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# Unusual Features of rotational bands in $^{184}$Au deformed doubly-odd nucleus

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***Abstract:*** *Two-quasiparticle rotational bands of doubly-odd $^{184}$Au have been investigated. The two quasiparticle plus rotor model (TQPRM) calculations are done for the bands where sufficient experimental data is available mainly for the ground state band{$3/2[532]_\pi \otimes 7/2[514]_\nu$}and the excited bands with configuration {$1/2[660]_\pi \otimes 9/2[624]_\nu$} and {$1/2[541]_\pi \otimes 9/2[624]_\nu$}. Peculiar features like second point of signature inversion, signature reversal and band crossing are observed in these bands of $^{184}$Au. The ambiguity regarding the configuration assignment of ground state band is resolved. The calculations for ground state band clearly show that the proton orbital changes from $3/2[532]_\pi$ to $1/2[541]_\pi$ with increasing spin. The mechanism of unusual feature like second point of signature inversion is also presented.*
***Keywords:*** *Signature inversion, Odd-even staggering, Coriolis coupling, Particle-Particle coupling,*

## I. Introduction:

The phenomenon of **signature inversion** observed in high-j rotational bands of odd-odd nuclei have been discussed by many authors [1-4]. Recently we have done the systematic study of signature inversion phenomenon for odd-odd nuclei in rare earth region [5] where we observed some interesting features like signature inversion, signature reversal [6], large odd-even staggering and shifting in point of signature inversion towards lower/higher spin as neutron/proton number increases. Also the magnitude of staggering before the inversion point becomes smaller with increasing neutron number in a chain of isotopes. Signature inversion and shifting in point of signature inversion is well reproduced by TQPRM calculations [7].

It is well known that for a two quasi particle configuration the favored signature is given by $\alpha_f=1/2(-1)^{j_\pi - (1/2)} + 1/2(-1)^{j_\nu - (1/2)}$ while the unfavored signature is determined by $\alpha_{uf}=1/2(-1)^{j_\pi - (1/2)} + 1/2(-1)^{j_\nu + (1/2)}$ or $\alpha_{uf}= 1/2(-1)^{j_\pi + (1/2)} + 1/2(-1)^{j_\nu - (1/2)}$, where $j_\pi$ and $j_\nu$ are angular momentum of the valence proton and neutron respectively. Generally the levels with $\alpha_f$ are expected to lie lower in energy than the levels with $\alpha_{uf}$. But in some of the bands with certain configuration, favored signature branch lies higher in energy than the unfavored signature at low spin. But after a certain spin $I_c(1)$ called Critical spin, the favored signature branch lies lower in energy than the unfavored signature at high spins [4]. This feature is termed as **signature inversion** [8-13]. It is also observed that after restoring the normal feature the abnormal feature reappears after a certain spin $I_c(2)$ and it is called as **second signature inversion.**

We have gone through the experimental data for rotational band in $^{184}_{79}$Au in which rich amount of confirmed experimental data is available for few bands. These bands are generally of high-j configuration like $h_{9/2}$, $h_{11/2}$, $i_{13/2}$ proton and $i_{13/2}$, $f_{7/2}$ neutron. We have seen above said unusual features in these bands of $^{184}$Au and there is an anomaly regarding the configuration assignment of ground state band in this nucleus. The phenomenon of signature inversion is well reproduced but the second signature inversion is new and needs more attention. As sufficient amount of experimental data is available for $^{184}$Au rotational bands, so it seems a very interesting problem to reproduce the second point of inversion. We have also to resolve the anomaly in configuration assignment of the ground band of this nucleus.

Firstly low spin states of $^{184}$Au were studied by using $\beta^+$ / EC decay of $^{184}$Hg by Ibrahim et al. [14] and four rotational bands were established by means of in-beam γ- ray spectroscopic technique [15]. Sauvage et al. [16] reported a further study on low spin states of $^{184}$Au. He suggested the nuclear structure of some levels of $^{184}$Au namely: (i) { $3/2[532]_\pi \otimes 7/2[514]_\nu$ }, $5^+$ for the ground state, (ii) { $3/2[532]_\pi \otimes 1/2[521]_\nu$ } for the $2^+$ isomeric state at 68.5 keV and (iii) { $\pi\, h_{9/2} \otimes 9/2[624]_\nu$ }, for the $3^-$ short lived isomeric state at 228.4 keV. He suggested that $4^+$ one at 146.5 keV have the same {$\pi\, h_{9/2} \otimes 7/2[514]_\nu$ }configuration as the $5^+$ ground state.

