^{74}Ge(p,α)^{71}Ga reaction at 36.25 MeV.

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The ^{74}Ge(p,α)^{71}Ga reaction has been studied at 36.25 MeV bombarding energy. Angular distributions of alpha particles were recorded and analyzed with distorted-wave Born approximation theory and a totally microscopic form factor for the three-particle transfers. Theoretical calculations in a restricted shell-model space using a modified surface δ interaction reproduce fairly well the ^{71}Ga excitation energies and the observed strengths in (d,^{3}He) and (p,α) spectra, with the exception of the (p,α) ground state transition. This disagreement confirms the anomalies observed by (d,^{3}He) reactions, in the occupation numbers $Z=32$ and between $N=40$ and 42, which can be related to changes in the nuclear shape.

[NUCLEAR REACTIONS, NUCLEAR STRUCTURE ^{74}Ge(p,α)^{71}Ga, E=36.25 MeV, measured $\sigma(E_x,\theta)$; enriched target; DWBA analysis. Calculated ^{71}Ga energy levels, ^{72}Ge(d,^{3}He)^{71}Ga and ^{74}Ge(p,α)^{71}Ga spectroscopic strengths.]

I. INTRODUCTION

In previous (p,α) investigations on $2s-1d$ target nuclei[1,2] we showed that a simple semimicroscopic-analysis, using the factorization of the (p,α) cross section in a dynamical and structural part with few dominant transfers, gives fairly good results. An improvement to this theoretical description of the (p,α) reaction has been obtained using a fully microscopic form factor as derived by Falk[3] and more recently by Bayman.[4]

In order to test the usefulness of the three-nucleon (p,α) transfer reaction as a spectroscopic tool, it is important to explore a nuclear region for which detailed shell-model wave functions of target and residual nuclei are not available in the literature. With this aim we have performed the present ^{74}Ge(p,α)^{71}Ga experiment at an incident bombarding energy of 36.25 MeV. The choice of the ^{74}Ge target nucleus was also motivated by a direct comparison of the (p,α) spectrum with the corresponding ^{72}Ge(d,^{3}He)^{71}Ga reaction at 26 MeV.[5] Furthermore, the structure of nuclei in the region of neutron numbers $N=40$ and 42 and proton numbers $Z=31$ and 32 shows anomalies in the occupation numbers[5]; consequently it becomes interesting to investigate the structure of these nuclei by the $^{74}_{32}$Ge(p,α)$^{71}_{31}$Ga reaction.

Finally the residual ^{71}Ga nucleus can be employed for solar neutrino experiments,[6] and the knowledge of its ground state wave function through different nuclear reactions is of valuable help for theoretical estimates of the neutrino capture rate.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The germanium target was bombarded with 36.25 MeV protons from the Milano azimuthally varying field cyclotron. The alpha particles were detected simultaneously using two silicon surface barrier detectors separated by an angular distance of 10°. The thickness of each detector was 700 μm, sufficient to stop the most energetic alpha particles from the reaction under study. No particle identification was performed, since the ^{74}Ge(p,α)^{71}Ga reaction Q value is $+1.58$ MeV compared to -12.477 MeV for the ^{74}Ge(p,^{3}He)^{72}Ga reaction.

The target was prepared by vacuum evaporation of germanium dioxide, enriched to (94.5$\pm$0.1)% in ^{74}Ge, onto a 100 μg/cm^2 carbon backing. The GeO_2 was provided by the Oak Ridge Isotopes

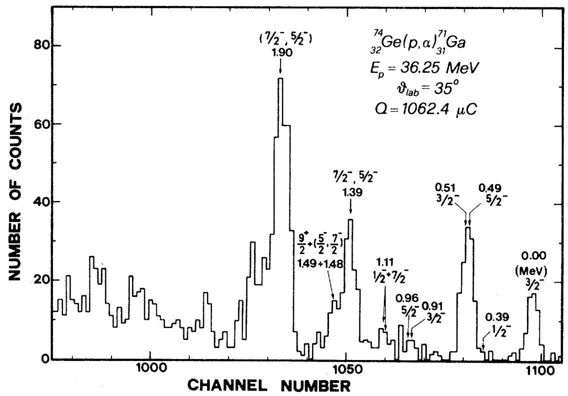

FIG. 1. Alpha spectrum from the ^{74}Ge(p,α)^{71}Ga reaction at 36.25 MeV and $\theta_{\rm lab}=35°$.

