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Levels of ^{70,72,74}Ge excited by the (p, t) reaction

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The ^{72,74,76}Ge$(p,t)^{70,72,74}$Ge reactions have been studied at 26 MeV incident energy with an overall energy resolution of 10 keV using a split-pole spectrometer. Many new levels are found below 5 MeV excitation energy. Angular distributions are obtained and comparison with distorted-wave-Born-approximation calculations allow spin and parity assignments. Several new $J^\pi = 0^+$ levels are observed around 2.5 MeV. The positions of some 2^+, 3^-, 4^+, 5^-, and 7^- levels are established.

[NUCLEAR REACTIONS ^{72,74,76}Ge(p,t), E=26 MeV; measured $\sigma=\sigma(\theta)$; ^{70,72,74}Ge deduced levels up to 4.5–5 MeV, J, π.]

I. INTRODUCTION

In previous papers[1–4] we have shown the necessity of gathering new experimental results in the $N=40$ region. Indeed the exact structure of the nuclei in this region is still not well known and phase transitions and the existence of supersoft nuclei have been postulated.[2] This theoretical approach requires a systematic experimental study of the nuclei in this region. In particular it is useful to locate the low-lying excited 0^+ states of these nuclei. For that purpose, we have performed the (p, t) reactions on all the stable even-even Ge isotopes; the results of the ^{70}Ge(p, t)-^{68}Ge reaction have been reported and analyzed in a previous paper.[4] The study of the (p, t) reaction also appears to be a powerful tool for measuring level spins and parities and for probing the neutron pairing correlations and the dynamical effects of pairing fields.

The previously published study on the ^{72,74,76}Ge(p, t) reactions is the work of Ball *et al.*[5] at $Ep=20$ MeV, but their energy resolution (30–40 keV) prevented them from separating several doublets at low excitation energy and many levels beyond 3 MeV excitation energy, due to the high density in this region. The present paper contains all our experimental data on the ^{70,72,74}Ge isotopes and the comparison with other experimental studies. A forthcoming paper[6] (to be referred to as paper II) will contain a discussion on our results, some model calculations, and conclusions about the structure of these nuclei.

II. EXPERIMENTAL PROCEDURE

The ^{72}Ge$(p, t)^{70}$Ge, ^{74}Ge$(p, t)^{72}$Ge, and ^{76}Ge(p, t)-^{74}Ge reactions have been performed with the Orsay MP tandem accelerator at a proton energy of 26 MeV. The experimental setup and procedure have been described in our previous paper.[4] The targets were composed of GeO_2 evaporated onto a 5 μg/cm^2 carbon backing; the areal density obtained was about 200 μg/cm^2. The isotopic enrichments are reported in Table I. The overall resolution was 10 keV full width at half maximum (FWHM). Figure 1 shows a spectrum of ^{74}Ge at a laboratory angle of 10°. Data were taken in 5° steps from 5° [7.5° for the ^{74}Ge$(p, t)^{72}$Ge reaction] to 60°. At each angle, two successive exposures were necessary at different magnetic fields in order to observe the complete energy spectrum. Angular distribution relative normalizations were obtained by using a Si(Li) monitor detector positioned at an angle of 115°. In the case of the ^{74}Ge$(p, t)^{72}$Ge reaction these normalizations were based on the collected charge (about 4 mC for each spectrum). Absolute cross sections were

TABLE I. Isotopic content of germanium targets.

	Isotopic content (%)				
Target	^{70}Ge	^{72}Ge	^{73}Ge	^{74}Ge	^{76}Ge
^{72}Ge	1.04	96.23	0.77	1.63	0.33
^{74}Ge	1.71	2.21	0.9	94.48	0.70
^{76}Ge	7.69	6.65	1.69	10.08	73.89

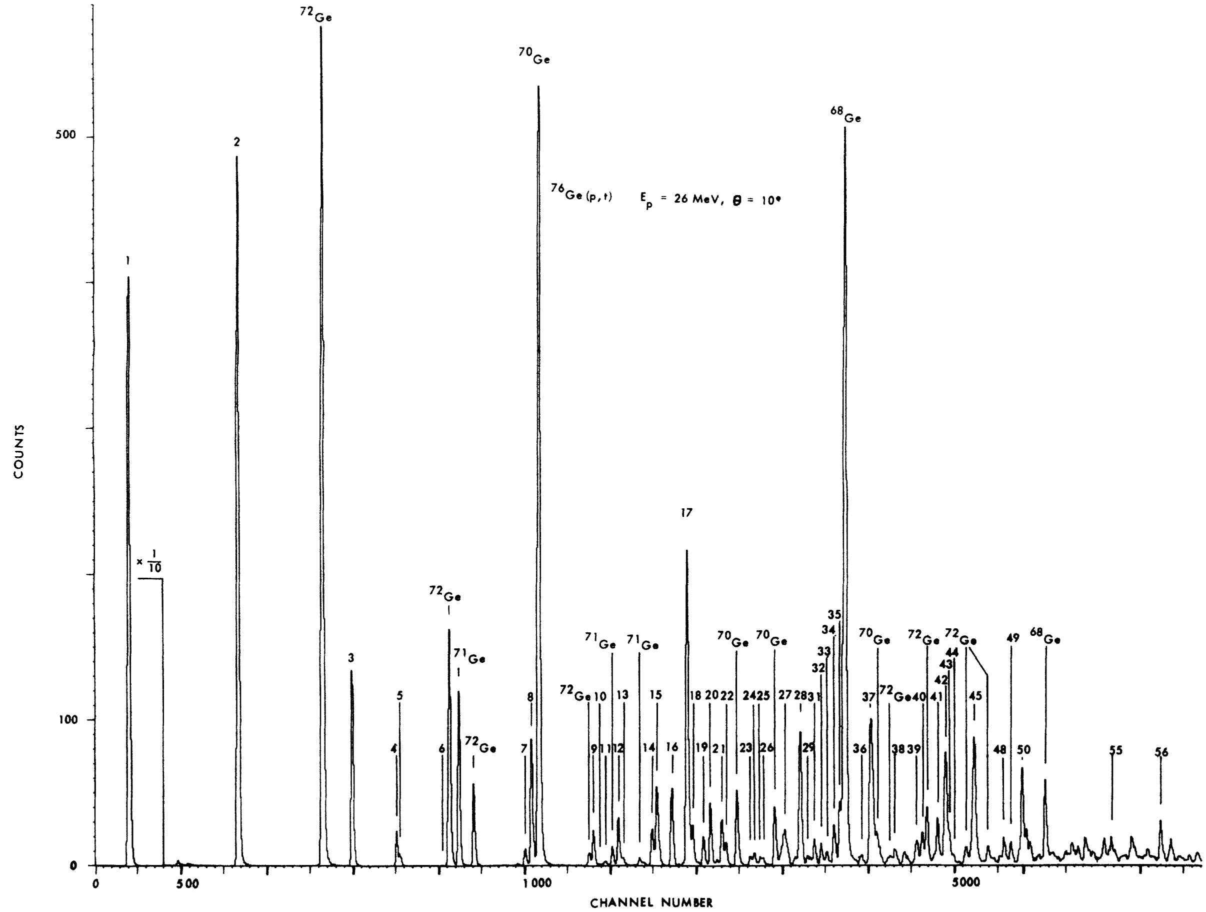


FIG. 1. Triton energy spectrum for the ^{76}Ge$(p,t)^{74}$Ge reaction at 10° lab. The numbers on top of the peaks refer to nuclear levels in ^{74}Ge (Table III). This spectrum is obtained by a calculated juxtaposition of all detector spectra at two magnetic fields; therefore, no attention must be paid to the channel calibration in the overlapping regions.

obtained from measured elastic scattering cross sections as explained in Ref. 4. The uncertainty on absolute cross sections is estimated to be about 20%. The relative normalization between the different isotopes was obtained using a natural Ge target: therefore, the estimated error is of the order of 1%.

III. ANALYSIS OF THE ANGULAR DISTRIBUTIONS

Distorted-wave–Born-approximation (DWBA) calculations were carried out using the code TWOPAR.[7] The optical model parameters used in this analysis are those of Becchetti and Greenlees[8] for the protons and those of Flynn *et al.*[9] for the tritons. They are summarized in Table II. The calculation of the form factor can be carried out with many configurations. However, only a few of them appear to give an important contribution to the calculated cross section.[5] The shapes of the calculated angular distributions for all the considered L values are not sensitive to the choice of a given configuration. Therefore, the spin and parity assignments deduced from these shapes do not depend on this choice. We have nevertheless used the same configuration to calculate the form factor corresponding to levels populated with the same L value in order to compare experimental and theoretical angular

TABLE II. Optical potential parameters used in the DWBA analysis.

