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Charge Exchange in ^{92}Zr$(d,p)^{93}$Zr†

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Excitation functions for the ^{92}Zr$(d,p)^{93}$Zr reaction to eight low-lying states in ^{93}Zr were measured from 4.2- to 11.2-MeV incident deuteron energy, a region including the (d,n) thresholds to the analogs of the observed states. Charge-exchange effects were observed for at least the $d_{5/2}$ ground state in ^{93}Zr. Also, ^{92}Zr(d,d) angular distributions were taken at 6.25, 7.5, and 11.0 MeV, in 5° steps from 40 to 165°, in order to obtain deuteron optical parameters. A ^{92}Zr(p,p) angular distribution was taken at 10.75-MeV proton energy in order to obtain proton optical parameters. Orbital angular momenta and estimates of spectroscopic factors were obtained for three previously unreported states in ^{93}Zr. The results of distorted-wave Born-approximation calculations for the excitation curves are discussed.

1. INTRODUCTION

A cusplike behavior exhibited in (d,p) excitation functions for several nuclei, almost all in the mass-90 region, has been the subject of several recent experimental investigations.[1-6] Such behavior is always observed near the threshold for the (d,n) reaction to the isobaric analog of the final state observed in the (d,p) reaction, and has been attributed to charge-exchange coupling.[7-9] In particular, ^{90}Zr(d,p) has been extensively studied[1,2]; also, to a lesser extent, (d,p) reactions on ^{91}Zr, ^{92}Zr, and ^{94}Zr have been studied.[1,2,4-6] Results of some of these investigations are discussed in Ref. 1.

In this article, we report on a study of ^{92}Zr(d,p)-^{93}Zr, including optical-model analysis of elastic scattering at appropriate energies in deuteron and proton channels, excitation functions for all observed states, and a complete distorted-wave Born-approximation (DWBA) analysis. Figure 1 shows a level diagram of the observed states in ^{93}Zr and their analogs in ^{93}Nb. The present work is a continuation and extension of the earlier investigations,

with the aim of making a thorough experimental study of the charge-exchange effect for a particular case and providing information regarding the isotopic systematics of the effect.

2. EXPERIMENTAL METHOD

The deuteron and proton beams for this experiment were obtained from the 12-MeV model-EN tandem Van de Graaff accelerator at the Center for Nuclear Studies, University of Texas at Austin. A beam of approximately 0.3 μA on target was used during most of the experiment. The beam energy spread was estimated to be less than 4 keV. Deuteron beams of energies from 4 to 11 MeV, and a proton beam of 10.75 MeV, were used. The beam energy was controlled by a 90° analyzing magnet, with the usual nuclear-magnetic-resonance probe. The magnet was calibrated using the ^{27}Al(p,n) threshold at 5.803 MeV.

The ^{92}Zr target was a rolled self-supporting foil, purchased from Oak Ridge National Laboratory, Separated Isotope Division, and enriched to 94.6% ^{92}Zr. The target isotopic thickness was determined

from low-energy, forward-angle, elastic proton
and deuteron scattering. Measurements were made
at several angles and energies, to insure that the
observed cross sections were due solely to Cou-
lomb scattering. Various detectors were used to
minimize systematic errors from measurements
of detector solid angle; results obtained from
different detectors agree to within 7%. The ^{92}Zr-
target isotopic thickness was determined as 0.46
mg/cm^2.

The excitation-function data were accumulated
with two 3-mm-thick Si(Li) detectors placed at
lab angles of 168 and 138° with respect to the inci-
dent beam, angles chosen because the charge-ex-
change effect has been observed primarily at back-
ward angles.[1-5] Collimators were mounted in front
of each detector to define the solid angle and to
decrease background from slit scattering. The
detectors were cooled to −78°C in order to improve
their resolution. In addition, permanent magnets
were mounted before each detector to prevent elec-
trons emitted by the target from entering the de-
tector.