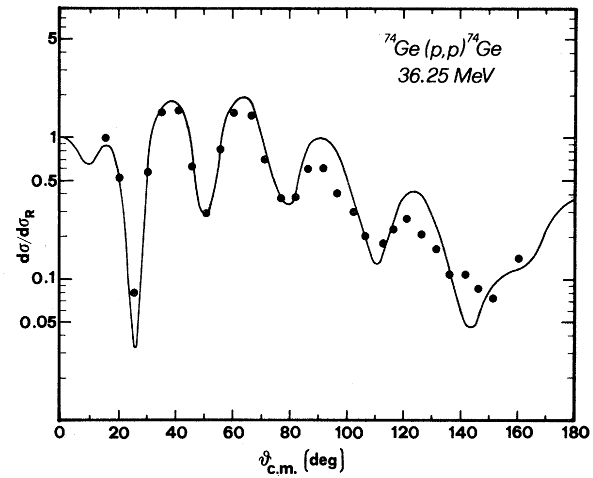

FIG. 2. Optical model fit to the proton elastic scattering data with the parameters described in Table I.

Division. The absolute cross sections were determined by reference to the optical model fit of 36.25 MeV elastically scattered protons from ^{74}Ge nuclei in the angular range 15°–150°. The accuracy of the absolute cross section thus determined is estimated to be $\pm 15\%$. For the ^{74}Ge(p,p) reaction we employed two counter telescopes separated by an angular distance of 10°. Each counter telescope consisted of a 3 mm totally and a 5 mm partially depleted silicon surface barrier detector.

A typical pulse height spectrum is shown in Fig. 1. The energy resolution (full width at half maximum) is of the order of 85 keV. The peaks are labeled by their excitation energies and, where known, by their spins and parities. The error associated with the ^{71}Ga excitation energy is ± 50 keV. The measured proton elastic scattering angular distribution plotted as $(d\sigma/d\sigma_{\rm Ruth})$ vs $\theta_{\rm c.m.}$ along with the optical model curve is shown in Fig. 2. The optical model parameters for the ^{74}Ge$+p$ channel were taken from Becchetti and Greenlees[7]; those for the ^{71}Ga$+\alpha$ channel were adapted from the literature.[8] Both sets are given in Table I. The DWBA calculations for the (p,α) transitions were carried out with the code DWUCK4 written by Kunz, using fully microscopic zero range form factors as derived by Bayman *et al.*[4] Figure 3 shows the angular distributions with the DWBA curves of alpha particles leading to the ground and excited states of ^{71}Ga up to 1.90 MeV excitation energy.

Finally, a direct comparison shown in Fig. 4 between the ^{74}Ge(p,α)^{71}Ga and ^{72}Ge($d,^{3}$He)^{71}Ga spectra shows peculiar differences. The largest discrepancy is observed for the ground state transition, which has a relative weak strength in the (p,α) reaction, but in the ($d,^{3}$He) spectrum is strongly excited corresponding to a large $2p_{3/2}$ proton-hole component.