Further investigation have been carried out by S.C. Li [17] by means of in-beam γ- ray spectroscopic technique using the multidetector array of GASP to get the more information about the band structures of $^{184}$Au. In this experiment the excited states of $^{184}$Au were populated via the $^{159}$Tb ($^{29}$Si, 4nγ) reaction at a beam energy of 140 MeV. Most of the γ- rays reported in the literature [15] were observed in this experiment .The newly observed γ- rays were based on the coincidences with the known γ- rays [14, 15]. From the detailed analysis of the coincidence data a level scheme of $^{184}$Au consisting of seven rotational bands has been established by

S.C.Li. There are total seven rotational bands in new level scheme which are numbered from 1 –7 bands. The four bands reported by Ibrahim et al. [15] have been extended to higher spins and bands 1, 2 and 4 to lower spins in reference [17]. The three new bands labeled as bands 5 – 7 have been identified by S.C.Li.

The experimental staggering plots of $\Delta E(I\rightarrow I-1)/2I$ with angular momentum (I) are shown in figure 1 which represents the important feature of second signature inversion $I_c(2)$ in Band 2 $\{1/2[660]_\pi \otimes 9/2[624]_\nu\}$ and in Band 4 $\{1/2[541]_\pi \otimes 9/2[624]_\nu\}$. An anomalous feature in Band 1, the proton is in the $\pi\ h_{9/2}$ (3/2[532]) orbital for lower spin region and for higher spin it is changing from (3/2[532]) to (1/2[541]) orbital of $h_{9/2}$ is also shown in this figure. There is an issue in assigning the configuration to this particular band. Due to the presence of such unusual features in the experimental data of this nucleus we focus our attention particularly for three bands (Band 1, 2 and 4). Therefore the aim of our paper is to reproduce the second signature inversion in Band 2 & 4 and to resolve the issue of configuration assignment for the strongly mixed rotational Band1 (ground state

A brief detail of model & Choice of parameters is given in Section-2. Section-3 presents the results and discussion. This section contains the results obtained by TQPRM calculations and mechanism of signature inversion phenomenon observed in these bands. Section-4 contains the conclusion of paper.

## II. Model and Choice of Parameters:

We have used an axially symmetric two-quasiparticle plus rotor model (TQPRM). A detailed description of the model may be found in many papers [4]. Since the model is well known, we discuss the necessary basic formulas for completeness.

The total Hamiltonian is divided into two parts, the intrinsic and the rotational,

$$H = H_{intr} + H_{rot} \qquad ..... [1]$$

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-proton interaction $V_{\nu\pi}$, so that

$$H_{intr} = H_{av} + H_{pair} + V_{\nu\pi} \qquad ..... [2]$$

The vibrational part has been neglected in this formulation. For an axially-symmetric reflection–symmetric rotor

$$H_{rot} = \hbar^2/ 2\mathfrak{I}\ (I^2 - I_3^2) + H_{cor} + H_{ppc} + H_{irrot} \qquad ..... [3]$$

Where

$$H_{cor} = -\hbar^2 / 2\mathfrak{I}(I^+j^- + I^-j^+),$$
$$H_{ppc} = \hbar^2 / 2\mathfrak{I}\ (j_\pi^+ j_\nu^- + j_\pi^- j_\nu^+),$$
$$H_{irrot} = \hbar^2 / 2\mathfrak{I}\ [(j_\pi^2 - j_{\pi z}^2) + (j_\nu^2 - j_{\nu z}^2)].$$

The particle angular momentum j is given by the sum of the angular momentum of the odd proton $j_\pi$ and the odd neutron $j_\nu$. The operators $I_\pm = I_1 \pm iI_2$, $j_\pm = j_1 \pm ij_2$, $j_{\nu\pm} = j_{\nu 1} \pm ij_{\nu 2}$ and $j_{\pi\pm} = j_{\pi 1} \pm ij_{\pi 2}$ are the usual shifting operators. $\mathfrak{I}$ is the moment of inertia with respect to the rotation axis. The set of basis Eigen functions of $H_{av} + H_{pair} + \hbar^2/ 2\mathfrak{I}\ (I^2 - I_3^2)$ may be written in the form of the symmetrised product of the rotational wave function $D_{MK}^I$ and the intrinsic wave function $|K\alpha_\rho\rangle$ can be written as -

$$|IMK\alpha_\rho\rangle = \left[\frac{2I+1}{16\pi^2(1+\delta_{K0})}\right]^{1/2} \left[D_{MK}^I|K\alpha_\rho\rangle + (-1)^{I+K} D_{M-K}^I R_i|K\alpha_\rho\rangle\right] \quad ..[4]$$

