Spectroscopy of ^{68}Ga with ^{69}Ga(d, t) and ^{70}Ge(d,α)†

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^{68}Ga has been studied with the ^{69}Ga(d,t) and ^{70}Ge(d,α) reactions at 17.0 and 14.5 MeV, respectively. Magnetic spectrograph analysis yielded resolutions of 7–10 keV. 20 of 45 states resolved below 2.2 MeV excitation were previously unknown. ^{69}Ga(d,t)^{68}Ga angular distributions were taken in 4°–5° steps from 8° to 60°. l_n transfers, spectroscopic factors, and J^π limits for levels below 1.4 MeV were deduced from comparison with zero range distorted-wave Born approximation calculations. J^π values and dominant configurations for some low-lying states could be assigned.

[NUCLEAR REACTIONS ^{69}Ga(d,t), E_d = 17 MeV, measured $\sigma(E_t, \theta)$. ^{70}Ge(d,α), E_d = 14.5 MeV, measured $\sigma(E_\alpha)$. Resolution 7–10 keV. DWBA analysis, deduced l, π, J, spectroscopic factors.]

I. INTRODUCTION

$^{68}_{31}$Ga has not previously been studied by direct, single-nucleon transfer reactions.[1] Consequently, essential spectroscopic information for all but the lowest seven states is tentative or absent. Definite parity assignments exist for only three levels. This is unusual for a nucleus so easily reached, and may be the result of the anticipated spectral complexity for a nucleus with 12 active nucleons.

We have investigated the reactions ^{69}Ga(d,t)^{68}Ga and ^{70}Ge(d,α)^{68}Ga as a part of a survey of inadequately explored regions in the f-p shell. The (d,α) reaction was used primarily in order to find low-lying T = 3 states, and to help identify states of a (core + two-hole) character. The (d,t) reaction provided unambiguous parity assignments, many l_n-transfer assignments, spectroscopic strengths and relatively close J^π limits for 23 levels up to 1.4 MeV. These results have been compared with existing γ-decay studies and ^{68}Zn(p,n)^{68}Ga measurements.[1-4]

II. EXPERIMENT

The experiments were conducted with emphasis on high resolution and level energy accuracy. Very thin (~ 20 μg/cm^2) targets of ^{70}Ge and ^{69}Ga on 10 to 20 μg/cm^2 C backings were used. Both isotopes were enriched to ≳98%, and spectra were taken with the Pittsburgh split-pole spectrograph. The ^{70}Ge(d,α)^{68}Ga reaction was measured at E_d = 14.5 MeV. Reaction products were detected with Ilford K-1 photographic emulsions of 50 μm thickness at θ_{lab} = 20°, 35°, and 50°. A semilog spectrum for θ_{lab} = 35° is shown in Fig. 1(a). Typical (d,α) resolutions were 8–10 keV. About 20 previously unknown states were resolved below E^* = 2.2 MeV. The ^{70}Ge(d,α) spectra were calibrated against the better known ^{70}Ga spectra, which were obtained under identical experimental conditions (E_d, B = const) from the ^{72}Ge(d,α) reaction and detected on the same photographic plate. We used a computerized calibration program[5] to correct for kinematics, target thickness, etc., for a fine calibration of the spectrograph, and thus obtained new measurements of known and unknown ^{68}Ga levels with an accuracy very close to that of the calibration spectrum. This method is most useful (and accurate to about ± 1 keV) if the known spectrum can be reached with the same reaction on a target of very similar mass and reaction Q value [here ^{72}Ge(d,α)^{70}Ga], as the focal plane and magnetic field settings should remain untouched. Uncertainties in the level energies obtained from ^{70}Ge(d,α)^{68}Ga are shown in Table I and ranged from ± 3 to ± 5 keV. They are primarily due to limited statistics in the three calibration runs and conservative error estimates for the peak centroids in instances of marginally resolved multiplets. There is good agreement for all well established levels with Ref. 1.

Comparison of the ^{72,70}Ge(d,α)^{70,68}Ga ground state Q values was satisfactory. Based on Q_0[^{72}Ge(d,α)] = 7036.6 ± 3.2 keV,[6] we measured ^{68}Ga Q_0 values that averaged to Q_0[^{70}Ge(d,α)] = 7218 ± 20 keV, which is to be compared with the expected value[6] of 7237 ± 5 keV. The difference of 19 keV is within the error bars, primarily because maximum allowances for spectrograph nonlinearity near ρ_{max} and errors in θ were made.

