Isobaric analog resonances in the $^{68}Zn(p,\gamma)^{69}Ga$ reaction*

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Isobaric analog resonances in ^{69}Ga corresponding to the ground $(1/2^-)$ and first excited $(9/2^+)$ parent states of ^{69}Zn have been studied by the ^{68}Zn(p,γ) reaction. The γ decay of the ground state of ^{69}Zn is compared with the β decay of the parent isobaric analog state. The latter is a pure Gamow-Teller transition to the ground $(3/2^-)$ and third $(3/2^-)$ excited states, while both Gamow-Teller and Fermi matrix elements can contribute in the decay to the second excited $(1/2^-)$ state of ^{69}Ga. The $M1$ decay widths obtained from the γ decay of the $J^\pi = 1/2^-$ isobaric analog state are in good agreement with the widths extracted from the log*ft* values in the first two of the three β-decay branches. However, the $M1$ decay width to the third excited state disagrees with the value deduced from the log*ft* value of the β decay of the ^{69}Zn g.s. to this state. In addition, the $M1$ transition strength of the $9/2^+$ $(T_>)$ state to the $9/2^+$ $(T_<)$ state in ^{69}Ga has been measured and is compared with the recently published systematic trends for the analog to antianalog transition in other f-p shell nuclei.

[NUCLEAR REACTIONS ^{68}Zn(p,γ), E=3.2–3.8 MeV. ^{69}Ga deduced resonances, measured E_γ and Γ_γ, $M1$ strength.]

I. INTRODUCTION

In medium nuclei, the study of the isovector transitions in the γ decay of the isobaric analog resonances (IAR) has provided valuable insights into the nuclear structure of both the parent and residual nuclei. For example, the spin part of the $M1$ matrix element is closely related to the β decay of the Gamow-Teller matrix element. As a result, comparison of the γ decay of the IAR with the β decay of the parent state enables us to estimate the importance of the orbital angular momentum operator in the $M1$ matrix element. The hindered β decay in certain medium mass nuclei has been shown to arise[1] from the Gamow-Teller giant resonance and it has been possible to locate[2,3] such resonances in the γ decay of the corresponding IAR in the case of ^{51}Ti and ^{63}Ni. These giant resonances yield important information about the particle-hole excitation in these nuclei. Furthermore, for nuclei in the f-p shell, the $M1$ transition from the IAR of the $\frac{9}{2}^+$ state in the parent nucleus to the $\frac{9}{2}^+$ state in the residual nucleus has tended to take[4] the role of an analog-antianalog transition while transitions from IAR corresponding to states with $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$ in the parent nucleus have not generally shown this behavior: because of its high spin the lowest $\frac{9}{2}^+$ state in the parent nucleus tends to be dominated by the single-particle configuration as seen[5] for example in the stripping reactions. A systematic study of the γ decay of the IAR of the $\frac{9}{2}^+$ states would enable us to study the manner in which this strength varies as more nucleons are put in the f-p shell nuclei.

II. EXPERIMENTAL DETAILS AND RESULTS

A proton beam from the Université Laval Van de Graaff accelerator was used to bombard isotopically enriched (95%) ^{68}Zn targets which were 1 to 6 keV thick for 3 MeV protons. The targets were prepared by electron-gun evaporation in vacuum of the isotopic material onto 30 μg/cm^2 thick carbon backing. The beam passed through the scattering chamber[3] and was collected in a 2 m long Faraday cup which was lined with tantalum to reduce background radiation. The design of the target chamber permitted us to measure simultaneously the γ rays produced in the (p,γ) reaction and the protons scattered at 167° in the laboratory system. A 50 cm^3 Ge(Li) detector having a resolution of 3 keV full width at half maximum for 1.3 MeV γ rays was used to detect the γ rays; the efficiency function[3] of this detector for γ rays of energies of up to 11 MeV in the geometry of the experiment was determined by measuring the γ rays from the resonance in ^{28}Si at E_p = 1.381 MeV excited in the proton bombardment of ^{27}Al and from a calibrated ^{60}Co source mounted in the same geometry with respect to the detector as the target in the (p,γ) experiment. The branching ratios for the γ rays in the ^{27}Al $(p,\gamma)^{28}$Si experiment were taken from Ref. 6.

