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^{71}Ga and ^{73}Ga levels as observed in the (t,p) reaction

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A study of the (t,p) reaction on the two stable Ga isotopes has been performed. The reaction protons were analyzed in a quadrupole-dipole-dipole-dipole spectrometer with a resulting energy resolution approximately 18 keV. Levels up to about 3 MeV excitation energy in ^{71}Ga and 2.75 MeV in ^{73}Ga were measured with 11 new levels observed in the first case and 18 in the second. The angular distributions have been compared to pure distributions observed in the ^{72,74}Ge(t,p) reactions at the same energy and found to correspond mostly to pure angular momentum (L) transfer although mixing of L's is allowed. A number of new spins assignments are made for Ga levels and the results are used to discuss the spin of ^{73}Zn$_{g.s.}$. The striking splitting of the $L = 0$ strength in three approximately equal components, observed in ^{73}Ga, strongly supports a transition in nuclear deformation between $N = 40$ and 42.

[NUCLEAR REACTIONS ^{69,71}Ga (t,p) $E_t = 17$ MeV $\sigma(\theta)$]

I. INTRODUCTION

The structure of the odd Ga isotopes has been experimentally studied using β decay, γ spectroscopy,[1-4] and single particle transfer reactions.[5-7] These isotopes have only 3 protons outside the $Z = 28$ closed shell and an even number of neutrons. They are therefore amenable to relatively simple theoretical interpretation. As an example, calculations[8] describing the negative parity levels by coupling a three proton cluster to the quadrupole vibrations of a doubly even core reproduce rather well the low energy part of the spectra for the ^{65}Ga, ^{67}Ga, and ^{69}Ga isotopes. The spectra of the heavier isotopes appear to have a somewhat different structure, the difference being particularly striking in single proton transfer experiments.[5-7] These isotopes have not been as thoroughly studied experimentally as the lightest ones and, although no theoretical calculation is currently available for them, it appears that further experimental studies are in order.

An important change in the nuclear structure of the Ge isotopes ($Z = 32$) between $N = 40$ and $N = 42$ has been experimentally observed recently both in the occupation numbers of the $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ proton orbitals as measured in the $(d,{}^3\text{He})$ reaction[7] and in a comparison of the population of the low-lying first excited 0^+ level in the (p,t) and (t,p) reactions.[9] One of the main goals of the work described in the present paper was to look for a possible similar change in the structure of the Ga isotopes between $N = 40$ and $N = 42$, that is, between ^{71}Ga and ^{73}Ga, using the (t,p) reaction. In addition, although the ^{71}Ga level scheme is relatively well known, the levels of ^{73}Ga were practically unknown except for a recent $(d,{}^3\text{He})$ study[7] and the present results complement these data in a further understanding of this nucleus.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experiment was performed with a beam of 17 MeV tritons from the Los Alamos Scientific Laboratory FN tandem Van de Graaff accelerator. The targets consisted of Ga_2O_3 vacuum evaporated onto a thin carbon backing. The isotopic enrichments were 99.75% for ^{69}Ga and 99.8% for ^{71}Ga. The areal density was of the order of 30 and 50 μg/cm^2 for the ^{69,71}Ga targets respectively, as determined by elastic scattering at 30°, which was compared to an optical model calculation using systematic optical model parameters.[10] It was necessary to use the quadrupole-dipole-dipole-dipole (Q3D) spectrometer for this elastic scattering measurement because of the presence in the targets of heavy contaminants (dominated by W).

The reaction protons were analyzed by a Q3D type II magnetic spectrometer operating at a solid angle of 14.3 msr and detected on the focal plane by a helical cathode position sensitive proportional counter of one meter length.[11,12] Proton spectra were taken in 5° steps, from 15° to 60° scattering angle, and cover a range of excitation energy of ≈3 MeV.

Spectra of ^{69}Ga (t,p) ^{71}Ga and ^{71}Ga (t,p) ^{73}Ga at 15° are shown in Fig. 1. The energy resolution is 18 keV (full width at half maximum) mainly due to the targets. Excitation energies for the observed levels of ^{71}Ga and ^{73}Ga are given in Tables I and II, respectively. These energies were obtained by using known states populated in the ^{70,72,74}Ge(t, p) reactions[13] to generate a polynomial expression between radius of curvature and channel number. The error in excitation energies from this procedure is estimated to be ±3 keV up to an energy of 2.5 MeV and ±6 to 10 keV above this. Tables I and II also present previously known results[4,7,14] on ^{71}Ga and ^{73}Ga. There is good agreement in excitation energies between the various results. The present work gives 11 new levels in ^{71}Ga and 18 in ^{73}Ga. The Tables also give (t,p) cross sections, summed between 15° and 60°.

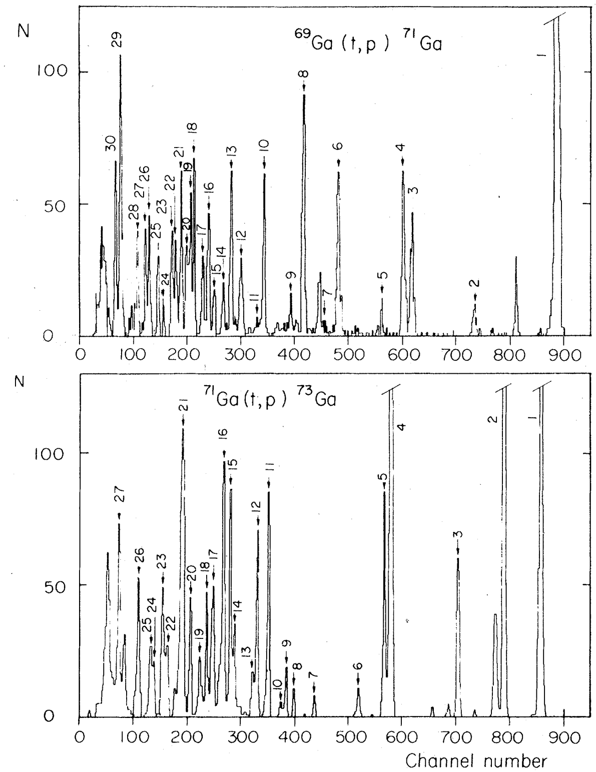

FIG. 1. Proton energy spectra of the ^{69}Ga(t,p) ^{71}Ga and ^{71}Ga(t,p) ^{73}Ga reactions at 15° lab. The numbers on top of the peaks refer to nuclear levels in respectively ^{71}Ga and ^{73}Ga (see Tables I and II).

