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Direct-Interaction (p,α) Reactions in ^{89}Y and ^{90}Zr†

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Alpha-particle energy spectra from (p,α) reactions in ^{89}Y and ^{90}Zr were obtained at 5-deg intervals between 15 and 90 deg. Bombarding energies of 20.2 and 22.5 MeV were used. Differential cross sections for reactions leading to the ground states and first excited states were determined. Distorted-wave calculations were done for the angular distributions for the reactions leading to each of the ground states and the 0.38-MeV first excited state in ^{87}Y. The calculated angular distributions reproduce the general features of the experimental angular distributions. Spectroscopic factors, obtained from normalization of the calculated angular distributions to the experimental data, are consistent with triton pickup as the dominant mechanism for direct-interaction (p,α) reactions. The normalization factors also indicate the ^{90}Zr ground-state proton configuration to be 70% $(2p_{1/2})^2$ and 30% $(1g_{9/2})^2$.

I. INTRODUCTION

EARLIER studies of (p,α) reactions[1,2] with 23- and 17-MeV protons showed that the major part of alpha-particle spectra obtained from targets with $Z \lesssim 50$ arise from compound-nucleus emission. The spectra also exhibited a high-energy forward-peaked component which was attributed to direct-interaction reactions.

There has been considerable discussion[3,4] about the mechanism of the direct-interaction component of the (p,α) reaction. This component of the reaction leads to relatively strong excitation of low-lying states in the final nucleus; the angular distributions are forward-peaked and exhibit pronounced structure. The discussion of the mechanism of the direct-interaction (p,α) reaction has been centered on whether the reaction proceeds by pickup of a quasi-triton by the incoming proton or by knockout of a quasi-alpha by the incident proton and capture of the latter into a bound state of the final nucleus.

To date, no complete theoretical treatment of the knockout reaction is available. It appears that, because the initial and final states for both reaction mechanisms are identical, it will be very difficult if not impossible to distinguish between the two mechanisms on the basis of reaction dynamics. Since the cross section for a direct reaction depends on both a reaction-dynamics term and a nuclear-structure term, any differentiation of the reaction mechanisms will probably have to be deduced from detailed differences in the nuclear-structure dependence. This requirement limits such a study to nuclei that have well-established shell-model configurations.

In the work reported here (p,α) reactions in two neighboring nuclei ^{89}Y and ^{90}Zr were studied in an attempt to get more definite evidence about the mechanism of the (p,α) reaction. Previous studies of nuclei in this mass region have shown that, at least for low-lying levels, these nuclei can be well described within the framework of a simple shell model limited to a very few nucleon configurations outside a ^{88}Sr core. This core state contains 38 protons and 50 neutrons. The 39th proton in ^{89}Y is expected (for the ground state) to occupy the $2p_{1/2}$ level. This is consistent with the known spin and parity of $\frac{1}{2}^-$ for the ^{89}Y ground state. Similarly, the 39th and 40th protons in ^{90}Zr would be expected to fill the $2p_{1/2}$ level. It has been demonstrated that this proton pair can also be easily excited into the unfilled $1g_{9/2}$ level and that the actual proton configuration in the ground state of ^{90}Zr is a linear combination of these two configurations.[5,6]

If the (p,α) reaction proceeds by the pickup of one proton and a neutron pair, then the reaction $^{89}\text{Y}(p,\alpha)^{86}\text{Sr}$ to the ground state of ^{86}Sr is expected to correspond to the incoming proton picking up the single proton in the $p_{1/2}$ level and a neutron pair from the $N=50$ neutron core. This is shown very schematically in Fig. 1. The neutron pair may come from either the $1g_{9/2}$ or $2p_{1/2}$ level since the ^{86}Sr ground state is probably a linear

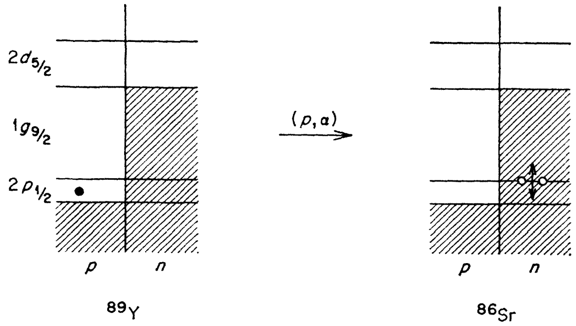

FIG. 1. Schematic representation of $^{89}\text{Y}(p,\alpha)^{86}\text{Sr}$ reaction.

[†] Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

[1] C. B. Fulmer and B. L. Cohen, Phys. Rev. **112**, 1672 (1958).

[2] R. Sherr, in Proceedings of the University of Pittsburgh Conference on Nuclear Structure, 1957 (unpublished); R. Sherr and F. P. Brady, Phys. Rev. **124**, 1928 (1961).

