are shown in Fig. 4.2 and data obtained from the analysis of this reaction are presented in Table 4.2. The ground state and first excited state at 0.564 MeV display some typical characteristics found in $\ell = 1$ transitions in pick-up reactions. The first minimum appears at 25° and the first maximum at 35° for both transitions. Each angular distribution has three maxima which are well defined. For the $3/2^-$ transition the second and the third maxima appear at 60° and 95° respectively. The second and the third maxima for the $1/2^-$ transition are located at 70° and 110° respectively. The transition to the $3/2^-$ state has a larger cross-section than the transition to the $1/2^-$ state. Fig. 4.3 shows an enlarged view of the $\ell = 1$ angular distributions plotted using an arbitrary scale. It can be seen that both look identical at forward angles up to the second minimum, but beyond this the maxima in the transition to the $1/2^-$ state are shifted towards backward

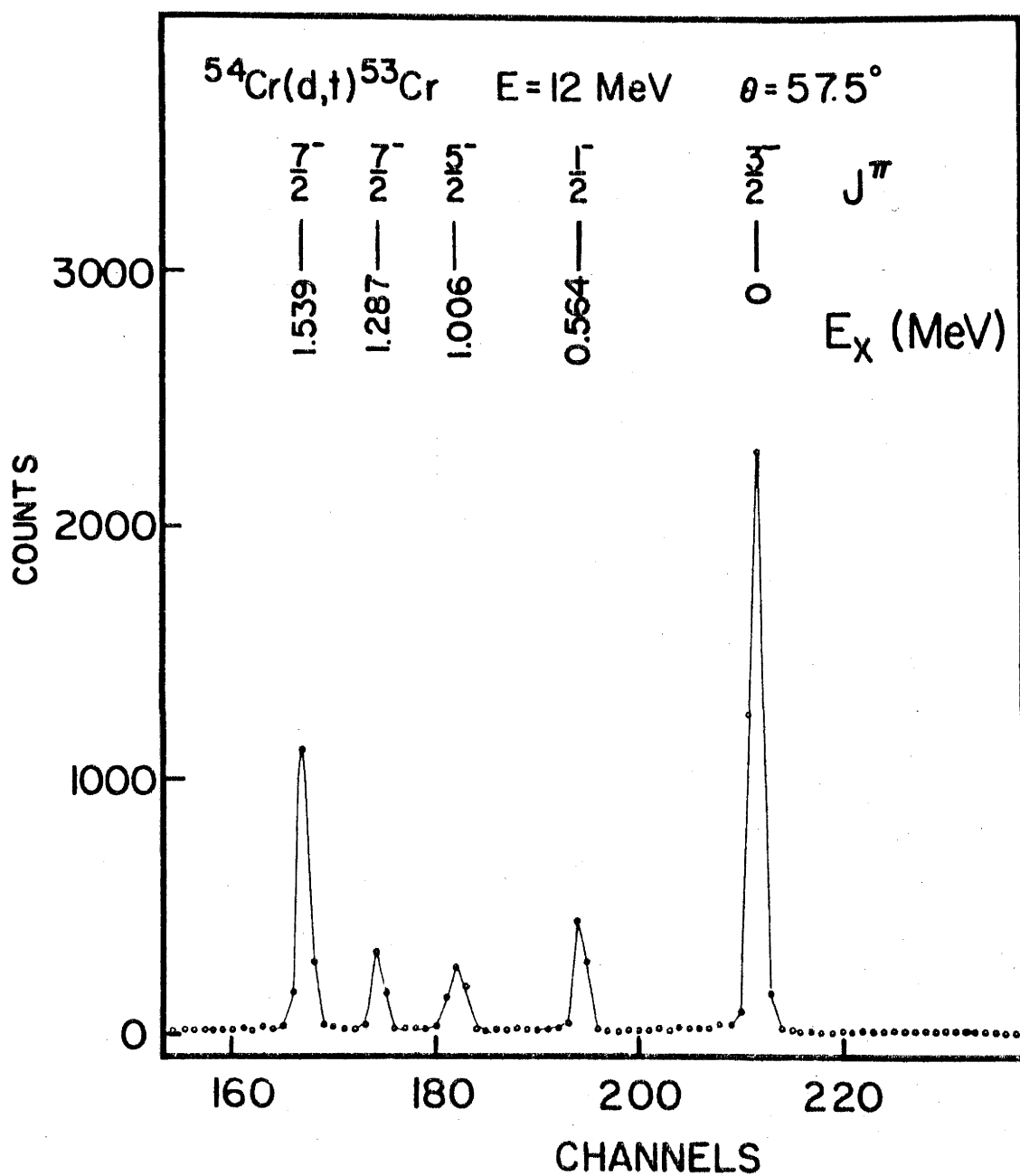


Fig. 4.1. Triton spectrum from the $^{54}\text{Cr}(d,t)^{53}\text{Cr}$ reaction.

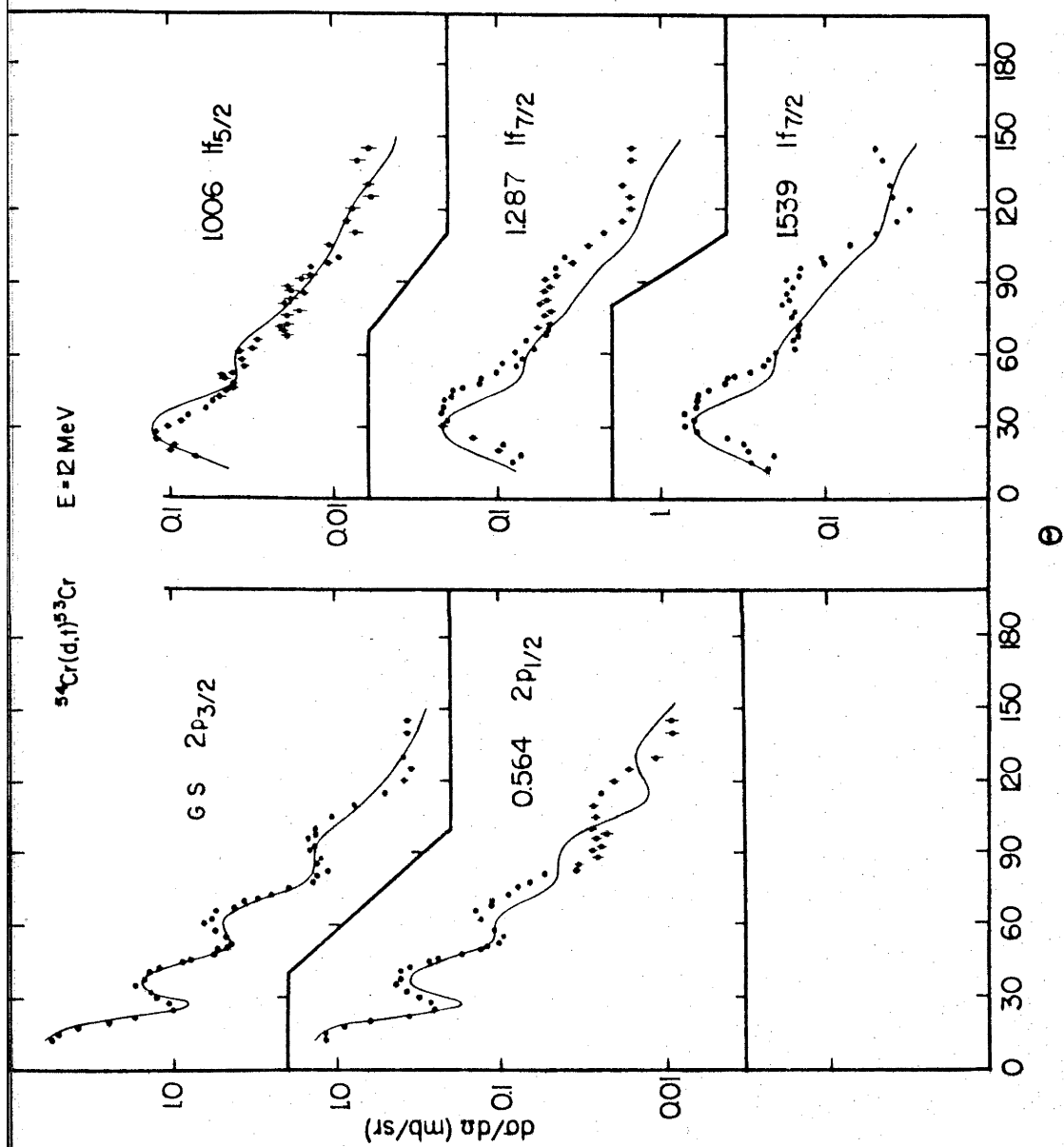


Fig. 4.2. Angular distributions from the $^{54}\text{Cr}(d,t)^{53}\text{Cr}$ reaction compared with DWBA predictions.

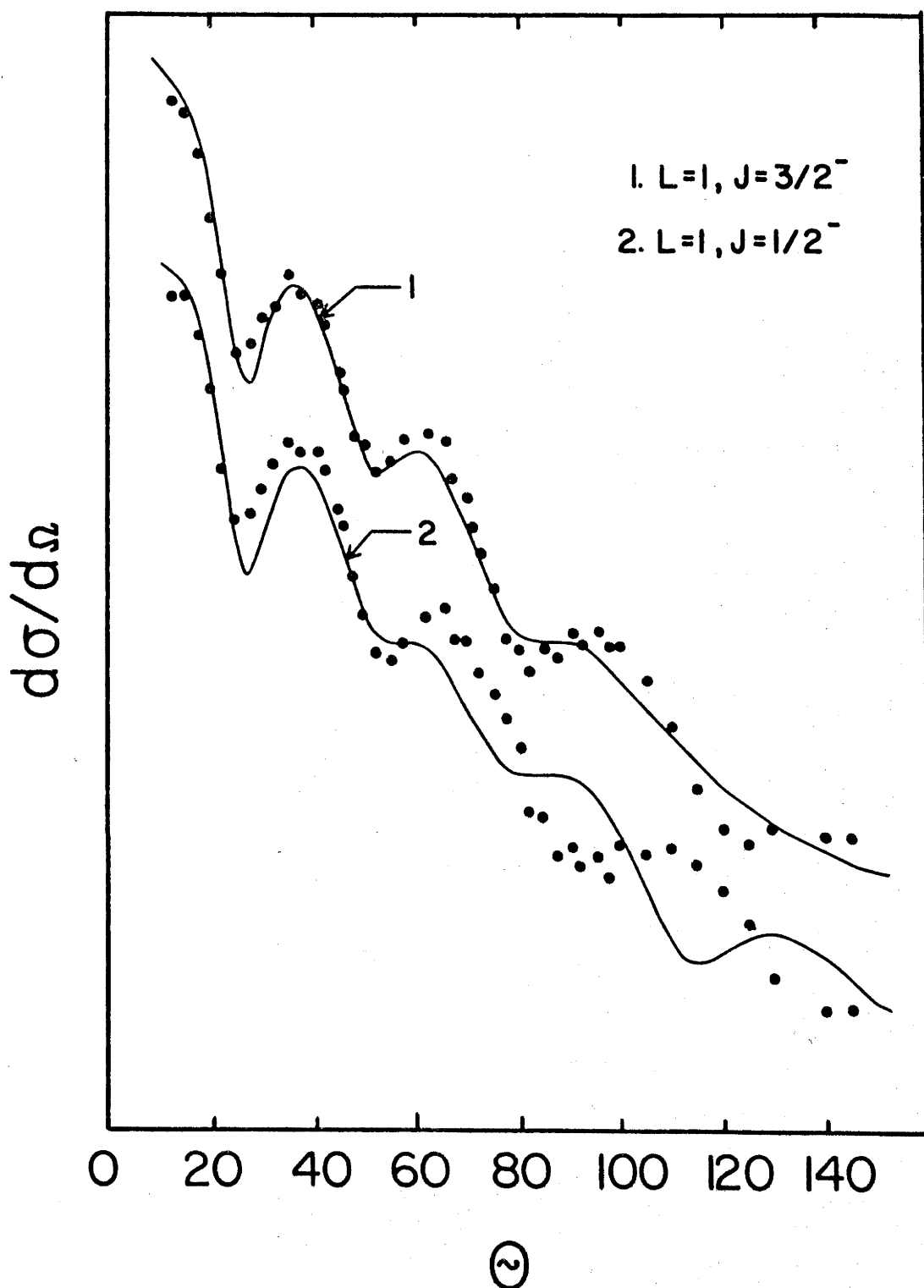


Fig. 4.3. Angular distributions corresponding to the $l=1, J=3/2^-$ and $l=1, J=1/2^-$ transitions in ^{53}Cr compared with DWBA predictions.

TABLE 4.2

SUMMARY OF RESULTS FROM SINGLE NEUTRON PICK-UP
TO STATES IN ^{53}Cr

E_x ^{a)} (MeV)	J^π a)	(d,t) ^{b)}		(d,t) ^{c)}	(p,d) ^{d)}	($^3\text{He},\alpha$) ^{e)}
		ℓ	S	S	S	C ² S
0	$3/2^-$	1	0.66	0.61	0.83	1.1
0.564	$1/2^-$	1	0.24	0.22	0.31	0.26
1.006	$5/2^-$	3	0.54	0.31	0.51	0.49
1.287	$7/2^-$	3	0.68	0.61	0.70	0.45
1.539	$7/2^-$	3	2.3	1.8	3.2	3.0

a) Adopted excitation energies and spin-parities from ref. [Nu 70].

b) Present work.

c) Ref. [Ft 67].

d) Ref. [Wh 67].

e) Ref. [Da 69].

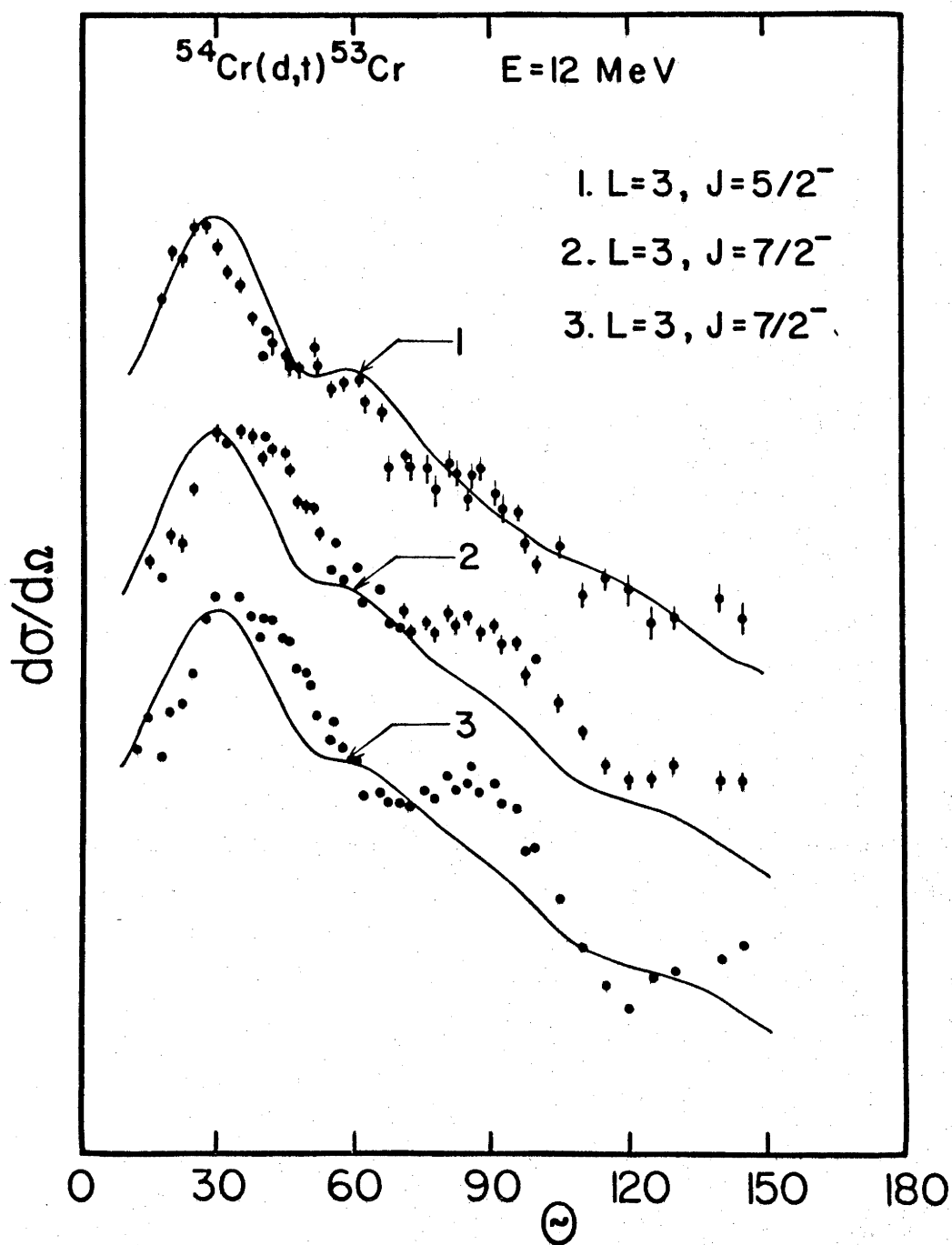


Fig. 4.4. The $l=3$ j -dependence observed for the 1.006, 1.287 and 1.539 MeV states in ^{53}Cr compared with the DWBA predictions.

j-dependence in contrast to the well established backward angle one for $\ell = 1$ transitions in (d,p) reactions. Fitz et al. [Ft 67] did not observe any $\ell = 3$ j-dependence in their data. They did not measure more forward than 20° and their forward angle statistics are worse than in the present measurement.

4.4 $^{67,68}\text{Zn}(d,t)^{66,67}\text{Zn}$

4.4.1. Previous Work

The level structure of the Zn isotopes has been studied in many ways. The first (d,t) experiment performed on $^{67,68}\text{Zn}$ was reported by Zeidman et al. [Ze 60]. They used the (d,t) reaction at 21.5 MeV deuteron energy to study a few nuclei of mass $A \approx 60$, including $^{67,68}\text{Zn}$. The tritons were recorded by a telescope detector made up of two NaI(Tl) crystals. The energy resolution achieved was not good enough to resolve more than 6 states in the $^{67}\text{Zn}(d,t)^{66}\text{Zn}$ reaction and three states in the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ reaction. Angular distributions for states in ^{66}Zn were obtained for transitions leading to the ground, 1.05 MeV and 2.75 MeV states and to the group of states at about 3.75 MeV. No angular distributions on resolved states could be measured for the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ reaction, but only for groups of states. Butler's formalism was used to extract ℓ values from the angular distributions.

Another (d,t) experiment on the Zn isotopes was reported by Lin and Cohen [Li 63]. They used a natural Zn target and a magnetic spectrograph to analyse the reaction products. The overall resolution was 90 keV. Eight levels in ^{66}Zn and four in ^{67}Zn were reported. No angular distributions were measured.

Studies of the β^+ decay of ^{66}Ga [Ph 70, Sc 60], ^{67}Ga [Ke 53, Me 53, Fr 66] and ^{67}Cu [Ea 53] have produced a consistent level structure in $^{66,67}\text{Zn}$. The level structure of ^{66}Zn has also been studied in an original

way by Shikazono and Kawarasaki [Sh 68] in a $^{66}\text{Zn}(\gamma, \gamma')$ experiment.

Despite these measurements one and two-nucleon transfer reactions have played an important role in studying the $^{66,67}\text{Zn}$ isotopes. The (d,p) reaction proved to be fruitful in providing spectroscopic information about the Zn nuclei. Lin and Cohen [Li 63] studied the (d,p) reaction on $^{64,66,67,68}\text{Zn}$ isotopes at 15 MeV energy. They analysed the angular distributions by use of DWBA. Von Ehrenstein and Schiffer [Eh 67] also measured the angular distributions from the (d,p) reaction on $^{64,66,68,70}\text{Zn}$ at 10 MeV deuteron energy. The typical resolution achieved in this experiment was around 50 keV. To be certain of resolving some closely spaced states they measured the angular distributions between 5° and 40° with a broad range magnetic spectrograph. The data were analysed using the DWBA. The empirical j-dependence rules for $\ell = 1$ transitions in (d,p) reactions were used for spin assignments. Since ^{65}Zn is not stable the levels in ^{66}Zn cannot be reached by the (d,p) reaction.

McIntyre [Mc 66] studied the Zn isotopes by both (p,d) and (p,t) reactions on $^{64,66,67,68,70}\text{Zn}$ at 17.5 MeV proton energy. Telescope detectors were used for the simultaneous detection of the deuterons and tritons. The energy resolution achieved was 70 keV. He observed several cases of j-dependence in the (p,d) angular distributions. The DWBA theory was used to analyse the data.

The (t,p) reaction on the Zn isotopes at 12 MeV triton energy was studied by Hudson and Glover [Hu 72] with a multigap spectrograph. They reported observing 56 states in ^{66}Zn up to an excitation energy of 4.688 MeV. Spins and parities were assigned to many of these states. Again no information on ^{67}Zn can be obtained by the (t,p) reaction because ^{65}Zn is not a stable isotope.

Ford et al. [Fo 67] have studied the energy levels of ^{66}Zn by the $^{65}\text{Cu}(^3\text{He}, d)^{66}\text{Zn}$ reaction at an incident energy of 18 MeV. Telescope

detectors were used and the overall resolution achieved was between 70 and 80 keV. A total of 17 states were excited in ^{66}Zn and the angular distributions were analysed using the DWBA.

Other means used to study the energy levels of $^{66,67}\text{Zn}$ were by inelastic scattering such as (p,p') [Ka 67, Ca 67, Br 67], (d,d') [Li 65a, Jo 69] and (α,α') [Al 70]. The (p,p') reactions have given useful information about the level structure in ^{66}Zn . These nuclei have also been studied by (p,α) , $(^3\text{He},\alpha)$, (p,n) , (α,t) , neutron capture and by other reactions [Nu 68].

