(p,d), (p,t), and (p,α) Reactions to the Same Final States in Fe^{56} and in Zr^{90}

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The reactions $Fe^{57}(p,d)$, $Fe^{58}(p,t)$, and $Co^{59}(p,\alpha)$, all exciting final states in Fe^{56}, and the reactions $Zr^{91}(p,d)$, $Zr^{92}(p,t)$, and $Nb^{93}(p,\alpha)$, all exciting final states in Zr^{90}, were studied with 22-MeV protons from the ORNL 86-in. Cyclotron. The angular distributions and cross sections for each of these reactions exciting the same final states were obtained. The cross sections for exciting a given final state by each of the reactions provides an indication of the relative probability for the single, double, and triple pickup process.

INTRODUCTION

PREVIOUS work on (p,d) and (p,t) reactions[1–3] with 22-MeV protons has shown that, at this energy, the reactions proceed primarily by a direct interaction process. In general, the low-lying states in the final nucleus are excited with the highest probability.

A survey[4] of (p,α) reactions at 23 MeV showed that the major contributions to the alpha-particle spectra for targets with $Z \gtrsim 50$ arise from low-energy compound nucleus emission. The alpha spectra observed in that work also showed a high-energy, forward peaked contribution; this contribution was attributed to direct interaction reactions.

In the work reported here, (p,α)-reaction-induced transitions to low-lying levels of the residual nucleus were observed with sufficient resolution to study the angular distributions of individual levels.

The purpose of this paper is to report two cases where the (p,d), (p,t), and (p,α) reactions were used to excite the same final states. The reactions are interpreted as being due to the pickup of one neutron, two neutrons, and two neutrons and a proton, respectively. The angular distributions of these levels were obtained between laboratory angles of 10° and 150°, enabling a reasonably good estimate of the cross sections to be made. Comparisons of the cross sections for exciting the same final states by (p,d), (p,t), and (p,α) reactions are made for the final states of Fe^{56} and Zr^{90}.

EXPERIMENTAL METHOD

The (p,d) and (p,t) data reported in this paper were originally taken at forward angles in the course of other investigations.[3,5] These data were since extended to large angles to enable determination of the cross sections for exciting the final states of interest. The data were taken with the experimental apparatus previously described.

Briefly, a $dE/dx - E$ counter telescope supplies pulses to a fast analog computer circuit which performs a multiplication and provides an output pulse proportional to the mass of the measured particle. This pulse is used to reset the address scaler of a 400-channel pulse-height analyzer, operating in a 4×100 channel mode, so that spectra due to different particles are stored in individual quadrants of the analyzer memory.

The raw data from the analyzer are automatically punched on cards by an IBM-024 card punch. The conversion of the raw data to energy spectra and cross sections is performed on an IBM-7090 computer. The output of the computer, in the form of punched cards, is then plotted automatically by a Moseley plotter attached to the 024 card-punch reading station.

The telescope used for the (p,d) and (p,t) data consisted of an 8-mil-thick silicon surface-barrier dE/dx counter and a NaI(Tl) crystal E counter.

The (p,α) spectra were taken with a modified version of the same counter telescope used previously.[4,6] For the earlier work the telescope consisted of a low pressure proportional counter and a CsI(Tl) crystal. This was modified by replacing the CsI(Tl) energy counter with

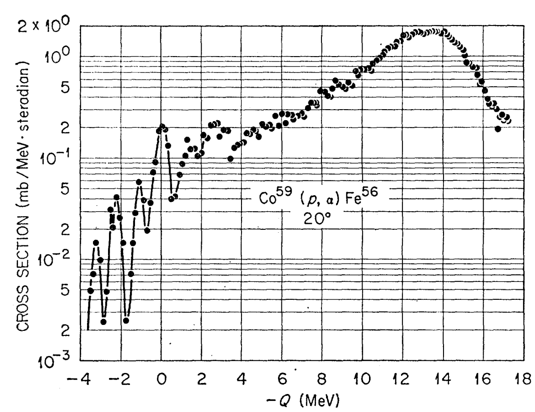

FIG. 1. Spectrum of alpha particles from bombardment of Co^{59} with 22.3-MeV protons.