[3] Jiro Muto, Hidehiko Itoh, Kotoyuki Okano, Naoko Shomi, Kyue Fukuda, Yasuya Omori, and Motohiro Kihara, Nucl. Phys. **47**, 19 (1963).

[4] B. F. Bayman, Proceedings of Symposium on Nuclear Spectroscopy with Direct Reactions, Argonne National Laboratory Report No. ANL-6878, 335, 1964 (unpublished).

[5] B. F. Bayman, A. S. Riener, and R. K. Sheline, Phys. Rev. **115**, 1627 (1959).

[6] I. Talmi and I. Unna, Nucl. Phys. **19**, 225 (1960).

TABLE I. Spectroscopic factors.

Reaction	Target-proton wave function	Final state $J\pi$	Final state E(keV)	S_n	S_p	$S_{\mathrm{tot}}=S_n\times S_p$
$^{89}\mathrm{Y}(p,\alpha_0)^{86}\mathrm{Sr}$	$(p_{1/2})^1$	$0+$	ground	1	1	1
$^{90}\mathrm{Zr}(p,\alpha_0)^{87}\mathrm{Y}$	$a(p_{1/2})^2{}_0+(1-a^2)^{1/2}(g_{9/2})^2{}_0$	$\frac{1}{2}-$	ground	1	$2a^2$	$2a^2$
$^{90}\mathrm{Zr}(p,\alpha_1)^{87}\mathrm{Y}$	$a(p_{1/2})^2{}_0+(1-a^2)^{1/2}(g_{9/2})^2{}_0$	$\frac{9}{2}+$	380	1	$2(1-a^2)$	$2(1-a^2)$

combination of both configurations. The effect of this will be discussed in Sec. III.

Similarly, the triton pickup mechanism in the reaction $^{90}\mathrm{Zr}(p,\alpha)^{87}\mathrm{Y}$ leading to the ground state of $^{87}\mathrm{Y}$ is expected to correspond to pickup of one of the pair of protons in the $2p_{1/2}$ level, and the identical neutron-pair pickup as in the $^{89}\mathrm{Y}$ reaction, leading to a $\frac{1}{2}^-$ state. The ground state of $^{87}\mathrm{Y}$ is known to have spin and parity $\frac{1}{2}^-$. The first excited state of $^{87}\mathrm{Y}$ is known to have spin and parity $\frac{9}{2}^+$. This state occurs at 381 keV and is most easily constructed by promoting the odd proton from the $2p_{1/2}$ level to the $1g_{9/2}$ level. Since the proton pair in the $^{90}\mathrm{Zr}$ ground state has some probability of being in the $1g_{9/2}$ level, the pickup of one of the pair in the (p,α) reaction will lead directly to the $\frac{9}{2}^+$ excited state in $^{87}\mathrm{Y}$. This process is indicated schematically in Fig. 2.

We can now consider the relative spectroscopic factors if these reactions occur via the pickup mechanism. For the final states under consideration the neutron pickup is identical and consists in all cases of picking up a pair of neutrons whose angular momenta are coupled to zero. This spectroscopic factor is unity for a filled $g_{9/2}$ level or for a filled $p_{1/2}$ level. Thus, if we treat the over-all spectroscopic factor as a product of the individual neutron and proton factors,[7] it will be identical to the spectroscopic factor for the protons. These spectroscopic factors are detailed in Table I.

We can use the distorted-wave theory, on the assumption of triton pickup, to extract spectroscopic factors from the experimental data and then examine them for consistency.

Since we cannot treat the dynamic part of the alpha-particle-knockout calculation, a similar treatment cannot be done at this time for this alternative assumption. Qualitatively, it seems that the relative intensities for the knockout reaction should be quite different from those listed in Table I for the pickup reaction. In the case of $^{90}\mathrm{Zr}(p,\alpha)$, a quasi-alpha can be constructed from the least-bound proton and neutron pairs. The proton can then be captured in any unfilled state. Since there are five times as many substates in the vacant $g_{9/2}$ level as in the vacant $p_{1/2}$ level, it might be supposed that the $\frac{9}{2}^+$ final state would be preferred over the $\frac{1}{2}^-$ final state by this process. In the case of $^{89}\mathrm{Y}(p,\alpha)$, a quasi-alpha must be constructed from the single proton in the $p_{1/2}$ level and another proton in a deeper level. To reach the ground state of $^{86}\mathrm{Sr}$, the incoming proton must then be captured into this single vacancy in the deeper level. From this standpoint we would expect that the ground-state transition in the $^{89}\mathrm{Y}(p,\alpha)$ reaction should be much smaller than that for the $^{90}\mathrm{Zr}(p,\alpha)$ reaction, if knockout is the predominant process.

