PHYSICAL REVIEW VOLUME 132, NUMBER 6 15 DECEMBER 1963

Nuclear Structure Studies in the Zinc Isotopes with Stripping Reactions*

E. K. Lin and B. L. Cohen
University of Pittsburgh, Pittsburgh, Pennsylvania

(Received 24 July 1963)

The (*d,p*) reactions on Zn^{64}, Zn^{66}, Zn^{67}, and Zn^{68} were studied with ~90-keV resolutions and analyzed with distorted-wave Born approximation calculations. About 20 levels from each of these reactions are identified and assigned to shell-model states. Sum rules are applied to estimate the degree of the filling of these. The results for this and locations of the "centers of gravity" of the shell-model levels are compared with results for isotonic nuclei, and with pairing theory. Measurements on (*d,t*) reactions are also included; among other things, they indicate that the 39th and 40th neutrons go predominantly into $g_{9/2}$ rather than $p_{1/2}$ states.

INTRODUCTION AND EXPERIMENTAL

STRIPPING reactions have been widely used for experimental and theoretical studies of nuclear structure. In previous papers[1-3] such a study was reported for the isotopes of titanium, iron, and nickel; in this paper, we extend the study to the isotopes of zinc, which is the next-heavier even element in this series. Shull and Elwyn[4] have reported a few low-lying energy levels in Zn^{65}, Zn^{67}, Zn^{68}, and Zn^{69} from (*d,p*) reactions. In their investigations of the energy spectra of protons with scintillator energy resolution, they assigned spins and parities on the basis of Butler stripping theory.[5]

The present work, carried out with better than 100-keV resolution is analyzed with distorted-wave Born approximation[6] (DWBA) calculations which have been found to be quite successful in this region.[1] In addition, some data are obtained from (*d,t*) reactions. This allows the assignment of spins and parities to almost all levels (up to about 5-MeV excitation) that are appreciably populated in these reactions. Since almost all levels with sizable components of the lowest-lying shell model states—$p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, $d_{5/2}$, and $s_{1/2}$—are observed, it is possible to apply sum rules to determine the degree of occupation of these states in each of the various isotopes. These results can then be compared with the predictions of pairing theory, and are available, along with the detailed level structure, to compare with more sophisticated shell-model calculations that may be forthcoming.

Targets of zinc isotopes were bombarded with 15-MeV deuterons from the University of Pittsburgh cyclotron. The reaction products were magnetically analyzed by a magnetic spectrograph and detected by photographic plates. A detailed description of the experimental method has been given elsewhere.[1-3,7]. The targets were highly enriched isotopic targets of Zn^{64}, Zn^{66}, Zn^{67}, and Zn^{68} on gold backings.[8] The target thicknesses were determined by measuring the cross sections for a few strongly excited levels with a natural zinc target of well-determined thickness, and normalizing measurements with the isotopic targets to these. This method led to uncertainties up to 30% in some cases; this is the principal source of error in the present measurements. In some cases, errors in cross sections may result from the Au background.

Typical data for (*d,p*) reactions are shown in Fig. 1. Data were taken at nine angles between 9 and 50° to obtain angular distributions. The resolution was about 90 keV at most angles, but was somewhat poorer at the forward angles.

For (*d,t*) reactions, the spectra were obtained at angles 45 and 60° by using a natural zinc target foil without Au backing; this eliminates the rather considerable confusion from Au backgrounds. The individual low-lying levels of Zn^{66}, Zn^{67}, and Zn^{69} were identified from their known energies. No levels of Zn^{63} and Zn^{65} were observed because of the large negative *Q* values for (*d,t*) reactions leading to these isotopes. Typical data for (*d,t*) reactions are shown in Fig. 2. The energy resolution here was about 70 keV.

Absolute cross sections are uncertain by about 25%; relative cross sections for various groups and for the same group at different angles are uncertain by about 10% except where statistics are meager or the background is large and/or uncertain.

RESULTS

Some of the angular distributions of protons from (*d,p*) reactions are shown in Figs. 3, 4, 5, and 6. The assignment of *l* values was made by comparison with DWBA calculations, some of which are shown in Fig. 7.

---

* This work was done at Sarah Mellon Scaife Radiation Laboratory and supported by the National Science Foundation.

[1] B. L. Cohen, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).

[2] R. H. Fulmer and A. L. McCarthy, Phys. Rev. **131**, 2133 (1963).

[3] R. H. Fulmer, A. L. McCarthy, B. L. Cohen, and R. Middleton (to be published).

[4] F. B. Shull and A. J. Elwyn, Phys. Rev. **112**, 1667 (1958).

[5] S. T. Butler, Proc. Phys. Soc. (London) **208**, 559 (1951).

[6] We are indebted to G. R. Satchler, R. H. Bassel, and R. M. Drisko for the distorted-wave Born approximation calculation. The calculations used here were for Ni-58, using the following optical-model parameters: For deuteron, $V=79.5$, $r_0=1.274$, $a=0.739$, $w'=82$, $r_0'=1.389$ $a'=0.625$; for proton, $V=57-0.58$ E_p, $r_0=r_0'=1.25$, $a=0.65$, $w'=42$, $a'=0.47$.

