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Study of the (*d*, *p*) Reaction on ^{92}Zr and ^{94}Zr†

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Angular distributions of the (d,p) reaction on ^{92}Zr and ^{94}Zr have been measured at 12 MeV with the Argonne split-pole spectrograph. Spectroscopic factors and l values of ^{93}Zr and ^{95}Zr levels up to 2.5-MeV excitation energy were extracted from comparison of the data with distorted-wave Born-approximation calculations. Some unreported levels, in particular $g_{7/2}$ states previously deduced from results of the (^{3}He, d) reaction to the corresponding analog states, have been identified.

The energy levels of ^{93}Zr and ^{95}Zr have been investigated[1-3] via β-γ decay and (d, p) and (d, t) reactions. In the present experiment the (d, p) reaction has been studied with improved energy resolution and statistics. The motivation for this study was to search for $l > 2$ states whose existence close to the $^{93}\mathrm{Zr}_{1.45}$ and $^{95}\mathrm{Zr}_{1.64}$ $\frac{3}{2}^+$ levels was suggested by evidence from the (^{3}He, d) reaction to the corresponding analog states.[4]

The 12.0-MeV deuteron beam from the Argonne tandem Van de Graaff was used to obtain angular distributions between 15° and 70°. The outgoing protons were momentum-analyzed with the Enge split-pole magnetic spectrograph and detected by Kodak NTB emulsion plates, covered with 20-mil acetate foils to stop particles heavier than protons. The exposed plates were scanned in $\frac{1}{4}$-mm strips by a computer-controlled plate scanner.[5]

Self-supporting ^{92}Zr and ^{94}Zr targets of thicknesses 175 and 190 μg/cm^2, respectively, were used. The thicknesses were determined by reference to 10-MeV ^{3}He elastic scattering measurements at small angles. Figure 1 shows typical spectra obtained in the present experiment. The energy resolution width is 15 keV. The spectra were analyzed with the peak-fitting program AUTOFIT[6] to extract excitation energies and relative cross sections.

Calculated and experimentally measured angular distributions, sorted according to l value, are compared in Figs. 2 and 3. The calculations were performed with the distorted-wave Born-approximation (DWBA) code DWUCK,[7] the optical-model parameters used being a set (Table I) chosen on the basis of elastic scattering data.[8,9] No attempt was made to fit the (d, p) reaction data by varying these parameters. The calculations were made without a lower cutoff.

The distorted-wave cross section is given by the expression

$$\frac{d\sigma}{d\Omega}=1.53\,\frac{2I_f+1}{2I_i+i}\,S\,\frac{\sigma_{\mathrm{DWUCK}}}{2j+1},$$

where I_i, I_f, and j are the total angular momenta of the target nucleus, the residual nucleus, and the transferred neutron, respectively. The spectroscopic factors were deduced by normalizing the DWBA results to the experimental peak cross sections, which in general resulted in an excellent over-all agreement between experimental and calculated angular distributions.

In Tables II and III are listed the excitation energies, l transfer, and final-spin assignments, and the observed strengths $(2I_f+1)S$. The results are briefly discussed below.

^{93}Zr. For the weakly populated level at 0.270 MeV, we obtain $l=2$. This level has been of special interest because of the prediction of a $(d_{5/2})^3$