If pickup is the predominant process in these reactions, then we expect to observe relative intensities consistent with the spectroscopic factors of Table I. Any deviation from these expected intensities should serve as an indication of the presence of the knockout process.

II. EXPERIMENTAL

Preliminary data were obtained at a bombarding energy of 22.5 MeV with the external beam of the ORNL 86-in. cyclotron. The experimental apparatus and procedure were the same as that previously described.[8]

The available beam intensity at the target varied from 10 to 20 nA. Spectra obtained with 3 to 4 h of beam time yielded rather low counting rates (at some angles less than 2 counts per hour) for the peaks of interest. The over-all energy resolution was 250–300 keV. The resolution width was due, almost entirely, to the poor quality of the incident proton beam. This energy resolution was sufficient to resolve the ground state, α_0, group from the (p,α) reaction in each of the targets. The 0.38-MeV α_1 peak in the $^{90}\mathrm{Zr}(p,\alpha)$ spectra was not resolved at all angles. It was not feasible to improve the resolution at the expense of the available incident beam intensity.

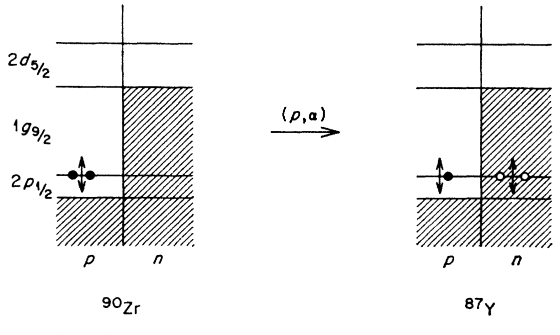

FIG. 2. Schematic representation of $^{90}\mathrm{Zr}(p,\alpha)^{87}\mathrm{Y}$ reaction.

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[7] R. Sherr, Padua Conference on Direct Interactions and Nuclear Reaction Mechanisms (Gordon and Breach Science Publishers, Inc., New York, 1963), p. 1025.

[8] J. B. Ball, C. B. Fulmer, and C. D. Goodman, Phys. Rev. **130**, 2342 (1963).

After the experimental work reported here had begun, an external proton beam of much higher intensity became available at the Oak Ridge Isochronous Cyclotron (ORIC). The experiment was moved to the new cyclotron to obtain the better resolution that could be achieved with the better quality and more intense beam.

When the experiments were begun at ORIC a beam of 22.5-MeV protons was not available. The nearest available bombarding energy was 20.2 MeV. Spectra from (p,α) reactions induced with 20.2-MeV protons were obtained at 5° intervals.

The over-all energy resolution width in an experiment of this kind arises from three main contributions: energy spread of the incident beam, gain drift and noise in the electronic equipment, and target thickness. The latter is a major contributor to the resolution width in the (p,α) spectra because energy loss for alpha particles is about 16 times as large as for protons of the same energy. In principle, the target angle can be adjusted to remove the target-thickness contribution to the energy resolution width.[9] This is usually not feasible, however, for (p,α) reactions. Figure 3 shows plots of calculated energy spread as a function of target angle of 20-MeV-proton-induced $^{90}\mathrm{Zr}(p,\alpha_0)$ reactions for detector angles of 30° and 50°. It is shown that a target angle of $\sim 87°$ would remove the target-thickness contribution to the over-all energy spread, and target angles $>80°$ are required to achieve appreciable improvement over the flat portions of the curves in Fig. 3.

From Fig. 3 it is apparent that realistic contributions of target thickness to the energy resolution width in the present experiment are ~ 140 keV/mg cm^{-2}. Target foils ~ 0.5 mg/cm^2 thick were used. The over-all energy resolution achieved was ~ 110 keV. In addition to the 70-keV contribution of the target thickness, electronic noise of about 70 keV and spread in incident beam energy of about 40 keV accounted for the observed resolution width.

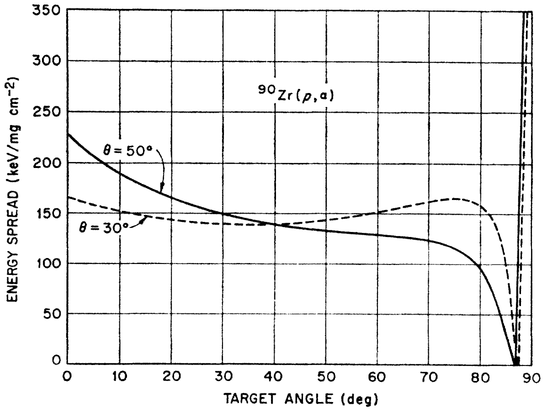

FIG. 3. Target-thickness contribution to resolution width as a function of target angle.