[7] B. L. Cohen, J. B. Mead, R. E. Price, K. S. Quisenberry, and C. Martz, Phys. Rev. **118**, 499 (1960).

[8] Targets were obtained from Atomic Energy Authority, Harwell, England.

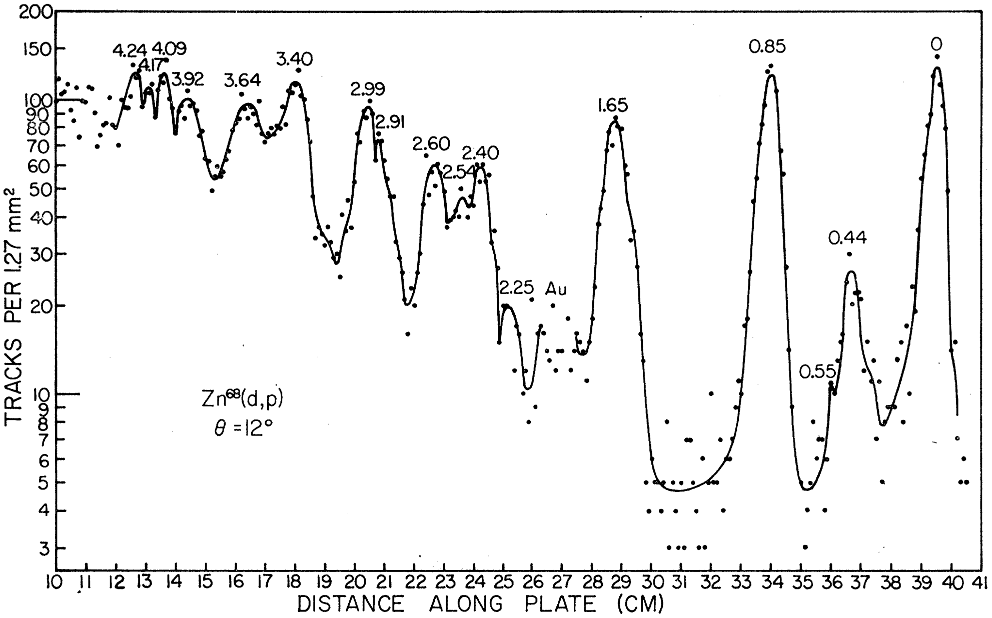

FIG. 1. Typical data for proton spectra from (d,p) reactions. These data are from Zn^{68} (d,p) observed at 12°. Numbers above peaks are excitation energies of final states in MeV. Peak labeled "Au" is the peak from the gold backing. The decision as to what is a true peak is made on the basis of data at all angles, not just the data shown here.

The results are summarized in Tables I-IV. In these tables, column (1) lists the observed energy levels which are then compared with previous data (where available) in column (2). Column (3) indicates the l values assigned.

For an even-even target nucleus, the cross section for exciting a level of spin I by a (d,p) reaction is given by

$$d\sigma/d\Omega=(2I+1)\sigma_r S, \qquad (1)$$

where σ_r is the result of the DWBA calculations. From the ratio of $d\sigma/d\Omega$ measured at the first peak in the angular distribution—listed in column (4) of Tables I-III—to σ_r at the corresponding peak in the calculated angular distributions, the product $(2I+1)\,S$ is derived and shown in column (5). The value of I is determined from the l by use of shell model except for the ambiguity between $p_{3/2}$ and $p_{1/2}$ in the $l=1$ levels; in a few cases this ambiguity is resolved by other information in the