A Digital Equipment Corporation PDP-7 com-
puter was used on-line for data storage and anal-
ysis, with 1024 channels provided for each detec-
tor. An integrated beam of 200 μC was collected
for each data point. The experimental resolution
was determined to be 40–50 keV. Preliminary
analyses of the spectra, as well as continous data
monitoring, was carried out automatically by the
program SUPERVISOR,[10] which also wrote the data
on standard IBM magnetic tapes. Final analysis
was carried out from the tapes on the University
of Texas CDC 6600 computer, using the program
DRAFT,[11] which performed a least-squares fit of
Gaussian peaks on a polynominal background to
the desired region of each spectrum. An example
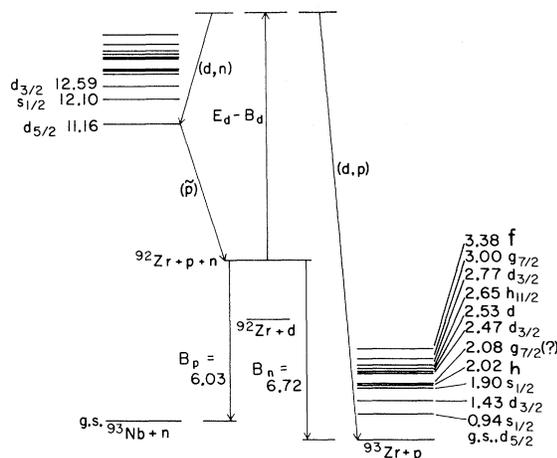
of such a fit for a typical spectrum is shown in
Fig. 2.

3.   RESULTS AND ANALYSIS

A.   Elastic Scattering Angular Distribution

Deuteron elastic scattering angular distributions
were taken at 6.25-, 7.5-MeV, and 11.0-MeV inci-
dent deuteron energy, and a proton elastic scatter-
ing angular distribution was taken at 10.75 MeV,
in order to perform optical-model analyses. The
angular distributions were taken in 5° steps from
40 to 165° (plus 168°) at each energy. These deu-
teron and proton angular distributions are shown
in Fig. 3. Also shown in Fig. 3 is the ^{92}Zr(p,p)
angular distribution at 12.7 MeV from data taken
by Dickens et al.[12]

Optical-model fits to the deuteron elastic scat-
tering data were obtained using a program written
by Smith,[13] as modified by P. A. Moore and the
authors. In order to eliminate ambiguities in the
fits, we required that the optical parameters fit
the data at 6.25, 7.5, and 11.0 MeV simultaneously,
allowing only a linear dependence of real and imag-
inary well depths on energy. In preliminary anal-
ysis, reasonable fits were obtained for all deuteron
elastic scattering data using several sets of deu-
teron optical parameters for ^{92}Zr. Two sets of
deuteron parameters were obtained, referred to as
Sets A and B. Set A was obtained by starting the
search with the ^{90}Zr potential of Dally, Nelson,
and Smith.[14] Set B was obtained starting with the
Perey and Perey[15] averaged parameters. The
parameter Sets A and B are given in Table I. The
χ^2 values for Sets A and B were obtained assuming
a fractional error of ±10% for all data points. The
calculated deuteron elastic scattering angular dis-
tributions are shown with the data in Fig. 3(a).

The proton elastic angular distribution at 10.75
MeV and the 12.7-MeV angular distribution of
Dickens et al.[12] were similarly fitted using an opti-

