Level structure of the odd-odd ^{62}Cu isotope

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The high spin structure in the nucleus ^{62}Cu has been studied using the reaction ^{50}Cr(^{16}O,3pn) at a beam energy of 75 MeV. Most of the levels known from earlier experiments have been confirmed and the spin parity assignments of a few of them have been verified. A number of levels have been proposed extending the energy scheme up to about 7.6 MeV. A simple interacting boson-fermion-fermion model calculation has been performed to explain the observed energy spectrum. [S0556-2813(99)06805-3]

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I. INTRODUCTION

The recent studies of proton rich nuclei in the mass-60 region have revealed a rich pattern of shape transformation and noncollective-to-collective transitions with increasing angular momentum. With a limited number of valence particles outside the doubly magic nucleus ^{56}Ni, the low spin level schemes of these nuclei are dominated by spherical shell model states. However, at intermediate spins the presence of high-j orbitals leads to the possibility of the existence of deformed rotational bands which are built on the multiparticle-multihole excitations across $N=Z=28$ closed shells. Because of the limited number of particles and holes occupying these orbitals, the maximum spin expected from such process is limited to 25–30 $\hbar$. When a rotational band with a particular configuration is followed to a high spin, eventually the total angular momentum available from the spin alignment of the particles outside the closed shells is exhausted and the band terminates [1,2]. Such a terminating band has been observed recently in the ^{62}Zn isotope [3].

In this paper we report the results of our study on the level structure of odd-odd $^{62}_{29}$Cu$_{33}$. This nucleus has been the subject of a number of studies in the past and the results can be found in the latest compilation by King [4]. It has been conveniently studied by β decay of ^{62}Zn ($t_{1/2}$=9.186 h) which populate states up to an excitation energy of 1.52 MeV. The spin-parities of the levels up to $E_x \sim 1.0$ MeV have been firmly established by these works. ^{62}Cu has also been studied using (n,2$n\gamma$) [4], (p,$n\gamma$) [5], (^{3}He,p) [5] reactions and transfer reactions such as (d,t) [6] and (d,α) [6,7]. As far as the high spin part of the level scheme is concerned, the relevant information has been obtained from the work based on the ^{60}Ni(α,$pn\gamma$) reaction [8] and ^{52}Cr(^{14}N,2p2$n\gamma$) heavy ion induced reaction studies [8]. But this later study [8], using heavy ion and a four detector setup, did not populate any new level that had not been found using α projectiles. All these reaction studies have provided energy levels up to an excitation energy of 4.747 MeV and the highest positive (negative) spin observed is $9^+(8^-)$.

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II. EXPERIMENTAL METHOD

In the present work, the level properties of ^{62}Cu were studied using the ^{50}Cr(^{16}O,3pn)^{62}Cu reaction at a beam energy of 75 MeV obtained from the 15 UD Pelletron Accelerator of Nuclear Science Center, New Delhi. The target was a 20 mg/cm^2 thick foil of isotopically enriched ^{50}Cr (isotopic abundance 92%), which was backed by a layer of gold of thickness 53 mg/cm^2. The resulting nuclei were investigated with standard in-beam γ-ray spectroscopy techniques which involved studies of γ-γ coincidence data and DCO ratios. The multidetector array (GDA) at NSC comprising twelve Compton-suppressed HPGe detectors along with fourteen BGO detectors (as a multiplicity filter), was employed for this purpose. The detectors were arranged in three groups, each consisting of four detectors at 45°, 99°, and 153° with respect to the beam direction. The same target-projectile combination was utilized to study the level properties of ^{63}Zn [9]. In the present case, eighty three million events corresponding to twofold or higher coincidences in HPGe detectors were recorded in the list mode. Each coincidence event with Ge-detectors was qualified with the condition that simultaneously at least two BGO detectors of the multiplicity filter should fire. The detectors were calibrated using the γ rays obtained from standard ^{152}Eu and ^{133}Ba radioactive sources. The pulse height of each detector was gain matched to 0.71 keV/channel and the γ-γ coincidence data were sorted out into a 4096×4096, E_γ-E_γ matrix. The energy spectra gated by γ rays of interest were generated from this matrix. Figure 1 shows the coincidence spectra with gates on a few γ rays of importance. The energies, relative intensities, and DCO ratios of the γ rays are given in Table I. Intensity

