PHYSICAL REVIEW C VOLUME 19, NUMBER 5 MAY 1979

^{72}Ge from the ^{70}Ge(t,p) reaction

S. Mordechai,* H. T. Fortune, R. Middleton, and G. Stephans
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 5 July 1978)

The reaction ^{70}Ge$(t,p)^{72}$Ge has been investigated with a 15-MeV triton beam. 30 levels of ^{72}Ge were observed up to about 4-MeV excitation, four of which were unreported previously. Angular distributions were measured and compared with distorted-wave Born-approximation calculations. Several new 0^+ states have been observed in ^{72}Ge, one of which, at 1.709 MeV, is a new state and is the third 0^+ level in ^{72}Ge. Many additional spin and parity assignments have been made. The ^{72}Ge nucleus shows a pattern of 0^+ states that is considerably different from that of other even Ge isotopes. But for higher spins and both parities, ^{72}Ge is very similar to other even Ge nuclei.

[NUCLEAR REACTIONS ^{70}Ge(t,p), $E_t = 15.0$ MeV; measured $\sigma(E_p, \theta)^{72}$Ge deduced levels, L, π, J. DWBA analysis.]

I. INTRODUCTION

The present is the last in a series of papers[1-3] reporting experimental results for (t,p) reactions on even Ge isotopes. It deals with ^{72}Ge, which has been extensively studied in various ways: through the β decay of ^{72}Ga (Ref. 4) and ^{72}As (Ref. 5), ^{72}Ge$(n,n'\gamma)$ (Ref. 6), ^{72}Ge(p,p') (Ref. 7), ^{72}Ge(d,d') (Ref. 8), ^{73}Ge(p,d) (Ref. 9), ^{74}Ge(p,t) (Ref. 10, 11), and ^{71}Ga$(^3$He$,d)$ (Ref. 12). (These are the most recent references for the individual reactions. The latest compilation[13] gives a survey of all the relevant measurements for ^{72}Ge and many earlier references.) From the investigations listed above, the level structure of ^{72}Ge is well established below 2-MeV excitation. Above this energy, many additional levels are known, but many of them do not have definite spin and parity assignments.

The ^{72}Ge nucleus differs from all other even Ge isotopes in its low lying spectrum. It is the only Ge isotope which is known to have a 0^+ first excited state. Except for ^{72}Ge, the only other nucleus that has a 0^+ first excited state, but without closed neutron or proton shells, is ^{98}Mo, in which there is a subshell closure of the $(1\,d_{5/2})^2$ neutrons. The first excited 0^+ state in the other Ge isotopes appears at a considerably higher energy. In ^{70}Ge the 0_2^+ level is above the 2_1^+ state, in ^{68}Ge it is just below the 2_2^+, and in ^{74,76,78}Ge it appears above the 2_2^+. It was recently noted[14] that this minimum in the energy of the first excited 0^+ state as well as the minimum around $N=40$ in the energy difference between the 4_1^+ and the 2_2^+ levels, $E_x(4_1^+)-E_x(2_2^+)$, may indicate the possibility that the Ge isotopes undergo a shape transition from oblate to prolate deformation with increasing neutron number. Similar behavior was found also for Se, Zn, and Kr isotopes. This evidence has prompted extensive experimental studies on the even mass $^{68-76}$Ge isotopes.[1,12,15,16] Vergnes *et al.*[16] have recently indicated from the comparison of (p,t) and (t,p) reactions on Ge isotopes that the structural transition in Ge and in Ga isotopes occurs between $N=40$ and $N=42$.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with a 15-MeV triton beam from the University of Pennsylvania tandem accelerator. The outgoing protons were momentum analyzed with a multiangle spectrograph and recorded on Ilford K5 nuclear emulsion plates in the angular range of 3.75°–86.25° (lab), in 7.5° steps. The ^{70}Ge target was enriched to 98.8% in ^{70}Ge, 70 μg/cm^2 thick, on a 10 μg/cm^2 ^{12}C backing. Mylar absorbers of thickness up to 0.015 in. directly in front of the focal plane stopped all particles except protons. The exposure was 3.0 mC.

Displayed in Fig. 1 is a spectrum from the ^{70}Ge$(t,p)^{72}$Ge reaction at 15 MeV and 11.25° lab. The energy resolution is about 20 keV full width at half maximum. Groups arising from states in ^{72}Ge are labeled with their excitation energies. These were obtained at each angle using the energy calibration of the multiangle spectrograph and averaged to get the values listed in Table I.

A separate, shorter (t,p) run was performed on a natural Ge target to assist in identifying impurity peaks due to the presence of small amounts of other stable Ge isotopes in the ^{72}Ge target. Impurity peaks are labeled in Fig. 1 according to their final state in the residual nuclei.

