The best-fit admixtures of $l=0$ and 2 for these two states are shown in Fig. 5, along with the data. The fits are slightly better than those of case (1) in Fig. 4, but the difference is not significant. The spectroscopic strengths extracted from the fits of Fig. 5 are listed in Table II, and are seen to be very similar to those extracted from the (d, p) data. It is clear that reversing the ordering of the mirror correspondence would produce inferior agreement between measured and calculated angular distributions. For both nuclei the $S_{l=0}:S_{l=2}$ ratio for the lower state is less than 1, whereas for the upper state it is greater than 1. Furthermore, the ratio of lower : upper state strength for $l=2$ transfer is approximately the same for both nuclei.

Finally, the spectroscopic factors presented in Table II for both the $^{10}B(d, p)^{11}B$ and $^{10}B(^3He, d)^{11}C$ reactions are consistent with

$$S_{l=0}(\text{upper state}) \approx S_{l=0}(\text{lower state}),$$

and

$$S_{l=2}(\text{upper state}) < S_{l=2}(\text{lower state}),$$

again in agreement with the expectations of possibility 1.

We thus conclude that the levels have not crossed in going from ^{11}B to ^{11}C, and hence that $^{11}B(9.19)$ and $^{11}C(8.65)$ are mirrors, as are $^{11}B(9.27)$ and $^{11}C(8.69)$. Given the J^π assignments in ^{11}B, we may then assign $J^\pi = \frac{7}{2}^+$ to the 8.65-MeV state in ^{11}C and $J^\pi = \frac{5}{2}^+$ to the 8.69-MeV state.

†Work supported by the National Science Foundation.

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^{69,71}Ga(*d*, *p*) and ^{71}Ga(*d*, *t*) Reactions*

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Angular distributions from the (d, p) reaction on ^{69}Ga and ^{71}Ga have been obtained with the 12-MeV deuteron beam of the Argonne tandem Van de Graaff. Excitation energies and l-transfer values have been obtained for a number of levels below 2 MeV excitation. The ground state of ^{72}Ga is not excited with observable cross section in the $^{71}Ga(d, p)^{72}Ga$ reaction. The first level excited with an appreciable cross section is the 1^+ level at 161 keV in ^{72}Ga. The (d,t) reaction on ^{71}Ga proceeds to the ground state of ^{70}Ga and, over the energy range covered, excites most of the levels observed to have a strong $l=1$ component in the $^{69}Ga(d, p)^{70}Ga$ reaction. The excitation of the ground state of ^{70}Ga via neutron pickup from ^{71}Ga suggests that the neutron ground-state wave function of ^{72}Ga has a large $(1g_{9/2})_{5/2+}{}^3$ component.

INTRODUCTION

The energy levels of ^{70}Ga and ^{72}Ga have been studied by thermal-neutron capture γ rays from the $^{69}Ga(n, \gamma)^{70}Ga$ and $^{71}Ga(n, \gamma)^{72}Ga$ reactions.[1,2] The present study of the $^{69}Ga(d, p)^{70}Ga$ and $^{71}Ga(d, p)^{72}Ga$ was started in conjunction with the (n, γ) studies,[1] in which primary transitions with dipole character are by far the most probable.[3] Therefore, the levels most likely to be directly populated from the 1^- and 2^- states in $^{70,72}Ga$ are expected to have spins from 0 to 3. On the other hand, levels populated in the (d, p) reaction at 12 MeV would be predominantly levels with an appreciable

TABLE I. The DWBA parameters used in the calculations. The parameters are derived from elastic scattering of protons, deuterons, and ^{3}He on the germanium isotopes.

Particle	V (MeV)	W (MeV)	W' (MeV)	r (fm)	a (fm)	r'_r (fm)	a' (fm)	r_0 (fm)	V_s (MeV)
d	94		19.0	1.15	0.81	1.34	0.68	1.30	6.0
p	53.5		13.4	1.25	0.65	1.25	0.47	1.25	6.0
t	173.0	18.0		1.14	0.723	1.55	0.80	1.40	

single-particle component. The ground states of ^{69}Ga and ^{71}Ga are known to have spin $\frac{3}{2}$.[4] The proton configuration is expected to be predominantly $(2p_{3/2})^3$. For $Z=38$ there appears to be an indication of the approximate closing of the $1f_{5/2}2p_{3/2}$ subshell, while $Z=40$ has to a reasonable approximation a $1f_{5/2}{}^6 2p_{3/2}{}^4(\alpha 2p_{1/2}{}^2+\beta 1g_{9/2}{}^2)$ proton configuration. If the same situation were to hold for $N=40$, one would expect to see strong transitions to the 1^+ and 2^+ levels with $2p_{1/2}$ transfer and to the 3^-–6^- levels with $1g_{9/2}$ transfer. If there is a considerable admixture of neutron holes in the $1f_{5/2}$ and $2p_{3/2}$ configurations, the experimental results become less simple to interpret, since the 1^+ and 2^+ levels can be reached by $2p_{3/2}$ and $1f_{5/2}$ transfer also and the 3^+ level could be reached both by $2p_{3/2}$ and $1f_{5/2}$ transfer, but the 4^+ level would be restricted to an $l\equiv 3$ transfer and the 0^+ level to a $2p_{3/2}$ transfer. In the case of the negative-parity levels, a $2d_{5/2}$ transfer could excite states with $J^\pi=1^-$–4^- and the $3s_{1/2}$ transfer could excite the 1^- and 2^- levels. In the event that mixtures occur, the strong j dependence effect characteristic of $p_{1/2}$ neutron transfer[5] may be much less pronounced than the dependence observed in even-even nuclei in this region.[6]

The comparison between the levels observed in the present experiment and the thermal-neutron-capture γ-ray experiment is hampered by the high level density above 1 MeV. Nevertheless, in a number of cases the possible spins of a level can be limited somewhat by a comparison of the possible spins from the (d,p) work and the presence or absence of a high-energy γ ray.

