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$^{92}Zr(d,p)^{93}Zr$ and $^{92}Zr(d,t)^{91}Zr$

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$^{92}Zr(d,p)^{93}Zr$ AND $^{92}Zr(d,t)^{91}Zr$

by N. Baron, C. L. Fink, P. R. Christensen,

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The structure of ^{93}Zr and ^{91}Zr was studied by the stripping reaction $^{92}Zr(d,p)^{93}Zr$ and the pick-up reaction $^{92}Zr(d,t)^{91}Zr$ using 13 MeV incident deuterons. The experiment was performed at the Tandem van de-Graaf facilities of the Bohr Institute and the University of Pittsburgh. The ^{92}Zr targets used were isotopically enriched and were about 0.7 mg/cm^2 thick. The reaction product particles were detected using a $\Delta E \times E$ counter telescope. The front transmission counter was a 51 micron thick, silicon surface barrier type. The rear stopping counter was a 3 millimeter thick, lithium drifted silicon surface barrier type. The solid angle subtended at the target by the counter telescope was 2.75×10^{-4} steradians.

In figure 1 is shown a block diagram of the electronic circuit used to process the detectors' output signals and is seen to be quite conventional. Reaction product protons, deuterons, and tritons were identified and the identification signals were used to rout the energy sum signals of these three different types of particles into different 1024 channel quadrants of a 4096 channel PHA memory core.

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The outputs of a dual pulser, which were adjusted to simulate a triton signal, were fed into the front ends of the ΔE and E preamplifiers, and the sum signal was collected in the triton portion of the PHA. The pulser was triggered to fire by the monitor counter. The system deadtime was obtained by comparing the monitor (or pulser trigger) counts with the PHA stored pulser counts. The pulser setting was unchanged throughout the experiment, and its sum signal was observed to fall in the same channel for all the runs. This provided evidence of no significant electronic drifts throughout the course of the experiment. Consequently, one linear energy calibration curve was generated using the ground state centroids for the (d,p_o), (d,d_o), and (d,t_o) levels from all of the runs. However, the quoted excitation energies of the observed levels should not be trusted to better than ±10 keV.

In figure 2 are shown some typical spectra from the reactions $^{92}Zr(d,p)^{93}Zr$ and $^{92}Zr(d,t)^{91}Zr$. The overall experimental resolution was 35 to 45 keV F.W.H.M. Each spectrum was analyzed by a nonlinear least squares peak fitting program(1) which included a background search. The absolute magnitudes of the cross sections were calculated using the measured integrated incident charge, solid angle, and target thickness. It is estimated that the quoted absolute cross sections are uncertain by ±10%.

Spin and parity assignments to the observed excited levels were made by comparing the experimental angular distributions with distorted wave Born approximation (DWBA) calculations. The DWBA computer program used was DWUCK(2). In figure 3 are shown the optical potentials used for calculating the bound state wave function, the proton optical potential, which

is that of Greenlees and Becchetti[3], and the triton optical potential[4]. The deuteron optical potential is also shown here and was obtained from the deuteron elastic cross sections that were measured in this experiment.

$^{92}Zr(d,p)^{93}Zr$

In figure 4 are shown the measured angular distributions compared to the DWBA calculation which agrees best with the data. Since most of the expected strength of the $2d_{5/2}$ shell was found in the ground state and first excited state, all other $\Delta l = 2$ transitions were assumed to populate $3/2^+$ levels. The levels populated in this stripping reaction are assumed to be those predicted by the shell model. Consequently, having determined the momentum transfer, Δl, the correct spin can be inferred with reasonable certainty since there is little ambiguity in the shell model predicted spin for a given l in this region.

In figure 5 are tabulated the excitation energies, momentum transfers, assumed spin and parity assignments, and spectroscopic strength factors for 44 of the observed excited levels in ^{93}Zr which were made on the basis of the DWBA calculations. In figure 6 are pictured the spectroscopic strengths for each level belonging to a given shell, and the total strength for that shell drawn at the energy center of gravity of the several levels. Up to an excitation energy of 4.84 MeV in ^{93}Zr, essentially all of the expected strength was obtained for the $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1g_{7/2}$ shells. The energy centroids of these shells were computed to lie at 0.003-, 1.21-, 2.23-, and 2.36-MeV respectively in ^{93}Zr. In addition, there was found 43% of the $1h_{11/2}$ strength, 21% of the $2f_{7/2}$ strength, and 3% of the expected $3p_{3/2}$ strength. The energy centroids of these shells were calculated to lie above 2.31-, 3.84-, and 3.57-MeV respectively in ^{93}Zr.

$^{92}Zr(d,t)^{91}Zr$

In figure 7 are shown the measured angular distributions compared to the DWBA calculated distributions which agree best with the data.

In figure 8 is shown the experimental angular distribution for the 1.196 MeV level in ^{91}Zr compared to DWBA calculations assuming a momentum transfer of 0 and 2. The calculation assuming a momentum transfer of 2 is clearly in better agreement with the experimental results. This level has been assigned previously a spin and parity of $1/2^+$(5,6,7,8,9,10). The assignment quoted in the (d,t) work of ref. 8 was inferred from the assignment given a level at about the same energy from the reactions $^{90}Zr(d,p)^{91}Zr$ (8,9,10), $^{91}Zr(p,p')^{91}Zr$ (5), and $^{88}Sr(\alpha,n\gamma)^{91}Zr$ (7). Consequently, it is surprising that the angular distribution for this level is best described by a DWBA calculation assuming it to be $5/2^+$ and a significant spectroscopic strength of 0.29±0.06. If this is true, then either this is not the same level reported at 1.204 MeV which was observed in the (d,p), (p,p'), and (α,nγ) work and found to have a spin and parity of $1/2^+$, or else that spin and parity assignment is incorrect. In view of the almost overwhelming evidence for a $1/2^+$ level at about this energy, it is reasonable to question the accuracy of the present (d,t) data. However, this data

was taken at both the tandem facility of the Niels Bohr Institute and the tandem facility of the University of Pittsburgh using different targets of ^{92}Zr, and the two sets of cross sections obtained at each facility are in excellent agreement with each other. Other evidence for the accuracy of the magnitude of the cross sections can be obtained from the (d,t) measurement of ref. 8. Although that $^{92}Zr(d,t)^{91}Zr$ measurement was made at only one angle, a spin and parity assignment of $1/2^+$ for this level was made because its energy corresponded to that for a $1/2^+$ level excited by the reaction $^{90}Zr(d,p)^{91}Zr$ (8). The quoted (d,t) spectroscopic strength was 0.15. Assuming the 1.196 MeV level of the present work to be $1/2^+$, we obtain a similar strength of 0.14. Thus the magnitude of the (d,t) cross sections of this level measured in the present work are consistent with those of ref. 8. This provides further credence to the data's accuracy.