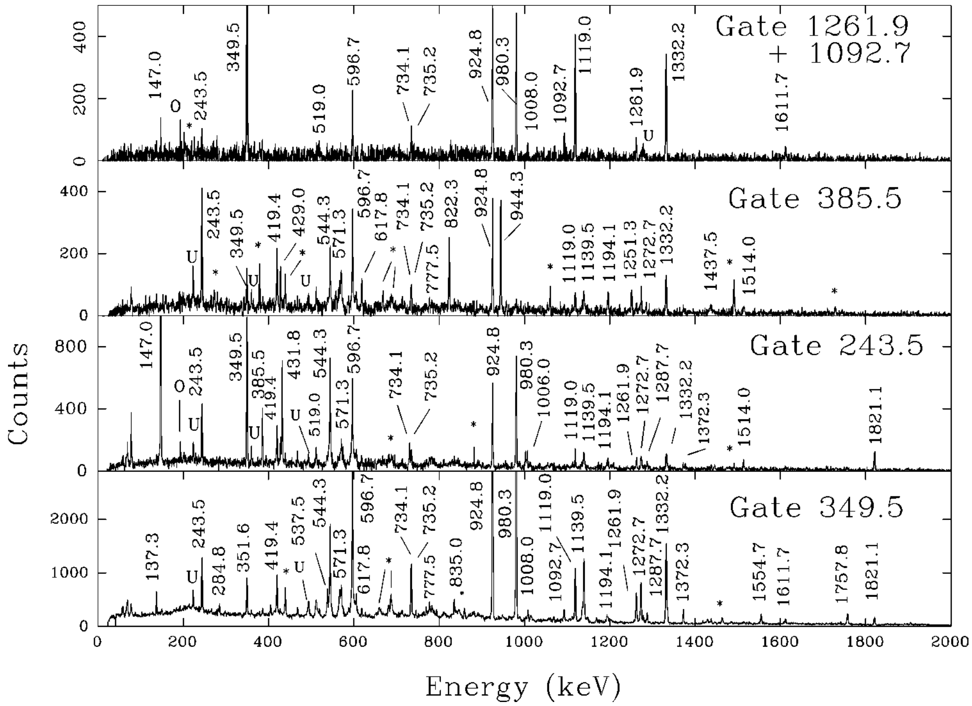

FIG. 1. Selected γ-γ coincidence spectra obtained in the present work for ^{62}Cu. The transitions of interest are labeled by their energies in keV. The transitions marked O are arising from other channels and have been identified. The transitions marked U probably belong to ^{62}Cu but could not be placed in the proposed level scheme. The transitions marked with an asterisk have been observed in the present work as well as in earlier experiments but are not shown in the partial level scheme.

values are obtained from the total projected spectrum and are normalized with respect to that of the 349.5 keV γ ray. The DCO ratios are obtained from the spectra gated by the 349.5 and 1332.2 keV γ rays. The DCO ratios of some of the transitions could not be measured because they are either weak in intensity or have close-lying transitions. A partial level scheme (Fig. 2) of ^{62}Cu has been constructed from the γ-γ coincidence data, the γ-ray intensities, and multipolarities of the γ rays, inferred from the DCO ratios measurements. For the DCO ratios measurements, 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

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

where a stretched $\Delta I=2$ transition (either 349.5 or 1332.2 keV) are chosen as γ_2. The expected values of DCO ratios for stretched $\Delta I=1$ and $\Delta I=2$ transitions are 2.0 and 1.0, respectively.

III. RESULTS

To facilitate discussion the tentatively assigned spin parities of the relevant levels, to which the transitions are connected, are also given in Table I. A total of 50 γ transitions has been placed in the partial level scheme. In the process eight levels are being proposed. Some transitions which have been observed in the present experiment as well as in earlier works [4], have been omitted in the scheme. Besides a number of transitions could not be placed though they probably belong to this nucleus. Table II gives a list of such transitions occurring in some of the gates.