Target	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	W_D (MeV)	r_0' (fm)	a' (fm)
			Protons				
^{76}Ge	57.51	1.12	0.78	3.02	7.30	1.32	0.63
^{74}Ge	56.77	1.12	0.78	3.02	6.92	1.32	0.60
^{72}Ge	56.22	1.12	0.78	3.02	6.63	1.32	0.59
			Tritons				
	164.7	1.16	0.75	2.17	0	1.50	0.82

distributions. The configurations used are (i) $(2p_{3/2})^2$ for $L=0$ and 2 transfers; (ii) $(2p_{3/2}, 2d_{5/2})$ for $L=1$; (iii) $(2d_{5/2}, 1g_{9/2})$ for $L=4$ and 6; (iv) $(1g_{9/2}, 2p_{3/2})$ for $L=3$, 5, and 7. The wave functions were calculated for a Woods-Saxon potential with $r_0=1.25$ fm, $a=0.65$ fm, and a binding energy of half the sum of the two-neutron separation energy. The (DWBA) curves are quite different for different L transfers and this allowed us to propose spin and parity assignments according to the usual selection rules.

IV. EXPERIMENTAL RESULTS

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

1. General analysis

The excitation energies of the 57 levels observed in this reaction are reported in Table III with an uncertainty of 3 keV (10 keV for a few weakly excited levels). In Table III are also reported the known energies, spins, and parities[10] and the results previously obtained by the $^{76}Ge(p,t)^{74}Ge$ reaction.[5,11] One can see on this table that spin and parity were unknown for many levels. The summed experimental cross sections between 10° and 60° are listed in Table III. We have also reported in this table the value R of the ratio of the experimental cross section at the peak (at 10° for $L=0$) to the one calculated by DWBA. These ratios should not be considered as absolute values for theoretical calculations, but they should be used only for a relative comparison of levels with the same spin and parity. An important difficulty in this study was a large number of spurious peaks. This was due to the poor enrichment (73.9%) of the target together with the low Q value for this reaction. A careful comparison between spectra recorded at 5 and 25° with natural and enriched targets allowed us to eliminate such spurious peaks. A few levels (e.g., the 2229 keV), hidden by peaks originating from strongly excited levels of other Ge isotopes, are, however, lost. The angular distributions are shown in Fig. 2 together with the DWBA predictions.

2. Levels below 2.5 MeV

Ground state. The ground state is the most populated level in the spectrum; it is about five times stronger than any other observed transition. Its angular distribution is well reproduced by an $L=0$ DWBA calculation.

0.597 MeV level. This $J^\pi=2^+$ level is also strongly excited in the reaction. Its angular distribution is fairly well reproduced by the DWBA calculation.

1.206, 1.461, and 1.481 MeV levels. These

TABLE III. Levels observed in the reaction $^{76}Ge(p,t)^{74}Ge$ at 26 MeV.

	Present work					Reference 10		Reference 10 $^{76}Ge(p,t)^{74}Ge$	
Level No.	E_x (MeV)	L	J^π	$\sum\left(\frac{d\sigma}{d\omega}\right)$ (μb)	R (See text)	E_x (MeV)	J^π	E_x (MeV)	L
1	0	0	0^+	6520	1.8	0	0^+	0	0
2	0.597		2^+	1395	1.05	0.5959	2^+	0.597	2
3	1.206		2^+	331	0.32	1.204	2^+	1.206	2
4	1.461		4^+	80		1.464	4^+		
5	1.481		0^+	107		1.483	0^+	1.479	0+ (4)
6	1.696			36		1.697			
						1.726			
						1.753 ?			
						1.910 ?			
7	2.165 [a]	4	4^+	54	0.125	2.166			
8	2.198	2	2^+	303	0.43	2.198	2^+	2.181	
						2.229	(0^+)		
9	2.542	3	3^-	342	0.46	2.536	3^-	2.535	3
10	2.572	4	4^+	8.6	0.025	2.569			
11	2.605	(1)	(1^-)	10.4	0.0023	2.600			
12	2.673	4	4^+	267	0.79	2.671		2.672	(4)
						2.694			
13	2.699			18		2.697			
						2.746			
						2.822 ?			
14	2.837	2	2^+	155	0.23	2.829		2.838	(2)
15	2.862	0	0^+	93	0.036				
16	2.940	2	2^+	252	0.32	2.935		2.941	

TABLE III. *(Continued)*.

	Present work					Reference 10		Reference 10 ^{76}Ge$(p,t)^{74}$Ge	
Level No.	E_x (MeV)	L	J^π	$\sum\left(\frac{d\sigma}{d\omega}\right)$ (μb)	R (See text)	E_x (MeV)	J^π	E_x (MeV)	L
						2.949	(3^-)		
						2.973			
						3.001			
17	3.022	2	2^+	765	1.4	3.034		3.024	(2)
18	3.053	4	4^+	239	0.81	3.049 ?			
						3.082	(3^-)		
19	3.111	5	5^-	185	1.4	3.105			
20	3.147	3	3^-	506	0.95	3.141		3.137	(3)
						3.176			
21	3.205	2	2^+	138	0.28	3.212		3.210	
22	3.225[b]	(2), (5)	$(2^+), (5^-)$	110	0.12, 0.56	3.316 ?			
23	3.342			22		3.343			
24	3.360	5	5^-	94	0.75				
25	3.388	3	3^-	52	0.10	3.385	(4^+)	3.373	
26	3.400	2	2^+	33	0.055	3.410		3.461	(5)
27	3.496	4	4^+	214	0.77	3.478		3.495	
						3.516	(4^+)		
28	3.575[a]	2	2^+	506	1.0	3.567		3.575	
						3.598 ?		3.598	(6)
29	3.613	0	0^+	11.7	0.004				
30	3.630	7	7^-	64	1.14	3.639 ?			
31	3.647	2	2^+	54	0.10				
32	3.681			91		3.697	(–)		
33	3.706	(2)	(2^+)	55	0.09	3.717 ?			
34	3.742	2	2^+	128	0.26	3.721			
35	3.773	0	0^+	83	0.026	3.807 ?			
						3.828			
36	3.872	2	2^+	49	0.085	3.895			
37	3.911	0	0^+	149	0.085	3.950		3.936	(0)
						3.976			
						3.995 ?			
38	4.023	5	5^-	115	1.18	4.020			
39	4.138	2	2^+	136	0.28	4.130			
40	4.164	2	2^+	124	0.24	4.201			
						4.223 ?			
41	4.239	0	0^+	71	0.027	4.235 ?			
42	4.273	(0)	(0^+)	160	0.066				
43	4.292	2	2^+	106	0.28	4.300			
44	4.311	4	4^+	71	0.31	4.367 ?			
45	4.405	0	0^+	234	0.09	4.478 ?			
46	4.515	4	4^+	63	0.33	4.480			
47	4.535	0	0^+	61	0.018				
48	4.591	2	2^+	88	0.22	4.611 ?			
49	4.627	(2)	(2^+)	72	0.15				
50	4.664	4	4^+	99	0.48				
51	4.681	(0)	(0^+)	112	0.05	4.680			
						4.698 ?			
						4.770			
52	4.920	(2)	(2^+)	92	0.21				
53	4.951	(2)	(2^+)	91	0.25	4.970			
54	5.021	(2)	(2^+)	62	0.18				
55	5.148					5.130	$(4^+, 5^+)$	5.131	(5)
56	5.352					5.300			
						5.440			
57	5.580	(0)	(0^+)		0.03	5.630			

[a] Mixed with tritons originating from other Ge isotopes.
[b] Unresolved doublet.