4.4.2. $^{67}\text{Zn}(d,t)^{66}\text{Zn}$

4.4.2a. $\ell = 1$ Transitions

Fig. 4.5 shows the energy spectrum of the tritons at 55° from the $^{67}\text{Zn}(d,t)^{66}\text{Zn}$ reaction. In the present experiment a total of 16 states from ^{66}Zn are excited while angular distributions for some 13 of these could be measured. These angular distributions are shown in Fig. 4.6 and Fig. 4.7 together with the DWBA calculations. Table 4.3 compares data extracted from the analysis of this experiment with data from previous transfer reactions. The dominant transitions are $\ell = 1$ assigned to the levels at 1.039 MeV, 1.873 MeV, 2.450 MeV, 2.781 MeV, 3.080 MeV, 3.229 MeV, 3.332 MeV, 3.502 MeV, 3.680 MeV and 3.791 MeV. The cross-section at the first maximum varies from 0.6 mb/sr for the 2.781 MeV transition down to 0.032 mb/sr for the 1.873 MeV transition. The first minimum occurs around 27° and the first maximum around 38° . The angular distributions do not show the same pronounced structure as the $\ell = 1$ transitions from the $^{54}\text{Cr}(d,t)^{53}\text{Cr}$ reaction. After the first maximum, the angular distributions for some of the states are almost flat and others display very weak oscillations.

The 1.039 MeV and 1.873 MeV states are known to have spin-parity

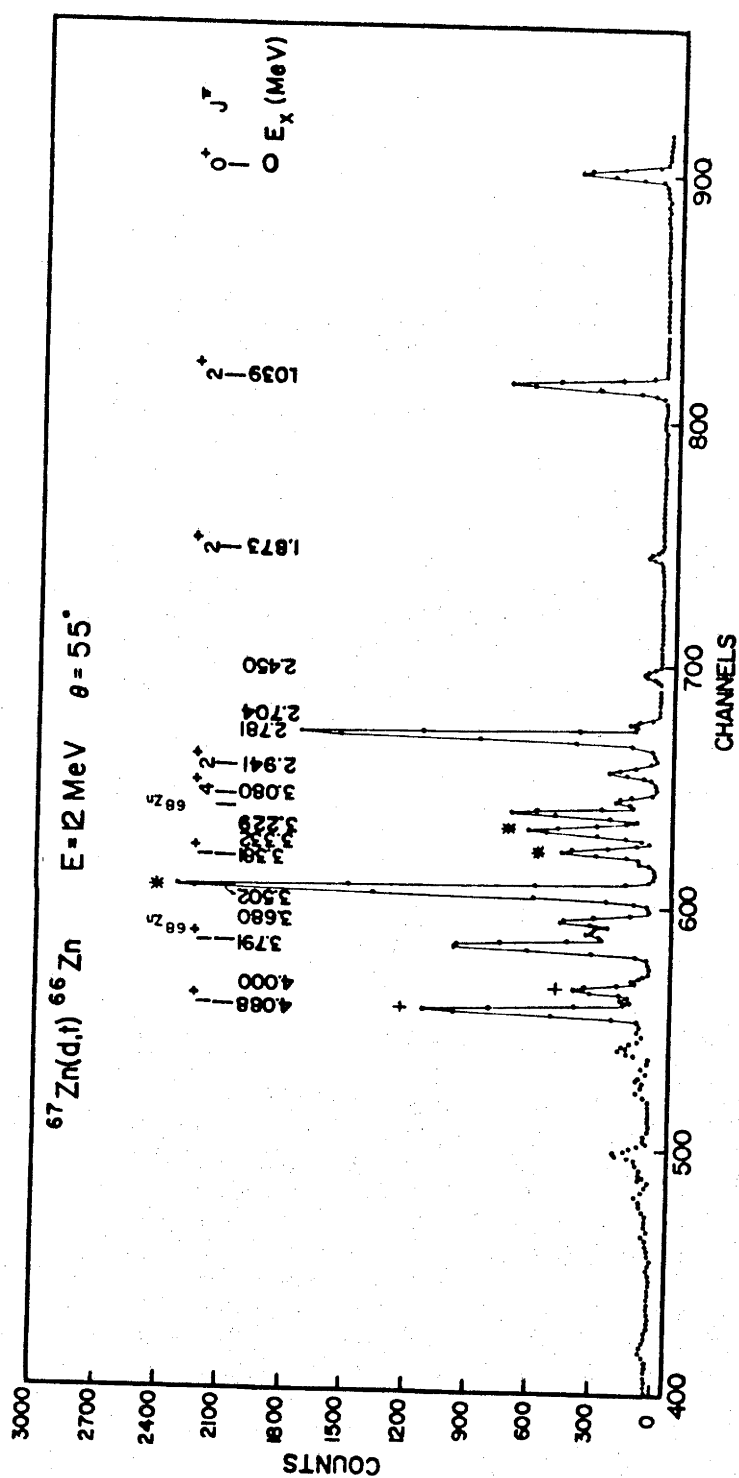


Fig. 4.5. Triton spectrum from the $^{67}\text{Zn(d,t)}^{66}\text{Zn}$ reaction. Peaks marked with a * or + were obscured by triton groups from other Zn isotopes (see text).

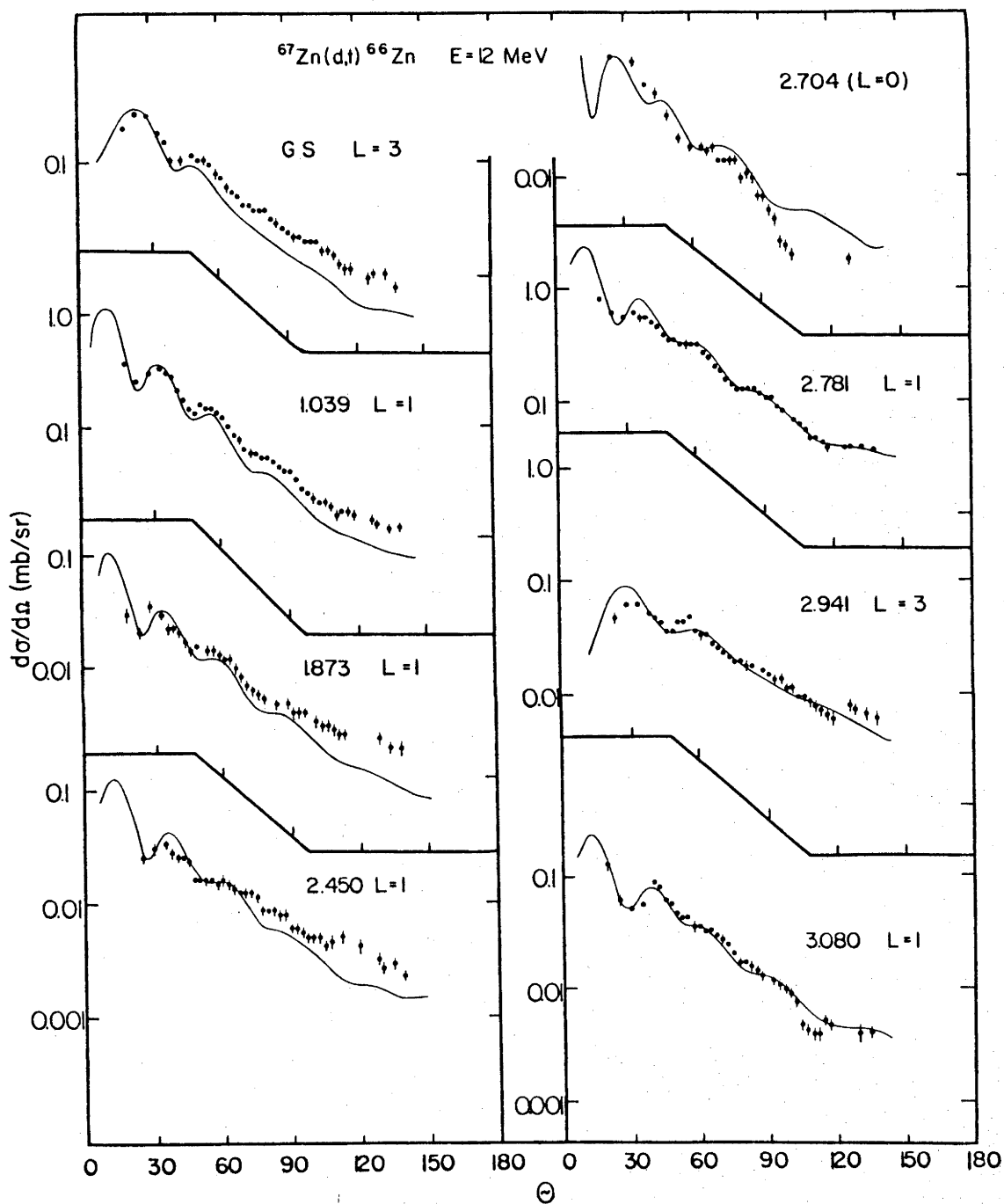


Fig. 4.6. Angular distributions from the $^{67}\text{Zn}(d,t)^{66}\text{Zn}$ reaction compared with the DWBA predictions.

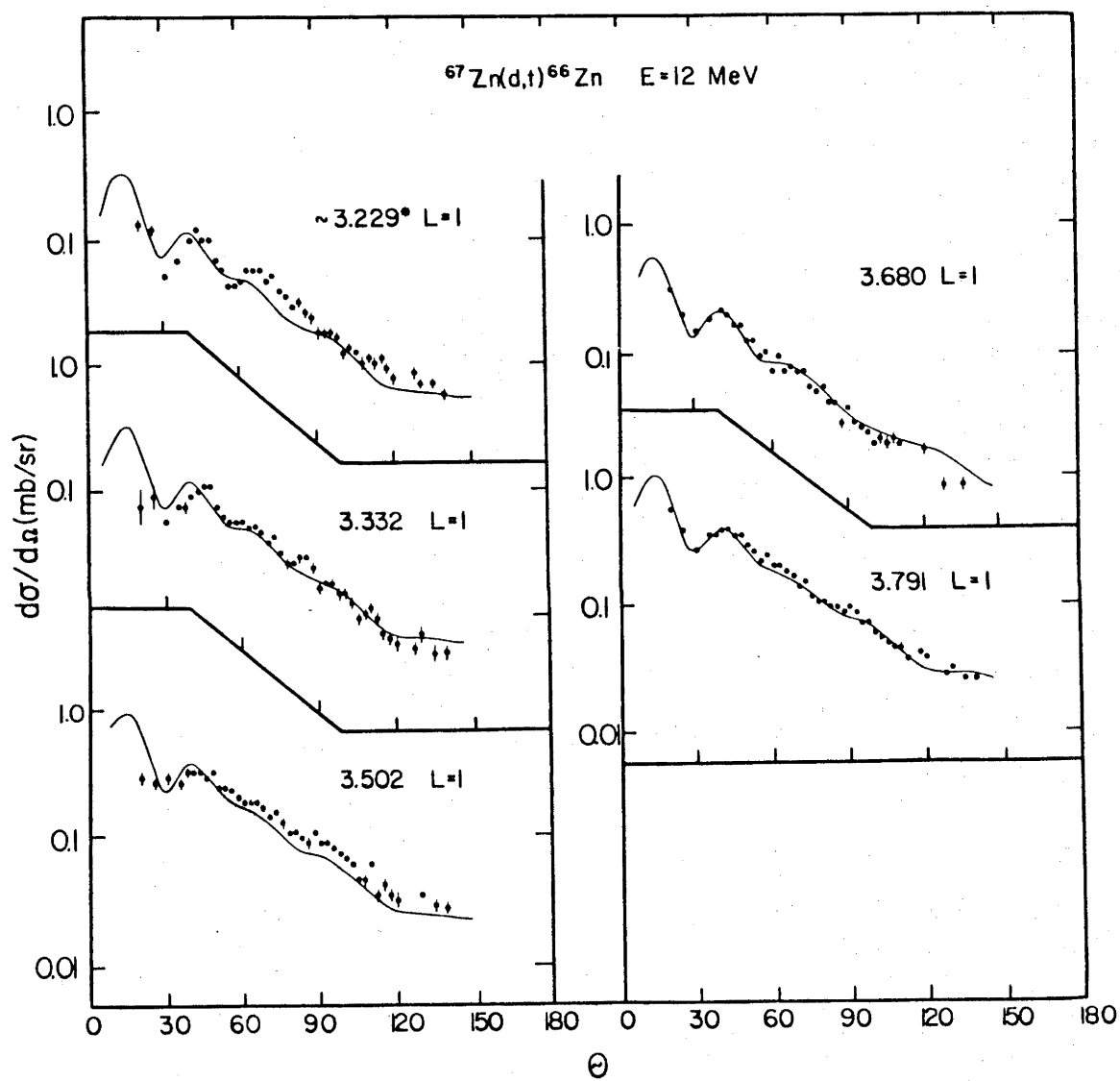


Fig. 4.7. Angular distributions from the $^{67}\text{Zn}(d,t)^{66}\text{Zn}$ reaction compared with the DWBA predictions.

TABLE 4.3

SUMMARY OF RESULTS FROM SINGLE NEUTRON PICK-UP REACTIONS
TO STATES IN ^{66}Zn

E_x ^{a)} (MeV)	J^π	(d,t) ^{b)}		(p,d) ^{c)}	
		ℓ	S ^{f)}	ℓ	S ^{g)}
0	0^+ a)	3	0.27	3	0.44
1.039	2^+ a)	1	0.10	1	0.10
1.873	2^+ a)	1	0.011	1	0.01
2.450	$(4^+)^d)$	(1)	0.02	(1)	0.02
2.704	$(2,3)^- b)$	(0)	0.056		
2.781	$(1,2)^+ b)$	1	0.55	1	0.52
2.941	$2^+ d)$	3	0.22	3	0.47
3.080	$4^+ d)$	1	0.062	1	0.10
3.229		1	0.12	1	0.15
3.332	$(1,2)^+ b)$	1	0.10	1	0.14
3.381	$1^+ e)$				
3.502		1	0.39	1	0.30
3.680		1	0.28	1	0.30
3.791	$1^+ e)$	1	0.56	1	0.80
4.000				1	0.10
4.088	$1^+ e)$			1	0.40

a) Adopted level energies and spin-parities ref. [Nu 68]

b) Present results. c) Ref. [Mc 66]. d) Ref. [Hu 72].

e) Ref. [Ph 70].

f) $\Sigma S(\ell=1) = 2.19$, $\Sigma S(\ell=3) = 0.49$

g) $\Sigma S(\ell=1) = 2.44$ (states at 4.000, 4.088 MeV not included),
 $\Sigma S(\ell=3) = 0.91$.

2^+ [Nu 68]. The $\ell = 1$ assignment for these states is in agreement with this assignment. The ground state spin of ^{67}Zn is $5/2^-$ and the selection rules discussed in Chapter 2 permit such an assignment. The state at 2.450 MeV was reported by Ford et al. [Fo 67] to be 4^+ ; however a definite spin could not be assigned to this state from the (t,p) reaction [Hu 72]. The cross-section for this state in the present work is very small and while the $\ell = 1$ assignment seems more probable than other values a definite conclusion can not be made. A weak $\ell = 1$ assignment to this state was also made from (p,d) work [Mc 66].

The state at 2.781 MeV cannot be distinguished from another reported [Nu 68] at 2.828 MeV. The level excited here seems to be at 2.781 MeV as the 2.828 MeV state is known to be 3^- and cannot be excited by $\ell = 1$ transfer. Spin assignments of 2^+ [Hu 72] and $1^\pm$ [Ph 70] were made from (t,p) data and ^{66}Ga decay respectively. The present $\ell = 1$ assignment, which agrees with the (p,d) work of McIntyre, rules out 1^- . This state has the highest cross-section of any excited in the present $^{67}\text{Zn}(d,t)^{66}\text{Zn}$ reaction.

A spin of 4^+ was assigned to the 3.080 MeV state by Hudson et al. The present $\ell = 1$ value for this state is in agreement with the (p,d) data and is consistent with a spin assignment of (1, 2, 3, 4) $^+$.

The states marked in Fig. 4.5 by a star at 3.229 MeV, 3.332 MeV and 3.502 MeV were obscured by the 0.093 MeV, 0.185 MeV and 0.394 MeV levels in ^{67}Zn which were strongly excited in the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ reaction. Knowing the absolute cross-sections for these states in ^{67}Zn (also measured in the present experiment) and the percentage of ^{68}Zn in the ^{67}Zn target, corrections were made for the absolute cross-sections of these three states in ^{66}Zn . A triplet has been reported [Nu 68] at around 3.229 MeV. Hudson and Glover [Hu 72] assigned a spin of 2^+ to a state at 3.216 MeV and Phelps et al. [Ph 70] assigned 1^+ to a state at 3.229 MeV.

The present $\ell = 1$ assignment is compatible with both spins. It is not possible in the present data to differentiate among the states of this triplet. The state at 3.332 MeV was assigned 2^+ by Hudson and $(0, 1)^{\pm}$ by Phelps. Assignments of $0^{\pm}$ and 1^- are not compatible with the $\ell = 1$ from the present work which therefore restricts possible spin values to $(1, 2)^+$. An assignment of $\ell = 1$ was made for the level at 3.502 MeV but no spin assignment was attempted either here or in other work.

The level at 3.680 MeV assigned $\ell = 1$ in the present experiment is close to the 3.674 MeV 2^+ level excited in (t,p) [Hu 72] and the 3.689 MeV $(0, 1)^{\pm}$ level from ^{66}Ga decay [Ph 70]. Assuming that all three measurements populate the same state, the $0^{\pm}$ and 1^- spins for this level would be ruled out by the $\ell = 1$ assignment, leaving possible spins of either 1^+ or 2^+ .

The last $\ell = 1$ angular distribution measured in ^{66}Zn is for the 3.791 MeV transition. Phelps et al. [Ph 70] reported two levels very close together, one at 3.791 MeV assigned 1^+ , and the other at 3.807 MeV assigned $(0, 1)^{\pm}$. The energy resolution in the present experiment is not good enough to distinguish between these two levels. An $\ell = 1$ assignment is compatible only with 1^+ . The level excited here could still be a doublet if both levels reported by Phelps have spin 1^+ .

Two levels at 4.000 MeV and 4.088 MeV can be seen in the energy spectrum for ^{66}Zn . They are each marked with a cross in Fig. 4.5. Angular distributions for these two states could not be measured due to contamination from the ground and 0.115 MeV state excited in the $^{66}\text{Zn}(d,t)^{65}\text{Zn}$ reaction. Since this reaction was not studied in the present experiment no corrections could be made to extract its contribution to the two levels from ^{66}Zn . McIntyre [Mc 66] assigned $\ell = 1$ for both these levels from (p,d) data.

4.4.2b. $\ell = 3$ Transitions

The ground and 2.941 MeV state angular distributions display typical $\ell = 3$ characteristics. The first maximum appears around 27° - 30° and is followed by a second maximum at 52° - 55° . After the second maximum the angular distribution shows very little structure. The absolute cross-section on the first maximum is 0.26 mb/sr for the ground state and 0.062 mb/sr for the 2.941 MeV state. The spin of the ^{66}Zn ground state is 0^+ and the spin of the state at 2.943 MeV was assigned 2^+ in ref. [Hu 72]. Phelps et al. [Ph 70] could not distinguish between $(0,1,2)^\pm$ from ^{66}Ga decay but the most probable spin for this state is 2^+ . The $\ell = 3$ assignment is in agreement with this spin assignment.

4.4.2c. Other Transitions

A state at 2.704 MeV was excited in the present experiment. This state was reported before only from (p,p') measurements [Br 67]. The cross-section for exciting this state in the (d,t) reaction is quite small, varying from 0.11 mb/sr at 25° to 0.002 mb/sr at 130° . No definite ℓ value can be assigned from the present data but a tentative value of $\ell = 0$ was assigned. The only spins compatible with $\ell = 0$ are $(2,3)^-$. Another state excited in the present experiment appears at 3.381 MeV. This state is very weakly excited and no angular distribution could be extracted from the experimental data. A spin of 1^+ was assigned by Phelps. This state was not reported before in (p,d) or $(^3\text{He},d)$ reactions.

McIntyre [Mc 66] reported as an interesting feature of the $^{67}\text{Zn}(p,d)$ reaction, the large fraction of strength appearing at relatively high excitation. The same characteristic can be seen from the (d,t) reaction. The ℓ values assigned in the present experiment also agree very well with those assigned from the (p,d) work [Mc 66] (see Table 4.3).

4.4.3 $^{68}\text{Zn}(d,t)^{67}\text{Zn}$

4.4.3a. $\ell = 1$ Transitions

The triton energy spectrum at 55° from the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ reaction is shown in Fig. 4.8. A total of 17 states in the residual ^{67}Zn nucleus were excited in this reaction. The triton angular distributions for these states are presented in Figs. 4.9, 4.10. Table 4.4 compares data extracted from the analysis of this experiment with data from previous transfer reactions. A total of eight angular distributions for states in ^{67}Zn situated at 0.093 MeV, 0.185 MeV, 0.394 MeV, 0.888 MeV, 1.142 MeV, 1.444 MeV, 1.542 MeV and 1.842 MeV display characteristics typical of $\ell = 1$ transitions in one-nucleon pick-up reactions. The first maximum appears at about 38° and is followed by another two maxima not as pronounced as the first one. The absolute cross-section on the first maximum varies from 1.34 mb/sr for the 0.394 MeV transition to 0.008 mb/sr for the 1.842 MeV transition.

The spins of the 0.093 MeV, 0.185 MeV and 0.394 MeV states are known to be $1/2^-$, $3/2^-$ and $3/2^-$ [Nu 68] respectively. The angular distributions for these three states show a definite j -dependence. An expanded view of the j -dependence is presented in arbitrary units in Fig. 4.11. It can be seen in Fig. 4.11 that the angular distributions for both $j = 1/2$ and $j = 3/2$ have the same shape at forward angles up to around 75° . Beyond 75° they oscillate in antiphase and at about 142° , the angular distribution corresponding to $j = 1/2$ shows a pronounced minimum not seen in the angular distribution for $j = 3/2$. This type of j -dependence for $\ell = 1$ transitions in ^{67}Zn resembles that for $\ell = 1$ transitions in (d,p) reactions, where a minimum appears at backward angles for $j = 1/2$. The j -dependence reported by Fulmer and Daehnick [Fu 64] for $\ell = 1$ transitions in (d,t) reactions to states in ^{55}Fe and $^{59,63}\text{Ni}$ has many characteristic features in common with the present j -dependence.

