Levels of ^{68}Ge excited by the (p, t) reaction

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The ^{70}Ge$(p,t)^{68}$Ge reaction has been studied at 26 MeV incident energy with an overall resolution of 10 keV using a split-pole spectrometer. Forty-one ^{68}Ge levels, among which twenty-eight are observed for the first time, are populated below 5.2 MeV excitation energy. Angular distributions are obtained, and comparison with distorted-wave Born approximation calculations allows spin and parity assignments. An interesting result is the discovery of the first excited 0^+ level at 1.753 MeV as well as seven other 0^+ levels above 2 MeV energy. Five $J^\pi = 2^+$ and four $J^\pi = 4^+$ levels are observed for the first time. We also establish the position of the first $J^\pi = 3^-$ level at 2.651 MeV and the possibility of a $J^\pi = 6^+$ level at 4.456 MeV excitation energy.

[NUCLEAR REACTIONS ^{70}Ge(p,t), $E = 26$ MeV; measured $\sigma = \sigma(\theta)$; ^{68}Ge deduced levels up to 5.2 MeV, J, π.]

I. INTRODUCTION

The structure of the nuclei in the $N = 40$ region is still a rather puzzling matter, even for the low energy excitation region. A systematic study of some nuclei in this region by one-nucleon transfer reactions, has already shown[1,2] the necessity of gathering new experimental results as only a few excited levels were well known until recently. We have studied the (p,t) reaction on all stable even-even Ge isotopes. This appears to be a powerful spectroscopic tool. For the neutron deficient ^{68}Ge only very little was known when we started our work: A recent compilation[3] of the Nuclear Data Group reports the previously known excited levels, all with only tentative J^π assignments. Levels up to 4.2 MeV excitation energy have been studied by β^+ decay[4] of the ^{68}As, ^{70}Ge(p,t) reaction[5,6] and in-beam γ-ray spectroscopy[7] using the ^{40}Ca$(^{32}$S$, 3pn\beta^+ + 4p)$ and ^{58}Ni$(^{12}$C$, 2p + pn\beta^+)^{68}$Ge reactions. The (p,t) reaction has been studied at $E_p = 27$ MeV by Shepard, Graetzer, and Kraushaar[5] and at $E_p = 20$ MeV by Hsu *et al.*[6] but the energy resolution (90 and 30 keV, respectively) or poor statistics did not allow resolution of many levels. The second purpose of our work was to locate the low lying excited 0^+ states in ^{68}Ge. This is particularly useful to give evidence for possible shape transition and the existence of supersoft nuclei in this region. This paper supersedes preliminary results given previously.[8]

II. EXPERIMENTAL PROCEDURE

The ^{70}Ge(p,t) reaction was performed at a proton energy of 26 MeV using the Orsay MP tandem accelerator. The outgoing particles were analyzed by a split-pole magnetic spectrometer and detected in the focal plane with six position-sensitive silicon detectors. The information delivered by each detector (E proportional to the energy lost in the detector and P proportional to the same output E times a function of the position of the particle along the length of the detector) was analyzed by a Télémécanique T 1600 computer. The P and E data were stored on magnetic tape for future analysis; particle identification was achieved by setting a window on the E signal, the ratio P/E was computed and displayed on line.

The target was made of GeO_2 (84.6% of ^{70}Ge) evaporated onto a carbon backing of 5 μg/cm^2 and had an areal density of about 200 μg/cm^2. The overall resolution was 10 keV full width at half maximum (FWHM). Data were taken in 5° steps from 5° to 60°. At each angle two consecutive exposures were needed at different magnetic fields, in order to observe the complete energy spectrum. Relative differential cross sections were based on the charge collected (about 4 mC for each spectrum). Absolute cross sections were determined at 5° and 25° using a natural germanium target. Its thickness was measured by proton elastic scattering and comparison with the optical model pre-

TABLE I. Optical potential parameters used in the DBWA analysis.

V (MeV)	r_0 (fm)	a (fm)	W (MeV)	W_D (MeV)	r_0' (fm)	a' (fm)
			Protons			
55.64	1.12	0.78	3.02	6.33	1.32	0.57
			Tritons			
164.7	1.16	0.75	21.7	0	1.5	0.82

dictions. The optical parameters are those of Ref. 9 (see Table I). The uncertainty on absolute cross sections is estimated to be about 20%.