Measurements for levels excited in ^{69}Ga(d,t)^{68}Ga were made at E_d = 17.0 MeV. The spectrograph field settings used put the ^{68}Ga ground state peak further below ρ_{max} [ρ_{max} corresponds to a distance of 50 cm in Figs. 1(a) and 1(b)]. Better statistics, resolution, and the absence of nonlinearity effects

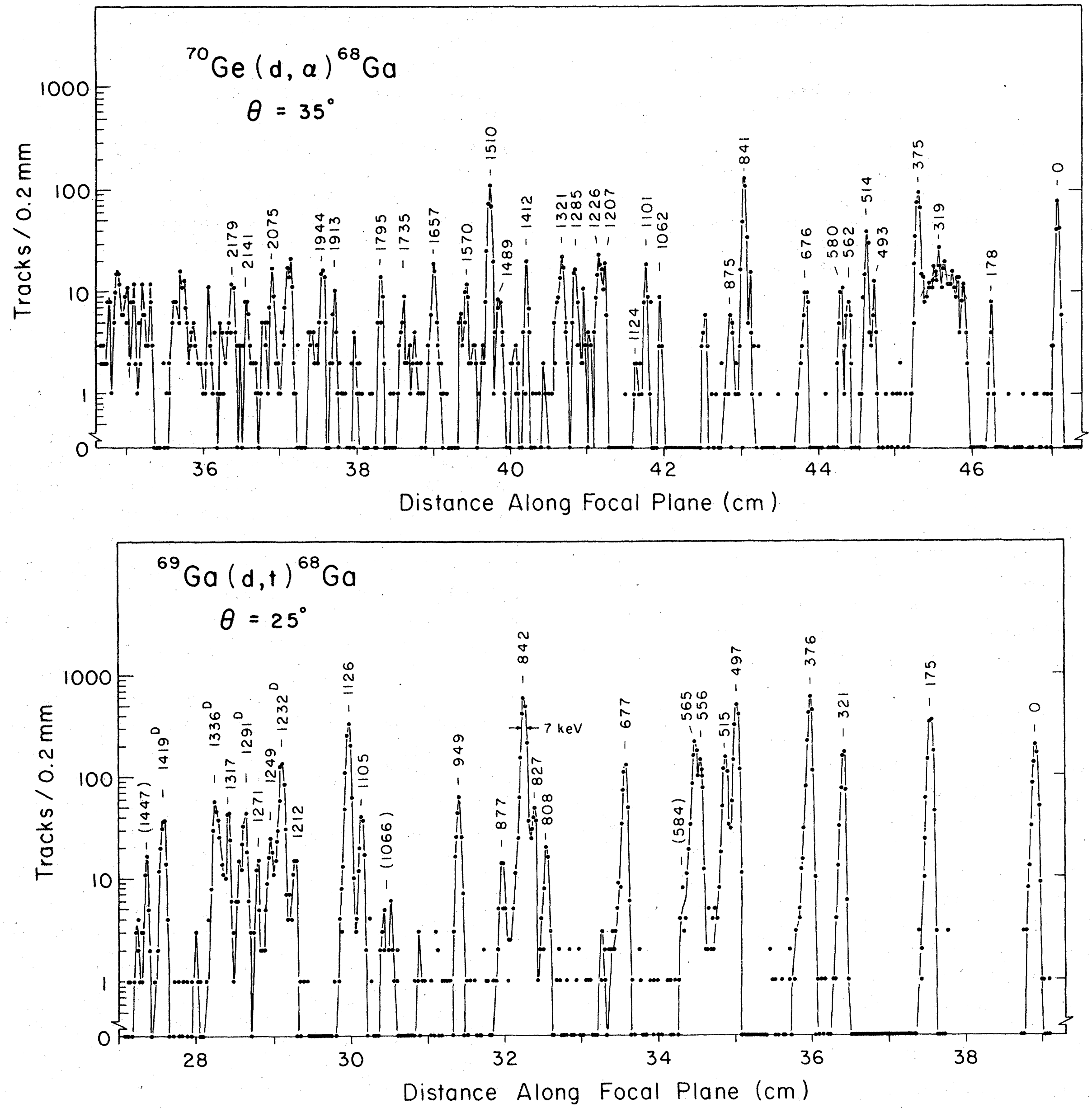

FIG. 1. (a) Semilog spectrum of ^{70}Ge(d,α)^{68}Ga for $E_d = 14.5$ MeV and $\theta_{lab} = 35°$. Full width at half maximum (fwhm) resolution in this spectrum was approximately 8 keV. Unless explainable by statistics, peaks with more than three points fwhm are interpreted as doublets. Peaks are identified by their measured (d,α) excitation energy in keV. The broad group under the 319 keV peak is a defocused light impurity peak. (b) Semilog plot of ^{69}Ga(d,t)^{68}Ga transitions for $E_d = 17$ MeV and $\theta_{lab} = 25°$, to the same final states as shown in (a). Resolution is 7 keV. Level energies are shown in keV as measured in the (d,t) reaction. Note the greatly differing enhancement of some states in the two pickup reactions (e.g., the first excited state 175 (178) keV, the fourth excited state at 497 (493) keV, the 1126 (1124) keV levels, etc.) All excitation energy values shown constitute the average of measurements for at least three angles.

permitted us to assign smaller uncertainties in E^* (typically ± 1–3 keV; see Table I). ^{69}Ga(d,t) resolution was ~7 keV. Although the individual E^* values from Ga(d,t) also show good agreement (within combined errors) with the E^* values adopted in the Nuclear Data Sheets,[1] our new data tend to come out systematically (1–3 keV) lower for levels above 500 keV.

Most of the ^{69}Ga(d,t)^{68}Ga data were taken with our position-sensitive gas proportional counter which is of the helical cathode type ("helix counter").[7] In addition to a position signal this coun-

TABLE I. Summary of experimental results and comparison with the compilation of Ref. 1. The three sets of excitation energies (shown with their comparable errors ϵ) were obtained in experiments that have different selection rules and may populate different levels. Only measured energies that seem to belong to the same level have been placed in the same row. Assumptions made in the derivation