Where the index $\alpha_\rho$ characterizes the configuration ($\alpha_\rho = \rho_\pi\rho_\nu$) of the odd proton and the odd neutron.

The projections of odd proton ($\Omega_\pi$) and odd neutron ($\Omega_\nu$) of the single quasiparticle angular momenta can couple in either parallel or antiparallel manner on the symmetry axis. This gives rise to Gallagher-Mosczkowski (GM) doublets: $K_+ = (\Omega_\pi + \Omega_\nu)$ and $K_- = |\Omega_\pi - \Omega_\nu|$. The neutron-proton interaction $V_{\nu\pi}$ splits the energy of this doublet and it is called GM splitting. As a result we have two rotational bands for each two quasiparticle configuration. The symbol $\sigma = \pm$ is used to denote the two types of bands $K_+$ and $K_-$. $E_{GM}$ is the Gallagher-Mosczkowski (GM) splitting energy and we have used GM splitting of $\pm$100keV for calculations.

The TQPRM calculations involve large number of free parameters. Three parameters namely Inertia parameter ($\hbar^2 / 2\mathfrak{I}$), Band Head Energy ($E_{\alpha\pm}$) and Newby shift ($E_N$) plays an important role in calculations. The Inertia parameter ($\hbar^2 / 2\mathfrak{I}$ ) is adjusted during the fitting process. The calculations require mixing of many 2qp experimentally known and unknown bands; so estimated energies of experimentally unknown bands is obtained by using semi-empirical formulation [18]. This formulation requires the single quasiparticle energies and the single particle energies are estimated from neighboring odd-A nuclei [19, 27]. The Newby shift ($E_N$) arises due to residual interaction between odd proton and neutron in case of $K_-= 0$ rotational bands [20, 21]. In our formalism the Newby shift term is defined as

$$C_\alpha = \langle \rho_\pi \Omega_\pi; \rho_\nu - \Omega_\nu | V_{\nu\pi} | \rho_\pi - \Omega_\pi; \rho_\nu \Omega_\nu \rangle \quad ........ [5]$$

Where $\rho_\pi$ and $\rho_\nu$ are the quasi-proton and quasi-neutron states respectively. But in these cases Newby shift of $K_-= 0$ bands is not effective in the calculations. The single particle matrix elements $\langle j_+ \rangle$ are calculated using Nilsson wave functions [22]. The matrix elements are also treated as free parameters. Initially a fixed attenuation of 50% of single particle matrix elements only for $i_{13/2}$ neutron is done and further these are adjusted during the fitting process.

The optimum values for all the variable parameters are calculated by minimizing the ( $\chi^2$ ) value

$$\chi^2 = \sum_{I=1}^{N} \left| \frac{E_{theor}(I) - E_{\exp t}(I)}{\Delta E_{\exp t}(I)} \right|^2 \quad \ldots\ldots [6]$$

$\Delta E_{\exp t}(I)$ is the experimental error in equation 6. The least square fitting problem is solved with help of Minuit code [23].

## III. Results and discussion:

In this paper we are presenting the calculations done for $^{184}$Au within the framework of TQPRM. Out of the total 7 bands we have carried out calculations only for three bands as sufficient amount of experimental data is available for these bands [17, 27] and some significant features are also seen in these bands that attract our attention. We have chosen Band1 {3/2[532]$_\pi$ ⊗ 7/2[514]$_\nu$} as it is showing the signature reversal and problem in configuration assignment. Also from the reference [16, 17] it is revealed that for Band 1 the proton is in the $\pi h_{9/2}$ (3/2[532]) orbital for lower spin region and it is in the $\pi h_{9/2}$ (1/2[541]) orbital as the spin increases. The experimental plots of Band 2 {1/2[660]$_\pi$ ⊗ 9/2[624]$_\nu$} and Band 4{1/2[541]$_\pi$ ⊗ 9/2[624]$_\nu$} show the feature of second signature inversion. The main objectives of our calculations are: (i) to resolve the issue of configuration assignment to Band 1. (ii) to reproduce the first and second point of signature inversion in Band 2 and Band 4, which we have done successfully.