III. EXPERIMENTAL RESULTS

A. General Analysis

Figure 1 shows a spectrum of ^{68}Ge at a laboratory angle of 10°. The numbers on top of each peak refer to nuclear energy levels in ^{68}Ge, the corresponding excitation energies being reported in

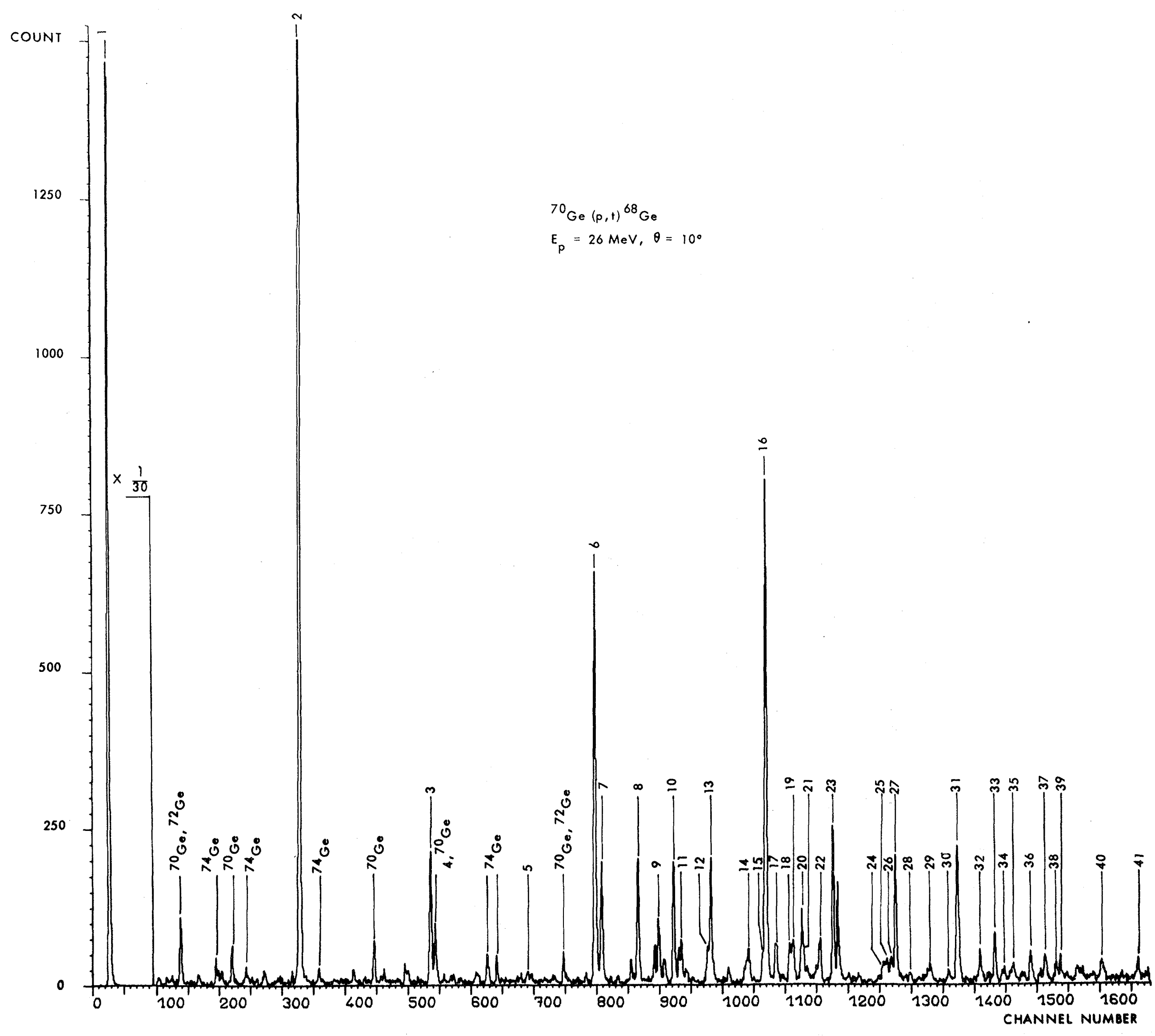

FIG. 1. Triton energy spectrum from the ^{70}Ge(p,t)^{68}Ge reaction at 10° lab. The numbers on top of the peaks refer to nuclear levels in ^{68}Ge. The other peaks originate from other Ge isotopes. This spectrum is obtained by a calculated juxtaposition of all detector spectra at two magnetic fields; therefore, no attention must be paid to the channel calibration in the overlapping regions.

TABLE II. Levels observed in the reaction $^{70}Ge(p,t)^{68}Ge$ at 26 MeV.