FIG. 1. Schematic energy-level diagram for ^{92}Zr(d,p)-
^{93}Zr and analogous ^{92}Zr$(d,n)^{93}$Nb^A reactions.
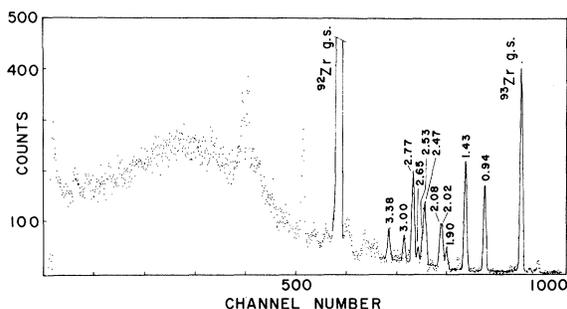
FIG. 2. Energy spectrum of charged particles from
^{92}Zr$+d$ at 11.0 MeV, observed at a lab angle of 105°.
Superimposed on the high-energy end of the spectrum
are peak fits generated by the program DRAFT.
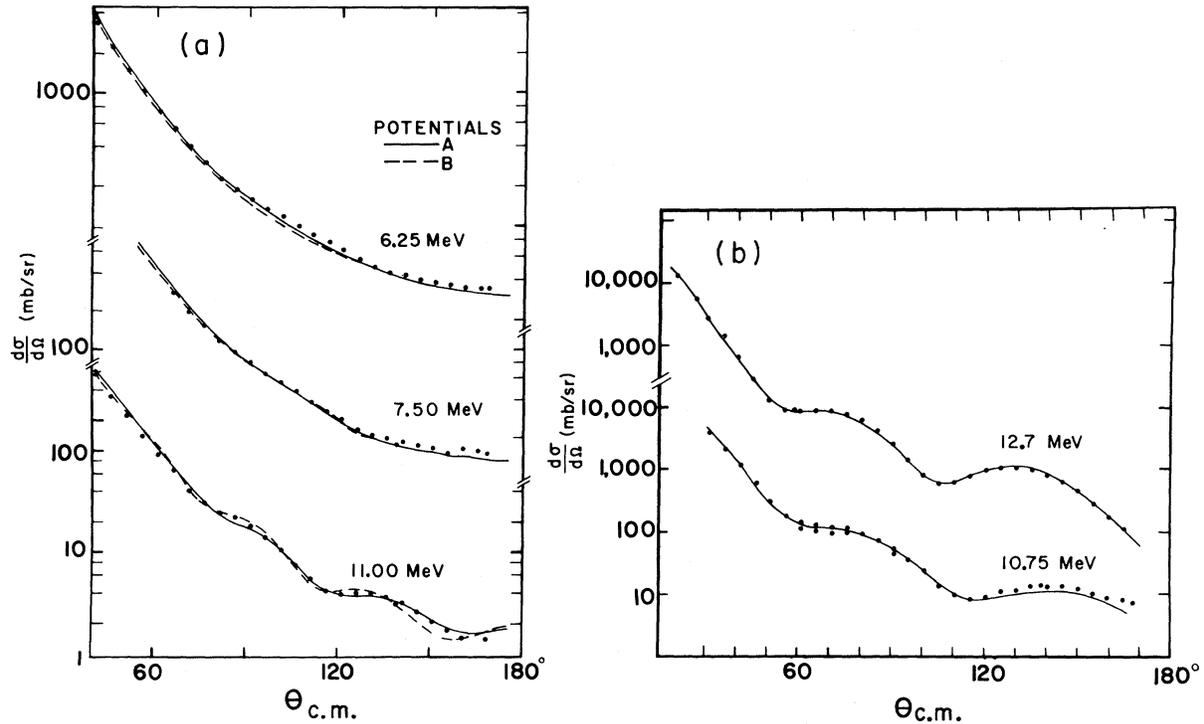
FIG. 3. (a) Deuteron elastic scattering angular distributions for ^{92}Zr target at 6.25, 7.50, and 11.0 MeV. The solid and dashed curved are, respectively, optical-model fits with parameter Sets A and B (see Table I). (b) Proton elastic scattering angular distributions for ^{92}Zr target at 12.7 and 10.75 MeV. The 12.7-MeV data is that of Dickens *et al.* (Ref. 12). Optical-model Set E is used (see Table II).

cal-model program written by Perey. Three sets of proton potentials, referred to as D, E, and F, were obtained. Set D was obtained by starting with the potential of Dickens, Eichler, and Satchler.[12] Set E was obtained starting with Set D, except for substituting spin-orbit parameters determined from ^{92}Zr(p,p) polarization measurements of Kossanyi-Demay and de Swiniarski.[16] These two sets gave identical fits, and only Set E is given in Table II. Set F in Table II was obtained by starting with the average parameters of Perey,[17] again with modified spin-orbit parameters. The χ^2 values for the various potentials were obtained assuming a fractional error of 5% for the 10.75-MeV data, and with the quoted errors given by

Dickens *et al.*[12] for the 12.7-MeV data. The calculated proton elastic scattering angular distributions are shown with the data in Fig. 3(b).

B. Excitation Functions

Excitation functions were obtained for (d,p) reactions to the ground state $(d_{5/2})$, and to the 0.94-MeV $(s_{1/2})$, 1.43-MeV $(d_{3/2})$, 1.90-MeV $(s_{1/2})$, 2.47-MeV $(d_{3/2})$, 2.77-MeV $(d_{3/2})$, 3.00-MeV $(g_{7/2})$, and 3.38-MeV $(l \geq 2)$ states in ^{93}Zr.[18] The measurements were made for incident deuteron energies from 4.2 to 6.0 MeV in 100-keV steps, and from 6.0 to 11.2 MeV in 50-keV steps. This energy region encompasses the threshold energies for the

TABLE I. Survey of optical parameters for ^{92}Zr$(d,d)^{92}$Zr.

E_{lab} (MeV)	V (MeV)	r_0 (fm)	a_0 (fm)	W_D (MeV)	r' (fm)	a' (fm)	V_{so} (MeV)	r'' (fm)	a'' (fm)	r_C (fm)	Ref.
6.25	88.61	1.278	0.72	15.85	1.29	0.747	0.0	...	...	1.278	a, Set A
	99.0	1.15	0.61	5.48	1.68	0.849	4.78	1.15	0.61	1.15	a, Set B
7.5	87.08	1.278	0.72	15.85	1.29	0.747	0.0	...	...	1.278	a, Set A
11.0	82.77	1.272	0.72	15.85	1.29	0.747	0.0	...	...	1.278	a, Set A
15.0	90.0	1.23	0.64	12.0	1.18	0.93	0.0	...	...	1.30	18

[a] This work.