III. DISCUSSION

It is important to remark that in the experimental study of the ($d,^{3}$He) reaction on even germanium isotopes at 26 MeV,[5] an abrupt change in the proton configuration has been observed between neutron numbers $N=40$ and $N=42$. This is clearly shown in Table II, where the summed spectroscopic strengths for different j_p transitions are reported. As can be seen from the table, there is one more proton in the $2p_{3/2}$ orbit and one less in the $1f_{5/2}$ orbit in the two lightest isotopes ($N=38$, 40) than in the two heaviest ones ($N=42$, 44). This anomaly has also been related to the structural transition, between $N=40$ and $N=42$ for the germanium isotopes, observed in a direct comparison of the (p,t)

TABLE I. Optical model parameters used in the calculation of DWBA.

Channel	V (MeV)	W (MeV)	W_D (MeV)	$V_{\rm so}$ (MeV)	r (fm)	a (fm)	r' (fm)	a' (fm)	$r_{\rm so}$ (fm)	$a_{\rm so}$ (fm)	r_c (fm)
$^{74}_{32}$Ge$+p$	48.692	5.27	4.36	6.2	1.17	0.75	1.32	0.605	1.01	0.75	1.25
$^{71}_{31}$Ga$+\alpha$	150	16			1.22	0.7	1.76	0.42			1.4
$^{71}_{31}$Ga$+p(n)$	a	0		($\lambda=25$)	1.25	0.65					1.25

[a]Adjusted to reproduce the binding energy of the transferred $p(n)$. See discussion.

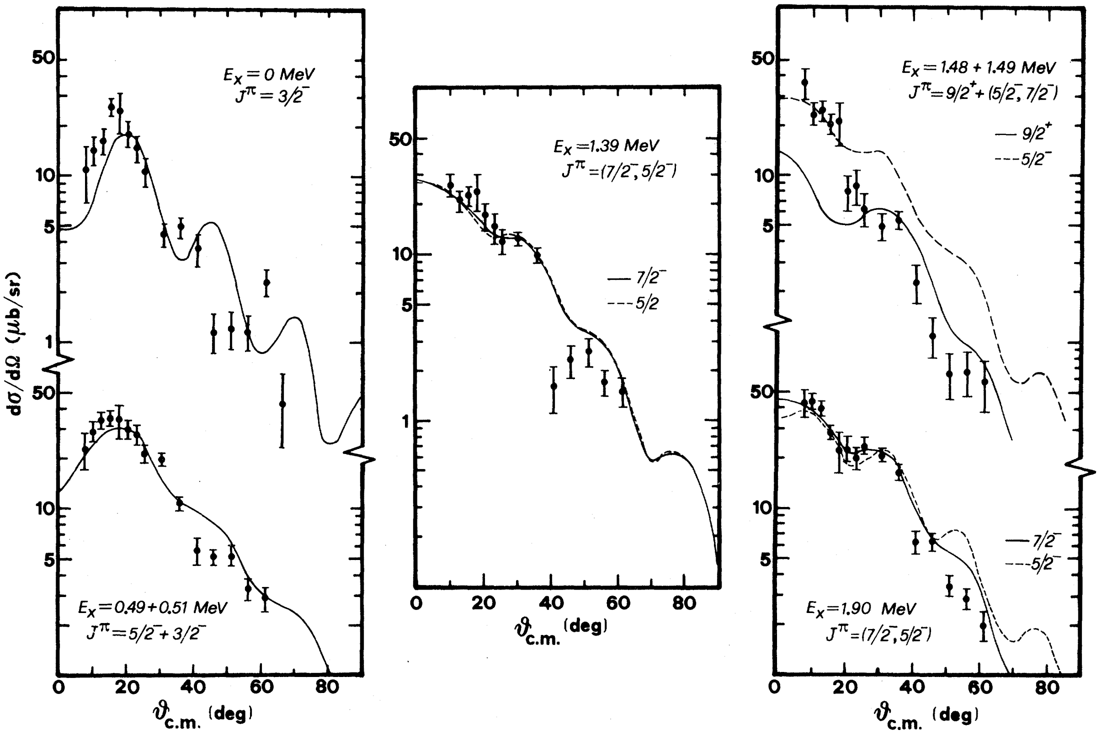

FIG. 3. Experimental ^{74}Ge$(p,\alpha)^{71}$Ga cross sections and DWBA calculations with optical model parameters described in Table I.

and (t,p) reactions.[9] In the attempt to explain if the weak ground state transition observed in the (p,α) reaction is caused by this sudden change in the $2p_{3/2}$ proton configuration or by some destructive interference effects, we need model wave functions which allow a direct comparison of the calculated strengths with the ones observed in (p,α) and $(d,{}^3$He) reactions, respectively.