The deformation parameters ($\epsilon_2$, $\epsilon_4$) used in the calculation is: (-0.150, 0.013) for $^{184}$Au doubly odd nucleus and are taken from P.Mollar and J.R. Nix paper [24]. The Nilsson model parameters, κ and μ are taken as 0.0620 and 0.614 for protons and 0.0636 and 0.393 for neutrons [22]. In the calculation all the input parameters are taken from a standard Nilsson Model. The parameters are adjusted during the fitting process. The results of our schematic TQPRM calculations with ΔE(I→I-1)/2I versus I are presented in the fig. 2. The first and second point of signature inversion {$I_c(1)$ and $I_c(2)$ respectively} is indicated by the arrow in the plots. In the following subsections we will discuss the TQPRM calculations and the details of each band.

### 3.1 Band 1, $K_+ = 5^+$, {3/2[532]$_\pi$ ⊗ 7/2[514]$_\nu$}:

The $K_+ = 5^+$, {3/2[532]$_\pi$ ⊗ 7/2[514]$_\nu$} band is the ground state prolate shape band of $^{184}$Au. From the experimental plots shown in fig.1 it is clear that initially there is no odd-even staggering [2-4] at lower spin but a strong odd-even staggering seems at high spin. The favored signature for this configuration is given by $\alpha_f = 0$ i.e. even spin should favor but odd-spins are favored at the higher spin region in the experimental plot showing some band crossing with other band. This anomalous effect is called signature reversal [6, 25].

We have done the TQPRM calculations by taking 24 rotational bands based on $h_{9/2}$ proton and $f_{7/2}$ neutron configuration. The excitation energies of these bands have been estimated from neighboring odd-A nuclei [19, 27] and the GM splitting is assumed 100keV. The value of the rotational parameters ($\hbar^2 / 2\Im$) is assumed to be 10.0 and 10.5keV for $K_+$ and $K_-$ bands respectively. These are adjusted during the fitting process. The single particle matrix elements $\langle j_+ \rangle$ are taken from Nilsson model [22]. The value of Newby Shift does not affect the pattern. The calculations are able to reproduce the signature reversal at high spin region and also justify the configuration for Band 1. The final set of parameters are obtained after making a least square fit to the $K_+ = 5^+$ band. The experimental and calculated results are shown by solid and dashed line respectively in fig.2.

It is clear from the calculations that behaviour of $K_- = 0^+$ {1/2[541]$_\pi$ ⊗ 1/2[541]$_\nu$}and $K_+ = 1^+$ {1/2[541]$_\pi$ ⊗ 1/2[541]$_\nu$}is reverse to each other, i.e. the $K_- = 0^+$ band favors odd spin and $K_+ = 1^+$ favors even spin. The opposite phases will be carried over to the higher bands by Coriolis and particle-particle coupling and give rise to odd-even staggering. The most important chain involved in the mixing shows that there is particle-particle coupling of Band 1 with $K_+ = 5^+$, {5/2[523]$_\pi$ ⊗ 5/2[523]$_\nu$}. This band favors the odd spin and its effect is transferring to the main band. Due to this reason instead of even spins, odd spins are favored and signature reversal is observed in the high spin region. It is mentioned earlier that Newby shift of $K_- = 0^+$ band is not playing important role but the decoupling parameter of ⟨1/2[541]|1/2[541]⟩ neutron is responsible for obtaining the required feature at higher spin. The fitted value of $\langle 1/2[541] | 1/2[541] \rangle_\nu$ is 5.2103(3.43435) where Nilsson matrix value is given in the parenthesis. If we increase or decrease the fitted value then the required feature gets disturbed and abrupt signature pattern appears.