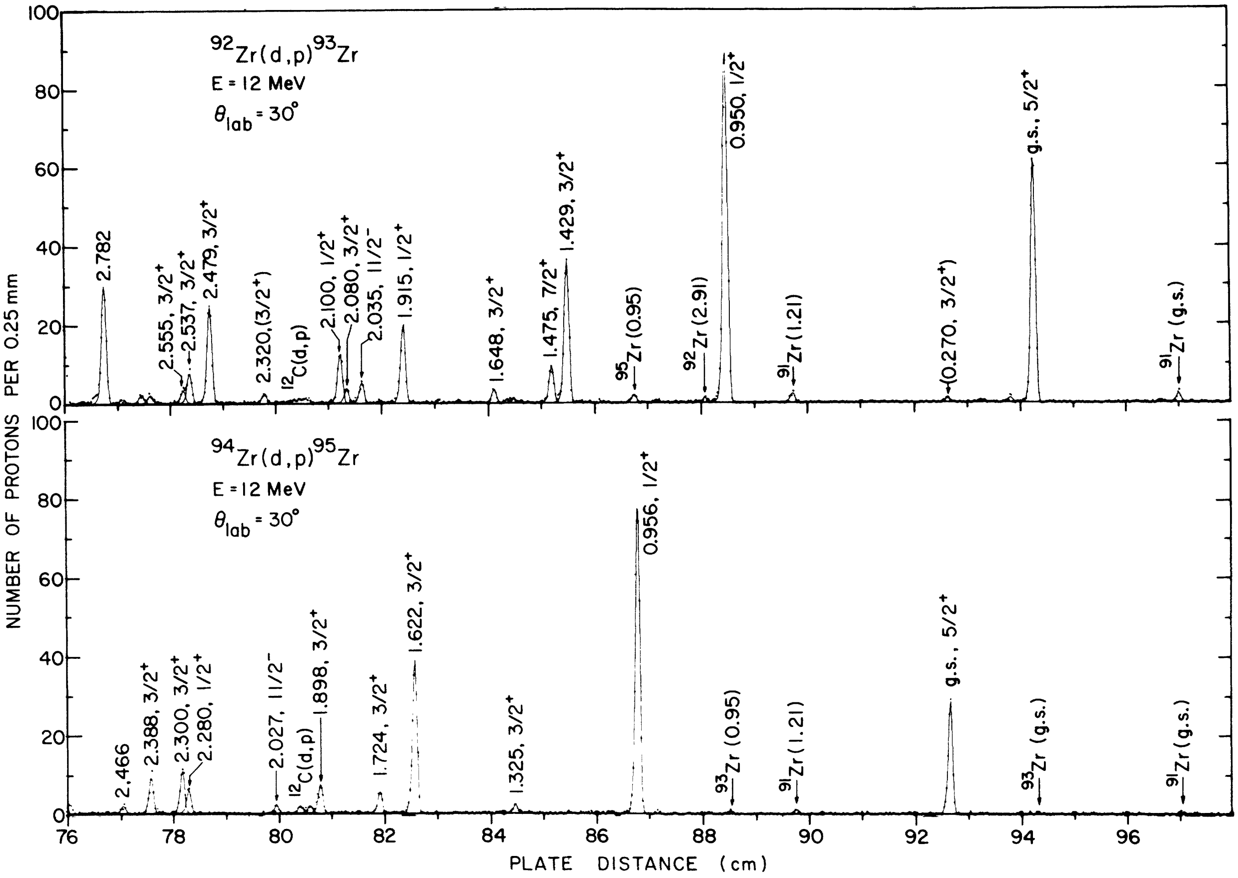

FIG. 1. Spectra and AUTOFIT plots for the ^{92}Zr(d,p)^{93}Zr and ^{94}Zr(d,p)^{95}Zr reaction.

state at nearly the same energy.[10] It has been observed[1] via γ rays following the β decay of ^{93}Y. The results of lifetime measurements[11] were in accordance with the mentioned configuration. However, since a state of this structure is not expected to be populated by the (d, p) reaction,[10] our result would indicate a $d_{3/2}$ or $d_{5/2}$ admixture. Unfortunately, the Q value leading to this level coincides (within ±10 keV) with that of the reaction ^{94}Zr-(d, p)^{95}Zr$_{g.s.}$. Therefore at least part of the observed proton intensity probably is due to a ^{94}Zr contaminant in the target. However, the ^{94}Zr percentage of <1% cannot explain the whole strength of the peak.

We see no indication of the 1.167-MeV state observed in the β-γ decay work of Arad *et al.*,[1] who identify this state with the $\frac{9}{2}^+$ member of $(d_{5/2})^3$ configuration predicted by Talmi[10] at 1.1 MeV. The levels at 1.429 and 1.475 MeV were observed by Cohen and Chubinsky[2] as an unresolved doublet. We confirm their assignment of $l=2$ for the 1.429-MeV state and deduce $l=4$ for the 1.475-MeV state. The tentatively assigned $l=4$ for the 1.648-MeV level was reassigned by us as $l=2$ by a better

TABLE I. Optical-model parameters used in the calculation with the code DWUCK.

Particle	V (MeV)	W' (MeV)	r_0 (fm)	a (fm)	r' (fm)	a' (fm)	r_c (fm)	V_{so} (MeV)	Reference
d	98.0	18.0	1.10	0.85	1.40	0.70	1.30	6.0	8
p	50.0	12.5	1.25	0.65	1.25	0.47	1.25		9
Bound state	a		1.20	0.70			1.25	$\lambda=25$	

[a] Adjusted to reproduce the binding energy of each level.

fit to the forward-angle data. The angular distribution for the transition to the level at 2.035 MeV indicates $l=5$ transfer in agreement with the result of Booth *et al.*[12]

Previously unresolved levels at 2.080 and 2.100 MeV were partly resolved and were assigned $l=2$ and 0, respectively, on the basis of the data. The previous[2] tentative assignment was $l=4$ for the doublet.