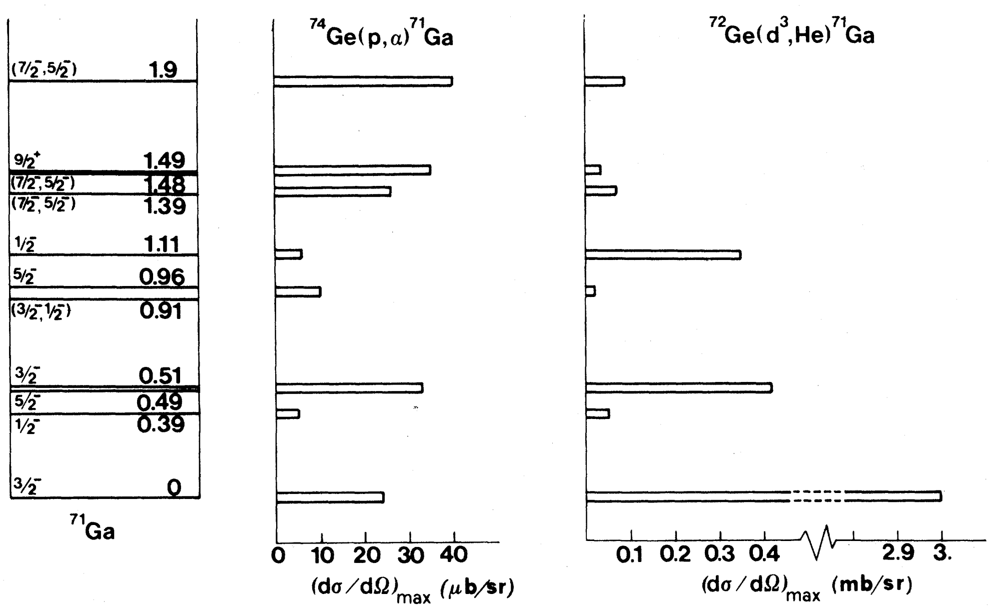

FIG. 4. Comparison of levels and differential cross sections observed in ^{74}Ge$(p,\alpha)^{71}$Ga and ^{72}Ge$(d,{}^3$He$)^{71}$Ga reactions.

TABLE II. Summed spectroscopic strengths observed in $(d,{}^3\mathrm{He})$ reactions on even germanium isotopes at 26 MeV from Ref. 5.

j_p \ N	38	40	42	44
$2p_{1/2}$	0.59	0.43	0.43	0.40
$2p_{3/2}$	2.36	2.35	1.44	1.25
$1f_{5/2}$	1.24	1.34	2.20	2.44
$2p+1f_{5/2}$	4.19	4.12	4.07	4.09