The levels in ^{70}Ga have also been studied with the ^{70}Zn$(p,n)^{70}$Ga reaction[7,8] and ^{68}Zn$(\alpha,d)^{70}$Ga reaction.[9] The levels in ^{72}Ga have been investigated through the β decay[10] of ^{72}Zn and the decay of its 40-msec isomeric state.[11]

EXPERIMENTAL PROCEDURE

The targets were prepared by evaporating isotopically enriched Ga_2O_3 on C. The gallium isotopes were enriched to ~99.5%. The (d,p) data, obtained at an incident-deuteron energy of 12 MeV, were taken on Kodak NTB-50 plates in the Argonne split-pole spectrograph. The plates were scanned with the computer-controlled scanning system,[12] and the spectra were analyzed with a set of computer programs.[13] Levels observed at at least four angles were assigned to ^{70,72}Ga. Data were taken over an angular range from 10 to 135°. In order to transform the data to absolute differential cross sections, some measurements were repeated in the 70-in. computed-controlled scattering chamber with detector telescopes. To determine the target thickness, the measured relative elastic scattering angular distribution was compared with the angular distribution obtained from the optical-model potential parameters used in the distorted-wave calculations. The distorted-wave Born-approximation (DWBA) calculations were made with the program JULIE.[14] The ^{71}Ga$(d,t)^{70}$Ga data were obtained with the 60-in. scattering chamber at the 22.6-MeV deuteron beam of the

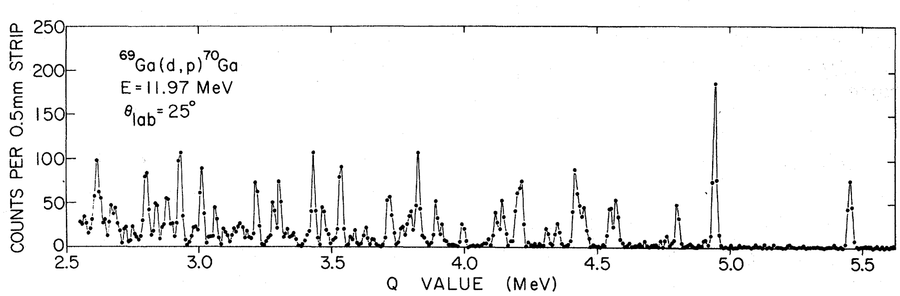

FIG. 1. Spectrum of the ^{69}Ga$(d,p)^{70}$Ga reaction at 25° lab.

Argonne 60-in. cyclotron. The particles were detected with an E-dE/dx telescope. Data were obtained over an angular range from 15 to 53° in 3° steps. At 27°, only the ground-state data could be analyzed. The parameters used in the calculation are listed in Table I. The uncertainty in the absolute differential cross section is estimated at ±20%.

EXPERIMENTAL RESULTS

A. $^{69}Ga(d,p)^{70}Ga$

A ^{70}Ga spectrum obtained at 25° is shown in Fig. 1. The resolution width in this experiment was about 18 keV. However, two peaks with approximately the same intensity or with different angular distributions can be separated by peak-shape fitting procedures if the energy difference is more than 10 keV. The angular distributions of the ^{70}Ga levels that could be fitted by distorted-wave curves at their primary maximum are shown in Figs. 2–4. Table II lists the excitation energies of all observed levels together with their peak cross sections, their ratios of observed to DWBA cross sections, and the nearby levels observed in the (n,γ) experiment. It is clear that for a number of levels considerable mixing occurs. The ground-state transition is observed with a spectroscopic factor $S = 0.43$. The next observed level is the 0.509-MeV level, which also has an $l = 1$ angular distribution and has about 1.6 times the intensity of the ground state. It seems probable that this is a 2^+ level. The 0.692-MeV level is excited only weakly in the present experiment. The 0.881-MeV $l = 4$ level and 0.904-MeV $l = 3$ levels are not seen in the (n,γ) spectrum, but a group near 900 keV is observed in the (p,n) reaction. Since these levels are not seen in the (n,γ) reaction, it is likely that their spins are greater than 3. For the $l = 3$ transition, the spin

