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^{74}Ge(t,p)^{76}Ge reaction

S. Mordechai,* H. T. Fortune,† R. Middleton, and G. Stephans
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
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The reaction ^{74}Ge(t,p)^{76}Ge has been investigated with a 15 MeV triton beam. Twenty-six energy levels of ^{76}Ge were identified up to about 4 MeV excitation, five of which were unreported previously. Angular distributions were measured and compared with distorted-wave Born-approximation calculations. The first and second excited 0^+ states in ^{76}Ge have been located at 1.911 and 2.901 MeV. Thirteen additional new spin and parity assignments have been made. The systematic structure of the low-lying 0^+ states observed in the Ge(t,p) reactions on several isotopes support the idea of a shape transition previously proposed for these nuclei but for $N \geq 46$ there is a rapid change toward a spherical shape.

[NUCLEAR REACTIONS ^{74}Ge(t,p), E_t=15.0 MeV; measured $\sigma(E_p, \theta)^{76}$Ge deduced levels, L, π, J. DWBA analysis.]

I. INTRODUCTION

The ^{76}Ge nucleus has been extensively studied via the reactions ^{76}Ge(p,p') (Ref. 1), ^{76}Ge($n,n'\gamma$) (Ref. 2) by β decay from ^{76}Ga (Ref. 3), Coulomb excitation[4], and by the inelastic scattering of α particles and heavier ions.[5] No study of ^{76}Ge via a direct transfer reaction has been reported. This is primarily due to the fact that there is no suitable target from which one may populate ^{76}Ge in a simple direct reaction except for (t,p).

The ^{76}Ge nucleus displays an energy structure of a somewhat vibrational character. However, it appears[5] to have at most two members of a two-phonon triplet state, while the neighboring nuclei ^{74}Ge and ^{76}Se both have all three members. The structure of the other even mass Ge isotopes has been extensively studied.[6-12] Recent results[7] indicate the possibility of an oblate to prolate shape transition with increasing neutron number N for both Ge and Se isotopes, and the existence of a critical zone around $N=40$ where there is coexistence of spherical, oblate, and prolate tendencies. It was noted[7] that such a shape transition may be correlated with the excitation energy systematics of the second 0^+ state and the energy difference between the 4_1^+ and 2_2^+ states, $E_x(4_1^+)-E_x(2_2^+)$. Further evidence for shape transition in the Ge isotopes was recently suggested also from the comparison of the (p,t) and (t,p) reactions on Ge isotopes.[12]

In this work we report on the ^{74}Ge(t,p)^{76}Ge reaction. The aim of the present work was to study the level structure of ^{76}Ge via a direct transfer reaction and thus to extend the knowledge on the systematics of the level structure of the even mass Ge isotopes in light of a possible shape transition.

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 spectograph, and recorded on Ilford K-5 nuclear emulsion plates in the angular range of 3.75° – 86.25° laboratory in 7.5° steps. The ^{74}Ge target was enriched to 94.5% in ^{74}Ge, 80 μg/cm^2 thick, on a 10 μg/cm^2 ^{12}C backing. Mylar absorbers of thickness up to 0.38 mm directly in front of the focal plane stopped all particles except protons. The exposure was 5000 μc.

Displayed in Fig. 1 is a spectrum from the ^{74}Ge (t,p)^{76}Ge reaction at 15 MeV and 18.75° laboratory. The groups arising from states in ^{76}Ge are labeled according to their excitation energies. The energy resolution is about 20 keV full width at half maximum. Excitation energies 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 ^{74}Ge target. Impurity peaks arising from the (t,p) reaction on ^{12}C, ^{16}O, and ^{32}S were also identified from their systematic shift with the scattering angle, and are labeled in Fig. 1 according to their final state in the residual nuclei.

The uncertainty in the absolute cross-section scale is about 25% and arises primarily from uncertainty in the target thickness. The target thickness was estimated by normalizing the elastic scattering (measured via a solid state monitor detector mounted at 40°) to the cross section predicted by the triton optical parameters (Table II, Set 1) used in the analysis of the present work.

III. RESULTS AND ANALYSIS

Measurable cross sections were observed for

TABLE I. Summary of experimental results from ^{74}Ge$(t,p)^{76}$Ge reaction and comparison with previous work.