The uncertainty in the absolute cross section is about 20% and arises primarily from the uncertainty in the target thickness. The target thickness was estimated by normalizing the elastic

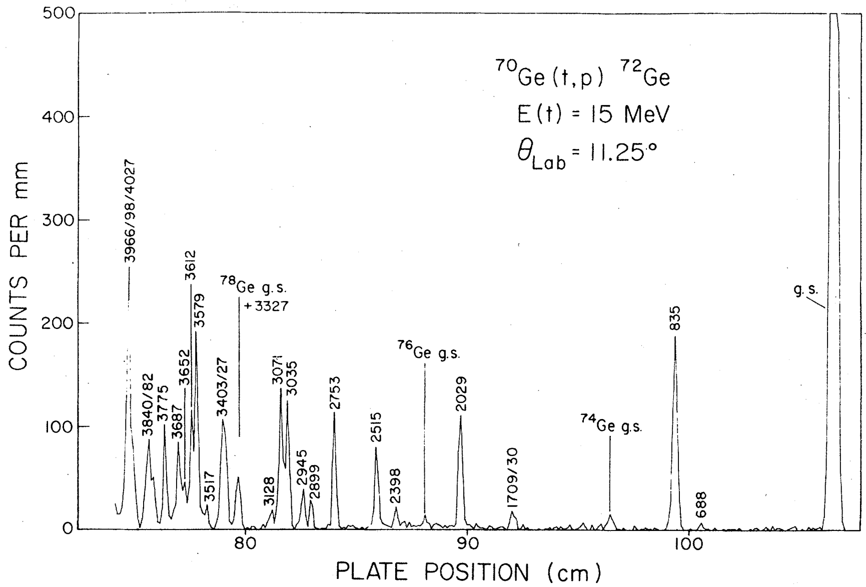

FIG. 1. Proton spectrum from the ^{70}Ge$(t,p)^{72}$Ge reaction measured at 15-MeV incident energy and at a lab angle of 11.25°. The levels in ^{72}Ge are indicated by their excitation energies. Impurity groups are labeled according to their residual nucleus.

scattering (measured in a solid state monitor detector mounted at 40°) to the cross section predicted by triton optical parameters (Table II) used in the analysis.

III. RESULTS AND ANALYSIS

Measurable cross sections were observed for 30 levels up to 4.03-MeV excitation in ^{72}Ge. Angular distributions were extracted for most of the levels and compared with the results of distorted-wave Born-approximation (DWBA) calculations using the code DWUCK.[17] The triton optical model parameters used in the analysis are identical to those obtained by Hardekopf *et al.*[18] from triton elastic scattering on ^{90}Zr, except for a small adjustment of the real well depth. For the exit channel the global proton parameter set of Perey[19] was used. These potentials have been successfully used in the analysis of (t,p) reactions on heavier Ge isotopes.[1-3]

Figure 2 shows the angular distribution for the ground state of ^{72}Ge, as well as for the other clear $L=0$ transitions observed in the present work. The curves are the results of DWBA calculations. Angular distributions characterized by $L=2$ and $L=4$ angular momentum transfer are displayed in Figs. 3 and 4, respectively. Figure 5 presents the angular distributions for odd L values, and those that appear to contain an admixture of two L values.

We assumed pure configurations (indicated on the figures) for the transferred neutron pair and therefore no attempt has been made to compare the magnitudes of the theoretical and experimental cross sections. In the present and earlier Ge(t,p) work, it was found that the shapes of the DWBA curves, especially for the even-parity states, are somewhat sensitive to the assumed wave functions (see Figs. 2–4), an effect not normally encountered in the (t,p) reaction. Nevertheless, this sensitivity is much less than the difference in curves for different L values, so that L assignments can be made unambiguously. It is not possible to determine if the configuration-dependent shapes are a real effect until detailed wave functions are available.

Table I summarizes the excitation energies, the maximum differential cross section, L value, and spin and parity measured in the present study. Also shown in Table I are the excitation energies and J^{π} values reported in the latest compilation[13] and the results from the reactions ^{71}Ga$(^3$He$,d)^{72}$Ge (Ref. 12) and ^{74}Ge$(p,t)^{72}$Ge (Ref. 10). Whenever correspondences can be made between states observed herein and in (p,t) our excitation energies appear to be consistently lower than those of Ref. 10 by 5–10 keV. We have no explanation for this result.

IV. DISCUSSION

A. 0^+ states in ^{72}Ge populated in the ^{70}Ge(t,p) reaction

With $J^{\pi}=0^+$ for the target and a singlet neutron pair transferred, the orbital angular momentum transfer L uniquely determines the spin and parity of the final state $J_f=L$ and $\pi_f=(-1)^L$. Figure 2 shows the measured angular distributions for the ground state (g.s.) and six excited states in ^{72}Ge, all of which have the typical $L=0$ character. Hence, these are all 0^+ states. The curves are

TABLE I. Summary of results for ^{70}Ge$(t,p)^{72}$Ge and comparison with previous work.

