^{72,74,76}Ge by the (t,p) reaction

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A systematic study of all of the stable even germanium isotopes by the (t,p) reaction has been performed. The reaction protons were analyzed in a quadrupole-dipole-dipole-dipole spectrometer with a resulting energy resolution approximately 15 keV. Levels up to 3 MeV in excitation energy were measured and the angular distributions compared to distorted wave analysis. A number of new spin assignments are made in the heavier germanium nuclei. Examination of the systematic trend of the ground state as well as various excited levels strongly supports a transition in nuclear deformation between $N = 40$ and $N = 42$. The data also indicate the effects of the approaching shell closure at $N = 50$.

[NUCLEAR REACTIONS ^{70,72,74}Ge(t,p), $E_t = 17$ MeV $\sigma(\theta)$, DW analysis.]

I. INTRODUCTION

The germanium nuclei offers a complex nuclear system which is subject to a variety of nuclear interactions. Both proton and neutron shells are unfilled and there is a strong tendency towards shape instability. There is strong evidence for proton orbital interchanges as a function of neutron number[1] indicating the possible effects of changes in nuclear shape. The nucleus ^{72}Ge is one of the few nuclei with a first excited 0^+ state and it has been argued that this may be due to a neutron subshell closure.[2] Recent evidence[3] indicates, however, that the occurence of this low-lying 0^+ state is related to a deformation change and that any possible subshell closure of neutrons is destroyed by the unclosed and active proton orbitals. There thus appears to be strong proton-neutron interactions occurring in the germanium nuclei.

In order to add further information on the nuclear phenomena occuring in this nuclear region, we have performed the (t,p) reaction on targets of ^{70,72,74,76}Ge. Such two nucleon transfer reactions are particularly sensitive to changes in ground state configurations brought about either through shell closures or deformation changes. These aspects have been previously exploited in the (p,t) reaction for the lighter germanium nuclei.[4] The sensitivity of the reaction in transitional nuclei has been demonstrated previously in the mass regions near $N=90$ (Ref. 5) and $A=100$.[6] The (t,p) reaction provides an excellent comparison with a number of the (p,t) results, permitting a probe of the overlapping of the various ground state shapes. This feature has been reported in a preliminary report on the present work.[3] A comparison of the two reactions also reveals the relative roles of particles above the Fermi surface as opposed to holes below, further revealing the intrinsic structure of many of the states excited. The (t,p) reaction also permits the examination of the heavier germanium isotopes not accessible to the (p,t) work. The nucleus ^{78}Ge was initially studied in some detail for the first time by this reaction.[7] A study of these heavier nuclei permits the evaluation of the effects on the level scheme of the approaching $N=50$ shell closure.

II. EXPERIMENTAL PROCEDURE

The ^{70,72,74}Ge$(t,p)^{72,74,76}$Ge reactions were studied at 17 MeV triton energy with the Los Alamos Van de Graaff accelerator. The targets were composed of GeO_2 evaporated onto a 5 $\mu g/cm^2$ carbon backing. Their areal densities and their isotopic enrichments are reported in Table I. The outcoming protons were analyzed by a quadrupole-dipole-dipole-dipole (Q3D) type II magnetic spectrometer and detected by a helical cathode position sensitive proportional counter of one meter length.[8,9] The overall proton energy resolution of 15–20 keV is essentially due to the target thickness. The levels of residual nuclei were observed up to 3.1-MeV excitation energy. Angular distributions were obtained from spectra taken

TABLE I. Isotopic content of germanium targets.

	Isotopic content (%)				
Target	^{70}Ge	^{72}Ge	^{73}Ge	^{74}Ge	^{76}Ge
^{70}Ge	84.62	5.54	1.47	6.36	2.01
^{72}Ge	1.04	96.23	0.77	1.63	0.33
^{74}Ge	1.71	2.21	0.9	94.48	0.78

from 10 deg to 60 deg in the laboratory system by 5-deg steps. A solid-state detector of known geometry was located at 30 deg to detect the elastically scattered tritons permitting absolute and relative cross sections to be obtained with an accuracy of 25%–30% and 5%, respectively. To determine the excitation energies, a polynomial relation between radius of curvature and channel number was established from well known ^{72,74}Ge excitation energies. The adopted values of energy are mean values from the spectra taken at different angles. The estimated errors on excitation energies are ±3 keV up to 2.7 MeV and ±7 keV above this. To estimate the contribution of contaminants from other isotopes, data were taken at 15 deg, 30 deg, and 50 deg with a natural Ge target and at the same magnetic fields. These data also gave a measure of the relative strength between the three reactions.

III. DISTORTED-WAVE ANALYSIS

To determine the L transfers we compared the experimental angular distributions to distorted-wave calculations (DW) using the code DWUCK.[10] The optical model parameters (Table II) are from systematic elastic scattering surveys of tritons[11] and protons.[12] In the two-nucleon transfer reaction, it is known that the choice of form factor has little effect on the shape of the angular distribution so simple configurations were used in these calculations with $(1g_{9/2})_J{}^2$ configuration for

TABLE II. Optical model parameters.

	Triton	Proton	Bound state
V_r	166.6	50	b
R_r	1.16	1.25	1.25
A_r	0.752	0.65	0.65
W_I	22.9	50.5	
W_{SF} a	0		
R_I	1.498	1.25	
A_I	0.817	0.47	

a Derivative form for imaginary potential.

b Adjusted to give correct binding energy.

even L transfers and $(1g_{9/2}1f_{5/2})_J$ configuration for odd L transfers. The ϵ enhancement factors were deduced from comparison between experimental and DW cross sections. In some cases the shape of the experimental angular distribution is not well accounted for by DW calculations but the L transfer may be assigned by a comparison to shapes corresponding to levels of well known spin and parity. Such cases will be discussed in the following section.

IV. EXPERIMENTAL RESULTS

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

A spectrum of ^{76}Ge obtained at a laboratory angle of 25° is shown in Fig. 1. Table III contains our results as compared to the data compiled in Ref. 13. These previous results are from γ-ray spectroscopy and (p,p') reactions. We have studied 15 levels and propose J^π values for 14 of them. The excitation energies are consistent with the previous ones although our values are systematically about 10 keV greater above 2.7 MeV. Figure 2 contains the angular distributions obtained in our experiment, compared with the DW calculations. In addition to the ground state, two levels at 1912 and 2908 keV show unambiguous $L=0$ patterns and correspond, respectively, to 4.2% and 2.2% of the total $L=0$ strength. The $J^\pi=0^+$ characteristics were not previously determined for these two levels but they are consistent with γ observations.