Level No.	Present work E_x (MeV)	Present work L	Present work J^π	Reference 3 E_x (MeV)	Reference 3 J^π	Reference 7 E_x (MeV)	Reference 7 J^π	$\left(\frac{d\sigma}{d\omega}\right)$ peak (μb/sr)	R (see text)
1	0	0	0^+	0	0^+	0	0^+	3250	1.33
2	1.017	2	2^+	1.016	(2^+)	1.016	2^+	250	1.45
3	1.753	0	0^+					19	0.012
4	1.779			1.779	(2^+)	1.778	2^+		
5	2.269	4	4^+	2.270		2.263	4^+	8.4	0.175
				2.430		2.429	$3^{(+)}$		
				2.454	(1)				
6	2.617	0	0^+					61	0.048
7	2.651	3	3^-	2.650 [a]		2.649	3	52	0.7
8	2.834	4	4^+	2.840 [a]	(4^+)			40	0.91
9	2.942	2	2^+					20	0.24
10	3.025	2	2^+	3.042	(2^+)			50	0.58
11	3.065	(3)	(3^-)					6	0.12
12	3.186	4	4^+					13.5	0.29
13	3.204	0	0^+					20	0.019
				3.220 [a]					
14	3.396								
15	(3.461)								
16	3.476	0	0^+					71	0.074
17	3.525	2	2^+					22	0.35
				3.550	(0^+)				
18	3.588 [a]	(5), (1)	(5^-), (1^-)			3.582	(5^-)		
19	3.604	4	4^+					22.5	0.55
20	3.636								
21	3.647	(4)	(4^+)			3.649	(5^-)	5.5	0.15
						3.696	(6^+)		
22	3.735	(2)	(2^+)					5.3	0.095
				3.787	(2^+)				
23	3.811	2	2^+					52	1.1
						3.883	(6^-)		
24	4.021	4	4^+					6.3	0.19
25	4.037	(2)	(2^+)					8	0.15
26	4.058					4.054	(7^-)		
27	4.078	0	0^+	4.076 [a]	$0^+ + 3^-$			16	0.021
28	4.146								
29	4.236	(2)	(2^+)	4.237				8.5	0.14
30	4.322	2	2^+					5.0	0.12
31	4.358	0	0^+					25	0.038
32	4.456	(6)	(6^+)			4.455		10	
33	4.564	(2)	(2^+)					6.1	0.17
34	4.614	(3)	(3^-)					4.1	0.12
35	4.658								
36	4.736	0	0^+					4.5	0.0087
37	4.789	0	0^+					4.1	0.01
38	4.857					4.837			
39	4.878								
40	5.074								
41	5.217								

[a] Possible doublet.

Table II with an uncertainty of 3 keV except for some states with very low cross section where it can reach 10 keV. Forty-one levels are observed below 5.2 MeV excitation energy. In Table II are also given the previously known levels reported in the compilation[3] of the Nuclear Data Group together with more recent results obtained by Nolte *et al.*[7] As can be seen, our energy values are in good agreement with the previously known ones. Twenty-eight ^{68}Ge levels are mentioned for the first time, several of which are at very low excitation energy.

To eliminate the spurious peaks due to the other Ge isotopes, the spectra obtained at 5° and 25° with the enriched target were compared with those obtained with a natural germanium target at the same magnetic fields and angles. The data obtained with the natural target allowed us to determine the Q value of the reaction by comparison with the Q value of the ^{72}Ge$(p,t)^{70}$Ge reaction. We obtain $Q=-11.242\pm0.007$ MeV in good agreement with the values obtained by Shepard *et al.*[5] (-11.245 ± 0.03) and by Hsu *et al.*[6] (-11.252 ± 0.013).

The angular distributions are shown in Fig. 2 and are presented according to increasing excitation energies together with the distorted-wave–Born-approximation (DWBA) predictions. DWBA calculations were carried out using the code TWOPAR.[10] The Becchetti-Greenlees[9] proton optical model parameters were used and are summarized in Table I. The triton parameters (see Table I) are those of Flynn *et al.*[11]

Many configurations are possible for the calculation of the form factor. However, only a few of them seem to give an important contribution to the calculated cross section.[12] The shapes of the calculated angular distributions for all the L values considered are not sensitive to the choice of a particular configuration. Therefore, the spin and parity assignments deduced from these shapes are not influenced by this choice. In order to compare experimental and theoretical cross sections for levels populated with the same L value, we have used for each of them the same configuration. The form factor for the $L=0$ and 2 transfers was calculated using a configuration $(2p_{3/2})^2$. For the $L=4$ and 6 calculations, a $(2d_{5/2}, 1g_{9/2})$ configuration was used whereas a $(1g_{9/2}, 2p_{3/2})$ choice was made for odd transfers ($L=3$ and 5). 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 of 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 (Table II).

