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Role of the $g_{9/2}$ neutron orbital in the structure of ^{65}Zn

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Measurements of γ-ray singles and $\gamma\gamma$-coincidence spectra, γ-ray angular distributions, and Doppler shift attenuation have been made, following the reaction ^{63}Cu(^{4}He,pn)^{65}Zn at 30 MeV. The level scheme has been confirmed up to 5773 keV. The spins and parities of the three states at 3227.6, 3785.7, and 4938.0 keV, hitherto uncertain or unknown, are found to be $17/2^+$, $17/2^+$, and $21/2^+$, respectively. The mean lives for these states, for which there is no information available in the literature, have been estimated, and the deduced $B(E2)$ values for the 4938.0$\rightarrow$ 3227.6 ($21/2^+ \rightarrow 17/2^+$), 3227.6 $\rightarrow$ 2053.5 ($17/2^+ \rightarrow 13/2^+$), and 3785.7 $\rightarrow$ 2053.5 ($17/2^+ \rightarrow 13/2^+$) keV transitions are all found to be strongly enhanced with respect to the Weisskopf single-particle estimates indicating collectivity in the structure of the concerned states. Evidence is presented in favor of the interpretation of the positive parity states in ^{65}Zn with J^π value $9/2^+$ to $21/2^+$, as arising from the weak coupling of a $g_{9/2}$ neutron to the quadrupole excitations of the ^{64}Zn core.

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I. INTRODUCTION

The level schemes of the odd-A zinc isotopes, viz., ^{65}Zn and ^{67}Zn, have been studied experimentally and in the framework of different theoretical models. These studies have indicated that the $1g_{9/2}$ neutron orbital, which lies in the vicinity of the Fermi level of these nuclei, plays a significant role in the formation of some of the excited states of these two nuclei. Thus Neal *et al.* [1] have shown that the positive-parity states of ^{67}Zn may be described as forming a decoupled band, arising from the coupling of a $1g_{9/2}$ neutron to the ground-state vibrational band of ^{66}Zn. This weak coupling scheme gives rise to states with $J = j + R$ and $J = j + R - 1$, where $j = 9/2$ for the odd neutron and R is the spin of the ^{66}Zn core state, at energies nearly equal to the sums of the core and the particle energies. The fully aligned states have been reported to be more strongly excited. In ^{64}Zn also, as in the neighboring even ^{66}Zn, the positive-parity ground-state sequence with $J^\pi = 0^+ \cdots 6^+$ is considered to result from the quadrupole excitations of an anharmonic vibrator [2]. As suggested originally by Nilsson and Sawa [3] and from the available experimental data, it appears resonable to expect that the positive-parity high spin states of ^{65}Zn result from the coupling of a $1g_{9/2}$ neutron orbital to the states of the $A - 1$ even core, as in ^{67}Zn. The marked similarity of these states in ^{65}Zn and ^{67}Zn lends further credence to this possibility.

However, the experimental information in the literature on the high spin positive-parity states of ^{65}Zn is incomplete. The spins and parities of several states in this nucleus, expected to belong to the above-mentioned band, are inconclusive and the γ-ray transition probabilities, which generally provide a better test for the models than excitation energies, are not reported. The aim of the present work is to provide additional information on the excited states of ^{65}Zn for a better investigation of its suggested band structure.

II. EXPERIMENTAL PROCEDURE

Excited states of ^{65}Zn were produced in the reaction ^{63}Cu(^{4}He,pn)^{65}Zn at $E = 30$ MeV at the Variable Energy Cyclotron Centre, Calcutta. Measurements were made on the γ-ray intensities, angular distributions and Doppler shifts and $\gamma\gamma$-coincidence relationships. Aside from the Doppler shift attenuation (DSA) measurements, all of the experiments were carried out using 10 mg/cm^2 thick, enriched (> 98%) ^{63}Cu, deposited target. The DSA studies were made with a self-supporting $\sim$ 8 mg/cm^2 natural Cu foil for ensuring a uniform stopping cross section for the recoiling nuclei. The use of natural Cu gives rise to the problem of exciting unwanted reaction channels. Incidentally, these did not interfere in the DSA analyses.