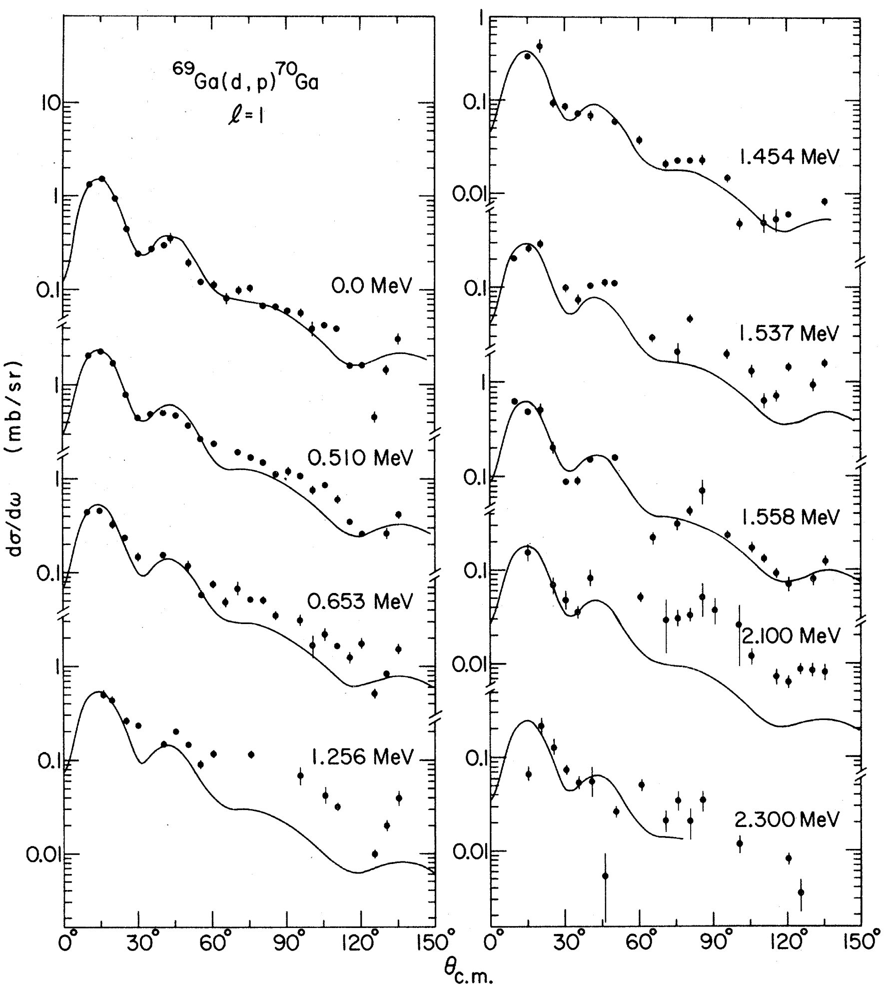

FIG. 2. Angular distributions of $l = 1$ transitions in the $^{69}Ga(d,p)^{70}Ga$ reaction.

would thus be 4^+. Since the 4^+ state is the only one that would not have an $l=1$ admixture and is the only $l=3$ state without $l=1$ admixture, 4^+ is probably a correct assignment. The ratio of observed to distorted-wave cross section for this level is about 0.7. Since some $l=3$ strength must of necessity go to 1^-–3^- levels, for which $l=1$ admixture is possible and for which such an admixture would mask the $l=3$ transfer rather effectively, it follows that the $1f_{5/2}$ shell in the ^{69}Ga ground state is only about $\frac{2}{3}$ filled. The transition to the 1.018-MeV level could not be fitted by a single distorted-wave curve. However, this level is also observed in the ^{72}Ga(d, t)^{71}Ga reaction and appears there to have a pronounced $l=3$ component. The 0.881-MeV level can be any one of the possible 4^-–6^- levels. The same observation can be made with respect to the 1.035-, 1.103-, and 1.237-MeV levels, all of which contain $l=4$ components. Since the 1.103-MeV level appears to have an admixture of $l=2$ and $l=4$, its spin would be limited to 4^- if one assumes that a 3^- assignment is excluded by the absence of this transition in the thermal-neutron-capture γ-ray experiment. If the level at 1.689 MeV does correspond to the (n, γ) level at 1.690 MeV, its spin would presumably be 3^-. Since this is the only $l=4$ transition in which the excitation energy corresponds to a level in the (n, γ) experiment, this assignment is plausible. On the other hand, some admixture of an $l=2$ transition might be expected in that case but does not appear to occur.

B. ^{71}Ga(d, p)^{72}Ga

A ^{71}Ga(d, p) spectrum at 25° lab is shown in Fig. 5. It is obvious that the ground-state transition,