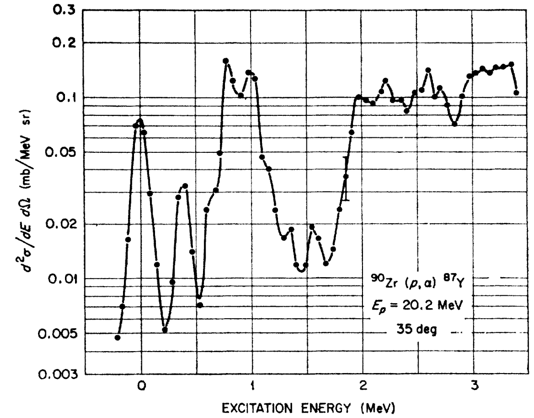

FIG. 4. Typical alpha-particle energy spectra. The abscissa values are excitation energies of the residual nucleus.

The ^{89}Y target foil was prepared from natural (100% ^{89}Y) yttrium metal and the ^{90}Zr foil was prepared from zirconium metal enriched to 98.66% ^{90}Zr. The absolute target foil thicknesses were determined both by weighing and by measurement of energy losses of alpha particles from ^{241}Am. Contributions to the errors in the cross sections due to uncertainties in target thicknesses and foil nonuniformities are $<10\%$. In most of the spectra, counting statistics are the dominant source of uncertainties in the measured cross sections.

The alpha particles were detected in a dE/dx-E telescope with a 100-μ and a 1500-μ silicon surface barrier detector. The sum pulse of the two detectors was fed to a multichannel analyzer, which was gated to record only pulses corresponding to alpha particles. Beam intensities up to 250 nA were used. Analyzer dead time was measured during the data runs and maintained below 3%. For most of the spectra, the integrated beam current was ~ 500 μC.

A typical alpha-particle energy spectrum is shown in Fig. 4. The abscissa values are excitation energies of the residual nucleus, thus zero corresponds to the ground-state transition. In addition to the α_0 and α_1 groups several levels of higher excitation are sufficiently resolved to determine the excitation energies and approximate angular distributions. The higher excited states will be discussed in a later publication.

Absolute differential cross sections were determined from the spectra obtained. Angular distributions of the α_0 groups from both targets were measured for 22.5- and 20.2-MeV bombarding energies. The angular distribution for the 0.38-MeV α_1 group from $^{90}\mathrm{Zr}(p,\alpha)$ was also obtained for the 20.2-MeV bombarding energy.

III. DISTORTED-WAVE CALCULATIONS

Distorted-wave calculations, assuming a product of nucleon orbitals for the pickup triton, were done for the (p,α_0) reactions for both targets at both bombarding

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[9] B. L. Cohen, Rev. Sci. Instr. **30**, 415 (1959).

TABLE II. Parameters used in the distorted-wave calculations.[a]

Quantity	Value $E_p=20.2$ MeV	Value $E_p=22.5$ MeV
Proton parameters		
Real well potential, V	-51.3 MeV	-52.2 MeV
Volume imaginary potential, W	-0.5 MeV	-0.5 MeV
Surface imaginary potential, W'	-10.6 MeV	-10.6 MeV
Spin-orbit potential, V_s	7.75 MeV	7.75 MeV
Radius parameter for real potential, r_0	1.177 F	1.26 F
Radius parameter for Coulomb interaction, r_c	1.25 F	1.26 F
Diffusivity parameter for real potential, a	0.712 F	0.614 F
Radius parameter for imaginary potential, r_w	1.277 F	1.23 F
Diffusivity parameter for imaginary potential, a_w	0.643 F	0.567 F
Alpha-particle parameters		
Real well potential, V	-50.0 MeV	-50.0 MeV
Volume imaginary potential, W	-13.0 MeV	-13.6 MeV
Radius parameter, r_0	1.538 F	1.538 F
Radius parameter for Coulomb interaction, r_c	1.40 F	1.40 F
Diffusivity parameter, a	0.56 F	0.56 F
Single-particle oscillator parameter, β	0.16 F^{-2}	
Alpha-particle oscillator parameter, α	0.53 F^{-2}	

[a] The details of the optical potentials used are given in Ref. 11.

energies, and for the (p,α_1) reaction in ^{90}Zr for the 20.2-MeV bombarding energy. These were calculated with the code JULIE.[10]

The optical-model parameters used in the calculations are given in Table II. The proton parameters were obtained from optical-model analysis of 22.5-MeV proton-elastic-scattering data on the zirconium isotopes.[11] The alpha-particle parameters were obtained by systematic extrapolation from analysis of alpha-elastic-scattering data on targets of lower A value.[12]

Calculations were done for both $(\nu g_{9/2})^2$ and $(\nu p_{1/2})^2$ pickup. Comparison of the results with experimental data suggests that $(\nu g_{9/2})^2$ pickup is predominant in the ^{89}Y and ^{90}Zr(p,α_0) reactions. The differences are insufficient, however, to exclude some contribution from $(\nu p_{1/2})^2$ pickup. The experimental differential cross sections are compared with the angular distributions predicted by the distorted-wave calculations in Figs. 5–9. For the calculated curves in these figures, $(\nu g_{9/2})^2$ pickup was assumed.

