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A Study of the (t,p) Reaction
on $^{90,92,94,96}\text{Zr}$ and $^{122,124}\text{Sn}$

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A Study of the (t,p) Reaction
on $^{90,92,94,96}\text{Zr}$ and $^{122,124}\text{Sn}^*$

by

Jerome G. Beery

*This report is derived from a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics from the Graduate School of the University of New Mexico.

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ABSTRACT

A study is made of the (t,p) reaction on targets of $^{90,92,94,96}\text{Zr}$ and $^{122,124}\text{Sn}$. The purpose of the study is to investigate the nuclear energy levels that are populated by putting two neutrons into a target nucleus.

The targets were bombarded with 20-MeV tritons from the Los Alamos tandem Van de Graaff facility. Protons were detected with a solid-state counter telescope and the data was recorded with an on-line digital computer. Energy spectra were taken for each of the targets utilizing a magnetic spectrometer in order to obtain excitation energies with an accuracy of ± 10 keV.

The zirconium data is analyzed with a distorted wave Born-approximation calculation and relative spectroscopic strengths are obtained. The energy level positions and strengths are compared to a nuclear structure calculation.

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Finally, the manuscript was typed by Mrs. Margaret Briesmeister whose patience and understanding are exceeded only by her distaste for poor spelling.

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I. INTRODUCTION

Nuclear direct reactions have been one of the main sources of information for nuclear structure for the past two decades. The first direct reaction was observed in 1935 by Lawrence, McMillan, and Thornton.¹ They studied deuteron-induced radioactivity in Na, Al, Si, and Cu. Oppenheimer and Phillips² explained these results in terms of the penetration of the neutron into the target nucleus while the proton remained outside the Coulomb barrier. The physical picture shows the deuteron moving in the field of the nucleus and being stretched by the combined action of Coulomb repulsion of the proton and nuclear attraction on the neutron. Of course, the proton is subjected to the nuclear attractive force as well, but the resultant attractive force acting on the proton is less than that acting on the neutron. The neutron is then captured by the nucleus. In present day terms one would say that Lawrence et al. were observing the (d,p) reaction, one of the single-nucleon stripping reactions. The term stripping is used because the neutron is stripped from the incident deuteron and added to the target nucleus.

The relevance of stripping reactions to the study of nuclear states was not recognized until 1950 when two teams of experimenters^{3,4} resolved energy groups corresponding to particular energy levels of the residual nucleus. The resulting angular distributions had large structural differences at forward angles. Butler⁵ recognized that these

differences would yield information regarding the spins and parities of energy levels in the residual nucleus. Since 1950 direct reactions have developed into one of the main spectroscopic tools used to study nuclear structure. Most of the stripping studies have been single nucleon stripping. In order to understand the type of information one hopes to obtain from double stripping, a discussion of single stripping is necessary.

When a single nucleon is stripped into the target nucleus, the angular distribution is characterized by the orbital angular momentum of the state into which the neutron is placed. The type of level formed is a single-particle excitation of the final nucleus. For example, a (d,p) reaction is useful in studying the single-particle neutron states in the residual nucleus. These are states which can be described by a model in which a single neutron is in orbit around an inert core consisting of the target nucleus.

The two-nucleon stripping reaction differs in some respects from the single-nucleon stripping reaction. In two-nucleon stripping the angular distribution is characterized by the total orbital angular momentum $\bar{L}$, where $\bar{L} = \bar{l}_1 + \bar{l}_2$ and $\bar{l}_1$ and $\bar{l}_2$ refer to the orbital angular momentum of the individual nucleons. Thus different values of $\bar{l}_1$ and $\bar{l}_2$ can lead to the same $\bar{L}$. The types of levels that can be excited include levels of two-nucleon excitations. Therefore, two-nucleon stripping reactions should provide a means of investigating levels of a more complicated nature than is provided by single-nucleon

stripping. Many reactions can be used for two nucleon stripping. Some possibilities are the ($^3\text{He},n$), ($^3\text{He},p$), (α,d), and (t,p) reactions. Of these the ($^3\text{He},n$) and (t,p) are most attractive because two nucleons of the same kind are being transferred and the interpretation of the experiment should be less complicated. While it is true that the ($^3\text{He},p$) and (α,d) reactions will allow one to study even more complicated levels the current state of nuclear theory is such that analysis is quite difficult.

Some ($^3\text{He},n$) work has been done but the difficulties with energy resolution and counting rates for the uncharged neutrons are the main problems. The study of (t,p) reactions has been confined to those laboratories which have a triton beam. Up to the present time, the (t,p) reactions above 10-MeV incident triton energy have been done either at the Atomic Weapons Research Establishment in Aldermaston, England, or at the Los Alamos Scientific Laboratory. Both laboratories have a tandem Van de Graaff with a triton beam. In the present work the 20-MeV triton beam at Los Alamos was used to bombard targets of four zirconium isotopes and two tin isotopes.

The original plan was to study the (t,p) reaction on several of the even-even tin isotopes using solid-state charged particle detectors and the 20-MeV triton beam from the Los Alamos tandem facility. After observing the reactions $^{122}\text{Sn}(t,p)^{124}\text{Sn}$ and $^{124}\text{Sn}(t,p)^{126}\text{Sn}$, it was clear that the resolution of 100 keV (full width at half maximum) was not adequate to study states above about 2.5-MeV excitation in the residual

nucleus. Therefore, the decision was made to study the (t,p) reaction on some of the even-even zirconium isotopes. There were two main reasons for changing to a study of the zirconium isotopes. The level spacing in the even-mass zirconium isotopes is large enough that levels for the first few MeV of excitation energy can be resolved. Also, since ^{90}Zr has a closed major neutron shell, considerable previous experimental and theoretical work has been done in the $A = 90$ mass region. The present work consists of a study of the (t,p) reaction on zirconium 90, 92, 94, and 96 and also the (t,p) reaction on tin 122 and 124.

II. REVIEW OF PREVIOUS (t,p) EXPERIMENTS

In order to place the present work in proper perspective, a review of previous (t,p) experiments is necessary. In this review only those experiments which used a triton beam of 10 MeV and above will be considered. The experiments discussed will be representative, but a complete review of all the experiments will not be done.

Starting in 1962 the Aldermaston group began to obtain results on the light elements. Middleton and Pullen^{6,7,8} gave results for various targets in the mass region 7-40 and for the $^{110}\text{Cd}(t,p)^{112}\text{Cd}$ reaction. Their data were analyzed with a plane-wave double-stripping theory which was not very reliable in helping to determine spins and parities for the levels. They did find that the 0^+ angular distributions had a characteristic shape that was easy to recognize. The angular distribution for an $L = 0$ transition had deep minima and a strong forward peaking. This characteristic shape for an $L = 0$ transition has since been found in all of the (t,p) reactions. This shape, combined with the fact that the $L = 0$ states can only be formed by simple configurations (both neutrons in the same shell model orbit) has led to an emphasis on studying the $L = 0$ states in the (t,p) reactions.

For the reaction $^{40}\text{Ca}(t,p)^{42}\text{Ca}$ one of the conclusions of Middleton and Pullen should be mentioned. Since ^{40}Ca is a doubly closed shell-model nucleus and this reaction is adding two neutrons, one would expect that the two neutrons would go into the $1f_{7/2}$ shell. On the basis of simple shell-model theory and assuming that neutrons go only

into the $1f_{7/2}$ shell, the lowest states should have spins and parities of 0^+ , 2^+ , 4^+ , and 6^+ . However, the spins and parities of the lowest levels they observed were 0^+ , 2^+ , 0^+ , 2^+ , and 4^+ . This fact indicates that ^{48}Ca perhaps does not have a well closed neutron shell or that the neutrons are going into shells other than the $1f_{7/2}$ shell. In the reaction $^{110}\text{Cd}(t,p)^{112}\text{Cd}$ the transition to the ground state is quite strong while the transitions to all of the excited states observed are comparatively weak. A similar effect has been observed in the tin region.

Since this early work of Middleton and Pullen, much additional experimental work has been done using the (t,p) reaction. Only five selected experiments will be discussed.

Bjerregaard and co-workers⁹ have studied the reactions $^{42,44,46,48,50}\text{Ca}(t,p)$. While they observed many states, they focused their attention on the 0^+ states. In addition to the ground state 0^+ transitions, they observed a number of strong 0^+ states in each nuclide except for ^{50}Ca . They concluded that the complexity of the $L = 0$ strengths observed rules out the possibility of interpreting the 0^+ states of the calcium isotopes in terms of pure two-neutron configurations. They also point out that the main configurations involved in the strong excited 0^+ states in all of the isotopes except ^{50}Ca are probably $(2p_{3/2})^2$ and $(2p_{1/2})^2$. They believe that these same configurations are the most important ones for the ground state of ^{50}Ca .

In the lead region several (t,p) experiments have been done. Two of these will be mentioned here. Bjerregaard, Hansen, and Nathan¹⁰ observed the $^{206}\text{Pb}(t,p)^{208}\text{Pb}$ reaction. Strong excitations were found for the ground state, the 2.62 MeV 3^- state and the 3.20 MeV 5^- state. The 3.71 MeV 5^- state was not observed. Only one excited 0^+ state, at 4.87 MeV, was observed. They suggest that more 0^+ states might be observed with a higher triton bombarding energy than 12 MeV. They point out that the shape of the $L = 0$ transitions have a smooth variation of the sharp minima as one increases in mass from ^{48}Ca through ^{240}U . They also mention that the fact that the strength of the two 5^- states are so different shows the selective character of the (t,p) reaction.

Flynn et al.¹¹ have observed the reactions $^{204}\text{Pb}(t,p)^{206}\text{Pb}$ and $^{208}\text{Pb}(p,t)^{206}\text{Pb}$ utilizing a 20-MeV triton beam. In their work the (t,p) reaction is quite selective in exciting certain states of the known states in ^{206}Pb . ^{204}Pb can be described as four neutron holes in a closed shell with the $(3p_{1/2})^{-2} \times (2f_{5/2})^{-2}$ configuration predominantly. This limits the variety of two-hole states that can be excited by the (t,p) reaction. Most of the states excited by the (t,p) reaction will, therefore, be one-particle three-hole states. Since ^{208}Pb is a closed shell, many different two-hole states can be excited by the (p,t) reaction. These assumptions are verified by their work. That is, they observe many more states in ^{206}Pb with the (p,t) reaction than with the (t,p) reaction.

Glover and McGregor¹² have observed the reaction $^{86}\text{Sr}(t,p)^{88}\text{Sr}$. Their primary reason for observing this reaction was to see how strongly 0^+ transitions other than the ground state were excited. Previous experiments had shown that for nuclei with $N > 29$ no 0^+ transitions other than the ground state were strongly excited. Glover and McGregor found that they observed two 0^+ transitions other than the ground state and both of these transitions were of the same order of magnitude as the ground state. Their combined strength was 1.6 times as strong as the ground state. This is the only (t,p) reaction that has been observed near $A = 90$.