* Operated for the U.S.A.E.C. by Union Carbide Corporation.
[1] C. D. Goodman and J. B. Ball, Phys. Rev. **118**, 1062 (1960).
[2] J. B. Ball and C. D. Goodman, Phys. Rev. **120**, 488 (1960).
[3] C. D. Goodman, J. B. Ball, and C. B. Fulmer, Phys. Rev. **127**, 574 (1962).
[4] C. B. Fulmer and B. L. Cohen, Phys. Rev. **112**, 1672 (1958).
[5] C. D. Goodman, C. B. Fulmer, and J. B. Ball (to be published); C. D. Goodman, J. B. Ball, and C. B. Fulmer, in "Proceedings of the International Symposium on Direct Interaction and Nuclear Reaction Mechanisms, Padua, 1962" (to be published).
[6] C. B. Fulmer and C. D. Goodman, Phys. Rev. **117**, 1339 (1960).

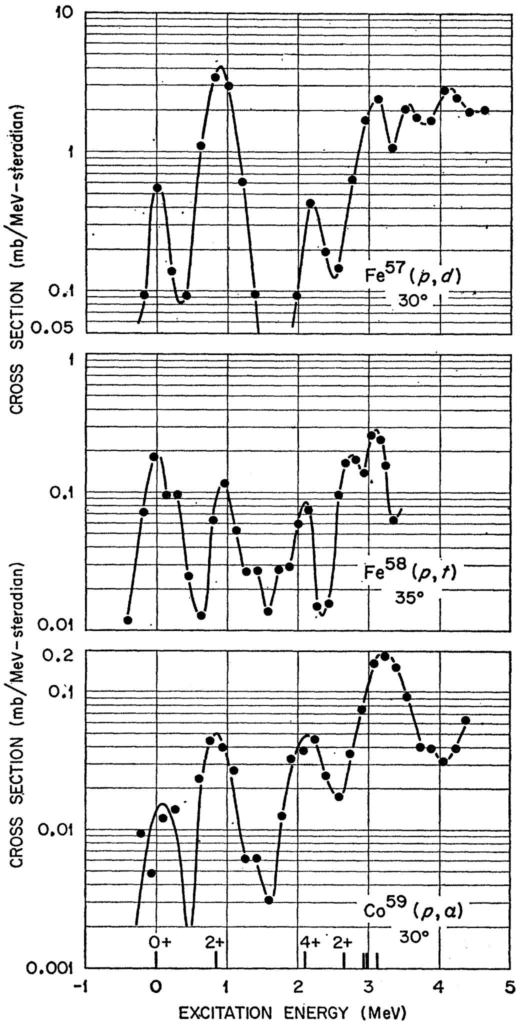

FIG. 2. Spectra of deuterons, tritons, and alpha particles for reactions leading to final states in Fe^{56}.

a 16-mil-thick silicon surface-barrier counter.[7] This solid-state counter was thick enough to stop the most energetic alpha particles encountered in this work but was thin enough to produce small pulses for the lighter particles. The solid-state E detector has several advantages over the CsI counter; the pulse-height response to alpha particles is linear and the resolution is better. Also, the silicon counter was put directly in the proportional counter gas, decreasing the total absorber. The amount of absorber due to the proportional counter front window and filling gas was 3.7 mg/cm^2 aluminum equivalent. The counter was calibrated with the 8.78-MeV alphas from Po^{212} and the ground-state alphas from the $F^{19}(p,\alpha)O^{16}$ reaction. To facilitate collection of alpha-particle spectra over the full range of energy, the same particle selection system was used as for the (p,d) and (p,t) work.

A typical alpha-particle spectrum is shown in Fig. 1. The spectrum exhibits the low energy compound nuclear contribution characteristic of nuclei in this mass region. Also in evidence are some strongly excited low-lying levels. These are the levels that we wish to compare with levels excited by the other reactions.

RESULTS

Spectra from the $Fe^{57}(p,d)Fe^{56}$, $Fe^{58}(p,t)Fe^{56}$, and $Co^{59}(p,\alpha)Fe^{56}$ reactions are shown in Fig. 2. Also indicated in the figure are the positions and assignments[8] of the known low-lying levels in Fe^{56}. It is seen that the ground state and the first two excited states of Fe^{56} are excited by all three reactions.

The angular distribution for the transitions exciting the ground state and the first two excited states of Fe^{56} are shown for the $Fe^{57}(p,d)$ reaction in Fig. 3, for the $Fe^{58}(p,t)$ reaction in Fig. 4, and for the $Co^{59}(p,\alpha)$ reaction in Fig. 5.

The cross sections obtained by integrating these angular distributions are listed in Table I. In most cases the major portion of the uncertainty comes from the uncertainty in the cross sections forward of 10°.