In figure 9 are tabulated the energy levels, momentum transfers, assumed spin and parity assignments, and spectroscopic factors, which were made on the basis of DWBA calculations, for 21 of the observed 26 ^{91}Zr levels. Several of the $\Delta l = 2$ and 4 transitions have been identified in other reaction studies such as (p,p')(5), (p,d)(6), (α,nγ)(7), and (d,p)(8,9,10) which lead to excited levels of ^{91}Zr. All $\Delta l = 2$ transitions are assumed to excite $5/2^+$ levels, except for the level at 2.036 MeV which was previously reported to be $3/2^+$(6,7,9,10). All $\Delta l = 4$ transitions are assumed to excite $9/2^+$ levels, except for the level at 2.186 MeV which was previously reported to be $7/2^+$(6,10). The six $\Delta l = 1$ transitions could be either $1/2^-$ or $3/2^-$, but it is to be expected that the lower lying $\Delta l = 1$ transitions are $1/2^-$ levels.

In figure 10 are shown the summed spectroscopic strength factors for each shell. If we consider the 1.196 MeV level to be $5/2^+$, we have a summed strength of 1.92±0.38 as compared to an expected summed strength of 2. The excitation energy of the center of gravity of these various $5/2^+$ levels is computed to lie at 0.442 MeV. Assuming that all $\Delta l = 4$ transitions are $9/2^+$ levels (except the 2.186 MeV level which was previously identified as $7/2^+$), we obtain a summed strength of 8.78±1.75 as compared to the expected value of 10. The excitation energy of the center of gravity of these various $9/2^+$ levels is computed to lie at 3.19 MeV. Among the six $\Delta l = 1$ transitions, the levels at 3.229-, 3.468-, and 3.568-MeV have also been previously observed in the (p,d) work(6) to be $\Delta l = 1$ transitions. Most likely, most of these lower lying levels are $1/2^-$ and will account for most of the expected strength of 2. However, it is expected that one or more of the higher lying levels represent neutrons picked up from the $2p_{3/2}$ shell.

In summation, for the $^{92}Zr(d,t)^{91}Zr$ reaction, there is confusion as to why the 1.196 MeV level seems to be a $\Delta l = 2$ rather than $\Delta l = 0$ transition. However, the expected strength of the $2d_{5/2}$, $1g_{9/2}$, and $2p_{1/2}$ shells is essentially observed. Furthermore, the departure of the level structure of ^{91}Zr and ^{93}Zr from what one would expect in a single particle model is to be expected from previous (p,p')(5) and (d,p)(10) work where attempts were made to explain the level structure of ^{91}Zr as resulting from particle (hole)-core coupling. In fact, many of the levels of ^{91}Zr reported in the

present work are presumed in refs. 5 and 10 to arise from such coupling schemes. Consequently it should be no surprise that one observes such significant fractionization of the single particle strength in the structure of ^{91}Zr and ^{93}Zr. From the spectroscopic strengths measured in the (d,t) reaction, one can conclude that ^{92}Zr ground state is roughly 76% $(2d_{5/2})^2$, 3% $(3s_{1/2})^2$, 9% $(2d_{3/2})^2$, and 12% $(1g_{7/2})^2$. This agrees reasonably well with the conclusion on ^{92}Zr ground state reported in the (p,d) work[6] and (d,p) work[8].

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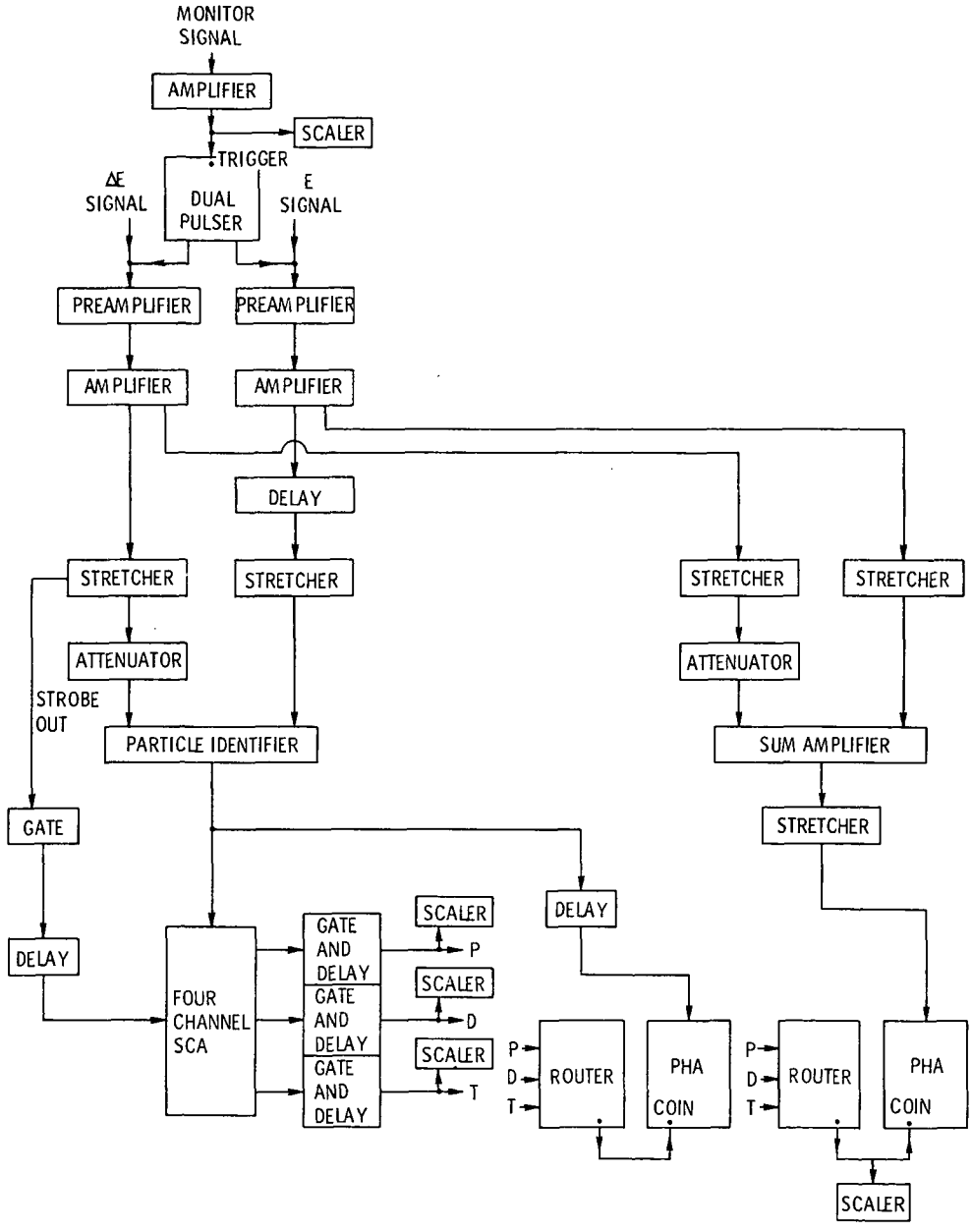

Figure 1. - Electronic arrangement.

