# Systematic Study of Signature Dependence in Two - Quasiparticle States in Deformed Nuclei

Kawalpreet Kalra*
*Amity Institute of Nuclear Science and Technology (AINST), Amity University Uttar Pradesh, Noida -201303, India*
*E-mail: kawal1211@gmail.com

## Introduction:

The collective structure of atomic nuclei, intermediate between the spherical and quadrupole deformed structure presents challenges to theoretical understanding. A number of models have been developed to deal with such deformed nuclei. The experimental and theoretical studies result in a large amount of data for one - quasiparticle (1QP), two - quasiparticle (2QP) and multi - quasiparticle (MQP) states. The energy spectrum of two-quasiparticle (2QP) rotational bands of deformed nuclei exhibits many interesting features like large odd–even staggering, signature inversion and signature reversal. The level structure of doubly even and doubly odd deformed nuclei is among the most complex topics in nuclear physics. The main objective of the work is the elucidation of the behavior of rotational bands and to study the structure of signature split bands observed in doubly even & doubly odd nuclei. We focus on the rotational properties of bands in terms of the Coriolis and particle – particle coupling.

## Formalism:

Various studies have been done in the framework of different models to elaborate the underlying mechanism for signature effect present in 2QP rotational bands. But, after so many investigations the mechanism is enough fuzzy and needs more detailed and specific study. The Two Quasiparticle plus Rotor Model (TQPRM) [1] has been used for identical particles to perform calculations for doubly even deformed nuclei. In the framework of TQPRM, the total Hamiltonian is divided into two parts, the intrinsic and the rotational,

$$H_{tot} = H_{intr} + H_{rot} \qquad \ldots\ldots [1]$$

The intrinsic part consists of a deformed axially symmetric average field $H_{av}$, a short range residual interaction $H_{pair}$, and a short range neutron - neutron /proton – proton residual interaction $V_{12}$, so that

$$H_{intr} = H_{av} + H_{pair} + V_{12} \qquad \ldots\ldots[2]$$

The long range vibrational interaction has been neglected in this formulation. For an axially - symmetric rotor we may write,

$$H_{rot} = \frac{\hbar^2}{2\mathfrak{I}} (I^2 - I_z^2) + H_{cor} + H_{ppc} + H_{irrot} \qquad \ldots\ldots[3]$$

Here, $\mathfrak{I}$ is the moment of inertia with respect to the rotation axis. The basis eigenfunctions may be written as $|IMK\alpha\rangle =$

$$\left[\frac{2I+1}{32\pi^2(1+\delta_{KO})}\right]^{½} \{D^I_{MK}(\,|K\alpha\rangle - |K^A\alpha^A\rangle) + (-1)^{I+K} D^I_{M-K} R_i\,(\,|K\alpha\rangle - |K^A\alpha^A\rangle)\} \qquad \ldots\ldots[4]$$

Where the index α characterizes the configuration ($\alpha = \rho_1\rho_2$) of the two neutrons or the two protons. The TQPRM calculations involve many parameters namely Inertia parameter$\left(\frac{\hbar^2}{2\mathfrak{I}}\right)$, Band head energy ($E_{\alpha\pm}$), decoupling parameter, Newby shift ($E_N$) and adjusted during the fitting process. The standard Nilsson parameters were used κ and μ with a deformation of $\epsilon_2$ and $\epsilon_4$ to obtain the single particle energies and $\langle j +\rangle$ matrix elements. The matrix elements are treated as free parameters. The quasiparticle energies were obtained by using a fixed value of pairing gap $\Delta$ = 1Mev and Gallagher Moszkowski splitting was assumed to be more than 300keV in all the cases which was modified during the fitting procedure if necessary. The calculations require mixing of many 2qp experimentally known and unknown bands; so estimated energies of experimentally unknown bands is obtained by using a semi-empirical formulation.

## Results and Conclusion:

The available experimental data for all isotopes from $_{62}$Sm to $_{74}$W for doubly even nuclei in rare earth region have been analyzed in detail. A large odd even staggering has been found in 22 cases out of total 86 experimentally known cases of doubly even nuclei throughout the rare earth region. A reverse signature pattern is found in $^{162}_{66}$Dy and $^{170}_{74}$W. The phenomenon of signature reversal has been observed in $^{170}_{70}$Yb and well explained by Goel et al. [2] The TQPRM calculations have been done for $^{170}$W and $^{162}$Dy. It has been revealed from the calculations that the reverse behavior of signature pattern in $^{170}$W is due to the Coriolis coupling which comes into picture through a chain of interacting bands [3].

The systematic study of doubly odd nuclei in rare earth region has been done. The data of 41 experimentally known cases of $\{(h_{11/2})_p \otimes (i_{13/2})_n\}$ orbitals for all available isotopes of $_{61}$Pm to $_{75}$Re have been analyzed. The large odd – even staggering and signature inversion have been observed in $\{(h_{11/2})_p \otimes (i_{13/2})_n\}$ orbitals. The main findings of the systematics are: The point of signature inversion ($I_c$), shifts towards lower spin with increasing neutron number in a chain of isotopes, secondly the point of signature inversion ($I_c$), shifts towards higher spin with increasing proton number in a chain of isotones. The magnitude of staggering before the inversion point becomes smaller in a chain of isotopes. We have done two sets of calculations. The results of the calculations are: In $_{67}$Ho chain; from $^{158}$Ho to $^{164}$Ho, with increasing neutron number, the point of signature inversion ($I_c$) shifts towards lower spin and in a chain of isotones $^{156}_{65}$Tb , $^{158}_{67}$Ho and $^{160}_{69}$Tm ; the point of signature inversion shifts towards higher spin with increasing proton number. However, to reproduce the inversion in lower mass region of rare earths, the inclusion of 1/2[541] proton states of $h_{9/2}$ orbital is necessary as seen in $^{156}$Tb doubly odd nuclei [4].

The TQPRM calculations for K = 0 band have been summarized. The K = 0 band exhibits an important feature known as Newby shift. The important point is that solely the Newby shift is responsible for odd – even staggering in K = 0 band. When $\Omega_p = \Omega_n = \Omega = 1/2$ orbital is involved, both the Newby term and decoupling parameter term become effective. We have analyzed total 36 cases of K = 0 rotational bands in doubly odd nuclei in rare earth region. Within the framework of TQPRM the importance of Newby shift has been investigated. The results of calculations are close to experimental value.

The anomalous feature of signature inversion is not limited to rare earth nuclei. To show this we extended the area of research above and below the rare earth region for doubly odd nuclei. The feature of second signature inversion and low spin signature inversion has been observed. In $^{184}_{79}$Au (above the rare earth region), TQPRM calculations are done for the ground state band; $K_+ = 5^+$, $\{3/2[532]_p \otimes 7/2[514]_n\}$ and for the excited bands with configuration $K_+ = 5^+$, $\{1/2[660]_p \otimes 9/2[624]_n\}$ and $K_+ = 5^-$, $\{1/2[541]_p \otimes 9/2[624]_n\}$ to reproduce the feature of second signature inversion. In $^{126}_{53}$I (below the rare earth region), the low spin signature inversion has been revealed for $K_+ = 6^-$, $\{3/2[411]_p \otimes 9/2[514]_n\}$ band [5]. The mechanism behind these features is same as in rare earths.

The overall conclusion is that TQPRM is unique which not only explains the signature inversion and odd - even staggering in doubly odd nuclei but also successfully reproduces the reverse signature pattern in doubly even nuclei. The calculations revealed that the signature effect present in high - j orbitals of rare earths is also present above and below the rare earth region.

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**References:**

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