High spin states in ^{63}Zn

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High spin states of ^{63}Zn isotope have been populated by ^{50}Cr(^{16}O, $2pn$) reaction at a beam energy of 75 MeV. A total of 37 γ rays and 18 energy levels have been placed in the proposed level scheme, extending it up to an excitation energy of 9776 keV. Positive and negative parity states up to $I=\frac{23}{2}$ and $\frac{31}{2}$, respectively, are found to be populated. A positive parity unfavored band and a negative parity band have been identified. The structure of this nucleus has been investigated in the framework of interacting boson-fermion model, incorporating both the quadrupole and the octupole excitations of the even-even ^{62}Zn core. The structure of the positive parity yrast band is described in terms of a weak coupling of the $g_{9/2}$ neutron motion to the multiphonon excitations of the even-even core. Some of the high spin negative parity states observed in the experimental spectrum cannot be described within the framework of the present model. One of the possible reasons may be that these states have large contributions from noncollective two-quasiparticle-type excitations. Experimental branching ratios of some of the transitions are compared with the results of our calculation. [S0556-2813(98)01604-5]

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I. INTRODUCTION

The nuclei in the $A=60-70$ region exhibit varieties of excitations, both single particle and collective with different shapes, namely, prolate, oblate, and triaxial. The single particle excitation mechanism involves valence nucleons outside the $N=Z=28$ core, while the collective excitation can be understood to arise as a consequence of the gaps observed in the Nilsson energy diagram at $N=Z=36$ for oblate deformation and at $N=Z=38$ for prolate deformation. In this mass region, the intruder high-j unique parity $g_{9/2}$ orbital plays an important role in producing the high spin states. On the other hand, its coupling to the close-lying $p_{3/2}$ orbital produces enhanced octupole correlations. Above $I^{\pi}=8^{+}$, a complex interplay between the single-particle and the collective excitations originating from the alignment of neutrons in the $g_{9/2}$ orbital has been observed in even-even ^{66,68}Ge nuclei [1,2].

The ^{63}Zn isotope, with two protons and five neutrons outside the $Z=N=28$ closed shell, lies in the transitional region defined by the spherical doubly closed-shell nucleus ^{56}Ni and the strongly deformed Kr and Sr isotopes. The shape of the nuclei in this transitional region is not properly defined at low-excitation energy and a superposition of different excitation modes constitutes the low energy structures of these nuclei. However, at moderate deformation, the nucleons may occupy the $g_{9/2}$ orbital and one can expect collective behavior at high spins. In this connection, the study of the high spin states of ^{64}Zn by Crowell *et al.* [3], aimed at verifying the prediction of γ stability at a spin of $8\hbar$ by Cranked-Nilsson-Strutinsky calculation, is worth mentioning. The experimental results, however, show exactly the opposite pattern; the rotational bands being less pronounced at high spins than at low spins. The structure of ^{65}Ge, which contains the same number of neutrons as that of ^{63}Zn, has recently been studied by Hermkens *et al.* [4]. No evidence of enhanced octupole correlation, as predicted from Strutinsky-type potential energy calculation by Nazarewicz *et al.* [5,6] is found in this isotope. The structure of the positive parity yrast band in ^{65}Ge appears to be consistent with a weak coupling of the odd $g_{9/2}$ neutron to the excitations of the even-even ^{64}Ge core.

Earlier studies on ^{63}Zn through (p,n) [7], (α,n) [8–10] and (^{12}C,$2pn$) [7] reactions and γ-ray spectroscopy, provide a level scheme extending up to $E_x=5344$ (2051) keV and $I=\frac{21}{2}$ ($\frac{9}{2}$) for the positive (negative) parity levels. It may be mentioned that the only experiment which used a heavy-ion projectile [7], was performed using two Ge(Li) detectors only. The aim of the present work is to study the interplay of the single-particle and the collective modes at high excitation energy and large angular momentum regime in a transitional nucleus like ^{63}Zn excited through heavy-ion fusion evapora-

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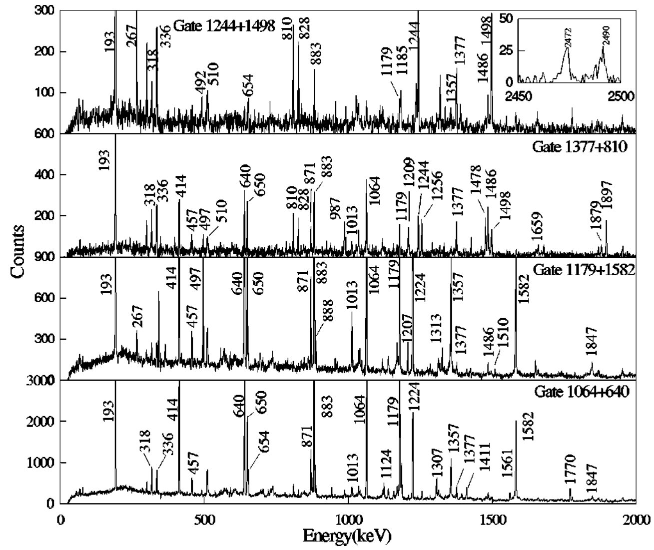

FIG. 1. Typical γ-γ coincidence spectra used to determine the level scheme of ^{63}Zn. The inset shows the high-energy part of the spectrum obtained in the sum gate of 1244+1498 keV γ rays.