B. Discussion of selected levels

Ground state. The ground-state transition dominates the entire spectrum and is about 40 times stronger than any other transition in the range of excitation energy observed. Its angular distribution is quite well reproduced by an $L=0$ DWBA calculation.

1.017 MeV level. This first known $J^\pi=2^+$ level is also strongly excited in our reaction. However, as opposed to other known $J^\pi=2^+$ levels (see discussion later), the experimental cross section at forward angles is larger by about a factor of 2 than the DWBA cross section. We have given elsewhere an interpretation of such an anomaly in terms of coupled-channels Born-approximation calculations.[13] These features were also observed in a few similar (p,t) transitions to other Ge isotopes. The flat structure of the angular distribution of this level also observed by Shepard *et al.*[5] in a similar ^{70}Ge(p,t) study (with an energy resolution of 90 keV) was attributed by them to the presence of an unseparated doublet (2^+-0^+). Our measurement shows clearly that no doublet is present at this excitation energy.

1.753 MeV level. This level is observed for the first time and appears as the second excited state of ^{68}Ge. Agreement is obtained with an $L=0$ transition leading to a $J^\pi=0^+$ assignment. An indication for this level can perhaps be found in the experiments of Paradellis, Houdayer, and Mark[4] where nonassigned 0.740 MeV γ rays are observed which may correspond to the $1.753\to1.017$ MeV transition. Furthermore, although Nolte *et al.*[7] did not point out the existence of the γ ray due to this transition, a nonassigned line is present in their coincidence spectrum that might correspond to this transition.

1.779 MeV level. This level was assigned $J^\pi=(2^+)$ by several authors.[3] Its existence has been well established in peak number 4 (Fig. 1). However, it can be concluded from our data on natural Ge and other Ge isotopes that at least two contaminant peaks (particularly the one corresponding to the 3.329 MeV ^{70}Ge level) are present in this peak. Hence no spin assignment can be deduced from our data. The $J^\pi=2^+$ assignment given by Shepard *et al.*[5] is doubtful because their angular distribution included at least the contamination due to the unresolved 1.753 MeV level.

2.269 MeV level. A good fit is obtained with an $L=4$ angular distribution for this weakly excited level, leading to a $J^\pi=4^+$ assignment. It was first observed by Paradellis *et al.*[4] Spin and parity values $J^\pi=4^+$ proposed by Nolte[7] on the basis of angular correlation measurements are in agreement with our results.

2.617 MeV level. This level is mentioned for the first time and appears well fitted by an $L=0$ transition. According to the known data, it is therefore the second $J^\pi=0^+$ excited level in ^{68}Ge.

2.651 MeV level. This level is populated with a large cross section by an $L=3$ transition. It is the first $J^\pi=3^-$ excited level observed in ^{68}Ge, at an energy very close to the energy of the known first $J^\pi=3^-$ level in other even Ge isotopes. It was previously known[3] and a tentative value $J=3$