For the weak 2.320-MeV level, we favor $l=2$ or $l=3$, in disagreement with the $l=4$ assignment by Cohen and Chubinsky.[2] A more definite angular distribution for this state could not be obtained because the proton group from the ^{12}C(d, p) ground-state reaction interfered at intermediate scattering angles.

A triplet of levels at 2.478, 2.537, and 2.555 MeV was observed instead of the level reported at 2.50 MeV. We obtain $l=2$ for each member of this triplet.

^{95}Zr. The level scheme was generally in agreement with earlier work by Cohen and Chubinsky.[2] The exceptions were the l assignments for the 2.027-MeV level and the weak unresolved 2.280- and 2.300-MeV levels. The 2.027-MeV level, previously believed to be $\frac{7}{2}^+$, was assigned $l=5$ on the basis of a better fit to the experimental data (Fig. 3). This confirms the corresponding result of Booth *et al.*[12] The partly resolved 2.280- and 2.300-MeV levels were tentatively assigned as $l=0$ and 2, respectively. This doublet was reported as $l=(1)$ by Cohen and Chubinsky.

As a brief summary of our results, Table IV presents the observed strengths $(2J_f+1)S$ summed over the particular single-particle states and compares them with the strengths expected when the subshells above the $2d_{5/2}$ shell are assumed to be empty. The occurrence of some strengths that exceed the expected maximum values indicates uncertainties involved in experiment and analysis (the accuracy of the derived spectroscopic factors is not expected to be better than 25%). Within this uncertainty, the $d_{5/2}$ strength is exhausted by the ground states. The most significant deviations

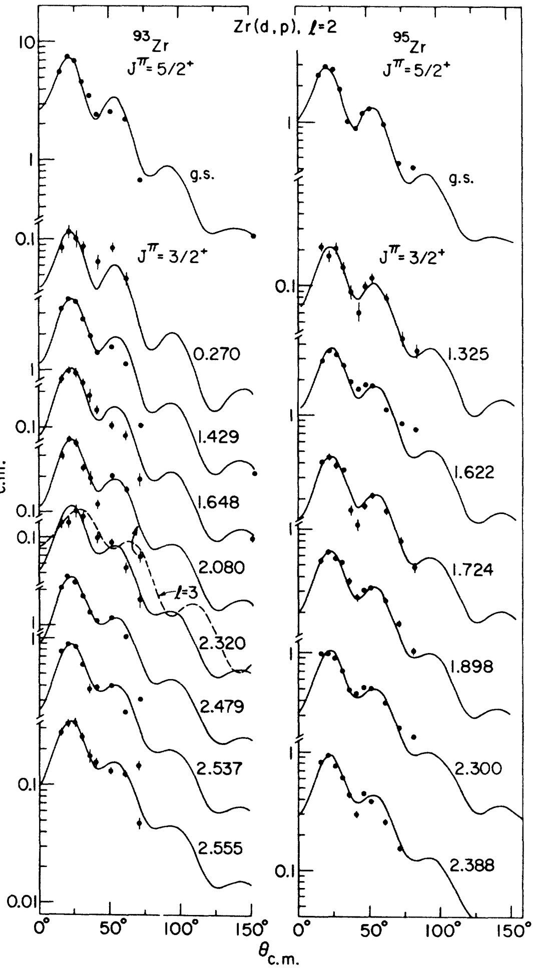

FIG. 2. Angular distributions and DWBA calculations for $l=2$. The statistical errors are shown with error bars. The final nuclei and the excitation energies E_x of the final states are indicated.

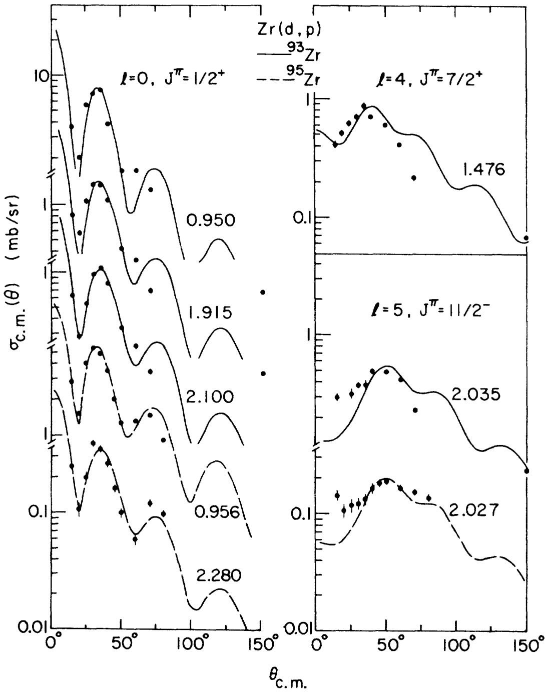

FIG. 3. Angular distributions and DWBA calculations for $l=0$, 4, and 5. The statistical errors are shown with error bars. The final nuclei and the excitation energies E_x of the final states are indicated.