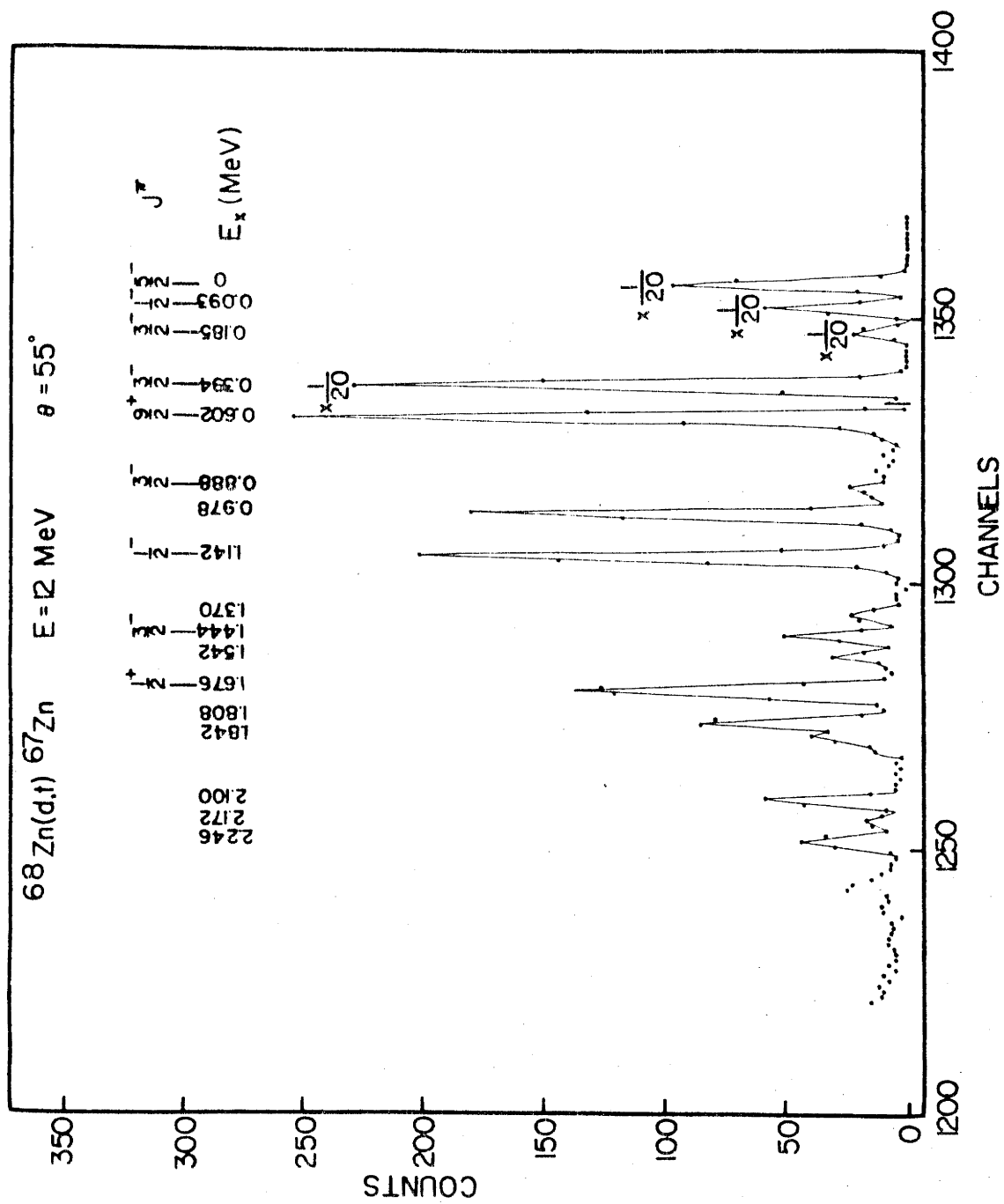


Fig. 4.8. Triton spectrum from the $^{68}\text{Zn}(\text{d,t})\ ^{67}\text{Zn}$ reaction.

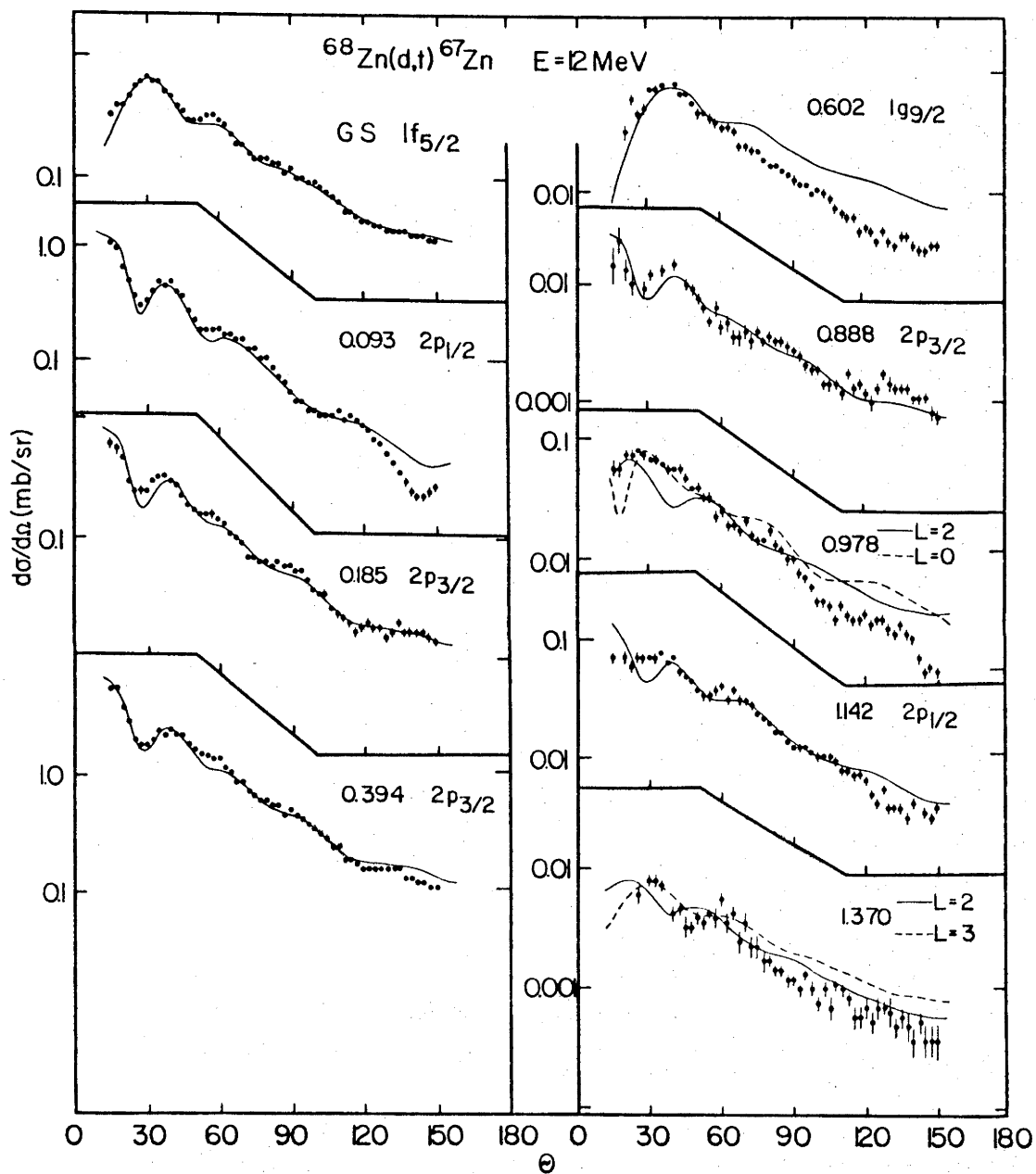


Fig. 4.9. Angular distributions from the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ reaction compared with the DWBA predictions.

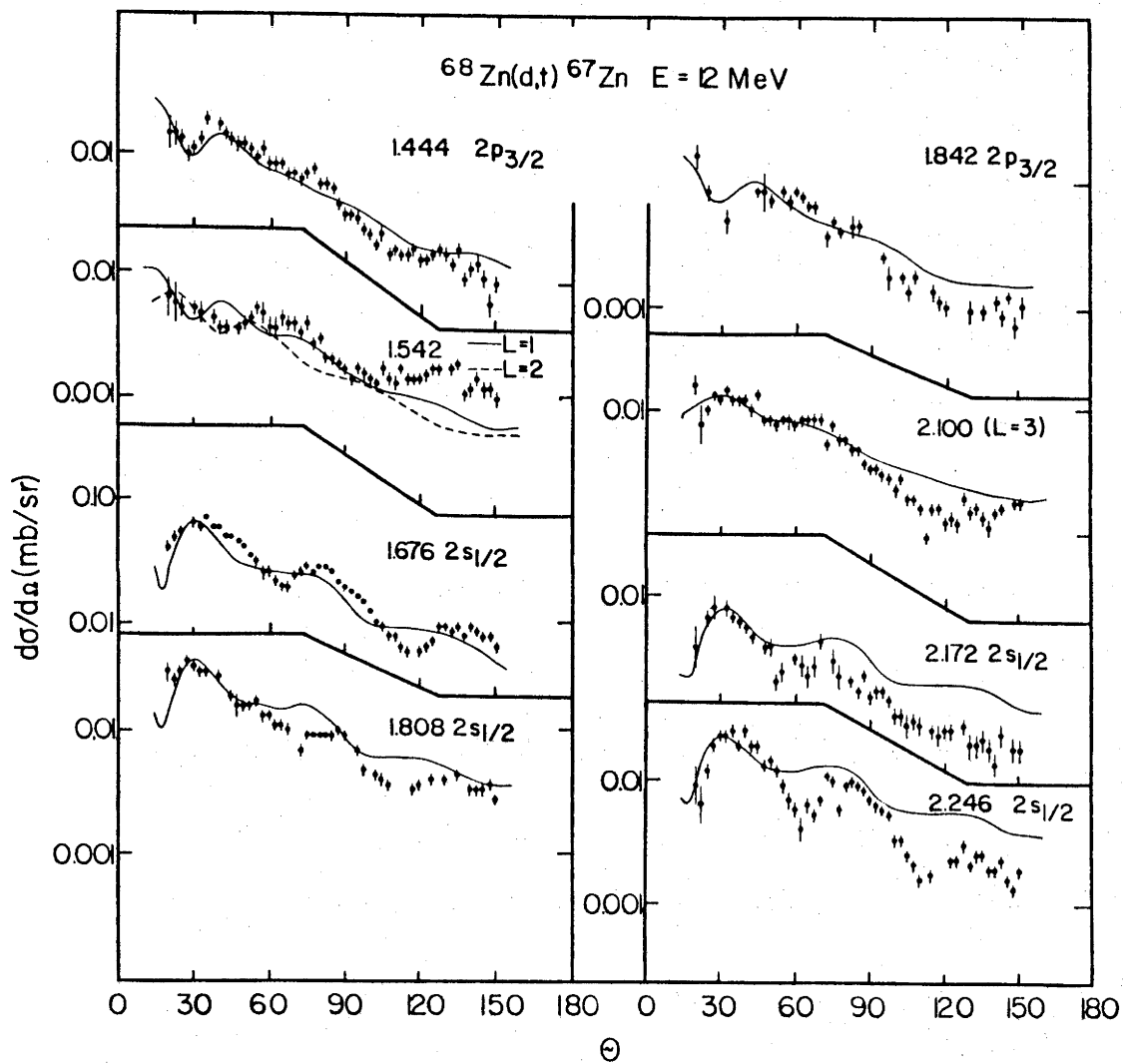


Fig. 4.10. Angular distributions from the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ reaction compared with the DWBA predictions.

TABLE 4.4

SUMMARY OF RESULTS FROM SINGLE NEUTRON TRANSFER REACTIONS TO STATES IN ^{67}Zn

E_x (MeV)	J^π b)	(d,t) c)			(p,d) d)			(d,p) e)			(d,p) f)		
		ℓ	j	S	ℓ	j	S	ℓ	j	S	ℓ	j	S
0	$5/2^-$	3	$5/2$	3.87	3	$5/2$	3.80	3	$5/2$	0.30	3	$5/2$	0.30
0.093	$1/2^-$	1	$1/2$	0.58	1	$1/2$	0.40	1	$3/2$	0.17	1	$1/2$	0.55
0.185	$3/2^-$	1	$3/2$	0.20	1	$3/2$	0.19	(3)	$5/2$	0.06	1	$3/2$	0.02
0.394	$3/2^-$	1	$3/2$	1.90	1	$3/2$	1.76	1	$3/2$	0.20	1	$3/2$	0.26
0.602	$9/2^+$	4	$9/2$	0.88	(4)		0.90	4	$9/2$	0.82	4	$9/2$	0.84
0.888	$3/2^-$	1	$3/2$	0.03	(1)		0.04	1,4		0.01			
0.978	$(5/2)^+$	(0,2)		0.39 ^g	(1)		0.06	2	$5/2$	0.23	2	$(5/2)$	0.26
1.142	$1/2^-$	1	$1/2$	0.19	1	$1/2$	0.18	1	$1/2, 3/2$	0.21	1	$1/2$	0.19
1.370		(2,3)		0.02 ^g									
1.444	$3/2^-$	1	$3/2$	0.05				1		0.02	1	$3/2$	0.02
1.542	$(3^-/2)$	(1,2)	$(3/2)$	0.03 ^h				1		0.02	1	$1/2, 3/2$	0.02, 0.01
1.676	$1/2^+$	0	$1/2$	0.32				0	$1/2$	0.10	0	$1/2$	0.12
1.808	$(1/2)^+$	(0)	$(1/2)$	0.19				0	$1/2$	0.04	(0)	$(1/2)$	0.001

Continued...

TABLE 4.4
(continued)

E _x (MeV)	j ^π b)	(d,t) c)		(p,d) d)		(d,p) e)		(d,p) f)	
		ℓ	j	ℓ	j	ℓ	j	ℓ	j
1.842	(3/2) ⁻	1	(3/2)	0.05				(1)	(1/2, 3/2)
2.100		(3)		0.42					
2.172	(1/2) ⁺	(0)	(1/2)	0.10					
2.246	(1/2) ⁺	(0)	(1/2)	0.28					
2.273 ⁱ⁾	(5/2) ⁺					2	5/2	2	(5/2)
2.407 ^{j)}	(5/2) ⁺							2	(5/2)
2.430 ^{j)}	1/2 ⁺					0	1/2	0	1/2

a) Adopted level energies from ref. [Nu 68] b) Probable-spin parities.

c) Present work.

d) Ref. [Mc 66].

e) Ref. [Li 63].

f) Ref. [Eh 67].

g) For ℓ = 2.

h) For ℓ = 1.

i) Little if any contribution in the present work.

j) Insufficient data at most angles.

They reported a j -dependence for angles greater than 70° with a dip at 125° in the angular distribution corresponding to $j = 1/2^-$.

The state at 0.093 MeV was assigned a spin of $1/2^-$ in ref. [Eh 67] from the j -dependence observed in the $^{66}\text{Zn}(d,p)^{67}\text{Zn}$ reaction. The same value was found in β - γ studies from ^{67}Ga decay [Fr 66] and also from γ angular distributions following Coulomb excitation [Ri 62]. The $1/2^-$ value assigned in these works is in contradiction with the value of $3/2^-$ assigned by Lin and Cohen [Li 63] from the $^{66}\text{Zn}(d,p)^{67}\text{Zn}$ reaction. The j -dependence observed in the present (d,t) experiment supports the $1/2^-$ spin assignment.

The 0.184 MeV level previously assigned as $5/2^-$ [Wa 59] was re-assigned as $3/2^-$ from the j -dependence observed in (d,p) [Eh 67]. The present j -dependence indicates $3/2^-$.

The previous $3/2^-$ value assigned to the 0.394 MeV state [Eh 67, Nu 68] is confirmed by the j -dependence observed in the present data.

The level at 0.888 MeV was assigned a spin of $3/2^-$ from measurements of internal conversion coefficients [Fr 66]. No spin assignment was possible from (d,p) or (p,d) reactions. This level was very weakly excited in the (d,p) reaction at 10 MeV [Eh 67] so that no angular distribution could be measured. It was more strongly excited in the (d,p) reaction at 15 MeV [Li 63] but still no spin could be assigned. It can be seen in Fig. 4.11 that the angular distribution for this state is compatible with a $3/2^-$ spin assignment based on the present j -dependence. The angular distribution does not show a minimum at backward angles as expected for an angular distribution corresponding to $1/2^-$.

The 1.142 MeV level was assigned a spin of $1/2^-$ from the j -dependence observed in the (d,p) reaction [Eh 67]. The present j -dependence supports this spin assignment but the j -dependence effect is not as pronounced as for the lower excited states.

The state at 1.444 MeV was assigned a spin of $3/2^-$ in ref. [Eh 67]. A $^{66}\text{Zn}(p,p'\gamma)^{66}\text{Zn}$ experiment [Si 72] using the triple angular correlation geometry of Goldfarb and Seyler supports this spin assignment. This state was not reported in (p,d) work [Mc 66]. A definite $\ell = 1$ value can be assigned to this transition from the present data, but the j -dependence is not strong enough to choose between $1/2^-$ and $3/2^-$. The shape of the angular distribution at backward angles favours $3/2^-$, but a confident conclusion cannot be drawn.

The spin of the 1.542 MeV level could not be assigned from (d,p) or (p,d) data. Von Ehrenstein and Schiffer [Eh 67] assigned an $\ell = 1$ value to this transition but no decision could be made between $1/2^-$ and $3/2^-$ due to unreliable data at backward angles. A tentative $3/2^-$ assignment was made from the $^{66}\text{Zn}(p,p'\gamma)$ data [Si 72]. This state is weakly excited in the present (d,t) reaction and the angular distribution shown in Fig. 4.10 was not fitted well by DWBA calculations assuming $\ell = 1$, especially at forward angles. Calculations assuming $\ell = 2$ gave a better fit at forward angles but a worse fit at backward angles. It was not possible from the present data to assign a spin or even the ℓ value for this transition.

The final $\ell = 1$ state excited in the present experiment is situated at 1.842 MeV. An $\ell = 1$ value was assigned to this transition by Von Ehrenstein and Schiffer [Eh 67] from the (d,p) reaction but no spin assignment was possible because of unreliable data at backward angles. This state is very close in energy to the 1.808 MeV state. The resolution achieved in the (p,d) reaction [Mc 66] was not good enough to separate these two states. From the present data an $\ell = 1$ value can be assigned to this state and a tentative spin of $3/2^-$. From the weak j -dependence at backward angles the $3/2^-$ assignment looks slightly more favourable than $1/2^-$.

4.4.3b. Other Transitions

The ground state of ^{67}Zn is known to be $5/2^-$ [Nu 68]. The angular distribution corresponding to the ground state transition displays characteristics typical of $\ell = 3$ transitions. The first maximum appears at 30° and the second maximum at 55° . After the second maximum the angular distribution shows little structure.

The 0.602 MeV level was assigned a spin of $9/2^+$ from the (d,p) reaction on ^{66}Zn [Eh 67]. The $\ell = 3$ assignment to this state from the (p,d) reaction is not convincing [Mc 66]. The angular distribution corresponding to this transition in the present work displays characteristics resembling an $\ell = 4$ transition. The DWBA calculation fits quite well at forward angles but is not as good beyond 60° . However it can be concluded that the $\ell = 4$ assignment is the most probable one.

The state at 0.978 MeV was assigned $\ell = 2$ and a tentative spin of $5/2^+$ from the (d,p) reaction on ^{66}Zn [Eh 67]. Thermal neutron capture γ -ray measurements [Ba 67] have also assigned $\ell = 2$. The (p,d) reaction on ^{68}Zn [Mc 66] was unable to make any definite assignment; the attempt to assign $\ell = 1$ was not convincing. The angular distribution for this state in the present (d,t) reaction on ^{68}Zn cannot be reproduced by DWBA calculations assuming an $\ell = 2$ transition. The most probable value for ℓ from the present data is $\ell = 0$, which would imply a spin of $1/2^+$ for this state. This value is in contradiction with the $5/2^+$ spin assignment from (d,p) or (p,p' γ) reactions [Eh 67, Si 72]. The $\ell = 0$ assignment is not a definite one but this assumption is more favourable than $\ell = 2$ in the present data. The fits to the experimental data for $\ell = 0$ or in fact for any value of ℓ are poor.

The 1.676 MeV transition was assigned $\ell = 0$ in ref. [Eh 67]. Another level situated at 1.642 MeV and excited in (d,p) could not be assigned an ℓ value. Thermal neutron capture γ -ray measurements [Ba 67]

were used to assign $\ell = 0$ to a state situated at 1.69 MeV. This level appears to be the 1.676 MeV level known to be $\ell = 0$ from (d,p). The angular distribution for this state in the present (d,t) experiment supports the $\ell = 0$ assignment. Since the 1.642 MeV level cannot be seen in the data it can be concluded that the spin of the 1.676 MeV level is $1/2^+$.

Another $\ell = 0$ state was reported at 1.808 MeV [Eh 67, Ba 67]. No information about this state was obtained from the (p,d) reaction [Mc 66]. The state is close in energy to the 1.782 MeV level [Eh 67, Nu 68] whose spin or ℓ value are not known. The energy resolution in the present experiment is not good enough to separate the 1.808 MeV and the 1.782 MeV levels. However, the energy spectrum in Fig. 4.8 does not show any sign of another transition apart from 1.808 MeV and the width of the 1.808 MeV peak is compatible with a single state. The angular distribution measured for the 1.808 MeV transition could contain a contribution from the 1.782 MeV level but the shape of the angular distribution strongly supports the $\ell = 0$ assignment. It can be concluded that the 1.782 MeV level is very weakly excited in the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ reaction and that the main contribution comes from the 1.808 MeV level. It could also be possible that the 1.782 MeV level has $\ell = 0$, in which case its contribution would not change the shape of the angular distribution.

A level at 2.172 MeV was excited in the (d,p) reaction but no information about the ℓ value could be obtained. This state is weakly excited in the (d,t) reaction but the angular distribution shows characteristics typical of an $\ell = 0$ transition. Therefore the spin of this level can be assigned the value $1/2^+$ in the present experiment.