Level No.	Present work E_x (MeV ± keV)	$d\sigma/d\Omega^{max}$ μb/sr	$L(t,p)$	J^π	Previous work[a] E_x (MeV ± keV)	J^π
0	0.0	(3600)[b]	0	0^+	0.0	0^+
1	0.562 ± 5	87	2	2^+	0.563 ± 3	2^+
2	1.109 ± 5	9	2	2^+	1.108 ± 4	2^+
3	1.411 ± 5	9	4	4^+	1.410 ± 6	4^+
					1.539 ± 6	
4	1.911 ± 5	180	0	0^+	1.911 ± 12[c]	
5	2.017 ± 5	5	(4)	(4^+)	2.020 ± 10	(4^+)
					2.206 ?	
					2.284 ± 3[d]	(3^-)
					2.478 ?	
6	2.502 ± 5	27	2	2^+	2.504 ?	
					2.517 ? ± 10	
					2.567 ? ± 10	
					2.591 ± 16	
					2.655 ± 3	
7	2.693 ± 5	58	3	3^-	2.692 ± 8	(3^-)
8	2.733 ± 5	8	4	4^+	2.727 ? ± 10	
					2.748 ± 8	
9	2.766 ± 5	7	2	2^+	2.769 ± 14	
10	2.841 ± 5	35	2	2^+	2.842 ± 14	
11	2.901 ± 5	76	0	0^+	2.898 ?	
					2.920 ± 7	
12	2.957 ± 5	38	5	5^-	2.966 ? ± 10	(3^-)
13	2.995 ± 5	72	4	4^+	3.009 ?	
14	3.040 ± 5	13	2	2^+	3.041 ?	
					3.053 ?	
					3.132 ?	
15	3.142 ± 5	17	2	2^+	3.142 ± 7	
16	3.191 ± 5	27	(2,3)	$(2^+,3^-)$	3.182 ± 6	(3^-)
17	3.231 ± 5	34	4	4^+		
18+19	3.314 ± 5[e]	9			{3.312 ± 13, 3.323 ± 7}	
					3.335 ± 5	
20	3.393 ± 5	8	(4)	(4^+)		
					3.409 ± 2	
					3.420 ?	
21	3.472 ± 5[e]	91			3.478 ? ± 5	
					3.484 ?	
					3.498 ? ± 10	(2^+)
22+23	3.539 ± 5[e]	110				
24	3.648 ± 5	30	(2)	(2^+)	3.633 ± 11	
25	3.718 ± 10	<14[f]				
26	3.798 ± 10	<9[f]				
27	3.890 ± 5	91	2	2^+	3.887 ± 2	

[a] Reference 5.
[b] The track density for the g.s. peak at 3.75° is too high to be scanned. The maximum cross section is estimated from the theoretical fit.
[c] This state has a 2^+ assignment in Ref. 2 and a 0^+ in Ref. 1.
[d] This state has not been observed in Ref. 2.
[e] Doublet.
[f] Angular distribution could not be extracted due to uncertainties in impurity contributions.

26 levels up to 3.9 MeV excitation in ^{76}Ge. Angular distributions were extracted for most of the levels and compared with the results of distorted-wave Born-approximation calculations using the code DWUCK.[13] The triton optical model parameters used in the analysis are identical to those obtained by Hardekopf *et al.*[14] 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[15] was used. The DWBA results obtained using these potentials were found to be almost identical in shape to those obtained using the triton parameters of Becchetti and Greenlees listed in the recent Perey review[15] with