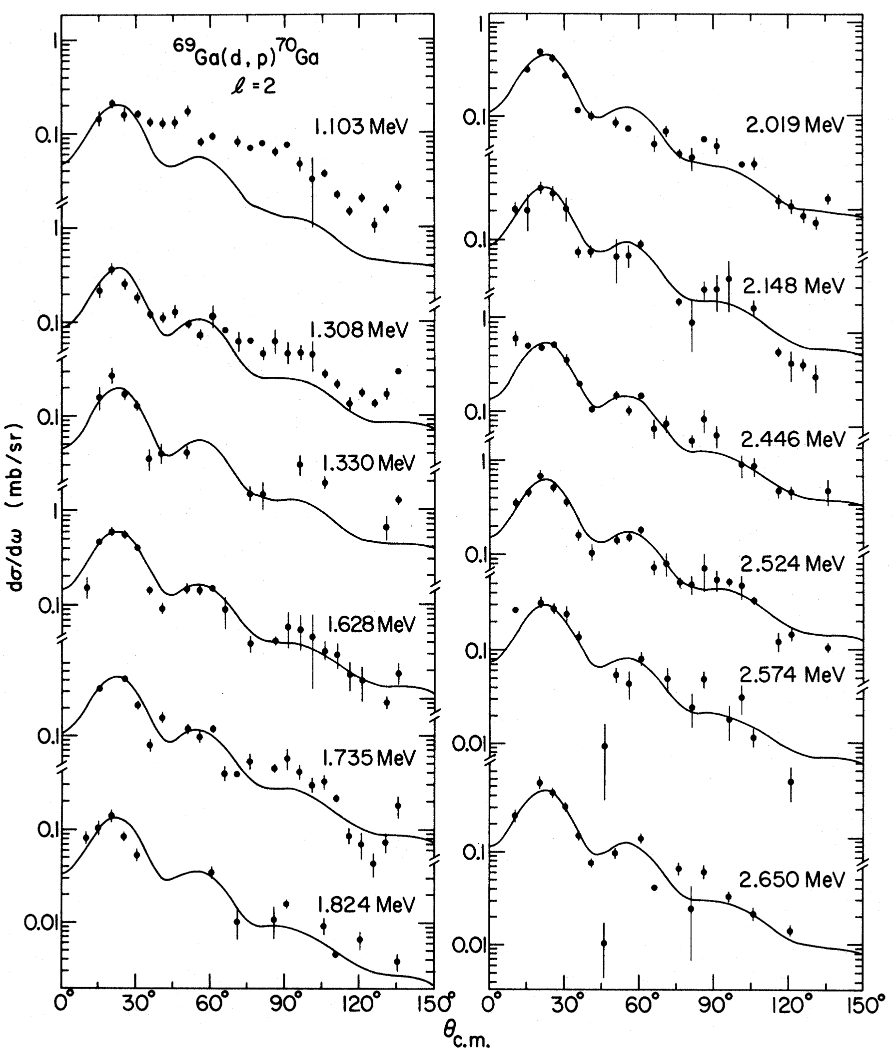

FIG. 3. Angular distributions of $l=2$ transitions in the ^{69}Ga(d,p)^{70}Ga reaction.

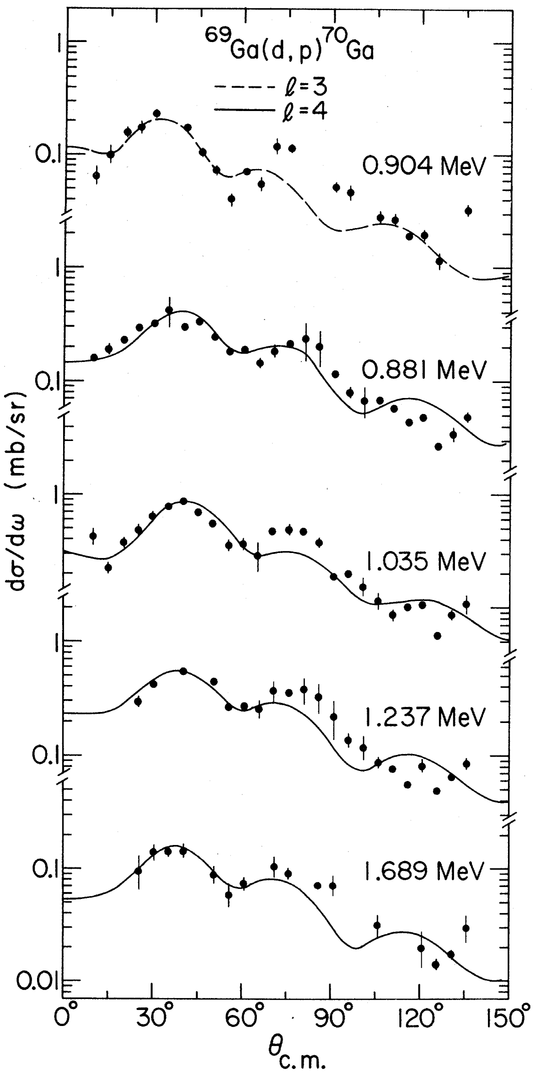

FIG. 4. Angular distributions of $l=3$ and $l=4$ transitions in the ^{69}Ga$(d,p)^{70}$Ga reaction.

which should correspond to $Q=4.295$ MeV, is not measurably excited. The ground-state spin of ^{72}Ga has been measured by Childs, Goodman, and Kieffer[15] to be 3. Therefore one would expect the transition to occur with a measurable $l=4$ transfer. The first observable level is at $Q=4.140 \pm 0.005$ MeV and shows an $l=1$ angular distribution. From the Q value and $l=1$ transfer this is probably the transition to the known 1^+ level at 161.7 keV. The electric-quadrupole moment of the ground state has been measured as $+0.59 \pm 0.03$ b, which is appreciably larger than the value expected from a simple shell-model configuration. Raz[16] has suggested that such a quadrupole moment could be explained if the 41 neutrons in ^{72}Ga are assumed to have a coupling similar to the 41 neutrons in ^{75}Se, which has a $\frac{5}{2}^+$ ground state, while the protons are coupled as in ^{71}Ga. Ikegami and Sano[17] have suggested that the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ levels in odd-even nuclei with either $41 \leq N \leq 47$ or $41 \leq Z \leq 47$ might be explained on the basis of a phonon-quasiparticle interaction. Nevertheless, one would expect some measurable admixture of the $l=4$ single-particle component for the ground-state transition.

The angular distributions of levels that could be fitted at the primary maximum by a distorted-wave curve are shown in Figs. 6–8; and the excitation energies of states observed, together with their l values, their peak cross sections, their ratio to distorted-wave calculation, and the excitation energies of neighboring levels from the slow-neutron-capture γ-ray experiment are listed in Table III.