The present work confirms all the levels proposed in the earlier level scheme using $(\alpha,pn\gamma)$ and heavy-ion induced reactions [8]. The ground state of ^{62}Cu is 1^+ state while the first excited state at 40.85 keV ($J^\pi=2^+$) is an isomeric state with $t_{1/2}=4.57$ ns [4]. Our experimental setup was not suitable for observing very low energy γ rays. So the 41 keV γ ray ($2^+\rightarrow 1^+$) is unobserved. It has, however, been possible to observe all the relevant transitions which indirectly provided its confirmation. Thus the present work confirms the existence of the excited levels at 40.9 (2^+), 243.5 (2^+), 390.2 (4^+), 426.1 (3^+), 675.1 (3^+), 1248.7 (2^+,3^+,4^+), 1370.4 (5^+), 1677.8 (3–5), 2148.3 ($6^{(+)}$), 2295.2 (6^-), 2891.9 (7), 3029.2 (7), 3191.5 (6), 3434.7 (8^-), 3627.4, 3979.0 (9), 4164.6 (9), and 4746.4 (9^+) keV. It is worthwhile to note that our measurement of the energy of the two γ rays, 924.8 keV (2295.2, $6^-\rightarrow$1370.4, 5^+) and 734.1 keV [3029.2, (7)$\rightarrow$2295.2, 6^-] agree with Ref. [8] and not with the compilation [4]. Consequently, the energies of the levels given in Ref. [4] as 2293.7, 2889.3, 3025.3, 3625.7, 3977.4, 4161.8, and 4744.7 keV are measured in the recent experiment to be 2295.2, 2891.9, 3029.3, 3627.4, 3979.0, 4164.6, and 4746.4 keV, respectively. The DCO ratio of the 980.3 keV transition is measured to be 3.5. We have found out that this value corresponds to a mixing ratio of -0.3. In an earlier experiment, the mixing ratio was measured to be -0.5 [8]. So our measurement agrees reasonably with them. In addition, we have observed a number of γ rays linking some of these already established levels. These have not been reported earlier. This has resulted in predicting and/or assigning spin parities of the known levels in a more conclusive way. We will first briefly discuss this aspect of the present work.

The level at 1248.7 keV: Since it is fed from a 5^+ level and in turn decays, among others, to the 2^+ level at 243.4 keV, the probable spin-parity values of this level are 3^+ or 4^+. A negative parity assignment may be ruled out because the lowest negative parity level is observed at 2295.2 keV(6^-). The theoretical calculations described in Sec. IV also predict this 6^- level to be the lowest negative parity one.

TABLE I. Energy levels in ^{62}Cu, as observed in the present work. The energies, intensities, and DCO ratios of the γ rays depopulating these levels are given. The spin-parity assigned in the earlier works and proposed in this work are also included. The error in γ-ray energy is about 0.1 keV. The DCO ratios of some of the transitions could not be measured because of their weak intensities.