Our TQPRM calculations summarize the some very important points: (i) at lower spin region maximum contribution is coming from the band with configuration $K_+ = 5^+$, {3/2[532]$_\pi$ ⊗ 7/2[514]$_\nu$}. (ii) It is clear from the value of wave function that as the spin increases the effect of {3/2[532]$_\pi$ ⊗ 7/2[514]$_\nu$} band is decreasing and the effect of $\{1/2[541]_\pi \otimes 7/2[514]_\nu\}$, $K_+=4^+$ band is increasing i.e. there is a kind of band crossing of $\{3/2[532]_\pi \otimes 7/2[514]_\nu\}$ with $\{1/2[541]_\pi \otimes 7/2[514]_\nu\}$. The behaviour of 1/2[541] proton orbital is dominating over 3/2[532] proton orbital with increasing spin which is very interesting. The results of TQPRM calculations are well supported by the results of experiment performed by S.C.Li et al. [17] and Sauvage et al. [16]. So, by TQPRM calculations we successfully reproduce the phase and magnitude of experimentally observed signature splitting. The configuration of Band 1 is $\{3/2[532]_\pi \otimes 7/2[514]_\nu\}$ and at the higher spin region 1/2[541] is the dominating proton orbital over 3/2[532] orbital of $h_{9/2}$.

**3.2 Band 2, $K_+=5^+$, $\{1/2[660]_\pi \otimes 9/2[624]_\nu\}$:**

Band 2 has been identified as the $\{1/2[660]_\pi \otimes 9/2[624]_\nu\}$ with $K_+=5^+$ structure [15, 26]. Fig.1 is presenting the experimental odd-even staggering plot of $\Delta E(I \rightarrow I-1)/2I$ versus angular momentum (I) for $K_+=5^+$ band in $^{184}$Au. This experimental graph shows that there is first signature inversion at $I_c(1) = 22$ and another interesting feature worth noting is that the signature splitting starts getting reinverted again beyond $I_c(2) = 28$ as quoted by S.C.Li [17]. This represents the second signature inversion phenomenon.

We have included 24 two quasiparticle bands based on $i_{13/2}$ proton and $i_{13/2}$ neutron configuration. The position of all the unknown configurations is estimated by using the experimental data of the single particle states in the neighboring odd-A nuclei [19, 27]. The moment of inertia parameters are chosen to be 10.0 and 10.5keV respectively and their values are adjusted during fitting procedure. The matrix elements $\langle j_+ \rangle$ are taken from Nilsson model [22]. The $i_{13/2}$ neutron elements are attenuated as usual to 50% of their original values. The final adjustments are made after the fitting procedure. The Newby shift for $K_-=0^+$ for $\{1/2[660]_\pi \otimes 1/2[660]_\nu\}$ and $\{3/2[651]_\pi \otimes 3/2[651]_\nu\}$ is assigned a value of 43.79keV(fitted value) and 10.0keV respectively. But the value of Newby Shift does not affect the odd-even staggering or the signature inversion. The neutron matrix element $\langle 5/2[642] | 3/2[651] \rangle$ plays an important role to obtain signature inversion in this band. The results of our calculations and the experimental results are shown by dashed and solid line respectively in fig.2.

The exact mechanism of signature inversion becomes clearer from the behaviour of the $K_-=0^+$ $\{1/2[660]_\pi \otimes 1/2[660]_\nu\}$and $K_+=1^+$ $\{1/2[660]_\pi \otimes 1/2[660]_\nu\}$ bands. The $K_-=0$ band favors even spin and $K_+=1$ favors odd spin. This reversal behaviour of $K_-=0$ and $K_+=1$ bands are transmitted through Coriolis coupling and Particle-Particle coupling to main band. The odd-even staggering and signature inversion observed in $K_+=5^+$ band is reproduced by these transmission. The value of neutron matrix element $\langle 5/2[642] | 3/2[651] \rangle$ is effective to get the signature inversion in this band. Its original value is 6.56003 and from fitting we get its value as 1.6006. If we vary this value to 2.00, 2.6006, 3.00 and finally 3.6006 we get the required odd-even staggering and first signature inversion at $I_c(1) = 21$. As compared to the experimental results ($I_c(1) = 22$) the critical spin $I_c(1)$ shifts to lower spin by one in calculated results. For first point of inversion neutron matrix element is important but after a certain spin proton matrix element $\langle 3/2[651] | 1/2[660] \rangle$ plays an important role to get second point of signature inversion. As we change its value in steps of 0.2 from 2.8 to 3.0, 3.2, 3.4, 3.6 and finally at 3.7046 we get the second point of signature inversion at $I_c(2) = 27$. Similar to $I_c(1)$, $I_c(2)$ also shifts to lower spin by one as compared to experimental data. However the energy level pattern beyond the second signature inversion has not been well established by the experimental as well as the theoretical results. The results of our calculations are well supported by the experiment performed by S.C.Li.