The excitation function in the γ channel at 55° and in the proton elastic channel at 167° were measured simultaneously in steps of 1 keV. Each point on the excitation function was obtained for a comparatively small charge of 100 μC of the integrated beam. After locating the resonances, spectra for an integrated charge of about 20 mC were taken on and off resonance. Typical spectra obtained on and off resonance are shown in Fig. 1. From the measured charge, target thickness, and the efficiency function of the Ge(Li) detector, the partial Γ_γ were extracted assuming that $\Gamma_\gamma \ll \Gamma$. At these low incident energies below the neutron threshold, the contribution to the total width Γ comes principally from the elastic channel and therefore Γ was set equal to Γ_{el}. The (p, p) excitation function measured with an overall resolution of the system of between 1 and 2 keV showed fine structure underlying the IAR corresponding to the $J^\pi = \frac{1}{2}^-$ ground state of ^{69}Zn. A target which was about 6 keV thick for 3 MeV protons was employed in a separate experiment to average out the fine structure. This enabled us to locate the IAR in the (p, p), (p, p', γ), and (p, γ) channels at $E_p = 3.25$ MeV. The Coulomb energy $\Delta E_C = 9.69 \pm 0.01$ MeV calculated from this resonance energy agrees with the value quoted in the literature.[5] It was not possible to observe the IAR corresponding to the $\frac{9}{2}^+$ first excited state of ^{69}Zn in the proton elastic channel because of the high angular momentum barrier encountered by $l = 4$ partial waves. In obtaining the excitation function in the γ channel, a window was set to accept the γ rays going to the low-lying high-spin states in ^{69}Ga (Fig. 2). With this arrangement, the IAR corresponding to the $\frac{9}{2}^+$ first excited state of ^{69}Zn was located easily. Three fragments of the IAR were observed in the excitation function and the Coulomb energy calculated from the centroid of these fragments was 9.683 ± 0.005 MeV, in agreement with that obtained from the ground state (g.s.) analog.

III. DISCUSSION OF THE RESULTS

A. Analog of the ground state ($\frac{1}{2}^-$) of ^{69}Zn

The γ decay of the analog of the ^{69}Zn g.s. can be directly compared with the β decay of the parent nucleus (Fig. 2) since the β decay is an allowed Gamow-Teller transition to the ground state ($J^\pi = \frac{3}{2}^-$, $\log ft = 4.48$), first excited state at 0.318 MeV ($J^\pi = \frac{1}{2}^-$, $\log ft = 8.7$), and to the third excited state at 0.872 MeV ($J^\pi = \frac{3}{2}^-$, $\log ft = 5.5$). In the γ decay of the analog, the corresponding transitions could be $M1$ and $E2$ to the ground and third excited states and pure $M1$ to the first excited state. Assuming that the transition is pure $M1$ and that the l part of the $M1$ operator is negligible, the value obtained for the $B(M1)$ for the transition to the g.s. of ^{69}Ga agrees within the experimental uncertainties with the value deduced from the β decay of the parent state in ^{69}Zn to the same final state in ^{69}Ga (Table I). This IAR does not show any measurable width for the transition to the first excited ($\frac{1}{2}^-$) state of ^{69}Ga and an upper limit for its value is shown in column 4 of Table I. This result is consistent with the large value of the $\log ft$ for the β decay to this state, which shows that this is a highly hindered transition. The spectroscopic factors[5] for the ^{68}Zn$(d, p)^{69}$Zn$_{g.s.}$ and the ^{68}Zn$(^3$He$, d)^{69}$Ga$_{0.318}$ are large, viz. 0.55 and 0.65, suggesting that these two states are largely single particle in character.