Recent observations have been made of the (t,p) reaction on the tin isotopes by Bjerregaard and co-workers¹³ studied the reactions $^{116}\text{Sn}(t,p)^{118}\text{Sn}$ and $^{118}\text{Sn}(t,p)^{120}\text{Sn}$. They found that the ground state transitions are the strongest transitions observed by a factor of seven or more. Any other 0^+ transitions were lower than the ground state by a factor of about 60. This agrees with the prediction of Yoshida and the reason for it will be discussed later.

In summary one should comment on what would be expected in the present work. For the zirconium isotopes 0^+ transitions should be observed to excited states with a reasonable strength, perhaps the same order of magnitude as the ground state strength. Since ^{90}Zr has a closed neutron shell of $N = 50$, one might expect to see strong transitions to excited 0^+ states as well. For the tin isotopes one expects to see strong ground state transitions and weak transitions to all of the other states.

It should be noted that predicting what to expect in the zirconium region based on observations near Ca and Pb is a little risky. Both ^{40}Ca and ^{208}Pb have a closed neutron shell and a closed proton shell while ^{90}Zr has only a closed neutron shell. The proton configurations in the ground state wave functions for the zirconium isotopes may affect the strengths of the states observed.

III. DISTORTED WAVE CALCULATIONS

The plane-wave stripping theories were successful as a tool for identifying angular distributions from light nuclei. However, the absolute cross sections predicted were generally too large by a factor of ten or more. Experimental data for heavier nuclei made it clear that the distortion by the Coulomb field was important and now it is known that distortion by nuclear scattering and absorption are also important. Satchler¹⁴ has commented that under no circumstances met with experimentally are distortion effects negligible, so that a plane-wave theory is never a good approximation.

The distorted-wave method is intended to give a more accurate description. It takes account of the scattering and absorption of the particle before and after stripping by using distorted waves instead of plane waves. These are generated by optical model potentials which are chosen to reproduce the observed elastic scattering from the same nucleus at the same energy.

The distorted wave Born-approximation (DWBA) analysis for two-nucleon transfer reactions has been developed by a number of investigators.¹⁵⁻¹⁹ The simplest way to treat the (t,p) reaction would be to regard the incident triton as two structureless particles; a proton, and another particle consisting of the two neutrons. Such a treatment would be appropriate if the residual state were a cluster state with the parentage of the target nucleus plus the stripped particle. If, however, one wants a description within the framework of the conventional

shell model, the stripped neutrons are captured into single particle states of the residual nucleus and the two neutrons do not necessarily retain the correlation they had in the triton. In order to point out the differences between single-nucleon stripping and two-nucleon stripping, the (d,p) reactions will be considered first.

In the (d,p) reaction the angular distribution is characterized by the single orbital angular momentum of the state into which the neutron is stripped. The type of level formed is a single-particle excitation of the final nucleus. The differential cross section for the (d,p) reaction may be expressed as

$$\frac{d\sigma}{d\Omega}_{(d,p)} \propto \sum_{j\ell m} \beta_{j\ell} |B_{\ell}^m|^2 \quad (1)$$

where B_{ℓ}^m is the amplitude for the transfer of a neutron with quantum numbers ℓ and m . B_{ℓ}^m contains the angular dependence of the scattering. The $\beta_{j\ell}$'s are the expansion coefficients for the final state expressed in terms of the single-particle states.

Equation (1) is incoherent in the orbital angular momentum ℓ and the total angular momentum j . The square of B_{ℓ}^m is taken before the sum is made. The cross section for the (d,p) reaction can be factored into two parts, one contains the nuclear structure information and the other depends upon the kinematics of the reaction. The first part is generally the strength S , while the second is called the reaction part and contains the energy and Q -dependence and is otherwise structure independent.

In the (t,p) reaction the angular momentum is carried by a pair of neutrons and many different configurations can contribute to a given angular momentum transfer. The resulting coherence can lead to a very strong transition to levels for which the coherence is constructive. This constructive coherence depends upon the degree to which the transferred neutrons are correlated in the nucleus. To illustrate what is meant by a correlation imposed by angular momentum coupling, suppose the two neutrons each with angular momentum j are coupled to a total angular momentum of zero. The classical orbits are then coplanar. Otherwise they move in planes that are tilted with respect to each other. The motion is spatially more highly correlated in the coplanar case. If the correlation is one which has a large overlap with the correlation possessed by the neutrons in the triton, then one can expect an unusually strong transition.

The (t,p) differential cross section may be written as

$$\frac{d\sigma}{d\Omega}(t,p) \propto \sum_{LSJM} \left| \sum_i \beta_{iLSJ} B_{iL}^M \right|^2 \quad (2)$$

where the capital letters L, S, J, and M refer to total quantum numbers for both neutrons transferred and the other symbols are the same as for Eq. (1). The index i refers to different neutron configurations. Notice that Eq. (2) is also incoherent in the total angular momentum, but it is coherent in the single-particle states of the stripped neutrons.

Since many different configurations can contribute to a given angular momentum transfer in the (t,p) reactions, the probability amplitude is a coherent sum of terms, each term involving a product of single-particle wave functions. Thus, while a (d,p) reaction yields information concerning the single-particle components of the wave functions, a study of the (t,p) reactions could yield information on the relative phases of the different single-particle components of the wave function. Since Eq. (2) is a coherent sum of terms, each term involving a product of single-particle wave functions, it is not possible to factor the cross section into two parts as could be done for the d,p cross section.

Drisko and Jurgensen^{20,21} suggest a possible candidate to use for a strength in two-nuclear transfer reactions. This strength or relative spectroscopic factor for a nuclear state with quantum numbers L, S, J, is given by

$$S_{REL}^{LSJ} = \sum_{\ell_1 \ell_2 j_1 j_2} a_{12} A \begin{pmatrix} \ell_1 & \frac{1}{2} & j_1 \\ \ell_2 & \frac{1}{2} & j_2 \\ L & S & J \end{pmatrix} \langle n_1 \ell_1 n_2 \ell_2 L | 00NL \rangle |^2 \quad (3)$$

and $\frac{d\sigma}{d\Omega} \propto S_{REL}^{LSJ}$.

In Eq. (3) a_{12} is a fractional-parentage coefficient, A is an identical-particle ℓs -JJ recoupling coefficient, $n_1, \ell_1, j_1, n_2, \ell_2, j_2$ are quantum numbers of the single-particle orbits, and L, S, J refer to the total quantum numbers for the pair of transferred neutrons. The third factor

is a Moshinsky bracket²² which transforms two-particle wave function expressed in coordinates with respect to the center of the potential well into a sum over wave functions expressed in relative center-of-mass coordinates with respect to the two nucleons. N is the harmonic oscillator quantum number. Harmonic oscillator wells are commonly used since one can separate relative and center-of-mass motion for such wells. The DWBA calculation expands the Saxon well as a series of harmonic oscillator wells.

Drisko has analyzed the present zirconium (t,p) data and extracted strengths using the expression

$$D_0^2 S_{REL}^{LSJ} = \frac{\sigma_{EXP}}{(2J_f+1)\sigma_{LSJ}^{(calculated)}} \quad (4)$$

In Eq. (4) D_0^2 involves the overlap of the triton and proton internal wave functions, σ_{EXP} is the experimental cross section, J_f is the total angular momentum of the final state, and $\sigma_{LSJ}^{(calculated)}$ is the calculated cross section for a neutron configuration having quantum numbers LSJ for the pair of neutrons. D_0^2 should be the same for all (t,p) experiments and is known empirically to be about 60. The strengths reported in this work are all normalized to a value of 1.0 for $^{90}\text{Zr}(t,p_0)^{92}\text{Zr}$ strength.

The input parameters for the DWBA calculation are the optical model parameters for the incident triton, the optical parameters for the emergent proton, and the parameters used to determine the bound state potential well. The input parameters used in the present work and their effect on the shape of the angular distributions will be discussed later.

The (t,p) reaction exhibits simple selection rules. They are

$$\pi_i \pi_f = (-)^L$$

and

$$J_f = J_i + L + S$$

where π_i and π_f are the parities of the initial and final states and LSJ refer to the quantum numbers of the transition. Since the total spin of the neutrons in the triton is zero and we assume that this relative spin configuration is retained in stripping then $S = 0$. Also since in the present work the target nucleus ground state had always $J^\pi = 0^+$, the rules are even simpler, namely $\pi_f = (-)^L$ and $J_f = L$. Therefore, one will observe states of spins and parities 0^+ , 2^+ , 4^+ etc., and 1^- , 3^- , 5^- , etc. Only if these selection rules are violated will unnatural parity states be observed.

IV. EXPERIMENTAL PROCEDURE

This experiment was done using the 20-MeV triton beam from the Los Alamos tandem Van de Graaff facility. The protons were detected with a solid-state counter telescope. The telescope consists of a thin ΔE detector to determine the rate of energy loss and an E detector to stop the particle. The total energy of the particle is obtained from the sum of the energies deposited in the ΔE and E detectors. If a suitable calculation is done with these two detector voltages (E and $E+\Delta E$), one can, in principle, determine what type of particle has been observed. Early systems based on this concept used an approximation of Bethe's energy-loss relation

$$\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{mV^2} N z \left[\ln \frac{2mV^2}{I} - \ln(1-\beta^2) - \beta^2 \right] \quad (5)$$

where dE/dx is the rate of energy loss of the particle, e is the charge of the electrons, m is the mass of the electrons, Z and V are the charge and velocity of incident particle, z is the atomic number of absorber, N is the number of atoms per cm^3 of absorber, β is equal to V/c , and I is the average ionization energy of the absorber atoms. If $\beta \ll 1$, Eq. (5) simplifies to

$$\frac{dE}{dx} = K_1 \frac{MZ^2}{E} \ln K_2 \frac{E}{M} \quad (6)$$

where $K_1 = \frac{2e^4}{m}$, $K_2 = \frac{4m}{I}$

and E , M , and Z are the energy, mass, and atomic number of the particle.

Since the logarithmic term is not a strong function of energy Eq. (6) is usually approximated further to give

$$\frac{dE}{dx}(E) = K_3 MZ \quad (7)$$

where $K_3 = K_1 \ln K_2 \frac{E}{M}$. Equation (7) has been the basis for early particle identification systems.²³⁻²⁵ The neglect of variation in the logarithmic term becomes a poor approximation at lower energies. In order to keep the logarithmic term constant over a wider range of energies, it is better to add a constant E_0 to Eq. (7).

$$\frac{dE}{dx}(E+E_0) = K_3 MZ^2 \quad (8)$$

Analog computers have been used to calculate Eq. (8) which gives the characteristic tag for the particle MZ^2 . The main restriction on this method has been that dE/dx really changes as the particle passes through the ΔE detector. For the product $\frac{dE}{dx}(E+E_0)$ to have any meaning, the ΔE counter must be thin and absorb only a small part of the total energy. Goulding and co-workers²⁶ have designed a new system in which the ΔE detector thickness is not limited by the previous considerations. Their system will now be discussed.