A state at 2.246 MeV is reported in ref. [Eh 67] but it was not possible to assign an ℓ value. The angular distribution corresponding

to this level in the present (d,t) reaction resembles that for an $\ell = 0$ transition. In this case a spin of $1/2^+$ can be assigned to the 2.246 MeV state in the present experiment. The (d,p) measurements reported a weak population of the 2.273 MeV state with $\ell = 2$ transfer so that there may be a small contribution from this state to what appears to be mainly $\ell = 0$ transfer.

4.4.3c. New States ^{*)}

Two states not reported before were excited in the present (d,t) reaction. One state is situated at 1.370 MeV and the second state at 2.100 MeV. The absolute error in the energy calibration is around 20 keV. Both states are weakly excited and it is difficult to assign ℓ values from the corresponding angular distributions. The most probable ℓ value for the 2.100 MeV state is $\ell = 3$. It was not possible to distinguish between $\ell = 2$ or $\ell = 3$ from the angular distribution for the 1.370 MeV level.

4.5. j-DEPENDENCE FITS

The aim of the DWBA analysis was to find a realistic set of optical model parameters which could reproduce the observed j-dependence and give satisfactory fits to the measured angular distributions. Set D_2 could not reproduce the observed j-dependence either in $^{68}\text{Zn}(d,t)$ or in the $^{54}\text{Cr}(d,t)$ reaction. Fig. 4.12 shows the angular distributions of the 0.093 MeV, 0.185 MeV and 0.394 MeV transitions in the $^{68}\text{Zn}(d,t)$ reaction together with the DWBA fits calculated with set D_2 . The DWBA calculations do not reproduce the observed j-dependence and the fits for the other angular distributions are poor.

^{*)} These two states were observed recently in (d,p) and (^3He ,p) reactions [Is 74].

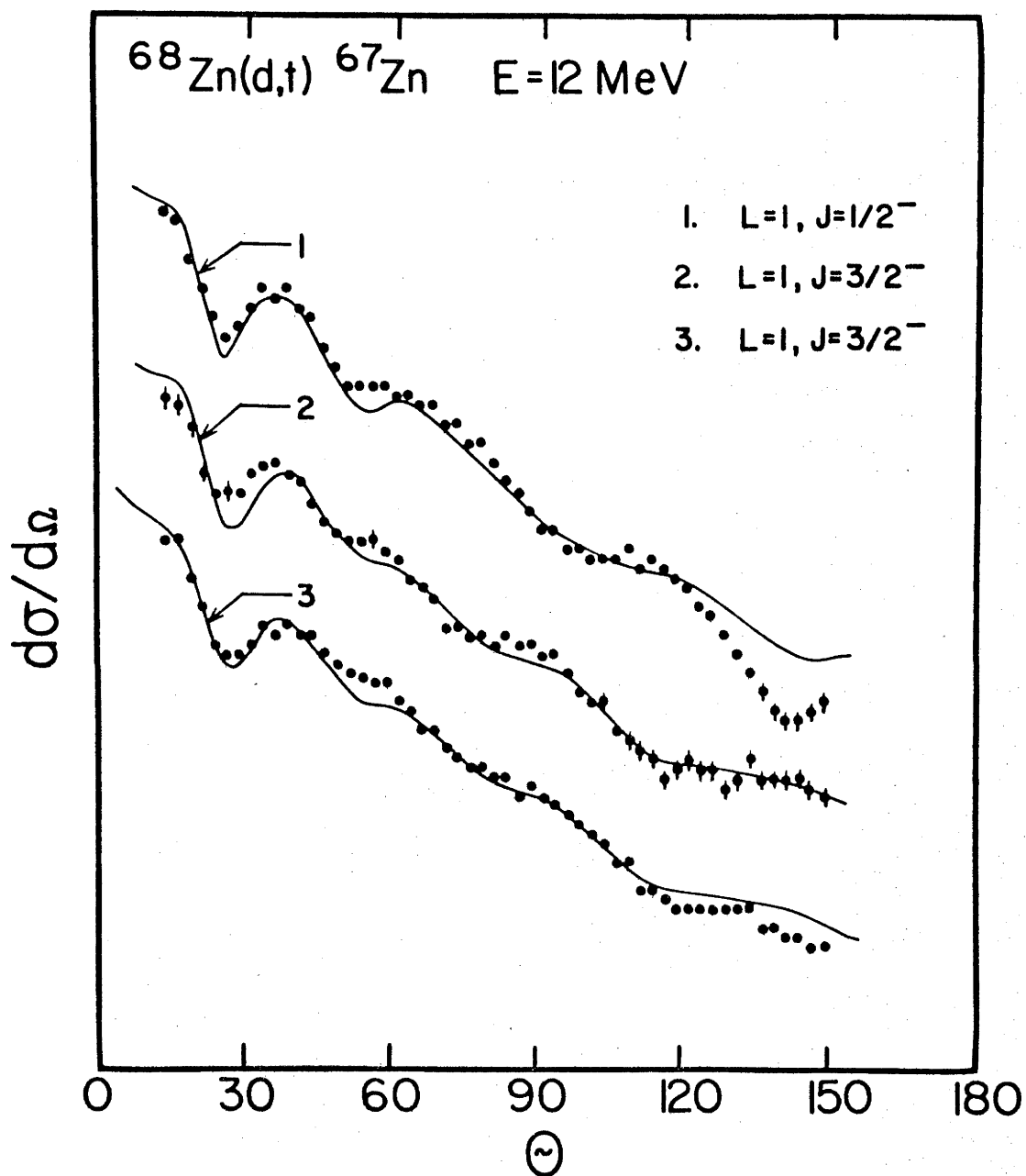


Fig. 4.11. The $l=1$ j -dependence observed for the 0.093, 0.185 and 0.394 MeV states in ^{67}Zn compared with DWBA fits calculated with set D_1 .

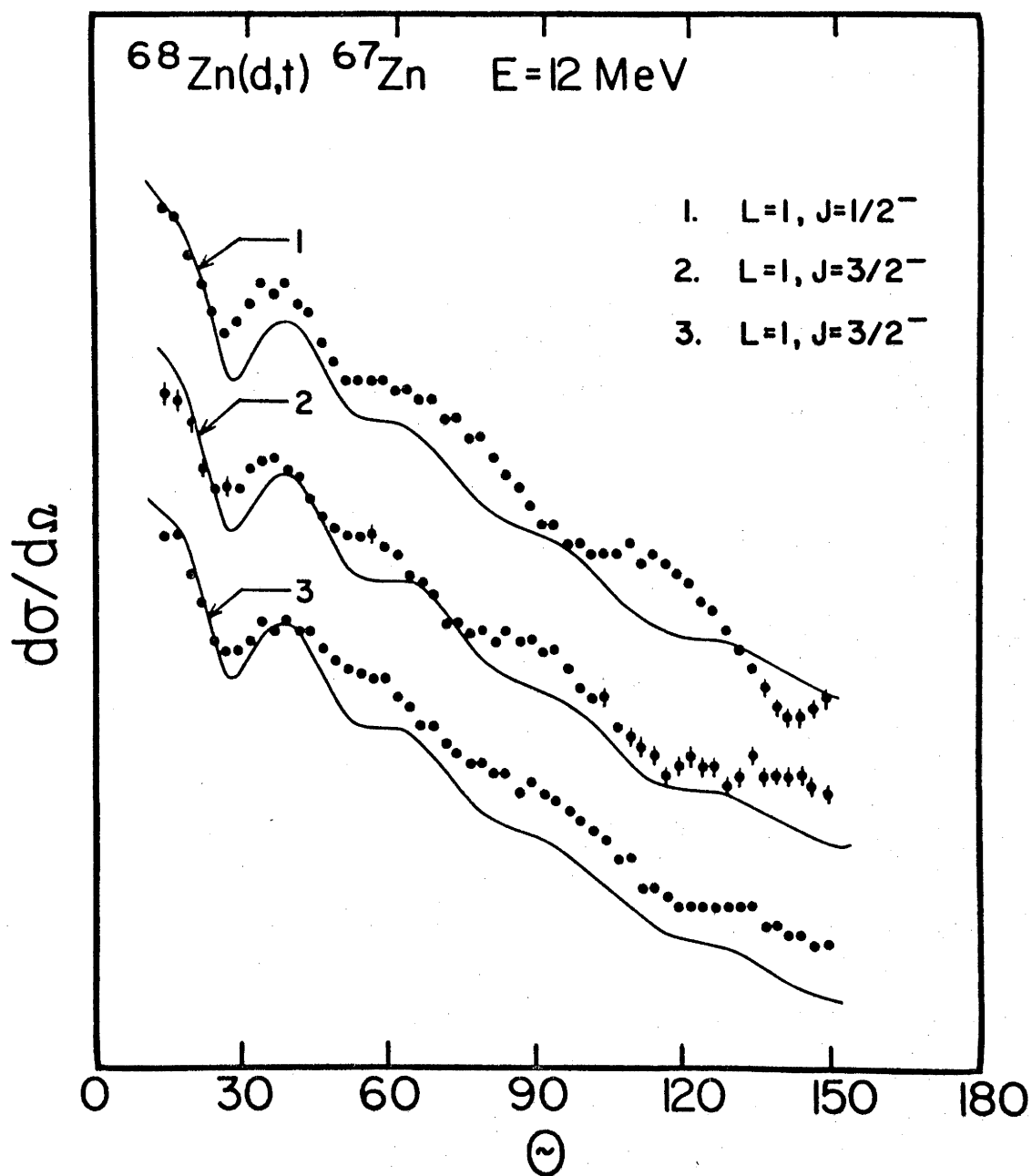


Fig. 4.12. The $l=1$ j -dependence observed for the 0.093, 0.185 and 0.394 MeV states in ^{67}Zn together with the DWBA fits calculated with set D_2 .

Fig. 4.11 shows the angular distributions for the same three transitions together with the DWBA calculations using the D_1 set of deuteron parameters. The $\ell = 1$ j -dependence in the ^{67}Zn transitions is well reproduced by these calculations and the agreement between the calculated angular distributions and the experimental ones in the $^{67,68}\text{Zn}(d,t)$ reactions are satisfactory.

The $\ell = 1$ and $\ell = 3$ j -dependence observed in the $^{54}\text{Cr}(d,t)$ reaction could not be reproduced by the DWBA calculations. Fig. 4.2 shows the measured angular distributions in this reaction together with the DWBA calculations performed with the D_1 set of deuteron parameters. The $\ell = 1$, $j = 3/2$ ground state and the $\ell = 3$, $j = 5/2$ 1.006 MeV transitions are reproduced reasonably well by the calculations. The fits for the other $\ell = 1$ ($j = 1/2$) and $\ell = 3$ ($j = 7/2$) transitions are poor. Fig. 4.4 shows that no j -dependence at forward angles is predicted by the DWBA calculations for $\ell = 3$ transitions. The angular distributions calculated by DWBA for the $\ell = 3$, $j = 5/2$ and $\ell = 3$, $j = 7/2$ transitions look very similar at the forward angles where $\ell = 3$ j -dependence appears in the experimental data. A small, almost insignificant difference appears at angles greater than 90° . The DWBA calculations for $\ell = 1$, $j = 3/2$ and $\ell = 1$, $j = 1/2$ transitions show a j -dependence effect. The calculated angular distribution corresponding to the $j = 1/2$ transition has a dip around 110° which does not appear in the angular distribution corresponding to the $j = 3/2$ transition. However this j -dependence effect shown by the calculated angular distributions does not reproduce the j -dependence seen in the experimental angular distributions.

In order to try and reproduce the $\ell = 1$ and $\ell = 3$ j -dependence observed in ^{53}Cr three more sets of deuteron parameters D_3 , D_4 and D_5 were tried. A spin-orbit part was also added to the set of triton parameters and calculations using volume absorption in the triton potential were performed. However it was noticed that the triton spin-orbit part

does not play an important role as far as the j -dependence is concerned. Its effect is almost negligible. The deuteron spin-orbit part is more important. The $\ell = 1$ and $\ell = 3$ j -dependence in ^{53}Cr could not be reproduced by any set of parameters. The fits to the angular distributions using the parameters mentioned above were not better than those given by set D_1 . It may be possible that the compound process contribution is not small, especially at backward angles. Since the DWBA calculations using deuteron sets D_2 , D_3 , D_4 and D_5 do not give better fits to the experimental angular distributions, all the calculations were done with set D_1 . This set of parameters having a small geometry spin-orbit part, was better able to reproduce the $\ell = 1$ j -dependence observed in the $^{68}\text{Zn}(d,t)$ reaction.

The small geometry in the deuteron spin-orbit potential was introduced for the first time by Schwandt and Haeberli [Sc 68] in an analysis of the scattering of polarized deuterons from ^{27}Al , ^{28}Si and ^{60}Ni and later from ^{40}Ca [Sc 69]. Differential cross-sections and polarizations were fitted over a range of energies, and good fits which proved to be insensitive to spin-orbit geometry in the range $0.5 \leq r_{so} \leq 0.9$ fm and $0.3 \leq a_{so} \leq 0.7$ fm were obtained. Yule and Haeberli [Yu 68] found that in order to reproduce the j -dependence observed in the polarization of protons from the (d,p) reaction on ^9Be , ^{12}C , ^{28}Si and ^{40}Ca , a progressively decreasing geometry was required as the mass of the target increased. The radius and diffuseness varied from 1.16 fm and 0.93 fm respectively for ^9Be to 0.65 fm and 0.5 fm for ^{40}Ca . Robson [Ro 68b] first used a small spin-orbit geometry in the deuteron optical potential in calculations of j -dependence in $^{40}\text{Ca}(d,p)^{41}\text{Ca}$ and $^{54}\text{Fe}(d,p)^{55}\text{Fe}$. Values of $r_{so} = 0.7$ fm and $a_{so} = 0.4$ fm were used.

It appears that in several cases, both in polarization measurements and j -dependence of cross-sections, a small geometry spin-orbit term in the deuteron optical model potential can give better fits to the data than the conventional geometry as usually employed for the central potential.

More data would be required concerning the j -dependence and deuteron polarization to establish the significance of the small geometry parameters for the spin-orbit potential in describing the nuclear processes. Differential cross-sections of deuteron elastic scattering are not sensitive to changes in the spin-orbit potential.

The fits to the $\ell = 1$ j -dependence from the $^{68}\text{Zn}(d,t)$ reaction in the present measurements show that a small geometry spin-orbit term in the deuteron optical model potential does a reasonably good job of reproducing the data.

4.6. SPECTROSCOPIC FACTORS

4.6.1. Extraction from Experimental Data.

The theoretical cross-section in terms of a quantity $\sigma_{\text{DW}}(\theta)$ calculated by the code DWUCK is given by

$$\frac{d\sigma(\theta)}{d\Omega} = F \cdot S_{\ell j} \cdot \frac{1}{2j_n + 1} \sigma_{\text{DW}}(\theta) \quad (4.11)$$

where $S_{\ell j}$ is the spectroscopic factor, j_n is the total angular momentum of the transferred neutron and F is an additional factor which includes corrections for the strength of the interaction and the overlap of the light particle wave functions. Assuming Hulthén wave functions for deuterons and Irving-Gunn wave functions for mass-3 particles, the calculated value for this factor is 3.33 for (d,t) reactions. The spectroscopic factors $S_{\ell j}$ are obtained by comparing absolute values of the experimental and theoretical cross-sections for each state separately.

The most common method used in extracting $S_{\ell j}$ is to match the calculated and the experimental angular distributions at the main maximum where cross-sections are largest and contain relatively small contributions from compound nucleus formation.

This method is not entirely satisfactory. Although the shape and

position of the main peak is quite stable, the absolute cross-section is sensitive to parameter changes and therefore the spectroscopic factors depend on the set of parameters chosen.

In the present data the spectroscopic factors were extracted by matching the calculated and the experimental angular distributions over an entire range of angles for which the fits were deemed satisfactory. The emphasis was on forward angles where the fits are better and statistical errors smaller. All relevant figures in this thesis display the way the distributions were matched in each case. Considering errors due to matching angular distributions, variations in optical model parameters and experimental uncertainties, the error of the spectroscopic factors is estimated to be $\approx 25\%$.

Spectroscopic factors determined from the $^{54}\text{Cr}(d,t)^{53}\text{Cr}$ reaction are presented in Table 4.2 together with spectroscopic factors from earlier (d,t) , (p,d) and $(^3\text{He},\alpha)$ reactions on ^{54}Cr . They are in reasonably good agreement with the previous work.

Table 4.3 presents the spectroscopic factors determined from the angular distributions measured for the $^{67}\text{Zn}(d,t)^{66}\text{Zn}$ reaction together with spectroscopic factors extracted from previous $^{67}\text{Zn}(p,d)^{66}\text{Zn}$ data. The agreement is good for the $\ell = 1$ transitions but a clear discrepancy exists for both $\ell = 3$ transitions excited in this reaction. The values derived from the (p,d) reaction are twice as large as those from the (d,t) reaction. Table 4.3 also presents the adopted spins and parities for the levels in the ^{66}Zn nucleus.

Table 4.4 presents the spectroscopic factors derived from the $^{68}\text{Zn}(d,t)^{67}\text{Zn}$ reaction compared with those derived from earlier (p,d) and (d,p) reactions leading to ^{66}Zn . The agreement between the (d,t) and (p,d) data is good. Adopted spins and parities for levels in ^{67}Zn are also presented in Table 4.4.

4.6.2. Discussion

The total spectroscopic strength from the present measurements can be compared to that from the (p,d) work of McIntyre [Mc 66] and also to that predicted from the sum rules of Macfarlane and French [Fr 61]. The total spectroscopic strength is split between states with isospin $T_< = T_0 - 1/2$ and $T_> = T_0 + 1/2$, where T_0 is the isospin of the target. States with the larger $T_>$ are known [Sh 65] to lie at high excitation in this region and are not expected to be observed here. The spectroscopic strength for pick-up from a given subshell is given by [Fr 61]

$$\sum_{T_<=T_0-1/2} S \equiv \sum S_< = \nu - \pi/(N-Z+1) \quad (4.12)$$

where ν is the number of neutrons and π the number of protons in the valence subshells. The number of neutrons and protons in the target are given by N and Z respectively.

The sum of the spectroscopic factors for all transitions corresponding to pick-up from a particular subshell should equal the average number of neutrons in the corresponding subshell in the target nucleus. These sums over all the spectroscopic factors are called occupation numbers. Ignoring pick-up from the $f_{7/2}$ shell and below, the total summed spectroscopic factor expected in the present (d,t) reactions on $^{67,68}\text{Zn}$ targets is expected to be $N-28$. Since only the $T_< = T_0 - 1/2$ states are observed, the sums should be compared with

$$\sum S_< = (N-28) - \pi/(N-Z+1) \quad (4.13)$$

where π is the number of protons above the $f_{7/2}$ shell, which is two for the Zn isotopes.

The total $\ell = 1$ strength in ^{66}Zn from the present work gives 2.19 which compares favourably with the 2.44 of McIntyre (the states at 4.000

and 4.088 MeV were omitted) [Mc 66]. The Macfarlane-French sum rule gives a total strength of 3.75 for $\ell = 1$ transitions. The sum rule prediction for $\ell = 3$ gives 5.0, which is considerably larger than the 0.91 of McIntyre and a value of only 0.49 from the present work. Since the ground state spin of ^{67}Zn is $5/2^-$, all states assigned to be $\ell = 1$ transfer could also have an $\ell = 3$ component. As for the (p,d) work, this seems to be the most likely explanation for the large discrepancy in $\ell = 3$ strength.

It can be safely assumed that all the strength of the f-p shell is seen in the present work on ^{67}Zn . This statement is also supported by results from the $^{66}\text{Zn}(d,p)^{67}\text{Zn}$ reaction [Eh 67]. It is therefore possible to compare the experimental results with the predictions of the simple pairing theory [Ki 60] which has been fairly successful in predicting both occupation probabilities and centre of gravity energies for a wide range of nuclei.

It is well known that the pairing interaction, which represents the most important component of the residual interactions, couples together pairs of identical nucleons to total spin zero. This causes configuration mixing between the shell model states and all the orbits of the outer shell are partially filled. The probability that an orbit is occupied is denoted by V_j^2 and is called filling coefficient. Because of the pairing interaction the single particle strength is split over the final nuclear states. The mean energy of the states over which the ℓj orbit is split is called centre of gravity energy $E_{\ell j}$ and corresponds to the effective single particle energy. Table 4.5 lists the experimental filling coefficients V_j^2 and centre of gravity energies E_j calculated using the relations

$$V_j^2 = N \frac{\sum_i S_i(\ell, j)}{(2j+1)} \quad (4.14)$$

TABLE 4.5

COMPARISON OF THE DERIVED FILLING COEFFICIENTS AND CENTRE OF GRAVITY
ENERGIES WITH THE PREDICTIONS OF THE PAIRING THEORY

ℓ_j	$\Sigma S_i(\ell, j)$	$n_j^{c)}$	v_j^2		E_j	
			Exp. ^{a)}	Theory ^{b)}	Exp. ^{a)}	Theory ^{b)}
$f_{5/2}$	4.29	5.23	0.87	0.79	0.21	0.32
$p_{1/2}$	0.77	0.94	0.47	0.16	0.35	0.54
$p_{3/2}$	2.26	2.76	0.69	0.85	0.44	0.58
$g_{9/2}$	0.88	1.04	0.10	0.16	0.60	0.55

a) Present work.

b) Ref. [Ki 60] using the following parameters:

gap parameter $G = 24/A$ for $A = 68$, $\lambda = 1.384$ MeV,

$\Delta = 1.458$ MeV, $\epsilon_{3/2} = -0.043$ MeV, $\epsilon_{5/2} = 0.371$ MeV,

$\epsilon_{1/2} = 2.742$ MeV, $\epsilon_{9/2} = 2.758$ MeV.

c) Using $N = 1.22$ (see text).

$$E_j = \frac{\sum_i S_i(\ell, j) E_x^i(j)}{\sum_i S_i(\ell, j)} \quad (4.15)$$

$$\text{and} \quad n = N \sum_{ij} S_i(\ell, j) \quad (4.16)$$

where $S_i(\ell, j)$ is the experimental spectroscopic factor for (ℓ, j) pick-up to state i , $E_x^i(j)$ is the excitation energy of this state, $n = 10$ is the number of neutrons in the f-p shell for ^{68}Zn and N is a constant which normalises the total extracted spectroscopic strength to the sum rule value. The experimental values of V_j^2 and E_j were compared with the theoretical predictions calculated from the relations

$$V_j^2 = \frac{1}{2} \left[1 - \frac{\epsilon_j^{-\lambda}}{[(\epsilon_j - \lambda)^2 + \Delta^2]^{1/2}} \right] \quad (4.17)$$

$$\text{and} \quad E_j = [(\epsilon_j - \lambda)^2 + \Delta^2]^{1/2} - \Delta \quad (4.18)$$

where ϵ_j , λ and Δ are the single particle energies, the chemical potential and the gap parameter, all defined in ref. [Ki 60]. The single particle energies were derived using the relations given in ref. [Ki 60] and the values suggested for $A = 58$ by Fournier et al. [Fo 73]. The parameters λ and Δ were determined by solving the gap equations [Ki 60] using the parameters listed in Table 4.5.