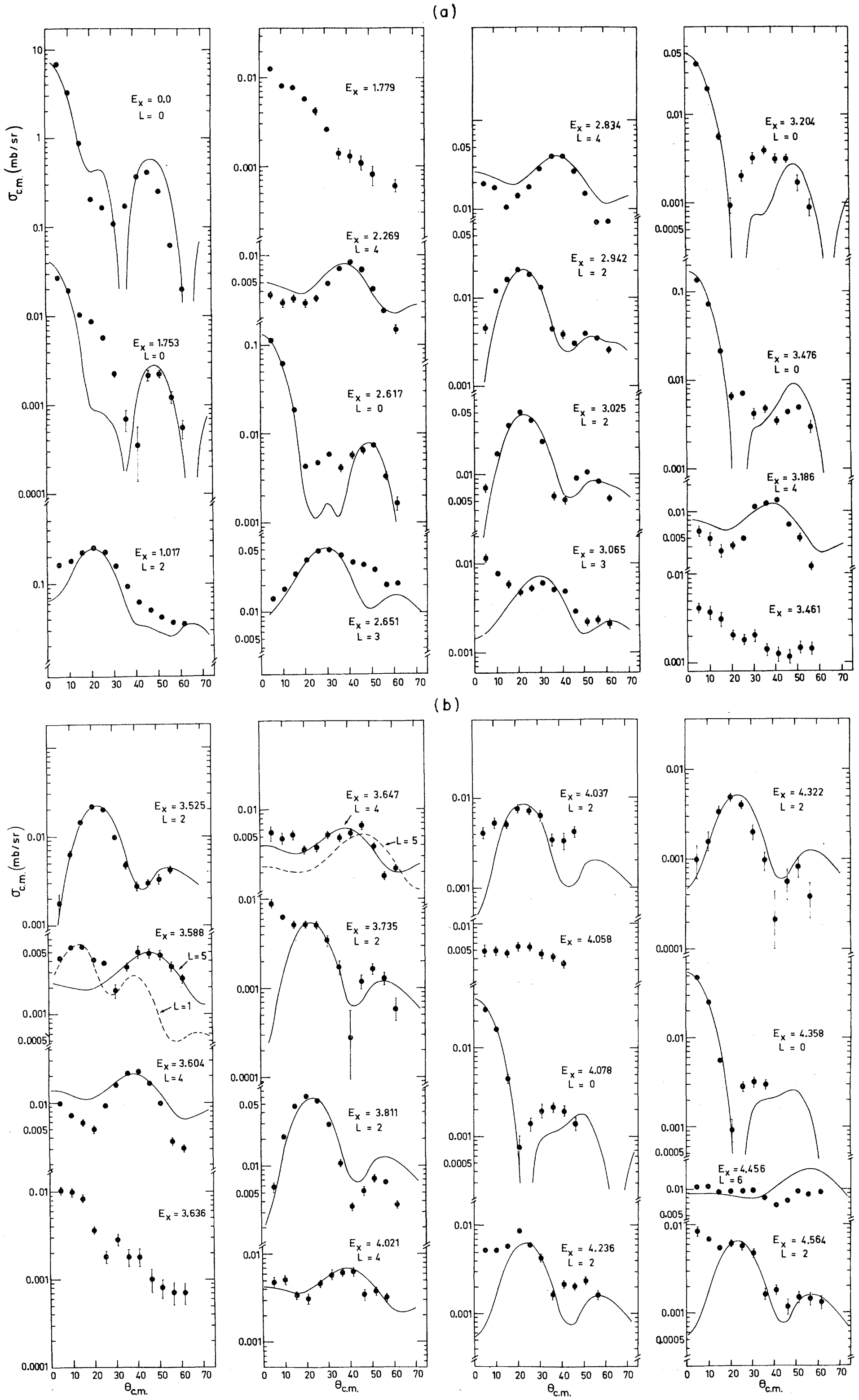

FIG. 2. Angular distributions of the ^{70}Ge$(p,t)^{68}$Ge reaction. Vertical bars are the statistical errors. Curves are DWBA predictions assuming the indicated L values.

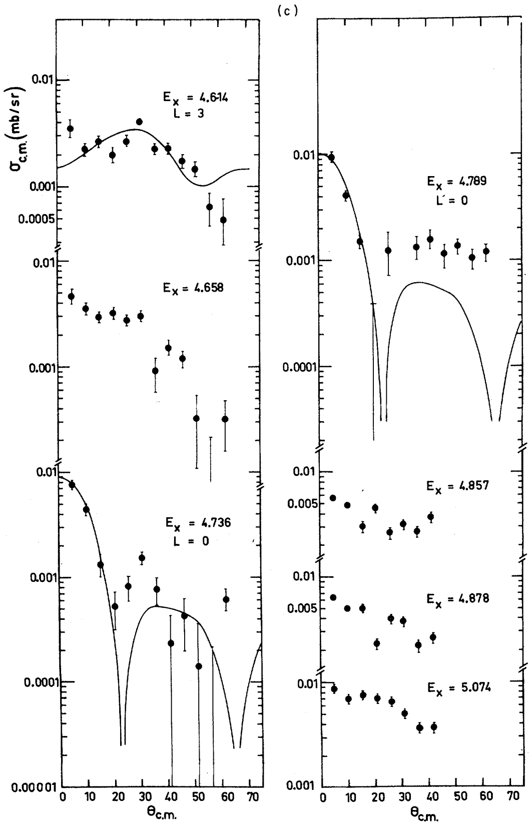

FIG. 2. (*Continued*)

was proposed by Nolte *et al.*[7] without parity assignment.