The normalization of the calculations to the experiment is done very subjectively, with the main criterion being a consistent set of normalization constants. A value of 17 for the normalization of the two ^{89}Y(p,α) spectra, shown in Figs. 5 and 6, seems to provide the best agreement with the two sets of data. The general features of the experimental angular distributions are reproduced by the calculated curves. The maxima and minima occur at angular positions that are well predicted by the distorted-wave calculation. It is interesting that the deep minimum near 60° arises in the calculation from an interference between the amplitudes from the central and spin-orbit parts of the potential.

The normalization factor is the product of the spectroscopic factor and an overlap integral between the internal wave functions of the triton and alpha particle. Two different choices of wave functions give theoretical estimates for this overlap integral of about 7 and 16.[13]

Since we expect the spectroscopic factor to be unity for the ^{89}Y(p,α) ground-state transition, the empirical normalization factor of the calculation is a factor of 17.

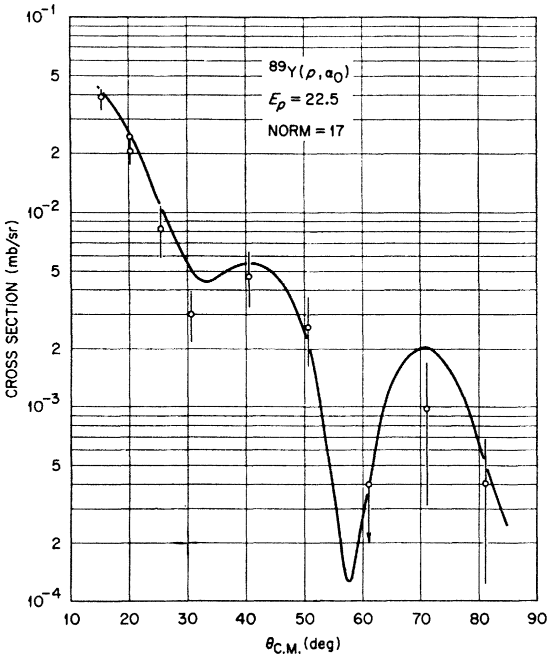

FIG. 5. Comparison of ^{89}Y$(p,\alpha_0)^{86}$Sr experimental data with the angular distribution predicted by the distorted-wave calculation. The bombarding energy was 22.5 MeV.

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[10] R. M. Drisko (unpublished).

[11] J. B. Ball, C. B. Fulmer, and R. H. Bassel, Phys. Rev. **135**, B706 (1964).

[12] R. H. Bassel (private communication).

[13] R. M. Drisko and R. H. Bassel (to be published).

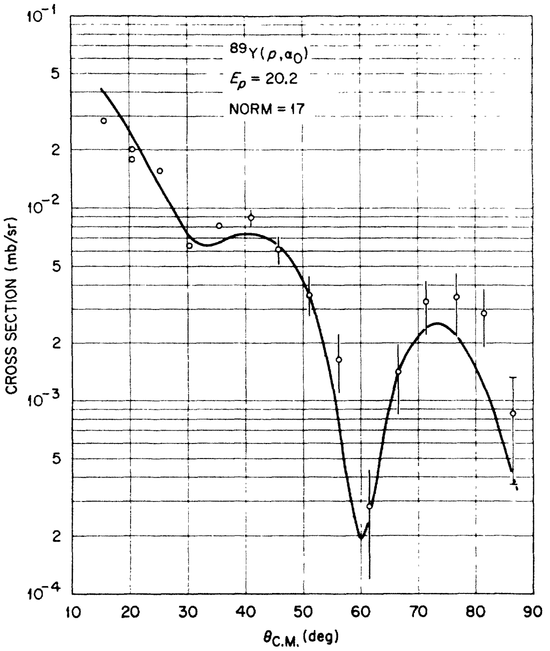

FIG. 6. Comparison of ^{89}Y$(p,\alpha_0)^{86}$Sr experimental data with the angular distribution predicted by the distorted-wave calculation. The bombarding energy was 20.2 MeV.

For the ^{90}Zr(p,α) transitions, the ground-state transition at both energies should have equal normalization factors. In addition, to be consistent with the triton pickup mechanism, the normalization factor for the α_0 and α_1 groups should sum to 34, i.e., twice the normalization factor for ^{89}Y(p,α_0). A comparison of calculated and experimental angular distributions with normalization factors meeting these requirements is shown in Figs. 7–9. Again, the general features of the curves are reasonably well reproduced by the distorted-wave calculations. In addition, the magnitudes of the cross sections are quite consistent with the limitations imposed on the spectroscopic factors by assuming a triton pickup mechanism.