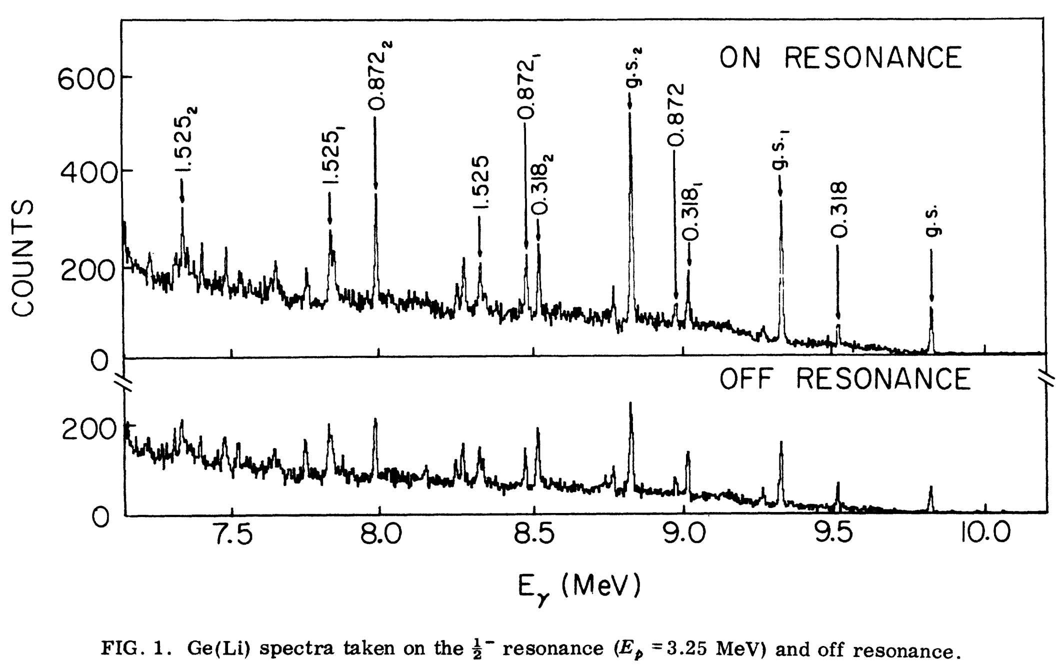

FIG. 1. Ge(Li) spectra taken on the $\frac{1}{2}^-$ resonance ($E_p = 3.25$ MeV) and off resonance.

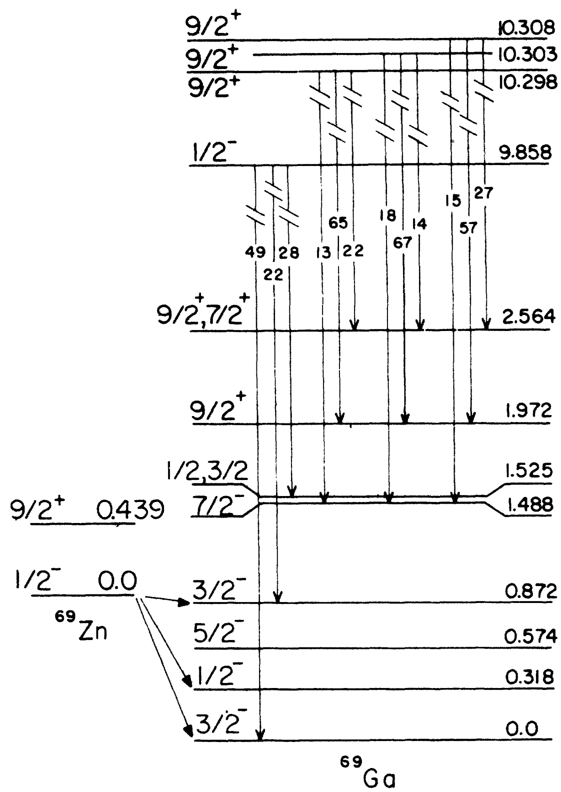

FIG. 2. γ-decay scheme of the $T_<$ states to which the IAR of the ground ($\frac{1}{2}^-$) and first excited ($\frac{9}{2}^+$) states in ^{69}Ga decay.