of the spectroscopic factors are discussed in the text. "σ_{av}" in the (d,α) column denotes the relative strength of the levels if the 20°, 35°, and 50° spectra are summed. σ_{max} (d,t) is the experimental cross section at the major stripping peak. Values in brackets are tentative, or less likely assignments. Known and partially resolved doublets are identified by the superscript D.

Ref. 1		^{70}Ge$(d,\alpha)^{68}$Ga			^{69}Ga$(d,t)^{68}$Ga						Assignments	
											J^π	J^π_{new}
E^* (keV)	ϵ (keV)	E^* (keV)	ϵ (keV)	σ_{av} (cts)	E^* (keV)	ϵ (keV)	σ_{max} (μb/sr)	l_n	C^2S $l=1$	C^2S $l=3$	Ref. 1	This work
0		0		609	0		820	1+3	0.09	0.44	1^+	1^+
174.9	0.2	178	3	40	175	1	890	1+3	0.11	0.96	$(2)^+$	2^+
324	2	319	3	66	321	1	1450	1	0.21		(1^+)	1^+2^+
375.6^D	1	375	3	581	375.5	1	2100	1+3	0.30	1.39	$(3)^+$	3^+
496	4	493	3	87	497	1	780	3		2.18	(4)	4^+
517	3	514	3	562	515	1.5	1120	1	0.18		$(1)^+$	$1^+2^+3^+$
556	5	} 562		32 {	556	2	1070	1+(3)	0.18	(0.2)		$1^+2^+3^+$
568	4				565	2	1980	1	0.33			$1^+2^+3^+$
584	3	580	3	58	•••		Weak				(2)	
678	3	676	3	61	677	2	320	1+3	0.05	0.42		$3^+2^+(1^+)$
806	4	(806)	5	(8)	808	3	32	(3)		0.12		$(3^+4^+5^+)$
828	5	826	5	45	827	2	430	1	0.09			$1^+2^+3^+$
844	4	841	3	681	842	2	4700	1	0.92			$3^+2^+(1^+)$
877^D		875	4	39	877	3	25	(4)				(3^-4^-)
952	3	•••		(6)	949	3	455	1	0.10			$0^+(1^+2^+3^+)$
1066	3	1062	3	44	•••		Weak					
1103^D	4	1101	3	87	1105	3	130	1+3	0.03	0.19		$2^+3^+(1^+)$
1128	3	1124	4	17	1126	2	2300	1	0.56			$2^+3^+(1^+0^+)$
		1207	4	103	1212	3	90	1	(0.03)			$1^+2^+3^+$
1223	5	1226^D	3	303								
1229	5				1232^D	3	1150	1	0.29			0^+–3^+
1247	5	(1246)	5	20	1249	3	50	(3)		(0.21)		
		1265	4	138								
1275	3				1271	4	77	1	0.02			0^+–3^+
		1285	3	201 }								
1297^D	3				1291^D	3	215 {	1	0.05			0^+–3^+
								3		0.21		1^+–5^+
1322	4	1321^D	4	117	1317	3	235	1	0.07			0^+–3^+
1340	4	(1344)	5	29	1336^D	3	335	1+3	0.08	0.17		0^+–3^+
		1412	3	182	1419^D	4	340	1	0.11			0^+–3^+
1425	4											
1461	4											
1495	4	(1489)	4	68								
(1507)		1510	3	503								
1523	4											
1551	5	(1548)	4	38								
1563	4											
		1570	3	160								
1590^D	4	(1591)	5	25								
1617	4											
		(1646)	5	40								
		1657	4	101								
		(1706)	5	33								
		(1721)	5	35								
		1735	5	56								
		1795^D	5	95								