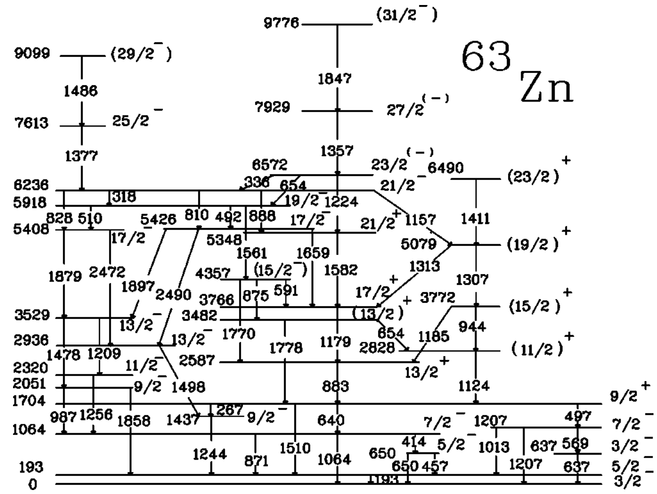

FIG. 2. Proposed level scheme of ^{63}Zn. The excitation energy in keV and the spin are given on the left and right side of the corresponding levels, respectively.

tion reaction. The interacting boson-fermion model (IBFM) has been applied to understand the underlying excitation mechanisms of the states observed in the experiment.

II. EXPERIMENTAL METHOD

The high spin states in ^{63}Zn have been populated through the ^{50}Cr(^{16}O, $2pn$) reaction at a beam energy of 75 MeV obtained from the 15 UD Pelletron Accelerator of Nuclear Science Center, New Delhi. An enriched ^{50}Cr (isotopic abundance 92%) target of thickness $\sim$ 20 mg/cm^2 backed by $\sim$53 mg/cm^2 of gold foil has been used. The other dominant channels observed at this projectile energy are $\alpha 2p$ and $3pn$ leading to the excited states of ^{60}Ni and ^{62}Cu, respectively. A majority of the prominent γ rays coming from different channels has been found to be nonoverlapping.

The γ-γ coincidence data have been collected with a multidetector array consisting of 12 Compton suppressed HPGe detectors along with 14 BGO detectors used as a multiplicity filter to reduce the radioactive background. The detectors are arranged in three groups, each consisting of four detectors fixed at 45°, 99°, and 153° with respect to the beam direction. The details of the experimental setup and data acquisition system can be found in Ref. [11]. Eighty three million events corresponding to two or higher-fold coincidences in the HPGe detectors have been recorded in List mode. Each coincidence event obtained with the Ge detectors is qualified with the condition that simultaneously at least two BGO detectors of the multiplicity filter should fire. The pulse height of each detector has been gain matched to the 0.71 keV/channel and the γ-γ coincidence data sorted out into a 4096 $\times$4096, E_γ-E_γ matrix. The energy spectra gated by γ rays of interest are generated from this matrix.

The multipolarities of the observed γ rays are determined through the directional correlation orientation (DCO) ratio measurements. For this purpose a separate 4096 $\times$ 4096 matrix has been generated with the events recorded at 99° along one axis and those recorded at 153° along the other axis. The DCO ratio has been determined as

$$R_{\mathrm{DCO}}(\gamma_1)=\frac{I(\gamma_1 \text{ at } 99^\circ \text{ with } \gamma_2 \text{ at } 153^\circ)}{I(\gamma_1 \text{ at } 153^\circ \text{ with } \gamma_2 \text{ at } 99^\circ)}$$

where a stretched $\Delta I=2$ transition is chosen as γ_2.

III. RESULTS

The level scheme of ^{63}Zn has been constructed from the γ-γ coincidence data, the γ ray intensities, and the multipolarities of the γ rays as deduced from the DCO ratio measurements. The relative intensities and the DCO ratios of the γ rays placed in the proposed level scheme of ^{63}Zn isotope are given in Table I. The DCO ratios of some of the γ rays could not be measured mainly because of their low intensities. The 1244 keV γ ray has been observed mainly in the coincidence spectrum with the 193 keV γ ray as the gate. As the 193 keV transition is of mixed nature, the DCO ratio of the 1244 keV transition cannot be evaluated. In this experiment we have extended the level scheme of ^{63}Zn up to a spin-parity of $(\frac{31}{2}^-)$ and an excitation energy of 9776 keV. Figure 1 shows the coincidence spectra with gates on a few selected γ rays. Figure 2 shows the level scheme of ^{63}Zn deduced in the present work. A total of 37 γ transitions and 18 levels have been placed in this level scheme. It may be mentioned that the 654 keV γ ray occurs twice in the level scheme since it is observed in coincidence with itself. The spins and parities of the ground state and those of a few low-lying levels were known from the earlier heavy-ion study [7]. The DCO ratios of the transitions from these levels obtained in this experiment are in conformity with these assignments.