A. Shell-model calculations

As stated above, the structure of the nuclei in the region of the neutron number $N=40$, 42 is rather complex, and exact shell-model calculations cannot so far be performed because of the large number of valence nucleons distributed over several single particle states. Therefore we have assumed for germanium isotopes ($^{70+n}$Ge, $n=2$ and $n=4$) a restricted shell-model space described as a mixture of $(1g_{9/2})^n_{J=0}$, $[(1g_{9/2})^{n-2}_{J=0}(2p_{1/2})_0{}^2]$ neutron configurations and of $(2p_{3/2})_0{}^4$, $[(2p_{3/2})_0{}^2(1f_{5/2})_0{}^2]$, $[(2p_{3/2})_0{}^2(2p_{1/2})_0{}^2]$ proton configurations. For the ^{71}Ga nucleus we have described the low lying negative parity states as coming from the $(1g_{9/2})_J{}^2$ and $(2p_{1/2})_0{}^2$ neutron configurations and from the $[(2p_{3/2})_J{}^2 j_p]$ proton configuration with the unpaired proton j_p in the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbits. For the residual interaction between i and j nucleons we have taken the modified surface delta interaction (MSDI) (Ref. 10) given by

$$V_{\mathrm{MSDI}}(i,j)=-4\pi A_T\delta(\bar{r}_i-\bar{r}_j)\delta(r_i-R)+B(\bar{\tau}(i)\cdot\bar{\tau}(j))+C\ .$$

For the parameters A_T, B, and C we have taken the empirical values of Ref. 10 [$A_0=A_1=B=(25/A)$ MeV, A being the mass number and $C=0$].

The values of the single particle binding energies relative to a $^{66}_{28}$Ni core have been adjusted to reproduce the neutron amplitudes of the ^{72,74}Ge ground state wave functions as obtained in (p,d) reactions at 20 MeV (Ref. 11) and to improve the agreement of the calculated ^{71}Ga spectrum with the experimental one. These values are the following: for the protons $E(2p_{3/2})=-8.53$ MeV, $E(1f_{5/2})=-7.51$ MeV, and $E(2p_{1/2})=-7.33$ MeV; and for neutrons $E(1g_{9/2})=-4.8$ MeV and $E(2p_{1/2})=-5.2$ MeV (these separation energies have been used for the fully microscopic zero range three particle transfers as reported in Table I). The numerical evaluation

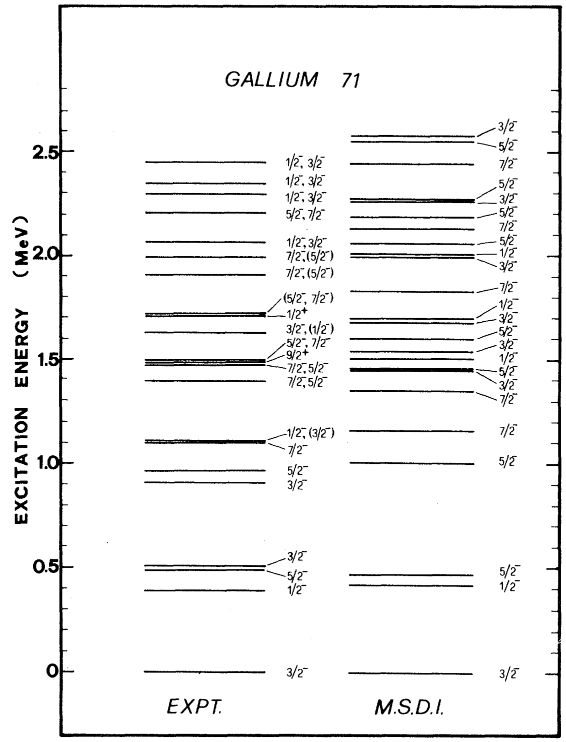

FIG. 5. A comparison between calculated and observed levels in ^{71}Ga up to 2.5 MeV excitation energy. The shell model calculations are relative only to negative parity states with angular momentum equal to $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$.

of the matrix elements and the subsequent diagonalization of the matrices were performed at the CDC CYBER-76 computer of the Centro di Calcolo Interuniversitario—Bologna.