TABLE I. (*Continued*)

Ref. 1		^{70}Ge(d,α)^{68}Ga			^{69}Ga(d,t)^{68}Ga						Assignments J^π	J^π_{new}
E^* (keV)	ϵ (keV)	E^* (keV)	ϵ (keV)	σ_{av} (cts)	E^* (keV)	ϵ (keV)	σ_{max} (μb/sr)	l_n	C^2S $l=1$	C^2S $l=3$	Ref. 1	This work
(1855)												
		1913	4	51								
		1944^D	5	126								
		(1972)	5	51								
		2028	4	86								
		2039	5	61								
		2075	4	132								
(2102)												
		2141	5	93								
		2179	5	80								

ter provides a ΔE proportional counter signal and a fast E signal from a plastic scintillator located inside the helix, immediately behind the ΔE section. The triple coincidence requirement resulted in background suppression equal to or better than that shown in Fig. 1(b), and resolution in the helix spectra was 7–9 keV. However, peaks near either end of the counter tended to be less symmetric than those of Fig. 1(b), which was undesirable for precise excitation energy measurements. [These changes in peak shape would not be visible in the *linear* plots of spectra frequently shown; however, we prefer to show semilog plots (see Fig. 1) which give a better indication of possible doublets and low-level impurity peaks.]

For angular distribution runs NaI scintillation monitors were used at $\theta=\pm 38°$, in addition to the conventional charge monitor. Random normalization errors typically were below 5% and are included in the error bars of Fig. 2. The estimated absolute scale error (not shown) is ±15% and mainly results from the uncertainty in the target thickness, which was deduced from elastic deuteron scattering at small angles and comparison with optical model predictions. The larger error bars in Fig. 2 are generally due to difficulties in resolving nearby levels or impurity peaks.

III. DISTORTED-WAVE BORN APPROXIMATION (DWBA) ANALYSIS

Calculations for ^{69}Ga(d,t)^{68}Ga* were made with DWUCK III,[8] a zero-range DWBA computer code. Sensitivity of the calculations to optical model parameter variations was tested with a number of "acceptable" sets of deuteron[9,10] and triton[11,12] parameters. It was found that the predicted angular distribution *shapes* were insensitive to the particular sets of parameters used, but the predicted absolute values differed by as much as ±30% from the values obtained with the parameters shown in Table II. The parameters chosen (Table II) were those that came closest to current folding model expectations for deuteron optical model parameters.[13]

Spectroscopic factors were obtained from the relation[8]

$$\sigma_{exp} = 3.33 C^2 S \frac{\sigma_{DWUCK}}{2j+1}$$

for all cases where j (transfer) was fairly clear. For $l=1$ cases the average of $j=l\pm\frac{1}{2}$ calculations was taken. This means that C^2S_l would have to be increased by 5% for $p_{1/2}$ transitions, and decreased by this amount for $p_{3/2}$ transitions. $l=4$ transitions were taken as $g_{9/2}$, and $l=3$ transitions as $f_{5/2}$, although some of the higher lying $l=3$ transitions may be $f_{7/2}$. For such $f_{7/2}$ cases C^2S_l would have to be multiplied by 0.67.