TABLE I. Energy, intensity, and DCO ratio of the γ rays assigned to ^{63}Zn. The intensity of the γ rays has been evaluated from total projected spectrum unless otherwise mentioned.

E_γ (keV)	Relative intensity	DCO ratio	Assignment $E_\gamma \to E_f$ (keV)	$I_i^\pi \to I_f^\pi$	E_γ (keV)	Relative intensity	DCO ratio	Assignment $E_i \to E_f$ (keV)	$I_i^\pi \to I_f^\pi$
193	1000	1.4±0.1	193 → 0	$\frac{5}{2}^- \to \frac{3}{2}^-$	1179	1604±80	1.1±0.1	3766 → 2587	$\frac{17}{2}^+ \to \frac{13}{2}^+$
267	43±2		1704 → 1437	$\frac{9}{2}^+ \to \frac{9}{2}^-$	1185	182±9	0.9±0.1	3772 → 2587	$(\frac{15}{2})^+ \to \frac{13}{2}^+$
318	105±5	1.4±0.3	6236 → 5918	$\frac{21}{2}^- \to \frac{19}{2}^-$	1207	296±16	1.0±0.2	1207 → 0	$\frac{7}{2}^- \to \frac{3}{2}^-$
336	110±6	2.0 ±0.4	6572 → 6236	$\frac{23}{2}(-) \to \frac{21}{2}^-$	1209	174±10	1.9±0.4	3529 → 2320	$\frac{13}{2}^- \to \frac{11}{2}^-$
414	718±36	2.3 ±0.2	1064 → 650	$\frac{7}{2}^- \to \frac{5}{2}^-$	1224	1088±55	2.1±0.2	6572 → 5348	$\frac{23}{2}(-) \to \frac{21}{2}^+$
457	86±4		650 → 193	$\frac{5}{2}^- \to \frac{5}{2}^-$	1244	301±16		1437 → 193	$\frac{9}{2}^- \to \frac{5}{2}^-$
492	50±3		5918 → 5426	$\frac{19}{2}^- \to \frac{17}{2}^-$	1256	201±11	0.8±0.2	2320 → 1064	$\frac{11}{2}^- \to \frac{7}{2}^-$
497	316±16	2.0±0.2	1704 → 1207	$\frac{9}{2}^+ \to \frac{7}{2}^-$	1307	255±13	0.9±0.2	5079 → 3772	$(\frac{19}{2})^+ \to (\frac{15}{2})^+$
510[a]	41±5		5918 → 5408	$\frac{19}{2}^- \to \frac{17}{2}^-$	1313	590±30	0.9±0.2	5079 → 3766	$(\frac{19}{2})^+ \to \frac{17}{2}^+$
569	75±6		1207 → 637	$\frac{7}{2}^- \to \frac{3}{2}^-$	1357	338±18	1.3±0.1	7929 → 6572	$\frac{27}{2}(-) \to \frac{23}{2}(-)$
591	204±10	1.3±0.6	4357 → 3766	$(\frac{15}{2}^-) \to \frac{17}{2}^+$	1377	293±15	0.7±0.2	7613 → 6236	$\frac{25}{2}^- \to \frac{21}{2}^-$
637	66±4		637 → 0	$\frac{3}{2}^- \to \frac{3}{2}^-$	1411	155±11	0.8±0.3	6490 → 5079	$(\frac{23}{2})^+ \to (\frac{19}{2})^+$
640	1836±91	1.8±0.1	1704 → 1064	$\frac{9}{2}^+ \to \frac{7}{2}^-$	1478	127±7	1.0±0.2	3529 → 2051	$\frac{13}{2}^- \to \frac{9}{2}^-$
650	497±25	>2	650 → 0	$\frac{5}{2}^- \to \frac{3}{2}^-$	1486	160±9	1.2±0.3	9099 → 7613	$(\frac{29}{2})^- \to \frac{25}{2}^-$
654			3482 → 2828	$\frac{13}{2}^+ \to (\frac{11}{2})^+$	1498	207±11	1.6±0.5	2936 → 1437	$\frac{13}{2}^- \to \frac{9}{2}^-$
654[b]	114±7	1.1±0.2	6572 → 5918	$\frac{23}{2}(-) \to \frac{19}{2}^-$	1510	44±5		1704→193	$\frac{9}{2}^+ \to \frac{5}{2}^-$
810	195±10	0.7±0.2	6236 → 5426	$\frac{21}{2}^- \to \frac{17}{2}^-$	1561	87±5		5918 → 4357	$\frac{19}{2}^- \to (\frac{15}{2}^-)$
828	279±15	1.0±0.2	6236 → 5408	$\frac{21}{2}^- \to \frac{17}{2}^-$	1582	929±47	1.2±0.1	5348 → 3766	$\frac{21}{2}^+ \to \frac{17}{2}^+$
871	330±17	1.2±0.1	1064 → 193	$\frac{7}{2}^- \to \frac{5}{2}^-$	1659	150±9	>2	5426 → 3766	$\frac{17}{2}^- \to \frac{17}{2}^+$
875	27±3		4357 → 3482	$(\frac{15}{2}^-) \to \frac{13}{2}^+$	1770	180±10	1.2±0.3	4357 → 2587	$(\frac{15}{2}^-) \to \frac{13}{2}^+$
883	2230±111	0.9±0.1	2587 → 1704	$\frac{13}{2}^+ \to \frac{9}{2}^+$	1778	52±4		3482 → 1704	$\frac{13}{2}^+ \to \frac{9}{2}^+$
888	33±3		6236 → 5348	$\frac{21}{2}^- \to \frac{21}{2}^+$	1847	63±6		9776 → 7929	$(\frac{31}{2}^-) \to \frac{27}{2}(-)$
944	143±9	1.4±0.4	3772 → 2828	$(\frac{15}{2})^+ \to (\frac{11}{2})^+$	1858	16±2		2051 → 193	$\frac{9}{2}^- \to \frac{5}{2}^-$
987	388±19	2.1±0.5	2051 → 1064	$\frac{9}{2}^- \to \frac{7}{2}^-$	1879	112±7	1.1±0.2	5408 → 3529	$\frac{17}{2}^- \to \frac{13}{2}^-$
1013	366±19	1.2±0.2	1207 → 193	$\frac{7}{2}^- \to \frac{5}{2}^-$	1897	193±11	1.0±0.2	5426 → 3529	$\frac{17}{2}^- \to \frac{13}{2}^-$
1064	1293±65	1.0±0.1	1064 → 0	$\frac{7}{2}^- \to \frac{3}{2}^-$	2472[a]	31±7		5408 → 2936	$\frac{17}{2}^- \to \frac{13}{2}^-$
1124	91±6	0.8±0.2	2828 → 1704	$(\frac{11}{2})^+ \to \frac{9}{2}^+$	2490[a]	20±7		5426 → 2936	$\frac{17}{2}^- \to \frac{13}{2}^-$
1157	359±19	1.4±0.3	6236 → 5079	$\frac{21}{2}^- \to (\frac{19}{2})^+$					