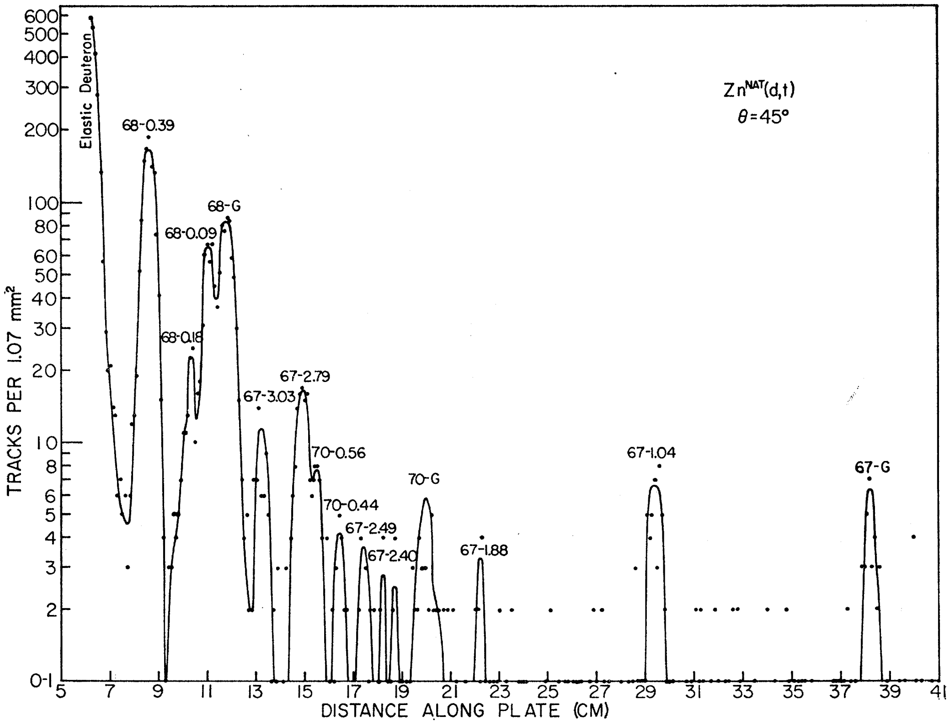

FIG. 2. Typical data for triton spectra from (d,t) reactions. Angle of observation is 45°. Peaks are labeled by the mass number of target isotope responsible and the excitation energies (in MeV) of level in final nucleus.

TABLE I. Summary of results from Zn^{64} (d,p) reactions.

E (MeV) This paper	E (MeV) Ref. 9	l	$\sigma_{\max}$ (mb/sr)	$(2I+1)S$	S.M. state	S
0	0	3	0.67	1.23	$f_{5/2}$	0.21
0.06	0.054	1	4.16	0.69	$p_{1/2}$	0.34
0.12	0.115	1	4.16	0.68	$p_{3/2}$	0.17
0.21	0.209	(3)	0.37	0.67	$f_{5/2}$	0.11
0.86	0.86	1	3.82	0.55	$p_{1/2}(p_{3/2})$	0.28 (0.14)
1.04	1.03	4	1.61	6.30	$g_{9/2}$	0.63
1.35	1.3	2	4.16	1.52	$d_{5/2}$	0.25
	1.38					
1.86	1.9	0	4.19	0.22	$s_{1/2}$	0.11
2.36		1	1.01	0.11	$p_{1/2}(p_{3/2})$	0.056 (0.028)
2.49	2.5	(2)	1.06	0.22	$d_{5/2}$	0.037
2.99		0	1.06	0.089	$s_{1/2}$	0.045
3.32[a]		...	...	...	...	...
3.47		2	1.84	0.32	$d_{5/2}$	0.053
3.55		(0)	3.52	0.17	$s_{1/2}$	0.085
3.65		0	1.66	0.076	$s_{1/2}$	0.038
4.40		0	10.5	0.54	$s_{1/2}$	0.27
4.78		0	15.0	0.83	$s_{1/2}$	0.42
5.16		Isotropic				

[a] Mixed with carbon at some angles.

TABLE II. Summary of results from Zn^{66} (d,p) reactions.

E (MeV) This paper	E (MeV) Ref. 9	l	$\sigma_{\max}$ (mb/sr)	$(2I+1)S$	S.M. state	S
0	0	3	1.15	1.82	$f_{5/2}$	0.30
0.09	0.093	1	4.82	0.67	$p_{3/2}$	0.17
0.18	0.184	(3)	0.23	0.36	$f_{5/2}$	0.06
0.39	0.388	1	6.16	0.81	$p_{3/2}$	0.20
0.60	0.59	4	2.34	0.82	$g_{9/2}$	0.82
0.74		Isotropic				
0.86	0.87	$\{1$	0.42	0.051	$p_{1/2}(p_{3/2})$	(0.03 0.01)
		4	0.45	1.57	$g_{9/2}$	0.16
0.98	0.98	2	6.65	1.53	$d_{5/2}$	0.23
1.14		1	3.25	0.42	$p_{1/2}(p_{3/2})$	0.21 (1.10)
1.44		1	0.73	0.08	$p_{1/2}(p_{3/2})$	0.04 (0.02)
1.49[a]		1	0.62	0.07	$p_{1/2}(p_{3/2})$	0.04 (0.02)
1.69	1.7	0	3.74	0.19	$s_{1/2}$	0.10
1.81[a]		0	1.74	0.086	$s_{1/2}$	0.04
2.28		2	2.28	0.43	$d_{5/2}$	0.07
2.42		0	3.98	0.21	$s_{1/2}$	0.11
2.60		0	0.60	0.029	$s_{1/2}$	0.01
2.67[b]		(0)	0.31	0.02	$s_{1/2}$	0.01
2.81		2	1.73	0.34	$d_{5/2}$	0.06
3.26[b]		...				
3.39[b]		(0)	2.73	0.14	$s_{1/2}$	0.07
3.55		0	12.1	0.62	$s_{1/2}$	0.31
3.85		0	8.36	0.46	$s_{1/2}$	0.23
4.06		0	4.62	0.27	$s_{1/2}$	0.13
4.30		2	7.24	0.76	$d_{5/2}$	0.13

[a] Doubtful level.
[b] Mixed with oxygen at some angles.

literature. These values of I are listed in column (6) and used in conjunction with column (5) to determine the S values listed in column (7).