TABLE II. Survey of optical parameters for ^{92}Zr$(p,p)^{92}$Zr.

E_{lab} (MeV)	V (MeV)	r_0 (fm)	a_0 (fm)	W_D (MeV)	r' (fm)	a' (fm)	V_{so} (MeV)	r'' (fm)	a'' (fm)	r_C (fm)	Ref.
10.75	55.34	1.23	0.60	9.66	1.18	0.67	6.4	1.20	0.42	1.25	a, Set E
12.7	52.2	1.25	0.65	12.3	1.25	0.525	6.0	1.25	0.65	1.25	12
	55.08	1.23	0.60	9.66	1.18	0.67	6.4	1.20	0.42	1.25	a, Set E
	53.1	1.23	0.64	10.0	1.23	0.76	7.0	1.23	0.64	1.25	b
	52.6	1.25	0.65	13.5	1.25	0.47	6.75	1.20	0.42	1.25	a, Set F
	54.5	1.23	0.596	9.2	1.18	0.668	6.4	1.23	0.596	1.23	12
14.25	50.0	1.25	0.65	9.0	1.25	0.65	6.2	1.25	0.65	1.25	c
18.6	51.49	1.24	0.65	12.27	1.28	0.50	6.78	1.20	0.42	1.25	16
19.4	50.9	1.20	0.70	10.3	1.25	0.65	6.2	1.20	0.70	1.25	d
22.5	46.6	1.26	0.66	10.6^e	1.23	0.567	7.72	1.26	0.664	1.26	f

^{a}This work.

^{b}J. K. Dickens and E. Eichler, Nucl. Phys. **101**, 408 (1967).

^{c}K. Matsuda *et al.*, J. Phys. Soc. Japan, **22**, 1311 (1967).

^{d}M. M. Stautberg and J. J. Kraushaar, Phys. Rev. **151**, 969 (1966).

$^eW=0.5$ MeV, also.

^{f}J. B. Ball, C. B. Fulmer, and R. H. Bassel, Phys. Rev. **135**, B706 (1964).

(d,n) reactions to the analogs in ^{93}Nb of all the states considered in ^{93}Zr. Specifically, the threshold energies range from 7.38-MeV incident deuteron energy for the analog of the ^{93}Zr ground state to 10.8 MeV for the analog of the 3.38-MeV state.

As previously discussed, the excitation-function data were taken at 138 and 168° in order to be sure of observing any threshold effects which might be present. Deuteron elastic scattering excitation curves were also obtained at these angles. These elastic scattering curves were well represented by optical-model calculations using either parameter Set A or B, and exhibit no resonant structure from 4.2 to 11.2 MeV.

As shown in Fig. 4, the excitation curves for the $d_{5/2}$ ground state indeed exhibit a strong threshold effect near 7.38-MeV deuteron energy. The 168°

FIG. 4. Excitation curves for ^{92}Zr$(d,p)^{93}$Zr$(d_{5/2}$, g.s.) at 138 and 168°, from 4 to 11 MeV. The curves are zero-range DWBA calculations using the deuteron potentials A and B, and the proton potentials D, E, and F (see Tables I and II).

curve confirms the results of Heffner *et al.*[5] and is similar to results found for other Zr isotopes.[1,2,4] As expected,[1] the effect is very important at 168° and is markedly reduced at 138°. The various curves in Fig. 4 are results of DWBA calculations, as discussed in Sec. 4 of this paper. The DWBA calculations are rather insensitive to the particular proton parameter set used, as can be seen in Fig. 4 for potentials AD, AE, and AF. However, the calculations are rather sensitive to the deuteron potential.

The measured cross sections for the (d,p) reactions to the $s_{1/2}$ states at 0.94 and 1.90 MeV are shown in Fig. 5. The thresholds for the (d,n) reactions to the corresponding analog states are 8.32 and 9.3 MeV, respectively. The measured cross section does differ noticably from the prediction of approximate finite-range DWBA calculations near the charge-exchange threshold, particularly for the lower-lying $s_{1/2}$ state, but the over-all trend of the curves is well described. These results tend to confirm observations[1,3,5] that the charge-exchange effect diminishes with increasing (d,n) threshold energy, vanishing when $Q<\frac{1}{4}\Delta_C$, where Q is the (d,p) Q value and Δ_C the Coulomb displacement energy of a proton in the residual nucleus.[9]