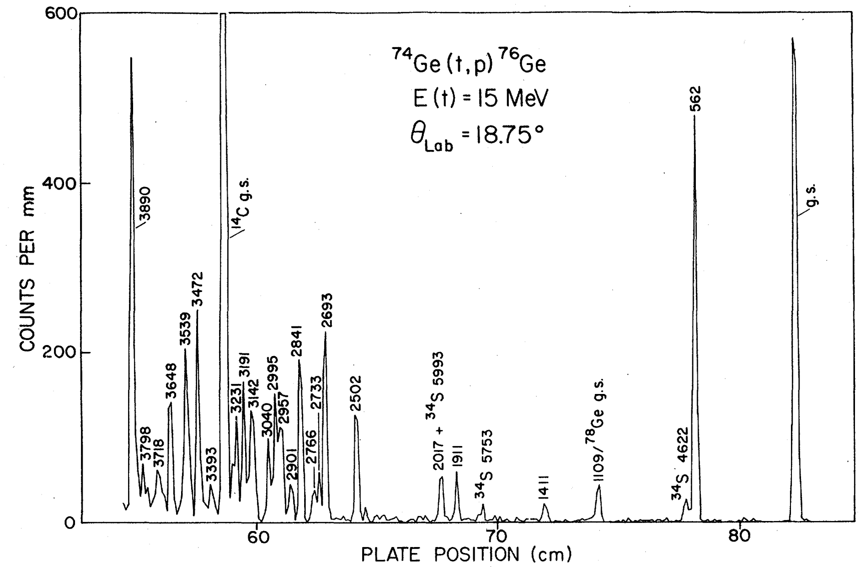

FIG. 1. Proton spectrum from the ^{74}Ge$(t,p)^{76}$Ge reaction measured at 15 MeV incident energy and at a laboratory angle of 18.75°. The levels in ^{76}Ge are indicated by their excitation energies. Impurity groups are labeled according to their residual nucleus.

the same set for the exit channel. An additional set for the triton and the proton used in a recent Ge(p,t) work[11] was also examined. No adjustments of the latter triton set have been done since this potential was derived for the same mass region as the present work. The two potential sets are listed in Table II.

Figure 2 shows the angular distributions for the ground state of ^{76}Ge and for two additional levels observed with $L=0$ transitions in the present work. The solid curves are the DWBA calculations using Set (1,1) of Table II. The dashed curve drawn with the ground state angular distribution represents the calculation using Set (2,2). It is clear that Set (1,1) is superior in fitting the ground state angular distribution, especially in the region of the second maximum. Therefore, for all the DWBA analysis presented below we chose Set (1,1). Figures 3 and 4 contain the angular distributions characterized by $L=2$ and $L=4$ angular momentum transfer, respectively. Figure 5 presents the angular distributions characterized by odd L value.

Since no shell model wave functions were available for ^{76}Ge, we assumed pure configurations for the transferred neutron pair and therefore no attempt has been made to compare the magnitudes of the theoretical and experimental cross sections. We have used the following configurations in the DWBA calculation: $(1g_{9/2})^2$ for $L=0$ and $L=2$ transfers, $(1g_{9/2})^2$ and $(1g_{7/2})^2$ for $L=4$, $(2p_{1/2}, 2d_{3/2})$, for $L=1$, $(2p_{1/2}, 2d_{5/2})$ for $L=3$, and $(2p_{1/2}, 1g_{9/2})$ for $L=5$.

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.[5]

TABLE II. Optical-model parameters used in the analysis of the ^{74}Ge$(t,p)^{76}$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)
^{74}Ge + t [a]	1	155[b]	1.20	0.65	13.5	0	1.60	0.87	1.3
^{74}Ge + t [c]	2	170.0	1.17	0.71	25.3	0	1.47	0.81	1.40
^{76}Ge + p [a]	1	48.6	1.25	0.65	0	50.8	1.25	0.47	1.25
^{76}Ge + p [c]	2	58.6	1.12	0.78	1.7	33.6	1.32	0.60	1.13
^{74}Ge + $2n$		d	1.26	0.60					

[a] Reference 14.
[b] V_0 was adjusted to fit the first minimum in the angular distribution for the ground state.
[c] Reference 11.
[d] Adjusted to give a binding energy to each particle of $0.5[Q(t,p)+8.482]$ MeV.