The two first $J^\pi=2^+$ states at 563 and 1107 keV had well established spin and parity. We confirm these assignments and note that the 2_1^+ transition is 12 times stronger than the 2_2^+ transitions. Three other levels at 2506, 2774, and 2850 keV are also populated with $L=2$ transfer. The angular distribution of the 2774 keV level is not as definitive as the other $L=2$ transitions because of the weak cross section and a contribution of a contaminant line (about 20%); however, we propose $J^\pi=2^+$ for all these three levels.

The shape of the experimental distribution of the 2698-keV level is not well fitted by DW calculations, but it is very similar to the shape of the 2513-keV $L=3$ transition in the ^{70}Ge$(t,p)^{72}$Ge reaction (Fig. 4). This ^{72}Ge level has well established $J^\pi=3^-$ characteristics (see Table V). Thus, we can attribute the value $J^\pi=3^-$ to the 2698-keV ^{76}Ge level and confirm the tentative J^π assignment for the level at 2692.4 keV in Ref. 13.

The first $J^\pi=4^+$ level in ^{76}Ge is located at 1409 keV. It is not strongly populated in the (t,p) reaction, but the fit of the angular distribution by an $L=4$ DW calculation is fair. Nevertheless, we observe that the experimental shape presents a

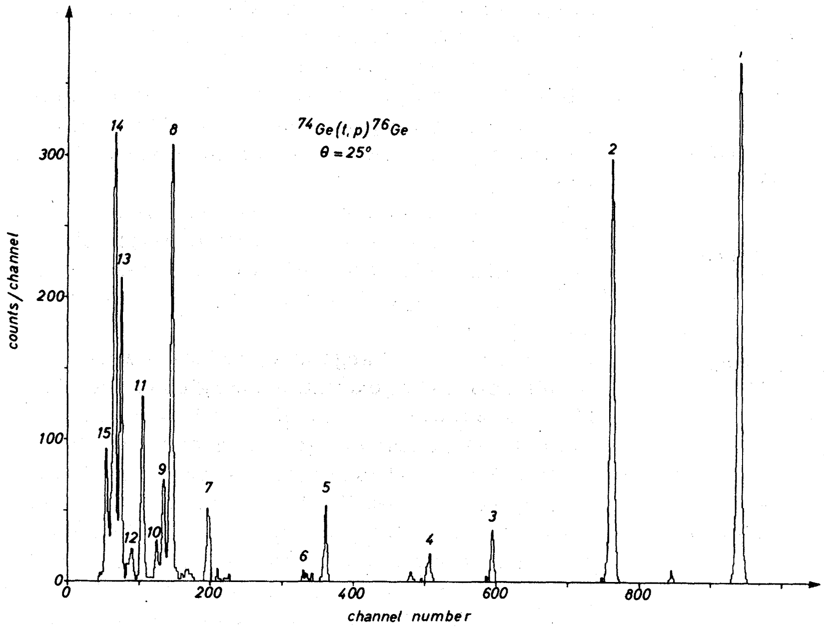

FIG. 1. Proton energy spectrum of the $^{74}Ge(t,p)^{76}Ge$ reaction at 25° lab. The numbers on top of the peaks refer to nuclear levels in ^{76}Ge (Table III).

"two maxima" pattern. The same pattern is obvious in the two strong transitions to the 2739-keV and 3001-keV levels. Based on DW results and the systematic shape of the angular distributions, we propose $J^\pi = 4^+$ for these two levels. In Ref. 13 the $J^\pi = 4^+$ characteristics were tentatively attributed to the level at 2018 keV. We cannot confirm this assignment from the experimental angular distribution because the cross section is too small, and the peak contains a contaminant (about 40%).

TABLE III. Levels observed in the reaction $^{74}Ge\ (t,p)\ ^{76}Ge$ at 17 MeV.

	Present work					Ref. 13	
Level N^0	E_x (keV)	L	J^π	$\Sigma \frac{d\sigma}{d\omega}$ (μb)	ϵ	E_x (keV)	J^π
1	0	0	0^+	2210	28	0	0^+
2	563	2	2^+	372	2.1	562.92	2^+
3	1107	2	2^+	32	0.18	1108.45	2^+
4	1409	4	4^+	26	0.13	1410.08	4^+
						1539.46	
5	1912	0	0^+	100	1.1	1911.09	
6	2018			12		2019.87	(4^+)
						2284.3	(3^-)
7	2506	2	2^+	81	0.54	2503.5	
						2591.10	
8	2698	3	3^-	303	5.2	2692.40	(3^-)
9	2739	4	4^+	74	0.36		
						2747.75	
10	2774	2	2^+	33	0.17	2768.78	
11	2850	2	2^+	132	0.86	2841.63	
12	2908	0	0^+	53	0.51	2897.6	
						2919.79	
13	2967	5	5^-	255	1.2	2966 ?	(3^-)
14	3001	4	4^+	293	1.3	3008.6 ?	
15	3047					3040.7 ?	

The transition to the 2967-keV state shows an $L = 5$ pattern, leading to $J^\pi = 5^-$ for this level. It is not likely that this state is the same as the 2966-keV state from Ref. 13 because of the systematic difference in energy noted above.

Due to the edge effect in the counter the cross section of the 3047-keV level could not be determined at several angles.

B. $^{72}Ge(t,p)^{74}Ge$ reaction

This reaction was previously studied by Darcey[14] at a triton energy of 13 MeV. Five levels (g.s., 2_1^+, 2_2^+, 0_2^+, 3_1^-) were seen in this experiment.

The results obtained in the present work are summarized in Table IV where we have also reported the results of the $^{76}Ge(p,t)^{74}Ge$ and $^{75}As(d,{}^3He)^{74}Ge$ experiments,[4,15] the data compiled by Kocher[16] and the results obtained by Taylor[17] from the study of the decay of ^{74}Ga. The angular distributions obtained in the present experiment are presented in Fig. 3 where the results of DW calculations are also shown.