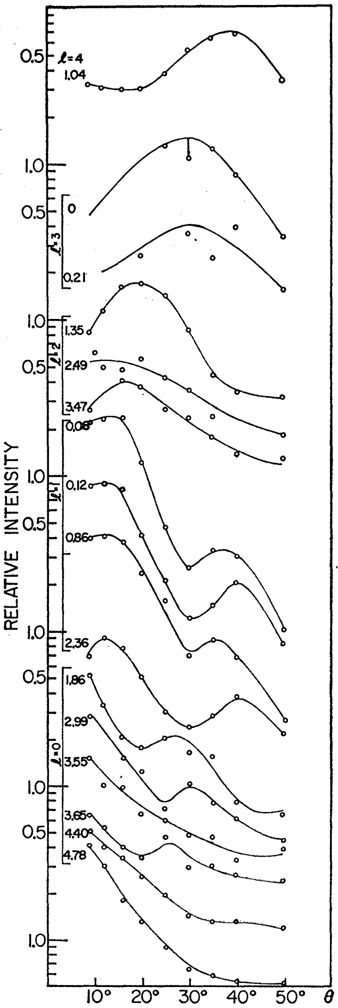

FIG. 3. Angular distributions of various peaks from Zn^{64} (d,p) Zn^{65}. Peaks are not in order of increasing excitation energy. Figures attached to the curves are excitation energy in MeV. Brackets at left enclose the curves assigned to a given l value, the orbital angular momentum of the stripped neutron.

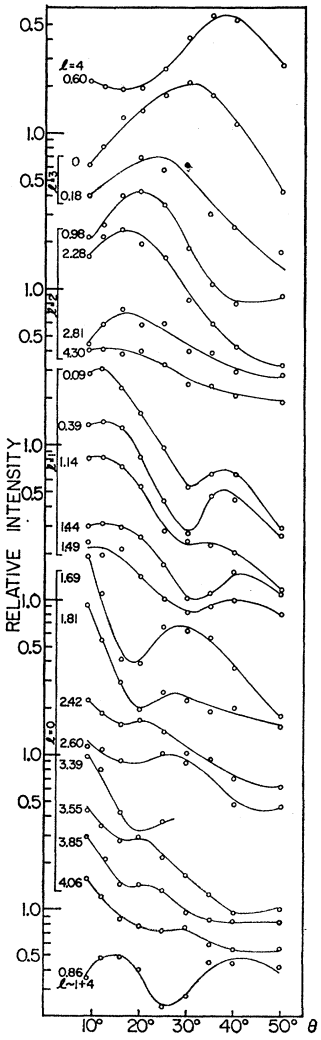

FIG. 4. Angular distributions of various peaks form Zn$^{66}(d,p)$Zn^{67}. See caption for Fig. 3.

For an odd nucleus such as Zn^{67}, we define S' by

$$d\sigma/d\Omega=(2j+1)\sigma_{r}S', \qquad (2)$$

where j is the total angular momentum of the stripped neutron. This quantity is then obtained in Table IV.

The results for the (d,t) reactions are shown in Table V. Cross sections are listed for the two angles at which measurements were made. The spins are those known from other data.

Some individual discussion of the data of Tables I–V follows:

$Zn^{64}(d,p)Zn^{65}$

The four low-lying levels 0, 0.06, 0.12, and 0.21 MeV, known[9,10] from the decay of Ga^{65}, were not well resolved. In our (d,p) data, the 0.06 and 0.12-MeV states are strongly excited and their angular distributions agree very well with $l=1$ expected from their previous assignment as $\frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. The ground- and 0.21-MeV states are weakly excited so that the experimental accuracy is rather poor especially in the small angle region, but beyond 25°, their angular distributions indicate $l=3$.

The 2.49-MeV state has an angular distribution corresponding to $l=2$, but it is probably an unresolved doublet. The angular distribution of the 3.32-MeV state is obliterated at angles 20 and 25° by the carbon contamination so that its spin and parity are not determined. The 4.40- and 4.78-MeV states are assigned as $l=0$, but their angular distributions suggest that unresolved levels with $l=2$ maybe contributing. The 5.16-MeV state appeared at the end of the photographic plate where the background is rather large; its angular distribution is approximately isotropic.

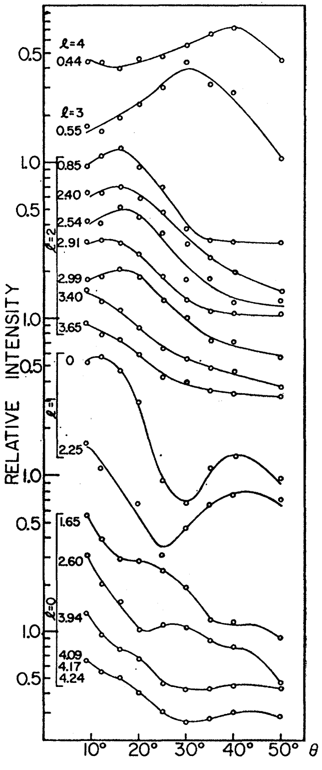

FIG. 5. Angular distributions of various peaks from $Zn^{68}(d,p)Zn^{69}$. See caption for Fig. 3.