III. ANALYSIS OF THE ANGULAR DISTRIBUTIONS

The experimental angular distributions for the reaction ^{69}Ga (t,p) ^{71}Ga are compared in Figs. 2 to 6 to pure "standard" $L=0$, 2, 3, or 4 angular distributions observed[13] in the ^{70}Ge (t,p) ^{72}Ge reaction at the same incident energy. A similar comparison is shown in Figs. 7 to 10 for the experimental angular distributions of the reaction ^{71}Ga (t,p) ^{73}Ga and the pure "standard" distributions observed[13] in the ^{72}Ge (t,p) ^{74}Ge reaction. The empirical "standard" reference shapes are shown as dotted lines in the figures. It appears that most of the measured angular distributions can be relatively easily classified as corresponding to a given L transfer and that there seems to be little mixing between the L values, although for all levels with spin $J>\frac{1}{2}$ an incoherent mixture of two L values is permitted by angular momentum conservation. The L values determined in this way are given in Tables I and II. Values within parentheses indicate a possible but dubious assignment.

The empirical comparison made between the Ga (t,p) and the Ge (t,p) angular distributions follows, of course, quite naturally from the fact that the two series of experiments have been performed under the same conditions (angles and incident energy) on targets with the same number of neutrons, but differing in Z by one unit, and that the L values are known in many cases for the Ge reactions. However, this comparison, and the resulting similarity observed for the shapes, convey the idea of an underlying weak coupling. We shall come back to this point later.

IV. SPECTROSCOPIC RESULTS

A. $L=0$ transitions

Levels populated in the (t,p) reaction by an $L=0$ transition have necessarily the same spin and parity as the target ground state. This permits us to confirm the previous assignment in ^{71}Ga of $J^\pi=\frac{3}{2}^-$ for the 509 keV level and to fix the spin of the 1633 keV level (previously $J^\pi=\frac{3}{2}^-, \frac{1}{2}^-$) as $J^\pi=\frac{3}{2}^-$. The transition to the 910 keV level of ^{71}Ga (previously $J^\pi=\frac{3}{2}^-, \frac{1}{2}^-$) has a forward peaked angular distribution, but the position of the secondary maximum is different from that observed for the other $L=0$ transitions. Although the value $J^\pi=\frac{3}{2}^-$ is very likely, it cannot be assigned with certainty.

In ^{73}Ga, we confirm the suggested value $J^\pi=(\frac{3}{2}^-)$ for the ground state and assign $J^\pi=\frac{3}{2}^-$ to the levels at 219, 915, 1800, and 2109 keV.

The total absolute integrated $L=0$ cross section in the ^{69}Ga (t,p) ^{71}Ga reaction is equal to 120±25% of the corresponding cross section in the ^{70}Ge (t, p) ^{72}Ge reaction.[13] (In order to make a meaningful comparison, one has to integrate over the same

TABLE I. Results for ^{71}Ga.

Previous work[a]		(d, ^{3}He) reaction[b]				Present work				
E_x (keV)	J^π	E_x (keV)	l	C^2S	$J^{\pi\ c}$	E_x (keV)	L	$J^{\pi\ c}$	$\frac{d\sigma}{d\Omega}$ μb/sr	Level No.
0.0	$\frac{3}{2}^-$	0.0	1	2.14		0.0	0	$\frac{3}{2}^-$	1024	1
389.9	$\frac{1}{2}^-$	388	1	0.04					<3.5	
487.3	$\frac{5}{2}^-$	487	3	1.14						
511.5	$\frac{3}{2}^-$	510	1	0.21		509	0	$\frac{3}{2}^-$	23	2
910.3	$\frac{3}{2}^-$, ($\frac{1}{2}^-$)	(910)		<0.01		910	(0)		67.1	3
964.7	$\frac{5}{2}^-$	964	3	0.2		965	2		96	4
1107.5	$\frac{7}{2}^-$									
1109	$\frac{1}{2}^-$	1113	1	0.39		1110	(2)		17.7	5
1395.2	$(\frac{5}{2}, \frac{7}{2})^-$	1396	3	0.52	$\frac{7}{2}^-$ ($\frac{5}{2}^-$)	1395	2		96.4	6
1493.8	$\frac{9}{2}^+$	1495	4	0.24		1490	(3)		12.3	7
1498.7	$(\frac{5}{2}, \frac{7}{2})^-$									
1631.5	$\frac{3}{2}^-$, ($\frac{1}{2}^-$)	1634		*V.W*		1633	0	$\frac{3}{2}^-$	129	8
1719.7	($\frac{5}{2}^-$, $\frac{7}{2}^-$)					1716	(2)		19.5	9
		1907	3	0.87	$\frac{7}{2}^-$ ($\frac{5}{2}^-$)	1904	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	55.3	10
						1937	(3)		23.0	11
2064.6	$(\frac{1}{2}, \frac{3}{2})^-$					2058	2		55.3	12
						2136	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	77.9	13
2190	$\frac{5}{2}^-$, ($\frac{7}{2}^-$)					2191	2		20.0	14
2247.2	$(\frac{7}{2})^+$					2244	3	$\frac{3}{2}^+$ to $\frac{9}{2}^+$	44.0	15
2294.5	$(\frac{1}{2}, \frac{3}{2})^-$					2295			58.4	16
(2320)	$(\frac{1}{2}, \frac{3}{2})^-$					2327	(2)		31	17
						2396	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	68.1	18
						2421	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	61	19
2450.6	$(\frac{7}{2})^+$					2449	3	$\frac{3}{2}^+$ to $\frac{9}{2}^+$	64.1	20
2488.3	$(\frac{7}{2})$					2487	3	$\frac{3}{2}^+$ to $\frac{9}{2}^+$	108	21
						2529	(4)		76.8	22
						2551	3	$\frac{3}{2}^+$ to $\frac{9}{2}^+$	63.5	23
						2614	3	$\frac{3}{2}^+$ to $\frac{9}{2}^+$	27.7	24
						2658	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	31.7	25
2720.1	$(\frac{7}{2}, \frac{9}{2})^+$					2723	3	$\frac{3}{2}^+$ to $\frac{9}{2}^+$	54.9	26
						2747	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	39.3	27
2805.4 2815.6	$(\frac{7}{2})^+$					2812	(4)		92	28
						2932	(3)		128	29
						2974	(4)		104.5	30

[a] Reference 4.
[b] Reference 7.
[c] Only if absolutely sure, more precise than given in column 2, or in contradiction with it.

TABLE II. Results for ^{73}Ga.