Spectra from the $Zr^{91}(p,d)Zr^{90}$, $Zr^{92}(p,t)Zr^{90}$, and $Nb^{93}(p,\alpha)Zr^{90}$ reactions are shown in Fig. 6. Again, the positions and assignments[8] of the known low-lying levels in Zr^{90} are indicated. The ground state of Zr^{90} is excited by all three reactions. A state at an excitation

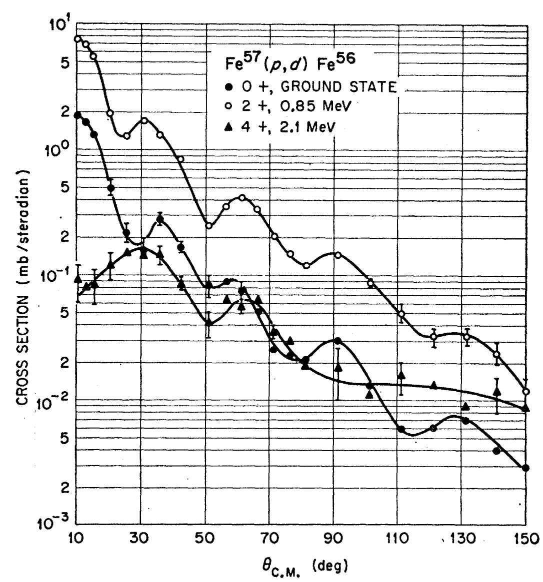

FIG. 3. Angular distributions of deuterons, from bombardment of Fe^{57} with 22.3-MeV protons, leading to the three lowest states of Fe^{56}.

[7] The silicon surface-barrier counter was fabricated by R. J. Fox of the Instrumentation and Controls Division of this Laboratory.

[8] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC 59-4, 60-4.

TABLE I. Cross sections and angular momentum exchange values for exciting states in Fe^{56}; cross sections are in millibarns.

Reaction	Level energy MeV	Level spin and parity	Angular momentum exchange, Δl	Spectroscopic factor, $\mathcal{S}$	Cross section, σ_{obs}	$\sigma_{obs}/\mathcal{S}$
$Fe^{57}(p,d)$	0	0+	1		1.20±0.1	
	0.85	2+	1		5.41±0.2	
	2.1	4+	3		0.46±0.1	
	Sum of 0+, 2+, and 4+			~1	7.07±0.25	7.1
$Fe^{58}(p,t)$	0	0+	0		2.11±0.3	
	0.85	2+	2		0.26±0.03	
	2.1	4+	4		0.06±0.02	
	Sum of 0+, 2+, and 4+			~1	2.43±0.3	2.4
$Co^{59}(p,\alpha)$	0	0+	3		0.016±0.002	
	0.85	2+	1		0.078±0.006	
	2.1	4+	1		0.100±0.008	
	Sum of 0+, 2+, and 4+			large	0.194±0.01	

of about 2.3 MeV is strongly excited in the (p,α) reaction.

The angular distributions for the three reactions exciting the ground state of Zr^{90} are shown in Fig. 7. The angular distribution for the 2.3-MeV state excited by the (p,α) reaction is shown in Fig. 8. The cross sections obtained by integrating these angular distributions are listed in Table II.

DISCUSSION

The probability of a direct interaction process can be expressed as the product of two factors,

$$\sigma_{obs}=\mathcal{S}\bar{\sigma}_r(E,Q,l).$$

The first factor represents the contribution from nuclear structure effects, generally referred to as a spectroscopic factor, and the second factor represents the effects of the reaction dynamics.

To treat direct interaction data in such a manner as to extract nuclear structure information, it is the general practice to employ a specific model for the interaction and calculate $\bar{\sigma}_r$.[9]

It is the purpose of this work to examine cases of the (p,d), (p,t), and (p,α) reactions where the estimation of the spectroscopic factor should be particularly simple. Any large differences in the determined values of $\bar{\sigma}_r$ should then reflect the probability differences for the single, double, and triple pickup processes.

Specifically, we have selected cases in which the final nucleus can be considered as a "core" and the targets

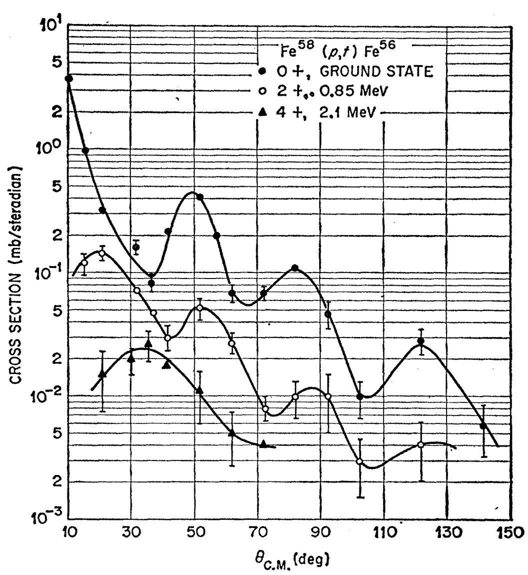

FIG. 4. Angular distributions of tritons, from bombardment of Fe^{58} with 22.3-MeV protons, leading to the three lowest states of Fe^{56}.