Three large volume, high efficiency (17–20%) HPGe detectors, one with a BGO anti-Compton Shield (ACS), with in-beam resolutions in the range 2.5–2.8 keV at $\sim$ 1 MeV were used. Two of the detectors at 55° and 90° to the beam axis served to determine the γ-ray relative intensities and their energies, respectively, while the third detector with the ACS, positioned at a distance of 20 cm from the target, was used to measure the γ-ray angular distributions and the Doppler shifts at five angles between 90° and 145° to the beam direction. The $\gamma\gamma$-coincidence relationships were deduced from a five-parameter (three energy and two time parameters) coincidence data, recorded in the List mode, with the three detectors at 5–8 cm from the target. Norsk data (ND 560 and ND 100) computers and a Canberra series 88 Multichannel Analyser, both coupled to tape-drive units, were used for data acquisition. Conventional, fast NIM electronics was employed.

Gated spectra were generated by setting appropriate digital gates on the energy and time spectra (time window: 40 ns) and subtracting the contributions due to random events and the Compton continuum of other γ

rays. The mean lifetimes τ of the excited states were measured following the method outlined in Refs. [4,5]. Although the side-feeding (direct feeding by high energy γ rays from the continuum) times could not be measured in the present work, corrections to the level lifetimes have been estimated assuming that the side-feeding times for the low-energy states near the ground state are $\simeq 0.1$ ps and decrease uniformly for the higher-lying states. This assumption has been previously found to be reasonable for excited states in nuclei with $A \sim 60$ [6,7].

The angular distribution coefficients A_2/A_0 and A_4/A_0 were determined from least-squares fit of the observed intensities, normalized to the yield at 55° to the beam axis, to the Legendre polynomial

$$W(\theta) = A_0 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta). \qquad (1)$$

These fits as also the $\chi^2(\sigma, \delta)$ analyses, yielding the γ-ray multipole mixing ratio δ and the most probable spin sequence $J_i \rightarrow J_f$ for a given transition, were carried out using the computer code THDST [8]. The fitted value of σ, the width of the assumed Gaussian distribution for the substate population of the excited states, shows a high degree of alignment.

III. EXPERIMENTAL RESULTS

The all-gated γ-ray spectrum in the reaction ^{63}Cu+^{4}He at $E = 30$ MeV is shown in Fig. 1(a). Prominent γ-ray lines belonging to ^{65}Zn are marked in the figure. Figure 1(b) shows a typical gated γ-ray spectrum taken in coincidence with the 201.4 keV transition deexciting the 1065.6 keV state. The level scheme for ^{65}Zn, based on the $\gamma\gamma$-coincidence relationships and the angular distribution studies carried out in the present work, as also on the previously reported results, is shown in Fig. 2. The γ-ray energies, and intensities relative to 100 for the 864.2 keV γ ray, are shown in the figure. The uncertainties in the intensities are typically less than 5% for strong γ rays (with intensities more than 10) and 5 –12 % for most of the weaker lines. It is observed (Fig. 2) that the positive-parity states at 1065.6, 2053.5, and 3227.6 keV are more strongly populated in the reaction ^{63}Cu(^{4}He,$pn\gamma$) as compared to the reaction ^{62}Ni(^{4}He,n) reported earlier [3].

The γ-ray branching ratios agree within experimental errors with previously published results summarized in Ref. [9], except for the branchings from the 864.2, 1065.6, and 2922.9 keV levels. Table I presents a comparison of the γ-ray branching percentages obtained in this work for a few levels with those reported in the literature [3,9–14]. For example, the 749.1 keV transition from the 864.2 keV state is found to account for 10.6±2.1% branching. This result is less than the values reported earlier in Refs. [11,12] but nevertheless shows agreement within experimental errors with the result of Neal *et al.* [13]. In the present work the relative intensity for the 749.1 keV decay is deduced from a comparison of the relative intensity of this γ ray with that of the 864.2 keV transition, observed in the 201.4 keV energy gate [Fig. 1(b)], appropriately corrected for the effects of angular distribution anisotropy.