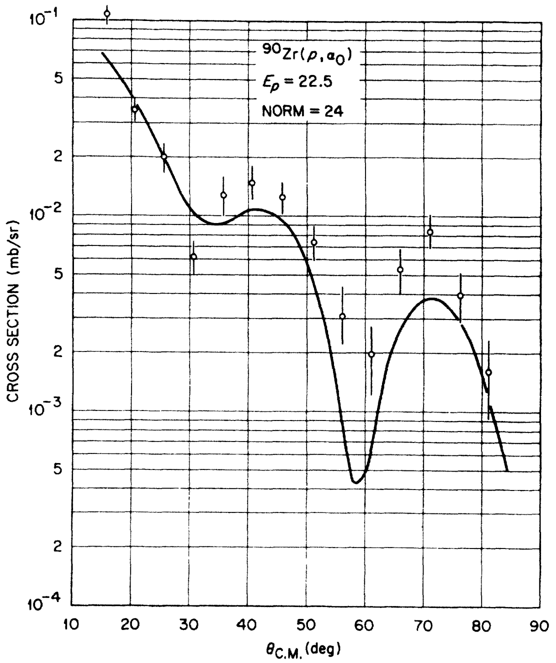

FIG. 7. Comparison of ^{90}Zr$(p,\alpha_0)^{87}$Y experimental data with the angular distribution predicted by the distorted-wave calculation. The bombarding energy was 22.5 MeV.

IV. DISCUSSION

The distorted-wave predictions, on the basis of a triton pickup mechanism for the (p,α) reaction, shown in Figs. 5–9 reproduce both the shapes and magnitudes of the experimental angular distributions. The spectroscopic factors for the α_0 and α_1 groups in the ^{90}Zr(p,α) reaction may be obtained by dividing their respective normalizations by the normalization factor for the ^{89}Y(p,α_0) reaction. This yields a spectroscopic factor of 1.4 for the $\frac{1}{2}^-$ state and 0.6 for the $\frac{9}{2}^+$ state.

Since the normalization of the calculations to experiment was done in a very subjective manner, it is impossible to assign a high accuracy to these spectroscopic factors. It is best to say only that this experiment is consistent with the proton configuration in the ^{90}Zr ground state being 70% $(\pi p_{1/2})^2$ and 30% $(\pi g_{9/2})^2$. Changes up to 10% in this configuration will certainly fall within the region of acceptable fits to the data. This experiment is thus in good agreement with the proton mixture configuration as determined by Bayman, Riener, and Sheline[5] (63–37%), Day, Blair, and Armstrong[14] (71–29%), and Cohen, Lawson, Macfarlane, and Soga[15] (64–36%). However, the recent determination by Yntema[16] (55–45%) is not consistent with our data.

Although good consistency is obtained between experiment and calculation assuming triton pickup, detailed agreement between the experimental and calculated angular distribution (Figs. 5–8) is somewhat better for ^{89}Y(p,α_0) than for ^{90}Zr(p,α_0). This is most apparent in the second minimum near 60°. The distorted-wave calculations predict a deep minimum in this angular region, and one is observed experimentally for ^{89}Y(p,α_0) at both bombarding energies. In the case of ^{90}Zr(p,α_0), however, the experimentally observed second minimum is not as deep as the calculations predict at either bombarding energy. There is also a pronounced difference in the experimental data in the region of the second minimum for the two energies. A much stronger energy dependence is observed than is predicted by the distorted-wave calculations. Calculations for which $(\nu 2p_{1/2})^2$ pickup is assumed predict a second minimum that is not as deep, but do not remove

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[14] R. B. Day, A. G. Blair, and D. D. Armstrong, Phys. Letters **9**, 327 (1964).

[15] S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga, Phys. Letters **10**, 195 (1964).

[16] J. L. Yntema, Phys. Letters **11**, 140 (1964).

the discrepancy between experimental results and calculated predictions. The distorted-wave calculations do not predict a large energy dependence of the cross section, such as is observed in the region of the second minimum for $^{90}\mathrm{Zr}(p,\alpha_0)$.