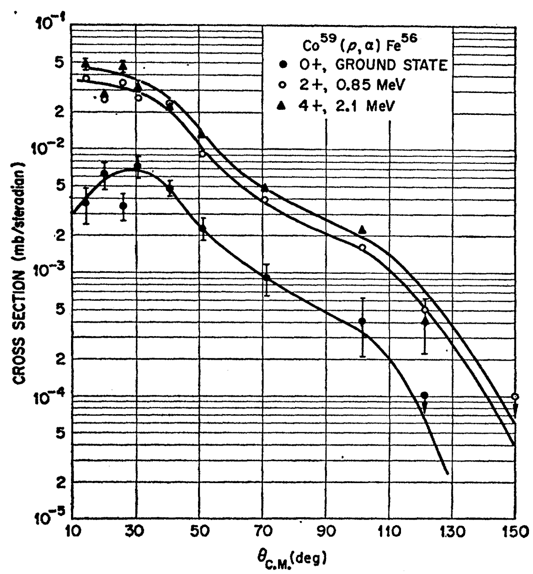

FIG. 5. Angular distributions of alpha particles, from bombardment of Co^{59} with 22.3-MeV protons, leading to the three lowest states of Fe^{56}.

[9] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. 32, 567 (1960).

TABLE II. Cross section and angular momentum exchange values for exciting states in Zr^{90}; cross sections are in millibarns.

Reaction	Level energy MeV	Level spin and parity	Angular momentum exchange, Δl	Spectroscopic factor, S	Cross section, σ_{obs}	σ_{obs}/S
$Zr^{91}(p,d)$	0	0+	2	~1	6.7±0.2	6.7
$Zr^{92}(p,t)$	0	0+	0	~1	1.83±0.2	1.8
$Nb^{93}(p,\alpha)$	0	0+	4	~1	0.028±0.006	0.03
	2.3	5−(4−?)	1	~2	0.11±0.02	0.055

consist of the core plus one neutron, core plus two neutrons, and core plus two neutrons and one proton, respectively, for studying the (p,d), (p,t), and (p,α) reactions. We compare only those final states which can be interpreted as resulting from the removal of the "extra-core" nucleons. This method can be most easily illustrated by examining the case where the various reactions all lead to final states in Zr^{90}.

The shell-model configuration for Zr^{90} has, to a good approximation, the $2p_{1/2}$ level completely filled for both protons and neutrons and the $1g_{9/2}$ level completely unfilled for protons and completely filled for neutrons. The low-lying states observed[10] in Zr^{90} have been extensively treated[11–14] as arising from proton excitation and the possible couplings of the proton pair $(p_{1/2})^2$, $(p_{1/2})(g_{9/2})$, and $(g_{9/2})^2$.

On the basis of a simple shell-model approach, the ground state of Zr^{91} is well described as a Zr^{90} core plus one neutron in the $2d_{5/2}$ level. In this case the pickup of the $d_{5/2}$ neutron by the (p,d) reaction, should excite only the ground state in Zr^{90} and the spectroscopic factor should be unity.