The excitation curves for $d_{3/2}$ states at 1.43-, 2.47-, and 2.77-MeV excitation energy are shown in Fig. 6. The corresponding (d,n) analog-state thresholds are 8.8, 9.8, and 10.1 MeV, respectively. The data are generally fitted quite well by the DWBA calculations shown. However, in all three cases, the 138° DWBA calculations tend to give a good description of the cross section below the respective thresholds, while the measured cross sections in all three cases decrease to a lower value than the DWBA prediction as the deuteron
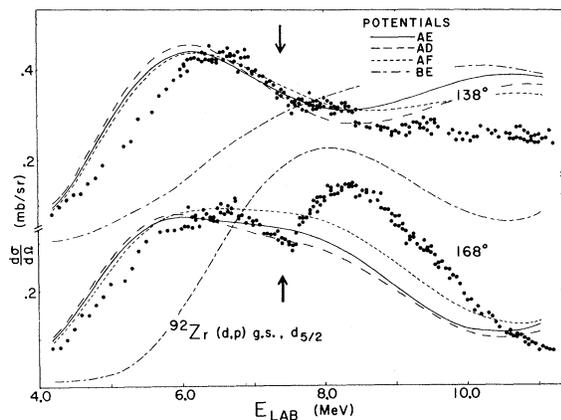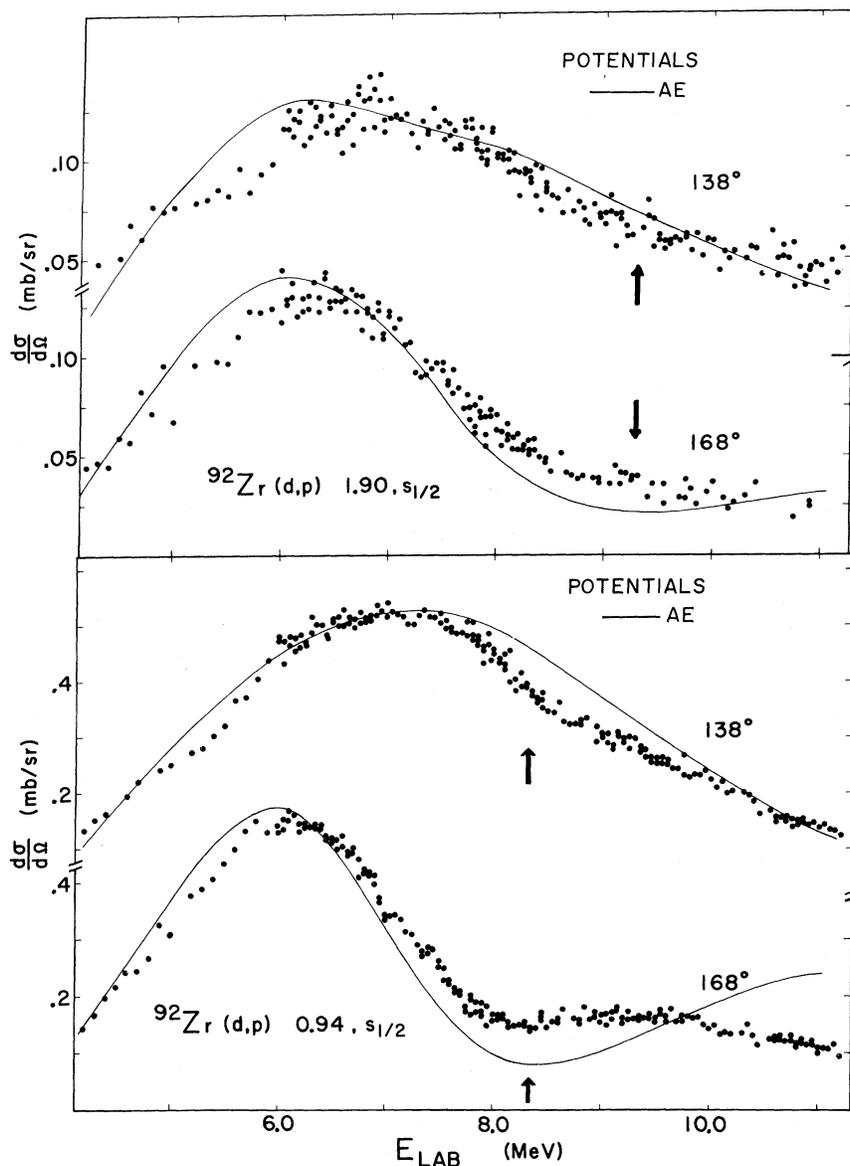
FIG. 5. Excitation curves
for $^{92}Zr(d,p)\,^{93}Zr(s_{1/2}$, 0.94
MeV and $s_{1/2}$, 1.90 MeV) at
138 and 168°, from 4 to 11
MeV. The solid curves are
local-energy-approxima-
tion DWBA calculations
using potentials A and E
(see Tables I and II).