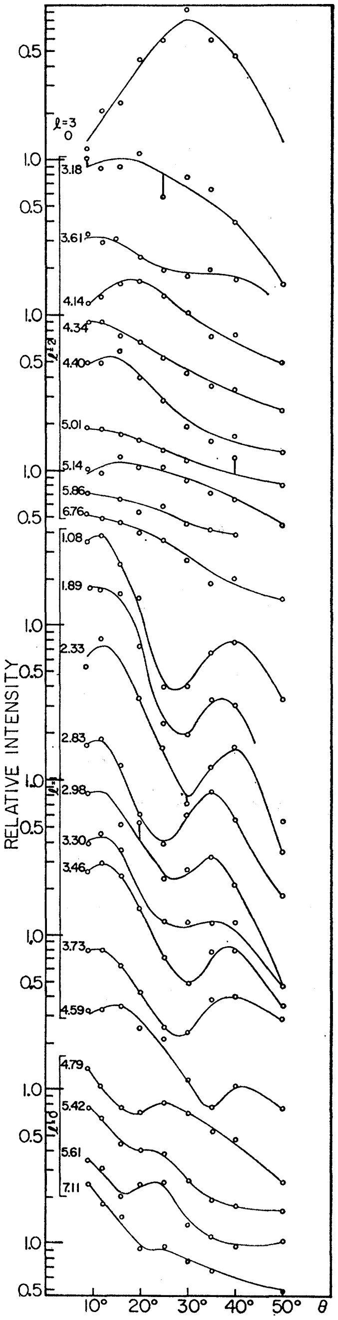

FIG. 6. Angular distribution of various peaks from $Zn^{67}(d,p)$ Zn^{68}. See caption for Fig. 3.

---

[9] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, Council, Washington 25, D. C.), NRC 59-2-23.

[10] E. M. Bernstein and H. W. Lewis, Phys. Rev. **107**, 737 (1957). The data from this paper must be used in conjunction with the fact that the ground state is $5/2^-$, as established here.

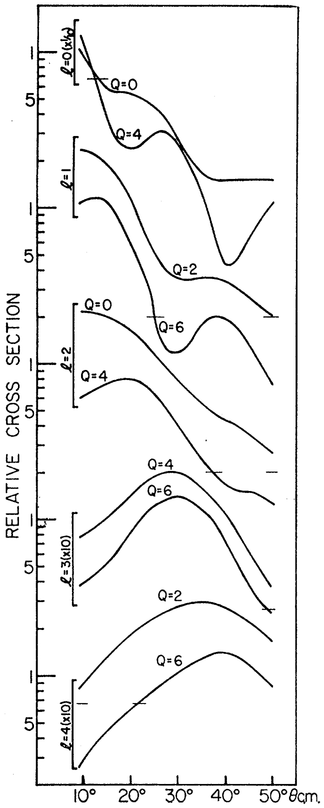

Fig. 7. Some typical theoretical DWBA curves from Ref. 6. Ordinate is σ_T as used in Eq. (1). Ordinate scale is relative; absolute values are indicated by horizontal lines through curves at $\sigma_T = 1.0$ mb/sr.

Table IV. Summary of results from Zn^{67} (d,p) reactions. The two values in the last column for $l=1$ levels are based on the assumptions that the shell-model states are $p_{3/2}$ and $p_{1/2}$, respectively.

E (MeV) This paper	E (MeV) Ref. 9	l	I^π	$\sigma_{\max}$ (mb/sr)	$(2j+1)S'$	S'
0	0	3	0^+	0.14	0.374	0.062
						$p_{3/2}$ $p_{1/2}$
1.08	1.08	1	2^+	0.44	0.092	0.023–0.046
	1.62					
1.89	1.89	1	2^+	0.36	0.063	0.016–0.032
2.33	2.32	1	2^+	0.50	0.083	0.021–0.042
	2.68					
2.83		1	1^+–4^+	0.34	0.026	0.006–0.013
2.98		1	1^+–4^+	0.30	0.025	0.006–0.012
3.18		2	0^-–5^-	0.36	0.105	0.018
3.30		1	1^+–2^+	0.90	0.088	0.022–0.044
3.46	3.47	1	$3^+(4^+)$	2.60	0.330	0.083–0.165
3.61		2	0^-–5^-	1.34	0.358	0.06
3.73	3.8	1	$4^+(3^+)$	2.64	0.302	0.075–0.151
4.14	4.1	2	0^-–5^-	2.50	0.595	0.099
4.34		2	0^-–5^-	0.90	0.208	0.035
4.40		2	0^-–5^-	0.72	0.165	0.028
4.59	4.5	1	3^+	1.96	0.163	0.041–0.082
4.79		0	$2^-, 3^-$	3.06	0.154	0.077
5.01	4.9	2	0^-–5^-	0.36	0.073	0.012
5.14	5.1	2	0^-–5^-	0.45	0.088	0.015
5.42	5.4	0	$2^-, 3^-$	3.02	0.149	0.074
5.61		0	$2^-, 3^-$	1.48	0.070	0.035
5.86		2	0^-–5^-	1.10	0.183	0.030
6.76		2	0^-–5^-	3.60	0.50	0.083
7.11		0	$2^-, 3^-$	8.66	0.48	0.24