The lowest four levels observed in the (n,γ) experiments are not observed in the (d,p) experiment, nor is the 197-keV level. In view of the high level density in this nucleus, it is improbable

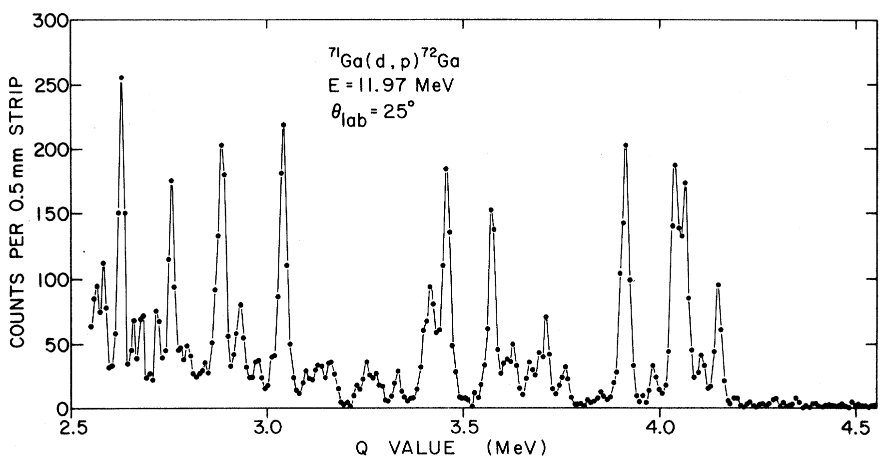

FIG. 5. Spectrum of the ^{71}Ga$(d,p)^{72}$Ga reaction at 25° lab.

TABLE II. Energy levels from the ^{69}Ga(d,p)^{70}Ga reaction.

E_x [a] (MeV)	l	$d\sigma/d\omega$ [b] (mb/sr)	$\left(\frac{d\sigma}{d\omega}\right)/\left(\frac{d\sigma}{d\omega}\right)_{DWBA}$	E_x (n,γ) [c] (MeV)	E_x [a] (MeV)	l	$d\sigma/d\omega$ [b] (mb/sr)	$\left(\frac{d\sigma}{d\omega}\right)/\left(\frac{d\sigma}{d\omega}\right)_{DWBA}$	E_x (n,γ) [c] (MeV)
0.00	1	1.7	0.38	0.00	1.627	2	0.63	0.16	1.631
0.510	1	2.4	0.52	0.507	1.662	(2?)	...	...	...
0.653	1	0.54	0.13	0.653	1.689	4	0.17	0.5	1.690
0.881	4	0.45	1.4	...	1.735	2	0.45	0.11	1.733
0.904	3	0.225	0.7	...	1.824	2	0.15	0.03	1.822
1.018	(1+3)	...	...	...	1.917	?	...	...	...
1.035	4	0.9	2.7	...	2.019	2	0.5	0.12	2.024
1.103	2, 4	0.225/0.18	0.13/0.6	...	2.100	1	0.27	0.06	...
1.237	4	0.6	1.9	...	2.148	2	0.36	0.08	2.140
1.256	1	0.63	0.15	1.250	2.234	?	...	...	2.231
1.308	(2)	0.40	0.1	1.310	2.300	1	0.16	0.03	...
1.330	2	0.22	0.05	...	2.446	2	0.59	0.14	...
1.454	1	0.36	0.08	1.455	2.524	2	0.32	0.07	2.518
1.537	1	0.33	0.07	1.531	2.574	2	0.68	0.15	2.569
1.558	1	0.72	0.16	1.553	2.650	2	0.5	0.11	2.648

[a] The uncertainty in the excitation energy is estimated to be less than 3 keV.
[b] Cross section at the primary peak of the angular distribution.
[c] Reference 1.