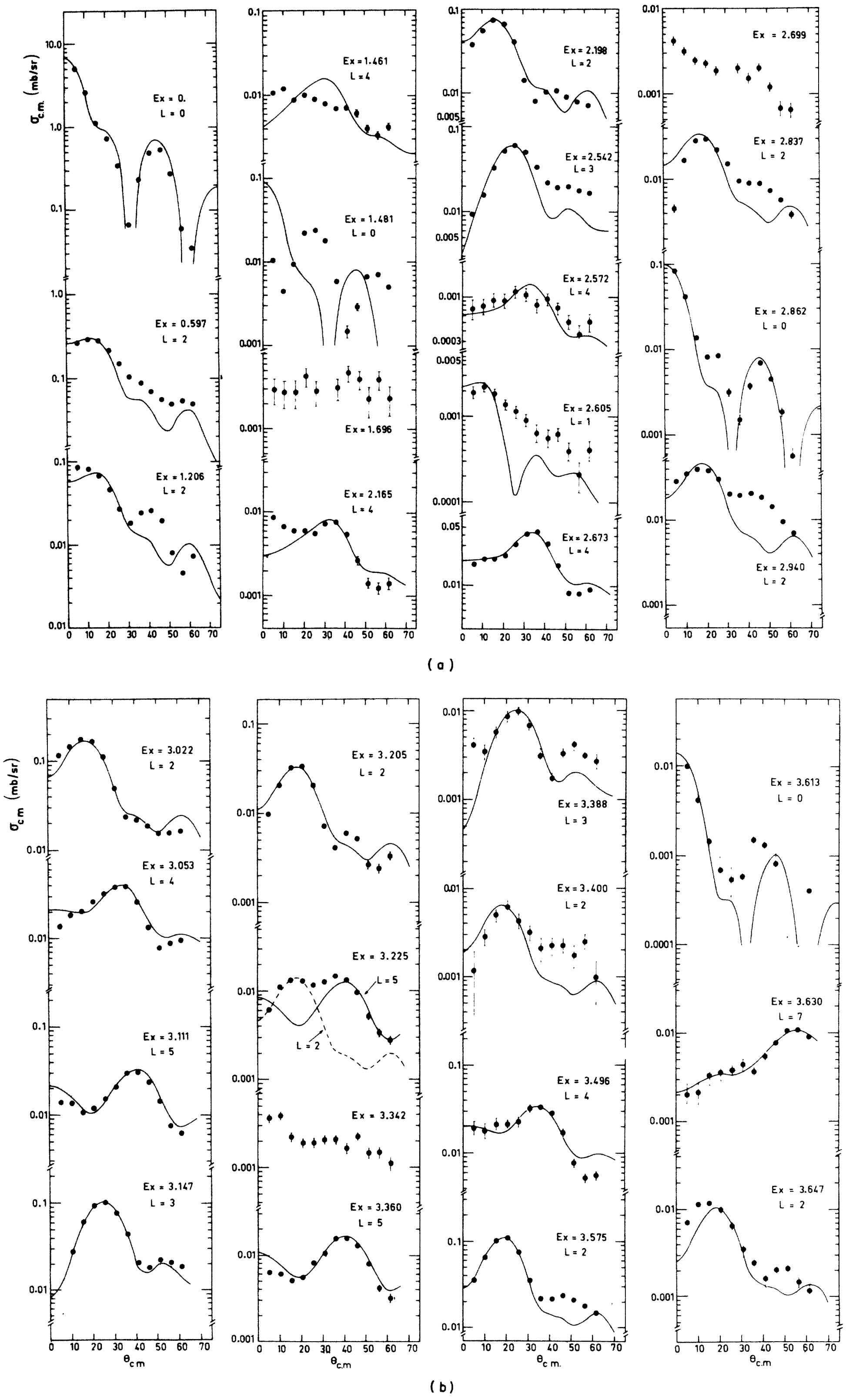
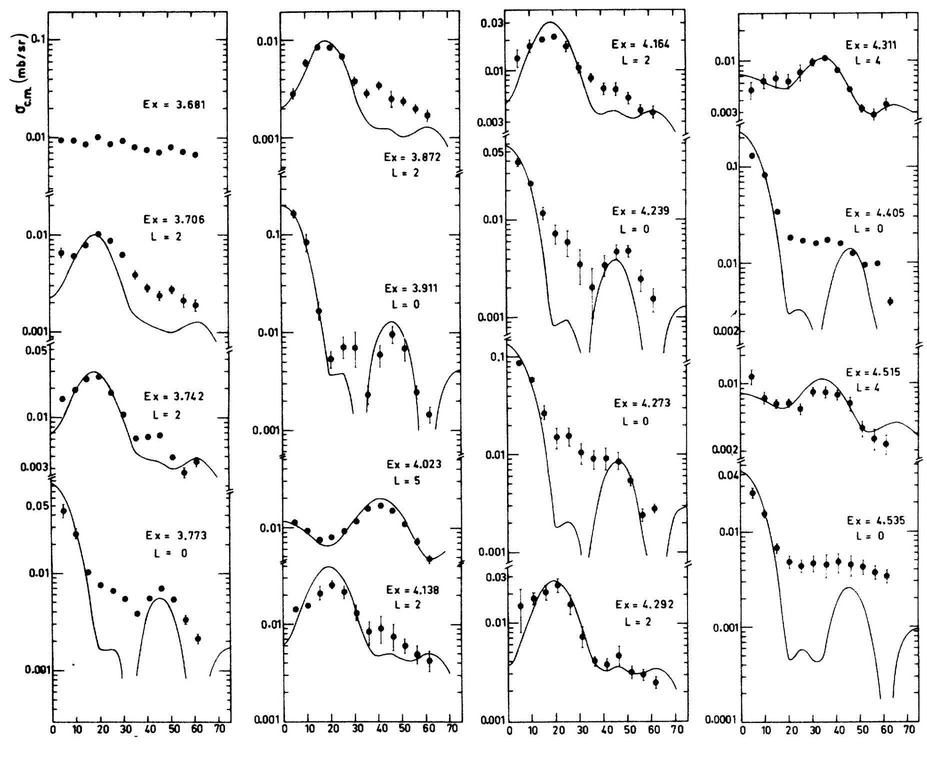
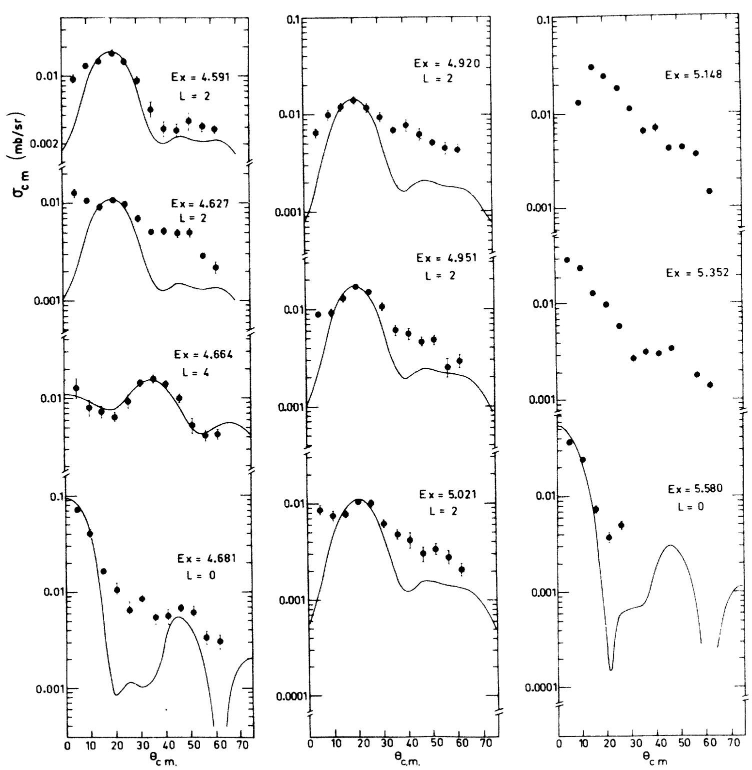


FIG. 2. Angular distributions of the $^{76}Ge(p,t)^{74}Ge$ reaction. Vertical bars are statistical errors. Curves are DWBA predictions assuming the indicated L values.



(c)



(d)

FIG. 2. *(Continued)*.

levels were previously known to be, respectively, $J^\pi = 2^+, 4^+, 0^+$. In this reaction their angular distributions are poorly fitted by the DWBA calculations. The possibility of the presence of an impurity was eliminated by careful comparison between spectra recorded with natural and enriched targets. This anomaly is discussed and interpreted as due to multistep processes in paper II.

1.696 MeV level. Assigned $J = (3)$ by Chung *et al.*[12] and $J^\pi = 3^+$ by Camp, Fielder, and Foster,[13] this level is very weakly populated, in agreement with the usual selection rules for the two-nucleon transfer.

2.165 MeV level. Tritons from the ^{73}Ge(p, t)-^{71}Ge reaction are responsible for the increase of the cross section at forward angles. Nevertheless, the good fit of the experimental distribution by an $L = 4$ DWBA calculation for angles greater than 25°, leads us to assign this level to be $J^\pi = 4^+$.

2.198 MeV level. This level was assigned to be $J^\pi = 2^+$ by several authors.[10] Its angular distribution is well reproduced by an $L = 2$ DWBA calculation.