Previous work [a] E_γ (keV)	(d, ^{3}He) reaction [b] E_x (keV)	l	C^2S	J^π	Present work E_x (keV)	L	J^{π} [c]	$\frac{d\sigma}{d\Omega}$ μb/sr	Level No.
	0.0	1	1.33	$\frac{3}{2}^-$, $(\frac{1}{2}^-)$	0.0	0	$\frac{3}{2}^-$	264.3	1
	198	3	1.87	$\frac{5}{2}^-$, $(\frac{7}{2}^-)$					
216	214	1	0.07	$\frac{1}{2}^-$, $\frac{3}{2}^-$	219	0	$\frac{3}{2}^-$	248.4	2
496	495	3	0.32	$\frac{5}{2}^-$, $(\frac{7}{2}^-)$	498	2		55.0	3
911	912	1	0.04	$\frac{3}{2}^-$, $(\frac{1}{2}^-)$	915	0	$\frac{3}{2}^-$	323.8	4
	952	3	0.5	$\frac{7}{2}^-$, $(\frac{5}{2}^-)$	956	2		77.2	5
	1112	1	0.43	$\frac{1}{2}^-$, $(\frac{3}{2}^-)$	1117	(2)		20.5	6
	1233	(4)	(0.37)	$(\frac{9}{2}^+)$	1235			<3.7	
					1396	4		13.0	7
	1534	3	1.79	$\frac{7}{2}^-$, $(\frac{5}{2}^-)$	1528			≈10	8
					1578			18.2	9
	1620	3		$\frac{7}{2}^-$, $(\frac{5}{2}^-)$	1618			<6.3	10
					1700	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	76.6	11
	1777	(3)			1771	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	55.5	12
					1800	0	$\frac{3}{2}^-$	13.9	13
					1925	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	34.4	14
					1952	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	68.7	15
					2001	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	132	16
					2067	3	$\frac{3}{2}^+$ to $\frac{9}{2}^+$	38.6	17
					2109	0 (+2)	$\frac{3}{2}^-$	42.0	18
					2160	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	26.4	19
					2221	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	46.5	20
					2277	4		23.8	21
					2380	4		55.2	22
					2411	(2)		44.9	23
					2467	(3)		35.2	24
					2498	3	$\frac{3}{2}^+$ to $\frac{9}{2}^+$	60.3	25
					2582	2	$\frac{1}{2}^-$ to $\frac{7}{2}^-$	53.9	26
					2726	(2 + 4)		112	27

[a] Reference 14.
[b] Reference 7.
[c] Only if absolutely sure, more precise or in contradiction with the values given in column 5.

angles as in the present work, 15° to 60°, instead of 10° to 60° in the original Ge paper.[13] This is true for all cross section comparisons made in the present paper.) The ^{71}Ga (t,p) ^{73}Ga total $L=0$ cross section is 75 ±20% of that for the ^{72}Ge (t,p) ^{74}Ge reaction. The large errors quoted are due to the Ga target difficulties mentioned above. Taking this into account, the total $L=0$ cross sections of the two Ga isotopes do not appear significantly different from that of the corresponding Ge isotopes. However, although the ground state cross section dominates the spectrum in the case

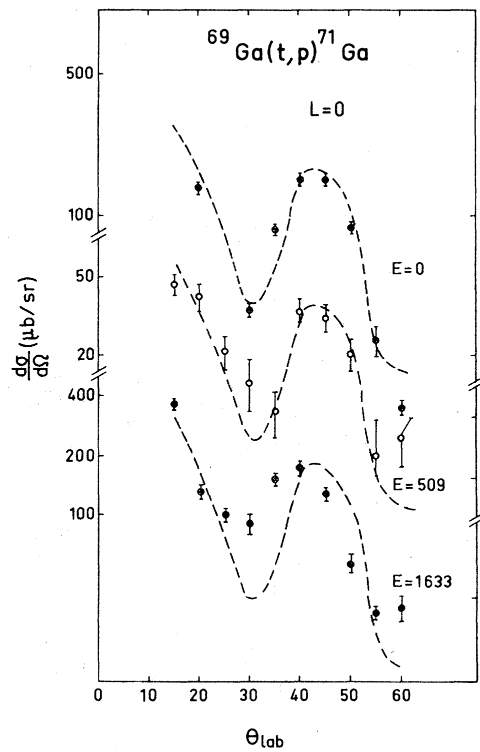

FIG. 2. Angular distributions of the ^{69}Ga(t,p) ^{71}Ga reaction showing a clear $L=0$ shape. The dotted curves are mean "standard" experimental curves for known transfer (here $L=0$) in the Ge(t,p) reactions (see Sec III).

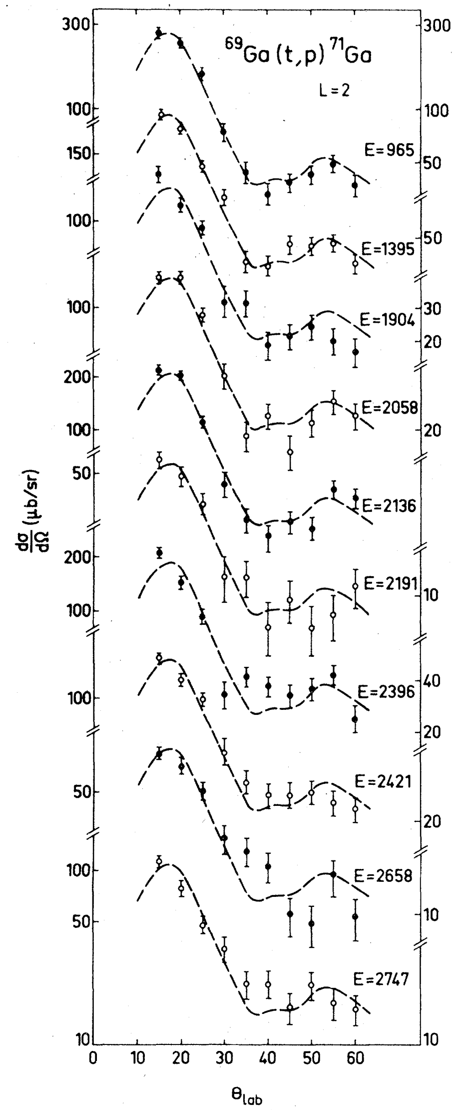

FIG. 3. Angular distributions of the ^{69}Ga(t,p) ^{71}Ga reaction showing a clear $L=2$ shape. See also caption for Fig. 2.

of the ^{69}Ga(t,p) ^{71}Ga reaction, there is an important splitting of strength in the case of the ^{71}Ga (t,p) ^{73}Ga reaction. We shall come back to this point in detail in Sec. V.

According to the preceding result, we shall assume in the following sections that the total $L=0$ strength is the same in the four reactions considered [^{69,71}Ga(t,p) and ^{70,72}Ge(t,p) reactions] and the strengths corresponding to $L=2$, 3, and 4 transfer shall be discussed in relative values, which are more accurately determined in each reaction than the absolute strengths.