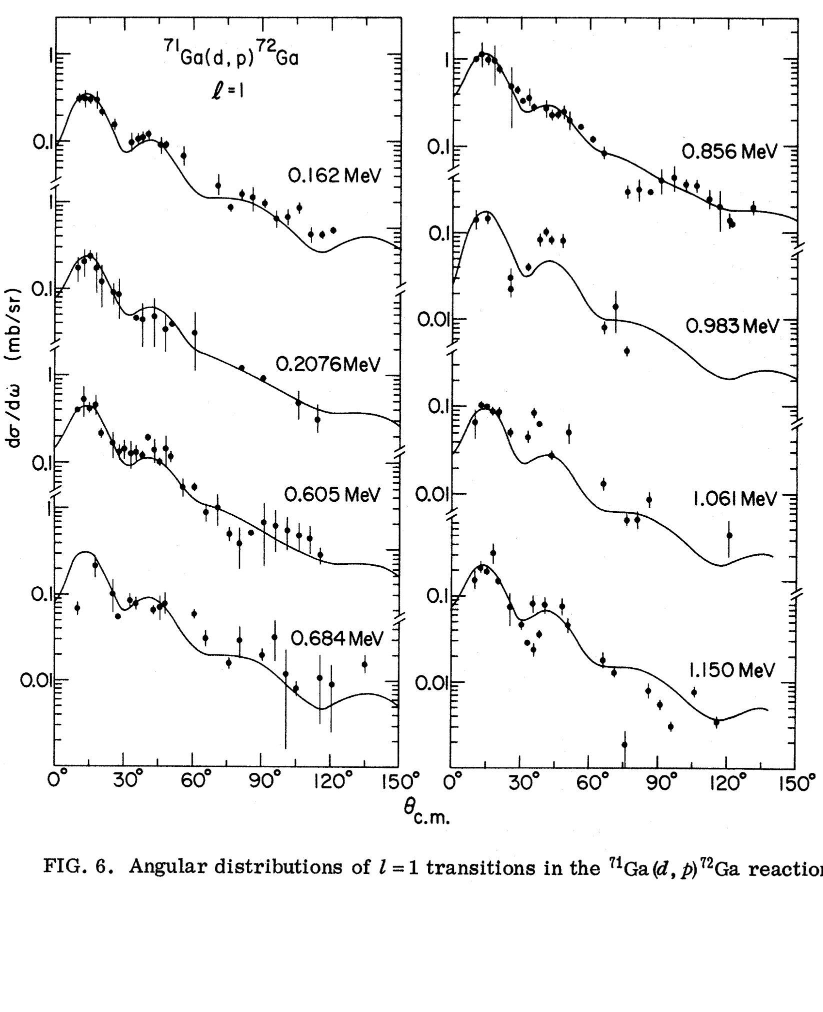

FIG. 6. Angular distributions of $l=1$ transitions in the ^{71}Ga(d,p)^{72}Ga reaction.

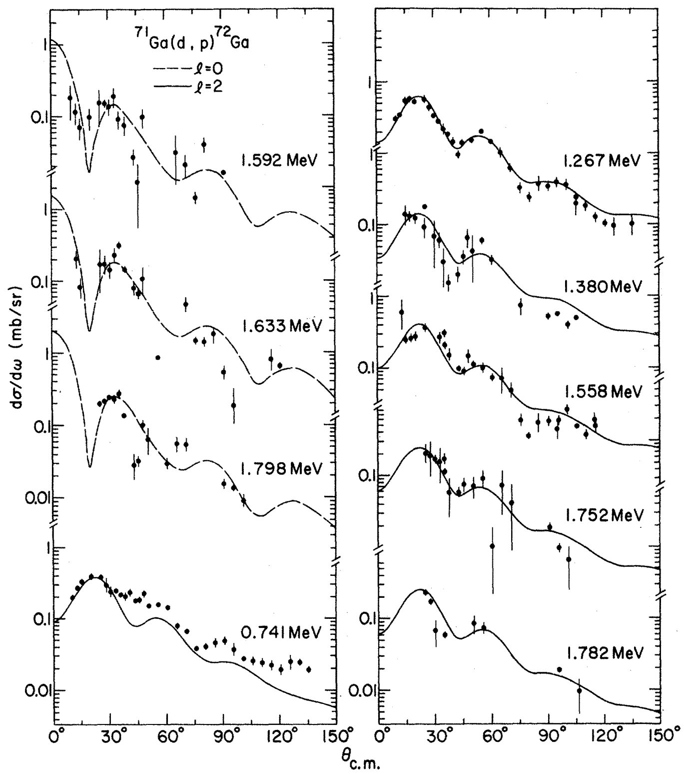

FIG. 7. Angular distributions of $l=0$ and $l=2$ transitions in the ^{71}Ga$(d,p)^{72}$Ga reaction.

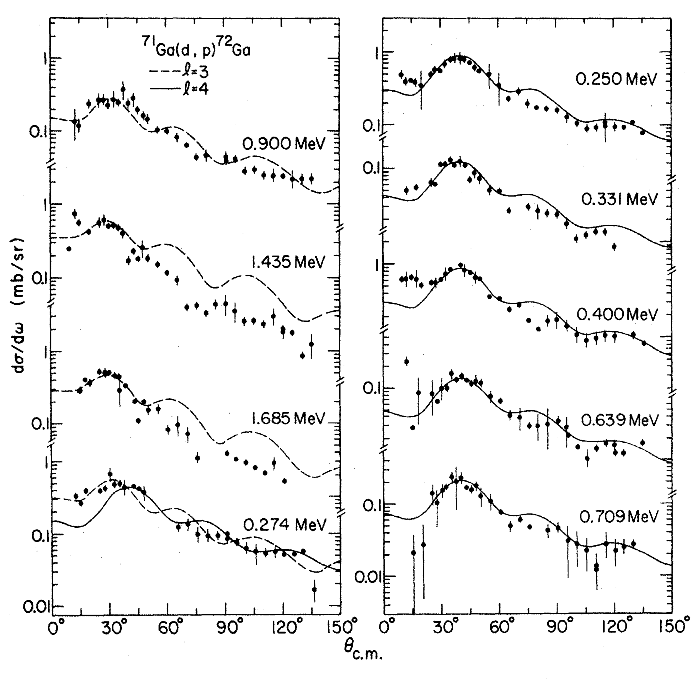

FIG. 8. Angular distributions of $l=3$ and $l=4$ transitions in the ^{71}Ga$(d,p)^{72}$Ga reaction.

TABLE III. Energy levels from the ^{71}Ga(d, p)^{72}Ga reaction.