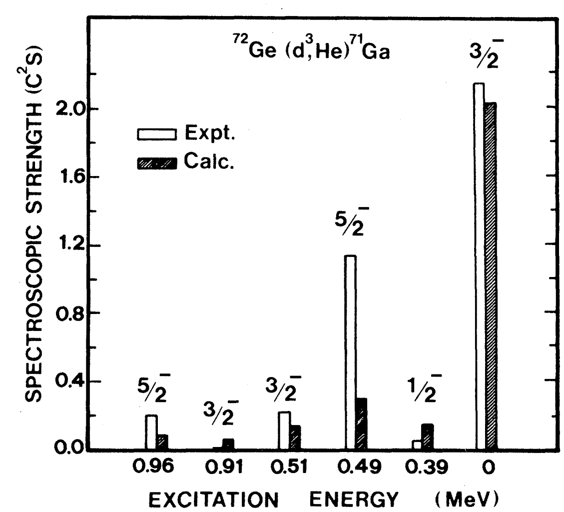

FIG. 6. Experimental and calculated spectroscopic strength in the ^{72}Ge$(d,{}^3\mathrm{He})^{71}$Ga reaction. For a better display the excitation energies are not in scale.

TABLE III. Spectroscopic amplitudes of the ^{74}Ge$(p,\alpha)^{71}$Ga reaction. Configurations are assigned as $(j_n)_I{}^2 j_p$, where j_n and j_p denote neutron and proton single particle states.

E_x (MeV)	J^π	Configuration	Spectroscopic amplitudes
0	$\frac{3}{2}^-$	$(1g_{9/2})_0^2 2p_{3/2}$	1.653
		$(1g_{9/2})_2^2 2p_{3/2}$	0.053
		$(2p_{1/2})_0^2 2p_{3/2}$	−0.956
0.39	$\frac{1}{2}^-$	$(1g_{9/2})_0^2 2p_{1/2}$	−0.453
		$(1g_{9/2})_2^2 2p_{3/2}$	0.057
		$(1g_{9/2})_2^2 1f_{5/2}$	−0.019
		$(2p_{1/2})_0^2 2p_{1/2}$	0.286
0.49	$\frac{5}{2}^-$	$(1g_{9/2})_0^2 1f_{5/2}$	−0.609
		$(1g_{9/2})_2^2 2p_{3/2}$	0.086
		$(1g_{9/2})_2^2 2p_{1/2}$	−0.033
		$(2p_{1/2})_0^2 1f_{5/2}$	0.368
0.51	$\frac{3}{2}^-$	$(1g_{9/2})_0^2 2p_{3/2}$	−0.420
		$(1g_{9/2})_2^2 2p_{3/2}$	0.117
		$(2p_{1/2})_0^2 2p_{3/2}$	0.212
0.91	$\frac{3}{2}^-$	$(1g_{9/2})_0^2 2p_{3/2}$	−0.356
		$(1g_{9/2})_2^2 2p_{3/2}$	0.151
		$(2p_{1/2})_0^2 2p_{3/2}$	−0.213
0.96	$\frac{5}{2}^-$	$(1g_{9/2})_0^2 1f_{5/2}$	−0.315
		$(1g_{9/2})_2^2 1f_{5/2}$	0.030
		$(1g_{9/2})_2^2 2p_{3/2}$	−0.128
		$(2p_{1/2})_0^2 1f_{5/2}$	0.180
1.11	$\frac{7}{2}^-$	$(1g_{9/2})_2^2 1f_{5/2}$	0.042
1.11	$\frac{1}{2}^-$	$(1g_{9/2})_0^2 2p_{1/2}$	0.218
		$(1g_{9/2})_2^2 2p_{3/2}$	0.104

For the $J^\pi=0^+$ ground state of germanium isotopes the matrix dimension is 6, while for the negative parity states of ^{71}Ga the matrix dimensions are the following: for the $J^\pi=\frac{1}{2}^-$ (12), $J^\pi=\frac{3}{2}^-$ (21), and $J^\pi=\frac{5}{2}^-, \frac{7}{2}^-$ states (26).