Energy level Energy (keV)	J^π	γ ray E_γ(keV)	I_γ	DCO ratio
243.5	2^+	243.5	30.5±1.9	
390.2	4^+	147.0	87.2±4.4	
		349.5	1000.0	1.1±0.1
426.1	3^+	385.5	135.4±6.9	
675.1	3^+	284.8	41.5±2.3	1.3±0.3
		431.6	16.5±4.8	
1248.7	$(3,4)^+$	822.3	45.7±2.5	
		858.7	27.6±2.1	
		1006.0	63.9±4.4	
1370.4	5^+	944.3	92.1±5.8	
		980.3	950.0±47.7	3.5±0.3
1677.8	5^+	429.0	76.0±4.3	
		1251.3		
		1287.7	45.6±3.6	1.6±0.3
2148.3	6^+	777.5	30.0±4.2	
		1757.8	86.6±12.3	
2295.2	6^-	617.8[a]		
		924.8	926.8±46.4	1.8±0.2
		1905.1	10.8±2.7	
2891.9	(7^-)	596.7	382.7±19.3	2.3±0.2
3029.2	(7^-)	137.3	16.1±1.1	0.9±0.2
		734.1	111.8±5.9	[b]
3191.5	(6^-)	1514.0[a]	21.2±3.5	
		1821.1	54.3±3.4	2.7±0.4
3434.7	(8^-)	243.5[a]	191.3±9.7	1.1±0.1
		1139.5	322.7±16.5	1.0±0.1
3627.4	(8^-)	735.2[a]	131.5±6.9	[c]
		1332.2	353.0±18.6	1.0±0.1
3979.0	(9)	351.6[a]	38.5±2.4	[d]
		544.3	159.0±8.2	2.1±0.2
4164.6	(9^-)	537.5[a]	62.4±3.5	2.1±0.2
		1135.3[a]	48.4±3.4	1.0±0.2
		1272.7	147.8±8.3	1.3±0.2
4446.6[a]	(9^-)	467.8[a]	50.9±3.0	0.7±0.1
		1012.8[a]	33.0±3.9	
		1417.8[a]	9.4±3.2	
		1554.7[a]	40.1±5.5	1.2±0.3
4628.8[a]		1194.1[a]	23.1±1.9	1.2±0.7
		1437.5[a]	18.5±1.6	
4746.4	(9^+)	1119.0	222.0±11.9	2.3±0.2
4999.6[a]	(9^-)	835.0[a]	289.0±14.8	1.5±0.3
		1372.3[a]	64.0±3.7	1.6±0.3
5048.2[a]		419.4[a]	67.1±3.7	1.8±0.3
		1069.0[a]	20.3±1.7	0.9±0.3
5619.5[a]		571.3[a]	91.3±5.1	2.8±0.4
6008.3[a]	(11)	1008.0[a]	63.0±6.3	0.8±0.3
		1261.9[a]	118.9±6.6	0.8±0.1
7101.0[a]	(12)	1092.7[a]	38.9±4.2	2.3±0.3
7620.2[a]	(12)	(519.0)[a]		
		1611.7[a]	39.4±3.1	3.0±0.5

[a]Energy level/γ ray not reported earlier.
[b]Could not be measured because of overlap with the 735.2 keV γ ray.
[c]Could not be measured because of overlap with the 734.1 keV γ ray.
[d]Could not be measured because of overlap with the 349.5 keV γ ray.

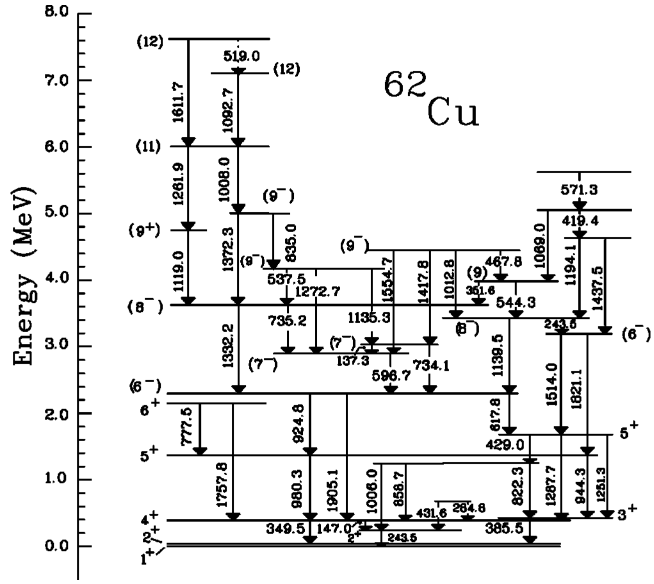

FIG. 2. The proposed partial level scheme of ^{62}Cu deduced from the present work.

The level at 1677.8 keV: There has been a controversy regarding the spin of this level. Bachner *et al.* [7] and Tsan Ung Chan *et al.* [8] have assigned spin parity 5^+ to this level while Daehnick *et al.* [6] has assigned 3^+ to it. In our scheme the two newly observed γ rays feeding this level, 617.8 and 1514.0 keV, arise from the levels at 2295.2 and 3191.5 keV, respectively. Of these the spin parity of the level at 2295.2 keV had been suggested to be 6^- [5,8] while the spin of the 3191.5 keV level was proposed to be 6. In the present work we have proposed negative parity for the level at 3191.5 keV. The fact that the level at 1677.8 keV is fed from two 6^- levels, rules out the 3^+ assignment, for this state.

The level at 2891.9 keV: It was earlier [5,8] assigned a spin value 7. It decays via a 596.7 keV dipole γ-ray to the 6^- level at 2295.2 keV. This has led us to tentatively assign a negative parity to this level. This level is also fed from the 8^- level at 3627.4 keV via a transition of energy 735.2 keV.