B. Other transitions in ^{71}Ga

1. L = 2 transitions

The total pure $L=2$ relative strength ($L=2$ total integrated cross section divided by the $L=0$ total integrated cross section) observed in the ^{69}Ga(t,p) ^{71}Ga reaction is [including the $L=(2)$ level at 1110 keV] $\approx 53\%$, which compares well with the $\approx 47\%$ observed[13] in the ^{70}Ge(t,p) ^{72}Ge reaction. This strength is distributed over 11 levels in ^{71}Ga, as compared to four 2^+ levels in ^{72}Ge and the centroid is 1928 keV as compared to 1430 in ^{72}Ge. Moreover, all the levels corresponding to $L=2$ transitions in ^{71}Ga lie at an excitation energy above the 2_1^+ energy of ^{72}Ge. This implies that the observed levels (with $\frac{1}{2}^- \leq J^\pi \leq \frac{7}{2}^-$) do not correspond to the weak coupling of the $J^\pi = \frac{3}{2}^-$ ground state with the 2_1^+ excitation (one should observe four levels with a centroid equal to the 2_1^+ energy of ^{72}Ge) or with all the 2^+ excitations of a ^{72}Ge core (the centroids of the total $L=2$ strength should be the same). Rather there is a complicated mixing of the levels corresponding to $2^+ \otimes \frac{3}{2}^-$ with weak coupling levels of the type $2^+ \otimes \frac{5}{2}^-$ and $2^+ \otimes \frac{1}{2}^-$ and with levels corresponding to more complicated configurations (see for ex-

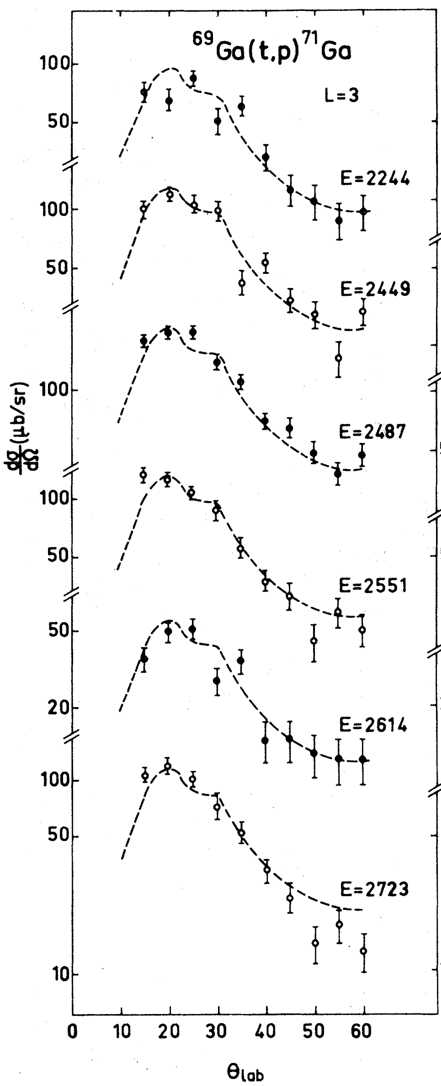

FIG. 4. Angular distributions of the ^{69}Ga(t,p) ^{71}Ga reaction showing a clear $L=3$ shape. See also caption for Fig. 2.

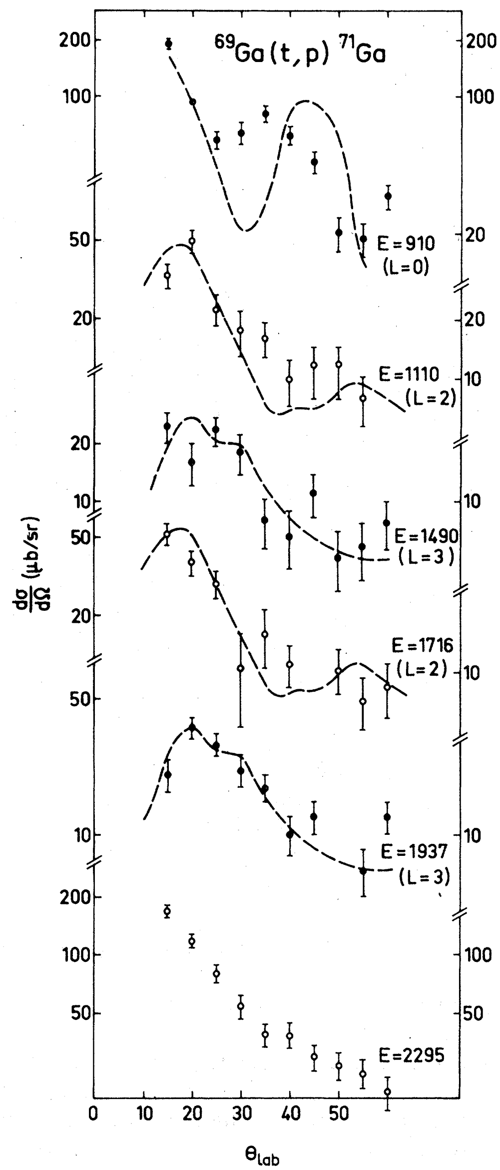

FIG. 5. Angular distributions of the ^{69}Ga(t,p)^{71}Ga reaction with dubious shapes. In some cases possible fits to "standard" shapes are shown; the L value is then given within parentheses.

ample Ref. 8). This mixing is further implied by the lack of any $(2J+1)$ rule for the $L=2$ states excited. For fairly collective 2^+ states such a rule has been observed for (t,p) reactions in the $A=110$ region,[15] although in this work a lowering of the $L=2$ centroid is observed as opposed to the raising noted above. In a recent work on the ^{59}Ni(t,p) ^{61}Ni reaction,[16] no simple $(2J+1)$ rule was obeyed either, although a clear differentiation between core coupled states and particle states could be made on the basis of the purity of L transfer. In that case, as in the present case, the ground state spin of $\frac{3}{2}^-$ permitted L mixing but core coupled multiplets tended to preserve their pure core L transfer with single particle states being substantially L mixed. Although in the present case, it is an odd proton rather than an odd neutron coupling, the rather pure L transfer of such states as the 965 ($J^\pi=\frac{5}{2}^-$) and 1395 keV ($J^\pi=\frac{7}{2}^-$) levels is still suggestive that their basic parentage lies in coupling to the quadrupole phonons. These levels also contain an appreciable part (about 25% for each level) of the total (t,p) strength expected for a weak coupling of a $p_{3/2}$ proton hole with the 2_1^+ excitation of ^{72}Ge.

