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Signature splitting in magnetic rotational bands

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Abstract. Nearly-spherical nuclei in three mass regions have recently been observed to exhibit rotational-like features. We have identified almost 80 such bands; largest number (43) lie in the lead region. Most of these bands are assigned oblate multi-quasiparticle configurations. Their interpretation in terms of 'magnetic rotation' does not allow for signature splitting in these bands. We have however found signature splitting as well as signature inversion in many bands. We apply the two-quasiparticle plus rotor model to understand the occurrence of signature splitting vis-a-vis the role of 'shears mechanism' in these bands.

Keywords. Magnetic rotation; shears mechanism; nearly spherical nuclei; signature splitting; Pb isotopes; particle rotor model.

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1. Introduction

Nuclear structure physics has been witness to the discovery of some very rare phenomena like superdeformation [1] and halo structure in select groups of nuclei. One such phenomenon which has recently been identified is the occurrence of rotational bands in nearly-spherical nuclei. It has been suggested that these bands arise out of the rotation of a magnetic dipole formed out of two or more high-j proton particles (holes) and high-j neutron holes (particles), which make up a resultant vector inclined at an angle to the axis of symmetry. The total angular momentum formed out of the resultant j and a small rotational angular momentum, is also tilted to the axis of symmetry. It was suggested by Frauendorf [2] that further angular momentum is generated by the closing of the particle angular momenta towards the total angular momentum giving rise to the name 'shears mechanism'. The rotational angular momentum thus plays a minor role in generating the higher spin states. The several particles generate a net magnetic dipole leading to the name 'magnetic rotation' (MR).

In this paper, we present evidence of strong signature splitting in many bands identified as MR bands; signature inversion is also present in some cases. We use the two-quasiparticle plus rotor model (TQPRM) to simulate the conditions of 'shears mechanism' at small oblate deformation and analyse the results to study the compatibility of signature splitting with the 'shears' explanation of these bands.

2. Properties of magnetic rotational bands and TAC

The magnetic rotational bands are expected to display the following properties:

1. A $\Delta I = 1$ structure rather than a $\Delta I = 2$ structure.
2. Intraband transitions are predominantly M1 in nature. Crossover E2 transitions are very weak or, absent. The ratio B(M1)/B(E2) is therefore quite large ∼10–100 (μ_N/eb)^2.
3. The bandhead lies at a high excitation energy (few MeV) and has a high spin $I \sim$ 10–15 $\hbar$.

Keeping these criteria in mind, we have been able to identify from the published literature on the experimentally observed level structures, about 80 MR bands. These are spread in three mass regions namely A = 105–110, 130–140 and 191–202 [3]. While most of these bands have been assigned an oblate many-quasiparticle configuration, several prolate configurations have also been assigned to bands in the lighter mass regions.

We find that in addition to the above mentioned features, the experimentally observed bands also exhibit the following features:

1. Many of these cascades do not display a regular $I(I+1)$ behaviour and are quite irregular in their structure.
2. Large number of MR bands display a signature splitting.
3. Backbending is observed in a large number of cases.