The level at 3029.2 keV: It was also assigned [5,8] a spin value of 7. The 137.3 keV transition arising from it appears to be stretched quadrupole in character. This level is fed from another level at 4164.6 keV ($J^\pi = 9^-$) via a stretched quadrupole transition of energy 1135.3 keV. A positive parity assignment to the level at 3029.2 keV will make the 137.3 keV γ ray an $M2$ transition. Because of the high retardation factor for $M2$ transitions, we do not expect to see such a low-energy $M2$ γ ray. Taking all the above facts into consideration the level has been assigned a spin-parity value (7^-). This assignment makes the multipolarity of the 137.3 keV γ-ray as E2 (but not stretched).

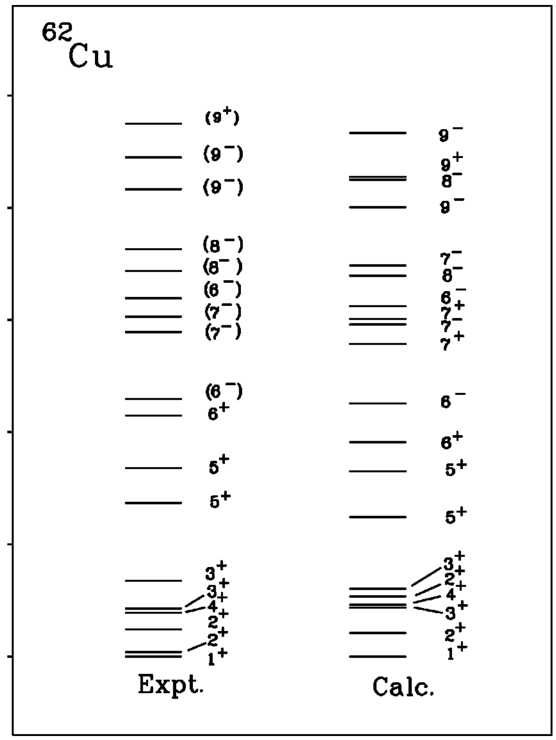

FIG. 3. A comparison of the experimental and the theoretical (obtained on the basis of IBFFM) level spectra in ^{62}Cu.

The level at 3191.5 keV: The DCO ratio measurement of the 1821.1 keV γ ray arising from it indicates that it is dipole in character. The 243.5 keV γ ray which depopulates the 8^- level at 3434.7 keV, is found to be of quadrupole character from the spectra gated by the 349.5 keV γ ray. Because of the large retardation factor for low energy $M2$ transitions, we expect the 243.5 keV to be an $E2$ transition and the level at 3191.5 keV is, hence, assigned tentatively a spin-parity (6^-).

The level at 3627.4 keV: It is known to decay [8] to the 6^- level at 2295.2 keV via the 1332.2 keV quadrupole transition. The latest compilation [4] has not shown any spin parity for this level although Chan *et al.* [8] have assigned a value of 8^- to it. The fact that the 1332.2 keV γ ray is of quadrupole nature confirm the latter assignment.

TABLE II. Some of the transitions observed earlier as well as in the present experiment but not shown in the level scheme. The transitions not placed in the level scheme but which probably belong to ^{62}Cu are also included.

Gate set on E_γ in keV	Transitions observed but not shown in Fig. 2 in keV	Unplaced transitions in keV
349.5	439.3, 668.0, 687.0, 859.2, 1463.5	223.2, 403.5, 494.2, 605.5, 681.5
243.5	201.0, 687.0, 882.0, 1491.2	223.2, 359.5, 494.2, 681.5
385.5	272.0, 378.5, 439.3, 587.5, 668.0, 687.0, 1060.3, 1491.2,1729.0	223.2, 359.5, 494.2, 1261.9
1261.9 and 1092.7	201.0	1278.0

The level at 3979.0 keV: The 544.3 keV transition depopulating it appears to be of dipole character. So the earlier spin assignment ($J=9$) to this level is confirmed in our experiment.

The level at 4164.6 keV level: It was predicted [8] to have a spin value of 9. The 1272.7 keV γ ray depopulating this level seems to be of quadrupole character and the 537.5 keV decay is found to be of stretched dipole character. These have led us to assign a negative parity to this level.