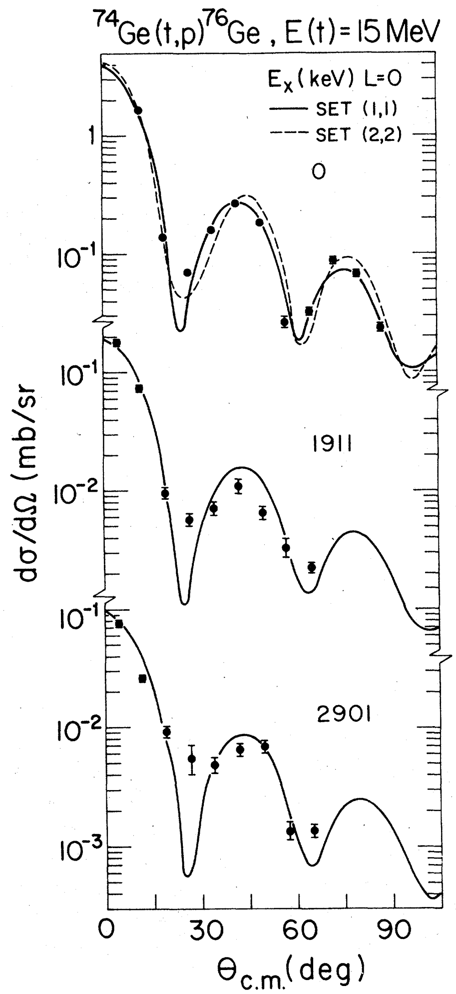

FIG. 2. Angular distributions exhibiting $L=0$ character in the $^{74}Ge(t,p)^{76}Ge$ reaction at 15 MeV incident energy. The solid curves are the results of DWBA calculations using the optical parameter Sets (1,1) of Table II. The dashed curve for the g. s. was calculated with Set (2,2).

IV. DISCUSSION

A. $L = 0$ angular distributions

Figure 2 shows the measured angular distributions to the ground state of ^{76}Ge, and to states at 1.911 and 2.901 MeV. All three angular distributions have an $L=0$ character, and hence correspond to final 0^+ states in ^{76}Ge.

A state near 1.91 MeV has different spin assignments in previous work. Curtis *et al.*[1] assigned 0^+ for a state at 1.902 MeV, using the $^{76}Ge(p,p')$ reaction, while Chung *et al.*[2] have reported 2^+ for a state at $E_x = 1.908$ MeV. In the recent compilation[5] no J^π assignment is given for this state. Our results allow a firm $J^\pi = 0^+$ assignment.

The state at 2.901 MeV also has a clear $L=0$ angular distribution, though its first minimum is not so well reproduced by the theory. We thus assign it as $J^\pi = 0^+$. No spin and parity had been reported previously for this state. Up to 3.9 MeV excitation no other 0^+ states are known in ^{76}Ge. Three states, between 3.3 and 3.6 MeV (discussed later) may be 0^+ levels.

A comparison between the low-lying 0^+ states in ^{76}Ge and those observed in the other Ge(t,p) reactions show an interesting behavior which will be discussed in sub section E.

B. $L = 2$ angular distributions

Figure 3 presents the angular distributions for 10 states in ^{76}Ge that are characterized by $L=2$ angular momentum transfer, together with the DWBA curves. The solid curves were obtained assuming a $(1g_{9/2})^2$ configuration for the transferred neutrons. The dashed curve shown with the 0.562 MeV distribution is the calculated DW curve assuming a $(1g_{9/2}, 1g_{7/2})$ configuration. While the first maximum does not change significantly, the second curve improves somewhat the fit at larger angles.

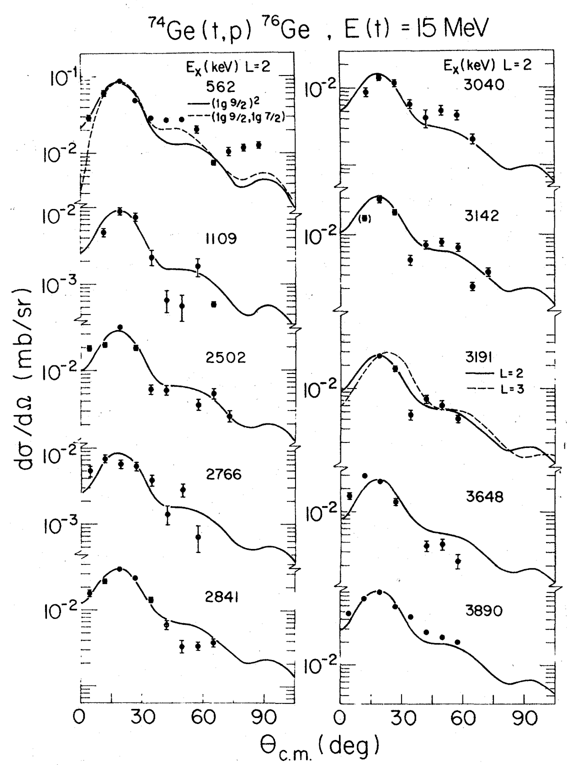

FIG. 3. Angular distributions for levels with $J^\pi = 2^+$ reached in the $^{74}Ge(t,p)$ reaction. The solid lines are DWBA calculations, using parameter Set (1,1).

