Structure of the low lying states in ^{69}Ga through the $(p,p'\gamma)$ reaction

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The $(p,p'\gamma)$ reaction is used to investigate the structure of the low lying states of ^{69}Ga. Measured angular distributions, level cross section, and centroid shifts allow spin, parity, and mean life assignments to be made to several excited states. The experimental results are compared with the theoretical three particle cluster-core coupling model.

NUCLEAR REACTIONS ^{69}Ga$(p,p'\gamma)$, E_p=3.0–5.1 MeV, enriched targets. Measured E_γ, I_γ, $I_\gamma(\vartheta)$, σ_γ, $\Delta E_\gamma(\tau)$ deduced ^{69}Ga levels, branching ratios, τ, $\delta(E2/M1)$, $B(E2)$ $B(M1)$; Ge(Li) detectors.

INTRODUCTION

The ^{69}Ga nucleus has been the subject of numerous experimental investigations.[1-12] β decay,[1,2] reaction studies,[3-5] Coulomb excitation,[6] angular correlation,[10,11] and $(\alpha,p\gamma)$ (Ref. 12) experiments have established the main features of the nuclear structure of this nucleus. Nevertheless, there are still some uncertainties concerning the spin assignment of some low lying states, which have to be clarified if a comparison is to be made[10] between the experimental structure of this nucleus and the theoretical predictions of the particle-core coupling model.

In the context of this model, Paar[13] described the structure of the low lying states of ^{69}Ga in terms of a three proton cluster moving outside the filled $Z=28$ shell coupled with the vibrations of an even-even ^{66}Ni core. As a result of such a description a $\frac{3}{2}^-$ ground state for ^{69}Ga is predicted together with two low lying $\frac{1}{2}^-$ and $\frac{5}{2}^-$ states of particlelike structure, followed by a quadruplet of vibrational-like states with $J=\frac{1}{2}^- - \frac{7}{2}^-$ which arise from the $(p_{3/2})^3_{3/2}$ configuration coupled to the first 2^+ vibrational state of the ^{66}Ni core.

Thus the proper experimental identification of the spin of the low lying states of ^{69}Ga can give important indications on the reliability of the particle-core model to describe nuclear properties in this mass region.

EXPERIMENTAL RESULTS

Targets of 4 and 0.8 mg/cm^2 in the form of KGa_5O_8 were settled on Au foils with the help of an organic binder. The targets were enriched to 98% in ^{69}Ga. The proton beam was provided by the NRC Demokritos T11/25 tandem Van de Graaff accelerator. The bombarding energies covered the region from 3 to 5 MeV.

A complete description of the experimental setup and the methodology used in the angular distribution and Doppler-shift attenuation method (DSAM) is given elsewhere.[14] Since the ^{69}Ga(p,n) threshold is at 3 MeV, the spectra obtained at higher energies are quite complicated and only

TABLE I. Results of the single angular distribution measurements.

E (keV)	A_2 ×100 at 4.8 MeV	A_4 ×100 at 4.8 MeV	A_2 ×100 at 4.5 MeV	A_4 ×100 at 4.5 MeV	A_2 ×100 at 4.2 MeV	A_4 ×100 at 4.2 MeV
318.7	−1±1	1±1	0±1	0±1	0±1	0±1
574.2	−12±1	0±1	−10±1	2±1	−11±2	0±2
709.5	−1±3	−1±4	−2±3	4±4	0±3	2±4
872.1	2±1	0±2	0±1	0±2	1±2	0±2
913.8	−40±10	10±10	−35±7	7±7	−25±10	10±10
1028.5	0±5	0±7	−1±5	0±6	1±5	1±6
1106.8	10±2	−4±3	8±2	2±2	10±2	−1±3
1336.6	25±4	−4±4	20±3	−2±3	28±4	−4±4
1487.9	31±8	−6±9	23±8	−5±9	22±8	−5±9

TABLE II. γ-ray energies, branching and mixing ratios determined in the present work and comparison with other available data.