[a]Relative intensity evaluated from 1244 gate.
[b]Relative intensity evaluated from 883 gate.

The lowest positive parity level, $\frac{9}{2}^+$, has been observed at 1704 keV and this is in conformity with earlier results. This level is depopulated by three $E1$ transitions, viz., 267, 497, and 640 keV and an $M2$ transition of 1510 keV. Such an $M2$ transition has also been observed in another nucleus, ^{65}Ge, in this mass region [4]. The 267 and the 1510 keV γ rays were not observed in earlier experiments. The positive parity band based on the $\frac{9}{2}^+$ level at 1704 keV and comprising a cascade of three (883, 1179, and 1582 keV) stretched $E2$ transitions (Fig. 2) is in perfect agreement with earlier results [7]. The states belonging to this band probably arise from the coupling of the neutron single-particle motion in the $g_{9/2}$ orbit to the collective vibration of the ^{62}Zn core.

The placement of the 1224 keV γ transition above the 5348 keV($\frac{21}{2}^+$) level is in accordance with the observed intensities of the γ rays and their coincidence relationships. The measured DCO ratio of the 1224 keV γ ray indicates its stretched dipole character. Therefore, the 6572 keV level is assigned a spin of $\frac{23}{2}$. The level scheme of the neighboring nucleus, ^{65}Ge, [4] also shows the presence of an $E1$ transition (similar to 1224 keV) on the top of its positive parity band. Hence we have tentatively assigned this level a negative parity. The 1357 and 1847 keV transitions which are in cascade with the 1224 keV transition, depopulate the proposed levels at 7929 and 9776 keV. The quadrupole nature of the 1357 keV γ transition suggests a spin-parity of $\frac{27}{2}^{(-)}$ for the 7929 keV level. The spin-parity of the 9776 keV levels is tentatively assigned to be $(\frac{31}{2}^-)$.