It can be seen from Table 4.5 that, in general, the experimental results are reasonably close to the predictions of the pairing theory. However, a marked difference occurs for the $p_{1/2}$ filling coefficient which is considerably larger than that predicted. These conclusions confirm earlier discrepancies for $V_{1/2}^2$ in the vicinity of neutron number $N = 40$. The filling coefficient derived from both (d,p) measurements [Eh 67] on Zn and (p,d) work [Fo 73] on Ge for $p_{1/2}$ transfer agree with the

present measurement in that all values are much larger than predicted by the pairing theory.

CHAPTER 5

THE (p,t) REACTION ON ^{78}Se AND ^{76}Se

5.1 PREVIOUS WORK ON ^{74}Se AND ^{76}Se

The energy levels of ^{76}Se have been the object of many works that studied the β -decay of both ^{76}As (26 h) [St 58, Na 73] and ^{76}Br (16 h) [Dz 69]. These levels have also been studied by Coulomb excitation [St 62] and by (p,p') [Da 63], (d,d') [Li 65a], (α ,xn γ) [Li 70], (HI,xnypz $\alpha\gamma$) [No 70] and (d,t) [Li 65b] reactions. High resolution gamma-gamma coincidence and directional-correlation measurements following the β -decay of ^{76}As and ^{76}Br have identified a total of 27 levels in ^{76}Se . However unambiguous spins and parities have been assigned for only a few of these levels. Very little spectroscopic information exists about ^{76}Se from transfer reactions.

The states of ^{74}Se have been studied following the β -decay of ^{74}Br [La 69] and a few low-lying levels observed from the β -decay of ^{74}As [Ku 68]. The most extensive study of the decay of ^{74}Br was done by Coban et al. [Co 72a]. In this work 39 levels in ^{74}Se were reported but definite spins and parities were assigned for only a few of these low-lying levels from angular correlation measurements. Lieder and Draper [Li 70] using Ge(α ,xn γ) reactions, reported a sequence of even parity, even angular momentum states up to 8^+ . This same sequence of states was also found by Nolte et al. [No 70] following (HI,xnypz $\alpha\gamma$) reactions. No other nuclear reactions leading to the ^{74}Se final nucleus have been performed.

The present study is aimed at providing the first detailed transfer reaction information on these Se isotopes. The well-known highly selective nature of the (p,t) reaction might also make it possible to distinguish

between some of the spin-parity options determined from the γ angular correlation works.

The two-nucleon transfer DWBA is often used to calculate the angular distributions measured in (p,t) reactions. While the approximations used in the DWBA calculations make it impossible to predict absolute cross-sections, DWBA has often been used successfully in predicting the shape of the angular distributions and hence the angular momentum L transferred. However in the $1f_{7/2}$ shell it has been shown by Baer et al. [Ba 73] that it is often difficult to make unique L transfer determinations because of the sensitivity of the calculated angular distributions to the input parameters and choice of pick-up configurations. Another aim of the present study is to test the reliability of DWBA in this mass region by comparing the experimental angular distributions for states of well known spin with calculations made using as large a range of triton optical model parameters as are available.

5.2 DWBA CALCULATIONS

The measured angular distributions were compared with DWBA calculations using the code DWUCK. The calculations were carried out in the distorted waves Born approximation assuming a zero-range interaction between the proton and the centre of mass of the two neutrons. No finite-range corrections were attempted. Corrections for non-locality were made using the same non-local range factors as were used in the (d,t) calculations. The neutron bound state wave functions were also calculated using the same neutron parameters as for the case of the (d,t) reaction. The neutron well depths V_n were adjusted to give each neutron a binding energy of $-0.5 (S_{2n} + E_x)$, where S_{2n} is the two-neutron separation energy and E_x the excitation energy in the residual nucleus.

5.2.1. Proton Potential

Two sets of proton optical model parameters were tried in the present DWBA analysis. The set P_1 was calculated from a set of formulae derived by Menet et al. [Me 71]. They obtained this set from systematics extending from 30 to 60 MeV and included reaction cross-sections to help in determining the imaginary potential. The set of formulae is given as

$$\begin{aligned}
 V_o &= 49.9 - 0.22 E + 26.4 (N-Z)/A + 0.4 (Z)/A^{1/3} \text{ MeV,} \\
 r_o &= 1.16 \text{ fm,} \quad a = 0.75 \text{ fm,} \\
 W &= 1.2 + 0.09 E \text{ MeV,} \\
 W_D &= 4.2 - 0.05 E + 15.5 (N-Z)/A \text{ MeV,} \\
 r' = r_W = r_D &= 1.37 \text{ fm,} \quad a' = a_W = a_D = 0.74 - 0.008 E \\
 &\quad + 1.0 (N-Z)/A \text{ fm,} \\
 V_S &= 6.04 \text{ MeV} \\
 \text{and } r_S &= 1.064 \text{ fm,} \quad a_S = 0.78 \text{ fm.}
 \end{aligned} \tag{5.1}$$

The second set of proton parameters P_2 were calculated using the formulae derived by Becchetti and Greenlees [Be 69a]. They fitted a large number of elastic differential cross-sections and polarization data for $A > 40$ and $E < 50$ MeV. This set is determined from

$$\begin{aligned}
 V_o &= 54.0 - 0.32 E + 24 (N-Z)/A + 0.4 (Z)/A^{1/3} \text{ MeV,} \\
 r_o &= 1.17 \text{ fm,} \quad a = 0.75 \text{ fm,} \\
 W &= 0.22 E - 2.7 \text{ MeV or zero whichever is greater,} \\
 W_D &= 11.8 - 0.25 E + 12 (N-Z)/A \text{ MeV or zero whichever} \\
 &\quad \text{is greater,} \\
 r' = r_W = r_D &= 1.32 \text{ fm,} \quad a' = a_W = a_D = 0.51 + 0.7 (N-Z)/A \text{ fm,} \\
 V_S &= 6.2 \text{ MeV} \\
 \text{and } r_S &= 1.01 \text{ fm,} \quad a_S = 0.75 \text{ fm.}
 \end{aligned} \tag{5.2}$$

The proton parameters calculated using these sets of formulae are

given in Table 5.1 where it can be seen that there is little difference between these two sets. The DWBA analysis was carried out using the Becchetti-Greenlees set of parameters P_2 .

5.2.2. Triton Potential

Four sets of triton optical model parameters were tried in the present analysis. Two sets use volume absorption and the other two sets use surface absorption. The four sets of triton parameters are given in Table 5.1 as T_1 , T_2 , T_3 and T_4 .

Set T_1 was calculated from a set of formulae derived by Becchetti and Greenlees [Be 70] from an optical model analysis of ^3He and triton elastic scattering data on nuclei of mass $A > 40$ and energies $E < 40$ MeV. This set was derived from the formulae

$$\begin{aligned}
 V_O &= 165.0 - 0.17 E - 6.4 (N-Z)/A \quad \text{MeV}, \\
 r_O &= 1.20 \text{ fm}, \quad a = 0.72 \text{ fm}, \\
 W &= 46.0 - 0.33 E - 110 (N-Z)/A \quad \text{MeV}, \\
 r' &= r_W = 1.40 \text{ fm}, \quad a' = a_W = 0.84 \text{ fm}, \\
 V_S &= 2.5 \text{ MeV} \\
 \text{and } r_S &= 1.20 \text{ fm}, \quad a_S = 0.72 \text{ fm}.
 \end{aligned} \tag{5.3}$$

No polarization data were considered in T_1 . The analysis was done using volume absorption.

The sets T_2 and T_2' were derived from an optical model analysis of the elastic scattering of 20 MeV tritons from 17 nuclei ranging from ^{40}Ca to ^{208}Pb . The analysis was carried out by Flynn, Armstrong, Beery and Blair [Fl 69]. Two parameter families based on real well radius parameters of 1.24 and 1.16 fm were considered in their analysis. The optical model potential was of volume absorption type. From this analysis

TABLE 5.1
Summary of the Proton and Triton Optical Model Parameters used in the present (p,t) work.

Particle	Set	Target	V_o (MeV)	r_o (fm)	a (fm)	W (MeV)	W_D (MeV)	r' (fm)	a' (fm)	V_s (MeV)	r_s (fm)	a_s (fm)	Ref.
p	P ₁	⁷⁸ Se	49.2	1.16	0.75	4.17	4.54	1.37	0.6	6.04	1.064	0.78	[Me 71]
p	P ₁	⁷⁶ Se	48.6	1.16	0.75	4.17	4.18	1.37	0.58	6.04	1.064	0.78	[Me 71]
p	P ₂	⁷⁸ Se	49.7	1.17	0.75	4.56	5.09	1.32	0.6	6.2	1.01	0.75	[Be 69a]
p	P ₂	⁷⁶ Se	49.17	1.17	0.75	4.56	4.8	1.32	0.58	6.2	1.01	0.75	[Be 69a]
t	T ₁	^{76,78} Se	161.0	1.20	0.72	25.60		1.40	0.84	2.5	1.20	0.72	[Be 70]
t	T ₂	^{76,78} Se	152.5	1.24	0.68	23.00		1.43	0.88				[Fl 69]
t	T' ₂	^{76,78} Se	169.0	1.16	0.74	22.00		1.5	0.83				[Fl 69]
t	T ₃	^{76,78} Se	135.7	1.1	0.853		28.5	1.308	0.75				(Br 73b)
t	T ₄	^{76,78} Se	152.9	1.23	0.72		29.7	1.15	0.85				[Nu 74]

Flynn et al. derived expressions for the imaginary part of the optical potential given by

$$\begin{aligned} W &= 38.2 - 121.8 (N-Z)/A \text{ MeV for } r' = 1.24 \text{ fm} \\ \text{and } W &= 37.5 - 127.4 (N-Z)/A \text{ MeV for } r' = 1.16 \text{ fm.} \end{aligned} \quad (5.4)$$

These expressions were used to calculate the parameters W for the sets T_2 and T_2^1 shown in Table 5.1. The other parameters V_o , a , r' , a' were obtained by averaging the parameters given by Flynn for different nuclei.

The set T_3 was used by Baer et al. [Ba 73] for the analysis of the (p,t) reaction on the even-A titanium isotopes. This set was derived by Braid et al. [Br 73b] and uses surface absorption. An energy dependence [Ba 73] of the form

$$\begin{aligned} V_o &= 138.8 - 0.157 E_t \text{ MeV} \\ \text{and } 4W_D &= 149.8 - 2.083 E_t + 0.0148 E_t^2 \text{ MeV} \end{aligned} \quad (5.5)$$

was used to calculate the parameters V_o and W_D , where here E_t is the triton laboratory energy. Braid's potential describes large sets of triton elastic scattering data in the range 20-80 MeV.

The set T_4 is another set of parameters that uses surface absorption. This set was obtained from an analysis of 20 MeV (t,t) scattering on $A \geq 40$ nuclei [Nu 74] in which no a-priori fixed value for the real well radius was assumed. The same analysis generated the triton optical model parameters employed in the analysis of the angular distributions from the (d,t) reactions and is described in Chapter 4. Since the energy of the tritons emerging from the (p,t) reaction is about 20 MeV no energy dependent corrections for the depths V_o and W_D were made.

5.2.3. Fits to the Data

The angular distributions for states of well known spins and

parities in ^{74}Se and ^{76}Se were compared with the DWBA calculations in order to try and choose a set of optical model parameters which fits the data best.

Fig. 5.1 shows the angular distributions for 11 such transitions in ^{74}Se and ^{76}Se together with DWBA calculations employing the sets (P_2, T_2) and (P_2, T_1) , both of which use volume absorption. It can be seen that for the Flynn triton parameters the fits to the angular distributions for the 0^+ ground state transitions are poor. The minima in the data are much deeper than is predicted by calculations and the first maximum is shifted towards forward angles by 2.5° for both nuclei. The angular distribution for the 2.726 MeV 0^+ transition in ^{74}Se is fairly well reproduced apart from the position of the first maximum. The fit is very poor for the 1.122 MeV 0^+ transition in ^{76}Se . The shape of the angular distributions for the 2^+ two-phonon states is better reproduced than for the 2^+ one-phonon states for both nuclei. The calculations fail to reproduce the first maximum of the angular distributions for both the 2.350 MeV 3^- state in ^{74}Se and the 2.429 MeV 3^- state in ^{76}Se .

The second set (P_2, T_1) of parameters using volume absorption in the triton potential gives better overall fits to the data than the set (P_2, T_2) . The minima in the angular distributions for the 0^+ ground state transitions are better reproduced and the fits to the angular distributions of the 1.216 MeV and 1.269 MeV 2^+ states are fairly good. The calculations fail to reproduce the angular distributions of either the 0.559 MeV and 0.635 MeV 2^+ one-phonon states or the 2.429 MeV and 2.350 MeV 3^- states. The shift of the first maximum in the data for the 0^+ transitions by 2.5° towards forward angles still exists and the fit to the angular distribution of the 1.122 MeV 0^+ transition in ^{76}Se is as bad as with set (P_2, T_2) .

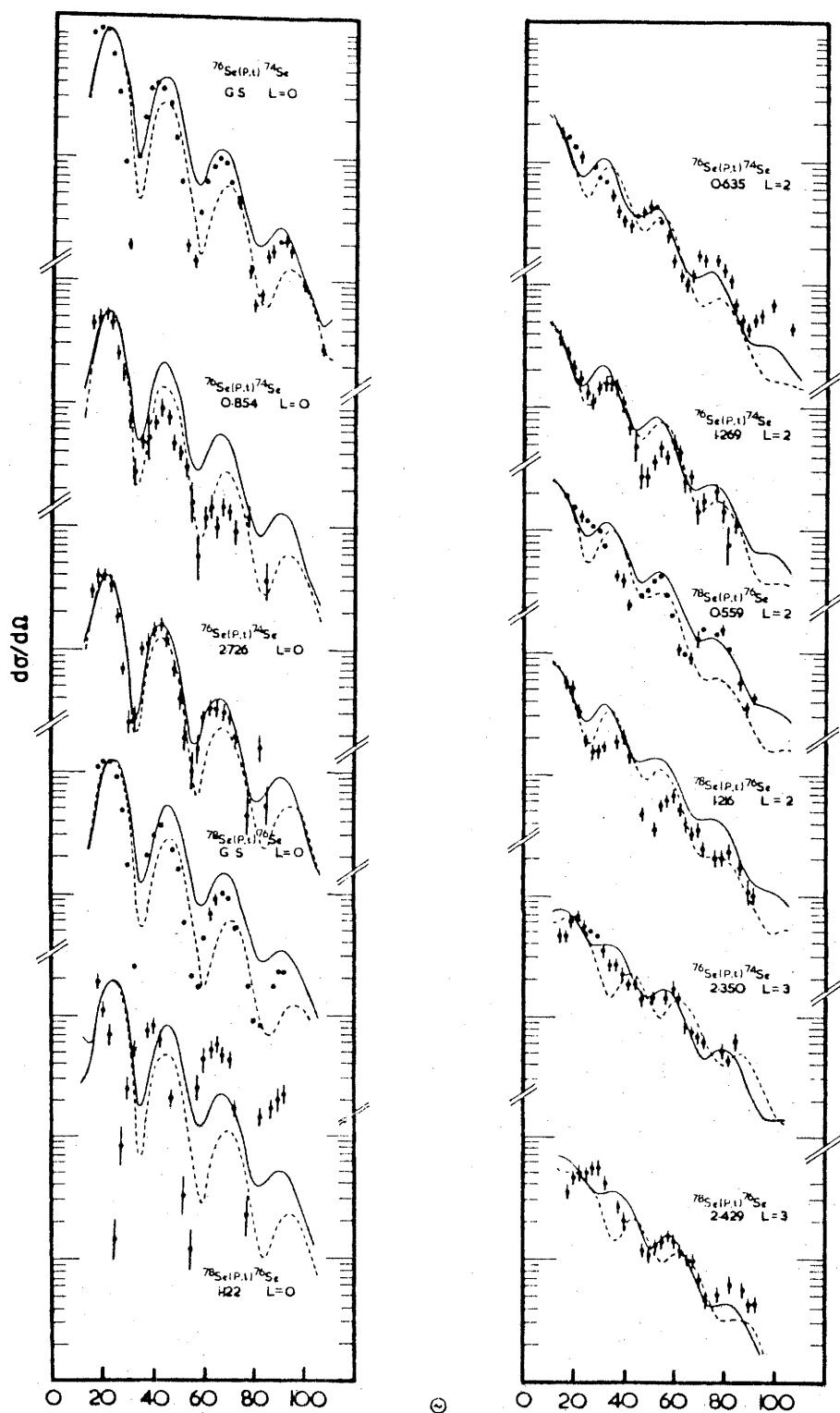


Fig. 5.1. Angular distributions from the $^{76}\text{Se}(p,t)^{74}\text{Se}$ and $^{78}\text{Se}(p,t)^{76}\text{Se}$ reactions for some states of known spin and parity. The solid line represents the DWBA predictions using the set (P_2, T_2) of optical model parameters. The dashed curve shows the DWBA predictions for the set (P_2, T_1) .

Fig. 5.2 presents the same angular distributions as in Fig. 5.1 together with DWBA calculations employing the sets of parameters (P_2, T_3) and (P_2, T_4) both of which use surface absorption in the triton potential. The set (P_2, T_3) gives a noticeable improvement in fitting the angular distributions for the 2.429 MeV and 2.350 MeV 3^- states. There is no significant difference between sets (P_2, T_3) and (P_2, T_1) as far as fitting the other angular distributions is concerned; any differences are slight. The set (P_2, T_4) however gives slightly better overall fits than any other set, apart from the fits to the 3^- states which are better reproduced by the set (P_2, T_3) .

The fact that the triton potential employing surface absorption gives better DWBA fits to the (p, t) data than that using volume absorption was also found by Baer et al. [Ba 73]. A strong energy dependence was noticed in the DWBA calculations during the present analysis. The shapes of the angular distributions especially at forward angles changed quite rapidly with a few MeV change in the triton energy.

The angular distributions measured in the present experiment are presented in Figs. 5.4, 5.5, 5.7 and 5.8 together with zero-range DWBA calculations using either the set (P_2, T_4) or both the (P_2, T_4) and (P_2, T_3) sets. Any differences in the fits given by the sets of proton parameters P_1 and P_2 are insignificant.

5.3 $^{76}\text{Se}(p, t)^{74}\text{Se}$

The triton energy spectrum at 27.5° from the $^{76}\text{Se}(p, t)^{74}\text{Se}$ reaction is shown in Fig. 5.3. Angular distributions for 19 states in ^{74}Se were extracted. Two states are strongly excited in comparison with the others; the 0^+ ground state and the first excited 2^+ state situated at 0.635 MeV. Another state strongly excited in this reaction is the state at 2.350 MeV which has been assigned a spin and parity of 3^- in the present

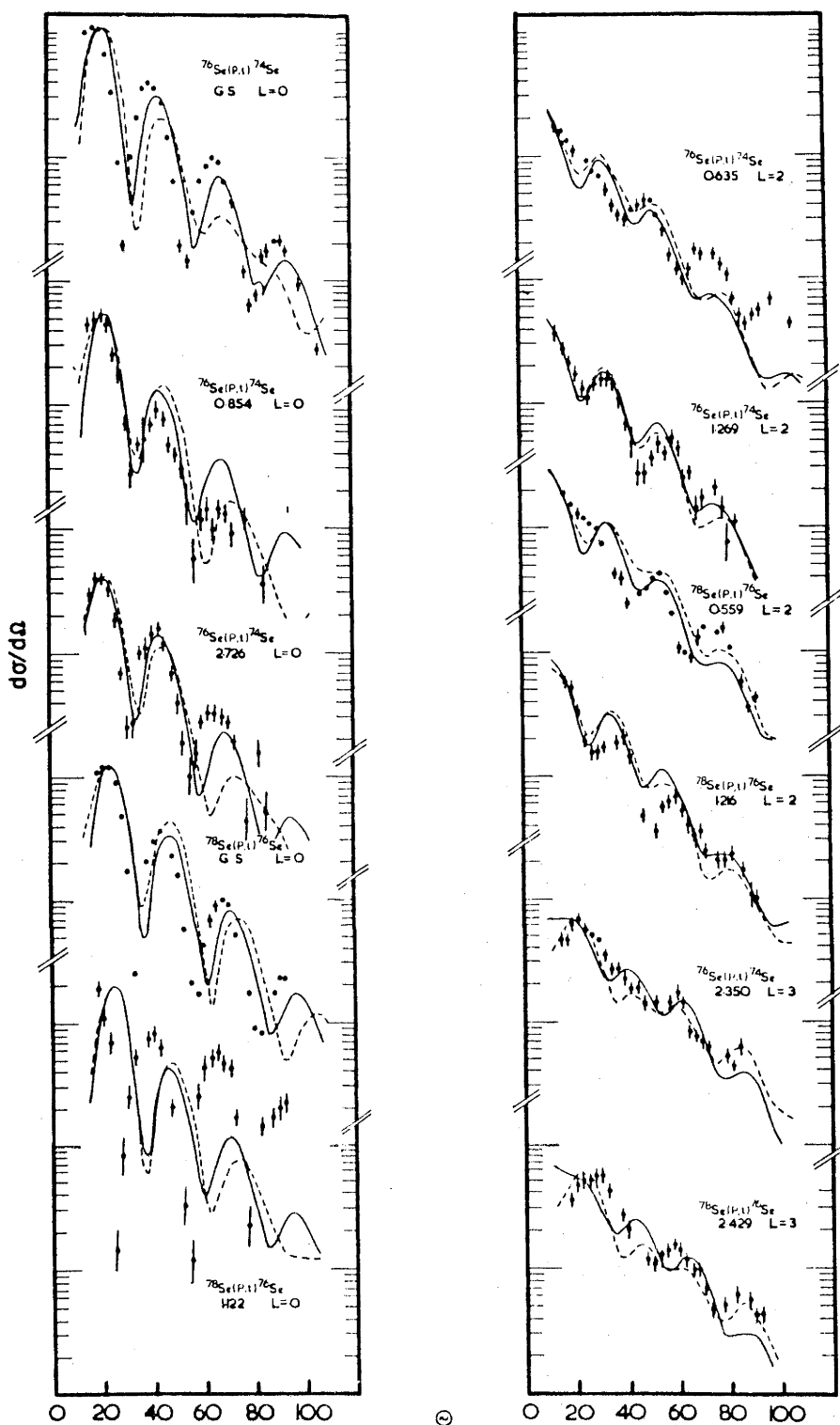


Fig. 5.2. Angular distributions from the $^{76}\text{Se}(p,t)^{74}\text{Se}$ and $^{78}\text{Se}(p,t)^{76}\text{Se}$ reactions for some states of known spin and parity. The solid line represents the DWBA predictions using the set (P_2, T_4) of optical model parameters. The dashed curve shows the DWBA predictions for the set (P_2, T_3) .