2.229 MeV level. This level, proposed by Moreh and Shahal[14] and Rotbard *et al.*[15] could not have been observed in our spectra due to a contamination by the ^{70}Ge ground state.

2.542 MeV level. This is the first $J^\pi = 3^-$ level. It was previously reported at 2.536 MeV (Ref. 10). Its angular distribution is well reproduced by an $L = 3$ DWBA calculation.

3. $L = 0$ angular distributions

Six levels at 2.862, 3.613, 3.773, 3.911, 4.239, 4.405, and 4.535 MeV show unambiguous $L = 0$ patterns. The 4.535 MeV level was unknown before this work. The experimental cross sections of levels at 4.273, 4.681, and 5.580 MeV are strongly peaked at forward angles, but difficulties due to the weak enrichment of the target and to the high level density in this energy region are responsible for the flat surface at other angles for the two former and for the impossibility of obtaining data at angles greater than 25° for the latter.

4. $L = 2$ angular distributions

$L = 2$ patterns are observed for levels at 2.837, 2.940, 3.022, 3.205, 3.400, 3.575, 3.647, 3.742, 3.872, 4.138, 4.164, 4.292, and 4.591 MeV which then receive $J^\pi = 2^+$ assignments. Tritons originating from the 2.519 MeV level of ^{72}Ge are responsible for the increase of the 3.575 MeV level cross section for angles between 35 and 60°. As can be seen in Fig. 2 and Table III, tentative $J^\pi = 2^+$ assignments have been made for the levels at 3.706, 4.627, 4.920, 4.951, and 5.021 MeV.

5. $L = 3$ angular distributions

Unambiguous $L = 3$ transitions are observed at 3.147 and 3.388 MeV excitation energy, leading to $J^\pi = 3^-$ assignment for these two levels.

6. $L = 4$ angular distributions

Six levels at 2.572, 2.673, 3.053, 3.496, 4.311, 4.515, and 4.664 MeV are populated by $L = 4$ transitions (Fig. 2) and we propose for these levels $J^\pi = 4^+$. These spectroscopic assignments are new for all these levels (see Table III). The last three levels seem to be observed for the first time.

7. $L = 5$ angular distributions

Three levels at 3.111, 3.360, and 4.023 MeV show unambiguous $L = 5$ patterns. We assign $J^\pi = 5^-$ to these levels. The level at 3.360 MeV was previously unknown.

8. Other levels

An $L = 7$ transition is observed for the level at 3.630 MeV which we propose to be a $J^\pi = 7^-$ level. A tentative attribution $J^\pi = (1^-)$ is proposed for a level at 2.605 MeV. In the distribution of the 3.225 MeV level, the possible presence of two components, $L = 5$ and $L = 2$, could be explained by the presence of a doublet at this energy or an unknown ^{71}Ge level. The nature of the angular distribution for a few other levels is not well defined as can be seen in Fig. 2. These levels cannot receive any J^π assignment.

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

1. General analysis

Thirty-six ^{72}Ge levels are populated up to 4.3 MeV excitation energy. The results are reported in Table IV together with the previously known[1,16,17] energy, spin, and parity values. Excellent agreement is found with the previously known energies. The levels at 3.378, 3.528, 3.850, 4.108, and 4.144 MeV are observed for the first time and those at 3.131, 3.588, 3.627, 4.016, 4.076, 4.230, and 4.282 MeV, proposed by Show[17] in an unpublished paper, are confirmed. We shall first present our results for the levels up to 2.5 MeV excitation energy, most which have well-known spin and parity assignments (Sec. IV B 2); the other levels will then be presented and discussed according to the angular distributions patterns (Secs. IV B 3 to IV B 8).

TABLE IV. Levels observed in the reaction $^{74}Ge(p,t)^{72}Ge$ at 26 MeV.

	Present work					Reference 1		References 16 and 17		Reference 5	
Level No.	E_x (MeV)	L	J^π	$\sum\left(\frac{d\sigma}{d\Omega}\right)$ (μb)	R (See text)	E_x (MeV)	J^π	E_x (MeV)	J^π	E_x (MeV)	L
1	0	0	0^+	4800	1.16	0	0^+	0	0^+	0	0
2	0.691	0	0^+	1370	0.37	0.690	0^+	0.691	0^+	0.690	0
3	0.835	a	2^+	1175		0.835	2^+	0.834	2^+	0.835	2
4	1.467	a	2^+	149		1.465	2^+	1.464	2^+	1.465	2
5	1.730	a,b	4^+	58		1.725	4^+	1.728	4^+	1.728	
6	2.029	a	(0^+)	54		2.029	$(0)^+$				
						2.062	1^+-3^+	2.064	$(3)^+$	2.064	
7	2.406	2	2^+	265	0.40	2.404	1^+-3^+	2.402		2.405	
8	2.468	4	4^+	44	0.11	2.466	$(4)^+$	2.464	(4^+)		
9	2.519	3	3^-	415	0.58	2.516	3^-	2.515	3^-	2.513	
								2.583			
						2.754	1^+-3^+	2.754	$\pi=-$		
								2.774			
						2.897	$\underline{0}^+-3^+$				
								2.940			
								2.943	3^-		
10	2.951			88		2.949	1^+-3^+	2.950		2.942 [c]	
11	3.037			99		3.034	1^+-2^+	3.036	(2^-)		
12	3.078	4	4^+	144	0.53	3.073	$(4)^+$			3.074	
13	3.098	2	2^+	120	0.23	3.094	1^+-3^+	3.094	4^+		
								3.119	$\pi=-$	3.129 [c]	
14	3.139	0	0^+	292	0.10			3.131			
15	3.185	4	4^+	31	0.095	3.179	$(4)^+$				
						3.223	1^+-3^+	3.228	$\pi=-$		
16	3.330	2	2^+	419	0.8	3.324	1^+-3^+	3.325	$(3)^-$	3.323 [c]	3, (2)
								3.338			
								3.342	$(2)^-$		
						3.357	1^+-3^+				
17	3.378	4	4^+	34	0.11						
								3.398			
18	3.421 [c]	2	2^+	700	1.10	3.422	1^+-3^+	3.419		3.411	(2, 3)
						3.436	1^+-3^+	3.439			
						3.468	2^--4^-	3.455			
19	3.509	2	2^+	49	0.10	3.506	1^+-3^+				
20	3.528	4	4^+	119	0.47						
								3.550			
21	3.554	(1)	(1^-)	26	(0.37)	3.565	1–4	3.566			
22	3.589	0	0^+	77	0.028			3.588			
						3.614	$(0)^+$	3.619			
23	3.625	2	2^+	22	0.038			3.627			
24	3.663	(6)	(6^+)	127	(0.76)	3.662	1^+-3^+	3.667			
								3.678			
						3.691					
25	3.703	2	2^+	46	0.10			3.708			
								3.759			
						3.777					
								3.803			
26	3.821	5	5^-	55	0.39	3.815	2^--4^-	3.816			
27	3.850	4	4^+	20	0.06						
						3.867		3.872			
28	3.890			288	(0.46)	3.895	1^+-3^+	3.890	$\pi=-$		
						3.975		3.965	$\pi=-$		
29	3.981	(2)	(2^+)	79	(0.15)			3.984			
								3.986			
						4.002	1^+-3^+	3.995			
30	4.013	4	4^+	81	0.28			4.016			

TABLE IV. (*Continued*)

Level No.	Present work E_x (MeV)	L	J^π	$\sum\left(\frac{d\sigma}{d\Omega}\right)$ (μb)	R (See text)	Reference 1 E_x (MeV)	J^π	References 16 and 17 E_x (MeV)	J^π	Reference 5 E_x (MeV)	L
						4.047	1^+-2^+	4.041			
31	4.076	5	5^-	119	1.0			4.076			
						4.092	1^+-3^+	4.090			
32	4.108	2	2^+	45	0.10						
33	4.144	4	4^+	70	0.28						
						4.147	1^+-3^+				
						4.171	1^+-3^+				
34	4.191 [c]	0 + (4)	$0^+ + (4^+)$	207				4.194	$\pi = -$		
35	4.229	(3)	(3^-)	74	(0.14)	4.224	2^--4^-	4.230			
36	4.285	3	3^-	54	0.14			4.282			

[a] Angular distribution not fitted by a DWBA calculation.
[b] Presence of an unseparated impurity.
[c] Presence of an unseparated doublet.