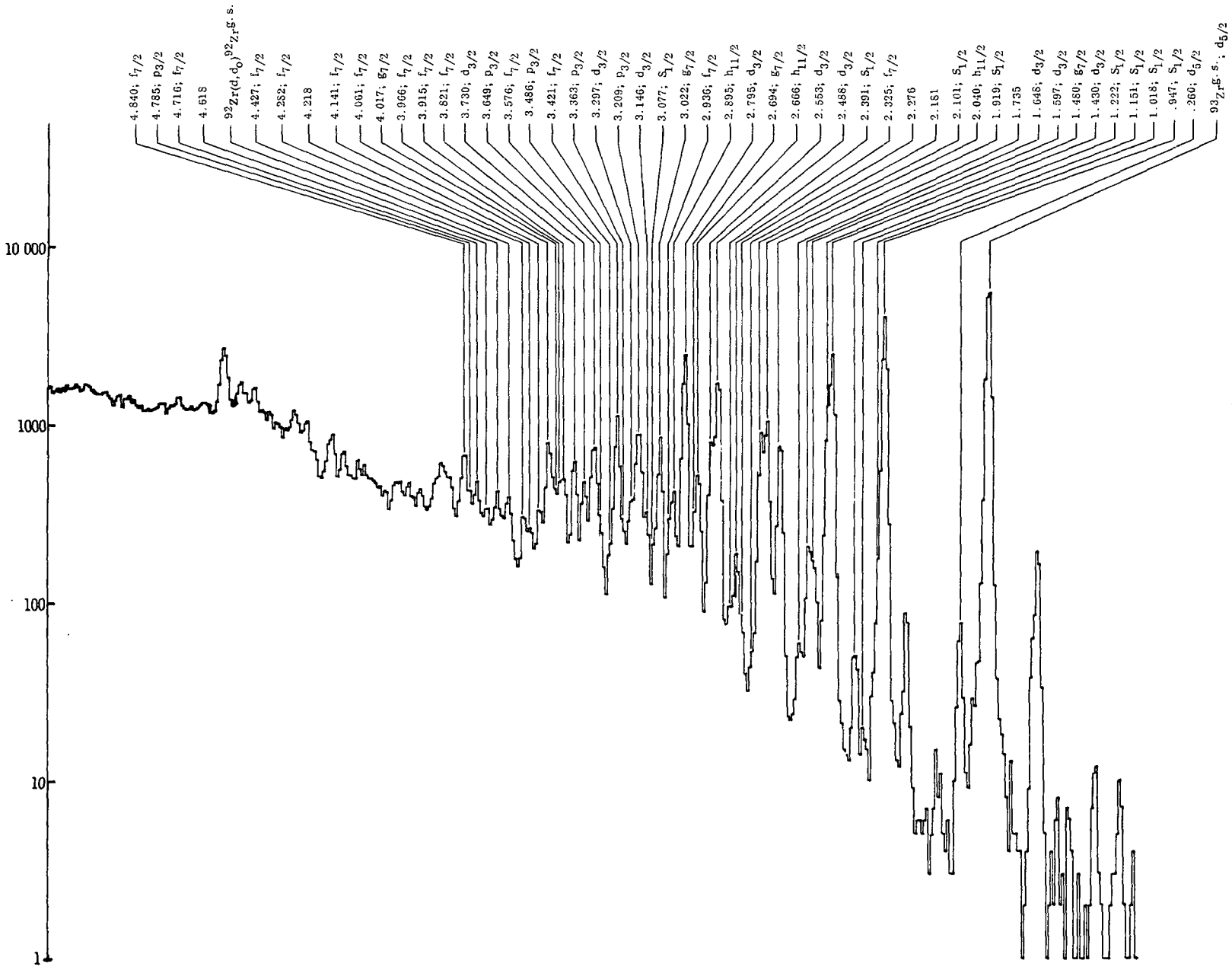

Figure 2. - $^{92}Zr(d, p)^{93}Zr$ spectrum; laboratory scattering angle = 60^{0}.

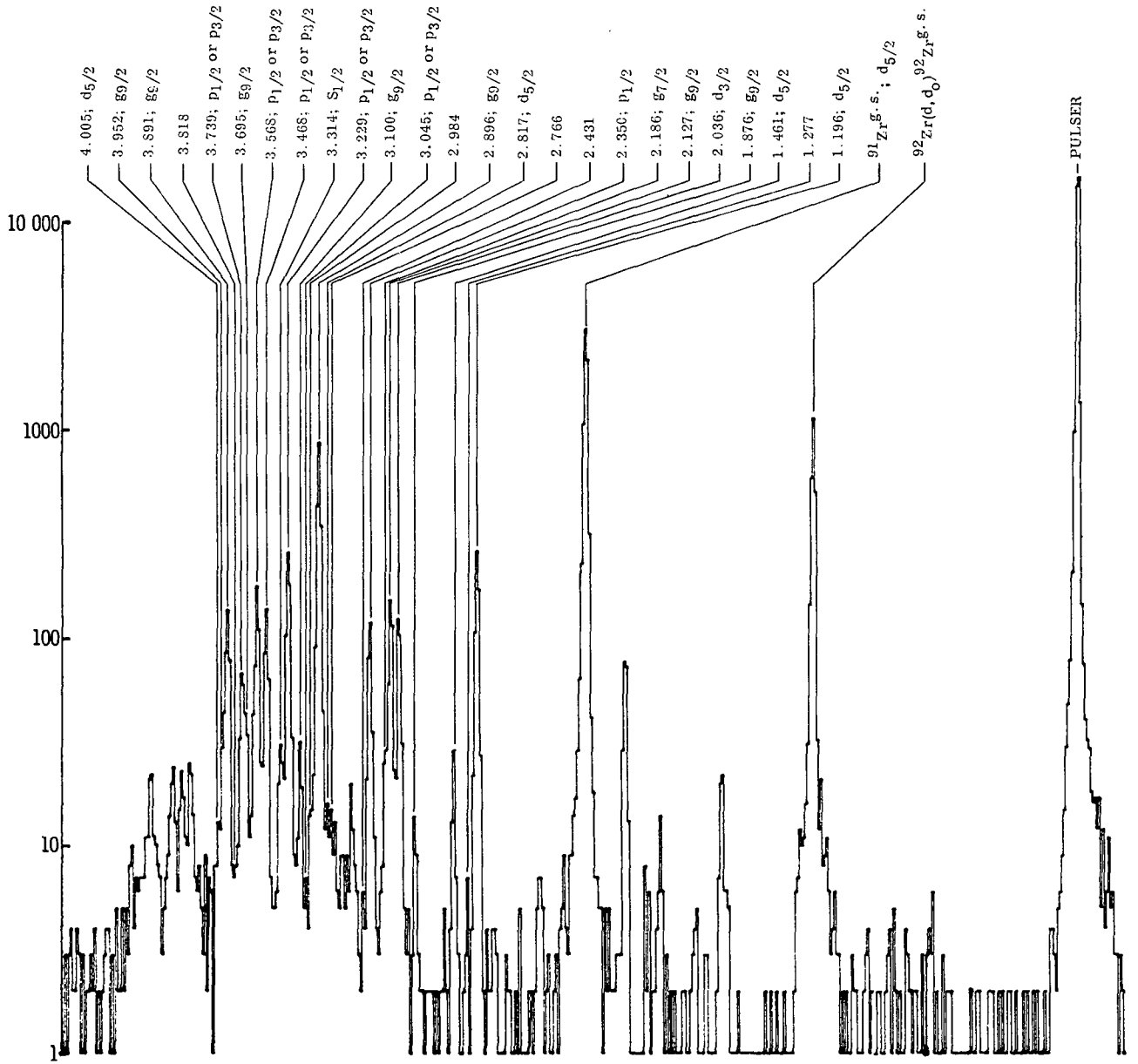

Figure 2. - Concluded. $^{92}Zr(d,t)^{91}Zr$ spectrum; laboratory scattering angle = 60°.