Other $J^\pi = 0^+$ excited levels. $L=0$ patterns are also observed for levels at 3.204, 3.476, 4.078, 4.358, 4.736, and 4.789 MeV excitation energy (see Fig. 2) leading to $J^\pi = 0^+$ assignments for all of them among which five are mentioned for the first time. A level at 4.0756 MeV was previously proposed by Paradellis *et al.*[4] but no spin value was assigned. The first three levels mentioned above were present in the peaks labeled 3.22, 3.55, and 4.06 MeV in the (p,t) study of Shepard *et al.*[5] but our better resolution shows that these peaks were in fact multiplets including the levels at 3.186, 3.525, and 4.058 MeV, respectively.

Other 2^+ excited levels. Unambiguous $L=2$ transitions are observed at 2.942, 3.025, 3.525, 3.811, and 4.322 MeV in ^{68}Ge. All these $J^\pi = 2^+$ levels are observed for the first time. As can be seen in Fig. 2 and Table II, tentative $J^\pi = 2^+$ assignments have also been made for the levels at 3.735, 4.037, 4.236, and 4.564 MeV. The presence of a transition originating from another Ge isotope in the peak observed at 3.735 MeV is responsible for the strong peaking at forward angles (Fig. 2) but the presence of an $L=2$ component attributed to ^{68}Ge seems, however, plausible according to our data on the natural Ge target at 5° and 25°. The level at 4.236 MeV is to be compared with the 4.237 level observed in the β decay study of Paradellis *et al.*[4]

Other 4^+ states. Five levels at 2.834, 3.186, 3.604, 3.647, and 4.021 MeV are populated by $L=4$ transitions (Fig. 2) and we propose for these levels $J^\pi = 4^+$. The levels at 3.186, 3.604, 3.647, and 4.021 MeV appear as new levels in ^{68}Ge. The level at 2.834 is to be compared with the doublet observed by Hsu *et al.*[6] and Shepard *et al.*[5] in their (p,t) experiments at 2.83 and 2.86 MeV, respectively. Due to a very low cross section, the fit for the 3.647 MeV level is not of good quality as can be seen in Fig. 2.

Other levels. Due to very low cross sections and/or possible contaminations from states belonging to a high level-density region in other Ge isotopes (^{72,74}Ge particularly), the nature of several angular distributions is not as well defined as for the preceding levels. Some of them cannot receive any L assignment as indicated in Table II. Some others are tentatively assigned according to the most reliable transferred angular momentum. The new levels at 3.065 and 4.614 MeV are thus proposed to be 3^- states. A tentative $J^\pi = 6^+$ assignment is given for the level at 4.456 MeV. In the distribution of the 3.588 MeV level, the possible presence of two components, $L=5$ and $L=1$, could be explained by the presence of a doublet at this energy. It is to be compared with the 3.582 MeV level tentatively assigned by Nolte[7] as $J^\pi = (5^-)$.

In Table II are listed the values of the experimental cross sections taken at the first peak of the angular distribution (at 10° for $L=0$). These values are summarized in Fig. 3. In Table II are also reported the values of the ratio (R) of the experimental peak cross section to the one calculated by DWBA. It is obvious that the R ratios should not be considered as absolute values for theoretical calculations. They should be used only for a relative comparison at least for levels of the same spin and parity. It is well known that the calculated cross section for two-nucleon transfer reactions may be very sensitive to the small components of the wave functions. They could not obviously be taken into account in our DWBA calculations due to the lack of reliable theoretical wave functions. For these reasons, no absolute normalization was attempted in the DWBA calculations.

From Fig. 3 it is clear that the ground state is the most strongly populated level. Its strength is 95% of the whole 0^+ strength, the remainder being distributed mainly over the 2.617 and 3.476 levels. The other 0^+ levels carry out at most 2.5% of the

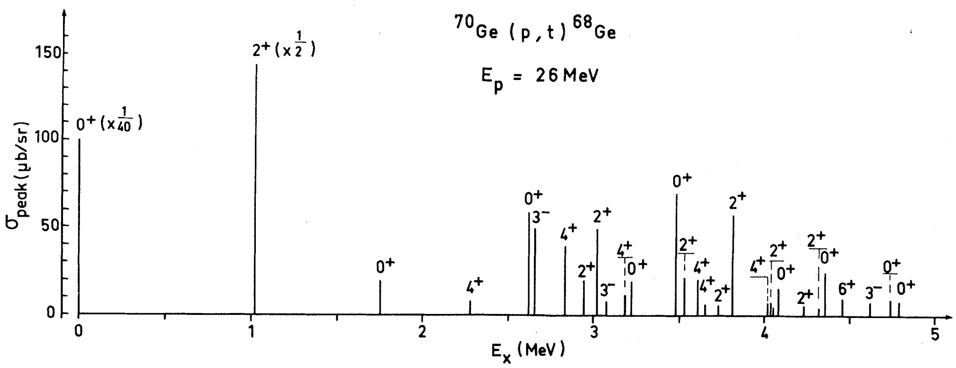

FIG. 3. Strengths distribution obtained for the ^{70}Ge(p,t)^{68}Ge reaction.