The level at 2828 keV is fed by a 654 keV γ ray from a positive parity $(\frac{13}{2}^+)$ level at 3482 keV and it subsequently decays to another positive parity, $\frac{9}{2}^+$, level at 1704 keV by emitting an 1124 keV γ ray. So the level is expected to have positive parity. One of the possibilities is that this state is a member of a particle vibration multiplet arising from the coupling of the $g_{9/2}$ neutron motion to the one-phonon core state. Then the likely spin parity of this level is $\frac{11}{2}^+$ or $\frac{13}{2}^+$. However, as the $\frac{13}{2}^+$ member of the said multiplet has already been identified at 2587 keV, we expect this level to have a spin-parity $(\frac{11}{2})^+$, although the assignment of $I^\pi = \frac{13}{2}^+$ cannot be ruled out altogether. As it will be clear from the theoretical results presented in Sec. IV, the states at 1704 and 2587 keV originate from the zero and one d-boson core states, respectively, coupled to the $g_{9/2}$ single-particle motion. The transition between these states is expected to be dominated by the contribution from the boson core. The electromagnetic transitions associated with a change in the number of d-bosons between the core states are predominantly of $E2$ nature. So the 1124 keV transition is expected to be of quadrupole nature even if the change in the spin value is only of one unit.

Another bandlike structure consisting of the 2828, 3772, 5079, and 6490 keV levels with three deexciting γ rays of energy 944, 1307, and 1411 keV in cascade, and built on the $(\frac{11}{2})^+$ level at 2828 keV has been observed. The last two transitions are predominantly quadrupole in nature since their DCO ratios are close to one. The level at 3772 keV also decays to the $\frac{13}{2}^+$ level at 2587 keV through the emission of an 1185 keV γ ray. The DCO ratio measurement suggests that this transition is also a quadrupole one. However, we have assigned a spin parity $(\frac{15}{2})^+$ to the 3772 keV level because it also decays to the $(\frac{11}{2})^+$ level at 2828 keV. The 2587 and 3772 keV levels arise from a coupling of one and two d-boson core states, respectively, to the $g_{9/2}$ neutron orbit. (Hence from the arguments presented in the previous paragraph, the 1185 keV γ ray is expected to be of quadrupole character even if there is one unit change in spin.) The levels at 5079 and 6490 keV have been assigned spin-parity values $(\frac{19}{2})^+$ and $(\frac{23}{2})^+$, respectively, because of the quadrupole nature of the 1307 and 1411 keV transitions which may correspond to the unfavored members of the $g_{9/2}$ band. It has been mentioned earlier that a spin-parity assignment of $\frac{13}{2}^+$ to the level at 2828 keV cannot be completely ruled out on the basis of our experiment. This assignment will in turn lead to a spin parity of $\frac{17}{2}^+$ to the 3772 keV level. In that case, the spin values of the levels in the band based on this state will increase by unity. The spin parity of the level at 5079 keV will then be $\frac{21}{2}^+$ and it will become yrast. However, this assignment contradicts the spin-parity assignment of the 5348 keV level made in the present as well as in an earlier work [7].

Another $\frac{13}{2}^+$ state is also proposed at 3482 keV. This is fed from the 4357 keV $(\frac{15}{2}^-)$ level through emission of an 875 keV γ ray and it decays in turn to the $\frac{9}{2}^+$ and $\frac{11}{2}^+$ states through emission of the 1778 and 654 keV γ rays, respectively. Although this level is fed from a negative parity state, it feeds only positive parity states and so we have assigned positive parity to it. The possible spin value for this level is $\frac{13}{2}$ because a spin value of $\frac{11}{2}$ will make the 875 keV transition to be $M2$ in character.

The decay pattern of the 2051 keV state is consistent with the earlier observation of Metford *et al.* [7]. We propose a level at 2320 keV to accommodate the 1256 keV γ ray observed in singles as well as in gated spectra. This placement is done in accordance with the our observation that this γ ray is in coincidence with the 1064 keV γ ray but not in coincidence with any of the other γ rays belonging to the yrast levels. Therefore, we propose that the 1256 keV γ ray arises from the decay of the proposed level at 2320 keV to the 1064 keV $(\frac{7}{2}^-)$ state. The quadrupole character of this γ ray indicates the spin parity of the state at 2320 keV to be $\frac{11}{2}^-$.

Two $\frac{13}{2}^-$ states have been proposed at 2936 and 3529 keV, respectively. Their spin-parity assignment is consistent with their decay patterns. The first $\frac{13}{2}^-$ level decays to $\frac{9}{2}^-$ state through emission of a 1498 keV γ ray, whereas the other $\frac{13}{2}^-$ level feeds the $\frac{9}{2}^-$ and $\frac{11}{2}^-$ states through two parallel transitions of 1478 and 1209 keV, respectively.

The proposed state at 4357 keV decays by emission of three γ rays of 1770, 875, and 591 keV to the 2587, 3482, and 3776 keV states, respectively. Furthermore, it is populated by a 1561 keV γ ray deexciting a state at 5918 keV with spin-parity of $\frac{19}{2}^-$. The DCO ratio measurement does not rule out an $E1$ character for the 591 keV transition. Considering these facts, the most probable spin parity of the 4357 keV state is $(\frac{15}{2}^-)$. This state may arise from the coupling of the octupole phonon excitation of the core to the $g_{9/2}$ single-particle orbit. The comparison of the decay pattern of this level with that of the 3^- octupole state in ^{64}Zn (discussed in Sec. IV) also supports this assignment.