Among the levels appreciably populated in (t,p)

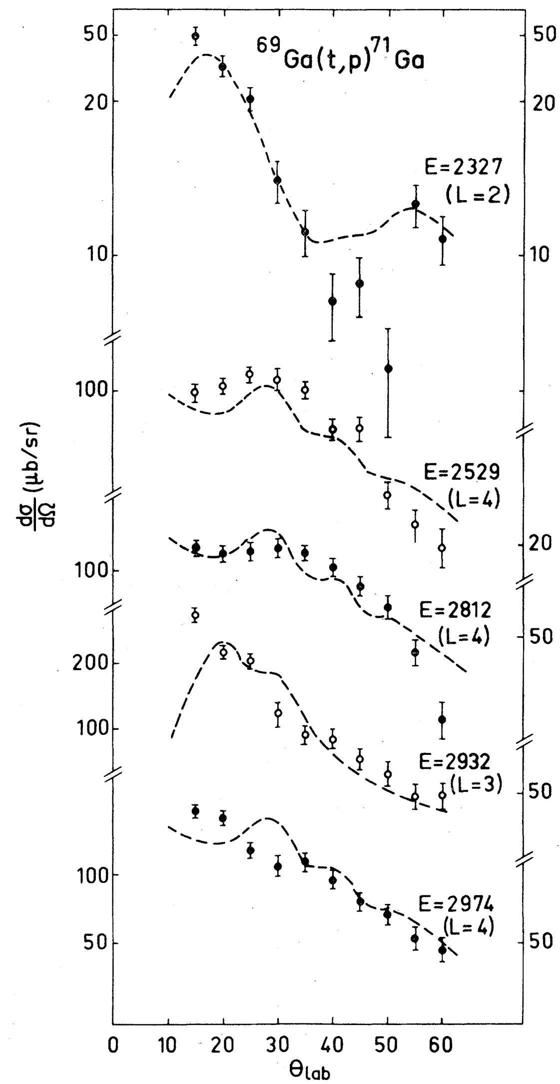

FIG. 6. Angular distributions of the ^{69}Ga$(t,p)^{71}$Ga reaction with dubious shapes. In some cases possible fits to "standard" shapes are shown; the L value is then given with parentheses.

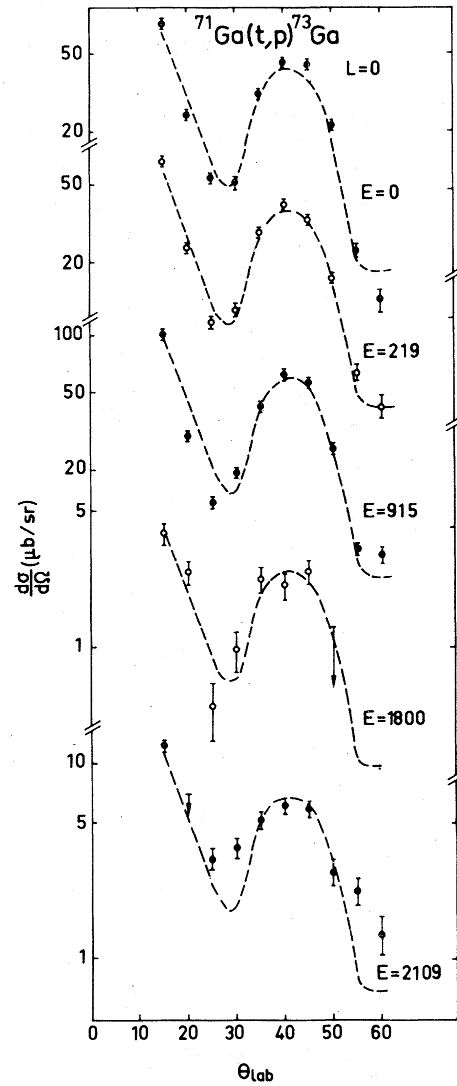

FIG. 7. Angular distributions of the ^{71}Ga(t,p) ^{73}Ga reaction showing a clear $L=0$ shape. See also caption for Fig. 2.

by an $L=2$ transfer, a few, such as the ones at 1395 keV, $J^{\pi}=(\frac{7}{2}^{-})$, and 1904 keV, $J^{\pi}=(\frac{7}{2}^{-})$, are also strongly populated in the $(d,{}^3\text{He})$ reaction indicating an important single proton hole component.

In summary, no overall simple weak coupling pattern is apparent in the case of the $L=2$ transfers, although some levels seem to contain an appreciable component of such a type, and strong mixing appears to be the rule.

2. $L = 3$ transitions

The total $L=3$ relative strength (integrated total $L=3$ cross section divided by the total $L=0$ cross section) of $\approx 42\%$ observed in the ^{69}Ga(t,p) ^{71}Ga reaction [including the $(L=3)$ levels at 1490 and 2932 keV] compares well with the $\approx 38\%$ observed[13] in the ^{70}Ge(t,p) ^{72}Ge reaction. This strength is distributed over 8 positive parity levels ($\frac{3}{2}^{+} \leq J^{\pi} \leq \frac{9}{2}^{+}$) as compared to two 3^{-} levels in ^{72}Ge and the centroid is 2620 keV as compared to 2594 in ^{72}Ge (the dominant 3_1^{-} of ^{72}Ge lies at 2513 keV with 80% of the strength). The positive parity levels therefore correspond more closely to the expectations from a weak coupling scheme and we shall discuss them in a little more detail than the negative parity ones.

Several positive parity levels have been observed by Zoller *et al.*[4] in the β decay of ^{71}Zn^{m} which has

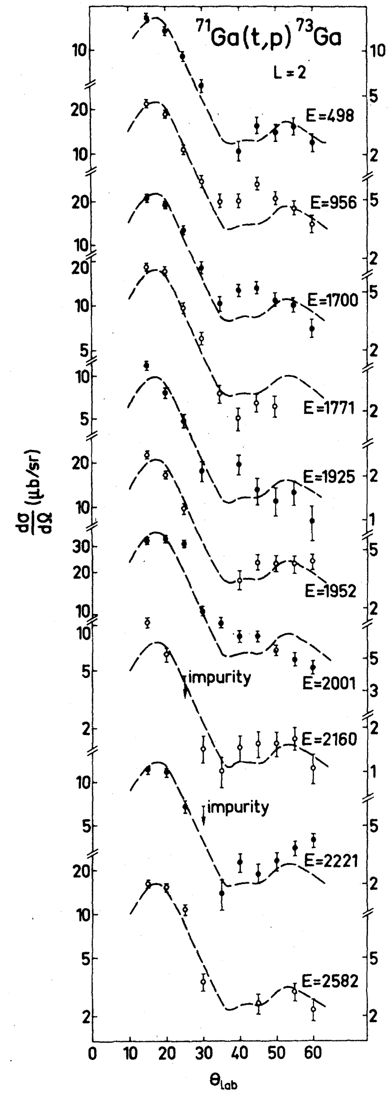

FIG. 8. Angular distributions of the ^{71}Ga(t,p) ^{73}Ga reaction showing a clear $L=2$ shape. See also caption for Fig. 2.