Considerable discrepancies exist in the literature [12–14] for the branching ratio of the 201.4 and 1065.6 keV γ rays from the 1065.6 keV state. The branch-

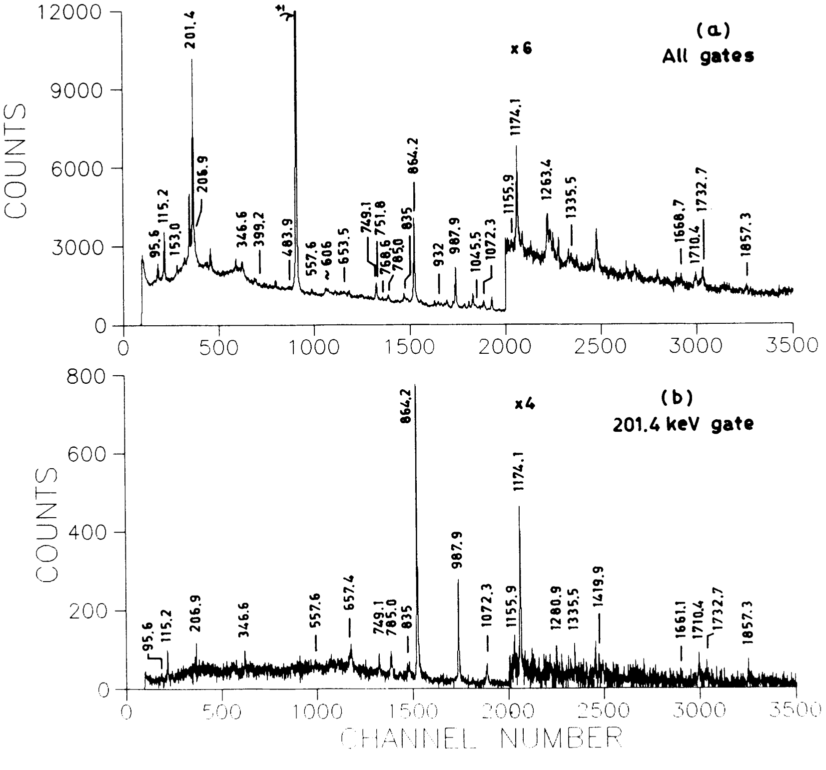

FIG. 1. Partial γ-ray spectra obtained in the reaction ^{63}Cu+^{4}He at $E = 30$ MeV. The all-gated spectrum is shown in (a). Prominent γ-ray lines belonging to ^{65}Zn are marked. The spectrum obtained in coincidence with the 201.4 keV energy gate is shown in (b). All energies are marked in keV.

TABLE I. A comparison of the percent gamma-ray branchings obtained in the present work for a few levels in ^{65}Zn with the previous results.

E_x	E_γ	% Branchings						
(keV)	(keV)	Present	Ref. [3]	Ref. [11]	Ref. [12]	Ref. [13]	Ref. [14]	NDS[9,10]
864.2	657.4	0.6±0.2			0.6±0.1			0.6
	749.1	10.6±2.1	13	23±1	15.3±1.2	14±2		15.3
	864.2	88.8±5.1	87	77±1	84.1±4.2	86±2		84.1
1065.6	201.4	95.6±4.6	100		91.0±6.0	84±4	95±1	91.0
	1065.6	4.4±0.9			9.0±0.8	16±4	5±1	9.0
2922.9	785.0	63.9±7.6	100			32±4		32
	1857.3	36.1±8.3				68±4		68
3785.7	557.6	25.4±5.3				34±8		
	1732.7	74.6±19.9				66±8		
4078.8	~ 606	56				57±14		
	1155.9	44				43±14		

ings percentages for the two transitions obtained in the present work are consistent with the result reported by Lornie *et al.* [14], but clearly disagree with those of Charvet *et al.* [12] and Neal *et al.* [13].