2. Levels below 3 MeV

The angular distributions for the ground state (0_1^+) and first excited 0^+ level (0_2^+) at 0.691 MeV are well reproduced by $L=0$ DWBA calculations (Fig. 3), the summed cross section for the 0_2^+ level being 29% of the ground-state one. These two transitions dominate the entire spectrum and represent about 90% of the $L=0$ strength in the range of excitation observed. The level at 2.406 MeV was previously known with the following spin-parity limits: $J^\pi = 1^+-3^+$.[1] The agreement with an $L=2$ transition (Fig. 3) leads to a $J^\pi = 2^+$ assignment. The good fit obtained with an $L=4$ calculation for the 2.468 MeV level firmly establishes the $J^\pi = 4^+$ assignment in agreement with the previously proposed value[1,16] $J^\pi = (4)^+$. The first $J^\pi = 3^-$ excited level in ^{72}Ge is populated with a large cross section by an $L=3$ transition. The levels at 0.835 and 1.467 MeV are not well fitted by the DWBA calculations. The shape of the angular distribution being the same as the corresponding levels in ^{74}Ge, the origin of the anomaly is probably the same (multistep process). The same is true for the 2.029 MeV level (proposed $J^\pi = 0^+-3^+$ in Ref. 1), whose angular distribution, although completely at variance with the standard forward shape $L=0$ angular distribution, is strictly similar with that of the known $J^\pi = 0^+$ level at 1.481 MeV in ^{74}Ge (Fig. 4). It is to be noted that this anomalous shape has been fairly well reproduced by preliminary coupled-channel–Born-approximation calculations.[18] For the 4_1^+ level at 1.730 MeV, we unfortunately cannot conclude the anomalous shape of the angular distribution; the corresponding peak is probably contaminated. It must, however, be noticed that its shape is similar to the angular distribution of the corresponding 4_1^+ state in ^{74}Ge.

The previously known level at 2.062 [$J^\pi = (3)^+$] is not at all populated in this study as expected in a direct mechanism. Transitions to other known levels below 3 MeV are either very weak or could not be observed due to contamination originating from other Ge isotopes (particularly 2.754 and 2.897 MeV).

3. L = 0 angular distributions

$L=0$ patterns are also observed for levels at 3.139, 3.589, and 4.191 MeV leading to a $J^\pi = 0^+$ assignment. No spin assignment was previously known for these three levels. The first two confirm the levels observed by Show at 3.131 and 3.588 MeV in a ^{73}Ge$(p,d)^{72}$Ge study. The level at 4.191 MeV appears as an unresolved doublet (Fig. 3). An indication of the presence of a $J^\pi = 0^+$ level in this group can, however, be deduced from our proposed $L = 0 + (4)$ pattern.

4. L = 2 angular distributions

The angular distributions for eight levels above 3 MeV are fitted by an $L=2$ transition (Table IV). The values of spin and parity $J^\pi = 2^+$ are then deduced except for the two levels at 3.625 and 3.981 MeV for which the poor quality of the fit casts some doubt about this assignment. For the other levels, no unique spin-parity was previously known; our $J^\pi = 2^+$ result falls within the 1^+-3^+ limits previously proposed[1] for some of them (see Table IV). The existence of a level proposed by Show[17] at 3.627 MeV is confirmed by our work. The possi-

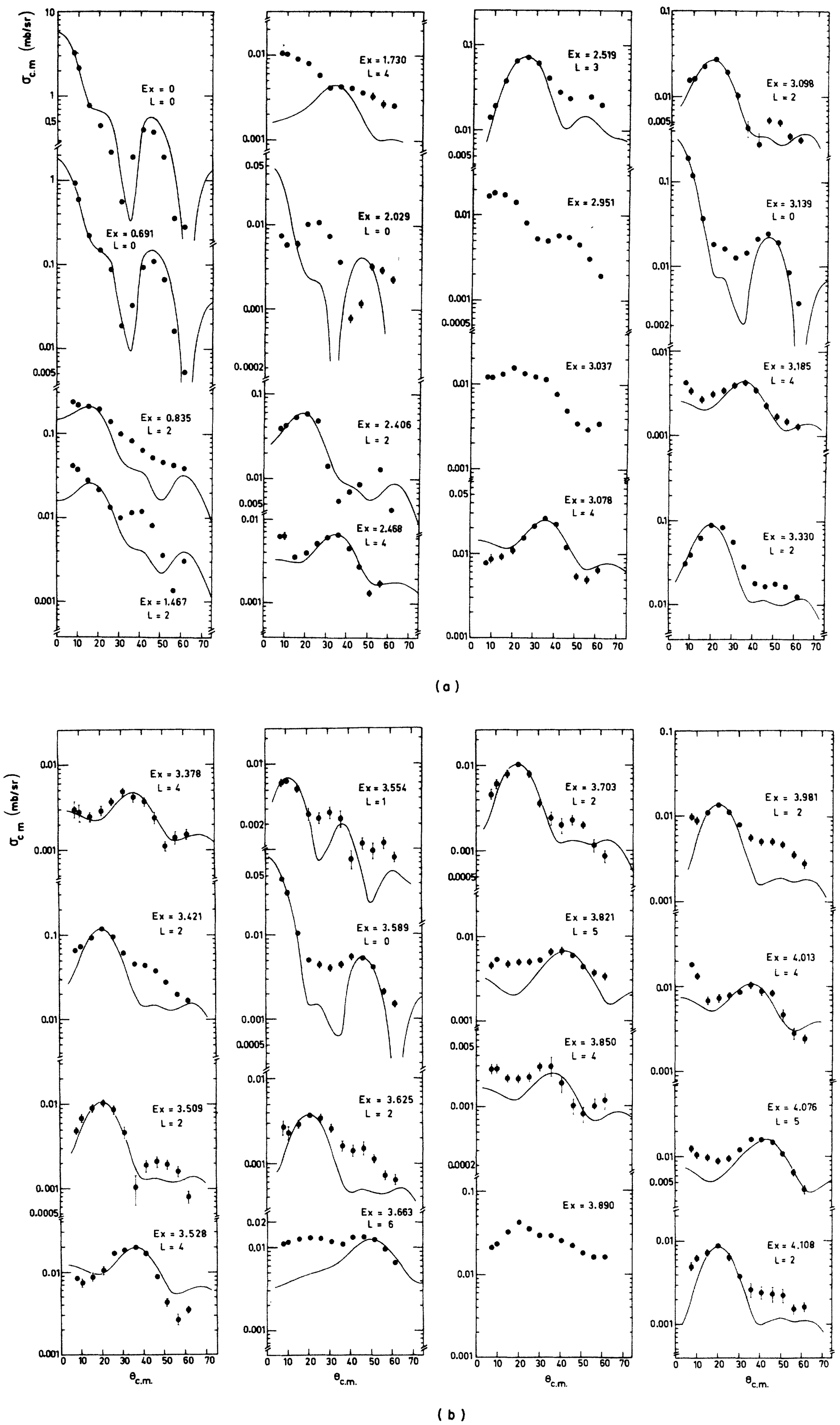


FIG. 3. Angular distributions of the ^{74}Ge$(p,t)^{72}$Ge reaction. See caption for Fig. 2.

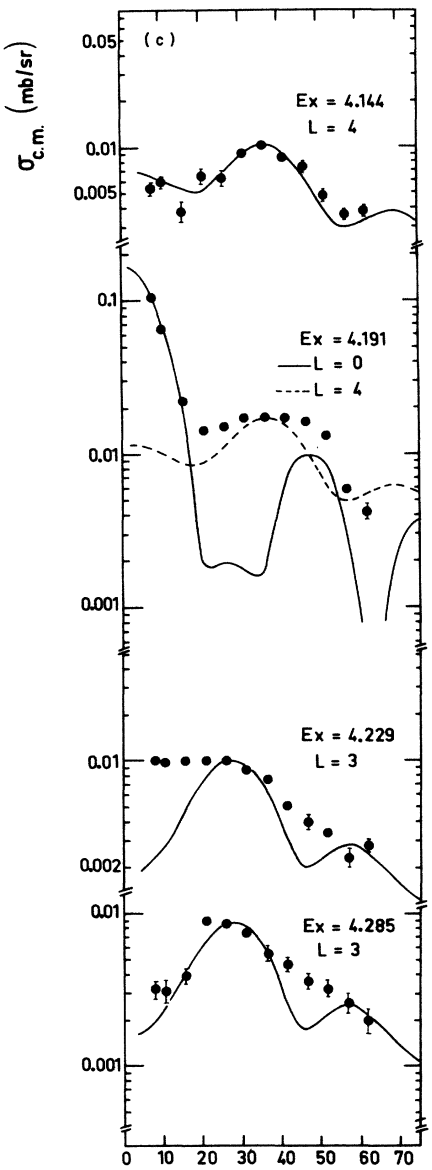


Figure 3 (*continued*)