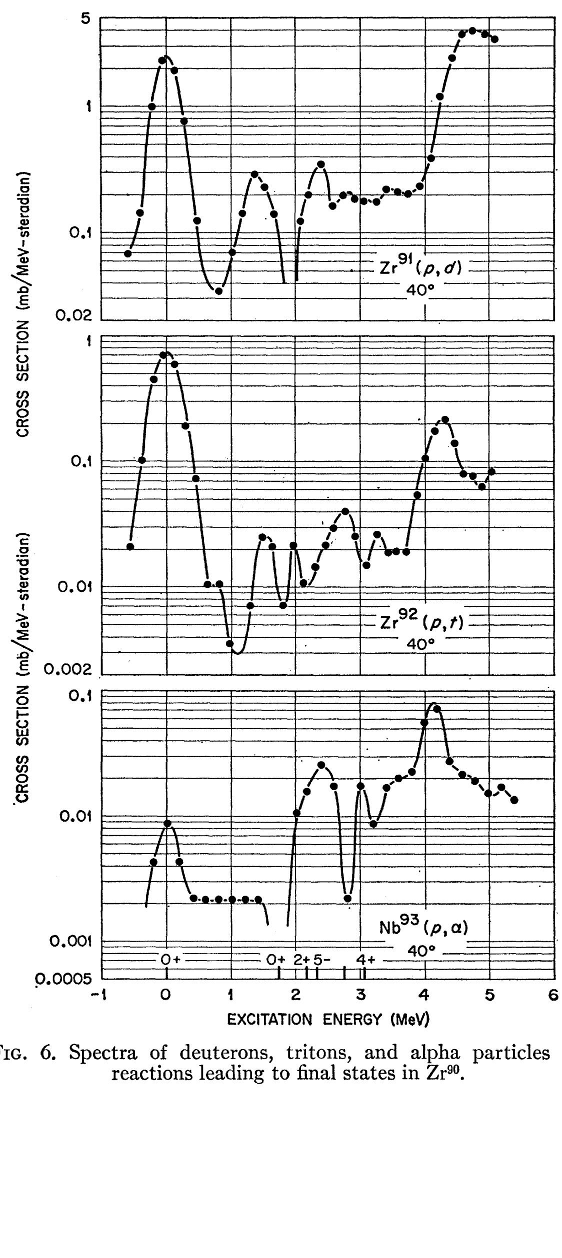

FIG. 6. Spectra of deuterons, tritons, and alpha particles for reactions leading to final states in Zr^{90}.

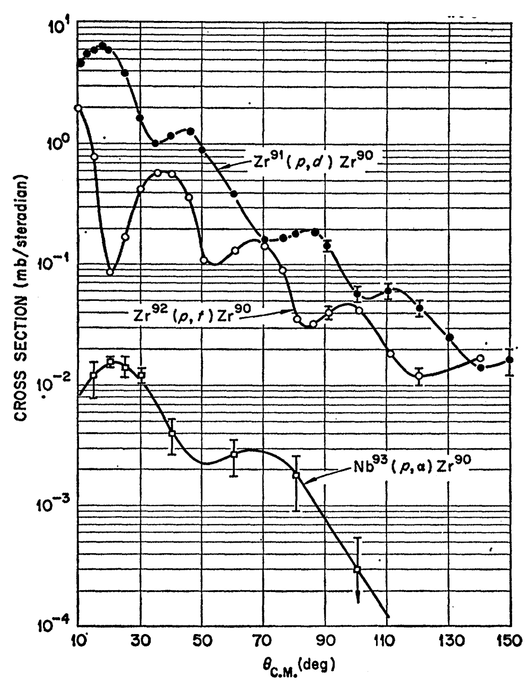

FIG. 7. Angular distributions of deuterons from Zr^{91}, tritons from Zr^{92}, and alpha particles from Nb^{93} leading to the ground state of Zr^{90}.

[10] S. Bjornholm, O. B. Nielsen, and R. K. Sheline, Phys. Rev. **115**, 1613 (1959).
[11] K. W. Ford, Phys. Rev. **98**, 1516 (1955).
[12] B. F. Bayman, A. S. Reiner, and R. K. Sheline, Phys. Rev. **115**, 1627 (1959).
[13] I. Talmi and I. Unna, Nucl. Phys. **19**, 225 (1960).
[14] V. K. Thankappan, Y. R. Waghmare, and S. P. Pandya, Progr. Theoret. Phys. (Kyoto) **26**, 22 (1961).

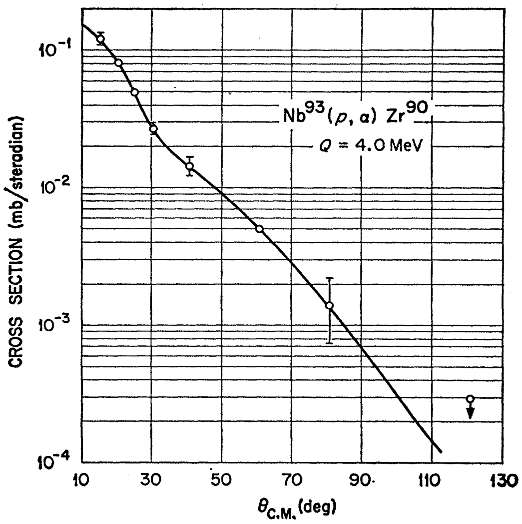

FIG. 8. Angular distribution of alpha particles from Nb^{93} exciting a state, or group of states, in Zr^{90} at an excitation of 2.3 MeV.

In practice, of course, coupling between the extra-core neutron and the core will give rise to configuration mixing and result in the possibility of exciting several final states in the residual nucleus by picking up the $d_{5/2}$ neutron. The spectroscopic factor for exciting the ground state would then be reduced.