DEUTERONS[a]		PROTONS[b]	TRITONS[c]	BOUND STATE POTENTIAL
V_R	94.7	$54 - 0.32E + 0.4(Z/A^{1/3}) + 24[(N-Z)/A]$	$165 - 0.17E - 6.4[(N-Z)/A]$	
a_R	.802	0.75	0.72	0.67
r_R	1.15	1.17	1.20	1.27
W_V		0.22E - 2.7, OR ZERO, WHICHEVER IS GREATER	$46 - 0.33E - 110[(N-Z)/A]$	
W_{SF}	47.8	$11.8 - 0.25E + 12[(N-Z)/A]$ OR ZERO, WHICHEVER IS GREATER		
a_I	.841	$0.51 + 0.7[(N-Z)/A]$	.84	
r_I	1.36	1.32	1.40	
r_{COUL}	1.25	1.25	1.3	
λ				32

E = INCIDENT LABORATORY ENERGY

[a]PRESENT WORK.
[b]BECCHETTI, F. D. AND GREENLEES, G. W., PHYS. REV. 182, 1190 (JUNE 1969).
[c]TORSTEINSEN, T., PRIVATE COMMUNICATION.

Figure 3. - Optical potentials used in DWBA calculations.

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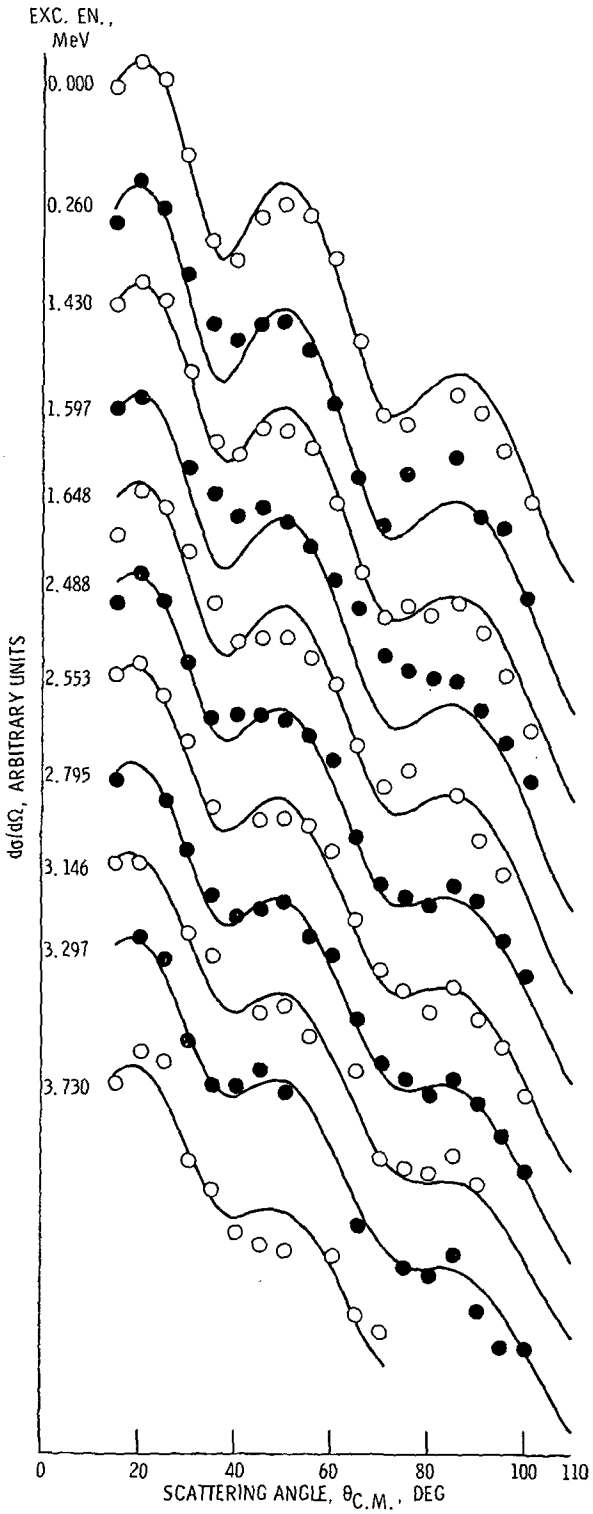
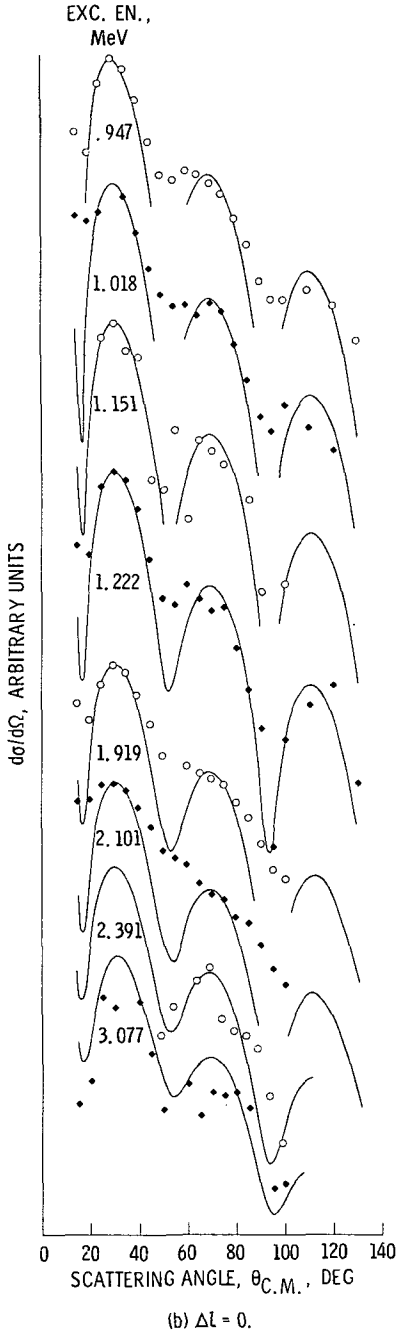