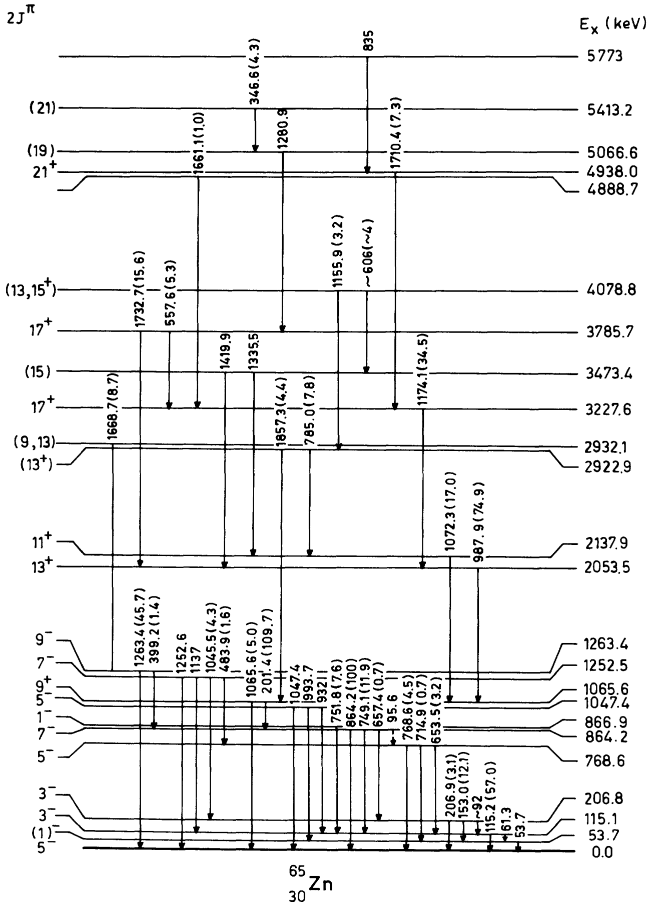

FIG. 2. Level scheme of ^{65}Zn obtained on the basis of the present as well as previous results. Level and transition energies are given in keV. The γ-ray intensities are shown within parentheses. Errors in the intensity values are stated in the text.

The 2922.9 keV state is found to decay predominantly (63.9±7.6% branching) by the 785.0 keV transition. This is in contradiction with the reported [13] γ-ray branchings for this state (see Table I). The γ-ray branchings from the 3785.7 and 4078.8 keV levels are in agreement with the only available results of Ref. [13] within experimental errors.

The level scheme up to 3.23 MeV in excitation was first reported by Nilsson and Sawa [3] while Neal *et al.* [13] have reported levels extending up to 5.42 MeV. The $\gamma\gamma$-coincidence relationships observed in this work corroborate the placements of all previously known transitions in the level scheme (Fig. 2). A level at 5773 keV has been tentatively proposed in the Nuclear Data Sheets [9,10], decaying to the 4938.0 keV state. The observation of an 835 keV γ ray in coincidence with the 1710.4 keV transition and with all other γ rays in the same cascade supports this. In addition, there is evidence, based on the 201.4 and 768.6 keV energy gates [Fig. 1(b)], to suggest that a 95.6 keV transition possibly connects the 864.2 and the 768.6 keV levels.

Angular distributions of several γ rays have been measured. The results of the analyses of these data for a few levels with $E_x \geq 864.2$ keV are summarized in Table II. The σ/J values obtained from the $\chi^2(\sigma,\delta)$ analyses, given in Table II, are consistent with reduced alignments for the low-lying states compared to the high energy ones. A spin and the multipole mixing ratio result is rejected if the corresponding minimum χ^2 exceeds the 0.1% confidence limit.

The present work corroborates the earlier spin and parity (J^π) assignments for levels up to 2053.5 keV. The previous J^π assignments for the higher-lying levels are, however, ambiguous or uncertain. The 3227.6 keV state, which was previously proposed to have $J \geq 13/2$, is found to decay by a pure quadrupole 1174.1 keV transition, restricting the spin and the parity of the level to $17/2^+$. Contributions in the yields of the 1174.1 keV γ ray due to interferences from neighboring γ-ray lines belonging to ^{60,62}Ni, reported to be considerably large in the reaction employed in the earlier work [3,13], were found to be small (less than 5%) in this work and have been appropriately accounted for in the analyses. For the 3785.7

TABLE II. Angular distribution coefficients and parameters of the analyses of the angular distribution results for ^{65}Zn in the present work. J_i and J_f in the fifth column are the presumptive spins of the initial and final states, respectively; σ is the width of the distribution of the substate populations of the initial state of excitation energy E_x, δ the multipole mixing ratio, and J_i^π in the last column is the spin and parity of the initial level proposed in this work. The assignments are discussed in the text.