**3.3 Band 4, $K_+=5^-$, $\{1/2[541]_\pi \otimes 9/2[624]_\nu\}$:**

The two-quasiparticle configuration of $\{\pi\ h_{9/2} \otimes \nu\ i_{13/2}\}$ with $K_+=5^-$ has been proposed for Band 4 of $^{184}$Au [15]. This band displays the strong odd-even staggering. It is specified by S.C.Li [17] that Band 4 should be described by the configuration $\{1/2[541]_\pi \otimes 9/2[624]_\nu\}$. Fig.1 represents the experimental plot of the signature splitting for this band. This figure shows that in Band 4 there is first signature inversion at $I_c(1) = 19$ and second signature inversion at $I_c(2) = 23$.

We have done the TQPRM calculations for $K_+=5^-$ band by incorporating 24 bands based on $h_{9/2}$ proton and $i_{13/2}$ neutron orbitals. The choice of parameters and estimation of excitation energies are done in the similar fashion as we have done earlier for the Band 1 and Band 2. The estimated values of band energies, moment of inertia parameter are used to calculate energies for this band by TQPRM. The value of the Newby shift for $K_-=0^-$ band is not effective in the calculations. The magnitude of odd-even staggering is very large as actual fitting of experimental data is not done. We have adjusted the single particle matrix element to obtain the required pattern. Fig.2 shows the plot between $\Delta E(I \rightarrow I-1)/2I$ versus angular momentum (I) for the calculated and theoretical values separately. The first and second point of signature inversion is shown by arrow in this figure.

The mechanism of signature inversion in Band 4 is identical to Band 2 in $^{184}$Au. The signature effect in the main band $K_+=5^-$ again follow from $K_-=0^-$ band. Band with $K_-=0^-$ $\{1/2[541]_\pi \otimes 1/2[660]_\nu\}$favors even spin and $K_+=1^-$ $\{1/2[541]_\pi \otimes 1/2[660]_\nu\}$favors odd spin and after a particular spin it also favors even spin. The signature inversion in the $K_+=5^-$ band also occur through a chain of bands by Coriolis and particle-particle coupling of bands. So the reverse behaviour of $K_-=0^-$ and $K_+=1^-$ is responsible for signature inversion. We get the first signature inversion at $I_c(1) = 17$ by TQPRM calculations.

The experimental energies are not in the confirmed form, so we can not apply the actual fitting process to this data. By reducing the energy of $\{3/2[532]_\pi \otimes 1/2[660]_\nu\}$ band the magnitude of staggering gets reduced and the first point of inversion has been shifted from 19 to 17. The second signature inversion is obtained at $I_c(2) = 26$ by adjusting the energy of band with configuration $\{1/2[541]_\pi \otimes 1/2[660]_\nu\}$. Systematic calculations reproduce the feature very well which is supported by S.C.Li [17]. However the first point of signature inversion $I_c(1)$ and the second point of signature inversion $I_c(2)$ has been shifted as compared with the experimental results.

## IV. Summary and Conclusion:

The results of TQPRM calculations for Band 1, $K_+=5^+$, $\{3/2[532]_\pi \otimes 7/2[514]_\nu\}$, Band 2, $K_+=5^+$, $\{1/2[660]_\pi \otimes 9/2[624]_\nu\}$ and Band 4, $K_+=5^-$, $\{1/2[541]_\pi \otimes 9/2[624]_\nu\}$ in doubly odd $^{184}$Au are presented in this paper. TQPRM calculations have been successfully justified and confirmed the configuration evolution from $\{3/2[532]_\pi \otimes 7/2[514]_\nu\}$ to $\{1/2[541]_\pi \otimes 7/2[514]_\nu\}$ with increasing spin in the ground state band (Band 1) of $^{184}$Au. For Band 2 $\{1/2[660]_\pi \otimes 9/2[624]_\nu\}$ with $K_+=5^+$ and Band 4 $\{1/2[541]_\pi \otimes 9/2[624]_\nu\}$ with $K_+=5^-$, first signature inversion $\{I_c(1)\}$ and second signature inversion $\{I_c(2)\}$ is well reproduced by TQPRM calculations. However the point of signature inversion has been shifted in both the cases but the feature is well reproduced. The experimental energies for Band 4 are not confirmed so the exact fitting of the parameters is not done but feature is well reproduced.