energy increases beyond threshold. Such discrep-
ancies can hardly be attributed *a priori* to charge-
exchange threshold effects. Coupled-channel
DWBA calculations[9] for an $l = 2$ transition in ^{90}Zr-
(d,p), with $Q < \frac{1}{4}\Delta_C$, indicate that at 155° the mani-
festation of the charge-exchange coupling can in-
deed be a slight depression of the cross section
just above threshold (see Fig. 5 of Ref. 9). How-
ever, the fact that here 168° is always well fitted,
and the 138° fit is consistently "off" in all three
cases, makes an explanation due to charge ex-
change unlikely.

Excitation curves were also obtained for the
states at 3.00 MeV $(g_{7/2})$ and 3.38 MeV $(l \geqslant 2)$. The
data extend only slightly above the charge-exchange

threshold for these two states, but the measured
cross sections are fitted rather well by the DWBA
calculations, as shown in Fig. 7.

C. Spectroscopy of ^{93}Zr

Nuclear spectroscopy was not the purpose of
this experiment, but a number of states of ^{93}Zr
were observed, including three previously un-
reported. A brief discussion of these results will
therefore be given. Angular distributions extend-
ing from 50 to 170° at 5° intervals were accumulat-
ed at 6.25, 7.5, and 11.0 MeV for the eight low-
lying states for which excitation curves are shown
in Figs. 4–7, as well as states at 2.02, 2.08, 2.53,
and 2.65 MeV (see Table III). The levels at 2.02

and 2.08 MeV were observed by Cohen and Chubin-
sky[18] as an unresolved doublet, which our data re-
solves at most angles. The same situation holds
for the 2.47- and 2.53-MeV states. Forward-angle
data would, of course, be preferred for reliable
extraction of spectroscopic factors and l values,
but we are able to make tentative assignments for
both. Results are summarized in Table III. We
assign $l = 5$ to the 2.02- and 2.65-MeV states, con-
firm Ref. 18's assignment of $l = 4$ for the 2.08-MeV
state, and assign $l = 2$ to both 2.47- and 2.53-MeV
states. Also, we find $l \geq 2$ for the state at 3.38

MeV in contrast to Ref. 18's $l = 1$ assignment.
Work published after submission of this manuscript
confirms several of those assignments. Booth *et
al.*[19] confirm $l = 5$ for the 2.02-MeV state, while
Kent, Lieb, and Moore,[20] find $l = 3$ for the isobaric
analog of the 3.38-MeV state.

4. DISCUSSION

The DWBA (d, p) excitation-function calculations
shown in Figs. 4 through 7 were done with a pro-
gram, modified by one of us (W.R.C.), based on the
DWBA codes NEPTUNE and VENUS, written by
Tamura, Rybicki, and Coker.[21] The calculations
were done including spin-orbit coupling, in the
zero-range approximation, except for the $s_{1/2}$
transitions. The $s_{1/2}$ transition calculations were
done with a version of the program which includes
a finite-range approximation.[22]