E_x [a] (MeV)	l	$d\sigma/d\omega$ [b] (mb/sr)	$\left(\frac{d\sigma}{d\omega}\right)/\left(\frac{d\sigma}{d\omega}\right)_{\rm DWBA}$ [c]	$E_x(n,\gamma)$ [d] (MeV)	E_x [a] (MeV)	l	$d\sigma/d\omega$ [b] (mb/sr)	$\left(\frac{d\sigma}{d\omega}\right)/\left(\frac{d\sigma}{d\omega}\right)_{\rm DWBA}$ [c]	$E_x(n,\gamma)$ [d] (MeV)
0.162	1	0.33	0.06	0.161	1.208	...	...	...	1.205
0.208	1	0.23	0.04	0.208	1.267	2	0.6	0.15	1.262
0.250	4	0.87	2.75	0.248	1.338	...	...	...	...
0.274	...	...	...	0.282	1.380	2	0.13	0.03	...
0.331	4	0.12	0.38	0.329	1.435	3	0.6	1.7	1.427
0.400	4	0.84	2.66	...	1.473	...	...	...	1.472
0.560	...	...	...	0.563	1.517	...	...	...	1.515
0.605	1	0.42	0.08	0.600	1.558	2	0.39	0.1	...
0.639	4	0.13	0.41	0.636	1.592	0	0.16	0.03	...
0.684	1	0.3	0.05	...	1.633	0	0.18	0.03	1.629
0.709	4	0.21	0.65	...	1.685	3	0.45	1.1	1.680
0.741	2	0.36	0.09	0.739	1.732	...	...	...	1.727
0.856	1	1.14	0.2	0.856	1.752	2	0.24	0.06	1.749
0.900	3	0.27	0.7	...	1.782	2	0.24	0.06	1.776
0.917	...	...	...	0.918	1.798	0	0.24	0.04	1.801
0.983	1	0.16	0.03	0.978	1.872	...	...	...	1.869
1.038	...	...	...	1.032	1.919	...	...	...	1.917
1.061	1	0.09	0.02	1.059	1.989	...	...	...	...
1.150	1	0.23	0.04	1.149	2.059	...	...	...	...

[a] Uncertainties in the excitation energies are estimated to be less than 3 keV.
[b] Peak cross section at the primary maximum, except that the secondary maximum was used for $L=0$.
[c] The DWBA calculations, made with the code JULIE, have been multiplied by 1.6.
[d] Reference 1.

that agreement of level energies within the experimental error of the (d, p) and (n, γ) reactions would allow one to draw conclusions as to the spins of the levels. A disturbing feature is the apparent existence of three $l=3$ transitions whose cross sections are far too great in comparison with those in the ^{69}Ga(d, p)^{70}Ga experiment. It is possible to generate an angular distribution having an approximate $l=3$ shape, at least near the primary maximum, by a judicious mixture of $l=2$ and $l=4$ transfers. It is not implausible that some of the angular distributions measured in the present experiment are due to such mixtures.

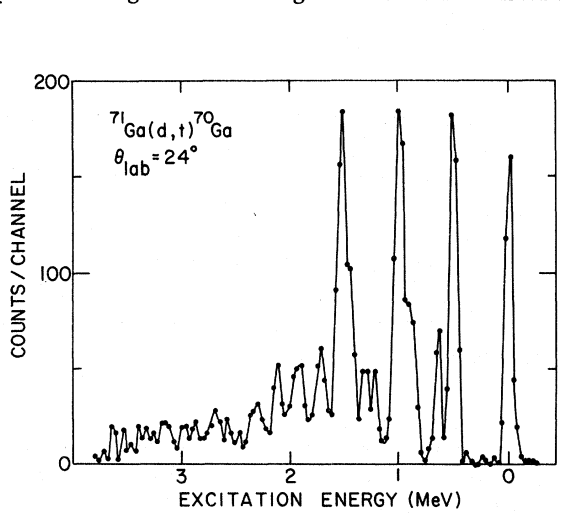

FIG. 9. Spectrum of the ^{71}Ga(d,t)^{70}Ga reaction at 24° lab.

C. ^{72}Ga(d, t)^{71}Ga Reaction

A typical ^{72}Ga(d, t) spectrum is shown in Fig. 9. The angular distributions for the analyzed transitions, together with the distorted-wave calculations, are shown in Fig. 10. The distorted-wave curve shown with the 0.925-MeV level was calculated with $l=3$, but the others drawn as solid curves are all calculated with $l=1$. The $l=3$ level at $E_x=0.925$ MeV in the (d, t) reaction is obviously the same as the one observed at 0.904 MeV in the ^{69}Ga(d, p)^{70}Ga reaction. The larger error in the (d, t) determination of its excitation energy is due to the poor separation from the strong 1.018-MeV transition. The dashed curves for the latter represent admixtures of $l=3$ and $l=1$ curves in ratios of 3 : 1 (short dashes) and 6 : 1 (long dashes). Clearly, the (d, t) reaction is not sensitive to the amount of $l=3$ admixture, but a pronounced deviation from the pure $l=1$ curve implies a large $l=3$ admixture. On the other hand, when C^2S for