E_x (keV)	E_γ (keV)	A_2/A_0	A_4/A_0	$J_i \rightarrow J_f^\pi$	σ/J	δ	χ^2	J_i^π
864.2	864.2	-0.53 ± 0.06	0.22 ± 0.07	$\frac{7}{2} \rightarrow \frac{5^-}{2}$	0.37	-2.33 ± 0.20	2.3	$\frac{7^-}{2}$
1065.6	201.4	-0.21 ± 0.02	0.02 ± 0.04	$\frac{9}{2} \rightarrow \frac{7^-}{2}$	0.38	0.02 ± 0.01	2.6	$\frac{9^+}{2}$
2053.5	987.9	0.29 ± 0.12	-0.22 ± 0.13	$\frac{13}{2} \rightarrow \frac{9^+}{2}$	0.26	-0.02 ± 0.10	0.7	$\frac{13^+}{2}$
3227.6	1174.1	0.26 ± 0.06	-0.14 ± 0.08	$\frac{13}{2} \rightarrow \frac{13^+}{2}$	0.35	0.81 ± 0.31	2.1	$\frac{17^+}{2}$
				$\frac{15}{2} \rightarrow \frac{13^+}{2}$	0.31	~ 0.4	7.9	
				$\frac{17}{2} \rightarrow \frac{13^+}{2}$	0.28	-0.07 ± 0.08	0.9	
3785.7	1732.7	0.39 ± 0.14		$\frac{13}{2} \rightarrow \frac{13^+}{2}$	0.31	0.91 ± 1.0	1.4	$\frac{17^+}{2}$
				$\frac{15}{2} \rightarrow \frac{13^+}{2}$	0.28	0.42 ± 0.17	2.2	
				$\frac{17}{2} \rightarrow \frac{13^+}{2}$	0.25	-0.13 ± 0.25	1.2	
4078.8	1155.9	0.04 ± 0.19	-0.11 ± 0.21	$\frac{13}{2} \rightarrow \frac{13^+}{2}$	0.29	-0.61 ± 0.50	0.2	$\left(\frac{13^+}{2}, \frac{15^+}{2}\right)$
				$\frac{15}{2} \rightarrow \frac{13^+}{2}$	0.27	0.22 ± 0.17	0.6	
				$\frac{17}{2} \rightarrow \frac{13^+}{2}$	0.24	-0.31 ± 0.20	3.4	
4938.0	1710.4	0.34 ± 0.11	-0.07 ± 0.12	$\frac{17}{2} \rightarrow \frac{17^+}{2}$	0.25	~ -0.13	0.6	$\frac{21^+}{2}$
				$\frac{19}{2} \rightarrow \frac{17^+}{2}$	0.23	0.42 ± 0.12	1.5	
				$\frac{21}{2} \rightarrow \frac{17^+}{2}$	0.23	-0.03 ± 0.15	0.6	

keV state, decaying by the 1732.7 keV γ ray, the present $\chi^2(\sigma, \delta)$ analyses favor the J^π assignment of $17/2^+$, although $13/2^+$ is not ruled out. However, the latter possibility is excluded by the excitation function data of Neal *et al.* [13]. The angular distribution analysis of the 1155.9 keV γ ray from the 4078.8 keV state is based on the assumption that the final state at 2922.9 keV has a J^π of $13/2^+$. The present work did not permit unambiguous J^π assignment for the latter level. However, Nilsson and Sawa [3] have reported 13/2 as the most probable spin for this state. The assumption of positive parity appears reasonable from the inspection of the multipole mixing ratio δ for the 1155.9 keV γ ray, reported in Ref. [3]. The present work shows that both $J^\pi = 13/2^+$ and $15/2^+$ are almost equally probable for the 4078.8 keV state and the 1155.9 keV γ ray has a significant quadrupole component. The 1710.4 keV γ ray from the 4938.0 keV state is found to have a large positive A_2/A_0 but the $\chi^2(\sigma, \delta)$ analyses favor both $J^\pi = 17/2^+$ and $21/2^+$. However, the $B(E2)$ value calculated for the 1710.4 keV γ ray, assuming it to be a $17/2^+ \rightarrow 17/2^+$ transition, is found to be ≤ 0.3 W.u. This is unrealistic compared to the $B(E2)$ values for other transitions in the same cascade (discussed subsequently). Hence, the 4938.0 keV level is proposed to have a spin and parity of $21/2^+$, which leads to realistic $B(E2)$ result.

