Description of Nuclear Structure of ^{73}Cu in a Self- Consistent Approach

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Abstract: The characteristic nuclear structure properties of odd mass ^{73}Cu nucleus has been calculated within two body effective interactions incorporated in a self consistent quantum mechanical framework known as - projected shell model in order to test the efficacy of the chosen valence space. The Projected Shell Model (PSM) uses a truncated valence space under the guidance of the deformed mean-field solutions so as to make the calculations feasible. This implies that the PSM is a novel and efficient way to bridge the two conventional techniques: the deformed mean-field approximations, which are widely applied to heavier nuclei but able to describe the physics only in the intrinsic frame, and the spherical shell model diagonalization method, which is most fundamental but practical only for lighter systems. The PSM calculations are performed to obtain the yrast line and also the description of the formation of the yrast level structures from multi-quasi-particle configurations based on $\pi f \otimes \nu g$ bands has been presented. The back-bending in moment of inertia and rotational alignment has also been studied. Back-bending is found to be attributed to the alignment of a pair of $g_{9/2}$ neutron along the rotation axis. The calculated results are also compared with the available experimental data and a good agreement has been found from the comparison.

Keywords: Projected shell model; yrast spectra; multi-quasi-particle configuration

1. Introduction

The region of medium-mass neutron-rich nuclei around Z = 28 and 40 < N < 50 has been found to be one of the fascinating subject because many intensive experimental investigations have been done in the last few years. [1-4] The reduction of the Z = 28 gap beyond N = 40 is found from indirect experimental indications in ^{70}Ni [5], ^{70,71,73}Cu [6,7] and ^{74}Zn [8], where increased collectivity is observed from measured B(E2) values in Coulomb excitation experiments. The discovery by [Franchoo et al.,] of the sharp drop of the 5/2- state in ^{71,73}Cu [2, 9,10] provided the first experimental evidence that the filling of the $g_{9/2}$ orbital can cause significant shifts in the energy of the $f_{5/2}$ and $f_{7/2}$ proton orbitals, similar to the $h_{11/2}$ and $g_{7/2}$ in the odd-A Sn and Sb isotopes, respectively [11]. Thus the incorporation of $g_{9/2}$ orbital in the valence space is believed to play an important role in the evolution of the shell structure away from stability [12]. β-decay studies have evidenced the sharp lowering of the $\pi 1f_{5/2}$ orbital in ^{73}Cu isotopes as the occupancy of the $\nu 1g_{9/2}$ orbital increases [2]. However, the level structure of the odd-mass, neutron-rich Cu isotopes is more complex to study, because of the presence of not only the proton single-particle states but also core-coupled and collective states are expected to lie at low excitation energies. Therefore, neutron-rich Cu isotopes, having one proton outside the Z = 28 shell, are good probes of the single-particle structure in the ^{78}Ni region. So one of the main aim of the present study is to calculate the nuclear structure properties of Cu nucleus with A = 73 by employing a quantum mechanical approach - Projected Shell Model. The purpose of the present work is to perform a systematic PSM study of the low and high-spin properties for the ^{73}Cu nucleus. The physical quantities to be described are energy spectrum, band diagrams, back-bending in moment of inertia and rotational alignments. In addition, the comparison of the available experimental data with theory in a systematic way is also made to test the efficacy of the

present framework. In Section 2, a brief outline of the theory is presented. The results of calculations and comparisons with experimental data are presented in Section 3. Finally, the summary is given in Section 4.

2. The Model

The PSM [13,14] is based on the spherical shell model concept. It differs from the conventional shell model in the sense that the PSM uses the angular momentum projected states as the basis for the diagonalization of the shell model Hamiltonian. The shell model truncation is first achieved within the quasi-particle (qp) states with respect to the deformed Nilsson + BCS vacuum; then rotational symmetry (and number conservation if necessary) are restored for these states by standard projection techniques to form a spherical basis in the laboratory frame; finally the shell model type of Hamiltonian is diagonalized in this deformed Nisson single particle basis.

For the present case i.e., for odd proton nuclei, the multi-quasi-particle states ($\left|\phi_k\right\rangle$) are spanned by the set

$$a_\pi^+\left|0\right\rangle, a_\pi^+ a_{\nu 1}^+ a_{\nu 2}^+\left|0\right\rangle \tag{1}$$

for odd proton nuclei, where $\left|0\right\rangle$ is the quasi-particle vacuum. $a^\dagger$'s is the quasi-particle creation operator for this vacuum. ν' s (π's) index runs over the neutron (proton) quasi-particle states.