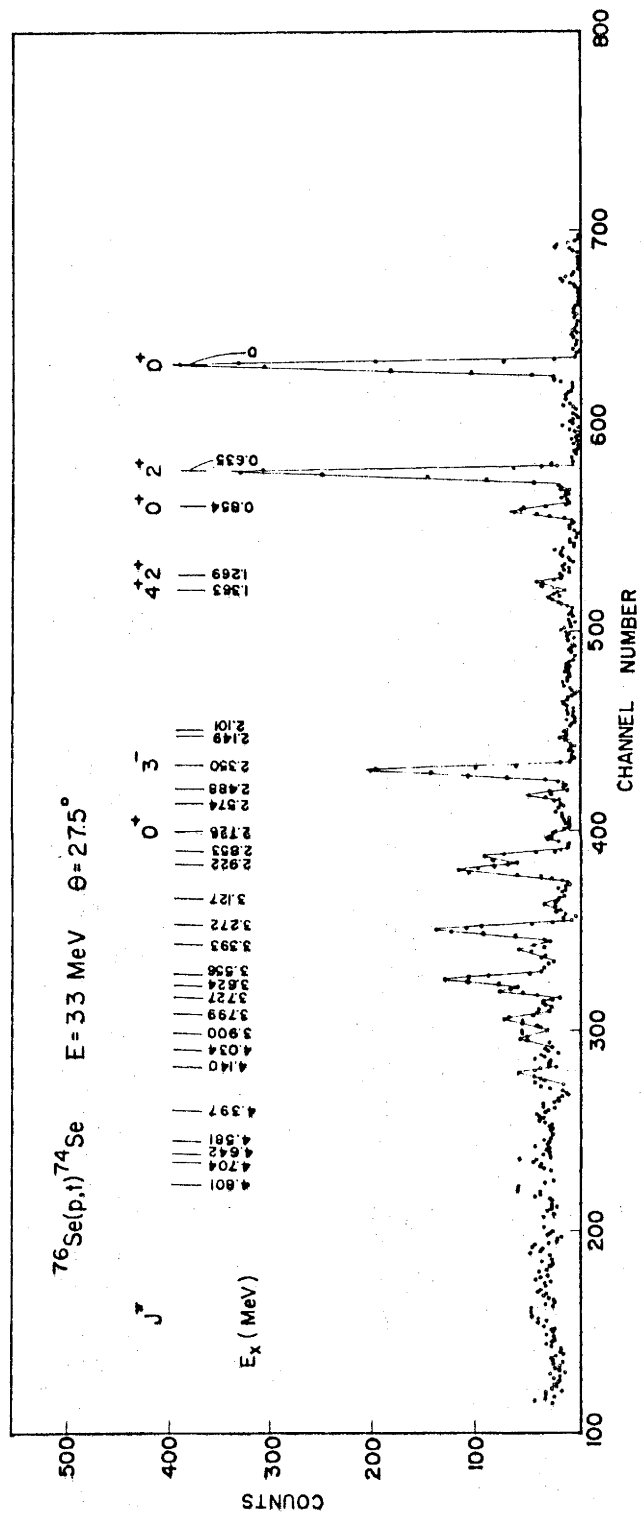


Fig. 5.3. Triton spectrum from the $^{76}\text{Se}(p,t)^{74}\text{Se}$ reaction.

work. Table 5.2 shows the levels in ^{74}Se excited in the present work together with levels reported from previous works.

5.3.1. Discussion of Results

5.3.1a. $L = 0$ Transitions

Figs. 5.4 and 5.5 show the angular distributions measured for the $^{76}\text{Se}(p,t)^{74}\text{Se}$ reaction together with the DWBA calculations. Three transitions display the typical shape of $L = 0$ transitions in (p,t) reactions. The angular distributions have an oscillatory pattern with pronounced maxima and minima.

The angular distribution for the $L = 0$ ground state transition was measured in the angular range from 15° to 107.5° . In this range the distribution has four pronounced maxima and three minima, the cross-sections varying from 0.99 mb/sr on the first maximum to 0.002 mb/sr at 107.5° . The second $L = 0$ transition observed in the present experiment is for the 0.854 MeV 0^+ state of the two-phonon triplet [St 62, Li 65a]. The third $L = 0$ transition corresponds to the 0^+ state at 2.726 MeV energy. This state has not been reported before.

The ground state transition is much more strongly excited than the other two $L = 0$ transitions. The peak cross-section for the ground state transition is more than 20 times larger than the peak cross-sections for the other two $L = 0$ transitions. It has been found from other (p,t) reactions [Br 73a] that $L = 0$ transitions from nuclei far away from neutron shell closure usually proceed strongly to the ground state only. The present data from both isotopes studied are in agreement with this empirical observation.

The shapes of these $L = 0$ angular distributions are typical of those observed in other (p,t) work. It is easy to assign spins for these states in a (p,t) reaction. The new state at 2.726 MeV in ^{74}Se

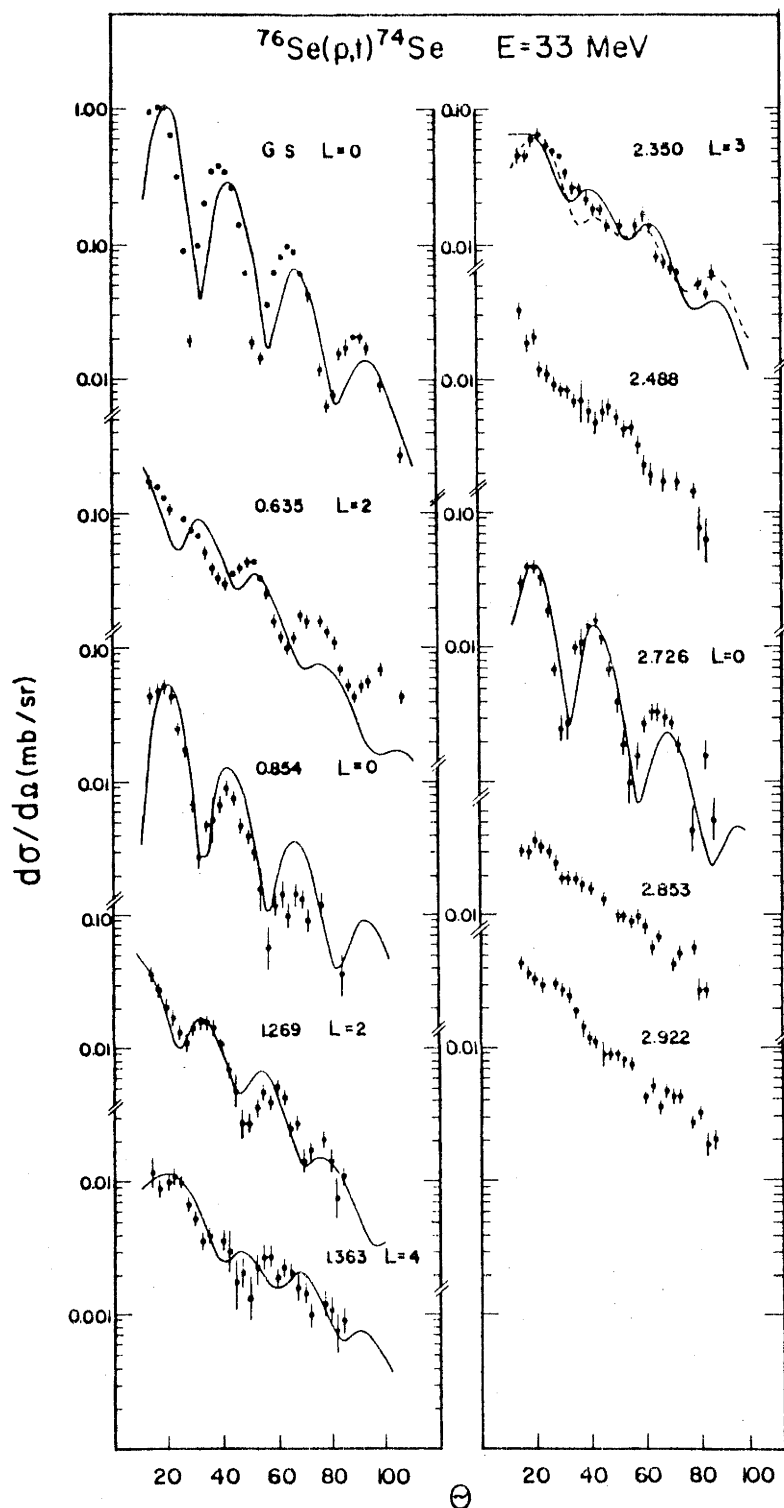


Fig. 5.4. Angular distributions from the $^{76}\text{Se}(p,t)^{74}\text{Se}$ reaction. The solid line represents the DWBA predictions using the set (P_2, T_4) of optical model parameters. The dashed curve shows the DWBA predictions for the set (P_2, T_3) .

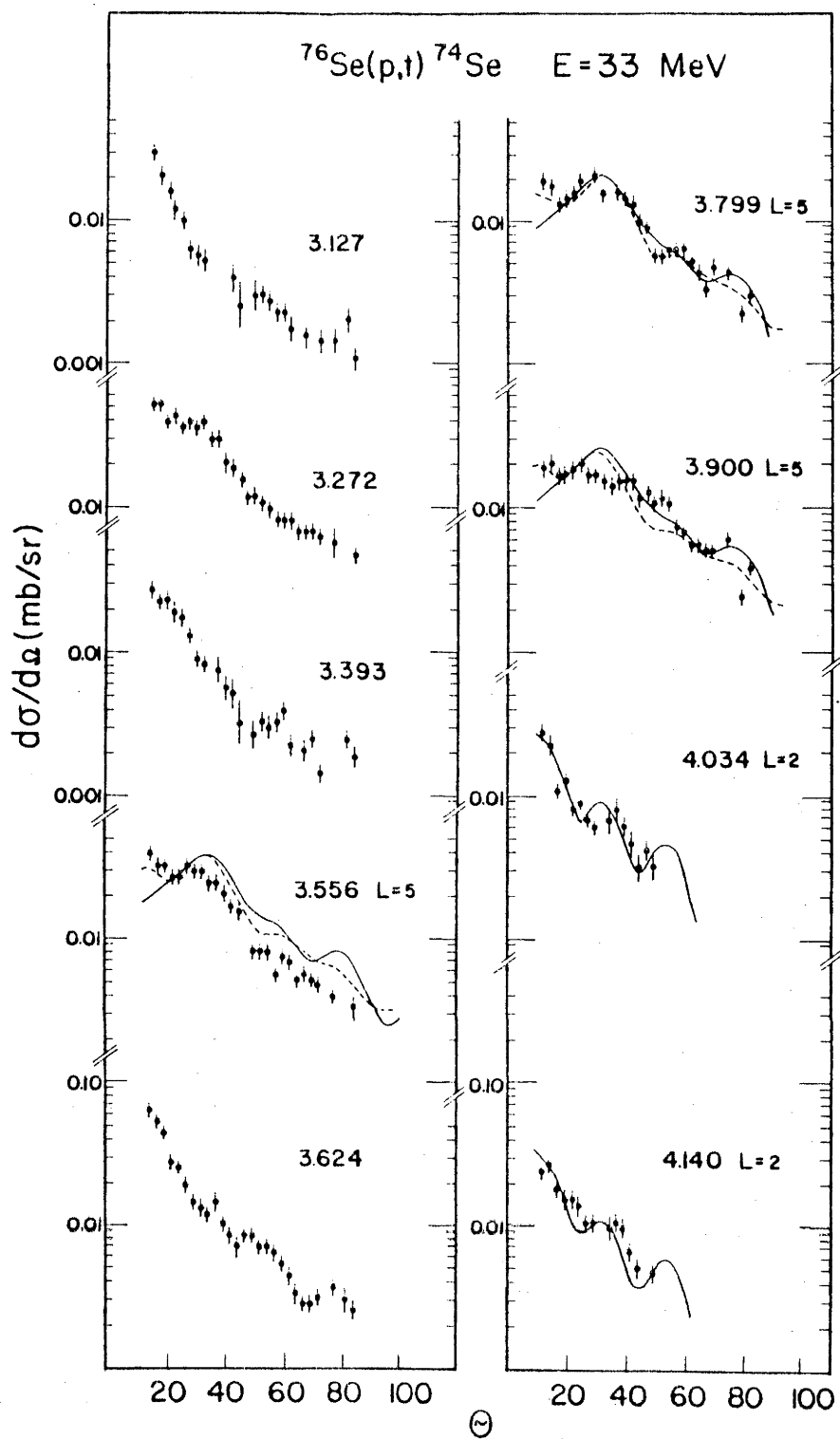


Fig. 5.5. Angular distributions from the $^{76}\text{Se}(p,t)^{74}\text{Se}$ reaction. The solid line represents the DWBA predictions using the set (P_2, T_4) of optical model parameters. The dashed curve shows the DWBA predictions for the set (P_2, T_3) .

TABLE 5.2

Summary of results for states in ^{74}Se

$^{76}\text{Se}(p,t) ^{74}\text{Se}$ ^{a)}		Decay of ^{74}Br ^{b)}		$\text{Ge}(\alpha, xn_\gamma) \text{Se}$ ^{c)}	
E_x	J^π	E_x	J^π	E_x	J^π
0.000	0^+	0.000	0^+	0.000	0^+
0.635	2^+	0.6348	2^+	0.635	2^+
0.854	0^+	0.8538	0^+		
1.269	2^+	1.2691	2^+		
1.363	4^+	1.3631	4^+	1.363	4^+
1.839		1.8387	(2^+)		
		1.8843	$(3^+, 4^+)$		
2.101		2.1080	$(3^+, 4^+)$		
2.149		2.2311	6^+	2.231	6^+
		2.3144	(2^+)		
2.350	3^-	2.3496			
2.488 ^{*)}	$(2^+, 3^-)$	2.5636	$(+)$		
2.574		2.6619	$(+)$		
2.726 ^{*)}	0^+	2.8185	$(+)$		
2.853	$(3^-, 4^+)$	2.8317			
2.922	$(3^-, 4^+)$	2.9186	$(+)$		
		3.0371	(2^+)		
		3.0780	$(+)$		
3.127		3.1123			
		3.2005		3.197	8^+
3.272	$(3^-, 4^+)$	3.2510	(2^+)		
		3.2532			
		3.3060			
3.393	$(2^+, 3^-)$	3.3798			
3.556	$(5^-, 6^+)$	3.5803	$+$		

(Cont.)

TABLE 5.2 (Cont.)

$^{76}\text{Se}(p,t)^{74}\text{Se}$ a)		Decay of ^{74}Br b)		$\text{Ge}(\alpha, xn\gamma)$ Se c)	
E_x	J^π	E_x	J^π	E_x	J^π
3.624	$(2^+, 3^-)$	3.6750	+		
3.727					
3.799	$(5^-, 6^+)$	3.7717	+		
3.900 ^{*)}	$(5^-, 6^+)$	3.9282			
4.034 ^{*)}	(2^+)	3.9310			
4.140 ^{*)}	(2^+)				
4.397		4.3092	$(3^-, 4^-)$		
		4.4415	$(3^-, 4^-)$		
		4.4964	$(3^-, 4^-)$		
		4.5164	$(3^-, 4^-)$		
4.581		4.5800	(-)		
		4.5862	$(3^-, 4^-)$		
		4.5926	$(3^-, 4^-)$		
4.642		4.6618	$(3^-, 4^-)$		
		4.6993	$(3^-, 4^-)$		
		4.7568	$(3^-, 4^-)$		
		4.7939	(-)		

a) Present Work.

b) Ref. [Co 72a].

c) Ref. [Li 70b].

*) Levels not reported before.

was assigned a spin of 0^+ in the present experiment from the similarity of its angular distribution to those for the other two well known 0^+ states.

A few characteristics of the $L = 0$ angular distributions in the $^{76}\text{Se}(p,t)^{74}\text{Se}$ reaction can be noted:

a) the angular distribution for the ground state transition appears to be shifted towards forward angles by 2.5° in comparison with the other two $L = 0$ transitions,

b) the ratio between the cross-sections on the first maximum and the second maximum is the same for the ground state and 2.726 MeV transitions but different for the 0.849 MeV transition of the 0^+ two-phonon state. The ratio between the cross-sections on the first maximum and the first minimum is different for each state.

5.3.1b. $L = 2$ Transitions

Two $L = 2$ transitions corresponding to well known 2^+ states in ^{74}Se were observed in the present work. One state is the one-phonon first excited state at 0.635 MeV while the second is a member of the two-phonon triplet situated at 1.269 MeV. A comparison of the angular distributions for these two transitions shows a slight shift toward forward angles and the complete absence of the first minimum in the angular distribution for the one-phonon state. The 0.635 MeV state is much more strongly excited in the present reaction than the 1.269 MeV two-phonon state. The ratio between the cross-sections at 15° is about 5.

5.3.1c. Other Transitions

The angular distribution for the $L = 4$ transition to the 1.363 MeV 4^+ two-phonon state in ^{74}Se shows less structure than the $L = 0$ and $L = 2$

transitions. It is the weakest of the two-phonon triplet states in ^{74}Se excited by this reaction.

A 3^- spin was assigned to a state situated at 2.350 MeV. This spin assignment was made from the similarity in shape of the angular distribution to that from known $L = 3$ transitions in the $^{78}\text{Se}(p,t)$ reaction and other (p,t) reactions. The DWBA calculations support the 3^- spin assignment for this state. The angular distribution shows little structure having a maximum at 22.5° .

The 3.556 MeV, 3.799 MeV and 3.900 MeV levels. 5^- and 6^+ were assigned as the most probable spins for these states on the basis of the DWBA fits in the present measurements.

The 4.034 MeV and 4.140 MeV levels. These states were assigned the spin 2^+ from the shape of the angular distributions and a comparison with DWBA calculations.

The 2.488 MeV, 3.393 MeV and 3.624 MeV levels. Both 2^+ and 3^- spins are equally likely for these states from the present data.

The 2.853 MeV, 2.922 MeV and 3.272 MeV levels. Both 3^- and 4^+ look possible spins for these states. The fits are not good enough to distinguish between these two possibilities.

The 3.127 MeV level. It is not possible to make any prediction about the spin of this state from the present data.

5.4 $^{78}\text{Se}(p,t)^{76}\text{Se}$

The triton energy spectrum at 27.5° from the $^{78}\text{Se}(p,t)^{76}\text{Se}$ reaction is shown in Fig. 5.6. Angular distributions for 19 transitions to states in ^{76}Se were measured in the angular range from 15° to 90° . The ground state 0^+ and the first excited 2^+ state at 0.559 MeV are strongly excited in comparison with the other states. Figs. 5.7 and 5.8 show the angular distributions measured in the present reaction. Table

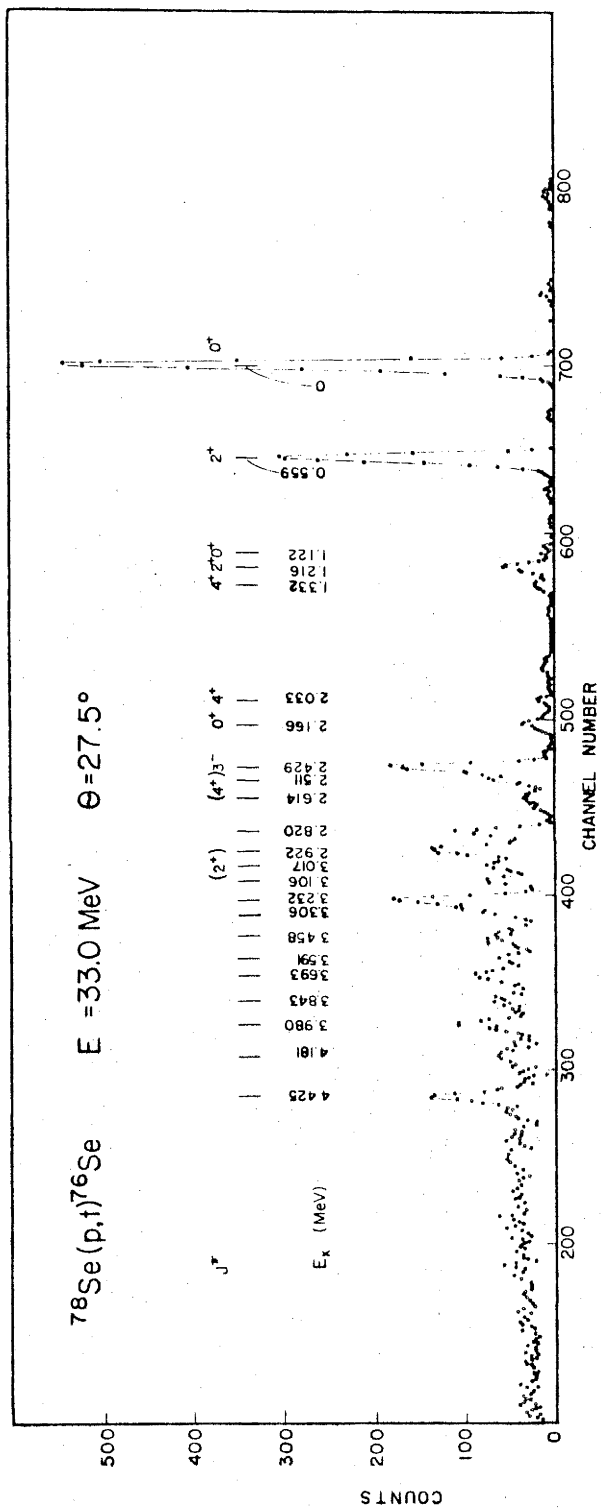


Fig. 5.6. Triton spectrum from the $^{78}\text{Se}(p,t)^{76}\text{Se}$ reaction.