The DWBA calculations were used to obtain l
values and "normalization" factors for the twelve
states observed in ^{93}Zr up to 3.5-MeV excitation
energy. The results of these calculations and a
comparison with the results of Cohen and Chubin-
sky[18] are given in Table III. The values given are
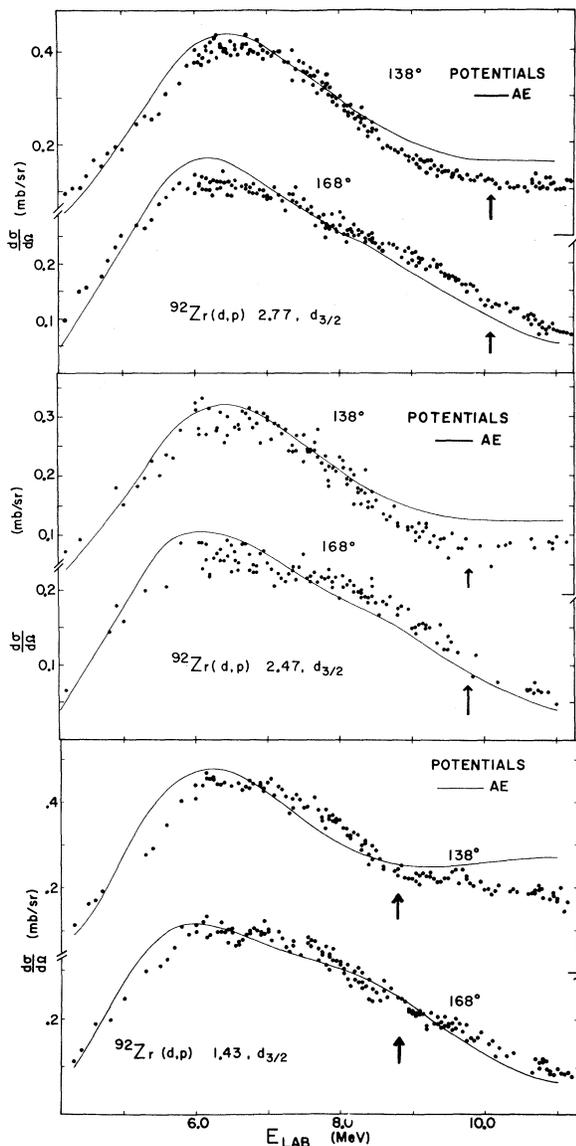
FIG. 6. Excitation curves for ^{92}Zr$(d,p)^{93}$Zr$(d_{3/2}$ states
at 1.43, 2.47, and 2.77 MeV) at 138 and 168°, from 4 to
11 MeV. The solid curves are zero-range DWBA calcu-
lations using potentials A and E (see Tables I and II).
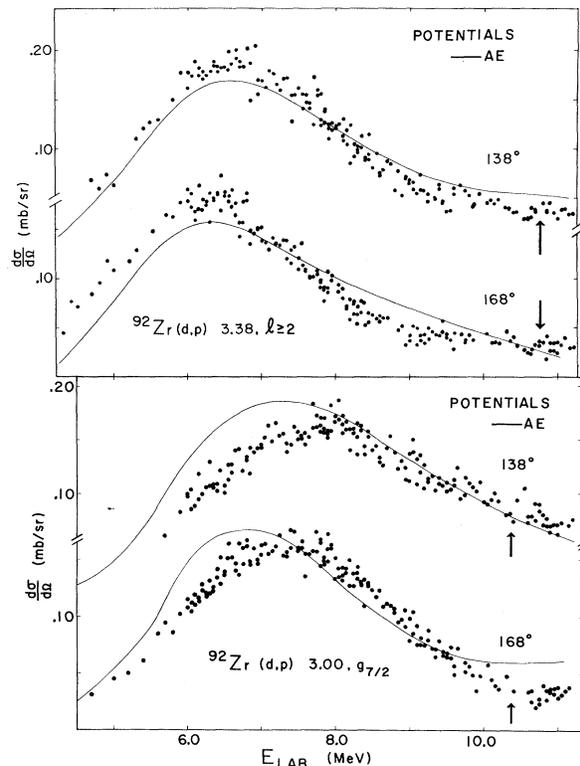
FIG. 7. Excitation curves for ^{92}Zr$(d,p)^{93}$Zr ($g_{7/2}$ at
3.00 MeV, d-f at 3.38 MeV) at 138 and 168°, from 4 to
11 MeV. The solid curves are local-energy-approxima-
tion DWBA calculations using potentials A and E (see
Tables I and II).

TABLE III. Energy levels in ^{93}Zr, with spectroscopic factors from the DWBA analyses of Ref. 18. Values in parentheses are uncertain. "Normalization" factors used in this work are given for comparison; l_j values are those assigned in this work.

Excitation (MeV)	l_j	S_{lj} This work	S_{lj} Ref. 18
0.0	$d_{5/2}$	0.55	0.54
0.28	...	...	...
0.94	$s_{1/2}$	0.70	0.91
1.43	$d_{3/2}$	0.60	0.38
1.64	$g_{7/2}$	...	0.11
1.90	$s_{1/2}$	0.13	0.21
2.02[a]	(h)	0.20	...
2.08	$(g_{7/2})$	0.48	0.42
2.32	$(g_{7/2})$	...	0.09
2.47	$(d_{3/2})$	0.25	0.24
2.53[a]	(d)	0.08	...
2.65[a]	$h_{11/2}$	0.12	...
2.77	(d)	0.29	0.21
3.00	$g_{7/2}$	0.37	0.30
3.19	$(d_{3/2})$	...	0.38
3.29	$(d_{3/2})$	...	0.03
3.38	$(f-d)$	~0.10	0.12[b]

[a] Not reported in Ref. 18.

[b] S_{lj} calculated assuming $p_{3/2}$ state.

averages for the three energies at which each angular distribution was taken, 6.25, 7.5, and 11.0 MeV.