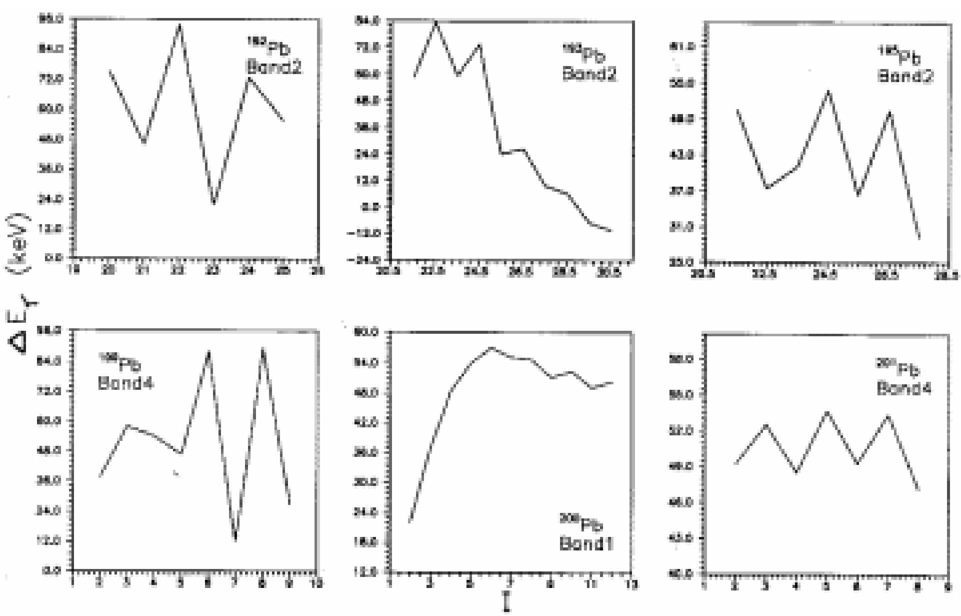

Figure 1. Signature splitting in some of the MR bands in Pb isotopes as observed in the experimental data. The spins are not known in the three cases in the bottom panels.

The rotational motion is usually studied in terms of the principal axis cranking (PAC) model and the particle rotor model (PRM). However, to explain the unusual features of these bands, Frauendorf suggested a tilted axis version of the cranking model (TAC) which is able to take care of the 'shears mechanism' of generating high spin states [4,5]. One of the most important consequences of the TAC is to mix the signature quantum numbers. It is therefore expected that MR bands will not display any significant signature splitting and give rise to a predominantly $\Delta I = 1$ like structure with enhanced B(M1) rates.

3. Signature splitting in MR bands of lead isotopes

Contrary to the expectations of the TAC, we find that a large number of MR bands do display a signature splitting. Since largest set of data on these bands exists in lead isotopes, we will concentrate our attention on signature splitting in lead isotopes only. We find that out of 43 bands classified as MR bands, as many as 14 display evidence of signature splitting. No judgement on the presence or absence of splitting could however be made in many cases where only 4–5 levels have been observed. In figure 1, we show the plots of $\Delta E_\gamma(I)$ vs. I for six cases. Here $\Delta E_\gamma(I) = E_\gamma(I \to I-1) - E_\gamma(I-1 \to I-2)$. We find that two of the cases shown here namely, ^{195}Pb, band 2 and ^{199}Pb, band 4 also exhibit a signature inversion. Observation of such features therefore raises questions about the explanation of these bands in terms of TAC model.

4. Signature splitting from the particle-rotor model

It is well-known that the PRM is quite successful in explaining the rotational spectra, and such features as odd–even staggering and signature inversion in odd-A and odd–odd nuclei [6,7]. This model treats the angular momentum coupling and its dynamics explicitly and is quite suited to describe such phenomena. However, the MR bands are based on many-quasiparticles and therefore the PRM must be extended to include many-particles which makes this approach more complex. Keeping this in mind, we decided to use the TQPRM for calculating the energies and to plot the geometry of the angular momenta as most of the basic features of tilted-axis can be simulated here. Frauendorf and Meng [5] recently compared the TQPRM with TAC results and found the two compatible with each other. The TQPRM Hamiltonian for an axially symmetric rotor is given by [8],

$$H = H_{\mathrm{intr}} + H_{\mathrm{rot}}. \tag{1}$$

The rotational part of the Hamiltonian may be further written as

$$H_{\mathrm{rot}} = \frac{\hbar^2}{2\Im}(I^2 - I_3^2) + H_{\mathrm{rpc}} + H_{\mathrm{ppc}} + H_{\mathrm{irrot}}, \tag{2}$$

where the rotation–particle coupling (or, the Coriolis term), particle–particle coupling and the irrotational terms are given by

$$H_{\mathrm{rpc}} = -\frac{\hbar^2}{2\Im}(I_+ j_- + I_- j_+), \tag{3a}$$

$$H_{\mathrm{ppc}} = \frac{\hbar^2}{2\Im}(j_{p_+}j_{n_-} + j_{p_-}j_{n_+}), \tag{3b}$$

$$H_{\mathrm{irrot}} = \frac{\hbar^2}{2\Im}[(j_p^2 - j_{p_3}^2) + (j_n^2 - j_{n_3}^2)]. \tag{3c}$$