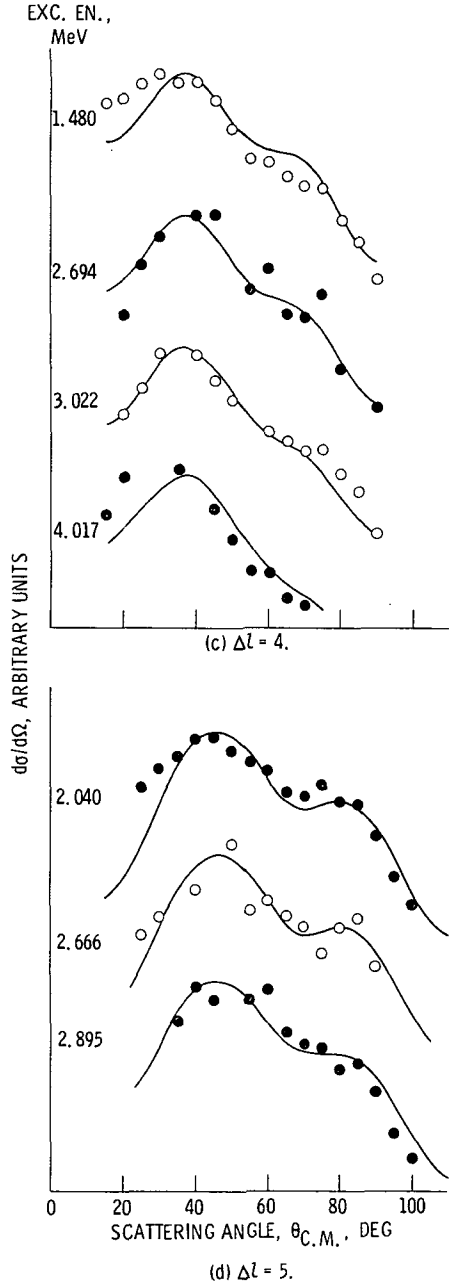
(a) $\Delta l = 2$.

Figure 4. - Comparison of experimental angular distributions with theoretical (DWBA) calculations for the observed excited levels in ^{93}Zr induced by the reaction $^{92}Zr(d, p)^{93}Zr$.



(b) $\Delta l = 0$.

Figure 4. - Continued.



(c) $\Delta l = 4$.

(d) $\Delta l = 5$.

Figure 4. - Continued.

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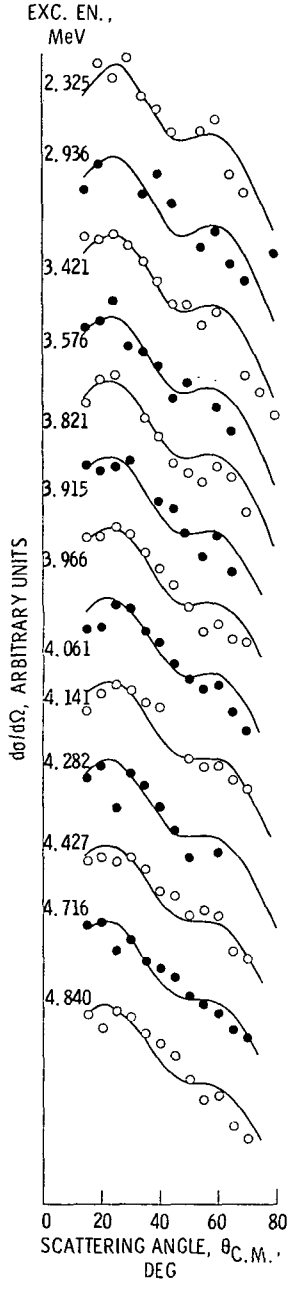
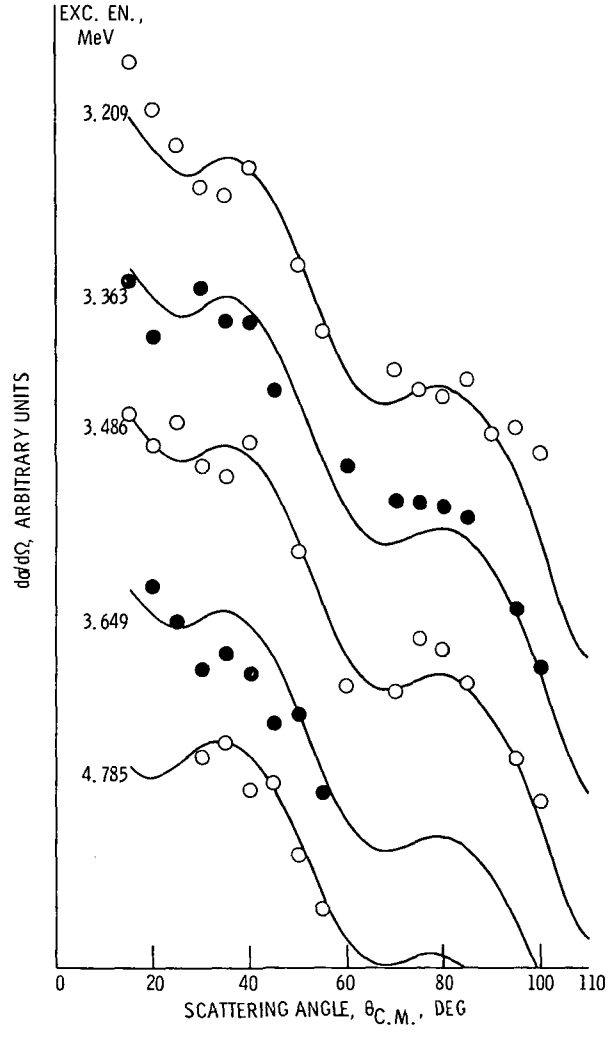


(e) $\Delta l = 3$.

Figure 4. - Continued.



(f) $\Delta l = 1$.

Figure 4. - Concluded.

EXC. EN. MeV	MOMENTUM TRANSFER, Δl	J^{π}	S	EXC. EN., MeV	MOMENTUM TRANSFER, Δl	J^{π}	S
g. s.	2	$5/2^+$	0.54 ±0.11	3.022	4	$7/2^+$	0.29 ±0.06
0.260	2	$5/2^+$	.007± .001	3.077	0	$1/2^+$	.018± .004
.947	0	$1/2^+$	.53 ± .11	3.146	2	$3/2^+$	.017± .003
1.018	0	$1/2^+$	.13 ± .03	3.209	1	$3/2^-$	.007± .001
1.151	0	$1/2^+$	.020± .004	3.297	2	$3/2^+$	.024± .005
1.222	0	$1/2^+$	.006± .001	3.363	1	$3/2^-$	.008± .002
1.430	2	$3/2^+$	.37 ± .07	3.421	3	$7/2^-$	.046± .009
1.480	4	$7/2^+$	.45 ± .09	3.486	1	$3/2^-$	.005± .001
1.597	2	$3/2^+$	.018± .003	3.576	3	$7/2^-$	.008± .002
1.648	2	$3/2^+$	.027± .005	3.649	1	$3/2^-$	.006± .001
1.735				3.730	2	$3/2^+$	.036± .007
1.919	0	$1/2^+$	.088± .018	3.821	3	$7/2^-$	.034± .007
2.040	5	$11/2^-$	.27 ± .05	3.915	3	$7/2^-$	.014± .003
2.101	0	$1/2^+$	.072± .014	3.966	3	$7/2^-$	.016± .003
2.181				4.017	4	$7/2^+$	.11 ± .02
2.276				4.061	3	$7/2^-$	.029± .006
2.325	3	$7/2^-$	.007± .001	4.141	3	$7/2^-$	.009± .002
2.391	0	$1/2^+$	.004± .001	4.218			
2.488	2	$3/2^+$	.20 ± .04	4.282	3	$7/2^-$	.007± .001
2.553	2	$3/2^+$	.081± .016	4.427	3	$7/2^-$	.008± .002
2.666	5	$11/2^-$	.096± .019	4.618			
2.694	4	$7/2^+$	.093± .019	4.716	3	$7/2^-$	.008± .002
2.795	2	$3/2^+$	.26 ± .05	4.785	1	$3/2^-$	.004± .001
2.895	5	$11/2^-$	.061± .012	4.840	3	$7/2^-$	.015± .003
2.936	3	$7/2^-$	.009± .002				

Figure 5. - Excitation energies, momentum transfers, assumed spin and parity assignments, and spectroscopic strength factors for excited levels in ^{93}Zr.