IV. DISCUSSION: SPECTROSCOPIC FACTORS AND J^π ASSIGNMENTS

As seen in Fig. 2, zero-range DWBA gives a good account of the ^{69}Ga(d,t)^{68}Ga angular distributions observed at $E_d = 17$ MeV. However, a closer comparison of DWBA (solid) and empirical (dotted) curves as shown for the 497 (4^+) and 515 (1^+) levels indicates a systematic forward shift of experimental maxima by 2° for $l=3$ and by approximately 1° for $l=1$. The $l=3$ shift had been noted earlier for $f_{5/2}$ transitions[14,15] as a j-dependent effect not reproduced by DWBA. The 1° shift of the $l=1$ stripping maxima is less significant, but larger than can be accounted for by experimental uncertainties in θ ($\Delta\theta \approx 0.5°$). This is noted here as an explanation for the use of empirical (rather than DWBA) curves in Fig. 2 and for the decomposition of transitions which show mixed l transfers. l mixing is expected since the ^{69}Ga target spin is $\frac{3}{2}^-$. Unless labeled otherwise, solid curves in Fig. 2 represent sums of *empirical* $l = 1 + 3$ curves.

The l values and spectroscopic factors extracted from fitting $l = 1$ and $l = 3$ curves to the data and from comparison with DWBA predictions are listed in Table I. A graphic presentation of the distribution of $l = 1$ and $l = 3$ spectroscopic factors is given in Fig. 3. Practically all of the expected $f_{5/2}$ strength $(\sum_i S^i_{f_{5/2}} \approx 6)$ is observed below 1 MeV and found to be concentrated in four low-lying levels in the ratios expected for a configuration