Initial level E (keV)	J_i	τ_i ps	Final level E (keV)	J_f^π	E_γ (keV)	Branch		δ Present	δ Other	$B(E2)$ (e^2b^2)	$B(M1)$ $(\mu_N)^2$
318.71 3	$\frac{1}{2}^-$	<140	0.0	$\frac{3}{2}^-$	318.71 3	100	$M1+E2$			0.013 ±0.002 [a]	>0.012
574.17 3	$\frac{5}{2}^-$	8.7 ±3 [b]	0.0	$\frac{3}{2}^-$	574.17 3	99.8 [c]	$M1+E2$	−0.06±0.03	−0.04±0.04 [d]	0.0004±0.0001	0.35 ±0.15
872.14 3	$\frac{3}{2}^-$	0.36±0.03	0.0	$\frac{3}{2}^-$	872.14 3	94.9	$M1+E2$	−0.13±0.04	−0.11±0.09 [d]	0.006 ±0.003	0.24 ±0.03
			318.71	$\frac{1}{2}^-$	553.38 15	4.9	$M1+(E2)$				
1028.52 7	$\frac{1}{2}^-$	1.8 ±1.5	0.0	$\frac{3}{2}^-$	1028.54 13	30.0	$M1+E2$			0.007 ±0.002 [a]	$0.01^{+0.04}_{-0.003}$
			318.71	$\frac{1}{2}^-$	709.80 10	70.0	$M1$				$0.06^{+0.3}_{-0.03}$
			574.1	$\frac{5}{2}^-$	(454.4)	≤3	$(E2)$				
1106.80 8	$\frac{5}{2}^-$	0.32±0.03	0.0	$\frac{3}{2}^-$	1106.80 8	96.4 [c]	$M1+E2$	0.41±0.05		0.021 ±0.004	0.11 ±0.01
1336.61 8	$\frac{7}{2}^-$	1.3 ±0.3	0.0	$\frac{7}{2}^-$	1336.61 8	93.9 [c]	$E2$	0.02±0.03		0.014 ±0.002	
1488.03 21	$\frac{7}{2}^-$	6 ±2 [e]	0.0	$\frac{3}{2}^-$	1488.03 21	58.0	$E2$	0.00±0.03		0.0011±0.0002	
			574.17	$\frac{5}{2}^-$	931.87 30	42.0	$M1+E2$	−2.54±0.10	−1.8 ±1.0[f] or −0.75±0.25	0.008 ±0.001	0.0008±0.0001
1525.80 30	$(\frac{3}{2}^-)$		0	$\frac{3}{2}^-$	1525.80 30	63.0					
	$(\frac{5}{2}^-)$		318.7	$\frac{1}{2}^-$	1207.25 30	37.0					

[a] Reference 6.
[b] Average of Refs. 1, 6, 8, and 9.
[c] Reference 2.
[d] Reference 7.
[e] Reference 8.
[f] Reference 10.

TABLE III. Lifetimes for levels in ^{69}Ga obtained by the DSAM from centroid shift and comparison with other available data.

Level (keV)	γ ray used (keV)	$F(\tau)$ at $\bar{E}p$ 4.8 MeV	4.5 MeV	4.2 MeV	3.0 MeV	τ (ps) Present	Ref. 8 Res. fluor.	Ref. 1. Res. fluor.	(Ref. 6) Coulomb exc.	(Ref. 9) DSAM
872.1	872.1	0.16 3	0.15 3	0.15 3	0.14 3	0.36 5	0.43 4	0.31 6	0.32 6	
1028	1028.5	0.11 8	0.09 8	0.10 8	0.07 6	1.8 15	>1			<0.16
	709.5									
1106.8	1106.8	0.18 3	0.16 3	0.17 3	0.18 5	0.33 5	0.37 3	0.24 3	0.30^a 4	0.36 10
1336.6	1336.6	0.06 5	0.05 5	0.05 4		2 1	1.8 1		1.0 2	0.48 16

^{a}Calculated from the $B(E2)$ value quoted in Ref. 6 and the currently measured δ.

the prominent peaks from the $(p,p'\gamma)$ reaction are visible. A spectrum obtained at 5 MeV bombarding energy is given elsewhere.[15] Above 3 MeV the ^{69}Ge nuclei are formed and decay back to ^{69}Ga thus interfering with some of the $(p,p'\gamma)$ lines. Since the half-life of ^{69}Ge is relatively long, however ($T_{1/2}$ = 39 h), the rate of this decay is small and by monitoring the radioactivity rate before and after each run at each energy, the necessary corrections were made to both angular distribution and DSAM data. The maximum of these corrections amounted to 15%. More information concerning the mean lives determination is given in Ref. 15.