Fourteen peaks are present in the spectra, some of them [labelled "a" in Table IV] appearing as a doublet at a few angles. We tried to separate the two components of these doublets assuming each component to have an assymetric gaussian shape. For all the peaks, except for peak number 11, this

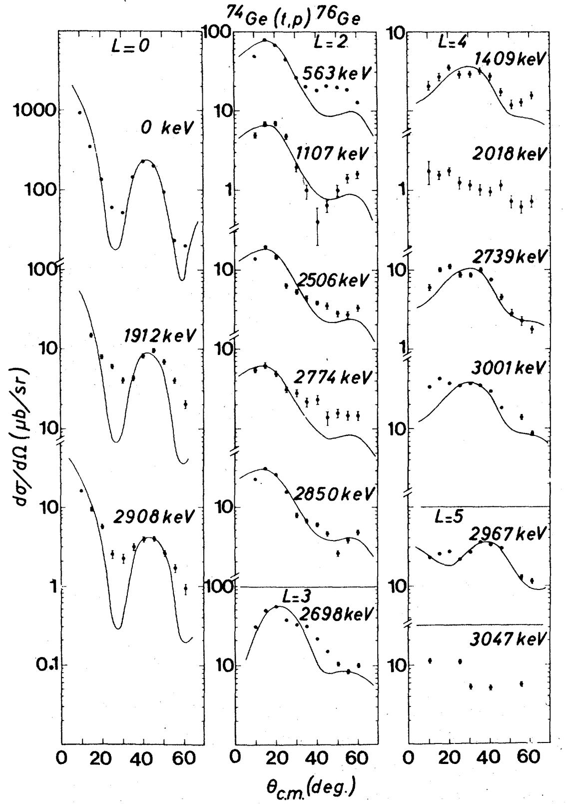

FIG. 2. Angular distributions of the ^{74}Ge(t,p)^{76}Ge reaction. The solid lines are DW calculations assuming the indicated L values. Vertical bars are statistical errors.

procedure was unsuccessful: The presence of the weaker component could be proved and the corresponding level energy determined, but the presence of the large component prevented us from obtaining a reliable angular distribution for the small one. We were able to separate correctly peak number 11 into two components: the larger one ($E_x = 2840$ keV) showing an $L=2$ pattern as expected because it is known to be a $J^\pi = 2^+$ level, the smaller one ($E_x = 2867$ keV) corresponding to the level given as 2862 keV and known[4] as $J^\pi = 0^+$. In the present experiment, the angular distribution of this level looks like the "abnormal" $L=0$ angular distributions previously observed for some other states in the $G(p,t)$ experiments.[4] Four other $L=0$ transitions were observed (Fig. 3). As usual, the strongest is the transition to the ground state (80% of the total strength). The angular distributions of all these levels, except the 2755-keV one, are fairly well reproduced by DW calculations with $L=0$ (Fig. 3). We emphasize the good fit of the 1485-keV level, well known as[16] $J^\pi = 0^+$, which had in the (p,t) work[4] an "abnormal" $L=0$ shape. The level at 2228 keV was obscured in the (p,t) experiment by the ^{72}Ge(p,t)^{70}Ge ground-state transition. The level at 2755 keV has been previously seen in the work of Brown[18] at 2746 ±10 keV. Although the angular distribution of this level is not well reproduced by $L=0$ DW calculations, we tentatively assign it to be a $J^\pi = (0^+)$ level.

Levels with $L=2$ angular distributions were seen in this reaction at excitation energies of 598, 1203, 2840, 2945, and 3017 keV. All these levels were seen in the (p,t) experiment and assigned as $J^\pi = 2^+$ levels.

Levels with $L=2$ angular distribution were seen in this reaction at excitation energies of 598, 1203, 2840 and 3017 keV. All these levels were seen in the (p,t) experiment and assigned as $J^\pi = 2^+$ levels. For the 2945 keV transition the $L=2$ DW shape gives the best fit of the angular distribution but according to the poor quality of the fit in the second part of the distribution we propose a tentative $J^\pi = (2^+)$ assignment for this level.

The level at 1466 keV, well known as $J^\pi = 4^+$, is obscured by the 1485-keV level. Two levels at 2673 and 3049 keV show an $L=4$ angular distribution.

The level at 2539 keV shows an $L=3$ angular distribution and is the well known first $J^\pi = 3^-$ level in ^{74}Ge.

As can be seen in Table IV and Fig. 3, six levels show angular distributions which cannot be characterized by a single L transfer. As discussed above, in four of these cases the problem is the near proximity of the large component of a doublet. The 1695-keV level is known to be $J^\pi = 3^+$,[17] and it is very weakly populated in agreement with the usual selection rules for two-nucleon transfer direct reactions.

The level at 2198 keV is well known to be $J^\pi = 2^+$ (Refs. 4, 16, 17) and is weakly populated [4% of the $L=2$ strength in the (0–3)-MeV energy range]. The absence of an $L=2$ pattern for this level could be explained by the ^{76}Ge ground-state contamination

C. ^{70}Ge(t,p)^{72}Ge reaction

In Table V are presented our results compared with previous results obtained with (p,t) and (^{3}He, d) reactions[4,19] and with other experiments.[20,21] The experimental angular distributions compared to DW calculations are shown in Fig. 4.

The $L=0$ strength is dominated by the ground-state transition which is fairly well reproduced by DW calculations. Three other levels have $L=0$ patterns. The first at 2028 keV is well fitted by the DW results. This level showed an "abnormal"

TABLE IV. Levels observed in the reaction $^{72}Ge\,(t,p)\,^{74}Ge$ at 17 MeV.

	Present work					Ref. 4 $^{76}Ge\,(p,t)\,^{74}Ge$		Ref. 16		Ref. 17		Ref. 15
Level N^0	E_x (keV)	L	J^π	$\Sigma \frac{d\sigma}{d\omega}$ (μb)	ϵ	E_x (keV)	J^π	E_x (keV)	J^π	E_x (keV)	J^π	E_x (keV)
1	0	0	0^+	1580	17	0	0^+	0	0^+	0	0^+	0
2	598	2	2^+	390	2.3	597	2^+	595.9	2^+	595.9	2^+	596
3	1203	2	2^+	15	0.09	1206	2^+	1204	2^+	1204	2^+	1204
4[a]	1466			<60		1461	4^+	1464	4^+	1464	4^+	1467
	1485	0	0^+	323	3.8	1481	0^+	1483	0^+	1483	0^+	
5	1695			7		1696		1697		1697	3^+	1700
								1726				
								1910				
						2165	4^+	2166		2165	4^+	2168
6[b]	2198			39		2198	2^+	2198	2^+	2197	2^+	2201
7	2228	0	0^+	39	0.56			2229	(0^+)			2222
8[a]	2539	3	3^-	197	3.5	2542	3^-	2536	3^-	2536	3^-	
	(2565)			<16		2572	4^+	2569				
								2600				
9[a]	2673	4	4^+	142	0.76	2673	4^+	2671				
	(2695)			<14		2699		2694		2693.9		
								2696				
10	2755	0	0^+	13	0.16			2746				
								2822				
11[a]	2840	2	2^+	145	0.79	2837	2^+	2829				2835
[c]	2867			<16		2862	0^+					2859
12	2945	(2)	(2^+)	123	0.66	2940	2^+	2935				2937
								2949	(3^-)			
								2973				
								3001				
13	3017	2	2^+	183	1.1	3022	2^+					3015
								3034		3034.1		
14	3049	4	4^+	203	1.0	3053	4^+	3049				