A possible explanation of the reduced $M1$ strength in the IAR decay and the hindrance in the β decay in spite of the single-particle character of these states is a cancellation effect between the different components of the transition matrix element arising from the phase differences in the wave functions of the initial and final states. If one assumes the transition to the third excited ($\frac{3}{2}^-$) state of ^{69}Ga to be pure $M1$ in character, the $B(M1)$ value deduced from the γ width of the IAR is found to be several times larger than the value deduced from the logft of the β decay of the $^{69}Zn_{g.s.}$ to this state. Two factors can contribute to this enhanced transition strength: the contribution of the l part of the $M1$ operator or appreciable $E2$ strength or both. Unfortunately since the spin of the initial state is $\frac{1}{2}^-$, no conclusions could be drawn in regard to the $E2$ admixture in the transition strength and hence the contribution of the l part in the $M1$ transition could not be assessed. The branching ratio for the transition to the 1.525 MeV state is 28% but its spin and parity are not established. In Table I we have calculated the transition strength for two possibilities viz. $B(M1)$ and $B(E2)$.

B. Analog of the first excited ($\frac{9}{2}^+$) state of ^{69}Zn

In the $^{68}Zn(d,p)^{69}Zn$ reaction, the first excited state with $J^\pi = \frac{9}{2}^+$ is observed[5] at 0.438 MeV with a spectroscopic factor of 0.9. In the proton bombardment of ^{68}Zn, three fragments corresponding to this state are observed. They decay preferentially to the $T_<$ states at 1.972 and 2.564 MeV in ^{69}Ga. An analysis of the γ-ray angular distribution taken on resonance shows these transitions to be $M1$ in character. The results obtained in a typical case are shown in Fig. 3.

The spin and parity of the state at 1.972 MeV is established to be $\frac{9}{2}^+$ while the J^π for the 2.564 MeV state could either be $\frac{7}{2}^+$ or $\frac{9}{2}^+$. Following the criteria established in Ref. 7, the transition to the 1.972 MeV state could be described as an IAR → AIAS (anti-isobaric analog state) transition. In the case of the state at 2.564 MeV in ^{69}Ga, if its spin were $\frac{7}{2}^+$, the transition to this state could be described as an IAR → SFS (spin-flip state); if the spin were to be $\frac{9}{2}^+$, the transition can be described

TABLE I. γ-decay properties of the IAR of the ($\frac{1}{2}^-$) ground state of ^{69}Zn at $E_p = 3.250$ MeV.

Transition	Assumed multipole order	Γ_γ (eV)	$B(M1)$ (μ_N^2)	$B(E2)$ ($e^2 fm^4$)	$B(M1,\sigma)$ [a] (μ_N^2)
IAR → g.s $\frac{1}{2}^- \to \frac{3}{2}^-$	$M1$	0.88 ±0.20	0.080	···	0.085
IAR → 0.318 $\frac{1}{2}^- \to \frac{1}{2}^-$	$M1$	<0.1	$<10^{-2}$	···	5×10^{-6} [b]
IAR → 0.872 $\frac{1}{2}^- \to \frac{3}{2}^-$	$M1$	0.48	0.08		0.01
	$E2$	±0.11		14.9	
IAR → 1.525 $\frac{1}{2}^- \to (\frac{1}{2}, \frac{3}{2})$	$M1$	0.52 ±0.14	0.08	···	···
	$E2$			16.0	

[a] Value deduced from β decay of ^{69}Zn.
[b] Value obtained assuming transition to be pure Gamow-Teller.