TABLE II. Summary of results from the $^{92}\mathrm{Zr}(d,p)^{93}\mathrm{Zr}$ reaction.

Previous results (Ref. 2)				Present results			
E_x (MeV)	l	$J^\pi{}_f$	$(2J_f+1)S$	E_x (MeV)	l	$J^\pi{}_f$	$(2J_f+1)S$
0	2	$\frac{5}{2}^+$	3.24	0.0	2	$\frac{5}{2}^+$	3.76
0.28				0.270	2	$(\frac{3}{2}^+)$	(0.05)
0.96	0	$\frac{1}{2}^+$	1.82	0.950	0	$\frac{1}{2}^+$	1.65
1.45	2	$\frac{3}{2}^+$	1.52	1.429	2	$\frac{3}{2}^+$	2.19
				1.476	4	$\frac{7}{2}^+$	7.34
1.64	(4)	$\frac{7}{2}^+$	0.88	1.648	2	$(\frac{3}{2}^+)$	0.16
1.94	0	$\frac{1}{2}^+$	0.42	1.915	0	$\frac{1}{2}^+$	0.31
				2.035	5	$\frac{11}{2}^-$	5.15
2.08	(4)	$\frac{7}{2}^+$	3.36	2.080	2	$(\frac{3}{2}^+)$	0.20
				2.100	0	$\frac{1}{2}^+$	0.22
2.32	4	$\frac{7}{2}^+$	0.72	2.320	(2), (3)	$(\frac{3}{2}^+), (\frac{7}{2}^-)$	(0.06), (0.10)
2.50	2	$\frac{3}{2}^+$	0.96	2.479	2	$\frac{3}{2}^+$	1.17
				2.537	2	$(\frac{3}{2}^+)$	0.40
				2.555	2	$(\frac{3}{2}^+)$	0.15
2.78	2	$\frac{3}{2}^+$	0.84				

from the maximum strengths are obtained for the $h_{11/2}$ states, which carry only 40% of the maximum strength in $^{93}\mathrm{Zr}$ and only 20% in $^{95}\mathrm{Zr}$. This indicates strong fragmentation of the $h_{11/2}$ shell into states beyond the studied region of excitation energy (rather than substantial filling of this shell in the target nuclei).

For the $g_{7/2}$ states, one would expect the center of gravity to be located within the studied region as it is for $^{93}\mathrm{Zr}$. It is therefore surprising that no $g_{7/2}$ state could be identified in $^{95}\mathrm{Zr}$. A possible solution would be that such a state is too close to the 1.622-MeV state (strongly populated by $l=2$ transfer) to be resolved. An $l=4$ contribution of the required strength would not modify the shape of the angular distribution drastically. In the analysis of this level, the shape of the peak (the full width at half maximum) indicates a possible doublet, at least at some angles. Indications for the presence of a $g_{7/2}$ state close to the $d_{3/2}$ state in

TABLE III. Summary of results from the $^{94}\mathrm{Zr}(d,p)^{95}\mathrm{Zr}$ reaction.

Previous results (Ref. 2)				Present results			
E_x (MeV)	l	$J^\pi{}_f$	$(2J_f+1)S$	E_x (MeV)	l	$J^\pi{}_f$	$(2J_f+1)S$
0.0	2	$\frac{5}{2}^+$	1.80	0.0	2	$\frac{5}{2}^+$	1.67
0.95	0	$\frac{1}{2}^+$	1.78	0.956	0	$\frac{1}{2}^+$	1.22
1.33	2	$\frac{3}{2}^+$	0.07	1.325	2	$(\frac{3}{2}^+)$	0.11
1.64	2	$\frac{3}{2}^+$	1.80	1.622	2	$(\frac{3}{2}^+)$	(1.80) [a]
1.73	(2)	$\frac{3}{2}^+$	0.20	1.724	2	$(\frac{3}{2}^+)$	0.22
1.91	2	$\frac{3}{2}^+$	0.30	1.898	2	$(\frac{3}{2}^+)$	0.32
2.03	4	$\frac{7}{2}^+$	0.85	2.027	5	$\frac{11}{2}^-$	1.94
2.29	(1)	$\frac{3}{2}^-$	0.50	2.280	0	$\frac{1}{2}^+$	0.09
				2.300	2	$(\frac{3}{2}^+)$	0.45
2.40	2	$\frac{3}{2}^+$	0.32	2.388	2	$(\frac{3}{2}^+)$	0.41

[a] Probable $g_{7/2}$ contribution.