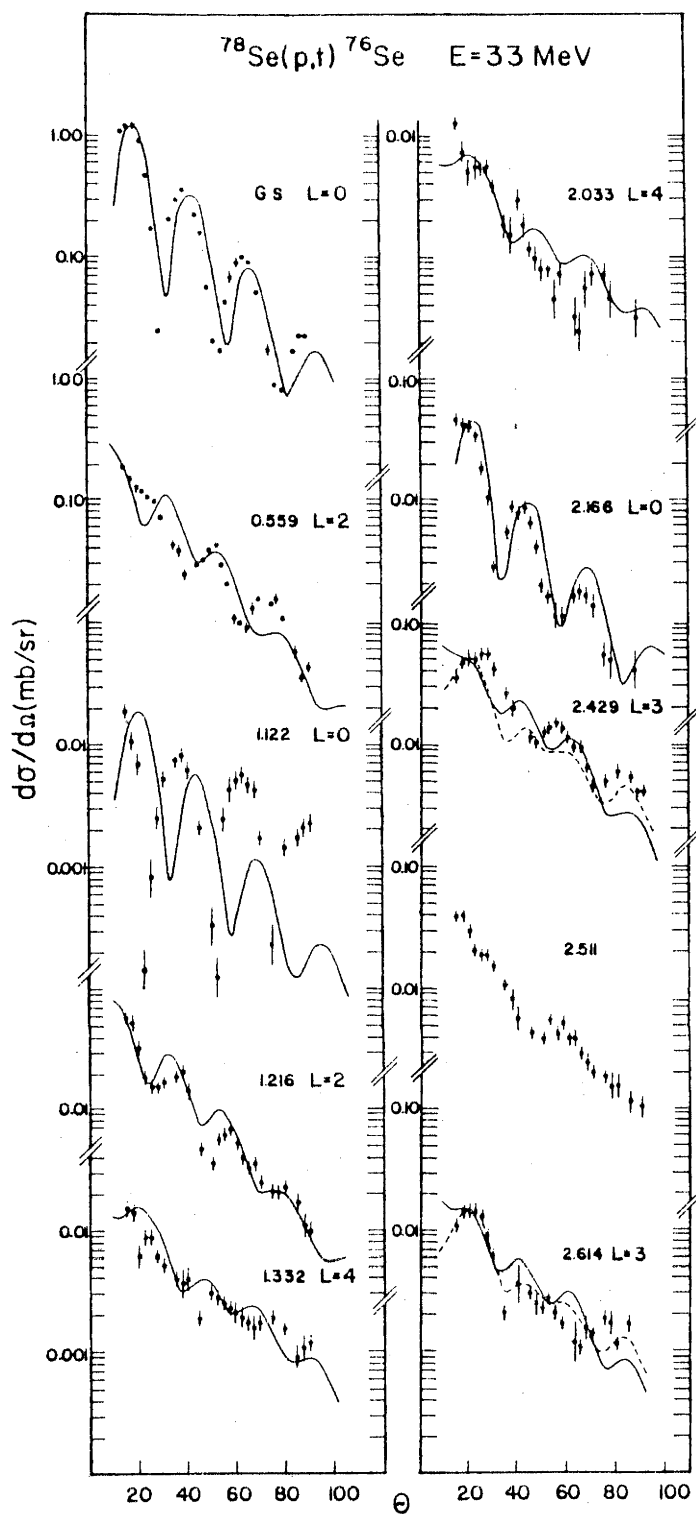


Fig. 5.7. Angular distributions from the $^{78}\text{Se}(p,t)^{76}\text{Se}$ reaction. The solid line represents the DWBA predictions using the set (P_2, T_4) of optical model parameters. The dashed curve shows the DWBA predictions for the set (P_2, T_3) .

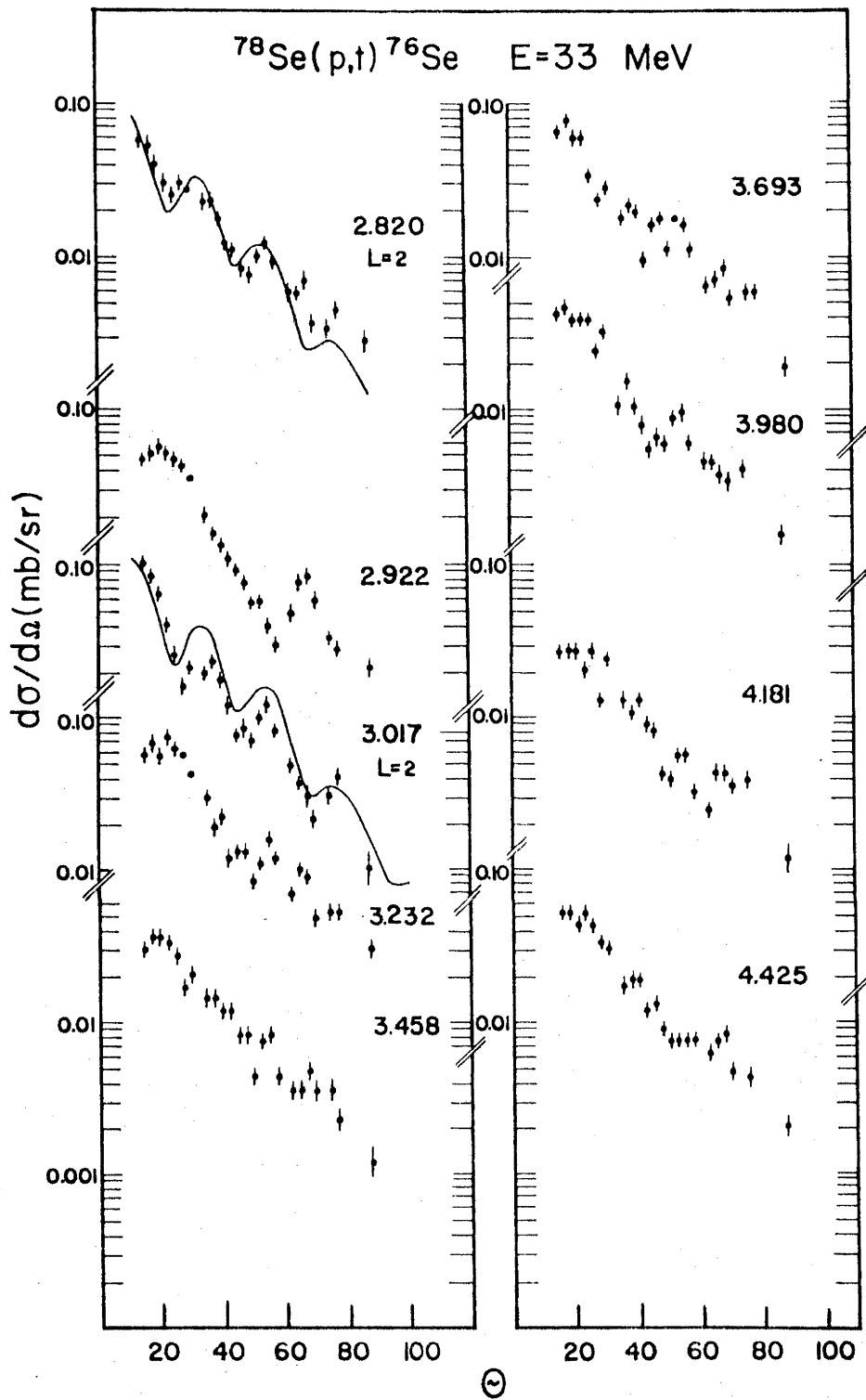


Fig. 5.8. Angular distributions from the $^{78}\text{Se}(p,t)^{76}\text{Se}$ reaction. The DWBA calculations for the 2.820 and 3.017 MeV states employ the set (P_2, T_4) of optical model parameters.

5.3 shows the levels in ^{76}Se excited in the present experiment together with levels reported from previous works.

5.4.1. Discussion of Results

5.4.1a. $L = 0$ Transitions

Three angular distributions correspond to $L = 0$ transitions. They display the typical oscillatory pattern with pronounced maxima and minima. The angular distribution for the $L = 0$ ground state transition has a cross-section that varies from 1.09 mb/sr at 17.5° to 0.007 mb/sr at 80° . The ratio between the first maximum and the first minimum is 50. Another $L = 0$ angular distribution measured in the present experiment corresponds to the 0^+ 1.122 MeV member of the two-phonon triplet. This state is very weakly excited, the cross-section varying from 0.017 mb/sr at 15° to only 0.0002 mb/sr at 75° . The third $L = 0$ transition observed in the present work corresponds to the level at 2.166 MeV. This state was observed before in studies of the β -decay of ^{76}As , but the spin could not be definitely assigned. Nagahara [Na 73] restricted the spin of this state to $(0,3,4)^+$. The angular distribution for this transition in the present experiment suggests a definite spin assignment of 0^+ .

5.4.1b. $L = 2$ Transitions

Two angular distributions corresponding to 2^+ states previously determined in ^{76}Se were measured in this reaction. These are the one-phonon state at 0.559 MeV and the 2^+ member of the two-phonon triplet at 1.216 MeV. The 0.559 MeV state is much more strongly excited, the ratio between these two cross-sections at 15° being 3.2. The angular distributions for these two 2^+ states show the same differences as those for the similar 2^+ states in ^{74}Se ; the absence of the first minimum and

TABLE 5.3
Summary of results for states in ⁷⁶Se

⁷⁸ Se(p,t) ⁷⁶ Se a)		Decay of ⁷⁶ As *)		(p,p') h)		(d,t) i)		(d,d') j)		Decay of ⁷⁶ Br **)	
E _x	J ^π	E _x	J ^π	E _x	J ^π	E _x	J ^π	E _x	J ^π	E _x	J ^π
0.000	0 ⁺	0.000	0 ⁺	0.00	0 ⁺	0.00	0 ⁺	0.00	0 ⁺	0.000	0 ⁺
0.559	2 ⁺	0.559	2 ⁺	0.56	2 ⁺	0.55	2 ⁺	0.56	2 ⁺	0.559	2 ⁺
1.122	0 ⁺	1.122	0 ⁺	1.12	0 ⁺			1.11	0 ⁺	1.122 ^{f)}	0 ⁺
1.216	2 ⁺	1.216	2 ⁺	1.22	2 ⁺	1.21	2 ⁺	1.22	2 ⁺	1.216	2 ⁺
1.332	4 ⁺	1.330	4 ⁺	1.34	4 ⁺			1.33	4 ⁺	1.332	4 ⁺
		1.689	(1 ⁺ ^{b)} , (3 ⁺ ^{c,e}) (3,4) ⁺ d)							1.689	
		1.780 ^{b)}									
		1.788	2 ⁺	1.79		1.80	(1,2) ⁺	1.80		1.788	2 ⁺
		1.881 ^{e)}	(0,3,4) ⁺							1.883 ^{g)}	
2.033	4 ⁺	2.026 ^{d,e)}	4 ⁺							1.942 ^{g)}	
		2.059 ^{c)}								2.048 ^{f)}	
		2.127	(1,3) ⁻ d)	2.04				2.05	—	2.127	
2.166	0 ⁺	2.170	(0,3,4) ⁺ e)	2.13		2.13		2.13	—	2.172 ^{f)}	
2.347		2.346 ^{e)}	(2,3,4) ⁺	2.28				2.21	—		
		2.363 ^{e)}	(2,3,4) ⁺					2.29	—		
2.429	3 ⁻	2.429	3 ⁻	2.43	(3 ⁻)					2.389 ^{g)}	
		2.444 ^{b)}						2.45	3 ⁻	2.429	
		2.454 ^{b)}									
2.511	(4) ⁺	2.515	(2,3,4) ⁺ e)	2.51		2.57		2.54	—		

TABLE 5.3 (Cont.)

$^{78}\text{Se}(p,t)^{76}\text{Se}$ a)		Decay of $^{76}\text{As}^*$		(p,p') h)		(d,t) i)		(d,d') j)		Decay of $^{76}\text{Br}^{**}$	
E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π
2.614	(3 ⁻)	2.655	(1,2,3) ^{-e} , (3 ⁻) ^d (2 ⁺) ^b , (1 [±] , 2 ⁺) ^c			2.63	(1,2) ⁺			2.629 ^f	
2.670		2.670	(1,2,3) ^{-e} , (2 [±] , 3 [±]) ^c , 2.66 (1 ⁺) ^b , (2 ⁺ , 3 ⁻) ^d					2.67		2.656	(3 ⁻) ^g
2.820	(2 ⁺)					2.86		2.87	-	2.890 ^g	
2.922	>2									2.949	
3.017	(2 ⁺)							2.98		2.990 ^g	
3.100						3.00				3.070	
3.232	>2							3.16		3.160 ^f	
3.300								3.30	-	3.350	
3.458	>2									3.459 ^f	
								3.54	+	3.556 ^f	
3.593										3.600 ^g	
3.693										3.910 ^g	
3.842										3.930	
3.983										3.972 ^f	
										4.030 ^g	
										4.065 ^f	

TABLE 5.3. (Cont.)

$^{78}\text{Se}(p,t)^{76}\text{Se}$ a)		Decay of ^{76}As *)		(p,p') h)		(d,t) i)		(d,d') j)		Decay of ^{76}Br **)	
E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π
4.181										4.084 ^{f)}	
4.425										4.140 ^{g)}	
										4.163 ^{f)}	
										4.197 ^{f)}	
										4.420 ^{f)}	
										4.440 ^{f)}	
										4.570 ^{g)}	
										4.605 ^{f)}	

a) Present data.

b) Assigned by Morcos et al. [St 58]

c) Assigned by McMillan and Pate [St 58]

d) Assigned by Ardisson et al. [St 58]

e) Assigned by Nagahara [Na 73]

f) Assigned by Dzhelepov et al. [Dz 69]

g) Assigned by Ladenbauer - Bellis et al. [Dz 69]

h) Ref. [Da 63]

i) Ref. [Li 65b]

j) Ref. [Li 65a]

*) A level is only marked if it was seen in less than two publications.

**) A level is not marked if it was seen in both works on decay of ^{76}Br [Dz 69].

a slight shift towards forward angles for the angular distribution of the one-phonon state.

5.4.1c. Other Transitions

The 4^+ 1.332 MeV member of the two-phonon triplet is weakly excited. As for the corresponding state in ^{74}Se the angular distribution for this state has little structure.

The state at 2.429 MeV was assigned a spin of 3^- for the first time from (d,d') measurements [Li 65a]. The DWBA calculations employing the set T_3 of triton parameters reproduce reasonably well the angular distribution corresponding to this state.

The 2.033 MeV level. This state was assigned a spin of 4^+ by Lieder and Draper [Li 70] from the study of $\text{Ge}(\alpha, \text{x}\gamma)\text{Se}$ reactions. The shape of the angular distribution for this level in the $^{78}\text{Se}(\text{p}, \text{t})$ reaction supports the 4^+ spin assignment. As in the case of the 4^+ two-phonon state the angular distribution has little structure. This state is weakly excited in the present experiment. Since this level decays via transitions to the two-phonon 2^+ and 4^+ states and the one-phonon 2^+ state, Nagahara [Na 73] suggests that this state may be a member of the three-phonon multiplet.

The 2.511 MeV level. From studies of the β -decay of ^{76}As Nagahara [Na 73] suggests an assignment of $(2,3,4)^+$ for this level. According to the selection rules in (p,t) reactions discussed in Chapter 2, a 3^+ unnatural parity state can be excited only if the reaction proceeds through a multi-step process. The angular distribution of this state displays little structure which makes the 4^+ spin assignment the most probable one.

The 2.614 MeV level. The shape of the angular distribution corresponding to this state suggests a spin 3^- . This state was not seen

in the decay of ^{76}As but a level at 2.629 MeV in ^{76}Se was reported by Dzhelepov et al. [Dz 69] from a study of the β -decay of ^{76}Br . However no spin assignment was given.

The 2.820 MeV level. The shape of the angular distribution for this level suggests a spin assignment of 2^+ . The DWBA calculations support the 2^+ spin assignment.

The 2.922 MeV level. It is not possible to assign a spin to this level from the present data. The angular distribution has a maximum at 20° . From the shape of the angular distribution the spins 0^+ and 2^+ can be ruled out.

The 3.017 MeV level. The shape of the angular distribution for this level shows characteristics of an $L = 2$ transition. This may be the same level reported at 3.00 MeV by Lin [Li 65b] from both (d,t) and (d,d') reactions. No spin assignment was given from those reactions.

The 3.232 and 3.458 MeV levels. A definite spin assignment for these levels cannot be made from the present data. The angular distributions look quite similar. From their shapes it can be concluded that spins greater than two are possible candidates for these states.

The 3.693, 3.980, 4.181, 4.425 MeV levels. Angular distributions for these levels were measured in the present experiment but no spin assignments were possible. All the angular distributions show that none of the spins for these levels are 0^+ .

Angular distributions for other weakly excited states in ^{74}Se and ^{76}Se shown in Tables 5.2 and 5.3 could not be extracted.

5.5. COMPARISON BETWEEN $^{76}\text{Se}(p,t)^{74}\text{Se}$ AND $^{78}\text{Se}(p,t)^{76}\text{Se}$

Three states of spin 0^+ were excited in both ^{74}Se and ^{76}Se nuclei. The ground states are much more strongly excited than the other states. The angular distributions for the ground state transitions look similar,

having maxima and minima at the same angles. Both ground states are equally excited in the (p,t) reaction.

The 0^+ two-phonon state in ^{74}Se is much more strongly excited than the corresponding two-phonon state in ^{76}Se . The ratio between the maximum cross-section in ^{74}Se and that in ^{76}Se for these states is 3.

The angular distributions for the 2.726 MeV 0^+ state in ^{74}Se and the 2.166 MeV 0^+ state in ^{76}Se look similar. Both states are equally populated. This is also the case for the 2^+ one-phonon states situated at 0.559 MeV in ^{76}Se and 0.635 MeV in ^{74}Se and for the 3^- states situated at 2.429 MeV and 2.350 MeV in the same nuclei.

The 2^+ state of the two-phonon triplet in ^{76}Se is more strongly populated than the corresponding 2^+ state in ^{74}Se . The ratio between the cross-sections for these states at 15° is 1.7. The angular distributions are similar.

The one-phonon 2^+ state is much more strongly excited than the 2^+ two-phonon state in both nuclei. The ratio between the cross-sections at 15° is 5 for ^{74}Se .

5.6. ANALYSIS

The use of the zero-range approximation makes it impossible to calculate absolute (p,t) cross-sections. However an empirical normalization which is hopefully constant over the periodic table can be found by analysing large bodies of data. Ball, Auble and Roos [Ba 71] have found a normalization constant $D_0^2 = 22 \times 10^4 \text{ MeV}^2 \cdot \text{fm}^3$ by comparing the magnitude of experimental (p,t) angular distributions in Zr to calculations done with wave functions from an extended shell model calculation. The relationship between the experimental absolute cross-section and the output of the code DWUCK is [Ba 73, Sh 72]

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \frac{D_0^2 (1/2 \pi \Delta^2)^{3/2}}{2L + 1} \times \epsilon \times S_{AB} \times \left(\frac{d\sigma}{d\Omega}\right)_{\text{DWUCK}} \quad (5.6)$$

where D_0^2 is the normalization constant introduced by the zero-range approximation, $\Delta = 1.7$ fm is the rms radius of the triton, $J = L$ is the total angular momentum transfer for an even-even target, $S_{AB}^{1/2}$ is the two-particle spectroscopic amplitude and ϵ is an enhancement factor which indicates the deviation of this renormalized theoretical prediction from the experimental cross-section [Ba 73, Ba 71, Sh 72].

The enhancement factor plays a similar role to the spectroscopic factor in one-nucleon transfer reactions except that in eq. (5.6) ϵ appears outside the sum over the participating shell model orbitals. The enhancement factor compares the experimental cross-sections with those calculated on the basis of specific assumptions about the nuclear wave functions involved. Any large deviation of the enhancement factor from unity would show that the wave functions chosen do not represent an adequate description of the transfer process. Since no complete wave functions for the Se isotopes are available, the calculations in the present work were made assuming pick-up from simple shell model orbits. Only a single shell model configuration was assumed to contribute. It has been shown that small admixtures in the wave functions can have large effects on the value of ϵ . By changing the transfer configuration the shape of the angular distributions is not altered significantly but the normalization between σ_{exp} and σ_{DWUCK} can be greatly changed.

The simplest model for calculating (p,t) spectroscopic amplitudes is to assume that the transitions occur between neutron configurations $j^n \rightarrow j^{n-2}$ (n even) which are seniority 0 and 2 eigenstates. This means for an even-even target nucleus that the protons are completely neglected and all contributing neutron pairs are considered in the same state (ℓj) coupled to total angular momentum zero. It has been shown by Bassani et

a1. [Ba 64] that in this simple model the spectroscopic amplitude can be expressed as

$$S_{AB}^{1/2} = \left[\frac{n}{2} \frac{2j+3-n}{2j+1} \right]^{1/2} \quad (5.7)$$

for $L = 0$ transitions between states of zero neutron seniority and

$$S_{AB}^{1/2} = \left[\frac{n(n-2)(2L+1)}{(2j-1)(2j+1)} \right]^{1/2} \quad (5.8)$$

for $L = 2, 4, 6, \dots$ transitions of seniority 2. Here j is the total angular momentum of the orbit from where the pick-up occurs and n is the number of neutrons in that orbit. For the $^{76,78}\text{Se}$ targets it was assumed that the neutrons fill the available orbits according to the simple shell model picture.