The calculated ^{71}Ga energy level spectrum up to an excitation energy of 2.5 MeV is compared with the experimental one in Fig. 5. The agreement is satisfactory; the experimental levels are well reproduced, the only discrepancy being for the second $J^\pi=\frac{3}{2}^-$ state which in the calculated spectrum occurs at an excitation energy larger than the observed one.

B. Spectroscopic amplitudes for ^{72}Ge$(d,{}^3$He$)^{71}$Ga and ^{74}Ge(p,α) ^{71}Ga reactions and concluding remarks

The shell-model wave function thus obtained were used for the calculation of the $(d,{}^3$He) and (p,α) spectroscopic amplitudes. For the single proton transfer reaction, we have calculated C^2S, where S is the spectroscopic factor and C^2 is an isospin Clebsch-Gordan coefficient given by

$$C^2(T_f \tfrac{1}{2} T_{fz} - \tfrac{1}{2} \mid T_i T_{iz}) \ ,$$

which couples the transferred proton $(\frac{1}{2},-\frac{1}{2})$ and the final nucleus (T_f,T_{fz}) to the initial target state (T_i,T_{iz}).

For pickup to states with $T_f=T_i+\frac{1}{2}$, we have

$$C^2=(2T_i+1)/(2T_i+2)$$

and in the case of the ^{72}Ge(d,^{3}He)^{71}Ga reaction C^2 is equal to 0.9.

Figure 6 shows the calculated spectroscopic strengths (C^2S) which are compared with the experimental ones. The calculations reproduce the experimental data fairly well, in particular for the $J^\pi=\frac{3}{2}^-$ ground, and 0.51 and 0.91 MeV states, as well as for the $J^\pi=\frac{1}{2}^-$ 0.39 MeV and $J^\pi=\frac{5}{2}^-$ 0.96 MeV states. Somewhat less satisfactory is the predicted C^2S value for the $J^\pi=\frac{5}{2}^-$ 0.49 MeV state.

Supported by the relative goodness obtained in fitting the excitation energies and spectroscopic factors for the (d,^{3}He) reaction we have calculated the spectroscopic amplitudes for the ^{74}Ge(p,α)^{71}Ga reaction. The spectroscopic amplitudes of three nucleon transfer defined as

$$\langle \psi_{J_i}(A) \,|\, \{\psi_{J_f}(B)(j_1j_2j_3)\}_{J_i} \rangle$$

were calculated as outlined in our previous works.[1,2] The transfers involved in the present experiment are

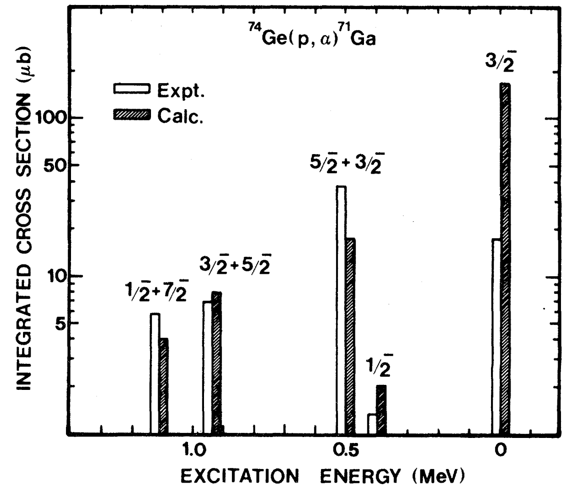

FIG. 7. Comparison of calculated and experimental integrated cross sections in the ^{74}Ge(p,α)^{71}Ga reaction.

TABLE IV. Summary of results from the ^{72}Ge(d,^{3}He)^{71}Ga and ^{74}Ge(p,α)^{71}Ga reactions.