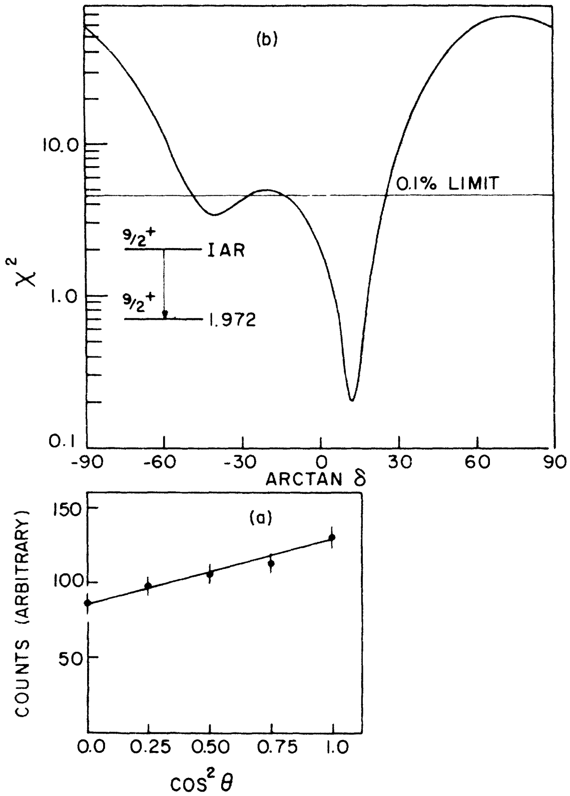

FIG. 3. (a) Plot of the experimental data and the best fit for the transition from the $\frac{9}{2}^+$ IAR at 10.303 MeV to the $\frac{9}{2}^+$ state at 1.972 MeV in ^{69}Ga. (b) Plots of χ^2 versus the mixing parameter arctanδ obtained by analyzing the γ angular distribution data shown in (a).

as an IAR→CPS (core-polarized state).

Using the definition[8] of the isovectorial $M1$ single-particle strength $\Gamma_{s.p.}$, the ratio $\Gamma_{exp}/\Gamma_{s.p.}$ summed over the three fragments are given in Table II. The ratio for the IAR→AIAS transition is about two times larger than that for the IAR→CPS (assuming that the 2.564 is a $\frac{9}{2}^+$) transition. This trend is similar to that observed[7] in neighboring nuclei such as ^{61}Cu. From the systematics[4] for the neighboring isotopes of nickel, the value of $\Gamma_{exp}/\Gamma_{s.p.}$ for the IAR→AIAS transition is found to be about 7×10^{-2} compared to the value is the present case of 3×10^{-3}. This decrease in the $M1$ strength is in part due to the character of the $T_<$, $J^\pi=\frac{9}{2}^+$ state at 1.972 MeV in ^{69}Ga which has a rather small spectroscopic factor of 0.4. We believe that this reduction in $M1$ strength is also a consequence of the configurational structure of the parent state itself. Recent experimental[9] and theoretical[10] work shows that the low-lying states of even and odd Zn isotopes are well described by the particle-vibration coupling model, in which for the

TABLE II. γ-decay properties of the IAR fragments of the first excited ($\frac{9}{2}^+$) state of ^{69}Zn.

Transition	Resonance at E_p = 3.690 MeV: Γ_γ (eV)	Multipole order	Γ_γ(exp)/Γ_γ(s.p.)	Resonance at E_p = 3.695 MeV: Γ_γ (eV)	Multipole order	Γ_γ(exp)/Γ_γ(s.p.)	Resonance at E_p = 3.700 MeV: Γ_γ (eV)	Multipole order	Γ_γ(exp)/Γ_γ(s.p.)	Total $M1$ strength Γ_γ(exp)/Γ_γ(s.p.)
IAR→1.488 $\frac{9}{2}^+\to\frac{7}{2}^-$	0.0024 ±0.0006	$E1$	...	0.004 ±0.001	$E1$	...	0.004 ±0.001	$E1$	...	
IAR→1.972 $\frac{9}{2}^+\to\frac{9}{2}^+$	0.0115 ±0.003	$M1$	8×10^{-4}	0.015 ±0.004	$M1$	1.0×10^{-3}	0.015 ±0.004	$M1$	1.0×10^{-3}	2.8×10^{-3}
IAR→2.564 $\frac{9}{2}^+\to\frac{9}{2}^+,\frac{7}{2}^+$	0.004 ±0.001	$M1$	3.4×10^{-4} [a]	0.003 ±0.0007	$M1$	3.0×10^{-4} [a]	0.007 ±0.001	$M1$	6.5×10^{-4} [a]	1.3×10^{-3} [a]