The range-energy relationship for particles of 10-100 MeV energy can be represented by

$$R = aE^b \quad (9)$$

where R is the particle range in absorber, a is a constant depending on the particle, b is a constant (about 1.73), and E is the incident particle energy. One can compare the ranges calculated accurately²⁷

using Eq. (5) with those calculated using Eq. (9). Equation (9) is a very good representation of Eq. (5) except for low energy ^4He and ^3He particles, but even for these particles the discrepancy between Eq. (9) and Eq. (5) is within $\pm 2\%$.

Consider a particle of energy E_i coming into a detector telescope consisting of a ΔE detector of thickness T and an E detector of sufficient thickness to stop the particle.

Then from Eq. (9) we have

$$R = aE_i^{1.73}$$

$$\text{and } R-T = aE^{1.73}$$

where R is the total range of the particle, E is the energy loss in the E detector, and $R-T$ is the range in the E detector. Combining these two equations we obtain the relation

$$T = aE_i^{1.73} - aE^{1.73}$$

$$\text{or } \frac{T}{a} = E_i^{1.73} - E^{1.73}$$

Since $E+\Delta E$ is equal to E_i we obtain

$$\frac{T}{a} = (E+\Delta E)^{1.73} - E^{1.73} \quad (10)$$

Goulding designed an analog circuit which would compute Eq. (10).

Since a is different for each particle, one has a voltage pulse which is different for each particle. In this work a fast digital computer was used to calculate Eq. (10) and then the particle sorting was done with computer instructions rather than electronic circuits. This

method has two main advantages over the analog computer method. The first advantage is that fewer electronic circuits are needed to do the particle separation, particularly if one wants to observe more than one particle simultaneously. The second advantage is that changes may be made in the system by computer instructions rather than wiring changes. This allows greater flexibility in sorting the data.

Figure 1 is the block diagram for the electronics required for the present experiment. The sum E_i equals $E + \Delta E$ was formed outside of the computer so that the computer analog-to-digital converter (ADC) was presented with E_i and E pulses. The sum pulse was put through a biased amplifier so that the top part of the energy spectrum could be magnified. The so-called sum pulse was actually $E + \Delta E - B_5$ where B_5 was the external bias level. Figure 2 shows the flow diagram in the computer after the sum and ΔE voltage pulses converted to digital information. When a gate pulse arrives the computer interrupt was enabled and the two pulses were read. B_5 was added to the sum and the mass function was calculated. The mass function m was actually T/a from Eq. (10). The program may be operated in a mass or energy mode. In the mass mode the pulses were sorted into a 512-channel array and the program exited. A typical mass (particle) array is shown in Fig. 3. This is a mass spectrum obtained from the bombardment of a ^{90}Zr target with a 20-MeV triton beam. Only singly-charged particles were observed since in this case the E detector was too thick (500 μ) to allow transmission of doubly-charged ^3He and ^4He particles. For this particular spectrum

Figure 1. Electronics block diagram.

ELECTRONICS BLOCK DIAGRAM FOR COMPUTER MASS IDENTIFICATION

Figure 2. Computer flow chart.

FLOW CHART FOR COMPUTER MASS IDENTIFICATION

the mass gates were set as shown by the arrows on Fig. 3. Once the mass gates were set, the program was switched into the energy mode. Here each sum pulse (in digital form) was sorted into one of four 512-channel arrays. In this example three arrays were used. The zero of each of those arrays may be shifted by the bias levels B_1 , B_2 , and B_3 . Since the ADC was capable of 1024 channel resolution and the arrays were 512 channels each, these bias levels were used to look at the top part of the energy spectra. The results of the sorting were three 512-channel energy spectra, one each for protons, deuterons, and tritons.

While the data were being taken, the computer was used for generating the cathode-ray tube display of one of the energy spectra and the computer was also used for peak fitting. A skewed Gaussian mathematical function was calculated and its parameters were varied to fit energy peaks in the spectrum. The program for this peak fitting was developed by W. S. Hall. It is based on a previous peak-fitting program.²⁸ It should be emphasized that the computer was doing these three jobs on a real-time basis. That is, the three jobs share time on the computer. This system is able to take data at a rate of about 5,000 events per second. The time limitation occurs in the analog-to-digital converter and the dead time was approximately 10% for a data rate of one kilocycle per second.

After the data accumulation for a given detector angle, the energy spectra were placed on magnetic tape. Then at a later time one could do more peak fitting of the energy spectra. A more elaborate version of the on-line peak-fitting code is used for off-line peak fitting.

Figure 3. Particle spectrum for the $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ reaction.

This code is called DABANA and was also written by W. S. Hall. It will fit up to nine peaks simultaneously. A typical DABANA fit to some data is shown in Fig. 4. The experimental points are shown by crosses and the calculated curve is given by the solid line.

For each of the five targets used in this work, a magnetic spectrograph exposure was made at one laboratory angle. The intent was to assure that levels observed with the solid-state counter data were actually single energy levels. The spectrograph energy resolution was about 20 keV compared to 100 keV for the counter data. It should be emphasized that all of the angular distributions in the present work were obtained with the solid-state counters and have a resolution of 100 keV.

Figure 4. Calculated fit to a typical energy spectrum.

V. RESULTS

In all of the present work, absolute differential cross sections were measured. Many of the previous (t,p) experiments were done without measuring absolute cross sections. Two of the problems which make absolute measurements difficult are measuring the target thickness accurately and obtaining adequate counting statistics since the cross sections are so low. The present system is well suited to making absolute measurements since the triton elastic scattering data is taken at the same time as the (t,p) data. Since the small-angle elastic scattering is mostly Rutherford scattering, the elastic cross section may be calculated accurately. The target thickness was determined by assuming that the small-angle elastic scattering cross section calculation was correct and by calculating the target thickness required to obtain the observed cross section. Then all of the absolute (t,p) cross sections were obtained by normalizing to the triton elastic scattering cross section. All of the (t,p) cross sections reported in the present work have an absolute accuracy of $\pm 15\%$. The errors given in the cross-section tables presented here are relative errors arising from the counting statistics.

The optical-model parameters used for the tritons in the incident channel and for the protons in the exit channel were obtained from optical-model fits to the elastic scattering cross sections. The optical-model potential for the tritons has a Saxon well for the real and imaginary parts and does not have a spin-orbit term. Since optical

parameter sets for fits to elastic scattering data are not unique, several sets were tried. The angular distribution for the $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ reaction was calculated for a number of different combinations of triton elastic parameters and proton elastic parameters. Table I gives the values for the three sets of triton optical model parameters which were used.

Table I
Triton Optical Model Parameter Sets

Set	Real Well Depth V (MeV)	Imaginary Well Depth W (MeV)	Real Radius r_0 (F)	Coulomb Radius r_c (F)	Real Diffuse-ness a (F)	Imaginary Radius r_0' (F)	Imaginary Diffuse-ness a' (F)
T2	168.5	19.6	1.157	1.4	0.737	1.508	0.748
T3	150.5	20.4	1.244	1.4	0.676	1.465	0.781
T4	147.9	20.6	1.256	1.4	0.667	1.456	0.788

The radial dependence of the real Saxon potential well is given by

$$f(r) = [1 + \exp(\frac{r-R}{a})]^{-1}$$

where the radius of the well R and the radius parameter r_0 are connected by the relation $R = r_0 A^{1/3}$ with A being the nuclear mass. The Saxon well for the imaginary potential has the same radial form with a being replaced by a' and r_0 by r_0' . The electrical charge is assumed to be distributed uniformly throughout a sphere with a radius parameter r_c .

The proton optical potential is similar in form to the triton potential. The only difference is that the imaginary potential is a surface potential having only a radial dependence which is the derivative of the Saxon well. The proton parameters were $V = V_0 - 0.33E$ where $V_0 = 50.6$ MeV and E is the energy of the outgoing proton, $r_0 = 1.186$ F, $r_c = 1.25$ F, $a = 0.778$ F, $V_{so} = 7.36$ MeV, $r_0' = 1.268$ F, $a' = 0.587$ F, and $W_s = 44.4$ MeV. W_s is the surface imaginary term and V_{so} is the spin-orbit term.

The other input parameters used in the DWBA calculation are the Saxon well parameters for the captured neutrons. They were: a radius parameter 1.25 F, a diffuseness 0.65 F, a binding energy of one-half the two-neutron binding energy, and a spin orbit term $\lambda = 25$ MeV where $V_{so} = \frac{\lambda V}{180.5}$. The well depth V was adjusted until the energy eigenvalue was equal to the binding energy.

All of the input parameters were provided by R. M. Drisko. The bound state parameters and the proton optical parameters both had very little effect on the shape of the angular distribution for $^{90}\text{Zr}(t, p_0)^{92}\text{Zr}$. The magnitude of the cross section was not affected by the choice of either proton or triton optical parameters as long as the parameter set fit the elastic scattering cross section. The effect of the triton set is shown in Fig. 5. Set T2 was then used for all of the subsequent DWBA calculations in this work. All of the DWBA calculations were done with a computer code written and provided by R. M. Drisko.

A. $^{90}\text{Zr}(t, p)^{92}\text{Zr}$

Figures 6 and 7 show typical spectra obtained at one angle for the solid-state counter data and for the spectrograph data, respectively.

Figure 5. The effect of the triton optical parameters on the $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ ground state angular distribution.

Figure 6. Counter energy spectrum for $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ at $\theta = 36^\circ$.

The solid curves through the experimental points on this energy spectrum and on all the subsequent spectra are drawn as a guide to the eye.

Figure 7. Spectrograph energy spectrum for $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ at $\theta = 36^\circ$.

Three of the states which appeared to be single states in the counter data appear as multiple states in the higher resolution data from the spectrograph. Figure 8 gives the energy levels observed in the present experiment, in the inelastic proton work of Stautberg and Kraushaar,²⁹ and the (d,p) work of Martin et al.³⁰ Column three is a composite of the inelastic deuteron data of Jolly³¹ and the beta decay work of Bunker et al.³² The energies from the present work have an uncertainty of ± 10 keV. All of the energies reported in the present work were determined from the spectrograph data. The 0^+ state at 1.390 MeV was very weakly excited by the (t,p) reaction. It has a strength of 1/20 of the ground state strength. The ground state Q-value is 7.353 ± 0.010 MeV compared to a value of 7.352 ± 0.005 MeV of Mattauch et al.³³ and Maples et al.³⁴ In all cases in the present work, the ground state Q-values were determined by sliding the energy scale of the spectrograph to make the energy of the $^{12}\text{C}(t,p_0)^{14}\text{C}$ ground state group agree in energy with the known Q-value. The Q-value for $^{12}\text{C}(t,p_0)^{14}\text{C}$ is known to an accuracy of better than 0.001 MeV. Then the energy scale determined was used to measure the Q-value for the zirconium or tin ground state. Figure 9 displays the calculated DWBA distributions and plots of the experimental data. The spins and parities given in the energy level diagrams for the present work were determined by using the shape predicted by the DWBA calculations. In most cases the J^π agrees well with assignments made by other experimenters. Although the simplest configurations possible were chosen for the neutrons in the DWBA

Figure 8. Energy level diagram for ^{92}Zr .