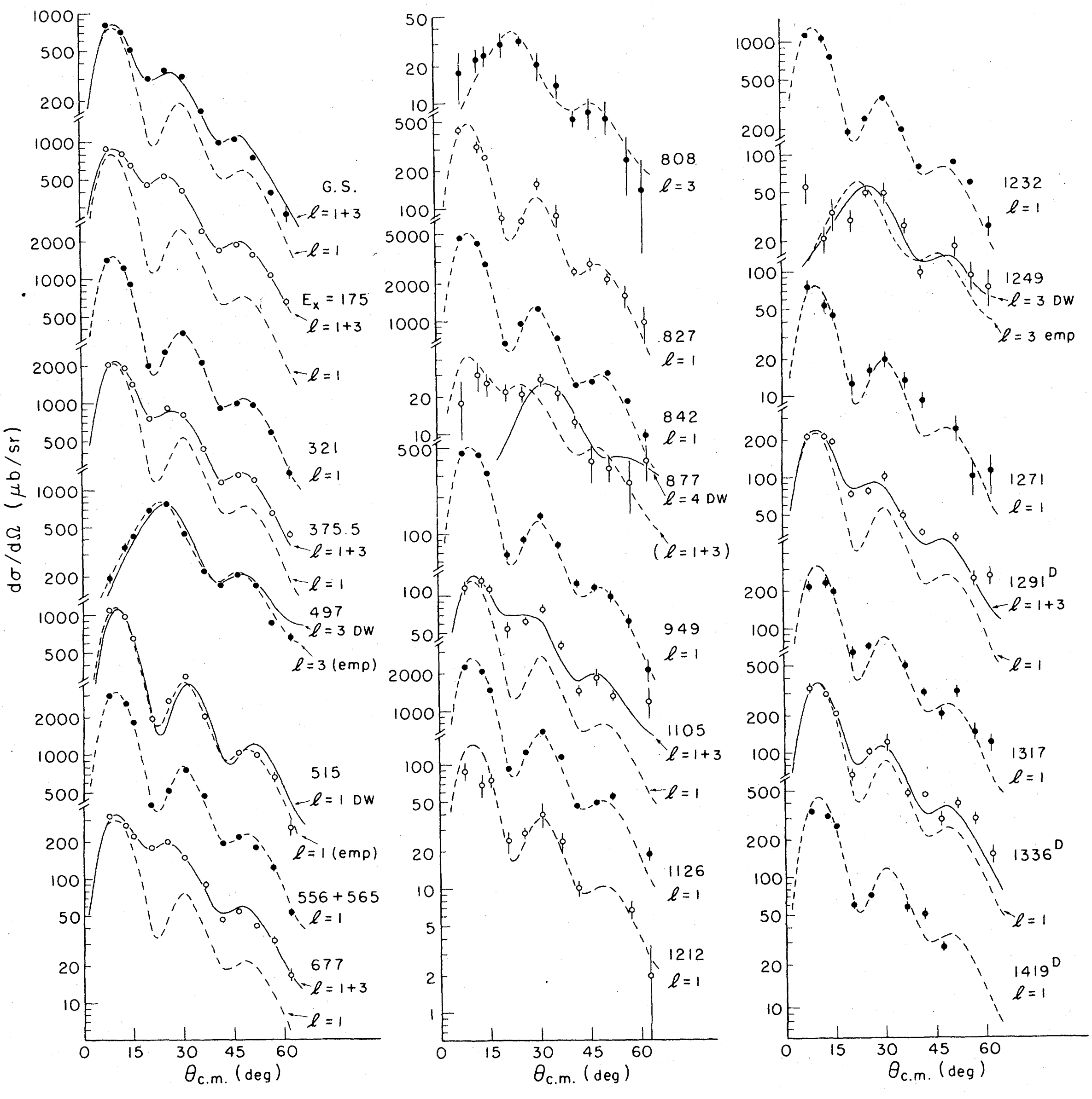

FIG. 2. Angular distributions for ^{69}Ga$(d,t)^{68}$Ga obtained at $E_d = 17$ MeV are ordered by final state excitation energy. Level energies are given in keV [as measured in the (d,t) reaction]. Error bars contain all known and estimated random errors. Dashed curves represent empirical shapes for pure $l = 1$ and $l = 3$ transfers. Solid lines—as labeled—show typical zero-range DWBA curves or sums of empirical curves. Although the $\frac{3}{2}^-$ ground state spin of ^{69}Ga permits l mixing for most levels the dominant l transfers are easily recognized. Where l mixtures are decomposed into their constituents empirical curves were used as DWBA did not reproduce the data with sufficient accuracy (compare curves for the strong 497 and 515 keV states).

TABLE II. Optical model parameters used in the ^{69}Ga$(d,t)^{68}$Ga zero-range DWBA calculations. Energies are given in MeV, lengths in fm. Nonlocality parameters used were 0.54 for deuterons and 0.3 for tritons.

Channel	V	r_0	a_0	W	$4W_D$	r_I	a_I	r_c	V_{so}	R_{so}	a_{so}
17 MeV d, Ref. 10	92.7	1.15	0.78	0	55.11	1.33	0.79	1.3	5.5	1.1	0.55
15 MeV t, Ref. 12	158.8	1.20	0.65	17.6	0	1.60	0.62	1.3	6.0	1.15	0.72
Bound neutron	a	1.20	0.75						$\lambda = 25$		

[a] Adjusted by DWUCK to give correct neutron separation energy.

$$|0^+ \text{core}, \pi p_{3/2} \nu f_{5/2}\rangle_{J^\pi}$$

of the odd-odd residual nucleus. The simple behavior of the $1f_{5/2}$ strengths allows us to confirm previous tentative J^π assignments[1] for the 175 (2^+), 375.5 (3^+), and 497 (4^+) levels, and suggest $|\pi p_{3/2}\nu f_{5/2}\rangle$ as the dominant configuration for the ground state, 175, 375, and 497 keV levels.

The wide fragmentation of the $l=1$ strengths suggests complicated configurations for most of the ^{68}Ga levels; however, close J^π limits can usually be given from (d,t) selection rules and spectroscopic sum rules. Since we observe no breakdown in the direct transfer mechanism we use the following strong selection rules for all significantly populated levels: For the parity of ^{68}Ga levels we have $\pi = -(-1)^{l_n}$. Spin limits for observed $l=1$ transfer are $0^+ \le J^\pi \le 3^+$, and for $l=3$, $1^+ \le J^\pi \le 5^+$; hence for simultaneous $l=1$ and $l=3$ contributions we are restricted to $J^\pi = 1^+, 2^+, 3^+$. Significant excitation of a level in ^{70}Ge$(d,\alpha)^{68}$Ga implies $\Delta T = 0$; hence $J^\pi = 0^+$ is ruled out. Further J^π restrictions are often possible by considering known γ transitions.[1] These rules have been used to obtain the values in the J^π_{new} column of Table I. In some cases, for instance for the 842 keV level, the large C^2S factors can be used to rule out some of the lower spin values still permitted by the strong selection rules. We find no disagreements with the existing (tentative) assignments adopted in the Nuclear Data Sheets. All but one are confirmed or supported by this study. [No (d,t) transfer is seen to the 584 keV ($J=2$) state).] A total of 20 new $T=3$ levels in ^{68}Ga are reported below $E^* = 2.2$ MeV.