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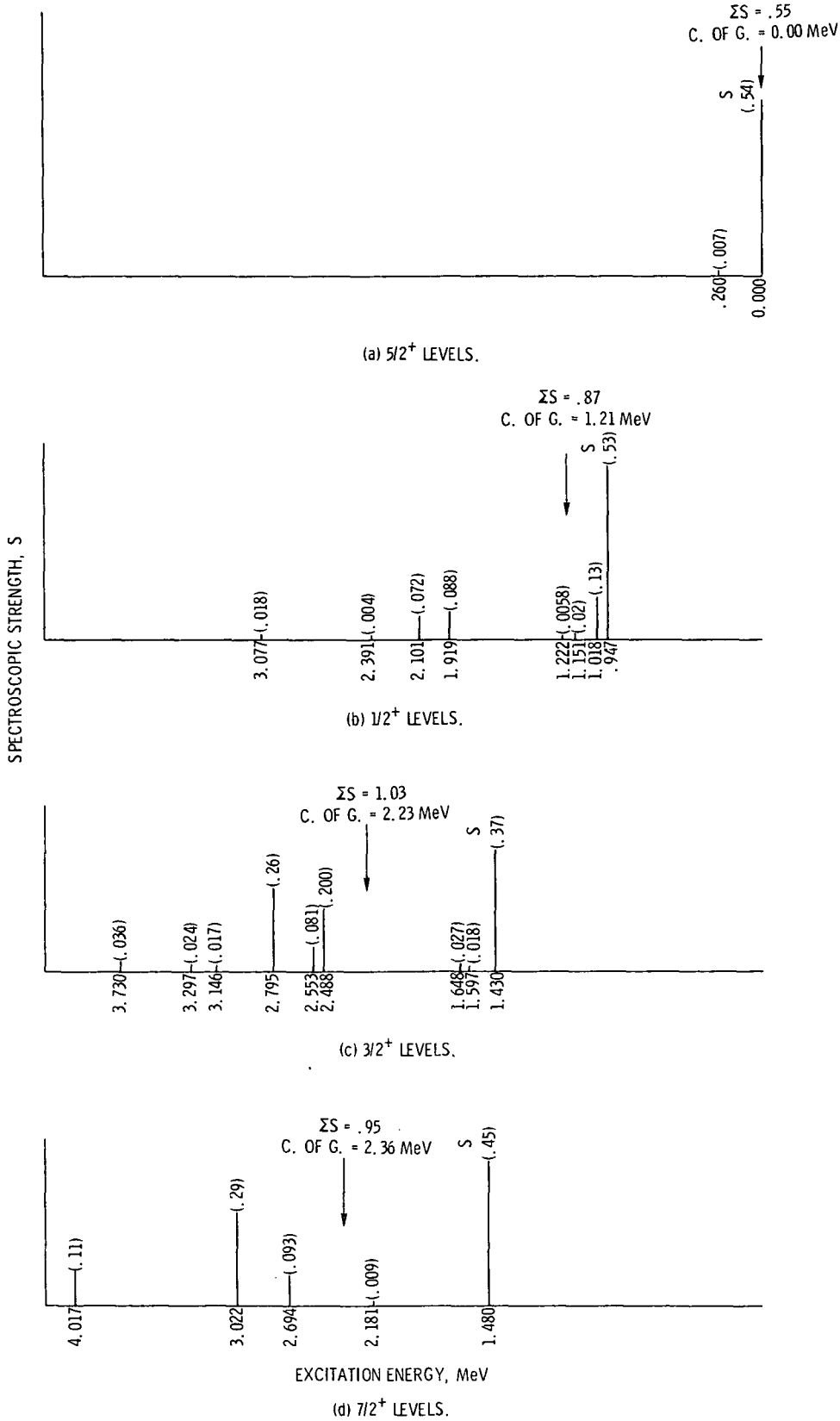
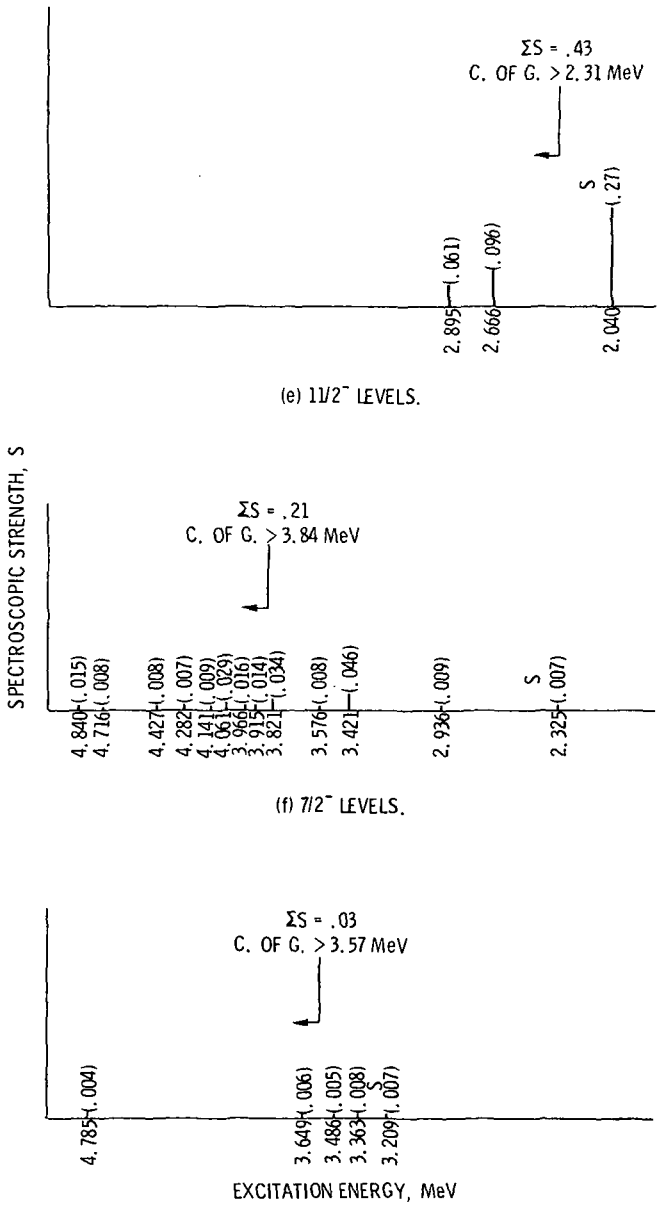


Figure 6. - Spectroscopic strength factors for levels excited in the reaction $^{92}Zr(d,p)^{93}Zr$.