No information about the lifetimes of states above 2.14 MeV is available in the literature. The DSA analyses in the present work lead to lifetime information for the levels at 3227.6, 3785.7, and 4938.0 keV states. These are summarized in Table III. In the absence of a reliable knowledge of the properties of the proposed level at 5773 keV, which decays to the 4938.0 keV state, the mean lifetime of the 4938.0 keV state is estimated to be in the range 0.18–0.30 ps. The possible uncertainties in the feeding from the 5773 keV state are included in the esti-

TABLE III. Results of lifetimes and $E2$ transition strengths for ^{65}Zn. The mean $F(\tau)$ is the mean of the experimental attenuation factors measured at different angles with respect to the beam direction.

E_x (keV)	E_γ (keV) $J_i^\pi \rightarrow J_f^\pi$	Mean $F(\tau)$	Mean life τ (ps)	$B(E2)$ (W.u.)
3227.6	1174.1 $\frac{17^+}{2} \rightarrow \frac{13^+}{2}$	0.13	$0.44^{+0.18}_{-0.14}$	54^{+25}_{-17}
3785.7	1732.7 $\frac{17^+}{2} \rightarrow \frac{13^+}{2}$	≥ 0.28	≤ 0.4	≥ 7
4938.0	1710.4 $\frac{21^+}{2} \rightarrow \frac{17^+}{2}$	0.35	$0.18 \leq \tau \leq 0.30$	$12 \leq B(E2) \leq 20$

mate. Similarly, an upper limit of mean lifetime 0.4 ps is assigned to the 3785.7 keV state since the lifetime of the 5066.6 keV state which feeds the level of interest could not be determined. The mean lifetime for the 3227.6 keV state was found to be $0.44^{+0.18}_{-0.14}$ ps. Corrections due to all feedings, both direct and cascade, are included in the calculation. The uncertainties in the direct feeding time (assumed to be within 0–0.1 ps) and those due to stopping time of the recoils in the target are included in the errors assigned to the result.

The $E2$ transition strengths deduced from the present lifetime results for the 1174.1, 1732.7, and 1710.4 keV transitions from the 3227.6, 3785.7, and 4938.0 keV states, respectively, are all found to be strongly enhanced with respect to the Weisskkopf single particle estimate (Table III) and are consistent with the proposed spin and parity assignments.

IV. DISCUSSION

The low-lying, negative-parity levels below 1 MeV excitation in ^{65}Zn have already been studied extensively [9,10] and are fairly well explained by simple shell-model calculations with the two protons and seven neutrons distributed in the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbitals. These and other negative-parity states are discussed at length in Ref. [3].

The structure of the positive-parity states in ^{65}Zn is, however, not well understood because their spin and parity assignments and γ-ray transition rates are either tentative or unkown. Only the J^π assignments for the 1065.5 and 2053.5 keV states, viz., $9/2^+$ and $13/2^+$, respectively, have been previously reported [3]. Also the $13/2^+_1 \rightarrow 9/2^+_1$ transition has been reported to be pure quadrupole in nature with $B(E2) \leq 28$ W.u. [3]. In the present work J^π assignments of $17/2^+$ and $21/2^+$ have been made for the two higher-lying levels at 3227.6 and 4938.0 keV, respectively. It is found that these four states at 1065.6, 2053.5, 3227.6, and 4938.0 keV form an yrast sequence connected with the $9/2^+$ state by a prominent cascade of transitions $21/2^+_1 \rightarrow 17/2^+_1 \rightarrow 13/2^+_1 \rightarrow 9/2^+_1$. The results of lifetime measurements in this work show the $21/2^+_1 \rightarrow 17/2^+_1$ and $17/2^+_1 \rightarrow 13/2^+_1$ $E2$ transition rates to be highly enhanced with respect to the Wiesskopf single particle estimates. On the basis of these experimental results, the four above-mentioned positive parity states may be interpreted as forming a sequence of states with prominent collective features. Furthermore, a comparison of the partial level scheme of ^{65}Zn with the ground-state sequence of ^{64}Zn, presented in Fig. 3, shows that these four positive-parity states of ^{65}Zn have a close energy correspondence and a similar decay pattern with respect to the g.s. (0^+), 991 (2^+_1), 2306 (4^+_1), and 3992 (6^+_1) keV states of ^{64}Zn. This conclusion provides convincing evidence in favor of the suggestion made earlier by Nilsson and Sawa [3] for a coupling scheme wherein the odd neutron in the $g_{9/2}$ orbital couples with the core states of ^{64}Zn to give rise to some of the positive-parity states of ^{65}Zn. Accordingly, the four strongly populated yrast states of ^{65}Zn at 1065.6 ($9/2^+$), 2053.5 ($13/2^+$), 3227.6 ($17/2^+$), and 4938.0 ($21/2^+$) keV may be identified as the fully aligned states arising from this weak coupling scheme, corresponding to the g.s. (0^+), 991 (2^+_1), 2306 (4^+_1), and 3992 (6^+_1) keV states of ^{64}Zn (Fig. 3). The positive-parity states of ^{64}Zn, as already stated in Sec. I, have been interpeted [2] as arising from quadrupole excitations of an anharmonic vibrator.