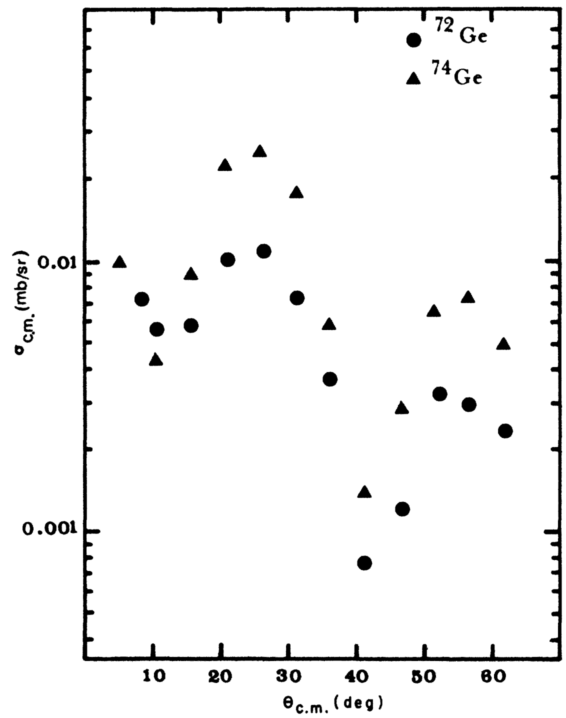


FIG. 4. Angular distributions of the 1.461 MeV level in ^{74}Ge and the 2.029 MeV level in ^{72}Ge.

bility of an unseparated doublet around the group number 18 at 3.421 MeV (Table IV) appears plausible from the peak width observed in the spectra. However, the presence of a strong $L = 2$ transfer is obvious in this transition, which is, together with the one at 3.330 MeV, the most important $L = 2$ transition observed in ^{72}Ge.

5. $L = 3$ angular distributions

Besides the previously discussed strong $L = 3$ transition (Sec. II), two levels at 4.229 and 4.285 MeV are weakly populated by an $L = 3$ angular distribution. The $J^\pi = 3^-$ assignment is new for the level at 4.285 MeV which can probably be identified to the 4.282 MeV level previously proposed by Show.[17] This assignment is less reliable for the level at 4.229 MeV on the basis of the experimental forward cross sections which (Fig. 3) fall, however, within the previously proposed limits $J^\pi = 2^- - 4^{-1}$ for this level.

6. $L = 4$ angular distributions

The two levels at 3.078 and 3.185 MeV in ^{72}Ge were first observed in our previous (^{3}He, d) study and proposed as $J^\pi = 4^+$ levels. Their existence and these spin-parity values are confirmed by the observed angular distributions (Fig. 3). Four new levels at 3.378, 3.528, 3.850 and 4.144 MeV are also populated by an $L = 4$ transfer and then receive $J^\pi = 4^+$ assignment. The same is true for the level at 4.013 MeV which is probably the 4.016 level mentioned by Show[17] in his (p, d) study.

7. $L = 5$ transitions

Two transitions at 3.281 and 4.076 MeV appear fairly well fitted by an $L = 5$ calculation. This leads to a proposed $J^\pi = 5^-$ assignment for these levels, in disagreement with the limits $J^\pi = 2^- - 4^-$ previously proposed in our (^{3}He, d) study for a level at 3.815 MeV. However, this discrepancy is only apparent because the 4^- spin limit in the

(^{3}He, d) study results from the existence of a very small $l=2$ component which in fact might very well be absent.

8. *Other levels*

Due to low cross sections and possible contaminations from other states, the nature of some angular distributions does not appear as well defined as for the preceding levels. Some of them are, however, tentatively assigned according to the most likely angular momentum transferred. The level at 3.554 MeV is thus proposed to be (1^-)states while a $J^\pi=(6^+)$ assignment is given for the 3.663 MeV level (Table IV).

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

1. *General analysis*

The results obtained in this reaction are summarized in Table V where the previously known results[19,2,5,14] are also reported. Fifty-four levels are observed below 5.5 MeV excitation energy. The energy values, determined in the present work, are in good agreement with the previously known ones. Figure 5 shows the experimental angular distributions together with the DWBA predictions.

2. *Levels below 2.6 MeV*

Three levels exhibit $L=0$ patterns below 2.6 MeV. Among them the ground state and the 1.216 MeV levels were previously known $J^\pi=0^+$ levels, while the 2.311 MeV level was tentatively attributed[19] $J^\pi=(0^+)$. The ground-state level is the most strongly populated. It dominates the entire spectrum and represent about 85% of the $L=0$ strength in the range of excitation observed. As in the case of the preceding isotopes, the known 2_1^+ and 2_2^+ levels at 1.037 and 1.708 MeV present angular distributions not very well fitted by $L=2$ DWBA calculations, this being particularly true for the first one. The 2.155 MeV level is a doublet composed of the 2.153 ($J^\pi=4^+$) and 2.158 MeV ($J^\pi=2^{(+)}$) levels; according to its angular distribution (Fig. 5) we can say that these two levels are populated in the reaction.

At 2.538 MeV a level shows an $L=2$ pattern. From our (^{3}He,d) work,[2] this level was found to be $J^\pi=1^+-3^+$. The present work leads us to attribute unambiguously a $J^\pi=2^+$ spin and parity to this level.

The 2.562 MeV level is populated with a very large cross section by an $L=3$ transition. It is the first $J^\pi=3^-$ excited level observed in ^{70}Ge at an energy close to the energy of the known first $J^\pi=3^-$ level in other Ge isotopes. The whole $L=3$ strength observed in our spectrum is concentrated on this level. The level at 2.452 MeV was proposed as $J=(3)$ in the compilation of Alvard and Raman.[19] It was observed in our (^{3}He,d) experiment[2] and proposed to be $J^\pi=1^+-3^+$. Morand *et al.*[20] have proposed $J^\pi=3^+$ for this level. Such a $J^\pi=3^+$ level would not be populated in the (p,t) reaction due to the selection rules. This is in agreement with the non observation of this level in our work.

3. *$L=0$ angular distributions*

$L=0$ patterns are observed for the levels at 2.891, 3.105, 3.329, 3.683, 3.740, 4.332, 4.539,

TABLE V. Levels observed in the reaction ^{72}Ge$(p,t)^{70}$Ge at 26 MeV.

	Present work					(^{3}He,d) Ref. 2		Reference 19		(p,t) Ref. 19	
Level No.	E_x (MeV)	L	J^π	$\sum\left(\frac{d\sigma}{d\omega}\right)$ (mb)	R (See text)	E_x (MeV)	J^π	E_x (MeV)	J^π	E_x (MeV)	L
1	0	0	0^+	6.2	1.5	0	0^+-3^+	0	0^+	0	0
2	1.037	(2)	2^+	1.6		1.040	1^+-3^+	1.0396	2^+	1.036	2
3	1.212	0	0^+	0.44	0.12	1.216	0^+-3^+	1.2158	0^+	1.213	0
4	1.708	(2)	2^+	0.12		1.709	1^+-3^+	1.7080	2^+	1.708	2
5	2.155 [a]		$(2^+)+(4^+)$	0.09				2.1530	(4^+)	2.148 [a]	2
						2.157	1^+-3^+	2.1568	$2^{(+)}$		
6	2.311	0	0^+	0.055	0.018	2.307	0^+-3^+	2.3071	(0^+)	2.301	0
						2.452	1^+-5^+	2.4516	(3)		
7	2.538	2	2^+	0.14	0.29	2.535	1^+-3^+	2.5355			
8	2.562	3	3^-	0.46	0.91	2.563	2^--6^-	2.5623	(3^-)	2.558	3
9	2.806	4	4^+	0.03	0.1	2.808	1^+-5^+	2.8067	(4)		
10	2.891	0	0^+	0.03	0.01	2.888	0^+-3^+	2.8871	(0)		
11	2.947	2	2^+	0.11	0.22	2.941	1^+-3^+	2.9453	(1, 2)	2.937	
								3.0468	(3^+)	3.058 [a]	4, (3)

TABLE V. *(Continued)*.