[a] Unresolved doublet.
[b] Contamined by ^{76}Ge ground-state.
[c] Angular distribution not fitted by DWBA calculations.

angular distribution and very weak strength in the (p,t) reaction.[4] The $J^\pi = 0^+$ value had previously been proposed[4] from comparison with a similar "abnormal" (p,t) angular distribution for a known $J^\pi = 0^+$ state at 1481 keV in ^{74}Ge. The present result confirms directly that assignment. The next $L=0$ transition corresponds to the level at 2756 keV in ^{72}Ge. In Fig. 4, several points are missing because of a ^{76}Ge contamination. In spite of this, the $L=0$ pattern seems plausible. A $J^\pi = 0^+$ assignment, however, would not be consistent with previous results in the $(^3He, d)$ reaction.[19] We note that this level was not populated in previous (p,t) data. Another weak transition is well fitted by $L=0$ DW calculations and corresponds to the 2896-keV level. We can propose $J^\pi = 0^+$ for that level previously known as $J^\pi = [0^+ - 3^+]$.[19] The angular distribution of the 688-keV transition is not fitted by $L=0$ DW calculations although the 688-keV level has well known $J^\pi = 0^+$ characteristics. The experimental shape is very similar to the other "abnormal" $L=0$ shapes seen in (t,p) or (p,t) reactions. We shall discuss this point later.

The principal $L=2$ transition corresponds to the $J^\pi = 2^+$ level at 833 keV in ^{72}Ge. The shape of the experimental angular distribution for this level is very similar to the shape for the 3034-keV transition. They are both fairly well reproduced by DW calculations. We propose for the 3034-keV level $J^\pi = 2^+$ which would agree with the previous $J^\pi = 1^+, 2^+$ assignment from Ref. 19. The angular distribution of the 2401-keV transition is not so well fitted, but it shows, nevertheless, an $L=2$ pattern which corroborates the $J^\pi = 2^+$ values proposed for this level from the previous

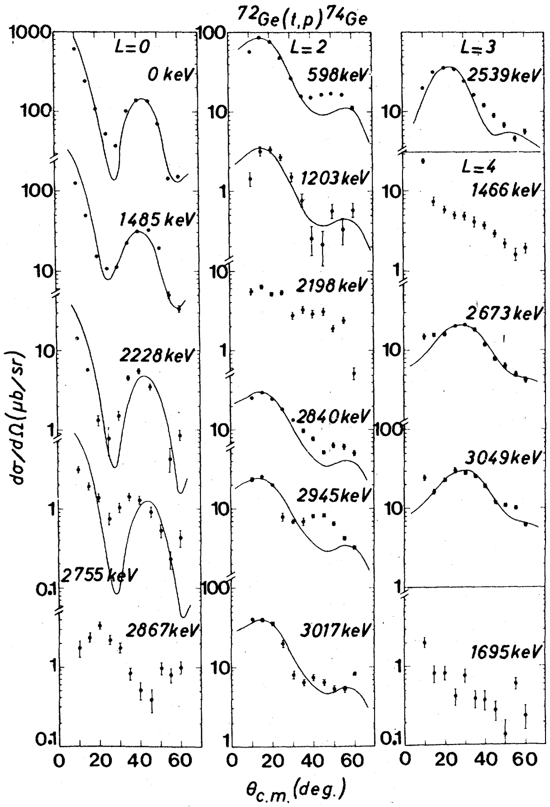

FIG. 3. Angular distributions for the ^{72}Ge$(t,p)^{74}$Ge reaction. See also caption for Fig. 2.

(p,t) experiment.[4] The second $J^{\pi}=2^{+}$ state at 1461 keV is very weakly populated in this (t,p) reaction and consequently the shape of the angular distribution is not significant.

The first $J^{\pi}=3^{-}$ level at 2513 keV is strongly populated in the (t,p) reaction. The shape of the angular distribution is well fitted by the DW calculations in spite of a slight "two maxima" pattern. The same shape is also seen in the case of the 2947-keV level. The 2951-keV level seen in the (p,t) reaction and the 2949-keV level seen in the (^{3}He, d) reaction[19] are likely the same even parity level which may be weakly populated in our experiment but in the transition to our 2947-keV level, the $L=3$ transfer is clearly dominant. So we confirm the presence of a $J^{\pi}=3^{-}$, 2947-keV level, already proposed at 2943 keV in Ref. 22.

Three $L=4$ transitions were seen in the (t,p) reactions below 3.15-MeV excitation energy, to well established $J^{\pi}=4^{+}$ levels at 1728, 2463, and 3072 keV. We emphasize the fact that the $L=4$ strength is mainly located in the 3072-keV level.

The peak corresponding to the level at 3126 keV is near the upper limit in energy and two points of the angular distribution are missing due to this. Nevertheless, the $L=5$ transfer is proposed. This tentative assignment corroborates the odd parity proposed for a level at 3119 keV in Ref. 20.

TABLE V. Levels observed in the reaction ^{70}Ge (t,p) ^{72}Ge at 17 MeV.