Using the value $D_0^2 = 22 \times 10^4 \text{ MeV}^2 \cdot \text{fm}^3$ assigned by Ball et al. [Ba 71], the numerical relationship between $(d\sigma/d\Omega)_{\text{exp}}$ and $(d\sigma/d\Omega)_{\text{DWUCK}}$ is given by

$$\left(\frac{d\sigma}{d\Omega} \right)_{\text{exp}} \left(\frac{\text{mb}}{\text{sr}} \right) = \frac{2127}{2L+1} \cdot \epsilon \cdot S_{AB} \left(\frac{d\sigma}{d\Omega} \right)_{\text{DWUCK}} \left(\frac{\text{fm}^2}{\text{sr}} \right) \quad (5.9)$$

Table 5.4 presents the enhancement factors extracted for the $L = 0$, $L = 2$ and $L = 4$ transitions. Since the DWBA calculations are known to be sensitive to the choice of the optical model parameters the enhancement factors were extracted for both (P_2, T_3) and (P_2, T_4) sets and also for the most probable configurations which could be involved in the transfer process.

To extract the enhancement factors the experimental angular distributions were matched with the DWBA calculations on the first peak in the case of $L = 0$ transitions and at forward angles for the $L = 2$ and $L = 4$ transitions. Since the fits to the 1.122 MeV 0^+ state in ^{76}Se are

TABLE 5.4

Enhancement coefficients from the $^{76,78}\text{Se}(p,t)^{74,76}\text{Se}$ reactions

^{76}Se Target		$L=0, E_x=0.0$ MeV	$L=2, E_x=0.635$ MeV	$L=0, E_x=0.854$ MeV	$L=2, E_x=1.269$ MeV	$L=4, E_x=1.363$ MeV	$L=0, E_x=2.726$ MeV
Set	Config.	ϵ	ϵ	ϵ	ϵ	ϵ	ϵ
(P_2, T_4)	$(p_{3/2})^4$	1.57	0.31	0.09	0.06		0.08
(P_2, T_4)	$(f_{5/2})^6$	23.56	4.41	1.33	0.92	0.36	1.2
(P_2, T_4)	$(p_{1/2})^2$	3.88		0.22			0.20
(P_2, T_4)	$(g_{9/2})^2$	15.59		0.88			0.8
(P_2, T_3)	$(p_{3/2})^4$	1.30	0.29	0.07	0.06		0.07
(P_2, T_3)	$(f_{5/2})^6$	22.82	4.4	1.33	0.92	0.44	1.40
(P_2, T_3)	$(p_{1/2})^2$	3.30		0.19			0.18
(P_2, T_3)	$(g_{9/2})^2$	9.84		0.50			0.43

(Cont.)

TABLE 5.4 (cont.)

Enhancement coefficients from the $^{76,78}\text{Se}(p,t)^{74,76}\text{Se}$ reactions

^{78}Se Target		$L=0, E_x=0.0$ MeV	$L=2, E_x=0.559$ MeV	$L=2, E_x=1.216$ MeV	$L=4, E_x=1.332$ MeV	$L=0, E_x=2.166$ MeV
		ϵ	ϵ	ϵ	ϵ	ϵ
(P_2, T_4)	$(p_{3/2})^4$	2.02	0.10	0.11		0.07
(P_2, T_4)	$(f_{5/2})^6$	29.54	4.77	1.48	0.46	1.10
(P_2, T_4)	$(p_{1/2})^2$	5.03				0.18
(P_2, T_4)	$(g_{9/2})^4$	10.97	8.18	8.37	2.14	0.42
(P_2, T_3)	$(p_{3/2})^4$	1.58	0.31	0.10		0.06
(P_2, T_3)	$(f_{5/2})^6$	2.33	4.33	1.40	0.35	0.98
(P_2, T_3)	$(p_{1/2})^2$	3.85				0.15
(P_2, T_3)	$(g_{9/2})^4$	0.74	19.64	5.95	1.17	0.25

very poor no attempt was made to extract enhancement factors for this state. Also no attempt was made to extract enhancement factors for states whose spins were not definitely known. It can be seen from Table 5.4 that the enhancement factors extracted for the two sets of parameters (P_2, T_4) and (P_2, T_3) are in reasonably good agreement for most of the states. It can also be seen that the enhancement factors for a given state differ by large factors for the various configurations tried in the DWBA calculations. The DWBA fits to the angular distributions for the first 2^+ excited states in both $^{74}, ^{76}\text{Se}$ nuclei are poor and the enhancement factors extracted for these two states are not reliable. They differ by large amounts from unity. The enhancement factors are closer to unity for the states whose angular distributions are better reproduced by the DWBA calculations.

5.7. SUMMARY AND CONCLUSIONS

The determination of the transition L values in the present work is based primarily on empirical features in the angular distribution shapes. The DWBA calculations were used only as a guide.

The most straightforward spin assignment is for the $L = 0$ transitions. The sharp diffraction pattern, characteristic of these transitions makes it very easy in general to assign 0^+ spins. Two new 0^+ states were identified in the present work, one at 2.726 MeV in ^{74}Se and the other state at 2.166 MeV in ^{76}Se . The latter was seen before in the β -decay of ^{76}As but no spin could be assigned.

The transition to the ground state carries most of the 0^+ strength in both $^{76}, ^{78}\text{Se}$ reactions. This agrees with previous empirical observations which have shown that for both (p,t) and (t,p) reactions the $L = 0$ transitions from targets far away from neutron shell closure usually proceed mainly to the ground state only [Br 73a]. No difference in

magnitude for ground state cross-sections was observed in going from ^{76}Se to ^{74}Se .

The angular distributions for the 2^+ one-phonon states in both isotopes have shapes that differ from those of the 2^+ two-phonon states. This means that care must be taken in assigning 2^+ spins from the experimental features in the angular distribution shapes in the present data. The shapes of the angular distributions for the one-phonon states are similar in both reactions. This is also true for the two-phonon states.

The overall DWBA fits to the data are poor. The triton potential T_4 with surface absorption was found to give the best fits, but it fails to reproduce either the shape of the angular distributions for the 2^+ one-phonon states or the position of the first maximum of the $L = 0$ ground state transitions. The angular distributions for the 2^+ two-phonon states are fairly well reproduced by T_4 while the $L = 3$ transitions are better reproduced by triton potential T_3 .

It has been found in other work [Ya 72, Co 72b] that the angular distributions leading to the first excited 2^+ states of some rotational and vibrational nuclei show an angular pattern which is quite different from that of the DWBA calculations. The distorted waves Born approximation uses a simple approach which assumes a direct, single-step mechanism for the two-nucleon transfer process. The fact that many of the angular distributions in the present work are not reproduced satisfactorily by DWBA calculations may indicate the existence of a multi-step process for the reaction mechanism. The occurrence of multi-step processes in (p,t) reactions, especially on deformed nuclei, is now fairly well established. Their existence is also supported by the observed population of unnatural parity states in (p,t) reactions on rotational nuclei [Fa 71]. The population of such states is not permitted via a direct, single-step mechanism.

More recently Yagi et al. [Ya 72] and Udagawa [Ud 74] have investigated (p,t) reactions on Cd and Te nuclei of a vibrational nature

using the coupled channel Born approximation (CCBA). In the two-step CCBA formalism it was found that quite different angular distributions from those of the DWBA were predicted at forward angles for the first 2^+ states of these "soft" nuclei. For "hard" nuclei both CCBA and DWBA predicted similar angular distributions. It was found that the two-step CCBA calculations were better able to reproduce the 2^+ one-phonon angular distributions for these nuclei. Udagawa found that even three-step processes were essential in CCBA in order to reproduce the angular distributions for 2^+ two-phonon states in some Cd nuclei.

The Se nuclei investigated in the present work have a low-lying level structure typical of vibrational nuclei. They also have large deformation parameters $\beta_2(^{76}\text{Se}) = 0.326$ and $\beta_2(^{78}\text{Se}) = 0.287$ which clearly establish these isotopes in the class of "soft" nuclei. The failure of the DWBA calculations to reproduce the one-phonon angular distributions for these nuclei may be another case of the type investigated by Yagi et al. and Udagawa. In particular the absence in the data of the first minimum predicted by the DWBA calculations is more typical of the type of CCBA prediction found in these works. However it should be noted that the DWBA fits to the 2^+ two-phonon states in the present work for both nuclei are reasonably good.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This chapter summarises the conclusions that can be drawn from the study of the (d,t) reaction on ^{54}Cr , $^{67,68}\text{Zn}$ and the (p,t) reaction on $^{76,78}\text{Se}$ presented in Chapters 4 and 5 of this thesis.

The present data have extended the range of (d,t) j-dependence systematics into this new mass region.

A clear backward angle j-dependence was observed for $\ell = 1$ transitions in the $^{68}\text{Zn}(\text{d,t})^{67}\text{Zn}$ reaction. The angular distributions for $j = 1/2$ transitions display a minimum at $\theta \approx 145^\circ$ which is not present in the angular distributions for $j = 3/2$ transitions. This j-dependence could be fitted by DWBA calculations employing a "small geometry" spin-orbit term in the deuteron channel. The change to a "small geometry" spin-orbit term has been used successfully in the past to reproduce the elastic scattering analysing power of vector polarized deuterons, (d,p) reactions induced by vector polarized deuterons and also to describe the j-dependence observed in (d,p) reactions.

A j-dependence for $\ell = 1$ transitions in the $^{54}\text{Cr}(\text{d,t})$ reaction was also observed. This differed from the j-dependence seen in both the $^{68}\text{Zn}(\text{d,t})$ and other (d,t) reactions and could not be reproduced by DWBA calculations. Since the compound nuclear processes could contribute to the reaction at this energy it would be interesting to study this reaction at higher energies where compound nuclear contributions are less important.

The first definite observation of forward angle j-dependence in $\ell = 3$ transitions was also observed in the $^{54}\text{Cr}(\text{d,t})$ data. This j-dependence could not be fitted by DWBA calculations.

Two new states at 1.370 and 2.100 MeV in ^{67}Zn were seen and a number of new spin-parity assignments have been made in both the Zn isotopes.

Spectroscopic factors from the $^{54}\text{Cr}(d,t)$ and $^{67,68}\text{Zn}(d,t)$ reactions were extracted in the present work and compared with those extracted for the same transitions from previous $(^3\text{He},\alpha)$, (p,d) and (d,t) reactions. These are in reasonably good agreement for $^{54}\text{Cr}(d,t)$ and $^{68}\text{Zn}(d,t)$ reactions. In the case of the $^{67}\text{Zn}(d,t)$ reaction the agreement is good only for $\ell = 1$ transitions. A clear discrepancy exists for both $\ell = 3$ transitions excited in this reaction. The values obtained from (p,d) work are twice as large although both this and the present work miss most of the expected $\ell = 3$ sum rule strength.

Filling coefficients V_j^2 and centre of gravity energies E_j were extracted from the $^{68}\text{Zn}(d,t)$ reaction and compared with the predictions of the simple pairing theory. In general, the experimental results agree reasonably well with these predictions although the $p_{1/2}$ filling coefficient is much larger than that predicted. This confirms earlier discrepancies for $V_{1/2}^2$ in the vicinity of neutron number $N = 40$.

Many levels not reported before in ^{74}Se and ^{76}Se were excited in the $^{76,78}\text{Se}(p,t)$ reactions. Two states in ^{74}Se were assigned spins of 0^+ and 3^- and two states in ^{76}Se were assigned spins of 0^+ and 4^+ in the present experiment. No definite spin assignments for other states could be made because of the lack of distinctive structure in the angular distributions. The angular distributions for the $L = 0$ transitions display a characteristic diffraction pattern which makes it possible to assign 0^+ spins from the empirical shape of the angular distributions only.

In general the DWBA fits to the angular distributions were poor in the (p,t) work. Four sets of triton optical model parameters were tried in the present analysis with a triton potential employing surface

absorption giving better fits to the data. However except for the 0^+ case reliable spin assignments could not be made by solely comparing the angular distributions with DWBA calculations. The same conclusion was drawn by Baer et al. [Ba 73] from an extensive study of the (p,t) reaction on the even-A titanium isotopes.

The transitions to the ground state dominate the spectra and carry almost all of the 0^+ strength in both $^{76,78}\text{Se}(p,t)$ reactions. This agrees with the results from all previous (p,t) reactions on nuclei that do not have closed neutron shells and are away from shape transition regions.

The angular distributions for the 2^+ one-phonon states differ in shape from those for the 2^+ two-phonon states. This difference has been noticed before in several nuclei and there is evidence from other work to suggest that the presence of multi-step processes in the reaction mechanism are responsible.

APPENDIX I

THE MATHEMATICAL FORMALISM FOR TWO-NUCLEON TRANSFER REACTIONS

The method presented here was developed by Glendenning [G1 63, G1 65] for a stripping reaction of the form $A(a,b)B$. The internal coordinates of the transferred nucleons are the spins σ_1, σ_2 , the isospins τ_1, τ_2 and the relative coordinates $\vec{x} = \vec{r}_1 - \vec{r}_2$. The channel coordinates are $\vec{\rho}$ and $\vec{r} = \frac{1}{2}(\vec{r}_1 + \vec{r}_2)$. The residual nucleus B can be looked upon as a core of target nucleus A plus two nucleons. Therefore the wave function of this nucleus can be written as

$$\begin{aligned} \phi_B = & \phi_{J_B T_B}^{M_B T_B} (\xi_A, \sigma_1 \sigma_2 \tau_1 \tau_2 \vec{x}, \vec{r}) = \sum_{LSJT, \gamma} \beta_{LSJT}^{\gamma} \\ & \times \left[\psi_{LSJT}^{\gamma} (\sigma_1 \sigma_2 \tau_1 \tau_2 \vec{x}, \vec{r}) \phi_{J_A T_A}^{M_B T_B} (\xi_A) \right]_{J_B T_B} \end{aligned} \quad (I.1)$$

where γ denote all quantum numbers necessary to specify the states of the system of two nucleons other than its orbital (L), spin (S), isospin (T) and total angular momentum (J). The separation of the wave function of the transferred nucleons into spin-isospin and orbital parts is written as

$$\psi_{LSJT}^{\gamma M_J T} (\sigma_1 \sigma_2 \tau_1 \tau_2 \vec{x}, \vec{r}) = \left[\phi_L^{\gamma} (\vec{x}, \vec{r}) \phi_{ST} (\sigma_1 \sigma_2 \tau_1 \tau_2) \right]_{JT}^{M_J T} \quad (I.2)$$

By using harmonic oscillator wave functions ϕ_L^{γ} can be constructed by coupling the single-particle orbital angular momenta $\vec{\ell}_1$ and $\vec{\ell}_2$ to $\vec{L}$, and then by a Talmi transformation ϕ_L^{γ} can be written in terms of coupled functions of the relative and C.M. coordinates of the transferred particles. Hence $\phi_L^{\gamma M} (\vec{x}, \vec{r})$ can be written as

$$\begin{aligned} \phi_L^{\gamma M}(\vec{x}, \vec{r}) &\equiv \left[\phi_{n_1 \ell_1}(\vec{r}_1) \phi_{n_2 \ell_2}(\vec{r}_2) \right]_L^M = \sum_{n\lambda, N\Lambda} \\ &\times \langle n\lambda, N\Lambda; L | n_1 \ell_1, n_2 \ell_2; L \rangle \left[\phi_{n\lambda}(\vec{x}) \phi_{N\Lambda}(\vec{r}) \right]_L^M \end{aligned} \quad (I.3)$$

where γ represents $(n_1 \ell_1, n_2 \ell_2)$, λ and Λ are the orbital angular momenta of the relative and C.M. motions, n and N are the corresponding principal quantum numbers and the coefficients $\langle \rangle$ are Brody-Moshinsky brackets.

The wave functions $\phi_{n\lambda}$ and $\phi_{N\Lambda}$ can be written

$$\begin{aligned} \phi_{n\lambda}^{m_\lambda}(\vec{x}) &= u_{n\lambda}(x) i^\lambda Y_\lambda^{m_\lambda}(\hat{x}) , \\ \phi_{N\Lambda}^{M_\Lambda}(\vec{r}) &= u_{N\Lambda}(r) i^\Lambda Y_\Lambda^{M_\Lambda}(\hat{r}) \end{aligned} \quad (I.4)$$

where $u_{n\lambda}$ and $u_{N\Lambda}$ are radial harmonic oscillator functions. Assuming that the particle b and the pair of transferred nucleons are in an S-state of relative motion, the wave function of the projectile a can be written as

$$\begin{aligned} \phi_a &\equiv \phi_{j_a t_a}^{m_a t_{za}}(\xi_b, \sigma_1 \sigma_2 \tau_1 \tau_2 \vec{x}, \rho) \\ &= \Psi_a(\vec{x}, \rho) \left[\phi_{j_b t_b}(\xi_b) \phi_{ST}(\sigma_1 \sigma_2 \tau_1 \tau_2) \right]_{j_a t_a}^{m_a t_{za}} \end{aligned} \quad (I.5)$$

where $\Psi_a(\vec{x}, \rho)$ is the radial part of the projectile wave function. This implies $\lambda = 0$ and $\Lambda = L$ in eq. (I.3) and (I.4). By assuming a Gaussian form Ψ_a can be written

$$\Psi_a(\vec{x}, \rho) = \chi_a(x) \theta_a(\rho) . \quad (I.6)$$

Assuming further a spin-isospin independent and scalar interaction so that $V_{bx} = V(\rho)$, the transition amplitude T_{ab} defined by eq. (2.17) can be written as

$$\begin{aligned}
T_{ab} = & \sum_{NLSJT} \sum_{MM_S M_J} \langle J_A M_A, J M_J | J_B M_B \rangle \langle LM, SM_S | JM_J \rangle \\
& \times \langle j_b m_b, SM_S | j_a m_a \rangle (2L+1)^{1/2} C_T b_{ST} G_{NLSJT} B_{NL}^M \quad (I.7)
\end{aligned}$$

where

$$\begin{aligned}
B_{NL}^M(\vec{k}_b, \vec{k}_a) = & (2L+1)^{-1/2} \int d\vec{r} \int d\rho \chi_b^{(-)*}(\vec{k}_b, \vec{r}_b) u_{NL}(r) \left[i^L Y_L^M(\hat{r}) \right]^* \\
& \times V(\rho) \theta_a(\rho) \chi_a^{(+)}(\vec{k}_a, \vec{r}_a) \quad (I.8)
\end{aligned}$$

is the kinematic amplitude and

$$G_{NLSJT} = g \sum_Y \beta_{LSJT}^Y \Omega_n \langle n_0, NL; L | n_1 \ell_1, n_2 \ell_2; L \rangle \quad (I.9)$$

with

$$\Omega_n = \int_0^\infty u_{n_0}(x) \chi_a(x) x^2 dx \quad (I.10)$$

In eq. (I.9) $g = 1$ if $(n_1 \ell_1 j_1) = (n_2 \ell_2 j_2)$ otherwise $g = \sqrt{2}$.

C_T is the isospin coupling coefficient and is defined as in eq. (2.28) and b_{ST} comes from the overlap of the spin-isospin functions of particles a and b .

The differential cross-section for a two-nucleon stripping reaction can be obtained by introducing the transition amplitude T_{ab} given by eq. (I.7) into eq. (2.10) so that

$$\frac{d\sigma}{d\Omega} = \frac{\mu_a \mu_b}{(2\pi \hbar^2)^2} \frac{k_b}{k_a} \frac{2J_B+1}{2J_A+1} \sum_{LSJTM} (C_T b_{ST})^2 \left| \sum_N G_{NLSJT} B_{NL}^M \right|^2 \quad (I.11)$$

APPENDIX II

A DESCRIPTION OF THE PARTICLE IDENTIFICATION TECHNIQUE AND THE A.N.U. PARTICLE IDENTIFIER

Two methods are more commonly used to separate the different charged particles from a given reaction according to their various masses.

The first method makes use of the empirical relationship found between the range R and the incident particle energy E . This can be written as

$$R = a E^b \quad (\text{II.1})$$

where b is practically a constant for all particles with energies above 10 MeV and a is another constant which depends on the mass and the charge of the incident particle but is approximately independent of the energy of the particle [Sk 67]. For a detector telescope, the quantity

$$T/a = E_T^b - (E')^b \quad (\text{II.2})$$

is a constant for a given particle over a wide energy range, where T is the thickness of the ΔE transmission detector, E_T is the total energy of the particle and E' is the energy deposited by the particle in the stopping detector [Go 64, Fi 67]. This relation holds only when the ΔE transmission detector is fully depleted. New range-energy tables for silicon [Sk 67] indicate a value for b of 1.69 at energies above 10 MeV. The ORTEC 423 particle identifier is based on this method.

The second method for particle identification uses the energy loss equation derived by Bethe as

$$\frac{dE}{dx} = \frac{c_1 M Z^2}{E_T} (\log c_2 E_T / M Z^2) \quad (\text{II.3})$$

Here M , Z and E_T are the mass, the charge and the energy of the incident particle and c_1 and c_2 are constants. By expanding eq.(II.3) the MZ^2 product can be written as

$$MZ^2 \approx \Delta E(E_T + k_0 - k_1 \cdot \Delta E + k_2 \cdot \Delta E^2 - k_3 \cdot \Delta E^3 + \dots) \quad (\text{II.4})$$

It was found empirically [Sk 67] that the optimum values for the constants k_0 and k_1 are 7.0 and 0.5 respectively.

The particle identifier built at A.N.U. and used for the present (d,t) and (p,t) measurements is based on the second method [En 73, En 71]. It produces the following three functions:

$$F_1 = (E_T + k_0) \cdot \Delta E \sim MZ^2 \quad (\text{II.5})$$

$$F_2 = (E_T - k_1 \cdot \Delta E + k_0) \sim MZ^2 \quad (\text{II.6})$$

$$F_3 = (E' + k_1 \cdot \Delta E + k_0) \sim MZ^2 \quad (\text{II.7})$$

where E_T is the total energy pulse and ΔE and E' are pulses produced in the ΔE transmission detector and the stopping detector respectively. The particle identifier is manufactured in such a way that the two constants k_0 and k_1 can be externally adjusted. In the present experiment they were initially set close to the values $k_0 = 7.0$, $k_1 = 0.5$ and then slightly changed until the resolution in the mass spectrum was the best.

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