In Table I the observed angular distributions at several bombarding energies are given. The energies of the γ rays observed their branching and other electromagnetic properties are summarized in Table II. Deduced mean lives from the DSAM method are given in Table III where a comparison with other available data is made.

SPIN AND PARITY ASSIGNMENTS

The analysis of the experimental angular distribution consisted of the determination of the multipole mixing ratio by minimizing x^2 for fixed values of initial and final spins. In applying the statistical model to obtain the theoretical angular distribution coefficients, ten states in ^{69}Ga and all observed states from the (p,n) reaction[15] have been considered. Additional data for spin determination were obtained by measuring the cross section for populating the ^{69}Ga states as determined from the γ-ray spectra and comparing with the theoretical values obtained from the statistical model. The use of the cross section magnitude in spin determination is discussed in Ref. 14. To minimize errors, relative cross sections have been measured with respect to the cross section of the 318 keV $\frac{1}{2}^-$ state in ^{69}Ga which was assumed to have the theoretically predicted value. At $Ep = 4.8$ MeV the measured cross section is $\sigma(318) = 2.1 \pm 0.4$ mb, while theory predicts 2 mb for $J^\pi = \frac{1}{2}^-$ for this level. The measured cross sections for the other levels and a comparison with theory is given in Table IV. The spin and parity of the ground and first excited states are well established as $\frac{3}{2}^-$ and $\frac{1}{2}^-$, respectively.[1-12]

574.1 keV level. The measured angular distribution is consistent with $J^\pi = \frac{5}{2}^\pm$ only (see Fig. 1). Since β decay data[2] indicate a negative parity for this state and since this state has been populated with an $l = 3$ proton transfer in (d,n) and $(^3\text{He},d)$ reactions,[4,5] a unique $J^\pi = \frac{5}{2}^-$ assignment can be made to this state. From the available mean life measurements[1,8,9] of this state and the Coulomb excitation data,[6] the solution $\delta = -2.75$ can be re-

TABLE IV. Comparison of measured and theoretical cross sections at $\bar{E}p = 4.8$ MeV.

Level (keV)	σ(exp)[a] (mb)	Theory in (mb) $\sigma(\frac{1}{2})$	$\sigma(\frac{3}{2},\frac{5}{2})$	$\sigma(\frac{7}{2})$	J from σ	Other J[b]	Adopted
574.1	2.6 ±0.2	1.4	2.5	1.9	$\frac{3}{2},\frac{5}{2}$	$\frac{5}{2}^-$	$\frac{5}{2}^-$
872.1	1.7 ±0.2	0.9	1.5	1.1	$\frac{3}{2},\frac{5}{2}$	$\frac{1}{2}^-,\frac{3}{2}^-$	$\frac{3}{2}^-$
1028.5	0.6 ±0.1	0.65	1.1	0.9	$\frac{1}{2}$	$\frac{1}{2}^-,\frac{3}{2}^-$	$\frac{1}{2}^-$
1106.8	1.1 ±0.1	0.55	0.9	0.7	$\frac{3}{2},\frac{5}{2}$	$\frac{5}{2}^-$	$\frac{5}{2}^-$
1336.8	0.40±0.04	0.30	0.52	0.40	$\frac{7}{2}$	$\frac{7}{2}^-$	$\frac{7}{2}^-$
1488.0	0.25±0.05	0.20	0.40	0.28	$\frac{1}{2},\frac{7}{2}$	$\frac{7}{2}^-$	$\frac{7}{2}^-$
1525.2	0.40±0.10	0.18	0.37	0.26	$\frac{3}{2},\frac{5}{2}$	$(\frac{3}{2}^-,\frac{5}{2}^-)$[c]	$(\frac{3}{2}^-,\frac{5}{2}^-)$[c]

[a]Normalized to the theoretical value for the $\frac{1}{2}^-$ 318 keV state.
[b]As derived from the angular distribution data of the present work.
[c]Reference 5.