A possible explanation of this "filling in" of the second minimum in the $^{90}\mathrm{Zr}(p,\alpha_0)$ reaction is that the ground state of $^{87}\mathrm{Y}$ is not necessarily a pure shell-model configuration. It is possible to construct a $\frac{1}{2}^-$ state from the configuration $(\pi g_{9/2})^1(\nu g_{9/2})^9(\nu p_{1/2})^1$; the ground state of $^{87}\mathrm{Y}$ should contain some of this configuration. This part of the ground state would be reached in the (p,α) reaction by pickup of one $g_{9/2}$ proton, one $g_{9/2}$ neutron, and one $p_{1/2}$ neutron. To first order, this pickup has the same form factor as the $(\pi p_{1/2})(\nu g_{9/2})^2$ pickup. It is possible, however, that detailed differences in the proton and neutron wave functions may sufficiently alter the form factor that interference between amplitudes arising from different configurations may destroy the deep second minimum. Such interference between configurations will not occur in the $^{89}\mathrm{Y}(p,\alpha_0)$ reaction. Such an explanation, however, cannot easily account for the apparent energy dependence of the structure in the $^{90}\mathrm{Zr}(p,\alpha_0)$ angular distributions.

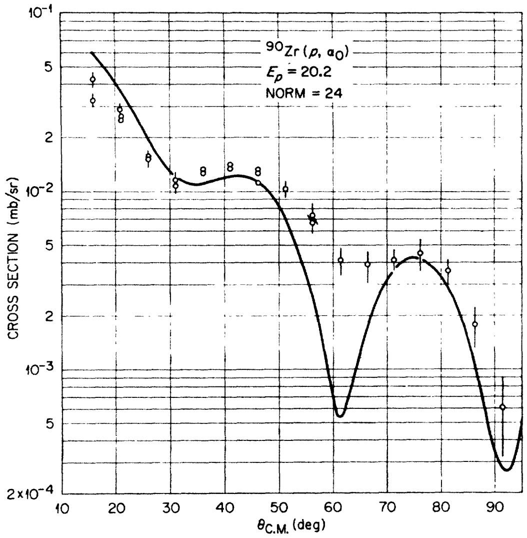

FIG. 8. Comparison of $^{90}\mathrm{Zr}(p,\alpha_0)^{87}\mathrm{Y}$ experimental data with the angular distribution predicted by the distorted-wave calculation. The bombarding energy was 20.2 MeV.

The Q value for $^{89}\mathrm{Y}(p,\alpha_0)$ is 1.3 MeV; for $^{90}\mathrm{Zr}(p,\alpha_0)$ the Q value is -1.08 MeV. Thus the probability of compound-nucleus (p,α) reactions contributing to the ground state is greater for $^{90}\mathrm{Zr}$ than for $^{89}\mathrm{Y}$. The probability of this in $^{90}\mathrm{Zr}$ is greater for 20.2-MeV bombarding energy than for the 22.5-MeV bombarding energy. If compound-nucleus reactions were contributing to the $^{90}\mathrm{Zr}(p,\alpha_0)$ reaction the effect would be to fill in the structure of the angular distribution. Such an effect is consistent with that observed in the $^{90}\mathrm{Zr}(p,\alpha_0)$ data. The second minimum of the angular distribution is more pronounced for the 22.5-MeV data than for the 20.2-MeV data. The $^{89}\mathrm{Y}(p,\alpha_0)$ data, for which the Q value is ~2.4 MeV larger, exhibit a deeper second minimum at both bombarding energies than do the $^{90}\mathrm{Zr}(p,\alpha_0)$ data.

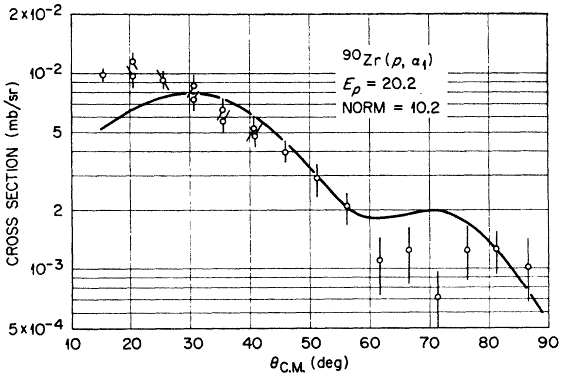

FIG. 9. Comparison of $^{90}\mathrm{Zr}(p,\alpha_1)^{87}\mathrm{Y}$ experimental data with the angular distribution predicted by the distorted-wave calculation. The bombarding energy was 20.2 MeV.