(e) 11/2⁻ LEVELS.

(f) 7/2⁻ LEVELS.

(g) 3/2⁻ LEVELS.

Figure 6. - Concluded.

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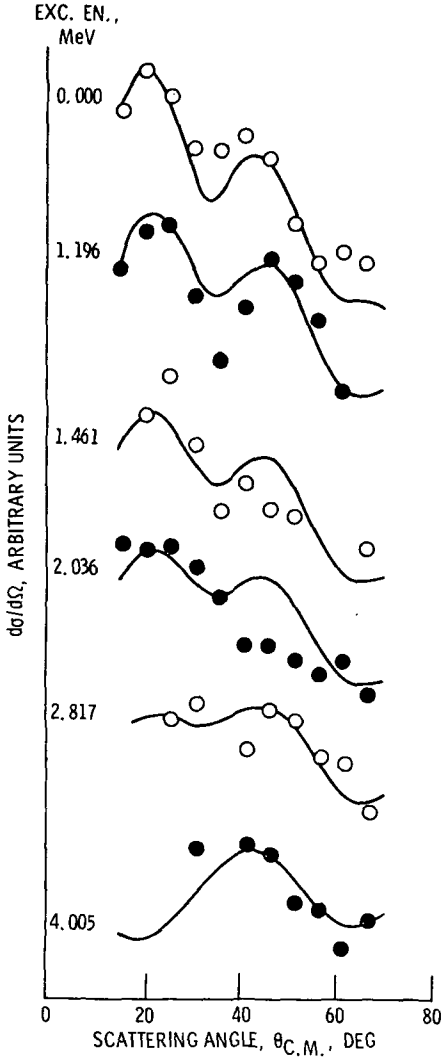
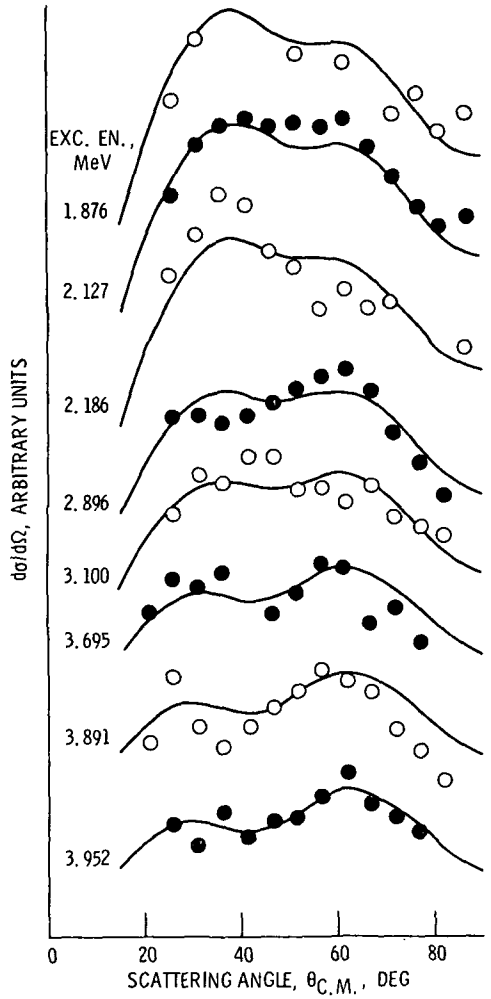


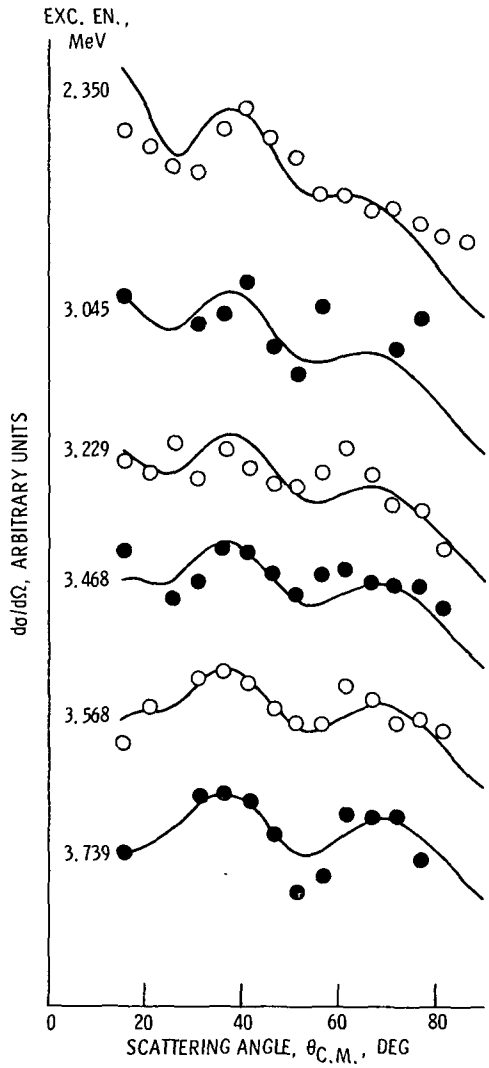
(a) $\Delta l = 2$.



(b) $\Delta l = 4$.

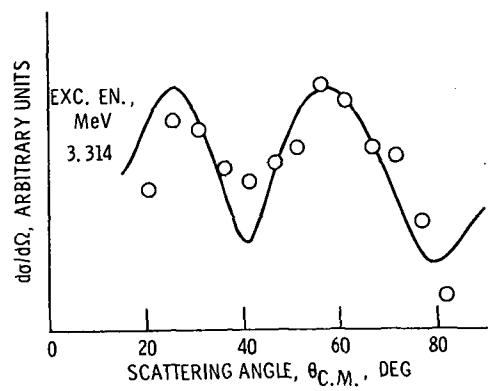
Figure 7. - Comparison of experimental angular distributions with theoretical (DWBA) calculations for the observed excited levels of ^{91}Zr induced by the reaction $^{92}Zr(d,t)^{91}Zr$.

Figure 7. - Continued.



(c) $\Delta l = 1$.

Figure 7. - Continued.



(d) $\Delta l = 0$.

Figure 7. - Concluded.