Present work				Previous work[a]					
						^{71}Ga(^{3}He,d)^{72}Ge[b]		^{74}Ge(p,t)^{72}Ge[c]	
E_x (MeV ± keV)	$d\sigma/d\Omega_{max}$ (μb/sr)	$L(t,p)$	J^π	E_x (MeV ± keV)	J^π	E_x (MeV)	J^π	E_x (MeV)	J^π
0.0	3560	0	0^+	0.0	0^+	0.0	0^+–3^+	0.0	0^+
0.688 ± 3	7	0	0^+	0.691 2 ± 0.2	0^+	0.690	0^+–3^+	0.691	0^+
0.835 ± 3	132	2	2^+	0.834 01 ± 0.02	2^+	0.835	1^+–3^+	0.835[d]	2^+
1.461 ± 3	<2			1.463 93 ± 0.04	2^+	1.465	0^+–3^+	1.467[d]	2^+
1.709 ± 5	8	(0)	(0^+)						
1.730 ± 5	11	4	4^+	1.728 25 ± 0.04	4^+	1.725	1^+–5^+	1.730[d, e]	4^+
2.029 ± 3	118	0	0^+			2.029	0^+–3^+	2.029[d]	(0^+)
				2.064 82 ± 0.05	$(3)^+$	2.062	1^+–3^+		
2.398 ± 5	6	(4+ 2)	$(4^+, 2^+)$	2.402 16 ± 0.09		2.404	0^+–3^+	2.406	2^+
2.464 ± 5	3	(4)	(4^+)	2.463 77 ± 0.06	(4^+)	2.466	1^+–5^+	2.468	4^+
				2.505 ? ± 5					
2.515 ± 5	77	3	3^-	2.514 69 ± 0.05	3^-	2.516	2^-–6^-	2.519	3^-
				2.583 5 ± 0.4					
2.753 ± 5	90	0	0^+	2.754 1 ± 0.2	$\pi = -$	2.754	1^+–3^+		
2.899 ± 5	18	0	0^+			2.897	0^+–3^+		
				2.939 87 ± 0.08					
2.945 ± 5	19	3	3^-	2.943 47 ± 0.06	3^-				
				2.950 3 ± 0.2		2.949	1^+–3^+	2.951	
3.035 ± 5	39	2	2^+	3.035 63 ± 0.12	(2^-)	3.034	1^+–3^+	3.037	
3.071 ± 5	59	4	4^+			3.073	1^+–5^+	3.078	4^+
				3.094 2 ± 0.1	4^+	3.094	1^+–3^+	3.098	2^+
3.128 ± 5	14	(5)+ (0)	$(5^-)+(0^+)$	3.119 ± 15	$\pi = -$			3.139	0^+
						3.179	1^+–5^+	3.185	4^+
				3.228 ± 10	$\pi = -$	3.223	1^+–3^+		
3.327 ± 5	24	(2+ 4)	$(4^+, 2^+)$	3.324 92 ± 0.04	$(2)^-$	3.324	1^+–3^+		
				3.338 1 ± 0.1				3.330	2^+
				3.341 72 ± 0.06	$(3)^-$				
						3.357	1^+–3^+		
								3.378	4^+
3.403 ± 5	41	(4)	(4^+)	3.398 ± 10					
3.427 ± 5	28	4	4^+	3.419 5 ± 0.3		3.422	1^+–3^+	3.421[f]	2^+
				3.439 3 ± 0.3		3.436	1^+–3^+		
				3.455 27 ± 0.09					
						3.468	2^-–4^-		
3.517 ± 5	11	(4)	(4^+)			3.506	1^+–3^+	3.509	2^+
								3.528	4^+
				3.550 7 ± 0.6				3.554	(1^-)
				3.566 0 ± 0.2		3.565	{1^+–3^+, 2^-–4^-}		
3.579 ± 5	145	0	0^+					3.589	0^+
3.612 ± 5	36	2	2^+	3.619 5 ± 0.5		3.614	0^+–3^+	3.625	2^+
3.652 ± 5	26	(5)+ (2)	$(5^-)+(2^+)$	3.666 8 ± 0.2		3.662	1^+–3^+	3.663	(6^+)
				3.678 1 ± 0.2					
3.687 ± 5	29	2	2^+			3.691	1^+–3^+	3.703	2^+
				3.708 3 ± 0.6					
				3.758 6 ± 0.8					
3.775 ± 5	48	(0+ 2)	$(0^+ + 2^+)$			3.777	1^+–3^+		
				3.803 7 ± 0.2					
				3.816 0 ± 0.3		3.815	2^-–4^-	3.821	5^-
3.840 ± 5	19	4	4^+					3.850	4^+
3.882 ± 5[g]	46	2	2^+	3.872 0 ± 0.5		3.867			
				3.890 ± 5	$\pi = -$	3.895	1^+–3^+	3.890	
3.966 ± 5	25	2	2^+	3.965 ± 10	$\pi = -$	3.975	{1^+–3^+, 2^-–4^-}		
				3.983 8 ± 0.2				3.981	(2^+)
				3.985 8 ± 0.2					
3.998 ± 5	95	(0+ 2)	$(0^+ + 2^+)$	3.995 0 ± 0.3		4.002	1^+–3^+		
								4.013	4^+
4.027 ± 5	15	4	4^+						
				4.040 8 ± 0.2		4.047	1^+–3^+		
								4.076	5^-

[a] Reference 13 (states above 4.041 MeV are not listed).
[b] Reference 12 (states above 4.047 MeV are not listed).
[c] Reference 10.
[d] Not fitted by DWBA in Ref. 10.
[e] Presence of unseparated impurity in Ref. 10.
[f] Unseparated doublet in Ref. 10.
[g] Unseparated doublet in present work.

TABLE II. Optical-model parameters used in analysis of the ^{70}Ge$(t,p)^{72}$Ge reaction.

	Set	V_0 (MeV)	r_0 (fm)	a (fm)	W (MeV)	$W'=4W_D$ (MeV)	r_0' (fm)	a' (fm)	r_c (fm)
^{70}Ge+ t [a]	1	150 [b]	1.20	0.65	13.5	0	1.60	0.87	1.3
^{72}Ge+ p [a]	1	46.1	1.25	0.65	0	49.9	1.25	0.47	1.25
^{70}Ge+ n		c	1.26	0.60					

[a] Reference 18.
[b] V_0 was adjusted to fit the first minimum in the angular distribution for the ground state.
[c] Adjusted to give a binding energy to each particle of $0.5[Q(t,p)+8.482]$ MeV.

the results of DWBA calculations using the optical potentials listed in Table II.

