Pairing Effects in Super-deformed Rotational Bands

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Introduction

Pairing effect of nucleons in the low energy nuclear systems and its interactions has been described by Molina in 2006 [1]. Theoretical studies with inclusion of collective quadrupole vibrations suggest that pairing correlations plays critical role in super-deformed ground states [2]. Pairing correlations in super-deformed rotational bands (SDRB's) varies in different mass regions – as most of them behaving like a rigid rotor at different rotational bands, angular momentum and moment of inertia [3-4]. Short ranged attractive forces between nucleons will favor nucleonic re-arrangements, especially in pairs in time reversed orbital [5]. Kinematic ($\mathcal{J}^{(1)}$) and Dynamic moment of inertia ($\mathcal{J}^{(2)}$) among SDRB's are very useful to predict and understand the systematic behavior of SD nucleus. It is to be noted that $\mathcal{J}^{(2)}$ is dependent on gamma ray transition energies while $\mathcal{J}^{(1)}$ is related to spin values of SDRB's. Most difficult part is to correctly assign spins of SDRB's, as most of them undergo de-excitation into known yrast states. In addition these nuclei will have very short life time in high spin states and show multiple bands in experimental spectrum. Therefore variation pattern of $\mathcal{J}^{(2)}$ in SDRB's are a function of rotational frequency at different mass region attributed to different ranges of angular momentum. Other important factor to consider is the changing pairing correlation at large deformations and characteristics of intruder orbital configurations. Several studies in SD bands, especially in A~190 mass region, have shown increasing dynamic moment of inertia with increasing rotational frequency (ħω). As ħω of SD bands increases the pairing correlation becomes weaker leading to increasing $\mathcal{J}^{(2)}$, which results in combined alignment of both high N-quasi protons and quasi neutrons. At the same time, in lower mass region like A~60, 80, 130 and 150 mass region dynamic moment of inertia was decreasing with increasing rotational frequency - probably because pairing correlations are strongly quenched than those in A~190 region, as explained through high N intruder occupation quantum numbers [6-9]. In the present work we have studied the behavior of SDRB's through $\mathcal{J}^{(2)}$ as a function of ħω for SD bands in A~60, 80, 130, 150 and 190 region using Variable Moment of Inertia (VMI) model through observed spectra and conclude that pairing effects are important in the behavior of $\mathcal{J}^{(2)}$ in SDRB's.

Methods

a) Experimental details

Experimentally, only γ-ray energies are available and γ-ray transition energies within a band is in the form:

$$E\gamma(I \rightarrow I-2) = E(I) - E(I-2) \qquad (1)$$

Rotational frequency (ђω) and dynamic moment of inertia for SDRB's are estimated through experimental inter-band E2 transition energies. This is expressed as:

$$\hbar\omega(I) = \frac{E\gamma(I) + E\gamma(I+2)}{4}\ \mathrm{MeV} \qquad (2)$$

$$\mathcal{J}^{(2)}(I) = \frac{4}{E\gamma(I+2) - E\gamma(I)}\ \hbar^2\mathrm{MeV}^{-1} \qquad (3)$$

Where Ђω and $\mathcal{J}^{(2)}$ are dependent on γ- ray transition energies.

b) Variable Moment of Inertia (VMI) Model

In VMI equation for $I_0 \neq 0$, the band head energies of rotational bands for odd-odd nuclei can be expressed as: [10-11]

$$E_I = E_0 + \frac{I(I+1) - I_0(I_0+1)}{2\mathcal{J}_I} + \frac{C(\mathcal{J}_I - \mathcal{J}_0)^2}{2} \qquad (4)$$

Where E_0 is band head energy of rotational band, $\mathcal{J}_0$ is the band head moment of inertia, the variable $\mathcal{J}_I$ is the moment of inertia of the nucleus for each spin value and C is the stiffness parameter. Modified VMI equation for SDRB's is expressed as: [12-13]

$$E\gamma(I \rightarrow I-2) = \frac{1}{2\mathcal{J}_0}[I(I+1) - (I-2)(I-1)] + \frac{1}{8C\mathcal{J}_0{}^4}\{[I(I+1)]^2 - [(I-2)(I-1)]^2\} \qquad (5)$$

The two parameters C and $\mathcal{J}_0$ were determined by fitting least square procedures of all known energies in observed spectra.