E_x (MeV)[a]	$J^{\pi a}$	L	C^2S^b expt.	C^2S calc.	Integrated cross section (μb) expt.	Integrated[c] cross section (μb) calc.	Angular interval (lab) of integration
0	$\frac{3}{2}^-$	1	2.14	2.02	17.4±3.5	174	7.5–65
0.39	$\frac{1}{2}^-$	1	0.04	0.14	1.3±0.7	2	7.5–20
0.49	$\frac{5}{2}^-$	3	1.14	0.29			
					35.5±7.2	17	7.5–60
0.51	$\frac{3}{2}^-$	1	0.21	0.13			
0.91	$\frac{3}{2}^-(\frac{1}{2}^-)$	1	⟨0.01	0.05			
					6.8±3.4	8	10–55
0.96	$\frac{5}{2}^-$	3	0.2	0.08			
1.11	$\frac{1}{2}^-+\frac{7}{2}^-$	1+3	0.39$(\frac{1}{2}^-)$		5.8±3	4	10–60
1.39	$(\frac{7}{2}^-,\frac{5}{2}^-)$	3	(0.52, 0.92)		22 ±4.4		7.5–60
1.48	$(\frac{7}{2}^-,\frac{5}{2}^-)$	3	(0.12, 0.21)				
					14.3±3.6		7.5–60
1.49	$\frac{9}{2}^+$	4	0.24				
1.90	$(\frac{7}{2}^-,\frac{5}{2}^-)$	3	(0.87, 1.59)		38 ±8		7.5–60

[a]From Refs. 5 and 13.

[b]From Ref. 5.

[c]The calculated cross section has been integrated in the same angular interval as the experimental one using a normalization factor equal to 420.

described by the $[(1g_{9/2})_{J_n}{}^2 j_p]$ and $[(2p_{1/2})_0{}^2 j_p]$ configurations, with the proton in the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbits. We have taken the major components of $\psi_{J_f}(B)$ which account for 80−90% of the ^{71}Ga wave function. The relative form factors weighted by the corresponding spectroscopic amplitudes, shown in Table III, were calculated by the HAVN program written by Bayman[12] and were used as external form factors for the DWBA code DWUCK4.

The theoretical cross sections have been calculated using the same normalization factor equal to 420 as adopted in our previous work.[2] The results are shown in Fig. 7 and compared with the experimental integrated cross sections. In addition, Table IV reports the summary of results from the ^{72}Ge$(d,{}^3$He$)^{71}$Ga and ^{74}Ge$(p,\alpha)^{71}$Ga reactions. The calculations reproduce fairly well the experimental spectrum but fail in the estimate of the ground state transition, which experimentally is less excited by one order of magnitude. The coherence effects between the $[(1g_{9/2})_0{}^2 p_{3/2}]$ and $[(1p_{1/2})_0{}^2 p_{3/2}]$ transfers which dominate the ground state (p,α) transition cannot explain the weakness of the observed strength. On the other hand, our shell model calculations predict the same number (3.27) of protons in the $2p_{3/2}$ orbit for both germanium isotopes $N=40$ and $N=42$. If we compare this value with the ones reported in Table II, we see that the number of protons in the $2p_{3/2}$ orbit for ^{74}Ge is overestimated by a factor of 2.3, which therefore enhances the calculated (p,α) ground state cross section. The disagreement between the calculated and observed ground state (p,α) transition would confirm the sudden decrease of the occupation number in the $2p_{3/2}$ oribt for $N=42$ and $Z=32$.

In conclusion, the present experiment has shown the importance of the (p,α) reaction as a spectroscopic tool. Simplified shell-model calculations in restricted neutron and proton configurations reproduce fairly well the excitation energies for ^{71}Ga and the ^{72}Ge$(d,{}^3$He) and ^{74}Ge(p,α) experimental data. The results obtained in the present experimental study further confirm the anomalies observed by $(d,{}^3$He) reactions in the proton occupation numbers for the $2p_{3/2}$ and $1f_{5/2}$ orbits. These anomalies can induce changes in the nuclear shape of the germanium isotopes.

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