Among the seven 0^+ states whose angular distributions are displayed in Fig. 2, only the g.s. and the 0.688-MeV level were previously assigned as 0^+. In (p,t) a tentative (0^+) assignment was given to a level at 2.029 MeV. As an example of the configuration dependence observed in the present study, the g.s. angular distribution is compared with two DWBA curves obtained assuming $(1g_{9/2})^2$ and $(2p_{1/2})^2$ configurations for the transferred neutron pair. The curves differ considerably in the region of the first minimum. It is clear that the $(1g_{9/2})^2$ curve fits the data better than the $(2p_{1/2})^2$ curve, although $(2p_{1/2})^2$ is more likely on the basis of the simple shell model. However, for the first excited 0^+ state at 0.688 MeV the opposite seems to be true—its gross structure is better fitted with the $(2p_{1/2})^2$ curve than with the $(1g_{9/2})^2$ curve. But it is an extremely weak state (~0.2% only of the g.s. strength) and for such weak states, other more complicated reaction processes may also be present and may somewhat distort the angular distribution shape.

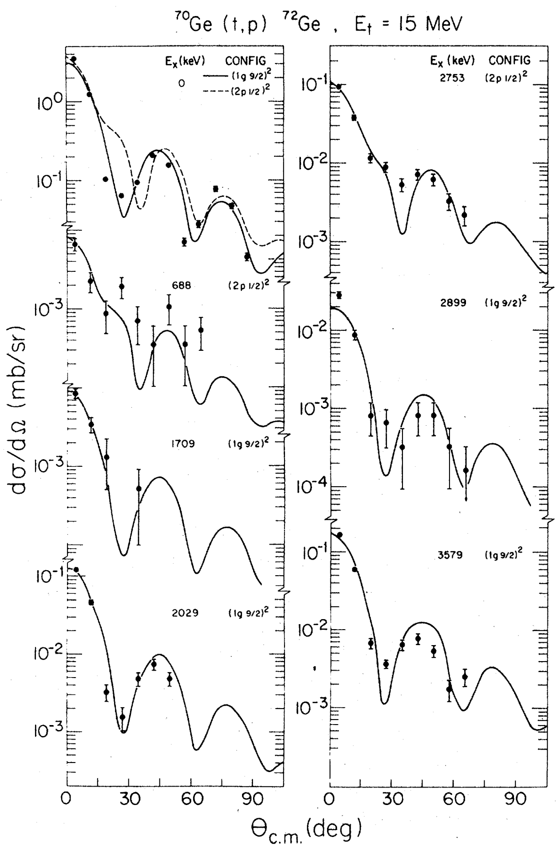

FIG. 2. Angular distributions exhibiting $L=0$ character in the ^{70}Ge$(t,p)^{72}$Ge reaction. The curves are the results of DWBA calculations using the optical parameter sets of Table II.

The state at 1.709 MeV is a new state in ^{72}Ge just below the well-known 4_1^+ at 1.730 MeV. Since it is weak and partly obscured by the 1.730-MeV state, its angular distribution could be extracted only at forward angles. However, it possesses the forward angle rise typical for $L=0$ transfer. Thus we make a tentative (0^+) assignment for this new state.

The states at 2.029 and 2.899 MeV were not reported in the latest compilation,[13] but they were

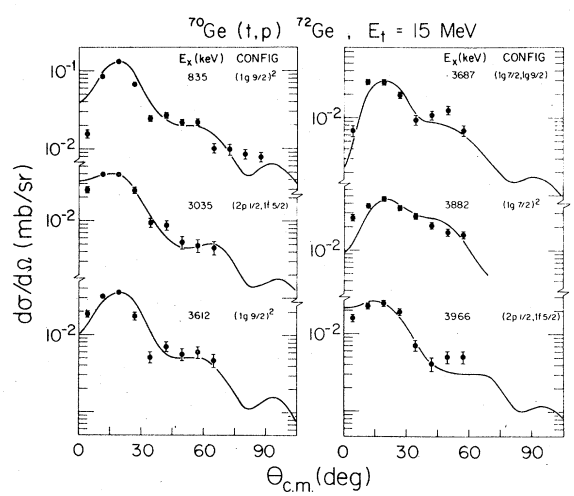

FIG. 3. Angular distributions for levels with $J^\pi=2^+$ reached in the ^{70}Ge(t,p) reaction, compared with $L=2$ DWBA calculations, using the configurations listed.

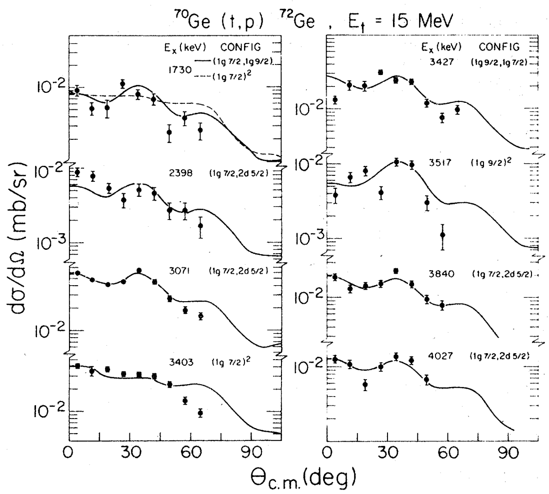

FIG. 4. Same as Figs. 2 and 3, but for $J^{\pi}=4^{+}$ levels.

observed in a recent study of ^{72}Ge with the (^{3}He, d) reaction,[12] where a limit $0^{+}-3^{+}$ has been given to both states. Our data show that these two states have the typical character of $L=0$, allowing us to make firm 0^{+} assignments for both states.