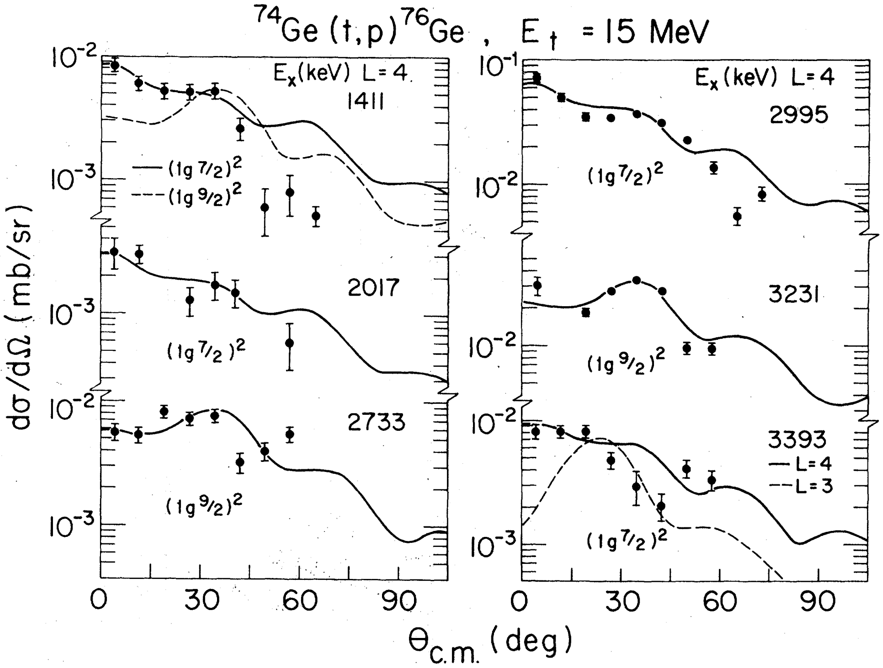

FIG. 4. Angular distributions for $J^\pi = 4^+$ levels reached in the ^{74}Ge(t,p) reaction. The curves are DWBA calculations.

As may be seen from Fig. 3, in most cases the first maximum is well fitted by the theory–implying unambiguous $J^\pi = 2^+$ assignments for these states. Except for the two states at 0.562 and 1.109 MeV which were known[5] previously to have $J^\pi = 2^+$, none of these levels had previous firm J^π assignments. These are the states at 2.502, 2.766, 2.841, 3.040, 3.142, 3.191, 3.648, and 3.890. In Fig. 3, the 3.191 MeV angular distribution is compared with both $L = 2$ and $L = 3$ curves. The data slightly favor $L = 2$, but no firm J^π assignment could be made. It is thus probable that this state corresponds to the state at 3.182 MeV previously reported as (3$^-$) (Ref. 5).

The first excited 2$^+$ state is about an order of magnitude stronger than the second 2$^+$ state. In fact, of the states assigned in the present work as 2$^+$, only the one at 3.890 MeV has a strength comparable to that of the lowest 2$^+$ level. This resembles, though not quite as prominently, the strength distribution observed for the $L = 0$ transitions.

C. $L = 4$ angular distributions

Figure 4 displays six angular distributions observed in the present study to proceed with an $L = 4$ transfer. The first of these is the level at 1.411 MeV, well-known previously as a 4$^+$ state.[5] Its experimental angular distribution is compared with two calculated DWBA curves assuming $(1g_{9/2})^2$ and $(1g_{7/2})^2$ configurations for the transferred neutron pair. Clearly the $(1g_{7/2})^2$ curve fits the data much better than the one calculated using the $(1g_{9/2})^2$ configuration. This sensitivity of $L = 4$ shapes to assumed configuration is not normally encountered in (t,p) reactions. However, the DWBA calculations assuming a transfer into the $1g_{7/2}$ orbital intend to give only a comparison between the calculated DW shapes assuming various orbitals. It is unlikely that the $1g_{7/2}$ orbital