0^+ strength. The 2^+ strength is mainly carried out by the 2_1^+ level at 1.017 MeV (60% of the whole). Two other levels at 3.025 and 3.811 MeV with $J^\pi = 2^+$ have important cross sections. The other ones are very weakly populated. The 2.834 and 3.604 MeV $J^\pi = 4^+$ levels are the only ones which are significantly populated (40 and 22.5 μb/sr, respectively), the other $J^\pi = 4^+$ levels having a cross section smaller than 20 μb/sr.

IV. COMPARISON WITH MODEL CALCULATIONS

Up to now the level schemes of the even Ge nuclei have been hardly investigated theoretically. Only two calculations for ^{68}Ge are available. The first one is a very recent work of De Vries and Brussaard[14] in which this nucleus is described as a vibrating core (^{40}Ca or ^{56}Ni) with a number of phonons $N \leq 4$, coupled with two-quasiparticle states by a dipole plus quadrupole interaction. The Sussex interaction plus a pairing force are used as a residual interaction and five orbits ($1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$) outside the core are considered for the valence nucleons (protons and neutrons). The spectra obtained for positive-parity states are shown in Figs. 4(a) and 4(b) together with the experimental data up to 3.4 MeV. They display a vibrational character that is not so evident in the experimental spectrum. Many levels were unknown when the fitting procedure was applied. It seems, however, that the calculations with a ^{56}Ni core show a better agreement with the experiment if we consider the 0^+ states first reported in this work.

More recently, a shell model calculation was also presented by De Vries and co-workers.[15] The nucleus was studied in a $2p_{3/2}, 1f_{5/2}, 2p_{1/2}, 1g_{9/2}$ configuration space with ^{56}Ni as an inert core. The $g_{9/2}$ orbit was available for neutrons only. A truncation over the number of particle distributions was made according to the ground-state distribution. The calculations have been performed by means of the Oak-Ridge–Rochester computer code using the modified surface δ interaction. Another calculation was made assuming an inert core of ^{64}Ge, i.e., only neutrons are active. It allows the study of the effect of the $p_{3/2}$ shell closure. These two kinds of calculations are displayed in Figs. 4(d) and (e). Both these investigations appear unsuccessful in reproducing the experimental data, particularly the first $J^\pi = 4^+$ level. The particle distributions assumed could be responsible for this failure.

In a previous paper,[2] we have presented the results of Hartree-Fock calculations using a Skyrme interaction for several Ge isotopes. Two distinct minima with an oblate deformation for the ground state appeared in the calculated potential energy curve for ^{68}Ge. These calculations predict a shape coexistence in ^{68}Ge. The eight $J^\pi = 0^+$ excited levels observed in this experiment at 1.753, 2.617, 3.204, 3.476, 4.078, 4.358, 4.736, and 4.789 MeV carry 0.58%, 1.9%, 0.6%, 2.2%, 0.5%, 0.8%, 0.14%, and 0.13% of the ground-state strength, respectively. It is clear that none of them is strongly excited. Qualitatively, these results do not support the existence of a very deep secondary minimum in the potential energy curve of ^{68}Ge taking account of the calculated spherical barrier height in ^{70}Ge. More complete calculations including dynamical effects and predicting transition strengths would be useful for a quantitative comparison with our results. However, one can speculate on the possibility of the 1.753 or 2.617 MeV level to be a candidate for a $K=0$ bandhead. The 2^+ and 4^+ levels at 2.942 MeV (or 3.025 MeV) and 3.604 MeV, respectively, could then be possible members of this band. The existence of a γ-vibrational band ($K=2$) could also be postulated with the sequence 2^+ (1.779 MeV, $3^{(+)}$ (2.430 MeV), and 4^+ (2.834 MeV).