A state at 2.754 MeV was assigned negative parity from the (p,d) reaction of Fournier *et al.*[9] but, in the recent work of Ardouin *et al.*,[12] a spin limit of $1^{+}-3^{+}$ was given to what appears to be the same state in contradiction to the $\pi=-$ assignment.[9] Our angular distribution for this state is well fitted by an $L=0$ curve, and we assign 0^{+} to it. Neither the 2.899- nor 2.754-MeV levels were observed in (p,t).

The state at 3.579 MeV is probably to be identified with a 0^{+} state reported at 3.589 MeV in (p,t). The present angular distribution has a clear $L=0$ shape, implying $J^{\pi}=0^{+}$.

Three additional states in ^{72}Ge below 4-MeV excitation may contain $L=0$ components in their angular distributions. These are the states at 3.128, 3.775, and 3.998 MeV, which will be discussed later in subsection D.

The main feature of the observed $L=0$ strengths is that the transition to the g.s. of ^{72}Ge dominates the spectrum. The 0_2^{+} and the 0_3^{+} are about three orders of magnitude weaker, while the higher 0^{+} states are one to two orders of magnitude weaker. This is in sharp contrast to the behavior of (t,p) reactions near shell closures, where transitions to excited 0^{+} levels are often stronger than to the ground state. From the (t,p) cross section of the 0^{+} states alone it seems that ^{72}Ge differs considerably from the heavier even isotopes. In ^{72}Ge the first excited 0^{+} state is the weakest 0^{+} observed up to 4-MeV excitation. In ^{74}Ge and ^{76}Ge the 0_2^{+} has the highest (t,p) cross section observed for an excited 0^{+} state and in ^{78}Ge it is among the strongest ones. The first 0^{+} state in ^{72}Ge that has a strength comparable to that of the first excited 0^{+} states in ^{74,76,78}Ge isotopes is the 0^{+} state at 2.029 MeV. Thus it seems doubtful if the 0.688-MeV 0^{+} state in ^{72}Ge could really be associated with the first excited 0^{+} state in ^{74,76,78}Ge isotopes as has been suggested recently.[14,16] The probable presence of an additional weak 0_3^{+} in ^{72}Ge at 1.709 MeV makes the correspondence even more complicated.

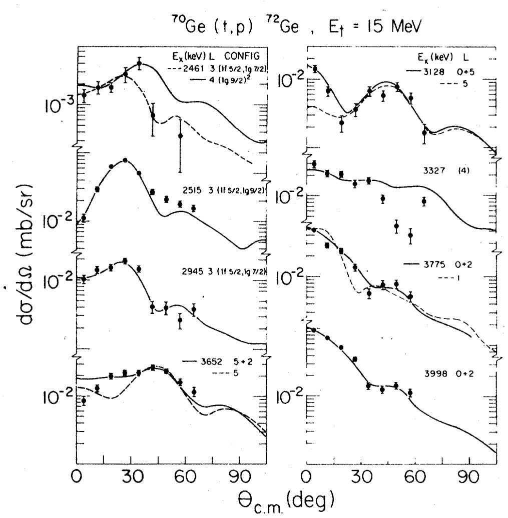

FIG. 5. Angular distributions leading to negative parity states in ^{72}Ge, and angular distributions fitted by an admixture of two L values, or for which no definite assignment could be made.

B. 2^{+} states in ^{72}Ge

Figure 3 presents the angular distributions for six states in ^{72}Ge which appear to be characterized by $L=2$ angular momentum transfer, together with the DWBA curves. The first of these states is at 0.835 MeV, well known previously to have $J^{\pi}=2^{+}$.

The second 2^{+} state at 1.464 MeV is so weak that no angular distribution could be extracted for it. The upper limit for its (t,p) cross section is 2 μb/sr.

Three additional 2^{+} states were observed in the present study at 3.035, 3.612, and 3.687 MeV. All three are well fitted with $L=2$ DWBA curves, allowing unambiguous 2^{+} assignment for these states. The configurations assumed for the different curves are indicated in the figure. The 3.612- and 3.687-MeV states probably correspond to the 2^{+} levels observed at 3.625 and 3.703 MeV in (p,t), and to states observed at 3.614 and 3.691 MeV in Ref. 12 and assigned $J^{\pi}=0^{+}-3^{+}$ and $J^{\pi}=1^{+}-3^{+}$, respectively. Our 2^{+} assignment for the 3.035-MeV state contradicts a previous[13] tentative (2^-) assignment given to this state, but agrees with the J^π limits 1^+-3^+ suggested in the recent ^{71}Ga(^{3}He, d) work.[12]

The states at 3.882 and 3.966 MeV observed in the present work both have been reported in the literature, but without definite J^π assignments. Our results allow a firm 2^+ assignment for both states.

No additional angular distributions were found in the present work to have a unique $L=2$ character. However, additional 2^+ states may exist as one member of various doublets. They are discussed further below.