The deuteron spectrum from $Zr^{91}(p,d)$, Fig. 6, shows a strong excitation of the Zr^{90} ground state, and strong excitation of states attributable to pickup of neutrons from the core, but only very weak excitation of other known levels in Zr^{90}. This is in excellent agreement with the assumed simple relationship between the ground states of Zr^{91} and Zr^{90}.

The angular distribution for the ground-state group, shown in Fig. 7, has the characteristic shape of an $l=2$ transition and thus confirms the pickup of a neutron from a d level. The lowest level due to core excitation occurs at 4.7 MeV ($Q=-9.6$ MeV). This state has an angular distribution characteristic of an $l=4$ transition which is consistent with picking up one of the $g_{9/2}$ neutrons from the core. The $g_{9/2}$ level is the least bound, filled neutron level in the Zr^{90} core. In the $Zr^{90}(p,d)Zr^{89}$ reaction an $l=4$ peak is observed at $Q=-10.2$ MeV and corresponds to the ground state transitions for that reaction.[5]

In general, any states at lower excitation than the first core excitation state must be considered as arising from the removal of the extra-core nucleon. This interpretation will become more important when the cases leading to final states in Fe^{56} are discussed.

In the case of $Zr^{91}(p,d)Zr^{90}$ only a weakly populated state at about 2.3 MeV is observed at a lower excitation than the lowest core excitation state. [The weak level at 1.4 MeV is due to the $Zr^{92}(p,d)Zr^{91}$ ground-state transition from Zr^{92} impurity in the Zr^{91} target.] The resolution of this experiment is not sufficient to exclude the possibility of the known 2+ level at 2.1 MeV from contributing to the observed deuteron group at 2.3 MeV. The 2+ level would be excited through the coupling of the $d_{5/2}$ neutron to the Zr^{90} core in the Zr^{91} ground state as previously mentioned. Even if the group is entirely due to exciting the 2+ level, as an upper limit, the amount of configuration mixing in the Zr^{91} ground state is quite small.

However, the 2.3-MeV group is probably due to exciting the known 5− level which has been interpreted as a state of proton excitation.[11–14] This state cannot be excited by a direct first-order process. It can be excited either by a direct second-order process or by an exchange process. In the direct second-order process the level would be reached by the pickup of the $d_{5/2}$ neutron and the simultaneous excitation of one of the $p_{1/2}$ protons into the vacant $g_{9/2}$ level. In the exchange process the state would be reached by the proton "knocking-out" a deuteron cluster, formed by the $d_{5/2}$ neutron and one of the $p_{1/2}$ protons, and then being captured into the $g_{9/2}$ level. In either process the two odd protons may then couple to either 5− or 4−. The 5− state is known from the radioactive decay scheme systematics but the 4− level is not expected to be excited by radioactive decay and has not yet been detected by other means. The pickup reaction should excite both states. The level at 2.3 MeV may possibly be both of these states. This level will be discussed again in the $Nb^{93}(p,\alpha)Zr^{90}$ case.

Special emphasis has been placed on the excitation of the 5− level by the (p,d) reaction because it serves as an indication that the simple interpretation of this reaction is the correct one. The ground state of the $Zr^{91}(p,d)Zr^{90}$ reaction can also be reached by the exchange process described above, the proton being captured into the $p_{1/2}$ level. The reaction leading to the ground state is an $l=2$ transition while excitation of the 4− or 5− states are $l=1$ and $l=3$ transitions, respectively. Depending on the actual character of the observed group, there may be some favoring of the ground-state cross section from angular momentum effects. However, statistical weighting strongly favors population of the 5− and 4− states. The observed group at $E=2.3$ MeV is seen most clearly near 40° (Fig. 6). The fact that the excitation of this group is down an order of magnitude from the excitation of the ground state indicates that for this (p,d) reaction the predominant process is the direct first-order pickup.

Two conclusions are drawn from the $Zr^{91}(p,d)Zr^{90}$ deuteron spectrum. First, the reaction proceeds primarily by a simple first-order pickup process, and second, the Zr^{91} ground state is well described as a Zr^{90} ground state plus an additional $2d_{5/2}$ neutron. The spectroscopic factor for exciting the ground state in this reaction is, therefore, close to unity and the observed cross section is directly a measure of $\bar{\sigma}_r$. This cross section is given in Table II.