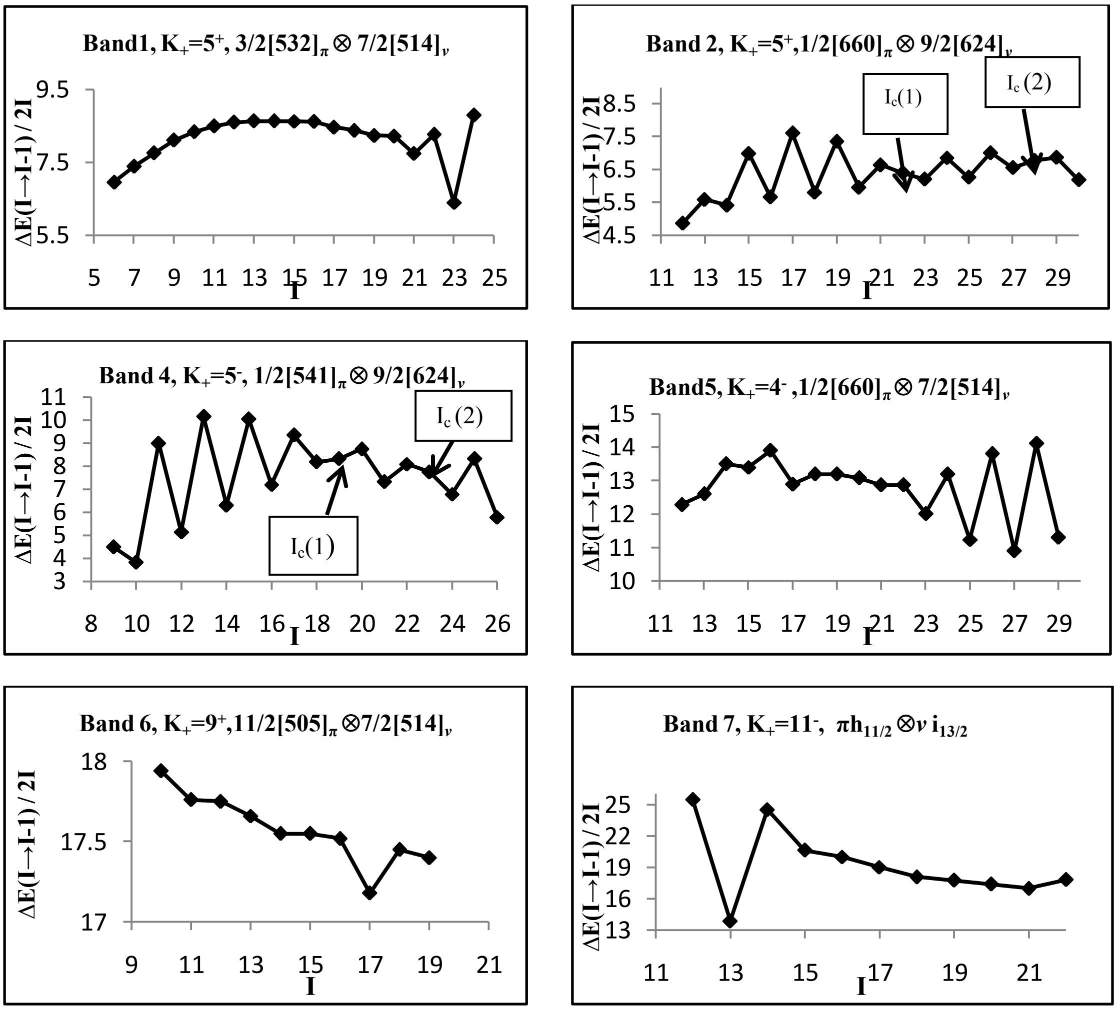


**Fig.1: E**xperimental plots for ΔE(I→I-1)/2I in (keV) vs. I are plotted for Band1 (ground band), 2, 4, 5, 6 and 7 of $^{184}$Au. It excludes Band 3 as the angular momentum (I) is in alternate order in the level scheme of this band. First point of signature inversion ($I_c(1)$) and second point of signature inversion ($I_c(2)$) is shown by arrow. The scale is different in all the plots. The data is taken from the reference [17, 27].