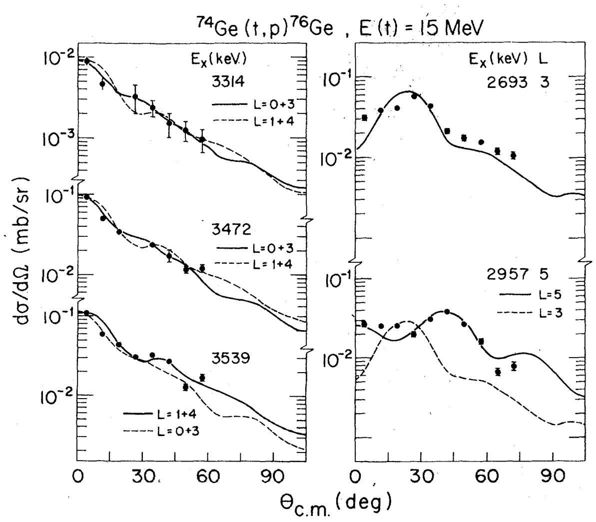

FIG. 5. Angular distributions leading to negative parity states in ^{76}Ge. The left-hand side presents the angular distributions fitted by admixtures of two L values in the ^{74}Ge(t,p) reaction.

can be a predominant component in the wave function of the low-lying states of ^{76}Ge, even though a slight lowering of the $1g_{7/2}$ orbital could be understood in view of the prolate deformation recently suggested for the ^{76}Ge nucleus.[7,12] We are still trying to understand the apparent configuration dependence of angular-distribution shapes. Angular distributions for other states characterized by $L=4$ shape, discussed below, are similar to that for the 1.411 MeV level.

The 2.017 MeV state has a tentative assignment of (4^+) (Ref. 5). The DWBA fit is moderate, allowing only a tentative (4^+) assignment for this state.

The state at 2.733 MeV has no previous assignment. Its angular distribution is well fitted by the $L=4$ DWBA curve. Therefore, we make a 4^+ assignment for this state.

The 2.995 MeV state has no previous assignment. It has an excellent fit in the forward angles with an $L=4$ shape, implying $J^\pi=4^+$.

The two states observed at 3.231 and 3.393 MeV were both unreported previously.[5] The angular distribution of the former is well fitted by $L=4$, allowing a firm 4^+ assignment. For the latter, $L=4$ gives a better fit than any other single L value. So if it is an isolated state, our results imply a tentative assignment of (4^+).

D. Angular distributions characterized by odd L values

Figure 5 shows the angular distributions for five states found in the present work to proceed with odd L values, corresponding to negative parity states in ^{76}Ge. The lowest of these, at 2.693 MeV, has a previous tentative assignment of (3^-) (Ref. 5). It has a clear $L=3$ character in the present work, allowing a firm $J^\pi=3^-$ assignment. A negative parity state at lower excitation energy, 2.284 MeV (3^-), reported in the $^{76}Ge(p,p')$ reaction[1] was not observed either in the present study or in the $^{76}Ge(n,n'\gamma)$ reaction.[2]

The angular distribution of the 2.957 MeV state is very well fitted with an $L=5$ shape. We therefore assign $J^\pi=5^-$ for this state. A nearby state (at 2.966? ± 0.010 MeV) has been reported as (3^-) in $^{76}Ge(p,p')$ (Ref. 1) but not in the $^{76}Ge(n,n'\gamma)$ reaction.[2] If this is actually the same state as the one observed in the present work at 2.957 MeV, then our $J^\pi=5^-$ assignment contradicts the previous tentative assignment.

We observe no angular distributions that are well fitted by $L=1$ curves. However, those for states at 3.314, 3.472, and 3.539 MeV possess enough of a forward rise that they must possess a large component of either $L=0$ or $L=1$. Our 3.314 MeV level probably corresponds to two states

TABLE III. Distribution of the 0^+ states below 2.5 MeV in $^{72,74,76,78}Ge$ populated in the $Ge(t,p)$ reaction[a].

J^π	70→72 E_x (MeV)	70→72 $d\sigma/d\Omega$ (μb/sr)	72→74 E_x (MeV)	72→74 $d\sigma/d\Omega$ (μb/sr)	74→76 E_x (MeV)	74→76 $d\sigma/d\Omega$ (μb/sr)	76→78 E_x (MeV)	76→78 $d\sigma/d\Omega$ (μb/sr)
0_1^+	0.0	1259	0.0	1188	0.0	1501	0.0	1260
0_2^+	0.688	2	1.485	249	1.911	69	1.539	46
0_3^+	1.709	3	1.913	1			2.326	25
0_4^+	2.029	45	2.164	2				
0_5^+			2.229	27				

[a]The cross sections are those measured at 11.25° (laboratory). The uncertainty in the absolute cross sections is about 25%. The relative cross sections have been checked using the (t,p) reaction on a natural Ge target and are accurate to about 10%.

observed at 3.312 ± 0.013 and 3.327 ± 0.007 MeV in ^{76}Ge(p,p'), but which have no J^π assignments. Our data suggest $L=0$ or 1 for one member and $L=3$ or 4 for the other. The 3.472 MeV level is moderately well fitted with $L=1$, but a mixture of $L=0$ and some higher L value does as well. Three possible states were previously reported near here—at 3.478? $\pm$ 0.005, 3.484?, and 3.498? $\pm$ 0.010 MeV, the latter with a tentative (2^+) assignment.