The DWBA calculations of the available excitation functions, shown in Figs. 4 through 7 and discussed in the previous section, were done using the "normalization" factors of Table III. Except for the charge-exchange threshold effects previously discussed, the DWBA calculations are seen to provide quite good fits to these excitation functions over the broad energy range measured here. The quality of the fits is particularly gratifying considering the fact that the data are at angles 138 and 168°, well within the region frequently not quantitatively fitted by DWBA calculations.

Reports[23] exist of an anomaly in the ^{90}Zr(d,p) $(d_{5/2}$, g.s.) spectroscopic factor at the (d,n) threshold. While the study here cannot rule out such behavior, since we do not include the forward stripping peaks in our data, it does seem clear that charge exchange can have very little, if any, effect on the total (d,p) cross section. Therefore we feel that one should not be concerned about the possibility of charge-exchange effects leading unknown experiments to the extraction of erroneous spectroscopic factors.

5. CONCLUSIONS

To summarize, we have seen prominent anomalies, attributable to charge exchange, in the (d,p) excitation functions at 168° for at least one of the residual ^{93}Zr states satisfying $Q(d,p) > \frac{1}{4}\Delta_C$ – the $d_{5/2}$ ground state. No significant departure from DWBA predictions is seen for any state of higher excitation. We conclude that the original explanation[2,7] given for such anomalies is consistent with the ^{92}Zr(d,p) data, and that careful optical and DWBA analysis is capable of a very satisfactory description of (d,p) excitation functions over a fairly broad (7-MeV) energy range, i.e., DWBA spectroscopic factors need not show any energy dependence.

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Gamma Rays from Thermal and Resonance Neutron Capture in Sb^{121} and Sb^{123} †

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Prompt high-energy γ rays resulting from neutron capture at thermal energies and in the resonances of Sb^{121} and Sb^{123} have been studied with the high flux beam reactor fast chopper using high-resolution Ge(Li) detectors. The binding energy B_n of the last neutron in Sb^{122} and Sb^{124} has been determined to be 6807±2 and 6468±2 keV, respectively. Based on prompt capture γ-ray data, we have assigned a spin of 4 to the 21.6-eV resonance of Sb^{123}. Energy levels populated by the neutron-capture γ rays are given up to an excitation energy of 2475 keV in Sb^{122} and up to 2221 keV in Sb^{124}. These data are compared with the existing (d,p) data on Sb^{121} and Sb^{123}. We have also studied the low-energy (<511 keV) γ rays originating in neutron capture in the different resonances. For Sb^{121}, the observed spectra are found to fall into two classes, each having its own characteristic intensity distribution depending on the spin of the capturing state. By comparing these spectra with those originating from the 6.24-eV resonance (3$^+$) and the 15.4-eV resonance (2$^+$), we have assigned the following spins to the resonances in Sb^{121}: 29.7 eV (3), 53.5 eV (2), 64.5 eV (3), 73.8 eV (2), 111.4 eV (2), and 126.8 eV (3). Similar, but more tentative, spin assignments are made for resonances in Sb^{123}.

The low-energy spectra have also been used to measure the half-life of the 61.6-keV isomeric state in Sb^{122} by a new method. This experimental procedure is described. The half-life of the isomeric state is found to be 2.3±0.6 μsec.

1. INTRODUCTION

Antimony is made up of two isotopes, Sb^{121} and Sb^{123}, with fractional abundances of 57.25 and 42.75%, respectively. Neutron capture in these isotopes populates levels in Sb^{122} and Sb^{124} by γ-ray emission. Except for the (d,p) work on Sb^{121} and Sb^{123} by Hjorth,[1] a study[2,3] of some low-lying levels of Sb^{122} and Sb^{124}, and some recent resonance (n,γ) measurements by Ing *et al.*,[4] there are no data on the energy levels of Sb^{122} and Sb^{124}. In the (d,p) data mentioned above, the resolution was limited to 40 keV. Also, the zero of the energy scale, and hence the binding energy of the last neutron in these odd-odd nuclei, was not known. Hence, it seemed to be of some interest to study neutron-capture γ rays in antimony. Great interest has been shown in the Sn-Sb region of the periodic ta-

ble, and detailed calculations have been made using the short-range residual interactions to take account of nuclear pairing effects.[5,6] We hope to supplement the experimental data on nuclei in this region with the present experimental work.

2. EXPERIMENTAL ARRANGEMENT

Neutron-capture γ rays in antimony were studied using the fast chopper at the high-flux beam reactor (HFBR) with a flight path of 21.66 m and a chopper speed of 10 000 rpm. Details of the chopper installation and the on-line data recording and analyzing system have been described before.[7,8] The chopper was operated at 1500 rpm for recording thermal-neutron-capture events. γ rays originating in resonance capture were recorded with a 10-cc Ge(Li) detector at a resolution of 10 keV at 7.7