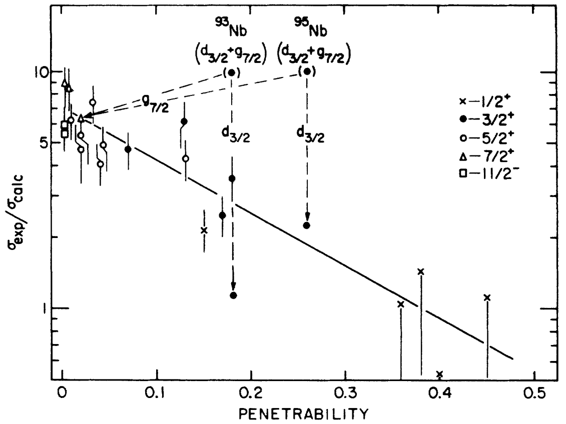

FIG. 4. Enhancement factors $\sigma_{exp}/\sigma_{calc}$ for cross sections of the (^{3}He, *d*) reaction to unbound analog states in $A \approx 90$ nuclei, plotted as a function of the penetrability of the transferred unbound proton. σ_{calc} is the calculated (^{3}He, *d*) cross section with the parent neutron wave function used as form factor: $\sigma_{calc} = 4.4[S_n/(2T_0+1)]\sigma^{DW}$. S_n is the spectroscopic factor of the parent state and T_0 the target isospin.

TABLE IV. Values of $(2J_f+1)\sum S$ summed over the indicated single-particle states.

	^{93}Zr		^{95}Zr	
	Observed	Expected	Observed	Expected
$d_{5/2}$	3.76	4	1.67	2
$s_{1/2}$	2.18	2	1.31	2
$d_{3/2}$	4.38	4	3.31	4
$g_{7/2}$	7.00	8		8
$h_{11/2}$	5.15	12	1.94	12

^{95}Zr (as in ^{93}Zr where it is resolved from the $d_{3/2}$ in the present experiment) have also been found from the (^{3}He, *d*) reaction to the corresponding analog state. This is briefly discussed below.

The present study was prompted by results of the (^{3}He, *d*) reaction populating the analog states of ^{93}Zr$_{1.45}$ and ^{95}Zr$_{1.62}$ in ^{93}Nb and ^{95}Nb, respectively. The cross sections for the transitions to these states (assumed to have spin $\frac{7}{2}^+$) fell badly out of the systematics observed for cross sections of the same reaction to other unbound analog states in the same mass region (as shown in more detail in Fig. 1 of Ref. 4). This can now be explained to be due to contributions from the $g_{7/2}$ state which the (^{3}He, *d*) experiment did not resolve from the neighboring $d_{3/2}$ state. The amount the unresolved $g_{7/2}$ states contribute to the (^{3}He, *d*) cross sections may be roughly estimated (in the frame of the empirical results presented in Fig. 1 of Ref. 4) by calculating the cross section σ_{calc} as explained in the caption of Fig. 4 and multiplying it by the empirical enhancement factor (~6) corresponding to the penetrability of the unbound $g_{7/2}$ proton. Figure 4 (which corresponds to Fig. 1 of Ref. 4) shows how subtracting these estimated $g_{7/2}$ cross sections from σ_{exp} shifts the points in question toward the average trend. (The spectroscopic factor S_n used in obtaining σ_{calc} was the one obtained in the present work for the $\frac{7}{2}^+$ state at 1.429 MeV in ^{93}Zr. For the $\frac{7}{2}^+$ state at 1.622 MeV in ^{95}Zr, for which no spectroscopic factor could be derived, we assumed $S_n = 0.6$.)

In summary, the improved energy resolution and statistics enabled us to analyze previously unobserved or unresolved levels of ^{93}Zr and ^{95}Zr. The anomalously large (^{3}He, *d*) cross section to analogs of ^{93}Zr$_{1.429}$ and ^{95}Zr$_{1.622}$ is found to be due to contributions from unresolved $g_{7/2}$ states. This confirms the systematics presented in Ref. 4 for (^{3}He, *d*) cross sections to unbound analog states.

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