	Present data					Ref. 4 ^{74}Ge$(p,t)^{72}$Ge		Ref. 19		Ref. 20, 21	
Level N^0	E_x (keV)	L	J^{π}	$\Sigma \frac{d\sigma}{d\omega}$ (μb)	ϵ	E_x (keV)	J^{π}	E_x (keV)	J^{π}	E_x (keV)	J^{π}
1	0	0	0^+	1661	16	0	0^+	0	0^+	0	0^+
2	688	a		12		691	0^+	690	0^+	691	0^+
3	833	2	2^+	386	2.1	835	2^+	835	2^+	834	2^+
4	1461					1467	2^+	1465	2^+	1464	2^+
5	1728	4	4^+	56	0.27	1730	4^+	1725	4^+	1728	4^+
6	2028	0	0^+	59	0.63	2029	(0^+)	2029	(0^+)		
						2062	1^+-3^+			2064	(3^+)
7	2401	(2)	(2^+)	37	0.16	2406	2^+	2404	1^+-3^+	2402	
8	2463	4	4^+	18	0.09	2468	4^+	2466	(4^+)	2464	(4^+)
9	2513	3	3^-	323	6.5	2519	3^-	2516	3^-	2515	3^-
10	2756	0	0^+	70	0.76			2754	1^+-3^+	2754	...
11	2896	0	0^+	11	0.12			2897	0^+-3^+		
										2940	
12	2947	3	3^-	79	1.4					2943	3^-
						2951		2949	1^+-3^+	2950	
13	3034	2	2^+	132	0.71	3037		3034	1^+-2^+	3036	(2^-)
14	3072	4	4^+	354	1.7	3078	4^+	3073	(4^+)		
						3098	2^+	3094	1^+-3^+	3094	4^+
15	3126	(5)	(5^-)	60	0.33					3119	...

[a] Angular distribution not fitted by DWBA calculations.

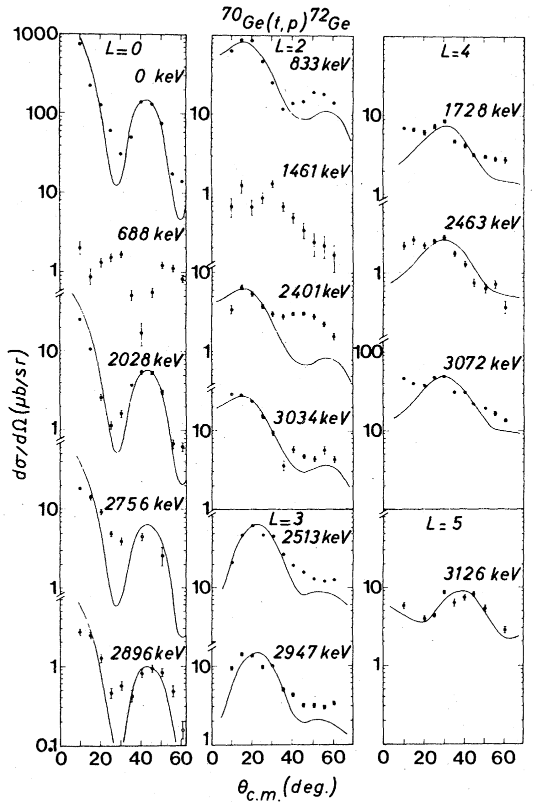

FIG. 4. Angular distributions for the $^{70}Ge(t,p)^{72}Ge$ reaction. See also caption for Fig. 2.

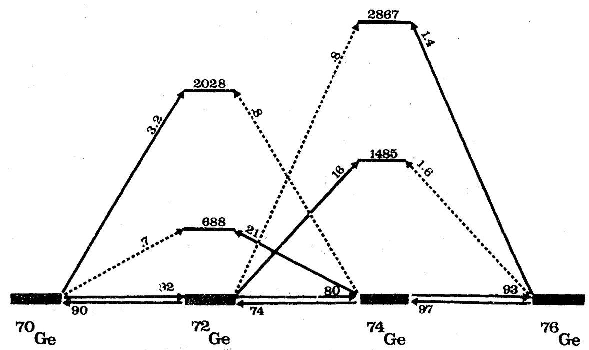

FIG. 5. 0^+ level scheme with "normal" (full lines) and "abnormal" (dotted lines) transitions in (p,t) and (t,p) reactions. The numbers on the transition lines are the strengths relative to the total observed 0^+ cross section (in %). The numbers on the level lines are the excitation energies (in keV).

V. DISCUSSION

The present results on the (t,p) reaction may be combined with previous (p,t) data on the germanium isotopes to discuss systematic trends. In particular each of the observed type of transfer ($L=0, 2, 3, \ldots$) will be examined as a function of neutron number. As stated earlier, the germanium isotopes span a complex region of nuclear phenomena. The isotopes examined all lie between closed shells and thus are subject to deformation-inducing instabilities with a possible interplay existing between prolate, oblate, and spherical shapes. It is known that the two-nucleon transfer reaction is sensitive to such shape changes[5,6] and this fact, along with systematics of energy level positions may be used to explore experimentally for such transitions.

A. 0^+ states systematics and evidence for a structural change between $N=40$ and 42

In a previous letter[3] we discussed the variation of the ratio $R=\sigma(0_2^+)/\sigma(0^+_{g.s.})$ for both the (t,p) and the (p,t) reactions on all of the even stable germanium isotopes. An abrupt maximum in this ratio at $N=42$ in the (t,p) data and $N=40$ in the (p,t) data was shown to suggest a shape transition in this region because of the similarity to such effects noted in known transition regions.[5,6] This maximum is explained in this hypothesis, by a reduced overlap between the ground states, the missing strength being mainly found in the first excited 0^+ levels considered as shape isomers. This situation is in contrast to a shell closure which produces a pairing vibrational 0^+ state populated either by the (p,t) or by the (t,p) reactions according as the target nucleus is above or below the shell closure and populated by both reactions only in the final nucleus corresponding to the closed neutron shell.