^{92}Zr

4.103				
4.058	=====			
4.030	=====	4.02	4.05	4.03
3.898	=====	3.87	3.90	
3.786	=====			3.81
3.728	=====			3.69
3.651	=====	3.62	3.67	
3.609	=====			3.49
3.473	===== 4 ⁺	3.44 (3 ⁻ , 4 ⁺)	3.44 (3 ⁻)	
3.376	=====	3.32		3.30
3.325	=====	3.22	3.25	
3.247	=====			
3.063	===== 2 ⁺	3.04 2 ⁺	3.04	3.06
2.961	=====	2.85 (2 ⁺)	2.85	2.91
2.871	===== 4 ⁺	2.75	2.75	
				2.66
2.491	=====	2.47	2.48	
2.346	===== 3 ⁻	2.33 3 ⁻	2.34 3 ⁻	2.40
2.071	===== 2 ⁺	2.05 2 ⁺	2.04 2 ⁺	2.07
1.842	===== 2 ⁺	1.85 (2 ⁺)	1.84 2 ⁺	1.88
1.497	===== 4 ⁺	1.49 4 ⁺	1.49 4 ⁺	1.50
1.390	===== 0 ⁺		1.38 0 ⁺	1.38
0.935	===== 2 ⁺	0.93 2 ⁺	0.94 2 ⁺	0.94
0.000	===== 0 ⁺ (t, p)	0.00	0.00	0.00
		(p, p')	(d, d')	(d, p)
			BETA DECAY	

Figure 9. Distorted wave Born approximation calculation and
experimental angular distributions for $^{90}\text{Zr}(t,p)^{92}\text{Zr}$.

$^{90}\text{Zr}(t, p)^{92}\text{Zr}$

calculation, Drisko has found that the shape of the angular distribution is insensitive to the configuration so long as the neutron single-particle states are chosen from the same major shell.

Tables II and III give the absolute differential cross sections. On these tables and all subsequent tables the errors are statistical. As mentioned previously, the absolute error in cross section is $\pm 15\%$.

B. $^{92}\text{Zr}(t,p)^{94}\text{Zr}$

Figures 10 and 11 show spectra for the counter data and spectrograph data, respectively. The counter resolution was adequate to resolve levels up to 2.374 MeV so angular distributions were obtained up to that level. Above 2.374 MeV level positions were obtained but no angular distributions were taken. The first excited 0^+ level at 1.304 MeV was only weakly excited. It has a strength of $1/16$ that of the ground state strength. The levels seen are shown in Fig. 12 along with the (p,p') work of Stautberg and Kraushaar²⁹ and the (d,d') work of Jolly, Lin, and Cohen.³⁶ The ground state Q-value is 6.469 ± 0.010 MeV compared to the previous value of 6.466 ± 0.005 .^{33,34} The DWBA calculations and the experimental angular distributions are shown in Fig. 13. Table IV gives the absolute differential cross sections.

C. $^{94}\text{Zr}(t,p)^{96}\text{Zr}$

Figures 14 and 15 show spectra from the counters and the spectrograph, respectively. Angular distributions were obtained for the ground state and the first three excited states. Here the first excited 0^+ state is quite strong in contrast to those observed in ^{92}Zr and ^{94}Zr .

Table II. Cross Sections for the $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ Reaction.

$^{90}\text{Zr}(t,p)^{92}\text{Zr}$

θ_{CM}	Ground State σ_{CM} ($\mu\text{b}/\text{sr}$)	0.935 MeV σ_{CM} ($\mu\text{b}/\text{sr}$)	1.497 MeV σ_{CM} ($\mu\text{b}/\text{sr}$)	1.842 MeV σ_{CM} ($\mu\text{b}/\text{sr}$)	2.071 MeV σ_{CM} ($\mu\text{b}/\text{sr}$)
12.2	282.4 ± 72.9	443.6 ± 90.5	445.3 ± 90.8		330.6 ± 78.0
15.2	177.7 ± 27.4	543.9 ± 47.9	357.8 ± 38.6	29.5 ± 11.2	278.3 ± 34.2
18.3	162.2 ± 17.5	511.4 ± 31.2	439.8 ± 29.0	40.1 ± 8.7	319.4 ± 24.6
21.3	95.8 ± 11.6	310.6 ± 20.8	399.4 ± 23.6	22.6 ± 5.6	168.2 ± 15.5
24.4	24.0 ± 5.1	220.5 ± 15.4	355.1 ± 19.5	8.56 ± 3.03	129.1 ± 11.7
27.4	13.5 ± 3.0	202.3 ± 11.7	385.8 ± 16.2	5.35 ± 1.89	62.1 ± 6.5
30.5	26.4 ± 3.5	145.3 ± 8.1	256.2 ± 10.8	11.87 ± 2.33	71.4 ± 5.7
33.5	48.0 ± 3.9	109.9 ± 5.8	198.9 ± 8.0	7.47 ± 1.52	71.6 ± 4.7
36.6	116.4 ± 6.8	116.4 ± 5.8	153.6 ± 7.7		60.8 ± 4.9
39.6	132.3 ± 8.3	85.7 ± 6.7	105.3 ± 7.4		50.8 ± 5.1
42.6	104.8 ± 6.1	66.0 ± 4.8	80.7 ± 5.3		42.4 ± 3.9
45.7	66.6 ± 4.7	67.4 ± 4.7	64.0 ± 4.6	1.63 ± 0.73	35.3 ± 3.4
48.7	35.8 ± 3.6	83.1 ± 5.6	64.0 ± 4.9	1.87 ± 0.84	37.0 ± 3.7
51.7	14.8 ± 0.8	77.7 ± 1.8	48.4 ± 1.4	5.02 ± 0.46	35.2 ± 1.2
54.8	10.9 ± 0.9	98.3 ± 2.6	44.9 ± 1.8	5.63 ± 0.62	48.3 ± 1.8
57.8	13.5 ± 0.9	65.0 ± 2.0	28.2 ± 1.4	4.58 ± 0.55	34.5 ± 1.5
60.8	28.5 ± 1.4	63.0 ± 2.1	32.9 ± 1.5	3.10 ± 0.46	35.2 ± 1.6
63.8	40.1 ± 1.4	40.4 ± 1.4	32.8 ± 1.2	3.18 ± 0.39	20.9 ± 1.0
66.9	43.0 ± 1.6	23.4 ± 1.2	28.0 ± 1.3	2.46 ± 0.37	15.3 ± 0.9
69.9	34.8 ± 1.4	27.8 ± 1.2	34.4 ± 1.3	1.32 ± 0.26	14.7 ± 0.9
72.9	24.4 ± 1.2	31.8 ± 1.3	31.7 ± 1.3	1.25 ± 0.26	13.3 ± 0.9

Table III. Cross Sections for the $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ Reaction.

$^{90}\text{Zr}(t,p)^{92}\text{Zr}$

θ_{CM}	2.346 MeV σ_{CM} ($\mu\text{b}/\text{sr}$)	2.871 MeV σ_{CM} ($\mu\text{b}/\text{sr}$)	3.063 MeV σ_{CM} ($\mu\text{b}/\text{sr}$)	3.473 MeV σ_{CM} ($\mu\text{b}/\text{sr}$)
12.2	328.3 $\pm$ 77.5	295.3 $\pm$ 73.8	590.6 $\pm$ 103.9	110.7 $\pm$ 45.2
15.2	185.5 $\pm$ 28.0	185.4 $\pm$ 28.0	378.4 $\pm$ 39.7	200.7 $\pm$ 28.9
18.3	214.0 $\pm$ 20.3	280.7 $\pm$ 23.0	462.8 $\pm$ 29.6	269.5 $\pm$ 22.6
21.3	252.9 $\pm$ 19.0	206.2 $\pm$ 17.1	327.9 $\pm$ 21.6	254.1 $\pm$ 19.1
24.4	180.7 $\pm$ 13.9	187.1 $\pm$ 14.2	214.5 $\pm$ 15.2	203.5 $\pm$ 14.6
27.4	145.2 $\pm$ 9.9	169.6 $\pm$ 10.7	172.4 $\pm$ 10.7	196.9 $\pm$ 11.4
30.5	88.6 $\pm$ 6.4	108.4 $\pm$ 7.0	125.0 $\pm$ 7.5	146.8 $\pm$ 8.2
33.5	66.2 $\pm$ 4.6	108.3 $\pm$ 5.8	108.9 $\pm$ 5.8	109.9 $\pm$ 5.8
36.6	59.4 $\pm$ 4.8	64.1 $\pm$ 5.0	96.2 $\pm$ 6.2	78.3 $\pm$ 5.5
39.6	50.7 $\pm$ 5.1	65.4 $\pm$ 5.8	80.5 $\pm$ 6.4	66.1 $\pm$ 5.8
42.6	40.0 $\pm$ 3.8	43.3 $\pm$ 3.9	83.8 $\pm$ 5.4	58.5 $\pm$ 4.6
45.7	35.5 $\pm$ 3.4	37.8 $\pm$ 3.5	76.6 $\pm$ 5.0	48.4 $\pm$ 4.0
48.7	42.0 $\pm$ 4.0	39.3 $\pm$ 3.8	90.6 $\pm$ 5.8	43.9 $\pm$ 4.0
51.7	31.4 $\pm$ 1.1	34.1 $\pm$ 1.2	64.3 $\pm$ 1.6	36.3 $\pm$ 1.2
54.8	37.1 $\pm$ 1.6	28.8 $\pm$ 1.4	67.7 $\pm$ 2.2	37.2 $\pm$ 1.6
57.8	30.0 $\pm$ 1.4	37.3 $\pm$ 1.6	59.8 $\pm$ 2.0	30.5 $\pm$ 1.4
60.8	33.7 $\pm$ 1.5	18.4 $\pm$ 1.1	48.1 $\pm$ 1.8	18.8 $\pm$ 1.2
63.8	23.2 $\pm$ 1.0	15.4 $\pm$ 0.8	35.5 $\pm$ 1.3	18.9 $\pm$ 0.9
66.9	15.4 $\pm$ 0.9	13.7 $\pm$ 0.9	30.4 $\pm$ 1.3	21.8 $\pm$ 1.1
69.9	13.8 $\pm$ 0.9	21.0 $\pm$ 1.0	21.1 $\pm$ 1.1	17.2 $\pm$ 1.0
72.9	11.9 $\pm$ 0.8	22.4 $\pm$ 1.1	19.1 $\pm$ 1.0	17.7 $\pm$ 1.0

Figure 10.. Counter energy spectrum for $^{92}\text{Zr}(t,p)^{94}\text{Zr}$ at $\theta = 36^\circ$.