Level No.	Present work E_x (MeV)	L	J^π	$\sum\left(\frac{d\sigma}{d\omega}\right)$ (mb)	R (See text)	(^{3}He, d) Ref. 2 E_x (MeV)	J^π	Reference 19 E_x (MeV)	J^π	(p,t) Ref. 19 E_x (MeV)	L
12	3.054	4	4^+	0.23	0.89	3.053	1^+-5^+	3.0592	(4^+)		
13	3.105	(0)	(0^+)	0.02	0.003			3.1072	(0)		
14	3.176	2	2^+	0.29	0.6	3.182	1^+-3^+	3.1810		3.187 [a]	
15	3.188	4	4^+	0.22	0.73			3.195			
						3.243	1^+-3^+	3.2406	(1)		
16	3.292			0.01				3.2931			
17	3.308	(1)	(1^-)	0.04	0.012	3.314	0^--4^-	3.3147			
18	3.329 3.340 [a]	0	0^+	0.11	0.04	3.335	0^+-3^+	3.3356		3.327 [a]	
19	3.412	5	5^-	0.07	0.6			3.419			
20	3.424	(2)	(2^+)	0.10	0.17	3.422	1^+-3^+	3.426		3.430 [a]	
21	3.455			0.01		3.452		3.456			
22	3.481			0.015		3.481	1^+-3^+	3.4823			
23	3.566 [b]			0.14		3.567	2^--6^-	3.570		3.566	(3,4)
24	3.634	(2)	(2^+)	0.35	0.83	3.628	0^+-3^+	3.6317		3.628	(2,3)
25	3.683	0	0^+	0.12	0.049	3.687	1^+-3^+	3.691		3.676 [a]	
26	3.740	0	0^+	0.02	0.007	3.733	1^+-3^+	3.740			
27	3.780	2	2^+	0.12	0.35	3.775	1^+-3^+	3.777			
								3.783			
28	3.868			0.024		3.854	2^--4^-	3.850			
								3.857			
						3.888	1^+-3^+	3.891			
29	3.898 [a]	(1)	(1^-)	0.033	0.008	3.903	1^+-3^+	3.9039			
30	3.922	4	4^+	0.040	0.17			3.928			
31	4.028	4	4^+	0.12	0.49	4.024					
32	4.086	4	4^+	0.059	0.21	4.080	1^+-3^+				
33	4.180	2	2^+	0.15	0.55			4.176			
34	4.226	2	2^+	0.04	0.13			4.227			
35	4.242	(4,5)	(4^+,5^-)	0.05		4.238	1^+-3^+	4.242			
36	4.264 [c]	2	2^+	0.02	0.061			4.261			
37	4.332 [c]	0	0^+	0.06	0.046	4.330	2^--4^-	4.334			
38	4.345 [c,d]	2	2^+		0.18	4.352	2^--4^-	4.357			
39	4.357 [c,d]	2	2^+		0.14						
40	4.449	2	2^+	0.07	0.27	4.446		4.448			
41	4.472	4	4^+	0.06	0.26	4.473	1^+-3^+	4.475			
						4.520	2^--4^-	4.520			
42	4.539	0	0^+	0.056	0.035						
						4.555		4.557			
43	4.629			0.04		4.613	1^+-3^+				
44	4.712 [c]	(2)	(2^+)	0.03	0.12	4.736	2^--4^-	4.716			
45	4.935	1	1^-	0.06	0.038	4.943	2^--4^-				
46	5.024	2	2^+	0.04	0.18						
47	5.050	0	0^+	0.013	0.008	5.048	2^-	5.049 [e]			
48	5.184	0	0^+	0.017	0.013						
49	5.290	0	0^+	0.034	0.033						
50	5.338	0	0^+	0.02	0.014						
51	5.403	0	0^+	0.02	0.014			5.400 [e]			
52	5.410										
53	5.441	(2)	(2^+)	0.03	0.16						
54	5.467	0	0^+	0.03	0.018						

[a] Unresolved doublets.
[b] Mixed with tritons originating from (p,t) reactions on other Ge isotopes.
[c] Uncertainty about 20 keV for these levels.
[d] Unresolved at 5 and 10° from the 4.332 peak.
[e] Reference 20.

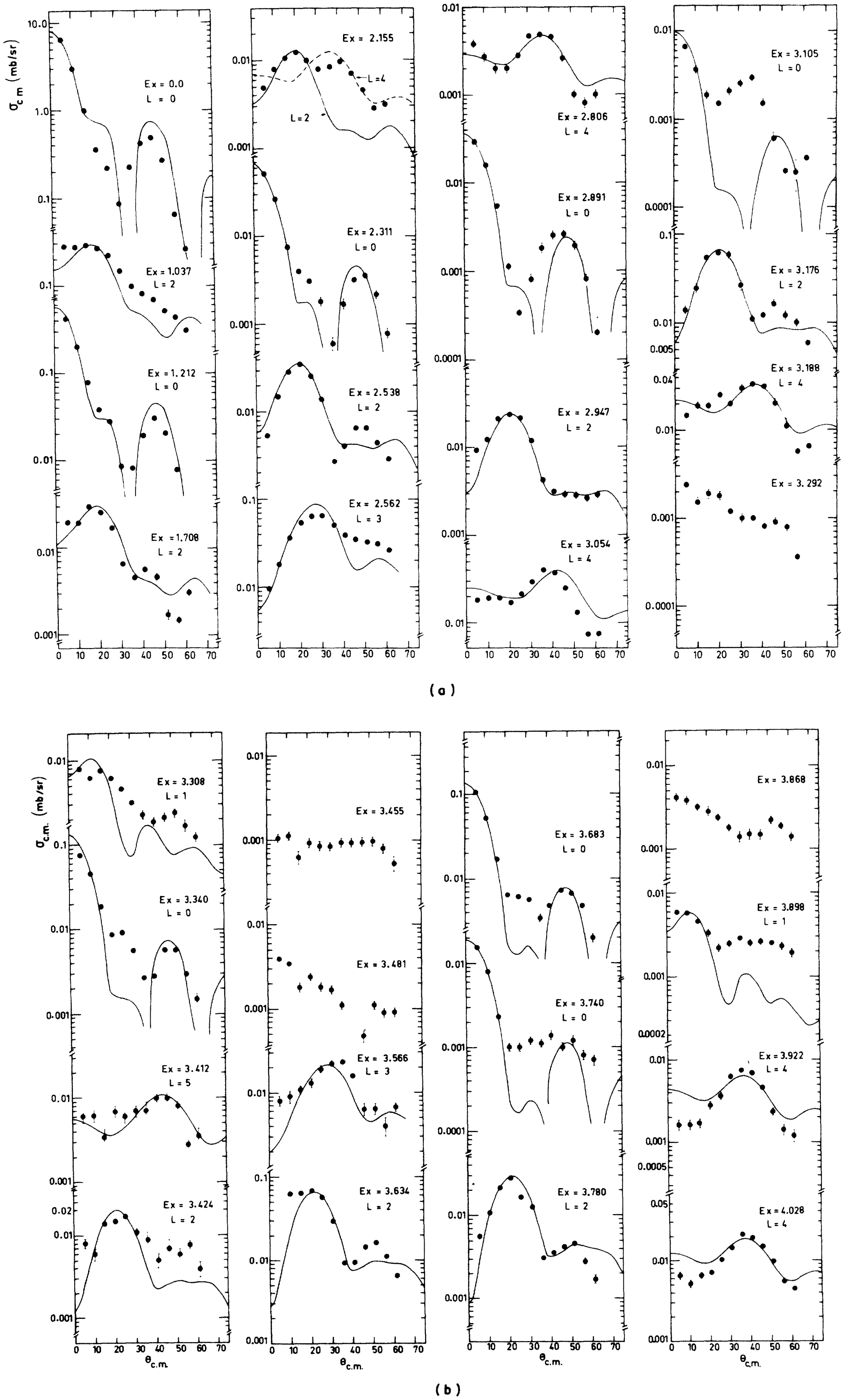
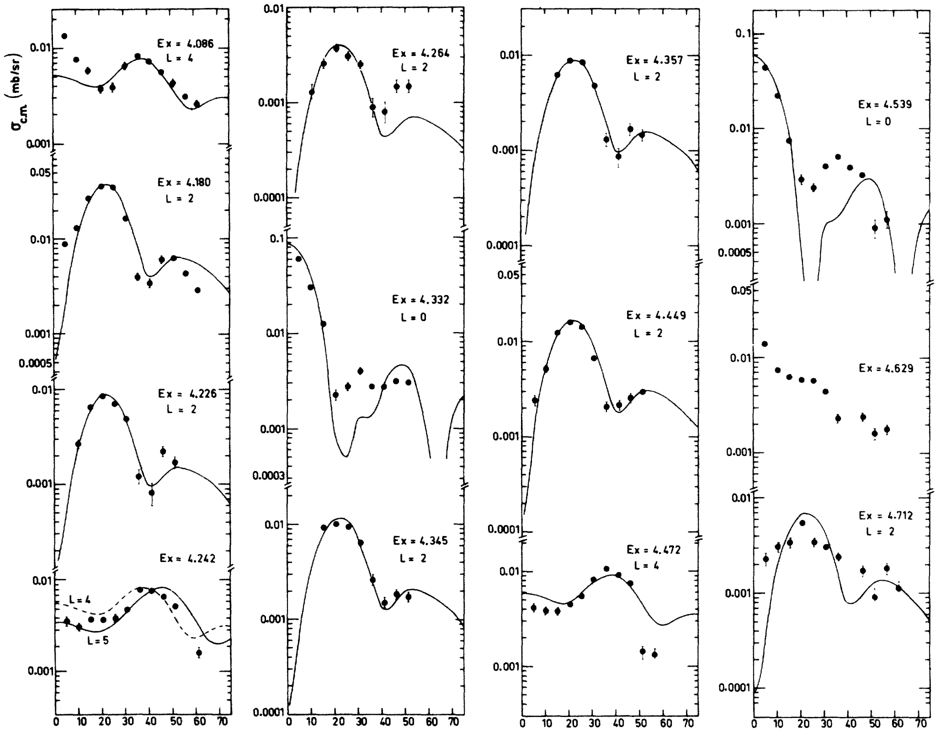
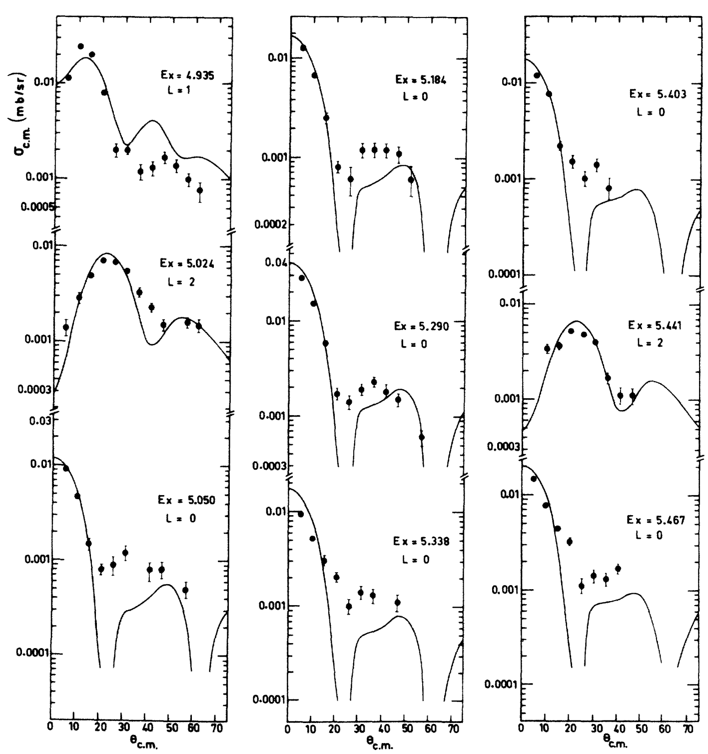