We will now discuss the levels that have been proposed in this work. They are at energies 4446.6, 4628.8, 4999.6, 5048.2, 5619.5, 6008.3, 7101.0, and 7620.2 keV.

The 4446.6 keV level: It decays, among others, to the level at 2891.9 keV through the 1554.7 keV quadrupole γ rays, respectively. Hence this level has been tentatively assigned a spin-parity (9^-).

The levels at 4628.8, 5048.2, and 5619.5 keV: The 1069.0 keV transition depopulating the level at 5048.2 keV is of quadrupole character. The 419.4 keV transition arising from the 5048.2 keV level is of dipole nature. The level at 5619.5 keV is proposed on the basis of the observation of a 571.3 keV γ ray in coincidence with the 419.4 keV γ ray.

The level at 4999.6 keV: It depopulates via the 835.0 keV and 1372.3 keV γ rays to the 4164.6 keV ($J^\pi=9^-$) and 3627.4 keV ($J^\pi=8^-$) states, respectively. Both these transitions are of mixed dipole-quadrupole nature and hence this level has been assigned spin-parity of (9^-).

The level at 6008.3 keV: It is found to deexcite via the 1261.9 keV γ ray to the previously known 4746.4 keV (9^+) level and through a 1008.0 keV one to the 4999.6 keV (9^-) level. Both these transitions are of stretched quadrupole nature. Hence a tentative spin of $J=(11)$ is assigned to this level.

The levels at 7101.0 and 7620.2 keV: These two states feed the same level at 6008.3 keV through the 1092.7 and 1611.7 keV γ ray which are observed to be dipole in nature. Hence both these levels are tentatively assigned spin values 12.

IV. DISCUSSIONS

The interacting boson-fermion-fermion model (IBFFM) has already been used to describe odd-odd Cu isotopes [10]. However, for the sake of completeness, we briefly discuss the method of calculation followed in that work. The structure of the odd-odd nuclei may be described as an unpaired proton and an unpaired neutron coupled to a boson core. The Hamiltonian for the odd-odd nuclei may be written as a sum of a boson part, two parts describing odd proton-core and odd neutron-core interactions, two parts describing the one body fermion terms and a part describing the residual interaction between the odd particles [11].

$$H=H_B+H_{B\pi}+H_{B\nu}+H_\pi+H_\nu+H_{\pi\nu}, \tag{1}$$

where π (ν) refers to proton (neutron) and B refers to the boson core.

The boson part is the usual IBM-1 Hamiltonian [12]. The odd particle core interaction is the simple form given in Refs. [13,14]. The interaction between the odd particles is in the form of a delta function [15] viz.

$$H_{\pi\nu}=-A(1-\alpha+\alpha\vec{\sigma}_\pi\cdot\vec{\sigma}_\nu)\delta(\vec{r}_\pi-\vec{r}_\nu), \tag{2}$$

where A and α are adjustable parameters.

In an earlier work [10] single particle levels consisting of $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ had been used for both type of particles, proton and neutron, to describe the low-lying states of the odd-odd Cu isotopes. The different parameters of the model were adjusted by fitting the energy levels of the even-even core (^{60}Ni), the two nuclei with core plus one nucleon (^{61}Ni,^{61}Cu) and the odd-odd nucleus (^{62}Cu). A surface δ plus spin δ interaction was taken as the residual interaction between the odd-proton and the odd-neutron [10]. The Hamiltonian for the odd-odd Cu isotopes [10] was diagonalized in the basis $|[j_\pi(j_\nu|n_d,v,L\rangle)_I]_J\rangle$ where $j_\pi(j_\nu)$ is the proton (neutron) angular momentum and n_d, v, and L refer to boson U(5) chain quantum numbers.

TABLE III. Major components of the wave function of some of the low lying levels as calculated in the IBFFM.