The principal difficulty with an explanation of the $^{90}\mathrm{Zr}(p,\alpha_0)$ data, based on compound-nucleus contributions, is the very small cross section for $^{90}\mathrm{Zr}(p,\alpha_0)$ at 90° (see Fig. 8). It is reasonable to assume that the anisotropy of compound-nucleus emission is such that $\sigma_{60°}/\sigma_{90°}$ would be less than two. Since we observe a ratio of $\sigma_{60°}/\sigma_{90°}$ of the order of seven, it appears very unlikely that compound-nucleus (p,α_0) reactions could

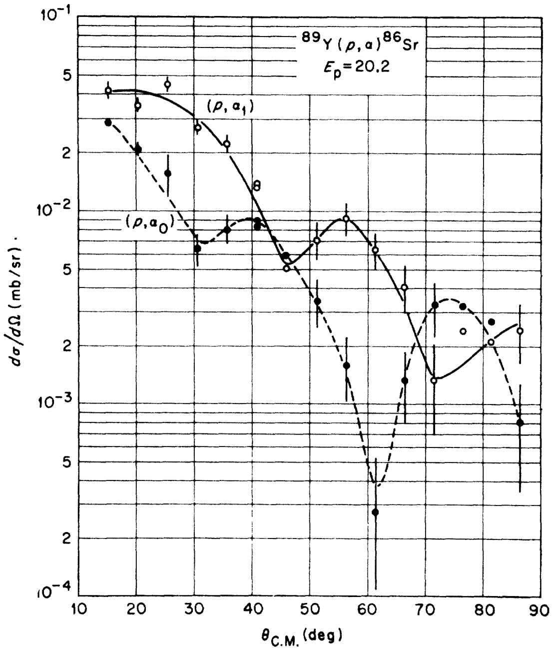

FIG. 10. Experimental angular distributions of the $^{89}\mathrm{Y}(p,\alpha_0)^{86}\mathrm{Sr}$ and $^{89}\mathrm{Y}(p,\alpha_1)^{86}\mathrm{Sr}$ reactions. The bombarding energy was 20.2 MeV. The lines serve only to connect the experimental points.

appreciably affect the data in the region of the second minimum.

As mentioned in the Introduction, the knockout process might be expected to compete more strongly in the ^{90}Zr(p,α) reaction, where the target ground state contains a pair of protons outside of the core state. It is possible that a knockout (p,α) reaction would be characterized by an angular distribution that is not identical to that of a pickup (p,α) reaction. It is also conceivable that the angular distributions for the two reactions would have different energy dependence. In this case variation of the bombarding energy would result in different displacements of the two diffraction patterns. This could account for the "filling in" of the second minimum of ^{90}Zr(p,α_0) at the 20.2-MeV bombarding energy. A detailed examination of the knockout contribution must await an adequate theoretical treatment of the reaction dynamics.

The angular distribution of the first 2+ level in ^{86}Sr excited by the ^{89}Y(p,α) reaction is compared with the ground-state angular distribution in Fig. 10. This state is probably largely due to the coupling of two $g_{9/2}$ neutron holes. The (p,α) reaction would excite this state by the pickup of two $g_{9/2}$ neutrons coupled to spin 2+ from the ^{89}Y ground state. The spectroscopic factor for this pickup is 5 (compared with 1 for the ground-state transition). As the available subroutines require the orbital angular momentum of the neutron pair to be coupled to 0, we cannot calculate the dynamic part of this transition. However, an examination of Fig. 10 shows qualitative agreement with the expected larger spectroscopic factor for the 2+ final state.

V. SUMMARY

The comparison of the experimental data with the distorted-wave calculations provides good evidence that pickup of a quasi-triton is the dominant mechanism for the (p,α) reactions to low-lying final states. This evidence is provided by the agreement of the general shapes of the experimental and calculated angular distributions, by the relative intensities of the (p,α_0) reactions in ^{89}Y and ^{90}Zr, and by the relative intensities of the (p,α_0) and (p,α_1) reactions in ^{90}Zr. It is not possible, however, to exclude completely some knockout contribution to the reaction in cases where the structure of the target nucleus is favorable for a knockout process.

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Photoproduction of π^0 from Hydrogen near the Second Pion-Nucleon Resonance*

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Angular distributions for π^0 photoproduction from hydrogen at energies between 660 and 800 MeV and proton center-of-mass angles from 0° to 140° have been measured and analyzed. Some variation from a pure $d_{3/2}$ state is seen in the resonance region. A possible high-momentum-transfer enhancement of the cross section is discussed.

I. INTRODUCTION

Pion photoproduction from nucleons has proved a useful tool in the study of the pion-nucleon interaction because of the dominance of the strong final-state interaction between emitted pion and recoil nucleon. There has remained, however, a noticeable lack of data at high momentum transfer in the region of the second pion-nucleon resonance. In particular, our zero-angle measurement[1] provides evidence against the hypothesis that the direct photoelectric term is responsible for the difference in position of this resonance in π^0 and π^+ photoproduction.[2]

The present experiment was designed to study this region using the Stanford Mark III linear accelerator. The results of the experiment establish that the discrepancy in resonance positions is not due to the photo-

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[1] Throughout this paper, the angle between incident photon and final recoil proton will be used (θ^* is the center-of-mass angle and θ the laboratory angle).

[2] A. M. Wetherall, Phys. Rev. 115, 1722 (1959).