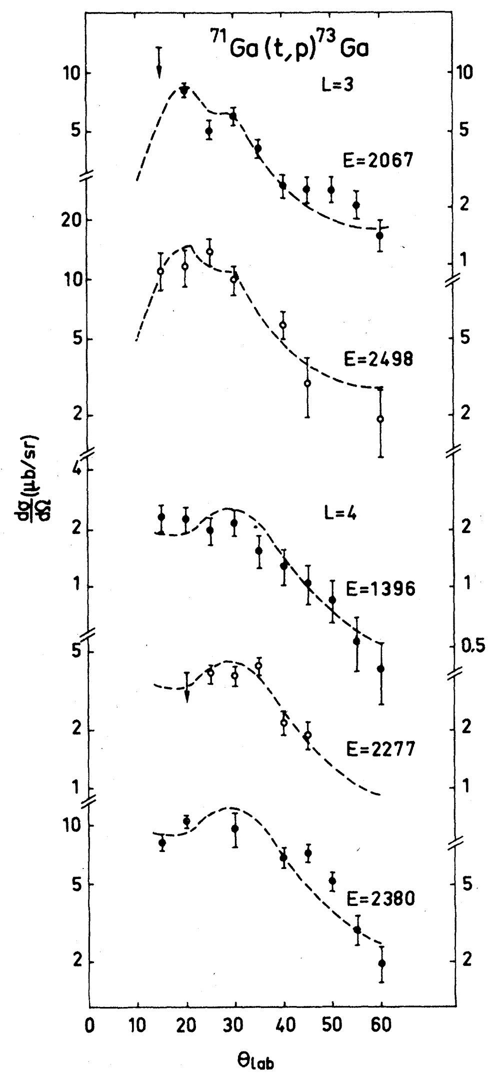

FIG. 9. Angular distributions of the ^{71}Ga(t,p) ^{73}Ga reaction showing clear $L=3$ and $L=4$ shapes. See also caption for Fig. 2.

a spin of $\frac{9}{2}^+$. The allowed nature of the β transitions permits us to limit spins to $J^\pi=\frac{7}{2}^+, \frac{9}{2}^+, \frac{11}{2}^+$ for the levels we observe at 2244, 2449, and 2723 keV. These levels, being clearly populated in our experiment by an $L=3$ transfer, are thus limited in spin to $J^\pi=\frac{7}{2}^+$ or $\frac{9}{2}^+$. Each of these levels contains an appreciable part (between 12.5 and 18%) of the total (t,p) strength expected from weak coupling of a $p_{3/2}$ hole with the 3_1^- level of ^{72}Ge. The γ decay favors $J^\pi=\frac{7}{2}^+$ for the first two levels.

The logft value (6.5) for the β transition feeding the level we observe in (t,p) at 2487 keV is a little higher than the generally adopted limit (6.4) for allowed transitions, but still suggests that the spin can be limited as for the levels at 2244 and 2449 keV, to $J^\pi=\frac{7}{2}^+, \frac{9}{2}^+$.

The levels at 2551 and 2614 keV, populated by $L=3$ transfer in the (t,p) reaction, are not observed in the decay of ^{71}Zn^m. This suggests their spin values are limited to $J^\pi=\frac{5}{2}^+, \frac{3}{2}^+$. Their strengths are 18% and 8%, respectively, of the ^{72}Ge 3_1^- strength, with 21% and 14% being expected from the $(2J+1)$ rule for the $\frac{5}{2}$ and $\frac{3}{2}$ members of the multiplet.

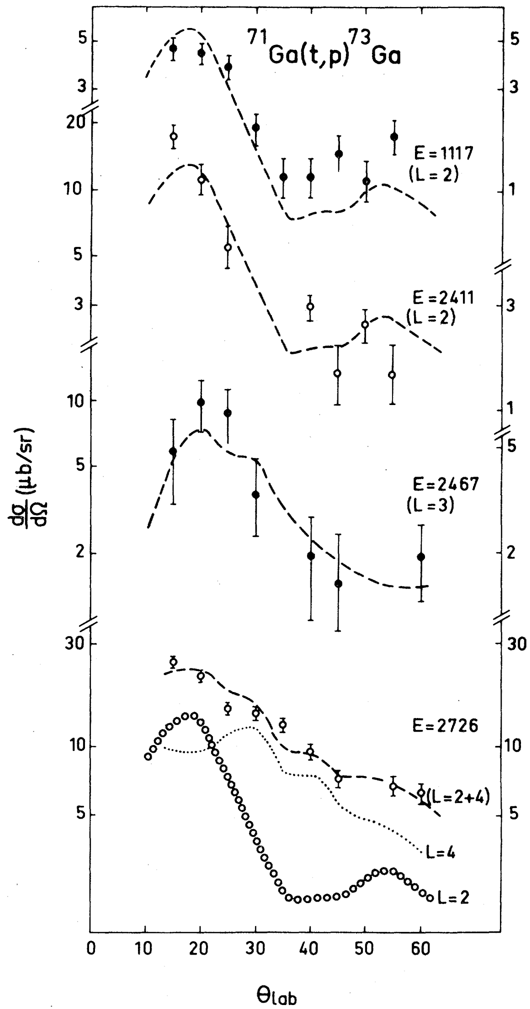

FIG. 10. Angular distributions of the $^{71}Ga(t,p)$ ^{73}Ga reaction with dubious shapes. See also caption for Fig. 5.

3. L = 4 transitions

Owing to the rather structureless shape of the $L = 4$ transfer and to the relatively large error bars, all the $L = 4$ assignments in ^{71}Ga are dubious. We shall therefore not discuss the corresponding energy levels. The total maximum possible $L = 4$ relative strength observed is $\approx 22\%$, to be compared to $\approx 38\%$ in ^{72}Ge. This shows clearly that an important part of the $L = 4$ strength lies above 3 MeV in ^{71}Ga.