The comparison of the partial level schemes of ^{65}Zn and ^{64}Zn (Fig. 3) further shows that several other states in ^{65}Zn are also possible members of this weakly coupled band. The 2137.9 keV, $11/2^+$ state decaying by the 1072.3 keV ($M1 + E2$) γ ray and lying slightly above the 2053.5 keV, $13/2^+$ state may be considered to be the next lower-spin member of the multiplet arising from the coupling of the odd neutron to the first 2^+ state of ^{64}Zn. The 2922.9 keV level, which bears a good energy correspondence with the second 2^+ core state, is observed in this work to decay to the 2137.9 and 1065.6 keV states with an estimated branching ratio of 64:36. As stated in Sec. III, this result contradicts the branching ratio reported by Neal *et al.* [13] but shows a behavior similar to that in the decay of the corresponding core state, where the $2^+_2 \rightarrow 2^+_1$ transition has a 77% branching. This result coupled with the angular distribution data of Nilsson and Sawa [3], which favors a J^π assignment of ($13/2^+$), marks the 2922.9 keV state to be a likely candidate for belonging to the band and identified with the second 2^+ core state. Similarly, the 3785.7 keV state which in the present work is assigned a J^π of $17/2^+$ may be identified with the 3077 keV, 4^+_3 (rather than the 2736 keV 4^+_2) vibrational state of the ($A - 1$) core on the basis of their respective decay patterns. The 3077 keV core state decays predominantly to the 2^+_1 and the 4^+_1 states whereas the 2736 keV level has no decay branch to the 2^+_1 level. The 3785.7 keV state in ^{65}Zn decays to the $13/2^+_1$ and $17/2^+_1$ states favoring its identification with the 3077 keV core state. Also, the 1732.7 keV, $17/2^+_2 \rightarrow 13/2^+_1$,

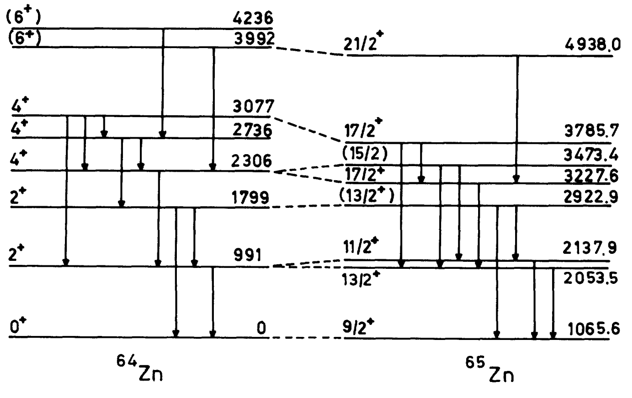

FIG. 3. A comparison of the sequence of positive parity states of ^{65}Zn with the ground state band of ^{64}Zn. The partial level scheme for ^{64}Zn is taken from Ref. [13].

$E2$ transition from the 3785.7 keV state is found to be enhanced with $B(E2) \geq 7$ W.u., indicating collectivity in its structure.

The 3473.4 keV state has been previously assigned $(15/2^+)$ [3]. Lying somewhat above the $17/2_1^+$ state and decaying to the $13/2_1^+$ and $11/2_1^+$ states, the 3473.4 keV state may also possibly be interpreted as the lower-spin member of the multiplet arising from the coupling with the 4_1^+ core state. Interpretation for the 4078.8 keV state (Fig. 2) is ambiguous as the J^π value for this state is uncertain. Both $J^\pi = 13/2^+$ and $15/2^+$ are found to be almost equally probable from the present work. The present experimental results for the 4888.7 keV state and the three states above 5 MeV are inadequate to permit a clear understanding.

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