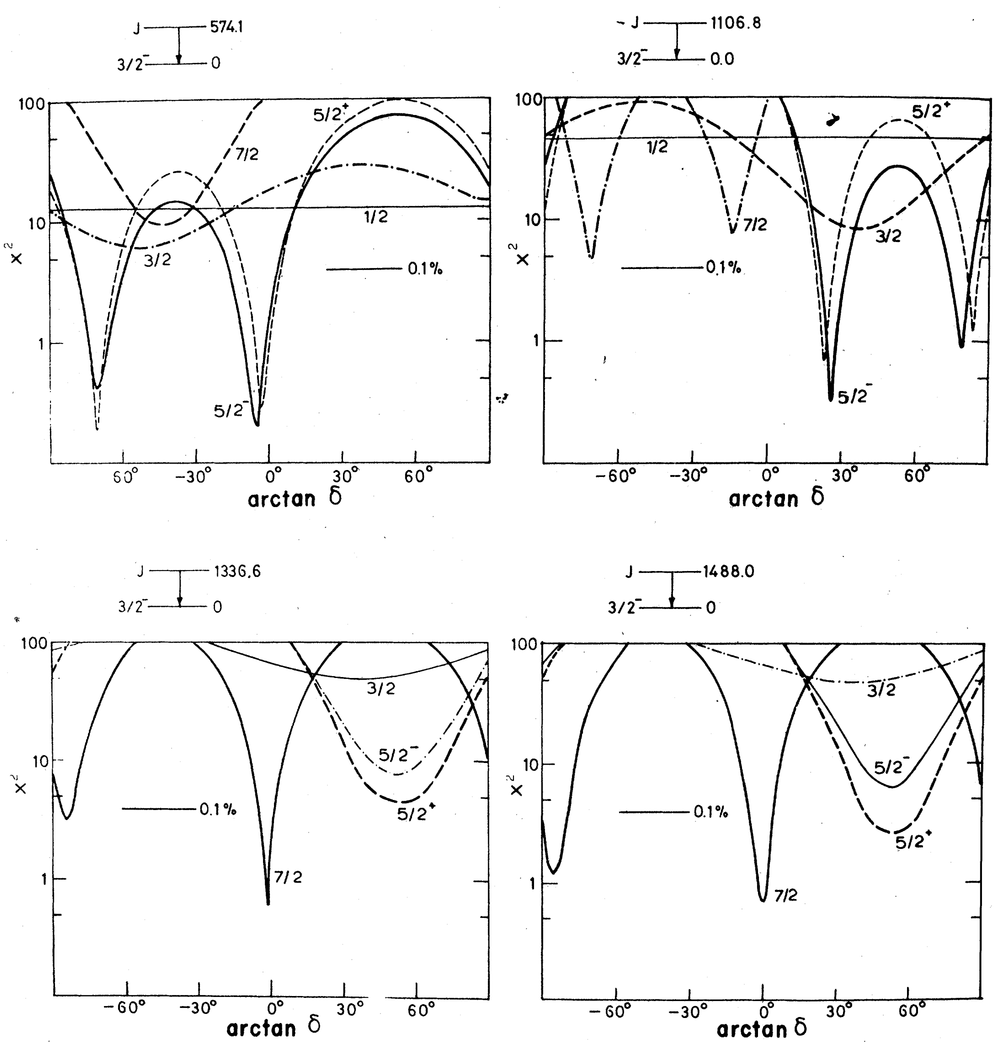

FIG. 1. The x^2 diagrams for some selected transitions. Data are taken from the $\bar{E}_p = 4.8$ MeV experiment.

jected and the unique value $\delta = -0.06 \pm 0.03$ is adopted for the 574 keV transition.

872.1 keV level. The angular distribution of the 872 γ ray (Table I) is consistent with $J=\frac{1}{2}$ or $\frac{3}{2}$. The measured cross section favors $J=\frac{3}{2}$ or $\frac{5}{2}$. Thus $J=\frac{3}{2}$ is adopted. Since the $(n, n'\gamma)$ experiments of Velkeley[3] indicate $J^\pi = \frac{3}{2}^-$ and since this state has been populated with an $l=1$ transfer,[4,5] a unique $J^\pi = \frac{3}{2}^-$ assignment can be made to this level.