[a] Assuming $J^\pi=\frac{9}{2}^+$ for 2.564 MeV level.

odd nuclei, a particle in a state j is coupled to the core in state J_C to form a state of spin J described by $|jJ_CJ\rangle$. This would also be a valid description of the low-lying states of ^{69}Ga which could be obtained by coupling a proton to the ^{68}Zn core. Two states with $J^\pi = \frac{7}{2}^-$ are found[5] in ^{69}Ga at 1.336 and 1.488 MeV. Of these the state at 1.488 MeV is not observed in the $^{68}Zn(^3He, d)^{69}Ga$ reaction while the state at 1.336 MeV has a measurable spectroscopic factor with an orbital angular momentum of $l = 3$ for the transferred particle. It seems reasonable to conclude that the 1.488 MeV state is well described by the particle-vibration coupling model; it would largely be a $|(\frac{3}{2}^- \otimes 2^+)\frac{7}{2}^-\rangle$ obtained by coupling a $p_{3/2}$ particle (which is the lowest unfilled proton orbit in ^{69}Ga) to the vibrational 2^+ first excited state of ^{68}Zn. In the present work it is noted that the $\frac{9}{2}^+$ IAR decays with an appreciable $E1$ transition strength to the $\frac{7}{2}^-$ state (Table II). Such a transition is possible only if there were a significant admixture of the $|(\frac{5}{2}^+ \otimes 2^+)\frac{9}{2}^+\rangle$ configuration in the wave function of the parent state. Evidence for such an admixture in the parent-state wave function comes from the fact that a fragment of the $d_{5/2}$ single-particle state at 0.872 MeV (Fig. 2) is observed in the (d, p) reaction with $l = 2$ and $S = 0.2$. To make a more quantitative comparison, full scale model calculations are desirable; before attempting such calculations additional experimental work on similar transitions in the neighboring zinc isotopes would be extremely useful. Such work is presently under way in our laboratory and it is hoped that this will enable us to understand better the structure of these nuclei in the f-p shell.

SUMMARY

The γ decay of the IAR corresponding to the ground ($\frac{1}{2}^-$) and first excited ($\frac{9}{2}^+$) states of ^{69}Zn have been studied by the $^{68}Zn(p, \gamma)^{69}Ga$ reaction. No clear-cut evidence for a Gamow-Teller giant resonance in ^{69}Ga has been found. The correspondence between the γ decay of the IAR of the ^{69}Zn ground state (g.s.) and the β decay of the ^{69}Zn g.s. to the ground and first excited states of ^{69}Ga is excellent. For the decay to the third excited state, the γ-decay strength (assuming the transition to be pure $M1$) is too large in comparison with the β-decay strength to this state (Table I). In this case $E2$ admixtures in the γ transition could be the contributing factor.

The γ decay of the IAR corresponding to the first excited ($\frac{9}{2}^+$) state of ^{69}Zn is dominated by the IAR $\rightarrow$ AIAS transition to a $\frac{9}{2}^+$ state at 1.972 MeV in ^{69}Ga. The $M1$ strength of this transition is relatively weak when compared with its value[4] observed in neighboring nuclei; this can be understood in terms of the configuration mixing in the parent state and the fragmentation of the AIAS. The transition to the 2.564 MeV state can be classified as an IAR $\rightarrow$ SFS or IAR $\rightarrow$ CPS depending on whether the spin of this state is $\frac{7}{2}^+$ or $\frac{9}{2}^+$. If it were to be the latter, the ratio of this transition strength to that of the IAR$\rightarrow$AIAS decay is in good agreement with the trend[7] observed in neighboring nuclei.

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