States excited in ^{69}Ga(d,t) should also be seen in ^{70}Ge(d,α) unless the two-nucleon transfer would have to proceed by $[j^2]_{J=\text{even}}$ terms (which usually means $J^\pi = 0^+$). The combination of a strong (d,t) spectroscopic factor with a weak (d,α) cross section favors $J^\pi = (\text{even})^+$ assignments for the residual ^{68}Ga state. This is borne out quite well for the lowest 2^+ (175 keV) and 4^+ (497 keV) states. The absence of any excitation in (d,α) of the 949 keV state favors a $[p_{3/2}{}^2]_{0^+}$ assignment for this level [the weak peak seen just below 949 keV in Fig. 1(a) shifts with angle and is not consistent with $E^* = 949 \pm 3$ keV]. Candidates for pure proton-hole states [i.e., states seen strongly in (d,α), but not in (d,t)] do not show up below 1 MeV. The data of Table I suggest that E^* values from (d,α) may be systematically 0.2% lower than E^* values from (d,t). Such a trend would be consistent with the accuracy claimed for this study; however, above 1200 keV too many poorly resolved multiplets appear in both spectra to correlate (d,t) and (d,α) peaks with confidence. It will probably take detailed particle-γ coincidence studies to fully unravel the ^{68}Ga level scheme above 1.2 MeV. The most closely related study on ^{68}Ga appears to be the ^{68}Zn$(p,n)^{68}$Ga experiment by Bass and Stelson.[3] With a few minor exceptions (e.g., for the 321 and 375 keV levels) there is very good

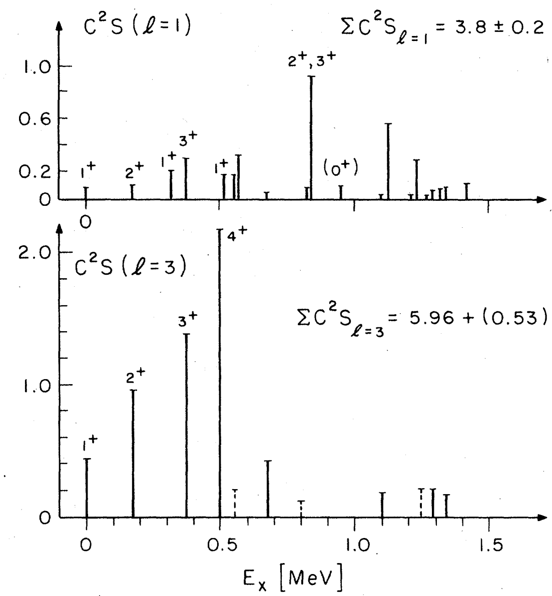

FIG. 3. Plot of ^{69}Ga(d,t) spectroscopic factors as a function of level energy. Solid bars indicate well-supported C^2S values. Dotted bars represent strengths which are less certain, because the corresponding levels or l admixtures are relatively weak. Note the fragmentation of the $l=1$ strength and the simple regularity of the $l=3$ ($f_{5/2}$) strengths.

agreement for all level energies below 1200 keV. Above this value a good correlation with our (d,t) data persists, although about half of their levels in this region may have to be classified as doublets. The spin assignments in their study appear somewhat less successful. We must rule out 3 (i.e., 30%) of their preferred J assignments on the basis of strong (d,t) selection rules and agree instead with J values that were suggested in earlier γ-decay work.[1,2,4]

Note added in proof. A recent study of high spin states in ^{68}Ga by C. Morand *et al.* [Z. Phys. A278, 189 (1976)] presents new γ-decay results. There is general agreement with the assignments in Table I, particularly for easily correlated states below 1 MeV.

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