$Zn^{66}(d,p)Zn^{67}$

The 0.18-MeV state is weakly excited and partially obscured at some angles by the very strongly excited 0.09-MeV state, so that the errors for the former are rather large; but the experimental points seem to be best fit by the angular distribution for $l=3$. Between two known states at 0.60- and 0.86-MeV, a new state is found at 0.74-MeV. This state is weakly excited but is present at all angles investigated; its angular distribution is isotropic. The 0.86-MeV state has been assigned as $\frac{3}{2}^-$ from gamma-ray angular correlation studies,[11] but in Ref. 4 it was assigned as $\frac{3}{2}^+$. In our data, the angular distribution seems to correspond to a mixture of $l=1$ and $l=4$, but the large errors (the state is very weakly excited) make any assignment doubtful. The 0.60-MeV state is the only certain $g_{9/2}$ state found, it was not resolved in Ref. 4. Levels at 1.49, 1.81, and 2.67 MeV are not quite certain as the peaks corresponding to these states are obscured at some angles. It is possible that the 2.67- and 2.60-MeV states are a single level at 2.62 MeV. The 3.55-MeV state is most prominent and strongly excited to an extent that is very unusual at such a high-excitation energy. It is assigned as $s_{1/2}$ with $S=0.31$.

Table III. Summary of results from Zn^{68} (d,p) reactions.

E (MeV) This paper	E (MeV) Ref. 9	l	$\sigma_{\max}$ (mb/sr)	$(2I+1)S$	S.M. state	S
0	0	1	7.38	0.95	$p_{1/2}$	0.47
0.44	0.434	4	2.56	8.10	$g_{9/2}$	0.81
0.55		3	0.86	1.72	$f_{5/2}$	0.29
0.85	0.8	2	7.40	1.64	$d_{5/2}$	0.27
1.65[a]	1.6	0	7.56	0.36	$s_{1/2}$	0.18
2.25		1	1.14	0.097	$p_{1/2}(p_{3/2})$	0.049 (0.024)
2.40		2	4.00	0.63	$d_{5/2}$	0.11
2.54		2	2.34	0.36	$d_{5/2}$	0.06
2.60		0	1.26	0.21	$s_{1/2}$	0.10
2.91		2	3.28	0.45	$d_{5/2}$	0.07
2.99		2	4.32	0.58	$d_{5/2}$	0.10
3.40[a]		2 (0)	11.0	1.27	$d_{5/2}$	0.21
3.65		2 (0)	7.56	0.84	$d_{5/2}$	0.14
3.94		0 (2)	5.22	0.32	$s_{1/2}$	0.16
4.09		0 (2)	5.96	0.37	$s_{1/2}$	0.19
4.17		0 (2)	4.32	0.28	$s_{1/2}$	0.14
4.24		0 (2)	4.10	0.34	$s_{1/2}$	0.27

[a] Unresolved doublet.

$Zn^{68}(d,p)Zn^{69}$

Seventeen levels were observed in this reaction, of which only the ground state and first excited state were known previously.[9] The 0.85-MeV state assigned here as $d_{5/2}$, was assigned in Ref. 4 as $d_{3/2}$ for reasons which are difficult to understand. The peaks at 1.65 and 3.40 MeV are somewhat broad which indicates that they may be unresolved doublets.

$Zn^{67}(d,p)Zn^{68}$

In this reaction, the resolution was sufficient to study 23 levels up to 7.11-MeV excitation energy. The

---

[11] L. H. Th. Rietjens and H. J. Van Den Bold, Physica **21**, 701 (1955).

TABLE V. Summary of results from natural Zn (d,t) reactions.

E (MeV)				
This paper	Ref. 9	I^π	$\sigma(45°)$ mb/sr	$\sigma(60°)$ mb/sr
		$Zn^{67}(d,t)Zn^{66}$		
0	0	0^+	0.126	0.047
1.04	1.04	2^+	0.016	0.059
1.88	1.87	2^+	0.016	$\sim$0.008
2.30			$\sim$0.007	$\sim$0.007
2.40	2.37		$\sim$0.008	$\sim$0.008
2.49			0.038	0.019
2.79	2.76		0.343	0.273
3.03			0.171	0.153
		$Zn^{68}(d,t)Zn^{67}$		
0	0	$5/2^-$	0.390	0.220
0.09	0.093	$3/2^-$	0.298	0.170
0.18	0.184	$5/2^-$	0.105	0.075
0.39	0.388	$3/2^-$	0.790	0.710
		$Zn^{70}(d,t)Zn^{69}$		
0	0	$1/2^-$	0.66	0.272
0.44	0.434	$9/2^+$	0.232	0.132
0.56(?)		$5/2^-$	0.82	0.392

l-value of the 1.89- and 3.46-MeV states which were uncertain in Ref. 4 are found to be both $l=1$. The first three excited states are known[9] to be 2^+. The one phonon vibrational state at 1.08 MeV is strongly excited in (α,α')[12] and (p,p')[13] reactions but in the present (d,p) reaction, it is excited with about same low intensity as other 2^+ state at 1.89 and 2.33 MeV. The peak corresponding to the 2.33-MeV 2^+ state is somewhat broad, and might be interpreted as a 2.29—2.37-MeV doublet which might be part of the two phonon group.