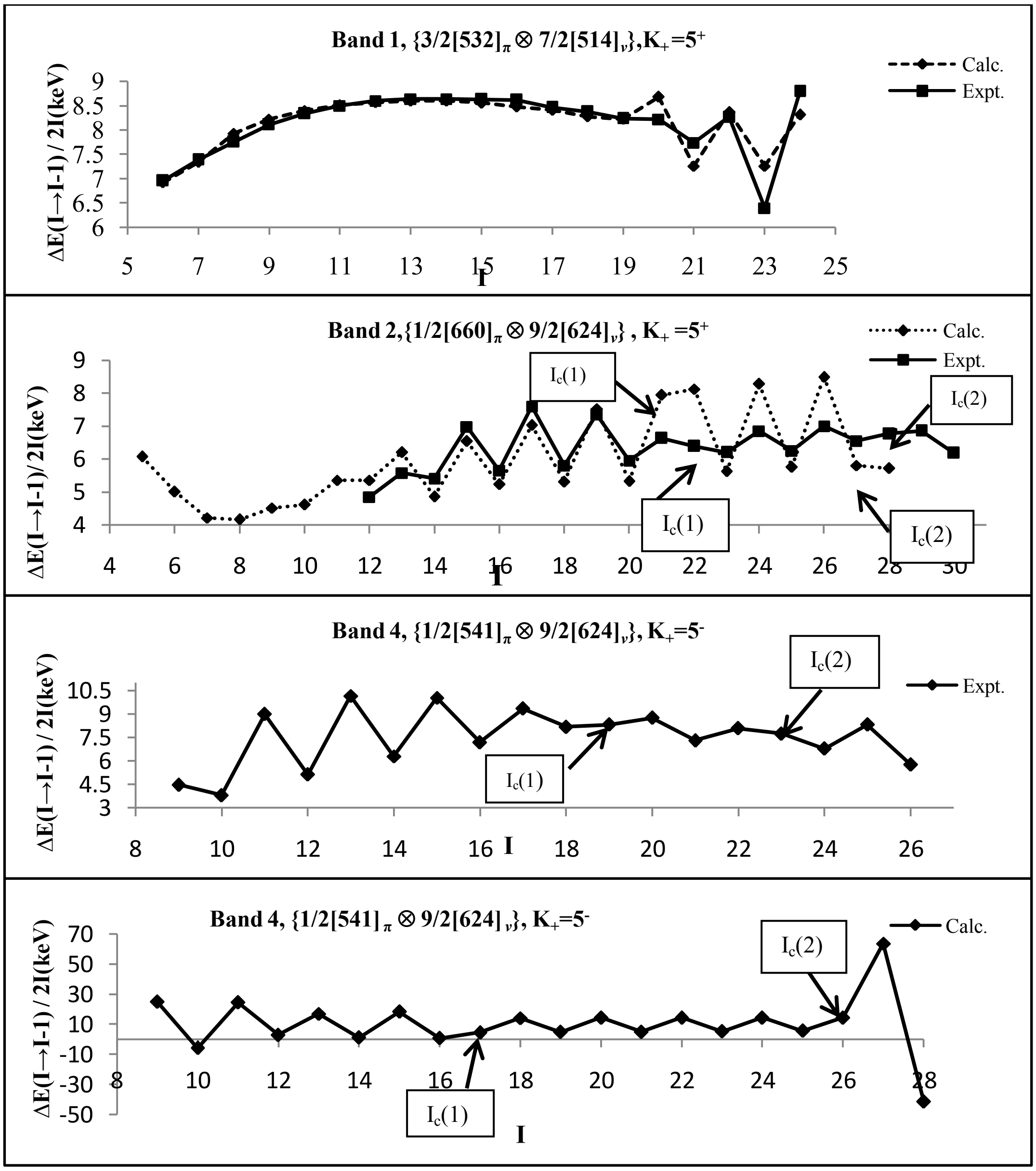


**Fig.2:** Results from the TQPRM calculations (dashed) compared with the experimental data (solid) for the two-quasiparticle rotational bands in $^{184}$Au. Note that the scale is different in two plots of Band 4. We can only compare the feature of theoretical and experimental plot as experimental data is not in the confirmed form and actual fitting is not done. The critical spin $I_c(1)$ and $I_c(2)$ are indicated by the arrow. $I_c(1)$ and $I_c(2)$ represent the first point of signature inversion and second signature inversion respectively for Band 2 and Band 4.

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