In the $Zr^{92}(p,t)Zr^{90}$ reaction, the ground state of the target nucleus should be well described, on the basis of a simple shell-model picture, as a Zr^{90} core plus a $2d_{5/2}$ neutron pair. The observed triton spectrum, Fig. 6, is in excellent agreement with this interpretation. The peak corresponding to the ground state of Zr^{90} is attributed to the pickup of the $d_{5/2}$ neutron pair. The peak at an excitation of about 4.3 MeV is attributed to the pickup of two of the $1g_{9/2}$ neutrons from the core. A state at the same Q value as this latter peak is observed as the ground state of the $Zr^{90}(p,t)Zr^{88}$ reaction.[5] Again no evidence is seen for strongly exciting states by a direct second-order process or by an exchange process. The spectroscopic factor for exciting the ground state of Zr^{90} with this reaction should be close to unity. This cross section is listed in Table II.

The formation of an alpha particle by the pickup process is complicated by the fact that in addition to the two neutrons, a proton must also be picked up. In the mass region considered in this work this "extra-core" proton will not occupy the same shell-model state as the "extra-core" neutrons. Certainly the relative motion of the particles to be picked up is important and this may cause some reduction in the alpha-particle pickup cross section.[15]

In the $Nb^{93}(p,\alpha)Zr^{90}$ reaction the target nucleus has two neutrons in $2d_{5/2}$ level and an odd proton in the $1g_{9/2}$ level. The ground state of Zr^{90} should be reached by picking up these three particles, and the spectroscopic factor should be close to unity. The cross section is given in Table II.

A state at about 2.3 MeV is more strongly excited than the ground state. The angular distribution of this state, Fig. 8, is seen to be more strongly forward peaked than the angular distribution for the ground state shown in Fig. 7. This implies a lower l value for this transition, which is consistent with exciting the $5-$ state previously discussed. Unlike the case of (p,d) and (p,t), the (p,α) reaction can populate the $5-$ state with the same direct pickup process as it populated the ground state. The ground state of Zr^{90} would be excited by the incident proton picking up the two $2d_{5/2}$ neutrons and the single $1g_{9/2}$ proton. The $5-$ state would be excited by the incoming proton picking up the two $2d_{5/2}$ neutrons and one of the $2p_{1/2}$ protons, leaving the other $p_{1/2}$ proton to couple with the $g_{9/2}$ proton and yield a $5-$ state. The other possible coupling, $4-$, should also be excited; the observed peak may actually be both states, not separated because of insufficient resolution. The other possibility is that the $5-$ to $4-$ splitting is an MeV or larger. It appears that the $Nb^{93}(p,\alpha)Zr^{90}$ reaction, done with high resolution, would be an excellent method of locating the $4-$ state and determining the splitting. If both states are included in the observed group, the spectroscopic factor should be close to 2. The cross section for exciting this group is given in Table II. This state has been included in the table since it has a relatively simple interpretation. States observed at higher excitation are attributed to removal of one or more particles from deeper levels in the Zr^{90} core, and the estimation of a spectroscopic factor is no longer simple.

It should be mentioned that all of these states discussed above in the (p,α) case can also be populated by an exchange process. In this reaction there is no way of estimating the contribution from the exchange process, but since the exchange contribution in the (p,d) and (p,t) reactions was shown to be small it will be assumed that the levels discussed are populated mainly by the direct pickup process.

The analysis of the reactions leading to final states in Fe^{56} follows the same pattern as the Zr^{90} cases. However, the interpretation of the levels is not so clear as in the Zr^{90} case, since the shell-model description of the target nuclei is more complicated.

In a previous paper[3] it was pointed out that the levels excited by (p,d) reactions on the iron isotopes could not be explained on the basis of a simple shell model. Instead, it was necessary to employ a form of the shell model with a nonspherical potential and to assume that the ground states of Fe^{56}, Fe^{57}, and Fe^{58} are distorted in a prolate configuration. Good agreement was found between the number and type of levels experimentally observed and those expected on the basis of the Nilsson model.[16]

The simple shell model would not allow the description of Fe^{57} as an Fe^{56} core plus an additional neutron since the Fe^{57} ground state would be expected to have 3 neutrons in the $2p_{3/2}$ level. The use of the Nilsson model, however, restores the simpler picture since the distorted potential removes the degeneracy of the spherical shell model states. On the basis of this treatment, the Fe^{57} ground state is described as an Fe^{56} "core" and an additional neutron in Nilsson orbit 20.

Comparison of the $Fe^{57}(p,d)$ spectrum with the $Fe^{56}(p,d)$ spectrum[3] suggests that in $Fe^{57}(p,d)$ the levels below about 3 MeV should be attributed to excitations caused by removal of the neutron from Nilsson orbit 20. The levels above this energy are attributed to removal of neutrons from the Fe^{56} core.