In general, the I values listed in Table IV represent the various couplings between the target spin $(\frac{5}{2}^-)$ and the angular momentum of the stripped neutrons as inferred from the l value and shell model. For the lowest four states spin assignments are known from other work, and in a few cases, they are restricted by the sum rules as will be discussed below.

Zn(*d,t*) Reactions

The isotopic abundance of natural Zn is 49.9% Zn^{64}, 27.8% Zn^{66}, 4.1% Zn^{67}, 18.6% Zn^{68}, and 0.62% Zn^{70}, but the large negative Q values preclude the observation of levels from Zn^{64} and Zn^{66}. Levels from Zn^{68} and Zn^{70} are identified from their known energies, and all other levels are assumed to be from Zn^{67}. The level assigned as the 3.03-MeV state of Zn^{66} was at the energy expected for the 0.85-MeV level from Zn^{70} (d,t). However, if it were assigned as the latter, the cross section would be much too large to be from a pick-up of a $d_{5/2}$ neutron, especially since that state is presumably empty in Zn^{70}. The levels assigned as the 0.44- and 0.56-MeV states from Zn^{70} (d,t) could be from Zn^{67}. A measurement with the enriched Zn^{67} target showed that the first of these is not from Zn^{67} (d,t). The resolution was insufficient to make a clear decision on the 0.56-MeV level, so its assignment is uncertain.

DISCUSSION

The sum of S's for all levels belonging to a given shell-model state is a measure of the emptiness, U_j^2, of that shell-model state in the target nucleus. The same is true for the S' in odd targets, which is the reason why that quantity was defined. The results for U_j^2 obtained in this way are listed in Table VI. In two cases, comparisons are made with the results for nickel isotopes of the same neutron number.

The entry in Table VI for the $f_{5/2}$ states excited in Zn^{67} (d,p) was obtained by estimating the maximum $l=3$ admixtures in the $l=1$ angular distributions. Since U_j^2 for the $d_{5/2}$ states should be essentially unity, it is

TABLE VI. Summary of results for $\Sigma S(U_j^2)$ and E_j, and comparison with results for isotonic nuclei[a] and pairing theory.[b]

(a) $Zn^{64}(d,p)Zn^{65}$

	ΣS			E_j(MeV)		
State	Zn^{64}	Ni^{62}	Theory	Zn^{64}	Ni^{62}	Theory
$f_{5/2}$	0.32	$\sim$0.46	0.58	0.07	0.1	0
$p_{3/2}$	0.17–0.34	0.34	0.27	0.12–0.61	0.3	0.12
$p_{1/2}$	0.34–0.68	0.75	0.82	0.06–0.58	0.6	0.33
$g_{9/2}$	0.63	0.88	0.98	1.04	1.7	2.92
$d_{5/2}$	0.34	1.19	1.0	$>$1.80	4.1	
$s_{1/2}$	0.97	$\sim$0.6	1.0	4.14	4.4	

(b) $Zn^{66}(d,p)Zn^{67}$

	ΣS			E_j(MeV)		
State	Zn^{66}	Ni^{64}	Theory	Zn^{66}	Ni^{64}	Theory
$f_{5/2}$	0.36	0.25	0.37	0.03	0	0
$p_{3/2}$	0.37–0.52	0.35	0.15	0.25–0.53	0.1	0.39
$p_{1/2}$	$\leqslant$0.32	0.44	0.69	$\sim$1.15	1.0	0.05
$g_{9/2}$	$\leqslant$0.98	0.83	0.97	0.64	1.0	2.43
$d_{5/2}$	0.52	1.15	1.0	$>$2.14	3.7	
$s_{1/2}$	1.01	$\sim$0.4	1.0	3.28	4.1	

(c) $Zn^{68}(d,p)Zn^{69}$

	ΣS		E_j(MeV)	
State	Zn^{68}	Theory	Zn^{68}	Theory
$f_{5/2}$	0.29	0.19	0.55	0.31
$p_{3/2}$	$<$0.03	0.07	$\sim$2.25	0.92
$p_{1/2}$	$\leqslant$0.52	0.46	$\leqslant$0.21	0
$g_{9/2}$	0.81	0.97	0.44	2.05
$d_{5/2}$	0.96	1.0	$>$2.48	
$s_{1/2}$	0.94	1.0	3.48	

(d) $Zn^{67}(d,p)Zn^{68}$

	$\Sigma S'$	
State	Zn^{67}	Theory
$f_{5/2}$	$\leqslant$0.36	0.26
$p_{3/2}$	$\leqslant$0.29	0.11
$p_{1/2}$	$\leqslant$0.58	0.58
$g_{9/2}$	...	0.97
$d_{5/2}$	0.38	1.0
$s_{1/2}$	0.43	1.0

[a] See Ref. 2.
[b] See Ref. 15.

---

[12] D. K. McDaniel, J. S. Blair, S. W. Chen, and G. W. Farwell, Nucl. Phys. 17, 614 (1960).