The Hamiltonian used in the present work is

$$\hat{H}_{QP} = \mathrm{H_o} - \frac{1}{2}\chi\sum_\mu \hat{Q}_\mu^\dagger \hat{Q}_\mu - G_M \hat{P}^\dagger \hat{P} - G_Q \sum_\mu \hat{P}_\mu^\dagger \hat{P}_\mu \tag{2}$$

where, H_o represents the Nilsson single particle Hamiltonian, involving spin-orbit interactions whose strength is given by the parameters, κ and μ; while the second term includes the quadrupole-quadrupole interaction and third and fourth terms denotes the monopole and quadrupole pairing interactions respectively. The strength of these two body quadrupole-quadrupole interaction is described by the parameter, χ, which is adjusted by the mean field calculations so that quadrupole deformation ε_2 is obtained. However the monopole pairing strength takes the form

$$G_M = \left(G_1 \mp G_2 \frac{N-Z}{A}\right)\frac{1}{A} \quad (\mathrm{MeV}) \tag{3}$$

where the -(+) sign is for neutron (proton). The choice of the strengths G_1 and G_2 depends on the size of the single particles gaps in the calculations. The quadrupole pairing strength G_Q is supposed to be proportional to G_M.

3. Analysis of Results

3.1 Yrast band and its formation

By the diagonalization of the Hamiltonian eq. (2) in the projected bases eq. (1), one thus obtains energy levels for a given spin which are then plotted in a diagram. A diagram in which the lowest projected energies of various bands is plotted against the spin (I) is referred to as a band diagram, which gives the projected energies for the configurations close to the Fermi surface to explain the underlying physics which contains incredibly rich information has been shown in Fig. 1. One can see from this figure that up to the spin value of $11/2^-$, the yrast band is made up of a 1-*qp* band with configuration: $1\pi f_{7/2}[-3/2]$, K= -3/2. Afterwards, a 3-qp band with configuration: $1\pi f_{7/2}[-3/2] + 2\nu g_{9/2}$

[5/2,-3/2], with K= -1/2 crosses the 1-qp band and forms the yrast band and thus band-crossing occurs at spin 11/2$^-$. After the spin value 27/2$^-$, three more 3-qp bands identified as: $1\pi f_{7/2}[1/2]+ 2\nu g_{9/2}$ [5/2,-3/2], with band head K=3/2; $1\pi f_{5/2}[1/2]+ 2\nu g_{9/2}$ [5/2,-3/2], K=3/2 and $1\pi f_{7/2}[-3/2]+ 2\nu g_{9/2}$ [5/2,1/2], with band head K=3/2 dives down in yrast regions and thus forms the yrast band up to the last calculated spin. The lowest energies obtained, thereafter configuration mixing, corresponding to particular angular momentum represents the yrast band or ground-band. The PSM results on yrast band are plotted against the spin for the ^{73}Cu isotope in Fig. 2. Further, for comparison, the available experimental data [15] is also plotted. A good agreement has been obtained from the comparison. Also, the experimental band head i.e., 3/2$^-$, has been reproduced with the present PSM calculations. It is further pertinent to mention here that the available experimental data is sparse i.e., up to the spin value of 9/2$^-$ and PSM calculations has been able to calculate the energy values up to the spin value of 53/2$^-$ which provides an opportunity for the nuclear physicists to look for this data.

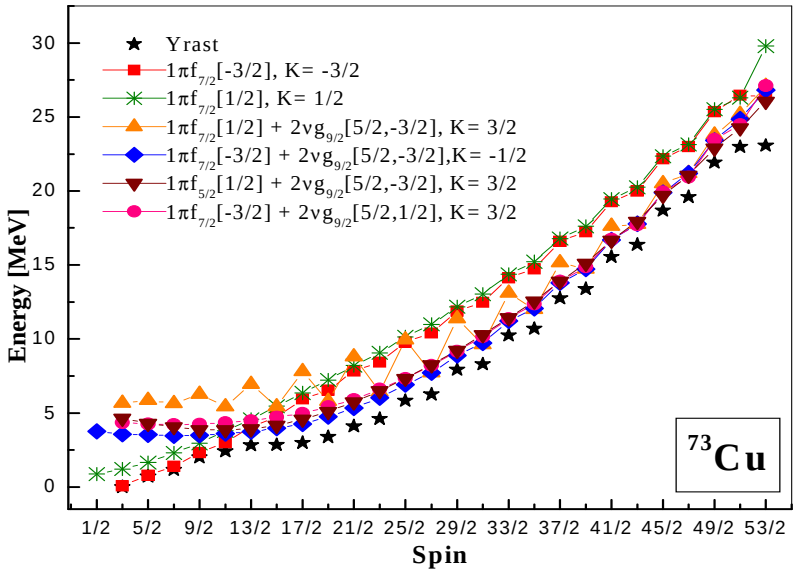

Fig. 1: Band diagram for ^{73}Cu nucleus. Only low lying bands are plotted.

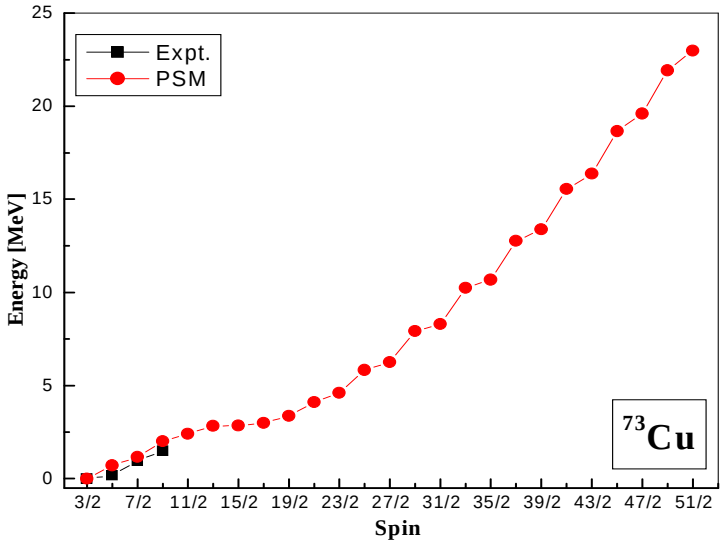

Fig. 2: Yrast band for ^{73}Cu nucleus.