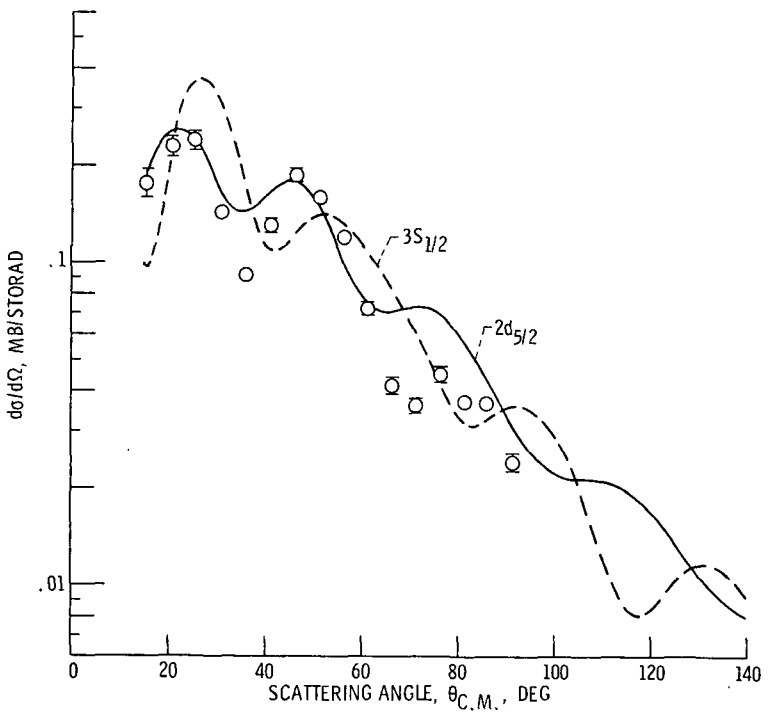


Figure 8. - Comparison of the ^{91}Zr 1.196 MeV level experimental angular distribution with theoretical (DWBA) calculations assuming a momentum transfer of 0 and 2.

EXC. EN., MeV	MOMENTUM TRANSFER, Δl	J^{π}	C^2S
0.000	2	$5/2^+$	1.49 ±0.30
1.196	2	$5/2^+$	.29 ± .06
1.277			
1.461	2	$5/2^+$	.014± .003
1.876	4	$9/2^+$	.052± .010
2.036	2	$3/2^+$	.21 ± .04
2.127	4	$9/2^+$	.63 ± .13
2.186	4	$7/2^+$	.30 ± .06
2.350	1	$1/2^-$	.21 ± .04
2.431			
2.766			
2.817	2	$5/2^+$	.030± .006
2.896	4	$9/2^+$	4.68 ± .93
2.984			
3.045	(1)	$(3/2^-)$, $(1/2^-)$	(.024± .005), (.028± .006)
3.100	4	$9/2^+$	.27 ± .05
3.229	1	$3/2^-$, $1/2^-$	.65±.13, .77±.15
3.314	0	$1/2^+$	.06 ± .01
3.468	1	$3/2^-$, $1/2^-$	.52±.10, .62±.12
3.568	1	$3/2^-$, $1/2^-$	.67±.13, .79±.16
3.695	4	$9/2^+$	.50 ± .10
3.739	1	$3/2^-$, $1/2^-$	.36±.07, .44±.09
3.818			
3.891	4	$9/2^+$	2.21 ± .44
3.952	4	$9/2^+$	.44 ± .09
4.005	2	$5/2^+$	.098± .020

Figure 9. - Excitation energies, momentum transfers, assumed spin and parity assignments, and spectroscopic strength factors for excited levels in ^{91}Zr.

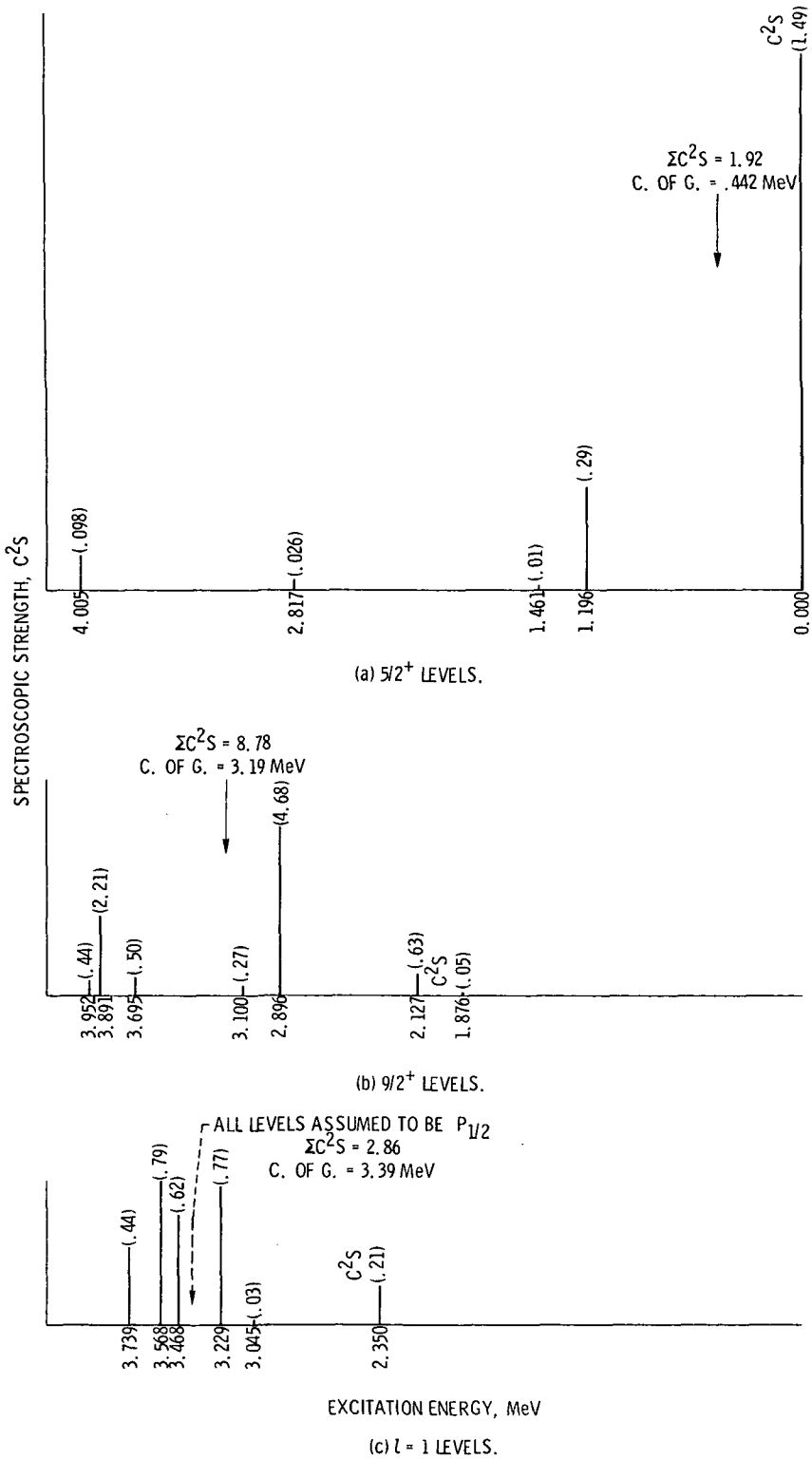


Figure 10. - Spectroscopic strength factors for levels excited in the reaction $^{92}Zr(d,t)^{91}Zr$.