The traditional character of the Ge isotopes is further illustrated by the anomalous shapes of certain $L=0$ transitions in the two-nucleon transfer reactions. Figure 5 summarizes the strength and type of shape for the $L=0$ states seen in the (t,p) and (p,t) reactions. It is striking that, with the exception of the ground states, none of the 0^+ levels we have observed in the (p,t) and (t,p) reactions is populated in both reactions by transitions with standard, normal, $L=0$ shapes. Always one of the two is anomalous. It is particularly striking that the 0^+ levels strongly excited in ^{72}Ge by the (p,t) reaction and in ^{74}Ge by the (t,p) reaction have uncharacteristic angular distributions when weakly excited by the opposite reactions. The observed behvaior would be qualitatively in agreement with the idea that these 0^+ levels are coexistence states of different deformation. The strong transition takes place between a ground and an excited 0^+ states of similar deformations whereas the weak transition takes place between a ground and an excited 0^+ levels of different deformations. The shape of the anomalous angular distributions which have

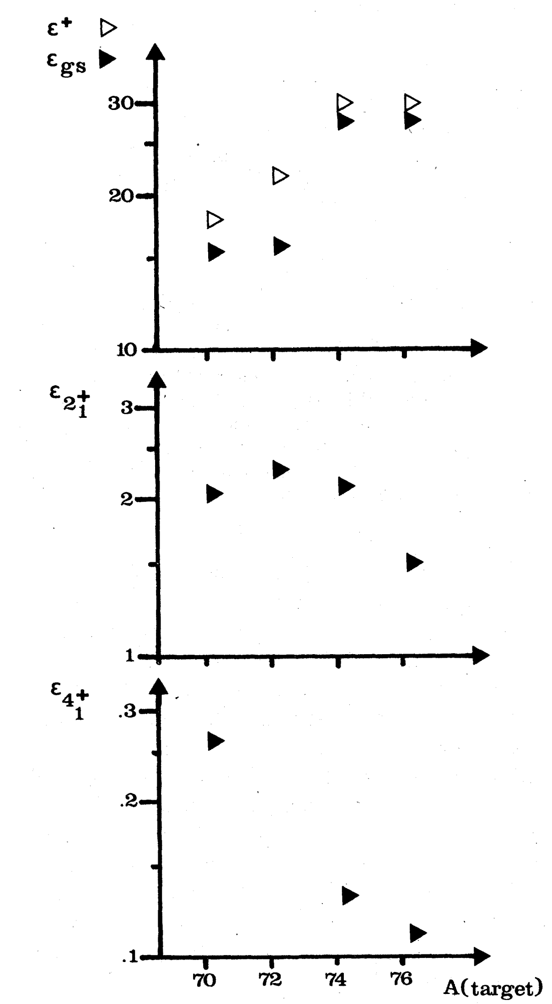

FIG. 6. Distorted-wave corrected cross sections (ϵ) for the ground, 2_1^+ and 4_1^+ states, and the total $L=0$ strength vs the target mass value.

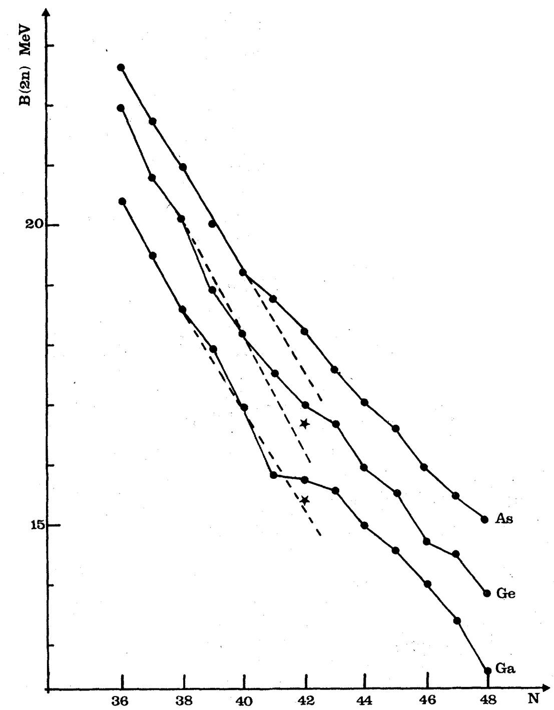

FIG. 7. Two-neutron binding energies versus neutron number for Ga, Ge, As nuclei from Ref. 24. The stars represent the centroids for $L=0$ (t,p) strengths.

been shown to be unexplainable[4,23] by direct DW calculations in (p,t) reactions. Particularly, such drastic effects cannot be accounted for by different choices of form factors which have only a small effect on the angular distributions. Preliminary calculations give a qualitative agreement with the (t,p) distributions by including two-step processes.[23] It would be of great interest to have γ-ray data to examine for a possible rotational band built on these excited 0^+ states.

Figure 6 contains a plot of the DW corrected cross sections (ϵ) for the ground states. Also shown are the total observed 0^+ ϵ values as a function of the target mass value. A maximum difference between the g.s. and summed 0^+ ϵ values is obviously occurring for the ^{72}Ge target corresponding to the observed enhancement of the ratio R as discussed above.

Figure 6 also indicates an abrupt increase in the ground-state transition strength above $N=42$ by a factor of 1.6 with near constant value above and below this value. It thus appears that the pairing correlations change at this region with resulting two-nucleon transfer at the higher N region. Examination of the summed 0^+ cross sections in Fig. 6 shows a smoother variation in N as expected since some of the missing ground-state cross section goes to excited states. There is thus a tendency towards preserving the total pairing strength. This conservation is also reflected in the systematics of the two-neutron binding energies, $B(2N)$, which is the appropriate energy scale for the pairing mode of elementary excitations. The $B(2N)$ values shown in Fig. 7 as a function of neutron number for Ga, Ge, and As nuclei show a break in their smooth behavior between $N=40$ and 42. The centroids for the $L=0$ (t,p) strengths for Ge and Ga nuclei (present work and Ref. 25) are closer to the extrapolated value beyond $N=40$. Thus, the pairing phonons tend to preserve their energy, independent of neutron number, as was previously observed in Sm and Mo nuclei[5,6] corresponding to a shape transition.

Actually, only small changes in shape might be required here; changes which would shift the Nilsson orbitals based on the $\frac{1}{2}^-$ orbital slightly with respect to the $\frac{9}{2}^+$ can easily account for some of the phenomena observed. The $\frac{1}{2}^-$ orbital carries five times the $\frac{9}{2}^+$ two-nucleon transfer strength and a shifting of these orbitals relative to the Fermi surface by changes in deformation may produce the fluctuations in pairing as quoted above. The relative strengths for two-nucleon transfer for orbitals around the Fermi surface are

$$g_{9/2}{}^2 : f_{5/2}{}^2 : p_{3/2}{}^2 : p_{1/2}{}^2 : d_{5/2}{}^2 = 1.0 : 0.46 : 9.5 : 3.6 : 14.3 .$$