Results and Discussion

The behavior of $\mathcal{J}^{(2)}$ as a function of ħω were studied with experimental data and VMI transition energies of SDRB's in different mass regions like A~60, 80, 130, 150 and 190. VMI equation was dependent on two parameters stiffness constant (C) and band head moment of inertia ($\mathcal{J}_0$). Values for these two parameters were obtained from known experimental transition energies and spin values using fitting procedures. The results are presented in table 1. In A~190 mass region most of the C value was smaller as compared to C values among A~60, 80, 130 and 150 mass regions. The rigidity of SD bands in A~190 mass region was less than those in in A~60, 80, 130 and 150 regions. In lower mass region SD bands were showing larger deformation and high rotational frequencies and therefore pairing effect have very crucial role in predicting the behavior of $\mathcal{J}^{(2)}$.

SD band	$\mathcal{J}_0$ (keV^{-1}).	C (keV^3)
^{61}Zn(band1)	0.0202	+39.5x10^7
^{80}Sr(band3)	0.0259	+55.5x10^7
^{136}Nd(band1)	0.0565	+12.2x10^7
^{148}Gd(band6)	0.1092	+8.7x10^6
^{194}Hg(band1)	0.0888	-5.7x10^6

In A~190 mass region, the $\mathcal{J}^{(2)}$ was increasing as a function of ħω. It is probably due to alignment of a relatively large number of high-j orbitals, or more generally, to a gradual alignment of several orbitals to decreasing pairing correlation. This was more commonly seen with unpaired particles in A~190 mass region suggesting that all SD bands in A~190 mass region shall transition to form good rotational cascades but dynamic moment of inertia increase with rotational frequency. This can provide insights on the underlying microscopic structure of SD bands and pairing effects at large deformation, which influences $\mathcal{J}^{(2)}$. In such cases, the static pairing correlation was more important. However we found that the behavior of $\mathcal{J}^{(2)}$ as a function of ħω decreases for SD bands in A~60, 80, 130 and 150 mass regions, due to paired particles in this regions which influences very high angular momentum (high N-intruder occupation quantum numbers)[6-13]. The microscopic structure of yrast SD bands depends mainly on intruder orbitals. In this mass region, the high-j and high-N intruder orbitals will bring SD Fermi levels closer through large deformations and high rotational frequencies; for proton N=6 ($i_{13/2}$) and neutron N=7 ($j_{15/2}$) states. These orbitals carry large intrinsic angular momentum and have quadrupole moment and strongly affects by Coriolis interaction. The occupation numbers of these orbitals will have a strong impact on the dynamic moment of inertia [6-9]. These results are presented in figures.

Conclusion

We have studied the variations in dynamic moment of inertia of SDRB's in A~60,80, 130, 150 and 190 mass regions using VMI equation and experimental spectra. The rigidity of SD bands in A~60, 80, 130 and 150 mass regions is higher than in A~190 region. Accordingly pairing correlations are important for predicting behavior of $\mathcal{J}^{(2)}$ as a function of ħω. In A~190 mass region in most SD bands increasing pattern of $\mathcal{J}^{(2)}$ was showing as a function of ħω, due to alignment of nucleon pairs in high-N intruder orbitals in the presence of pairing correlations. While in A~60, 80, 130 and 150 mass regions the $\mathcal{J}^{(2)}$ were decreasing as a function of ħω where pairing correlations are strongly quenched than those in A~190 region.

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Figure1: The variations of $\mathcal{J}^{(2)}$ of SD bands in A~60,80, 130, 150 and 190 regions. The dotted line represent experimental data and solid line represent VMI data.