Figure 11. Spectrograph energy spectrum for $^{92}\text{Zr}(t,p)^{94}\text{Zr}$ at $\theta = 36^\circ$.

Figure 12.. Energy level diagram for ^{94}Zr .

^{94}Zr

4.015	_____				
3.913	=====				
3.833	=====	3.87	_____	3.92	_____ (-)
		3.71	_____		
3.582	_____	3.57	_____	3.61	_____ (-)
3.482	_____	3.46	_____		
3.350	_____	3.33	_____		
3.242	_____	3.22	_____	3.28	_____
3.155	_____	3.14	_____		
3.014	_____				
2.940	_____	2.92	_____	2.89	_____
2.882	_____	2.84	_____		
2.611	_____	2.60	_____ (5 ⁻)	2.60	_____ (+)
2.374	_____ 2 ⁺	2.34	_____ (2 ⁺)	2.35	_____ (+)
2.064	_____ 3 ⁻	2.05	_____ 3 ⁻	2.06	_____ 3 ⁻
1.675	_____ 2 ⁺	1.66	_____ 2 ⁺	1.68	_____ (+)
1.471	_____ 4 ⁺	1.47	_____ 4 ⁺	1.47	_____ (-)
1.304	_____ 0 ⁺			1.31	_____ (+)
0.920	_____ 2 ⁺	0.92	_____ 2 ⁺	0.92	_____ (+)
0.000	_____ 0 ⁺	0.00	_____ 0 ⁺	0.00	_____ 0 ⁺
(t, p)		(p, p')		(d, d')	

Figure 13. Distorted wave Born approximation calculations and
experimental angular distributions for $^{92}\text{Zr}(t,p)^{94}\text{Zr}$.

$^{92}\text{Zr}(t,p)^{94}\text{Zr}$

Table IV. Cross Sections for the $^{92}\text{Zr}(t,p)^{94}\text{Zr}$ Reaction.

$^{92}\text{Zr}(t,p)^{94}\text{Zr}$

θ_{CM}	Ground State σ_{CM} ($\mu\text{b/sr}$)	0.920 MeV σ_{CM} ($\mu\text{b/sr}$)	1.471 MeV σ_{CM} ($\mu\text{b/sr}$)	1.675 MeV σ_{CM} ($\mu\text{b/sr}$)	2.064 MeV σ_{CM} ($\mu\text{b/sr}$)	2.374 MeV σ_{CM} ($\mu\text{b/sr}$)
18.3	197.5 $\pm$ 17.2	336.3 $\pm$ 22.2	138.1 $\pm$ 14.4	158.8 $\pm$ 15.4	296.0 $\pm$ 21.0	504.4 $\pm$ 27.2
21.3	138.7 $\pm$ 10.7	293.2 $\pm$ 15.5	181.4 $\pm$ 12.3	115.4 $\pm$ 9.8	295.6 $\pm$ 15.7	366.0 $\pm$ 17.2
24.4	74.9 $\pm$ 7.2	158.8 $\pm$ 10.3	190.3 $\pm$ 11.4	92.6 $\pm$ 8.0	283.4 $\pm$ 13.9	252.2 $\pm$ 13.1
27.4	43.2 $\pm$ 9.3	187.2 $\pm$ 19.1	157.2 $\pm$ 17.6	74.0 $\pm$ 12.1	332.3 $\pm$ 25.6	328.0 $\pm$ 25.6
30.5	80.3 $\pm$ 9.6	136.8 $\pm$ 12.5	169.4 $\pm$ 13.9	72.4 $\pm$ 9.1	259.1 $\pm$ 17.1	249.8 $\pm$ 17.0
33.5	143.1 $\pm$ 8.2	109.2 $\pm$ 7.0	127.5 $\pm$ 7.7	35.3 $\pm$ 4.1	145.9 $\pm$ 8.2	173.3 $\pm$ 8.8
36.6	197.8 $\pm$ 7.1	73.0 $\pm$ 4.4	77.0 $\pm$ 4.5	45.7 $\pm$ 3.5	105.9 $\pm$ 5.3	164.7 $\pm$ 6.6
39.6	246.2 $\pm$ 8.6	74.9 $\pm$ 4.8	74.3 $\pm$ 4.8	31.0 $\pm$ 3.1	98.4 $\pm$ 5.4	169.0 $\pm$ 7.1
42.6	237.9 $\pm$ 6.9	52.0 $\pm$ 3.2	39.9 $\pm$ 2.9	26.6 $\pm$ 2.3	85.5 $\pm$ 4.2	117.3 $\pm$ 4.9
45.7	173.7 $\pm$ 6.1	77.0 $\pm$ 4.0	37.6 $\pm$ 2.8	30.1 $\pm$ 2.5	75.9 $\pm$ 4.0	104.4 $\pm$ 4.7
48.7	111.1 $\pm$ 5.0	75.1 $\pm$ 4.1	34.0 $\pm$ 2.8	30.3 $\pm$ 2.6	66.1 $\pm$ 3.8	104.7 $\pm$ 4.8
51.7	44.6 $\pm$ 3.0	79.1 $\pm$ 4.0	27.2 $\pm$ 2.4	30.8 $\pm$ 2.5	62.7 $\pm$ 3.8	91.5 $\pm$ 4.3
54.8	23.4 $\pm$ 2.1	76.5 $\pm$ 3.7	20.5 $\pm$ 1.9	33.5 $\pm$ 2.4	63.4 $\pm$ 3.4	90.2 $\pm$ 4.0
57.8	40.3 $\pm$ 2.9	67.6 $\pm$ 3.7	17.9 $\pm$ 1.9	40.2 $\pm$ 2.6	69.0 $\pm$ 3.7	84.1 $\pm$ 4.1
60.8	60.4 $\pm$ 3.1	39.6 $\pm$ 2.5	18.7 $\pm$ 1.7	17.1 $\pm$ 1.6	46.4 $\pm$ 2.7	68.3 $\pm$ 3.3
63.8	73.5 $\pm$ 3.4	26.3 $\pm$ 2.1	14.8 $\pm$ 1.6	10.7 $\pm$ 1.3	42.2 $\pm$ 2.6	43.6 $\pm$ 2.7
66.9	88.8 $\pm$ 3.8	26.7 $\pm$ 2.1	19.4 $\pm$ 1.8	13.1 $\pm$ 1.5	41.0 $\pm$ 2.6	44.6 $\pm$ 2.7
69.9	84.1 $\pm$ 3.5	21.2 $\pm$ 1.8	17.3 $\pm$ 1.6	6.92 $\pm$ 1.0	25.0 $\pm$ 1.9	33.1 $\pm$ 2.2
72.9	66.5 $\pm$ 3.3	27.6 $\pm$ 2.1	17.9 $\pm$ 1.7	10.6 $\pm$ 1.3	21.2 $\pm$ 1.8	37.4 $\pm$ 2.7

Figure 14. Counter energy spectrum for $^{94}\text{Zr}(t,p)^{96}\text{Zr}$ at $\theta = 36^\circ$.

Figure 15. Spectrograph energy spectrum for $^{94}\text{Zr}(t,p)^{96}\text{Zr}$ at $\theta = 36^\circ$.

It has a strength of 0.42 times the strength of the ground state. This is about an order of magnitude stronger than the first excited 0^+ states in ^{92}Zr and ^{94}Zr . Some possible explanations for this are discussed later. The 2^+ state at about 0.9 MeV and the 4^+ state at about 1.45 MeV which were both present in ^{92}Zr and ^{94}Zr are missing in ^{96}Zr . This is expected since the configuration for these states is probably $(2d_{5/2})^2$ and in ^{96}Zr the last two neutrons can only couple to give a 0^+ state. This is evidence that these states in ^{92}Zr and ^{94}Zr are predominantly $(2d_{5/2})^2$ configurations. Figure 16 shows the energy levels observed in the (t,p) reaction, the (p,p') work of Stautberg et al.,³⁵ the (d,d') work of Jolly et al.,³⁶ and the Coulomb excitation data of Gangrskii and Lemberg.³⁷ There appears to be a systematic difference in excitation energies between the present work and the (p,p') work. This is probably due to a compression of the energy scale at high proton energies for the counter data. If one determines the excitation energies from the present counter data and compares that with the (p,p') work, they agree with each other. However, the spectrograph energies are based upon comparison with the $^{12}\text{C}(t,p_0)^{14}\text{C}$ energy and since the agreement is quite good, one tends to believe that the energies determined from the spectrograph are the most accurate. The explanation for the energy compression seems to be that the charge collection in the counter for high proton energies is not 100% efficient. The present ground state Q-value was 5.844 ± 0.010 MeV compared to a previous value of 5.824 ± 0.006 MeV.^{33,34} Figure 17 shows the experimental angular distributions and the DWBA calculations. Table V gives the absolute differential cross sections.

Figure 16. Energy level diagram for ^{96}Zr .

^{96}Zr

Figure 17. Distorted wave Born approximation calculations and
experimental angular distributions for $^{94}\text{Zr}(t,p)^{96}\text{Zr}$.

Table V. Cross Sections for the $^{94}\text{Zr}(t,p)^{96}\text{Zr}$ Reaction.