An inversion of orbitals with the rising "hot orbitals," those with large intrinsic two-nucleon strength, between $N=40$ and 42 would explain the observed effects. The rapidity of this change, however, must be due to corresponding rapid change in nuclear deformation. Such changes in deformation are suggested by the dynamic deformation theory of Kumar *et al.*[26,4] where the potential energy surface indicates an increasing tendency towards oblate deformation in the regionfrom $N=38$ to $N=42$. However, the deformation energy is less than 1.5 MeV, thus these nuclei do not become well deformed but may undergo the orbital changes suggested above. Particularly, occupation probabilities of the $p_{1/2}$ and $g_{9/2}$ orbitals were found to strongly depend on the deformation. The evolution of the single-particle occupation probabilities can also be studied[27,28] by the comparison of the (t,p) and (p,t) data. In Fig. 8(a) are plotted the 0^+ summed ϵ values in the (t,p) reaction (ϵ^+) and the corresponding ϵ^- values in the (p,t) reaction[4] as a function of the target mass value. As the Q dependence of the transfer cross sections are approximately removed by the use of ϵ values, we normalized the ϵ^+ and ϵ^- values by imposing the ground-state value to be the same for the inverse two-neutron transfer between the same nuclei. The normalization factor is found to be 1.4 and 1.6 times greater for ^{72}Ge ↔ ^{74}Ge and ^{74}Ge ↔ ^{76}Ge, respectively, than for ^{70}Ge ↔ ^{72}Ge. This effect is not understood. The difference between the two above sums ($\epsilon^+ - \epsilon^-$), plotted in Fig. 8(b), has been related[27] to the single-particle occupation probability numbers of the $J=0$ target nucleus. Sharp variations as a function of the target mass number around ^{72,74}Ge are probably related to a rapid change of the occupation probabilities of the various concerned subshells corroborating the possibility of inversion of orbitals quoted above.

From the $(d,{}^3\text{He})$ and $({}^3\text{He},d)$ data[1] and many other experimental facts known in this region important correlations between neutrons and protons have been found around $N=40$–42. Particularly, an important change in the occupation probabilities of the $p_{3/2}$ and $f_{5/2}$ proton orbitals has been observed when going from ^{72}Ge to ^{74}Ge. This can be correlated with the variations observed above for the neutron ground-state wave functions in the same nuclei. The measured proton occupation probabilities have been used[29] to build a simple semiempirical model for the 0^+ states proton wave functions. This model has proved[29] able to explain rather well many experimental facts observed in transfer reactions including the most salient features of the (p,t) and (t,p) reactions. Hence, it lays stress on the important role of protons excitations in describing the first 0^+ excited states since the neutron wave functions were supposed to be the same as in the ground states. On the other hand, it has been quoted in Ref. 26 and the third paper of Ref. 4 that the above particle excitation description of 0^+ states is consistent with a collective interpretation due to the small average deformation calculated for these nuclei. Particularly, a crossing of the $p_{3/2}$ and $f_{5/2}$ deformed orbitals has been found at small

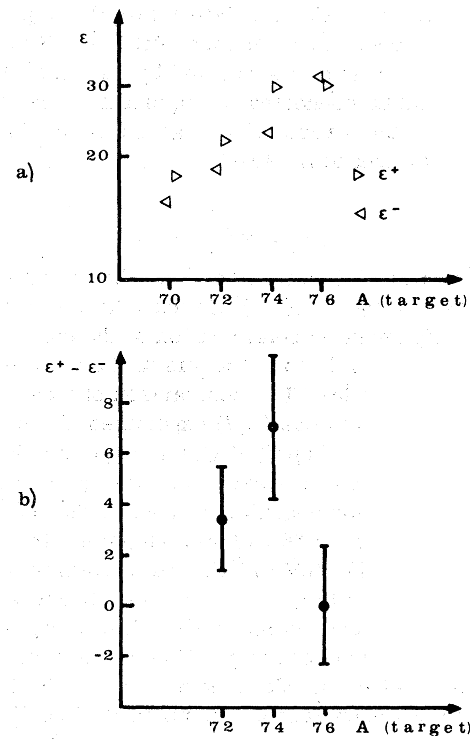

FIG. 8. (a) Summed ϵ values in (t,p) (ϵ^+) and (p,t) (ϵ^-) reactions as a function of the target mass value. (b) Differences between the ϵ values plotted in (a) vs the target mass value for ^{72,74,76}Ge. The error bars are deduced from relative experimental uncertainties remaining after normalization (see the text).

deformations, very consistent with the important change quoted above for these orbitals. Thus, the shape transition suggested by the present data could be connected to important microscopic effects in the structural change occurring in the Ge nuclei around $N \approx 40$-42.

B. 2^+ and 4^+ states

The present data together with the previous analysis of the ^{76}Ge$(t,p)^{78}$Ge data[7] have permitted the assignment or confirmation of the spin and parity of many 2^+ and 4^+ levels in the heavier Ge isotopes (^{78,76}Ge). The comparison of these results to the previous (p,t) experimental study of the lighter isotopes[4] (^{68}Ge) as well as other data on Ge nuclei shows: (a) a slow decrease of the excitation energies of most of these 2^+ and 4^+ levels from $N=38$ to $N=42$–44; e.g., the first 2^+ lies at 1.017 MeV in ^{68}Ge and is down to 0.563 MeV in ^{76}Ge and (b) for $N>44$, one observes a tendency towards an increase in the energies. A systematic study of the position of the first $J^\pi = \frac{9}{2}^+$ level in the odd-proton nuclei of the Ge region has been recently compared to the 2_1^+ energy evolution in the even-proton nuclei[30] and interpreted as evidence for a maximum deformation at $N \approx 42$. The Ge nuclei seem hence to take their maximum deformation for $N=42$–44 (^{74,76}Ge) and then for $N>44$ the trend is towards a spherical shape which should occur at the closed shell $N=50$. This is in agreement with the known data of $B(E2)$ values for the first 2^+ levels in the nuclei of this region where a slight maximum occurs around $N=42$ for all the nuclei. This conclusion is also in agreement with the microscopic calculations of the dynamic deformation theory[26] for Ge isotopes where an increasing deformation energy was found towards oblate shapes ($\beta=0.2$) for ^{74}Ge. Figure 6 shows the evolution for the 2_1^+ and 4_1^+ states of the cross sections corrected for the Q-dependent effect (ratio of the experimental to the DW calculated cross section) versus the neutron number of the residual nuclei for our (t,p) data. The small relative intensities (respectively, 15% and 1% of the ground state) are consistent with a pairing rotational description. A slight drop of these strengths is observed for ^{78}Ge; this is in agreement with a trend towards a spherical structure. Indeed, only a weak 2^+ (t,p) excitation is expected when reaching a closed neutron shell ($N=50$).