An interesting feature of the observed 2^+ states is that the 2_1^+ state at 0.835 MeV has the largest (t,p) strength while the next 2^+ at 1.461 is the weakest of them all. Similar behavior has also been observed in the heavier Ge isotopes.[1-3]

A smooth systematic dependence on N can be noted in both the energies and (t,p) strengths of the 2^+ states. Figure 6 shows the lowest three 2^+ states in ^{72}Ge populated in the present study compared with the corresponding states in ^{74}Ge, ^{76}Ge, and ^{78}Ge. The (t,p) strengths are indicated in the figure. We note the following as N increases:

(a) The energy of the 2_1^+ and 2_2^+ remains almost the same (especially above ^{72}Ge) while that of 2_3^+ decreases on the average.

(b) The (t,p) strength for the first 2^+ state decreases systematically, while $\sigma(2_2^+)$ increases.

(c) The summed 2^+ strength decreases. Since the transition to the g.s. has almost the same strength for all isotopes (~3.6 mb/sr), the ratio $\sigma(2_1^+)/\sigma(\text{g.s.})$ is significantly larger in ^{72}Ge and ^{74}Ge than in ^{76}Ge and ^{78}Ge. In previous (t,p) reactions on even-even target nuclei, it was found[20] that the 2_1^+ state is especially strongly excited in the transfer $N_0 \rightarrow N_0+2$ where N_0 represents a closed neutron shell.

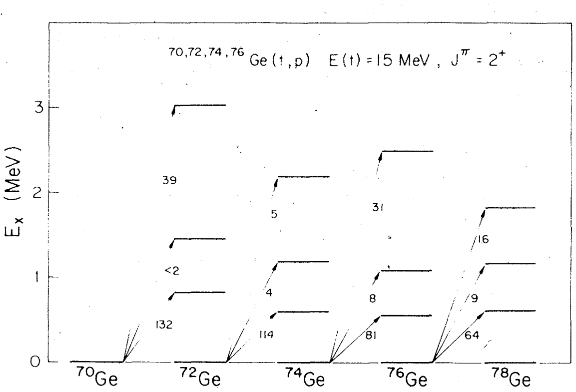

FIG. 6. $L=2$ transitions observed in the present work compared with the corresponding transitions observed in the (t,p) reaction on ^{72,74,76}Ge (Refs. 1–3). The numbers at the arrows are the maximum differential cross sections.

C. $J^\pi = 4^+$ states

Figure 4 displays eight angular distributions observed in the present study to be dominated by $L=4$ angular momentum transfer. In general the strong transitions could be well fitted by the theoretical curves, but the weak ones only moderately. The presence of the first 4^+ state at 1.730 MeV is well known. Our 3.071-MeV level is probably to be identified with the 4^+ state reported in (p,t) at 3.078 MeV. Its angular distribution is very well fitted with the $L=4$ theoretical curve, giving $J^\pi=4^+$. This state was reported for the first time in the ^{71}Ga(^{3}He, d) reaction,[12] with J^π limits of 1^+-5^+.

Our 4^+ assignments for states at 3.403 and 3.427 MeV are new. We do not observe the 2^+ level reported at 3.421 MeV in (p,t). If it is present it is unresolved from one of these 4^+ states, and weakly populated in (t,p). The 4^+ level at 3.517 MeV is probably to be identified with the 4^+ state observed in (p,t) at 3.528 MeV.

The angular distribution for the 3.403-MeV state differs somewhat from the others presented in the figure. While all the other $L=4$ distributions exhibit a local maximum at ~35°, the angular distribution for this state is rather flat in this region. It was found that the best fit could be obtained assuming a configuration $(1g_{7/2})^2$ and $L=4$ for the transferred two neutrons. No other single L value can reproduce this shape as well. We thus suggest (4^+) for this state, which has no previous assignment.

The states at 3.427 and 3.517 MeV both are suggested to have $J^\pi = 1^+-3^+$ in Ref. 12. The first is well fitted in the present work by an $L=4$ curve, while for the latter, which is a much weaker state, the fit is relatively inferior. We therefore assign 4^+ for the state at 3.427 MeV and tentatively (4^+) for the 3.517-MeV state.

The states at 3.840 and 4.027 are well fitted by the theory allowing us to make firm 4^+ assignments for both states. These states were not reported in the recent ^{71}Ga(^{3}He, d) reaction[12] nor in the older work,[13] but probably correspond to 4^+ states observed at 3.850 and 4.013 MeV in (p,t).

Our 4^+ assignment for the 2.398-MeV state does not agree with the J^π limits of 0^+-3^+ reported recently[12] for a state at 2.404 MeV. The (p,t) work assigns 2^+ to a state at 2.406 MeV. Our angular distributions could contain an $L=2$ component, but also appears to possess an appreciable $L=4$

contribution.

A state at 2.468 MeV, which has a 4^+ assignment in (p,t), is very weak in the present work and is discussed later.

D. Angular distributions characterized by odd or mixed L values

Figure 5 displays the (t,p) angular distributions characterized by odd L values and additional ones which cannot be fitted with any single L value. Up to 4-MeV excitation, we observe two $L=3$ transitions, leading to states at 2.515 and 2.945 MeV. Both were well known previously as 3^- (Ref. 13), and in both cases the theoretical $L=3$ curves give excellent fits to the data. An additional tentative $(3)^-$ state reported previously at 3.342 MeV (Ref. 13) was not observed in the present study.

The angular distribution of the 2.464-MeV state is compared with both $L=3$ and 4 curves. A state at this energy has a previous 4^+ assignment. Our data add no new information.