$^{94}\text{Zr}(t,p)^{96}\text{Zr}$

θ_{CM}	Ground State σ_{CM} ($\mu\text{b/sr}$)	1.594 MeV σ_{CM} ($\mu\text{b/sr}$)	1.758 MeV σ_{CM} ($\mu\text{b/sr}$)	1.905 MeV σ_{CM} ($\mu\text{b/sr}$)
18.3	187.9 $\pm$ 17.7	93.4 $\pm$ 12.4	399.6 $\pm$ 25.6	201.0 $\pm$ 18.3
21.3	113.9 $\pm$ 10.7	40.3 $\pm$ 6.4	300.7 $\pm$ 17.4	171.1 $\pm$ 13.2
24.4	48.9 $\pm$ 5.1		202.7 $\pm$ 10.3	154.1 $\pm$ 8.9
27.4	32.6 $\pm$ 3.7		139.1 $\pm$ 7.5	127.4 $\pm$ 7.3
30.5	51.8 $\pm$ 3.8	20.3 $\pm$ 2.4	113.2 $\pm$ 5.7	98.3 $\pm$ 5.2
33.5	113.0 $\pm$ 5.2	40.7 $\pm$ 3.2	101.6 $\pm$ 5.0	86.4 $\pm$ 4.6
36.5	147.4 $\pm$ 4.7	59.0 $\pm$ 3.0	81.9 $\pm$ 3.5	72.7 $\pm$ 3.3
39.6	173.0 $\pm$ 5.2	65.2 $\pm$ 3.2	72.1 $\pm$ 3.4	51.9 $\pm$ 2.9
42.6	173.6 $\pm$ 5.4	64.6 $\pm$ 3.2	77.0 $\pm$ 3.5	48.3 $\pm$ 2.8
45.7	130.5 $\pm$ 6.7	42.3 $\pm$ 3.8	88.9 $\pm$ 5.5	40.4 $\pm$ 3.7
48.7	84.2 $\pm$ 3.5	35.9 $\pm$ 2.3	93.8 $\pm$ 2.7	43.8 $\pm$ 2.5
51.7	39.7 $\pm$ 2.7	18.1 $\pm$ 1.9	89.2 $\pm$ 4.1	36.4 $\pm$ 2.6
54.8	28.0 $\pm$ 2.1	11.4 $\pm$ 1.3	81.9 $\pm$ 3.6	43.8 $\pm$ 2.6
57.8	36.0 $\pm$ 2.5	16.5 $\pm$ 1.7	82.2 $\pm$ 3.8	42.6 $\pm$ 2.7
60.8	49.0 $\pm$ 3.3	22.4 $\pm$ 2.2	63.6 $\pm$ 3.8	35.8 $\pm$ 2.8
63.8	66.5 $\pm$ 3.6	28.0 $\pm$ 2.4	43.0 $\pm$ 2.9	30.4 $\pm$ 2.4
66.9	75.7 $\pm$ 4.1	29.3 $\pm$ 2.5	36.5 $\pm$ 2.8	20.1 $\pm$ 2.1
69.9	70.8 $\pm$ 4.0	25.6 $\pm$ 2.5	26.2 $\pm$ 2.5	17.0 $\pm$ 2.0
72.9	40.4 $\pm$ 3.9	19.5 $\pm$ 2.7	28.8 $\pm$ 3.3	15.4 $\pm$ 2.4

D. $^{96}\text{Zr}(t,p)^{98}\text{Zr}$

No angular distributions were taken for the ^{96}Zr target. However, the ground state Q-value was measured and is 3.514 ± 0.010 MeV compared to the previously reported value of 4.241 ± 1.00 MeV.^{33,34} Figure 18 shows the levels observed. This target illustrates the usefulness of the (t,p) reaction in studying neutron-rich isotopes. Prior to the work very little was known about ^{98}Zr . It has been observed in the beta-decay work of Orth and Smith³⁸ who determined the mass of ^{98}Zr to an accuracy of about 1.0 MeV. The present work has been extended to include angular distributions for many of the levels in ^{98}Zr , but this data has not been fully analyzed.

E. $^{122}\text{Sn}(t,p)^{124}\text{Sn}$

Figures 19 and 20 show spectra from the counters and spectrograph, respectively. The contaminants shown are ^{12}C and ^{16}O . The spectrograph plate was only scanned over those regions where peaks were seen in the counter data. No 0^+ transitions other than the ground state were observed. The counter resolution was to resolve levels up to an excitation energy of 3.420 MeV. Above that a strong doublet was seen at 5.45 MeV, but it was only resolved at a few angles so no angular distributions were obtained. Further spectrograph exposures have been made and angular distributions for the members of the strong doublet at 5.45 MeV will be obtained. Figure 21 shows the levels observed along with the (d,d') work of Kim and Cohen³⁹ and the (p,p') work of Nealy and Sheline.⁴⁰ The ground state

Figure 18. Energy level diagram for $^{96}\text{Zr}(t,p)^{98}\text{Zr}$.

⁹⁸Zr

4.049 —————

3.381 —————

3.080 —————

2.818 —————

2.056 —————

1.814 —————
1.751 —————

1.228 —————

0.000 —————

(t,p)

Figure 19. Counter energy spectrum for $^{122}\text{Sn}(t,p)^{124}\text{Sn}$ at $\theta = 30^\circ$.

Figure 20.. Spectrograph energy spectrum for $^{122}\text{Sn}(t,p)^{124}\text{Sn}$ at
 $\theta = 36^\circ$.

Figure 21. Energy level diagram for ^{124}Sn .

^{124}Sn

3.420 ———

3.35 ——— -

3.19 ——— +

3.13 ——— -

2.98 ———

2.85 ——— +

2.605 ———

2.59 ——— -

2.604 ———

2.41 ———

2.428 ———

2.329 ———

2.21 ———

2.200 ———

2.209 ———

2.13 ———

2.101 ———

2.108 ———

1.132 ———

1.13 ——— +

1.131 ———

0.000 ——— 0^+
(t, p)

0.00 ———
(d, d')

0.000 ———
(p, p')

Q-value was 5.593 ± 0.010 MeV compared to a previously reported value of 5.956 ± 0.006 .^{33,34} Figure 22 gives the experimental angular distributions. Table VI gives the absolute differential cross sections.

F. $^{124}\text{Sn}(t,p)^{126}\text{Sn}$

Figures 23 and 24 show spectra from the counters and spectrograph, respectively. Here again there is a strong doublet at about 5.32 MeV, which was unresolved in the counter data. Further spectrograph exposures have been made and angular distributions will be obtained for the members of the strong doublet. The spectrograph data was scanned only for known peaks from the counter data from 93 cm to 83.5 cm. Figure 25 shows the energy levels observed. The ground state Q-value was 5.448 ± 0.010 MeV compared with the previously reported value of 5.454 ± 1.010 MeV.^{33,34} Figure 26 gives the experimental angular distributions. Table VII gives the absolute differential cross sections. Here again, as in the case of ^{98}Zr , the value of the (t,p) reaction for looking at neutron-rich nuclei is shown. Prior to the present work only the ^{126}Sn mass was known⁴¹ and that value had about a 1.0 MeV uncertainty.

Figure 22. Experimental angular distributions for the $^{122}\text{Sn}(t,p)^{124}\text{Sn}$ reaction.

Table VI. Cross Sections for the $^{122}\text{Sn}(t,p)^{124}\text{Sn}$ Reaction.

$^{122}\text{Sn}(t,p)^{124}\text{Sn}$

θ_{CM}	Ground State σ_{CM} ($\mu\text{b/sr}$)	1.132 MeV σ_{CM} ($\mu\text{b/sr}$)	2.108 MeV σ_{CM} ($\mu\text{b/sr}$)	2.209 MeV σ_{CM} ($\mu\text{b/sr}$)	2.329 MeV σ_{CM} ($\mu\text{b/sr}$)	2.605 MeV σ_{CM} ($\mu\text{b/sr}$)	3.420 MeV σ_{CM} ($\mu\text{b/sr}$)
12.1	521.7 $\pm$ 58.5						
15.2	434.9 $\pm$ 49.5	174.5 $\pm$ 31.5					
18.2	64.8 $\pm$ 14.5	64.8 $\pm$ 14.5					
21.3	9.90 $\pm$ 4.07	114.8 $\pm$ 13.5			78.9 $\pm$ 11.4	75.1 $\pm$ 11.2	
24.3	66.4 $\pm$ 8.1	63.0 $\pm$ 7.9	32.5 $\pm$ 5.6		29.2 $\pm$ 5.4	64.6 $\pm$ 8.0	30.4 $\pm$ 5.4
27.3	129.0 $\pm$ 11.0	23.8 $\pm$ 4.6	33.1 $\pm$ 5.3			59.3 $\pm$ 7.1	19.9 $\pm$ 4.2
30.4	238.0 $\pm$ 11.0	15.6 $\pm$ 2.8	34.7 $\pm$ 4.2	47.0 $\pm$ 4.9	35.9 $\pm$ 4.3	56.3 $\pm$ 5.3	34.5 $\pm$ 4.2
33.4	309.8 $\pm$ 12.0	9.54 $\pm$ 1.08	17.9 $\pm$ 2.9	34.9 $\pm$ 4.0	30.2 $\pm$ 3.8		34.9 $\pm$ 4.0
36.4	333.6 $\pm$ 11.5	4.26 $\pm$ 1.28	23.2 $\pm$ 3.0	37.3 $\pm$ 3.8	37.4 $\pm$ 3.8	38.4 $\pm$ 3.8	
39.4	251.9 $\pm$ 10.0	11.2 $\pm$ 2.2	17.6 $\pm$ 2.7	31.1 $\pm$ 3.7	31.8 $\pm$ 3.7	22.2 $\pm$ 3.1	7.69 $\pm$ 1.81
42.5	147.9 $\pm$ 7.0	19.3 $\pm$ 2.7	26.3 $\pm$ 3.2	45.6 $\pm$ 4.2	36.4 $\pm$ 3.7	16.3 $\pm$ 2.5	22.0 $\pm$ 2.9
45.5	68.8 $\pm$ 4.9	29.5 $\pm$ 3.2	30.4 $\pm$ 3.3	45.2 $\pm$ 4.0	18.3 $\pm$ 2.5	11.0 $\pm$ 2.0	
48.5	21.9 $\pm$ 2.8	10.6 $\pm$ 2.0	29.8 $\pm$ 3.4	24.7 $\pm$ 3.1	13.4 $\pm$ 2.2	4.53 $\pm$ 1.31	
51.6	43.2 $\pm$ 2.8	12.2 $\pm$ 1.5	19.5 $\pm$ 1.8	33.4 $\pm$ 2.4	17.6 $\pm$ 1.8	18.9 $\pm$ 1.8	7.88 $\pm$ 1.18
54.6	99.6 $\pm$ 3.9	7.14 $\pm$ 1.05	17.6 $\pm$ 1.6	20.0 $\pm$ 1.8	9.46 $\pm$ 1.20	15.3 $\pm$ 1.6	6.08 $\pm$ 0.96
57.6	137.6 $\pm$ 4.5	1.38 $\pm$ 0.43	19.4 $\pm$ 1.6	15.8 $\pm$ 1.5	9.08 $\pm$ 1.10	10.4 $\pm$ 1.2	6.07 $\pm$ 0.90
60.6	137.2 $\pm$ 4.0	1.66 $\pm$ 0.48	11.9 $\pm$ 1.3	15.4 $\pm$ 1.5	9.04 $\pm$ 1.09	7.85 $\pm$ 1.04	3.04 $\pm$ 0.65
63.6	121.6 $\pm$ 3.5	2.59 $\pm$ 0.54	12.8 $\pm$ 1.2	12.9 $\pm$ 1.2	7.42 $\pm$ 0.91	7.19 $\pm$ 0.85	6.48 $\pm$ 0.84
66.7	81.4 $\pm$ 3.0	9.03 $\pm$ 0.98	11.1 $\pm$ 1.1	13.4 $\pm$ 1.2	7.65 $\pm$ 0.92	7.66 $\pm$ 0.92	3.18 $\pm$ 0.59
69.7	44.7 $\pm$ 2.6	11.2 $\pm$ 1.3	12.0 $\pm$ 1.4	18.9 $\pm$ 1.7	9.55 $\pm$ 1.17	6.97 $\pm$ 1.03	8.00 $\pm$ 1.10
72.7	16.6 $\pm$ 1.6	4.19 $\pm$ 0.80	6.55 $\pm$ 1.06	17.0 $\pm$ 1.3	11.1 $\pm$ 1.3	8.54 $\pm$ 1.14	7.03 $\pm$ 1.03

Figure 23. Counter energy spectrum for $^{124}\text{Sn}(t,p)^{126}\text{Sn}$ at $\theta = 30^\circ$.