1028.5 keV level. The angular distributions of the 1028.5 and 709.8 keV γ rays from this level are consistent with $J=\frac{1}{2}$ or $\frac{3}{2}$. The measured cross section (Table IV) is consistent with $J=\frac{1}{2}$ only. This state has been populated by an $l=1$ transfer[4,5] and thus a unique $J^\pi = \frac{1}{2}^-$ assignment can be made to this state. This state is not populated or very weakly populated in the β^+ decay[2] of ^{69}Ge, a fact which is explained by the $J^\pi = \frac{1}{2}^-$ assignment to this state. The measured mean life of 1.8 ± 1.5 ps for this level is not consistent with the value of $\tau < 0.16$ ps found by Ivascu *et al.*[9] but agrees with the result of $\tau > 1$ ps obtained by Arnold *et al.*[8]

1106.8 keV level. The β^+-decay data[2] indicate $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$ for this state. Velkeley *et al.*[3] have assigned $J^\pi = \frac{3}{2}^-$ to this level. Paradellis *et al.*,[10] on the basis of the measured angular correlation of the 234–872 keV cascade originating from this level, adopt a $\frac{5}{2}^-$ assignment for this level, since a $\frac{3}{2}^-$ assignment would result in an $E2$ rate for the 234 keV transition exceeding 500 Wu (Weisskopf unit). Howe *et al.*,[13] although they obtain the same experimental coefficients of angular distribution as Paradellis *et al.*[12] for the same γ-γ cascade, adopt the $J=\frac{3}{2}^-$ over the $\frac{5}{2}^-$ assignment for this state based on previous rather sketchy data in the literature without examining the fact that this choice leads to a very unusual enhanced $E2$ rate for the 232 keV transition.

The angular distribution of the 1106 keV transition measured here allows (see Fig. 1) a unique $\frac{5}{2}$ spin assignment to be made for this state. The resulting large δ value and the measured mean life allow a negative parity assignment. Thus the $J^\pi = \frac{5}{2}^-$ assignment is established for this level. From the two possible δ values (Fig. 1) only the lower value is consistent with the available Coulomb excitation data.[6]

1336.6 and 1488.0 keV levels. The angular distribution of the γ rays deexciting these two levels (see Fig. 1) allows a unique $\frac{7}{2}^-$ spin and parity assignment to be made for these two levels.

DISCUSSION

The results of the present measurements combined with the other available data in the literature allow unique spin and parity assignments to be made for several low lying states in ^{69}Ga. Therefore the four states at 872.1 ($\frac{3}{2}^-$), 1028.6 ($\frac{1}{2}^-$), 1106.8 ($\frac{5}{2}^-$), and 1336.6 ($\frac{7}{2}^-$) keV can be identified with the members of the quadruplet arising from the coupling of the $(p_{3/2})^3{}_{3/2}$ cluster to the 2^+ vibrational state of the core. Had there been a $\frac{3}{2}^-$ spin and parity assignment for the 1106.8 keV state, it would have been very difficult to explain in the context of the cluster-core coupling model the appearance of two low lying $\frac{3}{2}^-$ states and the absence of the $\frac{5}{2}^-$ one. Especially for the 1106 keV level, the model[13] predicts that this state should have a very small spectroscopic factor and a strong $E2$ decay to the ground state. In both (d,n) and $(^3\text{He},d)$ experiments[4,5] this state is indeed very weakly populated while the observed (see Table I) $E2$ rate of the 1106 keV transition is consistent with theory.

The other three members of the quadruplet decay also with strong $E2$ rates (see Table I) as predicted by the theory,[13] while the second $\frac{7}{2}^-$ state observed at 1488 keV is not reproduced by it. Since in the theoretical work of Paar[13] the $f_{7/2}$ proton configuration is not included in the calculations, only one low lying $\frac{7}{2}^-$ state is predicted and is identified with the 1336.6 keV state on the basis of the observed $E2$ rate. It is very possible that the 1488 keV state is either due to a $f_{7/2}$ proton hole in the core or is the $\frac{7}{2}^-$ state arising from the $f_{5/2} \otimes 2^+$ configuration or may be a mixture of both. The observed $E2$ rates of the 1488 ($\frac{7}{2}^- \to \frac{3}{2}^-$) and 913 ($\frac{7}{2}^- \to \frac{5}{2}^-$) transitions are about 1 and 7 Wu respectively favoring the presentation of the 1488 keV state as an admixture of an $f_{7/2}$ proton hole and an $f_{5/2} \otimes 2^+$ configuration.

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