FIG. 5. Angular distributions of the $^{72}Ge(p,t)^{70}Ge$ reaction. See caption for Fig. 2.



(c)



(d)

Figure 5 (*continued*)

5.050, 5.184, 5.290, 5.338, 5.403, and 5.467 MeV. The $J^\pi = 0^+$ deduced assignments are in agreement with our (^{3}He,d) results $J^\pi = 0^+ - 3^+$ (Ref. 2) and previous data (Ref. 19) for the levels at 2.891 and 3.329 MeV. Though not well accounted for by the DWBA calculation, the $L = 0$ angular distribution found at 3.105 MeV is in agreement with the previous result $J^\pi = (0^+)$ (Ref. 2). The apparent discrepancies with the spin-parity limits proposed in our (^{3}He,d) experiment for the levels at 3.683, 3.740, 4.332, and 5.050 MeV could be explained by difficulties for a correct evaluation of the very small $l = 3$ (or 4) component in the $l = 1 + 3$ or $2 + 4$ admixtures in our (^{3}He,d) study and possible doublets not separated with our energy resolution (18–21 keV) in the above study. The levels at 5.184, 5.290, 5.338, and 5.467 MeV are mentioned for the first time.

4. *L = 1 angular distributions*

The level at 4.935 MeV excitation energy shows an unambiguous $L = 1$ pattern. We assume it to be $J^\pi = 1^-$. As can be seen on Fig. 4 and Table V, tentative $J^\pi = 1^-$ assignments have been made for the levels at 3.308 and 3.898 MeV. In the 3.898 MeV level the presence of an unresolved component in the peak is perhaps responsible for the increase of the experimental cross section at angles greater than 20°. The level at 3.308 MeV is to be compared with the 3.314 MeV level assigned to be $J^\pi = 0^- - 4^-$ in our (^{3}He,d) work.[2]

5. *L = 2 transitions*

Eleven levels at 2.947, 3.176, 3.780, 4.180, 4.226, 4.264, 4.345, 4.357, 4.449, and 5.024 MeV show unambiguous $L = 2$ angular distributions. In Table V we have assigned them as $J^\pi = 2^+$ levels. The levels at 3.424, 3.634, 4.712, and 5.441 MeV are not well fitted by $L = 2$ DWBA calculations (Fig. 5); they nevertheless are tentatively assigned as $J^\pi = (2^+)$. These assignments are in agreement with our (^{3}He,d) work or previous data for the 2.947 and 3.780 levels and are new for all the other levels (except the 4.712 one).

6. *L = 4 transitions*

Seven levels above 2.5 MeV are populated by $L = 4$ transitions (Fig. 4). They were previously known. The two levels at 2.806 and 3.054 MeV were proposed as $J^\pi = 1^+ - 5^+$ levels in our (^{3}He,d) experiment.[2] In Alvar's compilation,[19] they were proposed, respectively, as $J = (4)$ and $J^\pi = (4^+)$ levels. Their unambiguous $L = 4$ pattern leads us to assign them as $J^\pi = 4^+$ levels. For the 3.188 and 4.086 MeV levels, the apparent disagreement with the previously known values[2] $J^\pi = 1^+ - 3^+$ might be explained by the existence of unseparated doublets. The level at 4.472 MeV was proposed $J^\pi = 1^+ - 3^+$ in our (^{3}He,d) experiment,[2] but the quality of the fit was not as good as for other levels. In the present work, the angular distribution for this level shows an unambiguous $L = 4$ pattern and we assume it to be $J^\pi = 4^+$. The two levels at 3.922 and 4.028 MeV are to be compared with the ones at 3.928 (Ref. 12) and 4.024 MeV (Ref. 2), but their spin and parity were not previously known.

7. *Other levels*

The level at 3.412 MeV shows an $L = 5$ pattern. This level was previously known[19] but its spin and parity assignments $J^\pi = 5^+$ are new. For a few levels, the nature of the angular distribution is not well defined as for the preceding levels. One of them ($E_x = 4.242$) is tentatively assigned $J^\pi = (4^+, 5^-)$; the others cannot receive any L assignments as indicated in Table V.

IV. SUMMARY

The analysis of the angular distributions of the ^{72,74,76}Ge$(p,t)^{70,72,74}$Ge reactions has permitted us to propose a great number of new spin-parity assignments for ^{70}Ge, ^{72}Ge, and ^{74}Ge levels up to 4.5–5 MeV excitation energy. We emphasize the observation of several low-lying 0^+ states at 2.862 MeV in ^{74}Ge, 2.029 and 3.139 MeV in ^{72}Ge, and 2.311 and 2.891 MeV in ^{70}Ge, some of them appearing as the second excited 0^+ levels. Only one $J^\pi = 4^+$ state was previously well known in each Ge isotope: We have established the position of many 4^+ levels together with 2^+, 3^-, and 5^- states below 5 MeV excitation energy. A $J^\pi = 6^+$ level is proposed at 3.663 MeV in ^{72}Ge and an $L = 7$ transition leading to a $J^\pi = 7^-$ level is found at 3.630 MeV in ^{74}Ge. The analysis of the angular distributions in terms of DWBA has revealed the dominant character of a direct mechanism in our study except for some low-lying 0^+, 2^+, and 4^+ levels. An interpretation of these apparent anomalies will be given in a forthcoming paper together with some theoretical studies of the Ge isotopes. We believe that our high resolution systematic study of the (p,t) reaction on the Ge isotopes (present paper and Ref. 4) provides much new data necessary for theoretical investigations of these transitional nuclei.

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