Figure 24.. Spectrograph energy spectrum for $^{124}\text{Sn}(t,p)^{126}\text{Sn}$ at
 $\theta = 36^\circ$.

Figure 25. Energy level diagram for ^{126}Sn .

^{126}Sn

2.727 ———

2.165 ———

2.056 ———

1.146 ———

0.000 ——— 0^+

(t, p)

Figure 26. Experimental angular distributions for the $^{124}\text{Sn}(t,p)^{126}\text{Sn}$ reaction.

Table VII. Cross Sections for the $^{124}\text{Sn}(t,p)^{126}\text{Sn}$ Reaction.

$^{124}\text{Sn}(t,p)^{126}\text{Sn}$

θ_{CM}	Ground State σ_{CM} ($\mu\text{b/sr}$)	1.146 MeV σ_{CM} ($\mu\text{b/sr}$)	2.056 MeV σ_{CM} ($\mu\text{b/sr}$)	2.165 MeV σ_{CM} ($\mu\text{b/sr}$)	2.727 MeV σ_{CM} ($\mu\text{b/sr}$)
12.1	457.2 $\pm$ 66.0	112.6 $\pm$ 32.5			
15.2	360.7 $\pm$ 53.0				
18.2	63.8 $\pm$ 18.4	47.8 $\pm$ 1.6	47.8 $\pm$ 1.6	53.1 $\pm$ 16.8	42.5 $\pm$ 15.0
21.3	24.8 $\pm$ 8.3	16.5 $\pm$ 7.0	24.8 $\pm$ 8.3	22.0 $\pm$ 7.8	30.3 $\pm$ 9.0
24.3	60.6 $\pm$ 8.1	23.4 $\pm$ 5.0	10.6 $\pm$ 3.4	38.2 $\pm$ 6.3	25.5 $\pm$ 5.2
27.3	179.1 $\pm$ 20.0	14.8 $\pm$ 2.8	22.9 $\pm$ 3.5	43.9 $\pm$ 4.9	31.5 $\pm$ 4.1
30.4	275.2 $\pm$ 14.5	4.34 $\pm$ 1.82		48.6 $\pm$ 6.1	22.4 $\pm$ 4.1
33.4	349.6 $\pm$ 15.0	5.82 $\pm$ 1.96		50.4 $\pm$ 5.8	41.6 $\pm$ 5.3
36.4	305.5 $\pm$ 12.5	8.76 $\pm$ 2.10	25.6 $\pm$ 3.6		29.9 $\pm$ 3.8
39.4	238.3 $\pm$ 7.0	10.4 $\pm$ 1.5	16.2 $\pm$ 1.9	45.4 $\pm$ 3.1	15.9 $\pm$ 1.8
42.5	123.6 $\pm$ 6.5	9.76 $\pm$ 1.95	10.6 $\pm$ 2.0	37.7 $\pm$ 3.8	9.89 $\pm$ 1.95
45.5	53.3 $\pm$ 5.4	25.4 $\pm$ 3.6	4.63 $\pm$ 1.57	48.9 $\pm$ 5.1	
48.5	33.9 $\pm$ 3.7	11.2 $\pm$ 2.1	7.49 $\pm$ 1.74	36.0 $\pm$ 3.8	8.99 $\pm$ 1.91
51.6	40.3 $\pm$ 2.5	5.94 $\pm$ 0.96	8.27 $\pm$ 1.13	29.7 $\pm$ 2.2	7.04 $\pm$ 1.04
54.6	89.3 $\pm$ 3.6	3.97 $\pm$ 0.76	7.41 $\pm$ 1.04	21.5 $\pm$ 1.8	8.80 $\pm$ 1.14
57.6	127.6 $\pm$ 4.0	4.98 $\pm$ 0.83	6.96 $\pm$ 0.82	20.3 $\pm$ 1.6	9.21 $\pm$ 1.13
60.6	142.7 $\pm$ 4.5	2.64 $\pm$ 0.61	7.60 $\pm$ 1.02	18.5 $\pm$ 1.6	6.95 $\pm$ 0.87
63.6	130.0 $\pm$ 4.0	6.04 $\pm$ 0.87	8.26 $\pm$ 1.13	17.2 $\pm$ 1.6	5.87 $\pm$ 0.80
66.6	63.0 $\pm$ 2.8	3.96 $\pm$ 0.71	3.66 $\pm$ 0.68	14.2 $\pm$ 1.3	2.84 $\pm$ 0.60
69.7	37.0 $\pm$ 2.0	6.25 $\pm$ 0.83	3.25 $\pm$ 0.60	11.9 $\pm$ 1.2	2.13 $\pm$ 0.49
72.7	21.0 $\pm$ 1.6	10.9 $\pm$ 1.2	3.14 $\pm$ 0.62	11.8 $\pm$ 1.2	4.79 $\pm$ 0.76

VI. DISCUSSION

A. Zirconium Isotopes

The strength of the states observed in all of the zirconium isotopes is presented in Table VIII. The first column for each nucleus gives the excitation energy, the second column gives the spin and parity of the state, and the third column gives the ratio of the average cross section for that state to the average cross section for the $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ ground state transition.

TABLE VIII

Average Cross Sections for the (t,p) Reaction on the Zirconium Isotopes

^{92}Zr			^{94}Zr			^{96}Zr		
E_{EX}	J^{π}	σ_{AVG}	E_{EX}	J^{π}	σ_{AVG}	E_{EX}	J^{π}	σ_{AVG}
0	0^{+}	1.00	0	0^{+}	1.57	0	0^{+}	1.23
0.935	2^{+}	2.23	0.920	2^{+}	1.43	1.594	0^{+}	0.52
1.390	0^{+}	0.05	1.304	0^{+}	0.06	1.758	2^{+}	1.57
1.497	4^{+}	2.40	1.471	4^{+}	1.02	1.905	3^{-}	0.99
1.842	2^{+}	0.13	1.675	2^{+}	0.65			
2.071	2^{+}	1.25	2.064	3^{-}	1.78			
2.346	3^{-}	1.26	2.374	2^{+}	2.24			
2.871	4^{+}	1.33						
3.063	2^{+}	2.11						
3.473	4^{+}	1.33						

This simple shell model would predict that ^{90}Zr has a closed $1g_{9/2}$ neutron shell and from ^{91}Zr through ^{96}Zr the $2d_{5/2}$ neutron shell is filling. Figure 27 gives the positions of the shell model states as determined by Cohen et al.⁴² The proton configuration for zirconium is described by a ^{88}Sr core with two protons outside the core in the $2p_{1/2}$ and $1g_{9/2}$ orbitals. From a number of studies,⁴³ this proton configuration has been described as

$$\psi_{90\text{ZrGS}} = a(2p_{1/2})^2 + b(1g_{9/2})^2$$

where $a^2 = 0.64$ and $b^2 = 0.36$.

Recently Freedom⁴⁴ measured a^2 and b^2 for $^{90,92,94,96}\text{Zr}$. The results are given in Table IX.

TABLE IX

Coefficients of the $(2p_{1/2})^2$ and $(1g_{9/2})^2$ Terms in the Zirconium Ground State Wave Functions and Strengths of the First Excited 0^+ States

Isotope	a^2	b^2	Predicted Strength	Observed
^{90}Zr	0.64 ± 0.04	0.36		
^{92}Zr	0.55 ± 0.04	0.45	0.008	0.05
^{94}Zr	0.66 ± 0.04	0.34	0.013	0.06
^{96}Zr	0.86 ± 0.09	0.14	0.06	0.40

The 1.390 MeV 0^+ state in ^{92}Zr and the 1.304 MeV 0^+ state in ^{94}Zr have been described as being due to the proton configuration that is orthogonal to the ground state configurations. Therefore, one can use the numbers in Table IX to determine the expected strength of the first

Figure 27. Positions of the shell-model states in the zirconium region.

$n\ell_j$

ENERGY

$1h_{11/2}$ ————— > 5.1

$1g_{7/2}$ ————— 2.70
 $2d_{3/2}$ —————

$3s_{1/2}$ ————— 1.55

$2d_{5/2}$ ————— 0.00

$1g_{9/2}$ ————— -4.50

$2p_{1/2}$ ————— -5.00

excited 0^+ state relative to the ground state strength. It will be assumed for the moment that the 1.594 MeV 0^+ state in ^{96}Zr is a similar state. The predicted strength is given in Table IX along with the observed strength. Letting the unprimed coefficients refer to the target nucleus and the primed numbers refer to the residual nucleus, then the predicted strength is given by calculating the overlap

$$\left(\frac{-b'a + ba'}{aa' + bb'} \right)^2.$$

The predicted and observed strengths disagree by nearly an order of magnitude but in both cases the trend with increasing mass is the same. It would appear that while the changing proton configuration is affecting the strength of the first excited 0^+ states there must also be some other effect; probably the $(3s_{1/2})^2$ neutron strength is also appearing in the first excited 0^+ states or a mixed neutron configuration in the ^{94}Zr ground state. If one takes the coefficients for ^{94}Zr , namely $a^2 = 0.66$, $b^2 = 0.34$, then a^2 for ^{96}Zr would have to be 0.994 to account for the observed strengths.

One can take a different approach and assume that these states are strictly due to the proton configurations and calculate the proton configuration coefficients that would be required to obtain the excited state 0^+ strengths observed in the present experiment. The results of such a calculation are shown in Table X.

TABLE X

Predicted Coefficients of the $(2p_{1/2})^2$ Term in the Zirconium Ground State Wave Functions from Observed 0^+ Strengths

Isotope	Preedom's Work	Present Work		
		-----	-----	-----
^{90}Zr	0.64	0.64	0.55	0.71
^{92}Zr	0.55	0.83	0.76	0.88
^{94}Zr	0.66	0.97	0.93	0.99
^{96}Zr	0.86	0.86	0.92	0.80

The a^2 term for ^{90}Zr has been independently determined by a number of investigators. Table X has five columns; column two gives Preedom's values⁴⁴ for all the zirconium isotopes, column three gives the results of the present work starting with Preedom's values for ^{90}Zr , columns four and five give similar results starting with the extreme values⁴³ for ^{90}Zr of other investigators. It should be emphasized that the coefficients in Table X would be required if the only effect was a changing proton configuration.