Two close-lying levels have been proposed at 5408 and 5426 keV, respectively. The 5408 keV state decays to the $\frac{13}{2}^-$ levels at 2936 and 3529 keV through emission of the 2472 and 1879 keV γ rays, respectively. The level at 5426 keV also decays to the same $\frac{13}{2}^-$ states by emission of the 2490 and 1897 keV γ rays, respectively. The DCO ratios for the 1879 and 1897 keV transitions indicate their quadrupole nature. The negative parity assignment to these levels is based on the observation that they do not show any decay to the positive parity states. Accordingly, we have assigned spin parity of $\frac{17}{2}^-$ to both these levels.

The proposed levels at 5918 and 6236 keV are fed from the level at 6572 keV, $\frac{23}{2}^{(-)}$ state by the 654 and 336 keV γ rays, respectively. The decay patterns for these states are complex, showing transitions to both positive and negative parity states. The 6236 keV state decays to the $\frac{17}{2}^-$ levels at 5408 and 5426 keV through emission of the 828 and 810 keV γ rays (which are quadrupole in nature), respectively. Hence it is assigned a spin parity of $\frac{21}{2}^-$. The placement of this level is further supported by the fact that two other γ rays (1157 and 318 keV) could be placed in between this level and the two levels at 5079 $(\frac{19}{2}^+)$ and 5918 keV, respectively. As for the 5918 keV state we have assigned a spin parity of $\frac{19}{2}^-$, primarily based on the observed quadrupole character of the 654 keV γ ray. This is also consistent with the previous assignment of $(\frac{15}{2}^-)$ to the 4357 keV state. Otherwise, multipolarity of the 1561 keV γ ray deexciting the state at 5918 keV will come out to be $M2$. This level also decays to the $\frac{17}{2}^-$ states through emission of the 492 and 510 keV γ rays.

The 1377 and 1486 keV γ rays are placed above the 6236 keV level in accordance with the coincidence relationships. The 1377 keV transition is of quadrupole nature. Hence the spin parity of the 7613 keV level is proposed to be $\frac{25}{2}^-$. Since the DCO ratio of the 1486 keV γ ray does not rule out a quadrupole character, we tentatively assign a spin parity value of $(\frac{29}{2})^-$ to the level at 9099 keV.

TABLE II. The IBM parameters used in the present calculation. Parameters not described in the text are identical with Refs. [13,15].

Hamiltonian		ϵ_d	ELL	OCT	ϵ_f	A_{df}	A_0	Γ_0	Λ_0	Δ_0
parameters (MeV)		0.825	0.071	-0.011	3.000	-0.04	-0.074	0.265	0.868	0.300
Single particle	$j=$	3/2	5/2	1/2	9/2					
energy(ϵ_j) (MeV)		0.000	0.150	0.246	1.897					
Occupation probability (v_j^2)		0.624	0.295	0.197	0.034					
Transition		α	α_p	χ	g_d	g_l	η			
parameters		6.5	12.0	-1.15	1.0	0.0	1.0			

IV. RESULTS OF INTERACTING BOSON-FERMION MODEL (IBFM) CALCULATION

The level properties of ^{63}Zn have been calculated using the formalism of the IBFM to understand the underlying excitation mechanisms. The present calculation includes the interaction between the collective quadrupole as well as octupole and the single-particle degrees of freedom. The conventional interacting boson and boson-fermion models consider only the quadrupole excitations of the even-even core. We have not come across so far any calculation of the level properties of the odd-A nucleus in the framework of the IBFM incorporating octupole degree of freedom. A common feature of the nuclei in the $A=60$ region is the existence of octupole vibration states around 3 MeV. In the interacting boson model this feature is taken care of by introducing an f ($L=3$) boson of negative parity [12]. The total boson Hamiltonian can be written as a sum of three parts

$$H_B=H_{sd}+H_f+V_{sdf}, \tag{1}$$

where H_{sd} is the usual s-d boson Hamiltonian [13], H_f is the pure f boson term, and V_{sdf} is the interaction between the quadrupole and the octupole degrees of freedom. In the simplest approximation, H_f is taken as $\epsilon_f n_f$ where n_f is the number of f bosons. We restrict the maximum number of f bosons to unity. V_{sdf} is taken in the present calculation as

$$V_{sdf}=A_{df}(L_d\cdot L_f). \tag{2}$$

The parameter, A_{df} is identical with the parameter FELL used in Ref. [14]. For the odd mass nucleus, the total Hamiltonian consists of three parts,

$$H=H_B+H_p+V_{Bp}. \tag{3}$$

Here H_p refers to the particle term and V_{Bp} is the boson-particle interaction. For only one odd fermion, we have

$$H_p=\sum_j \epsilon_j[a_j^\dagger a_j]^0, \tag{4}$$

where ϵ_j is the single-particle energy of the level j. A particular feature of the structure of this odd mass nucleus is the interaction between the octupole phonon excitation and the single-particle degrees of freedom. The boson particle interaction can be written as a sum of two terms:

$$V_{Bp}=V_{sdp}+V_{sdfp}. \tag{5}$$

The first term describes the usual interaction between sd boson and the odd particle. We use the simple form based on microscopic considerations which has been described by Iachello and Scholten [15]. The second term contains f boson operators. We have taken the simple form given by

$$V_{sdfp}=\Delta_0(u_ju_{j'}-v_jv_{j'})\langle j\|Y_3\|j'\rangle[\{(s^\dagger\tilde{f}+f^\dagger s)+\chi_3(d^\dagger\tilde{f}+f^\dagger\tilde{d})\}^3\{a_j^\dagger\tilde{a}_{j'}\}^3]. \tag{6}$$

The code ODDA [16] has been modified to include the f boson in the core. The boson core is taken to be ^{48}Ca. The parameters of the boson Hamiltonian have been obtained by fitting the energy levels of ^{62}Zn. The single-particle energies have been taken from the energy levels of ^{57}Ni [17]. The occupation probabilities and the quasiparticle energies have been obtained from a self-consistent BCS calculation by taking the pairing strength to be equal to 0.3 MeV. We have slightly changed the quasiparticle energy for the $f_{5/2}$ level so as to reproduce the lowest $\frac{5}{2}^-$ level. The quasiparticle energies, the occupation probabilities for the single-particle levels and all other parameters used in the present calculation are given in Table II.

The operators for electromagnetic transition consist of two parts

$$T(\lambda)=T_B(\lambda)+T_p(\lambda). \tag{7}$$

The $E2$ and $M1$ transition operators for the boson part are given by

$$T_B(E2)=\alpha[(s^\dagger\tilde{d}+d^\dagger\tilde{s})^2+\chi(d^\dagger\tilde{d})^2], \tag{8}$$

$$T_B(M1)=g_d(d^\dagger\tilde{d})^1+\eta[T_B(E2)\times\hat{L}]^1. \tag{9}$$

The parameter, η is identical with the parameter $M1E2$ used in Ref. [14]. The fermion operator for $M1$ transition is given in Ref. [18]. For the $E2$ transition, the fermion $E2$ operator is given by

$$T_p(E2)=\sum_{jj'}\alpha_p\langle j||Y_2||j'\rangle(a_j^\dagger\tilde{a}_{j'})^2. \tag{10}$$

The orbital g-factor for neutrons is taken to be zero. The spin g-factor is quenched by a factor 0.6, a value frequently used in this mass region. The values of the other parameters are listed in Table II. However, it must be remembered that IBM-1 is not really suitable for describing the $M1$ transitions between levels arising out of different core states. So only a

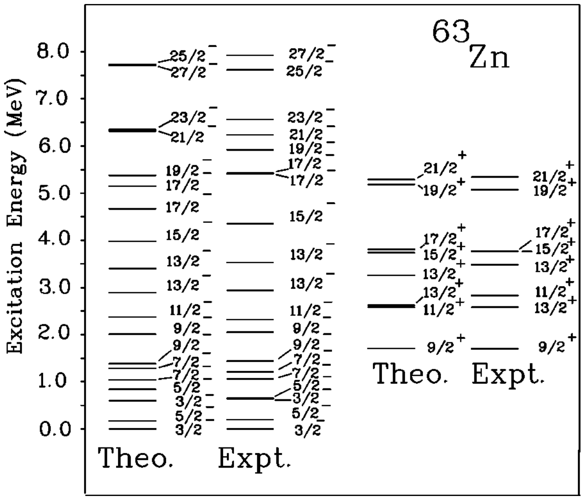

FIG. 3. Comparison of the experimental level scheme and the results of the theoretical calculation described in the text.

rough estimate for such transition rates is expected for low-lying states.

The experimental and the calculated energy levels are compared in Fig. 3. Some of the experimental branching ratios have been compared with the theoretical predictions in Table III. Single-particle transfer reaction shows that the $\frac{7}{2}^-$ level at 1064 keV has a finite contribution from the $f_{7/2}$ single-particle orbital [19], which is outside the model space used in the present calculation. This is possibly the reason for the poor agreement between the theoretical and the experimental branching ratios for the decay modes of the two $\frac{7}{2}^-$ states. The predictions for other branching ratios agrees reasonably well with the experimental values.

TABLE III. Comparison of calculated and experimental branching ratios.