3.2 Back-Bending in moment of inertia

The behaviour of rotational band can be studied by the phenomenon of back-bending in kinetic moment of inertia. The values of kinetic moment of inertia ($2\Im^{(1)}$) and rotational frequencies ($\hbar^2\omega^2$) are calculated by using the formulae as given below

$$2\Im^{(1)} = \frac{(2I-1)}{\omega} \tag{5}$$

$$\hbar\omega = \frac{E_\gamma}{\sqrt{(I+1)(I+2)-K^2} - \sqrt{(I-1)I-K^2}} \tag{6}$$

where, $E_\gamma = E(I) - E(I-2)$.

Fig. 3 gives the plot of kinetic moment of inertia verses the square of rotational frequency. From the figure, it has been found that the plot of calculated rotational frequency suddenly decreases from 0.377 to 0.161 with increase in kinetic moment of inertia at the spin value of 11/2$^-$, whereas the available experimental data is sparse to show this back-bend. It has also been seen from the band diagram of ^{73}Cu nucleus (see Fig. 1), the band crossing occurs at same spin value, i.e., at 11/2$^-$, at which the back-bending is observed.

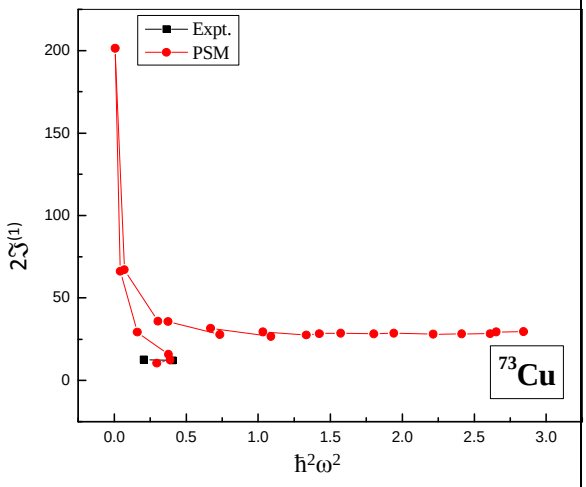

Fig. 3: Back-bending in moment of inertia in ^{73}Cu nucleus.

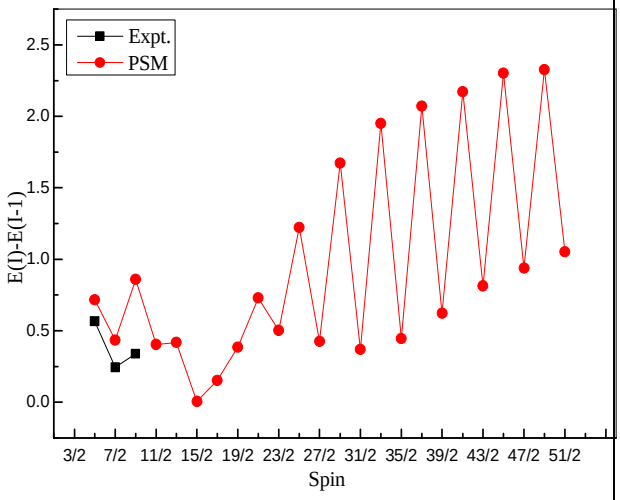

Fig. 4: Plot of Transition energies in ^{73}Cu nucleus.

Figure 4 gives the transition energies i.e. E(I)-E(I-1) values for ^{73}Cu nucleus. The calculated transition energies follow the same trend as that of experimental values. The PSM results predict a phase change in the signature dependence at the spin 11/2$^-$. This inversion in transition energy curve can be interpreted in terms of band mixing. As seen from Fig. 1, it is clear that 3-qp bands crosses 1-qp bands at the spin value of 11/2$^-$, thus the band crossing occurs at the same spin value i.e., 11/2$^-$ at which the spin inversion takes place in the transition energy plots for ^{73}Cu nucleus.

1. Summary

To summarize, one can say that the present PSM calculations reproduces the yrast energy levels of ^{73}Cu nucleus. Also, the formation of yrast bands from multi-quasi-particle bands is described successfully. It has been found that the low lying yrast band is obtained by 1-quasi-particle bands, whereas 3-quasi-particles bands contributes to the formation of yrast band for higher spin range. The phenomenon of back-bending in moment of inertia has been successfully explained by the present calculations. The good agreement of the calculation with the experimental data confirms that PSM provides the description of high spin structure of this nucleus.

Acknowledgements

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