C. Other transitions in ^{73}Ga

1. L = 2 transitions

The total $L = 2$ relative strength clearly identified (including the weak and somewhat dubious transition to the 1117 keV level) in the $^{71}Ga(t,p)$ ^{73}Ga reaction is $\approx 72\%$ which, although somewhat larger, is still in reasonable agreement with the $\approx 62\%$ observed[13] in the $^{72}Ge(t,p)$ ^{74}Ge reaction. This strength is distributed over 10 levels in ^{73}Ga, as compared to six 2^+ levels in ^{74}Ge, and the centroid is 1748 keV, as compared to 1830 keV in ^{74}Ge. It should be remarked that, although as in the case of ^{71}Ga a weak coupling description does not seem apparent here, the levels at 498 keV $[J^\pi = (\frac{5}{2})^-]$ 956 keV $[J^\pi = (\frac{7}{2})^-]$, and 117 keV $[J^\pi = (\frac{1}{2})^-]$ contain, each, between 70 and 80% of the (t,p) strength expected from the $(2J+1)$ rule for a weak coupling between a $p_{3/2}$ hole and the 2_1^+ level of ^{74}Ge. This good agreement with the $(2J+1)$ rule and the fact that the shapes of the angular distributions are rather pure $L = 2$ would support the phonon coupling argument. These levels are, however, also appreciably populated in the $(d, {}^3He)$ reaction indicating non-negligible single hole strength.

2. L = 3 transitions

The total $L = 3$ relative strength clearly identified in the $^{71}Ga(t,p)$ ^{73}Ga reaction is $\approx 11\%$, to be compared with the $\approx 15\%$ observed[13] in the $^{72}Ge(t,p)$ ^{74}Ge reaction. This strength is distributed over two levels only in ^{73}Ga, as compared to the 3^- level in ^{74}Ge and the centroid is 2323 keV, as compared to 2539 keV in ^{74}Ge. The two levels at 2067 and 2498 keV have therefore $\frac{3}{2}^+ \leq J^\pi \leq \frac{9}{2}^+$; their relatively large strength would favor a spin $J^\pi = \frac{7}{2}^+$ or $\frac{9}{2}^+$ based on a $(2J+1)$ weighting factor. Presumably other members of the octupole multiplet are found above 3 MeV.

It should be noticed that the $L = 3$ strength is about 4 times smaller in ^{73}Ga than in ^{71}Ga. A similar tendency has been observed in the $Ge(t,p)$ data between $N = 40$ and 42 and was associated with a possible increase in the deformation around $N = 42$.

3. L = 4 transitions

Some transitions in the $^{71}Ga(t,p)$ ^{73}Ga reaction have been classified as $L = 4$. The total observed relative strength is $\approx 10\%$ as compared to $\approx 26\%$ in the $^{72}Ge(t,p)$ ^{74}Ge reaction. This difference is probably due to a large part of the $L = 4$ strength lying above 2.75 MeV in ^{73}Ga.

D. Levels unobserved or weakly populated in the (t,p) reaction

The L values and strengths for all relatively strongly excited levels observed in the (t,p) reaction have been discussed above. However, a number of levels observed in other experiments were not excited or only weakly populated in the (t,p) reaction. Some additional information may be deduced from this fact.

It is apparent from the proton transfer reactions that a very striking change occurs in the behavior of the two first $J^\pi=\frac{1}{2}^-$ levels, when going from ^{69}Ga to ^{71}Ga. In ^{69}Ga, the first $J^\pi=\frac{1}{2}^-$ level at 317 keV is strongly fed both in the (^{3}He, d) and in the (d, ^{3}He) reactions.[5-7] The second one at 1029 keV is rather weakly excited in these reactions and is generally interpreted[17] as the $\frac{1}{2}^-$ member of the $(\pi p_{3/2})^3_{3/2}\otimes 2^+$ weak coupling multiplet. In ^{71}Ga the first $J^\pi=\frac{1}{2}^-$ level at 388 keV is weakly excited in the (^{3}He, d) and (d, ^{3}He) reactions, whereas the second one at 1113 keV is strongly excited with about the same spectroscopic factors as observed for the ^{69}Ga first $J^\pi=\frac{1}{2}^-$ level. The simplest hypothesis would then be to suppose an inversion of the two $J^\pi=\frac{1}{2}^-$ levels between ^{69}Ga and ^{71}Ga. However, if this were correct, the first $J^\pi=\frac{1}{2}^-$ level in ^{71}Ga would have a dominant $(\pi p_{3/2})^3_{3/2}\otimes 2^+$ weak coupling character and should be strongly excited in the (t,p) reaction. In fact, the level is not even observed in this reaction. Consequently, if we consider as well established the nature of the 1029 keV level in ^{69}Ga, the situation in ^{71}Ga appears more complex than a simple level crossing. In any case, it is clear that the first $J^\pi=\frac{1}{2}^-$ level at 388 keV in ^{71}Ga is neither a single proton (or proton hole) level nor the $\frac{1}{2}^-$ member of the $(\pi p_{3/2})^3_{3/2}\otimes 2^+$ multiplet.

The allowed nature of the transition feeding the 2601 keV level observed by Zoller *et al.*[4] in the β decay of ^{71m}Zn (spin $J^\pi=\frac{9}{2}^+$) limits its spin to $J^\pi=\frac{7}{2}^+, \frac{9}{2}^+$, and $\frac{11}{2}^+$. The lack of excitation of this level in the (t,p) reaction and the γ decay[4] strongly favor a $J^\pi=\frac{11}{2}^+$ assignment for this level.

In the ^{72,74}Ge(d, ^{3}He) ^{71,73}Ga reactions[7] more than 85% of the total $f_{5/2}$ strength is observed in the first $J^\pi=\frac{5}{2}^-$ level. These levels at 487 keV in ^{71}Ga and 198 keV in ^{73}Ga are not populated in the (t,p) reaction, confirming their rather pure proton hole character. Similarly, the main part of the $g_{9/2}$ strength is observed in the first $\frac{9}{2}^+$ state at 1495 keV in ^{71}Ga and this state is weakly populated in the (t,p) reaction.

Several known[4] negative parity levels of ^{71}Ga such as the 1107.5 keV first $J^\pi=\frac{7}{2}^-$ level and the 1498.7 keV, $J^\pi=\frac{5}{2}^-$ or $\frac{7}{2}^-$ level appear as weakly populated both in the single particle transfer reactions and in the (t,p) reaction and should therefore have a relatively complicated structure.

V. STRUCTURAL CHANGE BETWEEN $N=40$ AND 42

A very striking feature of the ^{71}Ga(t,p) ^{73}Ga reaction is the splitting of the $L=0$ strength. In the ^{69}Ga(t,p) ^{71}Ga reaction, the $L=0$ ground state to ground state transition dominates the spectrum, with more than 87% of the total observed $L=0$ strength. In the ^{71}Ga(t,p) ^{73}Ga reaction, the $L=0$ strength is split into 3 main components, the ground state to ground state transition representing only ≈30% of the total $L=0$ strength. This splitting is very reminiscent of the effect observed[18] between $^{151}_{88}$Eu and $^{153}_{90}$Eu as a result of the shape transition from spherical to deformed prolate between $N=88$ and $N=90$.