There are three levels in Fe^{56} which meet the requirement of arising from the pickup of the "extra-core" neutron in $Fe^{57}(p,d)$. These are the $0+$, $2+$, and $4+$ levels. An examination of the relative excitation of the levels shows that the higher spin levels compete favorably with the ground state. In fact, in the $Fe^{57}(p,d)$ reaction the $2+$ state is populated much more strongly than the $0+$ ground state. This indicates a large amount of coupling between the extra-core neutron and the core in the Fe^{57} ground state. This is not at all surprising from the very nature of the assumption of a

[15] H. C. Newns, Proc. Phys. Soc. (London) **76**, 489 (1960).

[16] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd **29**, No. 16 (1955).

deformation for the ground state, and suggests that these 2+ and 4+ levels in Fe^{56} constitute a collective band based on the ground state. The higher population of the 2+ level, despite the fact that both the 2+ and 0+ levels are reached by an $l=1$ transition, indicates that the ground state of Fe^{57} looks more like a neutron coupled to the 2+ state of Fe^{56} than to the ground state of Fe^{56}.

Since the removal of the least bound neutron in the $Fe^{57}(p,d)$ reaction populates several levels, the spectroscopic factor for the ground-state transition will not be unity as in the $Zr^{91}(p,d)$ case, but will be less than unity. There are, in fact, three levels populated and the sum of the three spectroscopic factors should be unity. The cross sections for these levels are given in Table I.

It is not strictly correct to add the cross sections for the three levels together to determine $\bar{\sigma}_r$ since $\bar{\sigma}_r$ is a function of both energy and angular momentum. However, we are interested mainly in gross differences between the different reaction cross sections and, for purposes of comparison with the Zr^{90} cases, the sum of the three levels is also included in Table I.

In the $Fe^{58}(p,t)$ reaction, the target nucleus is now considered as an Fe^{56} core plus a neutron pair in Nilsson orbit 20. The 0+, 2+, and 4+ low-lying states in Fe^{56} are populated; these are attributed to pickup of the extra-core neutron pair from Fe^{58}. The spectroscopic factors for the three states should sum to unity as in the $Fe^{57}(p,d)$ case. The cross sections for exciting these three states, as well as the sum of all three cross sections, are given in Table I. The same remarks apply to the summing of the cross sections here as were made about the (p,d) summation.

The $Co^{59}(p,\alpha)$ reaction is more complex than the cases described above, and the estimation of a spectroscopic factor is no longer simple. In the previous study of the iron isotopes[3] it was found that, while the ground states of Fe^{56}, Fe^{57}, and Fe^{58} appeared to be deformed, the ground state of Co^{59} is spherical. Thus, the spherical shell-model degeneracy which was removed in the above treatment of the $Fe^{57}(p,d)$ and $Fe^{58}(p,t)$ reactions is present in the $Co^{59}(p,\alpha)$ reaction, and the ground state of Co^{59} cannot be considered as two neutrons and one proton outside an Fe^{56} core but at best is a Ca^{48} core surrounded by seven $1f_{7/2}$ protons and four $2p_{3/2}$ neutrons. The spectroscopic factor for the proton picking up the necessary nucleons to make an alpha particle is then much greater than unity. The cross sections for exciting the 0+, 2+, and 4+ states in Fe^{56} with the (p,α) reaction are listed in Table I. The sum of the three cross sections is also included for completeness.[17]

An over-all look at Tables I and II shows that for both the iron and zirconium cases the value of $\bar{\sigma}_{p,d}/\bar{\sigma}_{p,t}$ is 3.3 within the limits of the experimental uncertainties. The value of $\bar{\sigma}_{p,t}/\bar{\sigma}_{p,\alpha}$ from the zirconium case is about 40.

SUMMARY

The cross sections of the (p,d), (p,t), and (p,α) reactions exciting selected final states have been compared to obtain an estimate of the relative probability of the single, double, and triple pickup reactions. It is hoped that the comparison of these cross sections will serve as useful information for the eventual normalization of double and triple pickup calculations.

The double pickup process resulting in a (p,t) reaction seems to compete very well with the single pickup (p,d) reaction. This may not be too surprising since we have compared the case where the two neutrons are paired in the same level and thus should be expected to have a large overlap in their wave functions.

The (p,α) reaction does not seem to compete with any unusual strength and there does not seem to be any evidence that any high degree of alpha-particle preformation in the nuclear surface is contributing to the cross section for exciting low-lying final states. The magnitude of the observed cross sections seem quite compatible with a direct pickup process for this reaction.

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[17] See also R. Sherr, in "Proceedings of the International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962" (to be published) for additional discussion of (p,α) reactions in the $1f_{7/2}$ proton shell.