Initial level J^π	Initial level keV	Final level J^π	Final level keV	Branching ratio Calc.	Branching ratio Expt.
$\frac{3}{2}^-$	637	$\frac{1}{2}^-$	248	5	5[a]
		$\frac{3}{2}^-$	0	95	95[a]
$\frac{5}{2}^-$	650	$\frac{5}{2}^-$	193	10	15
		$\frac{3}{2}^-$	0	90	85
$\frac{7}{2}^-$	1064	$\frac{5}{2}^-$	650	51	20
		$\frac{5}{2}^-$	193	28	15
		$\frac{3}{2}^-$	0	21	65
$\frac{7}{2}^-$	1207	$\frac{3}{2}^-$	637	0	4
		$\frac{5}{2}^-$	193	22	56
		$\frac{3}{2}^-$	0	39	40
$\frac{9}{2}^-$	2051	$\frac{7}{2}^-$	1064	90	100
		$\frac{5}{2}^-$	193	10	0
$\frac{13}{2}^-$	3529	$\frac{11}{2}^-$	2320	60	60
		$\frac{9}{2}^-$	2051	40	40
$\frac{13}{2}^+$	3482	$(\frac{11}{2})^+$	2828	30	43
		$\frac{9}{2}^+$	1704	70	57
$(\frac{15}{2})^+$	3772	$(\frac{11}{2})^+$	2828	10	21
		$\frac{13}{2}^+$	2587	90	79
$(\frac{19}{2})^+$	5079	$(\frac{15}{2})^+$	3772	74	
		$\frac{17}{2}^+$	3766	26	

[a]Experimental data taken from Ref. [7].

The spin parity of the state at 4357 keV has been proposed to be $(\frac{15}{2}^-)$. We assume this level to originate from the coupling of the $g_{9/2}$ orbit to the 3^- octupole state of the core. This level decays to the first and the second $\frac{13}{2}^+$(at 2587 and 3482 keV) states and the $\frac{17}{2}^+$ (at 3766 keV) state through the emission of the 1770, 875, and 591 keV γ rays, respectively. The corresponding experimental branching ratios are 60:35:5. The first and second $\frac{13}{2}^+$ levels arise from the coupling of the $g_{9/2}$ to the first and second 2^+ states of ^{62}Zn, respectively. The $\frac{17}{2}^+$ level has the structure $g_{9/2} \otimes 4_1^+$. The 3^- level in neighboring ^{64}Zn [3] nucleus decays to the 2_1^+ and 2_2^+ states. So the decay pattern of these states (in ^{63}Zn) agrees reasonably well with that observed in the even-even core.

The $\frac{17}{2}^-$ levels at 5408 and 5426 keV decay to the $\frac{13}{2}^-$ (at 2936 and 3529 keV) states. Since there is no decay to the $(\frac{15}{2}^-)$ level at 4357 keV, we conclude that these states have very little octupole contribution.

The structure of the $\frac{19}{2}^-$, $\frac{21}{2}^-$, and $\frac{23}{2}^-$ levels present a problem. The energies of the $\frac{21}{2}^-$ and $\frac{23}{2}^-$ levels are very low. So they are not expected to arise from the quadrupole excitation of the core. In the neighboring ^{65}Ge isotope, these states have been described as arising from the coupling of the negative parity states in the even-even core to the $g_{9/2}$ single-particle level [4]. However, all the negative parity core states in this mass region do not arise from octupole vibration. In neighboring Ge isotopes, it has been found necessary to include noncollective fermion pairs along with the usual sdf boson space that we have used [20]. For example, in ^{64,66,68}Ge, the lowest 5^- state has almost 30% contribution from the fermion pair states and the lowest 7^- and 9^- states are almost pure fermion pair states coupled to the sd boson space. In ^{64}Zn, the lowest 5^- state arises mainly from the quadrupole-octupole vibration and hence can be adequately described by the sdf boson model. However, the 7_1^- state in ^{64}Zn decays to the $6_{1,2}^+$ states but not to the 5_1^- state. It has been suggested that many of the irregularly spaced negative parity levels having $J > 7^-$ possibly arise due to noncollective quasiparticle excitations [3].

V. CONCLUSIONS

The level scheme of ^{63}Zn has been studied through the ^{50}Cr(^{16}O,$2pn$) reaction at a beam energy of 75 MeV to explore the nature of the high spin states of ^{63}Zn. A total of 37 transitions and 18 energy levels have been placed in the proposed level scheme. A positive parity unfavored band and a negative parity band have been established, in addition, to confirming the levels already known from earlier work. The structure of this nucleus has been investigated in the framework of IBFM. For this purpose both the quadrupole and the octupole excitations of the even-even ^{62}Zn core have been taken into account. The structure of the positive parity yrast band based on the $\frac{9}{2}^+$ level at 1704 keV is understood in terms of a weak coupling of the $g_{9/2}$ neutron to the quadrupole phonon excitations of the even-even core. The $(\frac{15}{2}^-)$ state at 4357 keV has been predicted to be of octupole nature originating from the coupling of the $g_{9/2}$ orbit to the 3^- level of the core. However, all the negative parity states in this mass region cannot be described simply in terms of the coupling of octupole and quadrupole vibrational states. In neighboring Ge isotopes [20], for example, noncollective fermion pair states were included along with the usual sdf-boson space, (that we have used) to explain the observed level structure. Inclusion of similar noncollective fermion pair states seems to be necessary for understanding the structure of some of the negative parity levels proposed in the present work.

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