[13] B. L. Cohen and A. G. Rubin, Phys. Rev. 111, 1968 (1958).

clear that many $d_{5/2}$ levels were missed in the analysis of all data except that for Zn^{68}. As mentioned previously, they are probably not resolved from neighboring $s_{1/2}$ states which dominate the angular distribution. In Zn^{67}, many $s_{1/2}$ states are also apparently missed.

The data for the p states are somewhat ambiguous because of the uncertainty in I assignments; the agreement with theory is best if all $l=1$ states of unknown spin are assigned $I=\frac{1}{2}$. Even then, the ΣS for the $p_{1/2}$ states is unexpectedly small. This may be because some of these levels are missed.

In general, Table VI gives a qualitatively understandable picture, but with many quantitative difficulties. Many of these are believed to be due to incompleteness of the data resulting from insufficient energy resolution. The comparison with the nickel data, which were taken with better energy resolution, reinforces these conclusions.

A comparison with pairing theory predictions for both U_j^2 and the excitation energy of the center of gravity of levels for a given shell-model state, E_j, is also shown in Table VI.[14] The pairing theory parameters were those used for the Ni isotopes of the same neutron number by Kisslinger and Sorensen.[15]

The difficulties with the U_j^2 discussed above are again seen in this comparison. The energies E_j agree somewhat better, but it is notable that the $g_{9/2}$ levels are lower in energy then predicted. This was also observed[1,2] to be the case in the Ni isotopes, so that it is undoubtedly due to an overly large single particle energy assumed in the calculations; in fact, it is difficult to understand the basis on which the large single particle energy for $g_{9/2}$ in Ref. 15 was chosen.

For (d,p) reactions on the odd nucleus Zn^{67}, the contributions to the sum of the S' from the various spin states I_f of the final nucleus should be proportional to $2I_f+1$. For example, for $p_{3/2}$ states, the final spin states 1^+, 2^+, 3^+, and 4^+ should be populated in the ratio 3, 5, 7, and 9, respectively This may be used in some cases to determine spin assignments. For example, if $(2j+1)S'$ for $p_{3/2}$ and $p_{1/2}$ are assumed equal—a conservative assumption for our calculation according to Table VI—the relative values of $(2j+1)S'$ for states of spin 1^+, 2^+, 3^+, and 4^+ should be 3, 10, 14, and 9, respectively. Normalizing these to the sum of $(2j+1)S'$ for the $l=1$ states in Table IV gives $\Sigma(2j+1)S'$ for the various spin states to be 0.10, 0.33, 0.46, and 0.29, respectively. Known 2^+ states in Table IV consume $\Sigma(2j+1)S'=0.24$, so that no state can be 2^+ for which $(2j+1)S'$ is greater than 0.09. Thus, the 3.46-MeV state is very probably 3^+ or possibly 4^+. If it is 3^+ or 4^+, the 3.73-MeV state must be 4^+ or 3^+, respectively. In either case, the 4.59-MeV state must be 3^+. Since this essentially exhausts the sum for 3^+ and 4^+, the 3.30-MeV level must be 1^+ or 2^+.

It is interesting to note from the Zn^{67} (d,p) data that the first excited (2^+) state of Zn^{68} includes more $(f_{5/2}p_{1/2})$ than $(f_{5/2})^2$ in its configuration. If the ground state were the only important $f_{5/2}$ state in Zn^{67} (as is indicated in Table II), pairing theory gives

$$d\sigma/d\Omega=(1-U_j^2)\sigma_T,$$

whence from (2) and Table IV, $U_{5/2}^2=0.63$ in Zn^{68}. If the excited $f_{5/2}$ state in Zn^{67} at 0.18 MeV is taken into account crudely from Table V, this is reduced to 0.50. This is still in rather poor agreement with the direct determination listed in Table VI, 0.29, which seems more reasonable. This might be explained as due to inaccuracy in the Q-value dependence of the DWBA calculations, or as missed $f_{5/2}$ states in Zn^{67} (d,p).

The (d,t) reactions give rather cruder information than the (d,p) since they are less completely analyzed. The relatively large cross sections for the $g_{9/2}$ and $f_{5/2}$ states relative to the $p_{1/2}$ state in Zn^{70} (d,t) indicates that the 39th and 40th neutrons are predominantly $(g_{9/2})^2$ rather than $(p_{1/2})^2$. The rather strong excitation of the first excited (2^+) state in Zn^{67} (d,t) is somewhat unusual for a collective level.

It is clear that this study of the occupation of the various shell-model states in the zinc isotopes falls far short of giving consistent quantitative results. To do this even to the accuracy that it has been done by our group in nickel, zirconium, and tin would require very much improved energy resolutions, and a more extensive study of the (d,t) reactions.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to G. R. Satchler for providing the DWBA calculations, to R. H. Fulmer and A. L. McCarthy for their providing help and discussion.

---

[14] Pairing theory does not take neutron-proton residual interactions into account, and is therefore usually applied only to single closed shell nuclei. However, it is the only theory readily available, and should be at least crudely applicable here.

[15] L. S. Kisslinger and R. A. Sorensen, 32, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 32, No. 9 (1960).