State	Expt. energy (keV)	Wave function
1_1^+	0	$0.672|\pi p_{3/2}\nu f_{5/2}\rangle-0.467|\pi p_{3/2}\nu p_{3/2}\rangle$
		$-0.324|\pi f_{5/2}\nu p_{3/2}\rangle+0.330|\pi f_{5/2}\nu f_{5/2}\rangle$
2_1^+	41	$0.531|\pi p_{3/2}\nu f_{5/2}\rangle-0.504|\pi p_{3/2}\nu p_{3/2}\rangle$
		$-0.498|\pi p_{1/2}\nu p_{3/2}\rangle-0.233|\pi f_{5/2}\nu f_{5/2}\rangle$
2_2^+	243.4	$0.586|\pi p_{3/2}\nu f_{5/2}\rangle+0.605|\pi p_{3/2}\nu p_{3/2}\rangle$
3_1^+	426.1	$0.225|\pi p_{3/2}\nu f_{5/2}\rangle+0.928|\pi p_{3/2}\nu p_{3/2}\rangle$
3_2^+		$0.848|\pi p_{3/2}\nu f_{5/2}\rangle-0.217|\pi p_{3/2}\nu p_{3/2}\rangle$
4_1^+	390.2	$0.955|\pi p_{3/2}\nu f_{5/2}\rangle$
4_2^+		$0.727|\pi f_{5/2}\nu p_{3/2}\rangle+0.353|\pi f_{5/2}\nu f_{5/2}\rangle$
		$+0.278|\pi p_{3/2}(\nu p_{3/2}\otimes 2_1^+)_{5/2}\rangle$
		$+0.215|\pi p_{3/2}(\nu p_{3/2}\otimes 2_1^+)_{7/2}\rangle$
5_1^+	1370.4	$0.837|\pi f_{5/2}\nu f_{5/2}\rangle+0.324|\pi p_{3/2}(\nu f_{5/2}\otimes 2_1^+)_{7/2}\rangle$
		$+0.229|\pi p_{1/2}(\nu f_{5/2}\otimes 2_1^+)_{9/2}\rangle$
5_2^+	1677.8	$0.280|\pi f_{5/2}\nu f_{5/2}\rangle-0.800|\pi p_{3/2}(\nu f_{5/2}\otimes 2_1^+)_{7/2}\rangle$
		$+0.419|\pi p_{3/2}(\nu p_{3/2}\otimes 2_1^+)_{7/2}\rangle$

In the present work, we have extended the model space to include both the positive parity orbitals $\nu g_{9/2}$ and $\pi g_{9/2}$. However, to describe high spin states, the best results could be obtained only after increasing the energy of the *d* boson of the core by 100 keV. So the present calculation uses a *d*-boson energy $\epsilon_d = 1.4$ MeV. It may be noted that there is a typographical error in Ref. [10] in the sense that the energy values of $\epsilon_{3/2}$ and $\epsilon_{5/2}$ in ^{61}Ni have been interchanged. The description of other parameters and their values are given in Ref. [10]. The calculated energy values up to spin 9 of both negative and positive parity states are compared with the experimental results in Fig. 3. It has been already shown that the positive parity states below 1 MeV excitation energy are described fairly well in this framework [10]. Here we see that the energy and the spin of the lowest negative parity state is correctly reproduced. In general the agreement between the theoretical prediction and the experimental observation is found to be fairly satisfactory up to about 5 MeV excitation energy. The high spin states above spin 9 is not expected to be explained by this model as there are only two *d* bosons outside the ^{56}Ni core. The interacting boson model can take care of the higher spin states by assuming a different configuration involving particle hole excitations across the shell gap [16]. However, that involves detailed knowledge of the different configurations of the core as well as that of the odd nuclei and it will also be a prohibitively large calculation. Since we know only a few levels above the levels with spin 9, this has not been attempted.

It has been suggested [8] that the 1^+, 2^+, 3^+, and 4^+ levels at 0, 159, 362, and 574 keV, respectively, in ^{64}Cu are multiplets of the $\pi p_{3/2} \nu f_{5/2}$ configuration. However, the present calculation suggests that the lower levels are of mixed configuration. In Table III, we give the major components of the wave function of some of the low-lying levels.

V. SUMMARY

The nucleus ^{62}Cu has been studied using a heavy ion projectile to populate its high spin states. Most of the earlier levels have been confirmed and the spin parity assignments of a few of them have been verified. A number of new levels have been proposed extending the energy scheme up to about 7.6 MeV. A simple IBFFM calculation seems capable of explaining the observed energy spectrum up to spin 9 of both positive and negative parity states.

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