We have already shown[1,2] the occurrence of

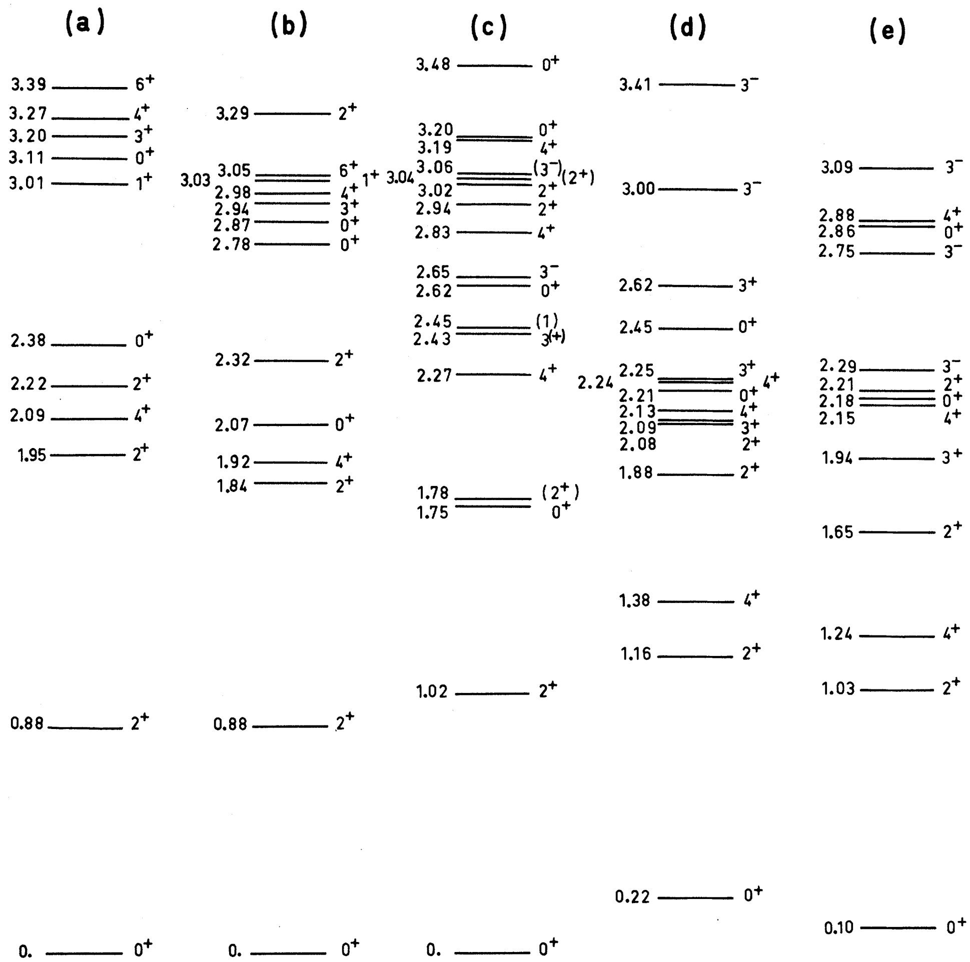

FIG. 4. Calculated and experimental energy spectra for ^{68}Ge. (a) A quasiparticle-phonon model with a ^{40}Ca core. (b) A quasiparticle-phonon model with a ^{56}Ni core. (d) and (e) refer to shell model calculations. In (e) the $2p_{3/2}$ shell is assumed to be closed (see text). (c) refers to our experimental results together with previously known data.

particle and quasiparticle states together with collective states at low excitation energies in Ge isotopes (particularly the first excited 0^+ state in ^{72}Ge). In ^{68}Ge such states with both collective and single particle configurations are most likely present. The $J^\pi = 0^+$, 2.617 MeV level might well be such a state with mixed configurations.

V. CONCLUSION

The analysis of the angular distributions of the ^{70}Ge$(p,t)^{68}$Ge reaction has permitted us to propose about twenty-five new spin-parity assignments for ^{68}Ge levels. We emphasize the observation of the two first excited 0^+ states at 1.753 and 2.617 MeV as well as the first excited 3^- state at 2.651 MeV. Many $J^\pi = 2^+$ states are proposed below 5.2 MeV excitation energy. Up to now, the level scheme of ^{68}Ge has been hardly investigated theoretically. It seems to us that collective as well as single particle features are present in the Ge spectrum. An attempt to understand this nucleus would include both these aspects. They are taken into consideration in a microscopic way for ^{72}Ge in a recent work of Didong *et al.*[16] Our high resolution study of ^{68}Ge gives new and much more complete data for a similar study of the ^{68}Ge nucleus.

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