We observe no angular distributions that are well fitted by $L=5$ curves. However, those for states at 3.128 and 3.652 MeV have a maximum near $\theta=45°$ and thus must possess an appreciable component of a large L value. The first can be moderately well fitted by $L=5+0$. A 0^+ state was reported at 3.139 MeV in (p,t) and probably accounts for the $L=0$ component. But an additional state (with large J) may be present. A state at 3.119 MeV was assigned as $\pi=-$ in the recent compilation.[13] The doublet at 3.652 MeV may correspond to the states at 3.667 and 3.678 MeV,[13] with no rigorous J^π assignment. The 3.653-MeV angular distribution can be fitted with a combination of $L=2$ and some large L value (5 or 6). A tentative (6^+) state was suggested at 3.663 MeV in (p,t). This is probably the same state.

There is a striking similarity in the structure of the negative-parity states observed in ^{72}Ge and the corresponding states in the heavier Ge isotopes. Each negative parity state observed in the present work has a close counterpart in ^{74}Ge and also in ^{78}Ge. In ^{76}Ge only one 3^- state and one 5^- state have been observed. Table III summarizes the excitation energies and (t,p) strengths for the 3^- and 5^- states observed in the even Ge isotopes.[1-3] The states listed in the table are the only 5^- and 3^- states observed in ^{72,74,76,78}Ge up to about 4-MeV excitation, except for ^{74}Ge and ^{78}Ge where only the lower two 3^- states have been listed.

Figure 5 also shows the angular distribution for a weak state at 3.327 MeV, which has been reported with contradicting parity assignments.[12,13] No theoretical curve for a single L value can adequately fit this distribution, but a sizable $L=4$ component appears to be present. A 2^+ state was reported at 3.330 MeV in (p,t). We make no definite assignment for this state.

In the present work we observe no clear $L=1$ transition up to 4-MeV excitation. The angular distributions for the states at 3.775 and 3.998 MeV possess enough of a forward rise that they must possess a large component of either $L=0$ or $L=1$. The analysis shows that in both cases an admixture of $L=0$ and $L=2$ fits the data better than $L=1$ or a mixture of $L=1$ and some higher L value (not shown in Fig. 5). We thus tentatively assign $J^\pi=(0^++2^+)$ for both doublets. The 2^+ member of our 3.775-MeV level probably corresponds to the state at 3.777 ($J^\pi=1^+-3^+$) observed in the ^{71}Ga(^{3}He$,d$) reaction[12] and the 0^+ member to the state at 3.758 reported in an earlier work but without any J^π assignment.[13] Similarly, our level at 3.998 MeV probably corresponds to the two close lying states at 4.002 ($J^\pi=1^+-3^+$) of Ref. 12, and the state at 3.995 MeV reported earlier[13] but without any assignment.

We find no evidence for a 4^+ level reported at 3.185 MeV in (p,t). If present, it is very weak in (t,p).

TABLE III. The distribution of the lowest two 3^- and 5^- states in ^{72,74,76,78}Ge populated in the Ge(t,p) reactions.[a]

	70→72		72→74		74→76		76→78	
J^π	E_x (MeV)	$\frac{d\sigma}{d\Omega}$ (μb/sr)	E_x (MeV)	$\frac{d\sigma}{d\Omega}$ (μb/sr)	E_x (MeV)	$\frac{d\sigma}{d\Omega}$ (μb/sr)	E_x (MeV)	$\frac{d\sigma}{d\Omega}$ (μb/sr)
3_1^-	2.515	77	2.538	38	2.693	59	2.744	11
3_2^-	2.945	19	3.144	23	···		(3.236)	≈60
5_1^-	3.128	≈9	3.108	17	2.957	35	2.639	31
5_2^-	(3.652)	26	3.683	22	···		4.036	16

[a] The relative cross sections have been normalized using the $^{\rm Nat}$Ge(t,p) reaction. The uncertainty in the relative cross sections is about 10%.

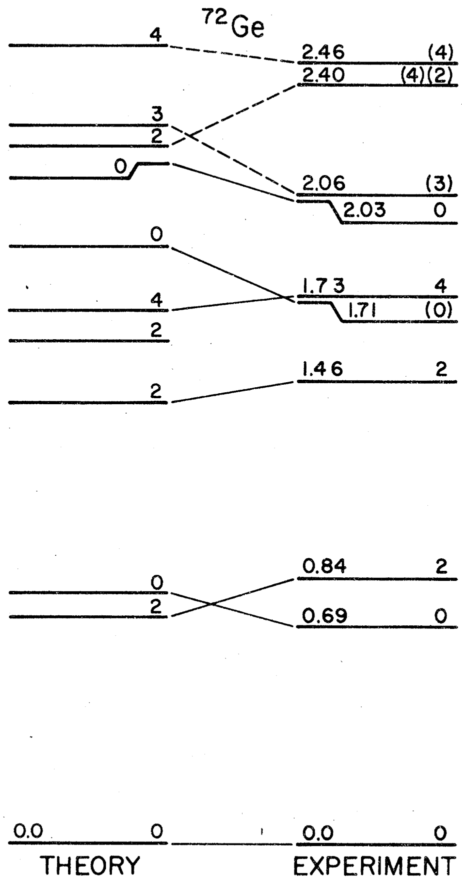

FIG. 7. Level scheme of ^{72}Ge from previous results and the present study, compared with the dynamic deformation theory calculations of Kumar (Ref. 21).