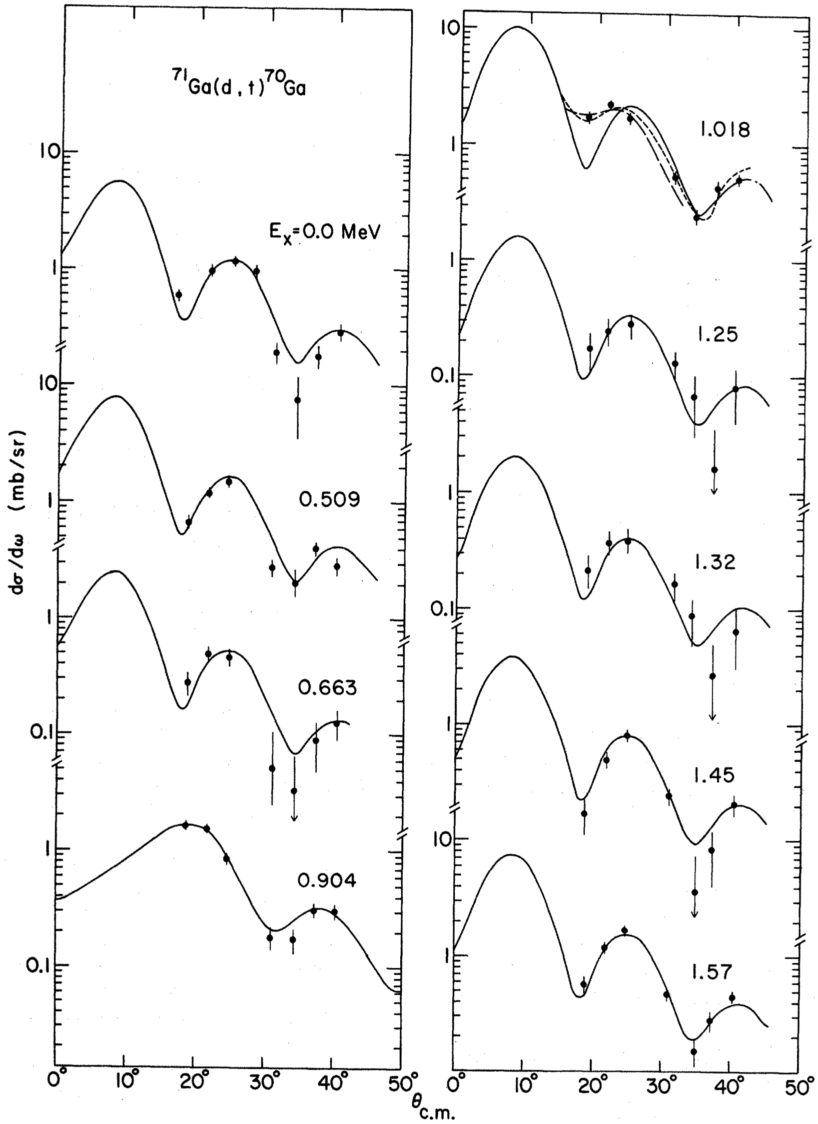

FIG. 10. Angular distributions of ^{71}Ga$(d,t)^{70}$Ga transitions.

TABLE IV. Energy levels from the ^{72}Ga$(d,t)^{71}$Ga reaction.

E_x [a] (MeV)	l	C^2S
0.0	1	0.33
0.509	1	0.5
0.663	1	0.17
0.904	3	1.5 (l =3)
1.018	1, 3	0.7 (l =1)
1.25	1	0.1
1.32	1	0.12
1.45	1	0.25
1.57	1	0.5

[a] The uncertainty in E_x is estimated to be about 10 keV.

the $l=1$ transitions is computed from the secondary maximum of the $l=1$ distribution, its value is hardly affected by the amount of $l=3$ admixture. The transition to the 1.32-MeV level does not appear to correspond to any $l=1$ level in the ^{69}Ga$(d,p)^{70}$Ga reaction. The data are summarized in Table IV, which also lists the C^2S values derived from the comparison with the distorted-wave calculations.

DISCUSSION

The summed ratios of observed to distorted-wave cross sections for the (d,p) reactions are given in Table V. Since the angular distributions of a number of levels could not be fitted and the

TABLE V. Summed ratios of the observed to the calculated cross sections for the (d,p) reaction on ^{69}Ga and ^{71}Ga.

Reaction	$\sum (d\sigma/d\omega)/(d\sigma/d\omega)_{\text{DWBA}}$ $l=0$	$l=1$	$l=2$	$l=3$	$l=4$
^{69}Ga$(d,p)^{70}$Ga	···	1.58	1.25	0.7	6.5
^{71}Ga$(d,p)^{72}$Ga	0.10	0.52	0.49	3.5	6.85

expected contributions from higher l values are masked, these summed values have to be regarded as lower limits. It is nevertheless clear that an appreciable $1f_{5/2}^{-2}$ component is present in the ground-state wave functions of both stable isotopes and that ^{69}Ga already has an appreciable $1g_{9/2}^{2}$ neutron component. While some restrictions can be placed on the spins of a few of the levels of ^{70}Ga, the high level density in ^{72}Ga makes it impractical to do so. Some levels from the slow-neutron-capture γ-ray spectrum are not observed in the (d,p) experiment. In ^{69}Ga, the first of these are near 1 MeV excitation; but in ^{72}Ga the whole (n,γ) group near the ground state is missing in the (d,p) spectrum. The upper limit for the ground-state cross section is estimated at 0.04 mb – less than 5% of the cross section for the $l=4$ transition to the 0.250-MeV level. It is not clear why the $l=4$ single-particle 3^- configuration should not mix with the predominant ^{72}Ga ground-state configuration to a greater extent.

ACKNOWLEDGMENT

The assistance of John J. Bicek, Jr., is gratefully acknowledged.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

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