The three dominant $L=0$ transfers into ^{73}Ga total about 90% of the ^{71}Ga ground state transition, when distorted-wave Born approximation (DWBA) corrected, and thus strongly appear to be fragments of the pairing phonon present in the ^{69}Ga(t,p) ^{71}Ga ground state transition. This effect, as noted in the Eu isotopes, is due to a decreased overlap between the shapes of initial and final nuclei and reflects a tendency of the pairing phonon to preserve its total strength and energy centroid even though the ground state may be changing in binding energy. In the Eu case, the excited $L=0$ strength went to states with Nilsson orbitals originating from the shell model orbital of the target nucleus.

If the structural change observed in the Ga and Ge isotopes between $N=40$ and $N=42$ is similarly due to a shape transition, the shape of the $J^\pi=\frac{3}{2}^-$ levels at 219 and 915 keV in ^{73}Ga, strongly fed in the (t,p) reaction, will be different from that of the ^{73}Ga and ^{74}Ge ground states. Accordingly, these levels should be weakly populated in the ^{74}Ge (d, ^{3}He) ^{73}Ga reaction. This is indeed the case as can be seen in Table II.

It should be remarked that the dramatic splitting of the $L=0$ strength just discussed for the ^{71}Ga(t,p) ^{73}Ga reaction is not observed in the case of the ^{75}As(p,t) ^{73}As reaction where 94% of the $L=0$ strength is found in the ground state to ground state transition.[19] Because in both cases the two nuclei involved in the reaction have respectively 40 and 42 neutrons, this seems to imply that the structural change observed between $N=40$ and $N=42$ for the Ga($Z=31$) and the Ge($Z=32$) does not occur for the As($Z=33$).

VI. SPIN OF ^{73}Zn

Four γ rays of 216 ± 2, 496 ± 2, 911 ± 3, and 1198 ± 4 keV have been observed by Erdal *et al.*[14] in coincidence with the β decay of a $T_{1/2}=23.5\pm0.1$ s level of ^{73}Zn, presumably the ground state. It is clear from Table II that the first three γ rays correspond to the ground-state decay of the levels we observe at 219, 498, and 915 keV in our (t,p) experiment and at 214, 495, and 912 keV in our $(d, {}^3\text{He})$ experiment.[7] The weak 1198 ± 4 keV γ ray could correspond to the transition from the level observed at 2109 keV in (t,p) to the 915 keV level. As already stated, the (t,p) experiment permits us to assign with certainty the spin $J^\pi=\frac{3}{2}^-$ to the ground state and to the levels at 219, 915, and 2109 keV in ^{73}Ga and the $(d, {}^3\text{He})$ reaction limits the spin of the 498 keV level to $J^\pi=\frac{5}{2}^-, \frac{7}{2}^-$, with a clear preference for $\frac{5}{2}^-$. Therefore, only levels with $J^\pi=\frac{3}{2}^-$ and $\frac{5}{2}^-$ are measurably populated in the β decay of ^{73}Zn.

Although the fraction of the β rays going to the $^{73}\text{Ga}_{\text{g.s}}$ is not known, we may try to make a rough estimate of the log*ft* values. The ground state and the 219 keV levels both have $J^\pi=\frac{3}{2}^-$. Because the β maximum energy is very large ($E_\beta \geq 4.7$ MeV), it is reasonable to assume about the same feeding for the two levels. With this hypothesis and using the γ ray intensities given by Erdal *et al.*[14] (or estimated from the spectrum for the 1198 keV γ ray) we compute, using the monogram of Ref. 20, $5.6 < \log ft < 6.2$ for the 5 levels populated. Even assuming a very large β feeding of the $J^\pi=\frac{3}{2}^-$ ground state as compared to the $J^\pi=\frac{3}{2}^-$ level at 219 keV (6 times larger) we would get a log*ft* of 5.4 for the ground state, still smaller than 6.4 for the other $J^\pi=\frac{3}{2}^-$ levels and equal to 6.6 for the $J^\pi=\frac{5}{2}^-$ level at 498 keV. It is therefore clear that the transitions from ^{73}Zn to the $J^\pi=\frac{3}{2}^-$ levels of ^{73}Ga are allowed ($\Delta J=0$ or ±1, $\pi_i\cdot\pi_f=+$). Therefore, the spin of $^{73}\text{Zn}_{\text{g.s.}}$ is limited to $J^\pi=\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$. The strong feeding of the $J^\pi=\frac{5}{2}^-$ level (log*ft* <6.6) eliminates the value $J^\pi=\frac{1}{2}^-$ and therefore the $^{73}\text{Zn}_{\text{g.s}}$ spin is either $J^\pi=\frac{3}{2}^-$ or $J^\pi=\frac{5}{2}^-$. This result is somewhat surprising because, by looking at the systematics of the known level schemes of the odd Zn isotopes, a spin $J^\pi=\frac{1}{2}^-$ or $\frac{9}{2}^+$ would normally be expected. It should, however, be recalled that a striking change of structure has been observed in the Ge and Ga isotopes between $N=40$ and 42 and that a similar change of structure between ^{71}Zn ($N=41$) and ^{73}Zn ($N=43$) is not unlikely.

VII. CONCLUSIONS

The angular distributions of the majority of states excited in ^{71,73}Ga are characterized by single L transfers, although mixed L transfers are allowed. This feature indicates that the (t,p) reaction on these odd nuclei is predominantly described by particle-vibration coupling with the L transfer the same as the core states. Considerable mixing of the multiplets is evidenced by the large displacement of energy weighted centroids and the general lack of agreement with the statistical weighting rules for weak coupling multiplets. In this regard, the even parity multiplets seem better described by weak coupling than the odd and this may be expected because of the considerably fewer states of odd parity in the Ge core nuclei with resulting smaller mixing.

The rapid change of distribution in $L=0$ strength between ^{71}Ga and ^{73}Ga is evidence for a shape transition between $N=40$ and 42, as has been discussed previously.[9] The ground state transition in the $^{69}\text{Ga}(t,p)\,^{71}$Ga reaction is, within error limits, of the same order as the ground state transition in the $^{70}\text{Ge}(t,p)\,^{72}$Ge reaction, as would be expected for a normal proton-neutron phonon interaction. However, considerable fragmentation of this same neutron phonon into three approximately equal states is seen to occur in the $^{71}\text{Ga}(t,p)\,^{73}$Ga case. This behavior is characteristic of transitional nuclei and may be interpreted as due to a change in the ground state configurations and binding energy induced by a change in the potential energy surface. The tendency of the pairing phonon to preserve its intrinsic total strength and binding energy in spite of ground state changes results in increased strength to excited states and a fractionization of such strength to underlying levels of the same spin and parity.

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