Several other states can be discussed without reference to the present DWBA calculations. The 1.842 MeV 2^+ state in ^{92}Zr is thought to be primarily $(1g_{9/2})^2$ proton excitation with 25-30% neutron $(2d_{5/2})^2$ excitation. In the present work this state (at 1.842 MeV) is fairly weak so the above interpretation seems reasonable. The first 2^+ and first 4^+ states in ^{92}Zr and ^{94}Zr are probably primarily due to $(2d_{5/2})^2$ and

$(2d_{5/2})^{-2}$ neutron configurations, respectively, with respect to a closed ^{90}Zr neutron core. These states disappear when the $2d_{5/2}$ shell is closed at ^{96}Zr . Since at ^{96}Zr the last two neutrons put in can couple only to zero, these 2^+ and 4^+ states cannot be formed. So the present work confirms the previous predictions regarding these states. The 1.675-MeV state in ^{94}Zr was thought to be 4^+ mainly due to the $(1g_{9/2})^2$ proton configuration just like the 1.842-MeV state in ^{92}Zr . The present work excites the latter state 5 times stronger than the former so there may be a fair amount of neutron strength in this state.

Stautberg and co-workers²⁹ have suggested that the 1.758 MeV 2^+ state in ^{96}Zr is primarily due to $(d_{5/2}^{-1}s_{1/2})$ and this state is excited strongly so that interpretation seems reasonable.

Relative spectroscopic strengths were obtained for a number of states in $^{92,94,96}\text{Zr}$. These were measured by comparing the experimental angular distributions to a DWBA calculation. The neutron configuration was assumed to be $(2d_{5/2})^2$ in all cases except $J^\pi = 3^-$ where the configuration was assumed to be $(2d_{5/2}, 1h_{11/2})$. The strengths for other configurations were also calculated and will be discussed later.

Table XI presents the spectroscopic strengths.

TABLE XI

Relative Spectroscopic Strengths for the $^{90}\text{Zr}(t,p)^{92}\text{Zr}$ Reaction

J^π	Excitation	$\frac{\sigma_{\text{EXP}}}{\sigma(2d_{5/2})^2}$	Theory	
			S	Excitation
0_1^+	0.00	1.00	0.97	0.00
2_1^+	0.935	1.06	0.94	0.91
0_2^+	1.390	--- [†]	0.007	1.59
4_1^+	1.497	0.82	0.98	1.49
2_2^+	1.842	0.06	0.05	2.0
2_3^+	2.071	0.50	----	----
4_2^+	2.871	0.43	0.01	2.64
2_4^+	3.063	0.84	0.006	2.90
4_3^+	3.473	0.45	0.0005	3.50
3_1^-	2.346	2.65*	----	----

*($2d_{5/2}, 1h_{11/2}$)[†]No DWBA calculation was done for this state.

The subscript in the first column refers to the number of the state. That is, 0_1^+ is the lowest energy 0^+ state, 0_2^+ is the next highest 0^+ state. Column three gives the relative spectroscopic strength based on a DWBA calculation which assumed a neutron configuration of $(2d_{5/2})^2$ for all states except $J^\pi = 3^-$. Column three is normalized to a value of 1.0 for $^{90}\text{Zr}(t,p_0)^{92}\text{Zr}$. Columns four and five give the expected strengths and excitation energies predicted by a nuclear

structure calculation done by R. M. Drisko. This calculation assumes that all of the zirconium isotopes treated here have an inert ^{90}Zr core of fifty neutrons and the additional neutrons are all in $2d_{5/2}$ orbits. The protons are allowed to be in $(2p_{1/2})^2$ or $(1g_{9/2})^2$ configurations. The level positions are predicted reasonably well and the strengths predicted are in fair agreement until the 2.871 MeV 4^+ level where the other neutron orbitals are beginning to be important. The small observed strengths for the 1.390-MeV state and the 1.842-MeV state are consistent with the picture that these states are primarily due to proton excitation.

Table XII presents similar results for $^{92}\text{Zr}(t,p)^{94}\text{Zr}$.

TABLE XII

Relative Spectroscopic Strengths for the $^{92}\text{Zr}(t,p)^{94}\text{Zr}$ Reaction

J^π	Excitation	σ_{EXP}	Theory	
		$\sigma(2d_{5/2})^2$	S	Excitation
0_1^+	0.00	1.84	1.30	0.00
2_1^+	0.920	0.88	0.32	0.91
0_2^+	1.340	----- [†]	0.005	1.74
4_1^+	1.471	0.41	0.33	1.45
2_2^+	1.675	0.38	0.01	2.23
2_3^+	2.374	1.24		
3_1^-	2.064	5.08*		

*($2d_{5/2}, 1h_{11/2}$)

[†]No DWBA calculation was done for this state.

Here the agreement is reasonable for the ground state, but for the first 2^+ states there is a gross discrepancy between the observed strength of 0.88 and the predicted strength of 0.32. This is a clear indication of configuration mixing and represents a defect in the simple wave function assumed in the structure calculation. There is probably an admixture of the $(2d_{5/2}, 3s_{1/2})$ configuration in this state.

In both Tables XI and XII the 3^- states are quite strongly excited. While the strengths for these states were determined assuming a $(2d_{5/2}, 1h_{11/2})$ configuration it is quite possible that one is seeing here a p-d admixture where the p-shell neutron is coming from the 2p shell below the $2d_{5/2}$ shell or the 3p shell above.

Table XIII gives similar results for $^{94}\text{Zr}(t,p)^{96}\text{Zr}$.

TABLE XIII

Relative Spectroscopic Strengths for the $^{94}\text{Zr}(t,p)^{96}\text{Zr}$ Reaction

J^π	Excitation	σ_{EXP}	Theory	
		$\sigma(2d_{5/2})^2$	S	Excitation
0_1^+	0.000	1.42	0.98	0.000
0_2^+	1.594	0.57	0.008	1.99
2_1^+	1.758	0.95	----	----

Here the disagreement between theory and experiment is quite large. The simple wave functions do not predict the first excited state either in strength or position. One should recall that the $2d_{5/2}$

neutrons added to ^{94}Zr can couple only to 0^+ in ^{96}Zr so that the first 2^+ and 4^+ states which in ^{92}Zr and ^{94}Zr were due to $(2d_{5/2})^2$ configurations are not present in ^{96}Zr .

To summarize Tables XI, XII, and XIII the simple wave functions seem to give reasonable predictions for the first 2 MeV of excitation in ^{92}Zr and for the ground states of all three isotopes. For the rest of the states in ^{92}Zr , and all but the ground states in ^{94}Zr and ^{96}Zr , these simple wave functions are not adequate representations of the data. The DWBA calculation predicts relative strengths for the ground state transitions for the $^{92,94,96}\text{Zr}$ of $1 : 1.33 : 1$. The wave functions used for the structure calculation predict $0.97 : 1.30 : 0.98$ and the experimental results are $1 : 1.84 : 1.42$. If one assumes that ^{90}Zr is a well closed neutron shell, then it is likely that the ground states of ^{92}Zr and ^{94}Zr have mixed neutron configurations. This would account for two effects observed in the present work, namely the ratios of the ground state strength and the larger strengths for the first excited 0^+ states in all three isotopes. Further work is presently being undertaken which will include more complicated wave functions including mixed neutron configurations.

The DWBA calculation was used to predict relative strength for different neutron configurations. The results of these calculations are shown in Table XIV. These strengths are all normalized to the strength for a $(2d_{5/2})^2$ configuration.

TABLE XIV

Relative Strengths for Different Neutron Configurations

J^π	Configuration	Strength
0^+	$(2d_{5/2})^2$	1.000
	$(3s_{1/2})^2$	1.005
	$(2d_{3/2})^2$	0.671
	$(1g_{7/2})^2$	0.065
2^+	$(2d_{5/2})^2$	1.000
	$(2d_{5/2}, 3s_{1/2})$	3.028
	$(2d_{3/2}, 3s_{1/2})$	2.037
	$(2d_{3/2})^2$	0.587
	$(2d_{5/2}, 2d_{3/2})$	0.502
	$(2d_{5/2}, 1g_{7/2})$	0.048
	$(2d_{3/2}, 1g_{7/2})$	0.664
	$(1g_{7/2})^2$	0.068
4^+	$(2d_{5/2})^2$	1.000
	$(2d_{5/2}, 2d_{3/2})$	4.011
	$(2d_{5/2}, 1g_{7/2})$	0.260
	$(1g_{7/2})^2$	0.080
	$(1g_{7/2}, 2d_{3/2})$	0.492
	$(1g_{7/2}, 3s_{1/2})$	1.202

It is clear from the results of Table XIV that configurations other than $(2d_{5/2})^n$ are clearly going to affect the observed states and that structure calculations need to use more complicated wave functions. For example, the 0.920 MeV 2^+ state in ^{94}Zr probably has

some $(2d_{5/2}, 3s_{1/2})$ admixture and the ground state transitions of all three isotopes probably have some $(3s_{1/2})^2$ admixture.

B. Tin Isotopes

The ground states of the tin isotopes are thought to be superconducting.⁴⁶ The term superconducting comes from an analogy to an electron gas in a metal where a correlation between pairs of electrons leads to an electronic state that is lower in energy than the normal state. There is a finite energy gap between the superconducting state and the normal state. In the nuclear case, the energy gap may be estimated from the neutron separation energies. This has been done by Kisslinger and Sorensen.⁴⁷ They give a value of 1.1 MeV for the tin isotopes. Yoshida⁴⁸ has predicted that the ground state transitions for the tin isotopes will be enhanced by an order of magnitude or more over what they would be if the states were simple neutron configurations. Yoshida also states that the cross section should be proportional to $(2\Delta/G)^2$ where Δ is the energy gap and G is the pairing interaction. G has a value of 0.187 for the tin isotopes.⁴⁷ One can calculate the change in the energy gap and compare that to the change in cross section observed for the $^{122}\text{Sn}(t,p)^{124}\text{Sn}$ and $^{124}\text{Sn}(t,p)^{126}\text{Sn}$ reactions. The results are that while the energy gap squared increases by 15% in going from ^{124}Sn to ^{126}Sn , the (t,p) cross section increases by 3%. Since the cross section has an absolute error of $\pm 15\%$, the agreement is within the experimental error.

The strongly excited doublets at about 5.5 MeV in both ^{124}Sn and ^{126}Sn deserve further study. Spectrograph exposures have been made at a number of angles in order to obtain angular distributions. These states are probably due to neutron orbitals in the next major neutron shell at about 5 MeV above the neutron shell which is filling in the tin region.

To summarize the present tin (t,p) data, one can say that the tin ground states indeed appear to be superconducting and that it is important to study states at higher excitation than was done in the present work.

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