We would like to emphasize in contrast the important variation of the 2_2^+ strength as a function of N: 1.8%–14% of the 2_1^+ strength when going from ^{72}Ge to ^{78}Ge in (t,p) reactions. The same feature was observed in (p,t) reactions[4] where the ratio of the 2_2^+ strength over the 2_1^+ strength varies from 8% to 24% when going from ^{70}Ge to ^{74}Ge (final nuclei).

Some high energy 2^+ levels are clearly favored by the (t,p) reaction. These are the levels at 3.034 in ^{72}Ge, 3.017 in ^{74}Ge, 2.850 in ^{76}Ge, and 2.439 MeV in ^{78}Ge whose cross sections are about 30%–40% of the 2_1^+ cross section. It might be pointed out that the 3.034 MeV level in ^{72}Ge has been found to have a large single-particle proton component in the ^{71}Ga(^{3}He, d)^{72}Ge data[1] and that 2^+ levels ranging from 3 to 3.5 MeV were strongly populated in the Ge(p,t) reactions.[4] Our limited range of excitation energy ($E_x < 3.1$ MeV) in this experiment prevents us from observing all the same states as in the (p,t) reaction. However, one of these strongly populated levels in the (p,t) data was the level at 3.017 MeV in ^{74}Ge which is precisely the most populated 2^+ level (except the 2_1^+ level) in the present ^{72}Ge$(t,p)^{74}$Ge reaction. One possible interpretation of the strong excitation of these states could be that they are mainly two particle or particle-hole states and that the two transferred neutrons are picked up or put in $g_{9/2}$ (or higher) subshells.

Several 4^+ states (at 3.072, 3.049 and 3.001 MeV in ^{72,74,76}Ge, respectively) are also strongly populated in this reaction and again correspond for ^{72,74}Ge to the higher $L=4$ strengths observed in the (p,t) data. The same explanation as above for the 2^+ levels could be advanced for these states.

C. 3^- states, 5^- states

Our (t,p) data has permitted us to observe new 3^- and 5^- levels: the first 3^- state in ^{76}Ge and several 5^- states in all the Ge isotopes. A comparison with the previous (p,t) data for the lighter Ge isotopes[4] shows that the excitation energy of the first 3^- state is remarkably constant ($E_x \approx 2.5$ MeV) in all the isotopes with nevertheless a small increasing between ^{74}Ge and ^{76}Ge. On the other hand, the energy of the 5^- states is decreasing from 3.6 to 2.6 MeV between ^{68}Ge and ^{78}Ge. A striking feature of the $L=3$ strength is a sharp minimum found in ^{74}Ge correlated with a splitting of this strength observed in the ^{76}Ge$(p,t)^{74}$Ge reaction. Such a splitting cannot be observed in the ^{72}Ge$(t,p)^{74}$Ge reaction due to our limited range of energy but the decrease of the (t,p) ϵ values at $N=42$ strongly suggests it. Such splittings are well known in the (p,t) or (t,p) data for well-deformed nuclei. This feature could be correlated to the increasing deformation energy discussed above around $N=42$. It again suggests crossings of deformed orbitals in this region, to which our two-nucleon transfer is very sensitive, leading to new available particle-hole configurations to build negative parity states.

We have presented in our previous paper[7] possible explanations and alternatives for the observed difference in the behavior of the 3^- and 5^- excitation energies and the occurrence of important $L=5$ transitions with increasing N, based on an evolution towards less deformed nuclei. New information is now available to try to understand these features. Recent systematics[31] of the $(N-Z)$ dependence for the energy of the first 3^- state suggest that the 3_1^- state in ^{78}Ge lies near 3.1 MeV and then could not have been observed due to our limited range of energy ($E_x < 3$ MeV). In fact, in their (t,p) work, Mateja *et al.*[7] observe a weak $J^\pi = 3^-$ transition at 2744 keV and a doublet with a strong $L=3$ component at 3236 keV. Moreover, crossing of deformed orbitals have been deduced just above from the splitting of the $L=3$ strength and in Sec. V A according to several features of our data. This has been also found in the microscopic calculations[4] for the Ge nuclei at small deformations region. Particularly, a different evolution of the $p_{3/2}$ (or $f_{5/2}$) and $p_{1/2}$ orbitals needed to build 3^- and 5^- states by coupling to positive parity orbitals could give a possible understanding of the observed intensities and energies together with a simple shell closure tendency caused by the proximity of $N=50$.

The 3^- states also show systematic disagreement with the DW results. Since these states have a relatively strong $B(E3)$ there may be a large two-step contribution to the cross section. This would involve a path through the inelastic excitation of the 3^- state and a direct $L=0$ transfer.

VI. CONCLUSION

The present analysis of the ^{70,72,74}Ge$(t,p)^{72,74,76}$Ge reactions has permitted us to observe the excitation spectra of the Ge nuclei up to 3.1 MeV. The analysis of the angular distributions in terms of DW has revealed the dominant character of a direct reaction mechansim, leading us to propose 13 new spin-parity assignments in these nuclei. We emphasize the observation for the first time of the first excited 0^+ state in ^{76}Ge as well as several other 0^+, 2^+, and 4^+ in all the isotopes. The comparison of the present work to the previous data for the ^{76}Ge$(t,p)^{78}$Ge (Ref. 7) and the $^{70\ 72\ 74\ 76}$Ge$(p,t)^{68\ 70\ 72\ 74}$Ge reactions[4] adds much to our knowledge of the Ge nuclei structure. The Ge nuclei are mainly superfluid ones between $N=36$ and 46 but the comparison of the (p,t) and (t,p) cross sections reveals a pairing phase transition between $N=40$ and 42. This change could be due to a slight shape transition as suggested by the comparison with the data on Sm nuclei and by the behavior of the first 3^- state in our whole (p,t) and (t,p) data. This is also in agreement with predictions of recent microscopic calculations[26,4] and the coexistence of different types of deformations suggested by some striking anomalous shapes of (t,p) and (p,t) $L=0$ transitions. The previous $(d,{}^3\mathrm{He})$, $({}^3\mathrm{He},d)$, and (p,t) data together with the present (t,p) data have also permitted us to see the important role of the neutron-proton correlations in this transition due to the occurence of neutrons and protons in the same subshells. Another feature of our data lies also in the possible observation of some favored particle-hole states around 3-MeV excitation energy.

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