V. SUMMARY AND CONCLUSIONS

In the present study of ^{72}Ge via the ^{70}Ge(t,p) reaction, many new spin and parity assignments have been made above 1.5-MeV excitation. Several new 0^+ states have been observed, the first of which is probably at 1.709 MeV. In view of this new observation it is not clear which 0^+ in ^{72}Ge has the character of the first excited 0^+ states in ^{74,76,78}Ge isotopes.

There is a striking similarity in the structure of the 2^+ states and the negative parity states observed in ^{72}Ge and those observed in the (t,p) reaction on heavier even Ge isotopes.

Recently Kumar[21] has studied the spectra of ^{70,72,74}Ge using a dynamic deformation theory. Figure 7 presents a comparison between the experimental level scheme of ^{72}Ge obtained from previous and present work and the theoretical level scheme calculated by Kumar. Except for the higher 2^+ states, there is a remarkable agreement between experiment and theory up to 2.5 MeV. It is especially interesting to mention that the new 0^+ states at 1.709 and 2.029 MeV are both predicted by the model within less than 200-keV deviation. Thus these two states correspond to the 0_3^+ and 0_4^+ states in ^{72}Ge respectively.

The particular lowering of the 0_2^+ state in ^{72}Ge in comparison with the neighboring nuclei is well accounted by the theory and is attributed according to the model to the spherical-oblate shape transition in the Ge isotopes. However, the calculations predict the 2_1^+ and the 0_2^+ in ^{72}Ge in a reverse order. The 2_3^+ and 2_4^+ states predicted by the theoretical calculations near 2-MeV excitation have no clear counterpart in the present study. These may lie in the weak states not observed in the present study but reported in earlier works, i.e., the states at 2.062 (Ref. 12) and 2.505 MeV (Ref. 13).

We are grateful to Dr. G. E. Moore, Dr. M. E. Cobern, and Dr. R. V. Kollarits for help with the data acquisition, and to the National Science Foundation for financial support. We also thank L. Csihas for preparing the ^{70}Ge target and Mrs. Kalliopi Coliukos for the careful scanning of the nuclear emulsion plates.

*Present address: Department of Physics, Ben-Gurion University, Beer-Sheva, Israel.

[1]J. F. Mateja, L. R. Medsker, H. T. Fortune, R. Middleton, S. Mordechai, G. E. Moore, M. E. Cobern, J. D. Zumbro, and C. P. Browne, Phys. Rev. C 17, 2047 (1978).

[2]S. Mordechai *et al.*, Phys. Rev. C 18, 2498 (1978).

[3]S. LaFrance, S. Mordechai, H. T. Fortune, R. Middleton, Nucl. Phys. A307, 52 (1978).

[4]A. C. Rester, A. V. Ramayya, J. H. Hamilton, D. Krmpotic, and A. Venugopala Rao, Nucl. Phys. A162, 461 (1971); H. Behrens and F. Brodt, Z. Phys. 243, 402 (1971).

[5]A. C. Rester, J. H. Hamilton, A. V. Ramayya, and Noah R. Johnson, Nucl. Phys. A162, 481 (1971).

[6]K. C. Chung, A. Mittler, J. D. Brandenberger, and M. T. McEllistrem, Phys. Rev. C 2, 139 (1970).

[7]T. H. Curtis, H. F. Lutz, and W. Bartolini, Phys. Rev. C 1, 1418 (1970).

[8]M. Kregar and B. Elbek, Nucl. Phys. A93, 49 (1967).

[9]R. Fournier, J. Kroon, T. H. Hsu, B. Hird, and G. C. Ball, Nucl. Phys. A202, 1 (1973).

[10]F. Guilbault *et al.*, Phys. Rev. C 16, 1840 (1977).

[11]G. C. Ball, R. Fournier, J. Kroon, T. H. Hsu, and B. Hird, Nucl. Phys. A231, 334 (1974).

[12]D. Ardouin, T. Tamisier, G. Berrier, J. Kalifa, G. Rotbard, and M. Vergnes, Phys. Rev. C 11, 1649 (1975).

[13]Nucl. Data Sheets, 11, No. 2 (1974).
[14]D. Ardouin, T. Tamisier, M. Vergnes, G. Rotbard, J. Kalifa, G. Berrier, and B. Grammaticos, Phys. Rev. C 12, 1745 (1975).
[15]F. Guilbault, D. Ardouin, T. Tamisier, P. Avignon, M. Vergnes, G. Rotbard, G. Berrier, and R. Seltz, Phys. Rev. C 15, 894 (1977).
[16]M. N. Vergnes, G. Rotbard, F. Guilbault, D. Ardouin, C. Lebrun, E. R. Flynn, D. L. Hanson, and S. D. Orbesen, Phys. Lett. 72B, 447 (1978).
[17]P. D. Kunz, the Code DWUCK, Univ. of Colorado (unpublished).
[18]R. A. Hardekopf, L. R. Veeser, and P. W. Keaton, Jr., Phys. Rev. Lett. 35, 1623 (1975).
[19]F. G. Perey, Phys. Rev. 131, 745 (1963).
[20]R. A. Broglia, O. Hansen, and C. Riedel, *Advances in Nuclear Physics*, edited by M. Baranger and E. Vogt (Plenum, New York, 1973), Vol. 6.
[21]K. Kumar, J. Phys. G4, 849 (1978).