The state at 3.539 MeV, unreported previously, has a very similar shape to the one observed for the 3.314 MeV. It appears to be a doublet, one member having $L=4$ or 3, the other having $L=0$ or 1.

E. Conclusion

In the present study of ^{76}Ge via the ^{74}Ge(t,p) reaction many new spin and parity assignments have been made above 1.4 MeV excitation, where only tentative assignments had been made previously. We emphasize the observation of the 0_2^+ and 0_3^+ states at 1.911 and 2.901 MeV, respectively, 4_2^+ and 4_3^+ states at 2.017 and 2.733 MeV, respectively, and the 2_3^+ state at 2.502 MeV in ^{76}Ge.

The structure of the low-lying positive parity states in the Ge isotopes may provide a sensitive experimental test for the structure of these nuclei.

Table III summarizes the excitation energies and the (t,p) cross sections for the 0^+ states observed in ^{76}Ge up to 2.5 MeV excitation and those observed in ^{72,74,78}Ge in the Ge(t,p) reaction up to the same excitation. The most conspicuous feature of the Ge(t,p) reactions is the dominance of the ground state transitions. Except for the first excited 0^+ state in ^{74}Ge which has about 20% of the g.s. intensity, the transitions to other excited states are about two orders of magnitude weaker than the g.s. transitions. This is in strong contrast to the behavior of the (t,p) results near shell closures where excited 0^+ states often are as strong as the g.s.

From Table III several differences in the structure of the low-lying 0^+ states between ^{76}Ge and the other isotopes could be pointed out:

(a) The energy of the first excited 0^+ state in ^{76}Ge (1.911 MeV) is considerably higher than the 0_1^+ state in ^{72}Ge and (to a lesser extent) the 0_1^+ state in ^{74}Ge and ^{78}Ge. The first excited 0^+ states in ^{70}Ge and ^{68}Ge are at 1.212 and 1.753 MeV, respectively. Thus there is an abrupt minimum in the energy of the first excited 0^+ state at $N=40$. It was noted that such discontinuity in the energy systematics of the first excited 0^+ state may indicate the possibility of an oblate to prolate shape transition with increasing neutron number N.[7] In ^{78}Ge, however, the 0_1^+ state is observed at about 400 keV lower than in ^{76}Ge.[6] This may indicate that ^{78}Ge does not continue the trend towards prolate deformation but starts to return towards a spherical shape. Such behavior is expected from the simple shell model as ^{78}Ge with $N=46$ approaches the $N=50$ closed shell.

(b) Only one excited 0^+ state has been observed in ^{76}Ge up to 2.5 MeV, while three, four, and two excited 0^+ states have been observed in ^{72}Ge, ^{74}Ge, and ^{78}Ge, respectively, up to the same excitation.

(c) The $0_{g.s.}^+$ strength in ^{76}Ge as well as the summed 0^+ strengths up to 2.5 MeV are clearly higher in ^{76}Ge than the corresponding strength in the other isotopes by about 20%. This feature as well as that mentioned in (b) imply that there is a larger overlap between the g.s. of ^{74}Ge and ^{76}Ge.

In view of the proposed shape transition in the Ge isotopes this may indicate that ^{74}Ge and ^{76}Ge are more similar in their g.s. shape than is the case for the lighter or heavier isotopes.

(d) The maximum cross section for an excited 0^+ state occurs in ^{74}Ge—i.e., shifted by two mass units from the g.s. to g.s. maximum. The unusual strength with which the (t,p) reaction connects the g.s. of ^{72}Ge with the 1.485 MeV 0_2^+ state in ^{74}Ge indicates an enhanced overlap between these two states. No such enhanced transition to an excited 0^+ state was observed in ^{76}Ge.

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*On leave from Department of Physics, Ben-Gurion University, Beer-Sheva, Israel.

†Currently at Kernfysisch Versneller Instituut, Groningen, The Netherlands, on leave from the University of Pennsylvania.

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