Here I_3 is the component of I along the symmetry axis. The operators $I_\pm = I_1 \pm iI_2$, $j_\pm = j_1 \pm ij_2$, $j_{n\pm} = j_{n_1} \pm ij_{n_2}$, and $j_{p\pm} = j_{p_1} \pm ij_{p_2}$ are the usual shifting operators. $\Im$ is the moment of inertia with respect to the rotation axis. Hamiltonian (1) is diagonalized within the basis

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

where the index α_ρ characterizes the 2qp configuration ($\alpha_\rho \equiv \rho_p\rho_n$) of the odd proton and the odd neutron. To explain the observed signature splitting in MR bands, we considered a complete basis space of $h_{11/2} \otimes i_{13/2}$ and proper choices of Fermi energy for proton–neutron configuration which may give rise to the shears mechanism.

5. Results and discussion

In figure 2, we show the staggering patterns for a deformation aligned (DAL) proton particle in $9/2[514]$ and rotation aligned and mid-shell neutron hole in $1/2[600], 5/2[602]$

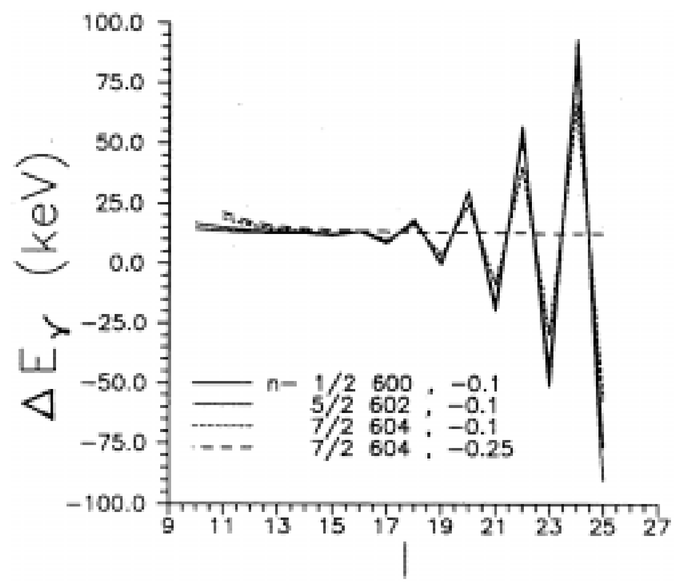

Figure 2. Staggering patterns for a DAL proton particle in $9/2[514]$ and RAL and mid-shell neutron hole in $1/2[600], 5/2[602]$ and $7/2[604]$ for a small oblate deformation $\epsilon_2 = -0.1$ and also the result for a DAL proton particle in $9/2[514]$ and a neutron hole in $7/2[604]$ for deformation $\epsilon_2 = -0.25$.

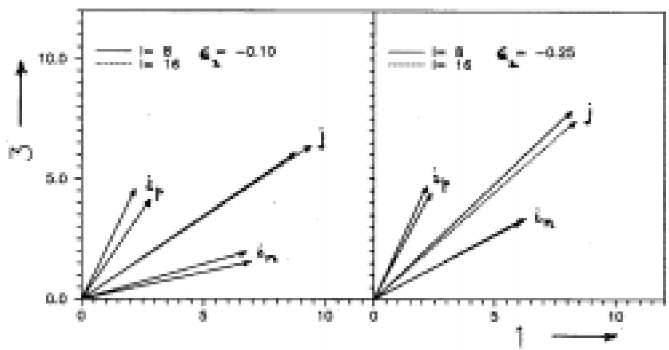

Figure 3. Geometry of particle angular momenta at $I = 8$ and 16 for small oblate deformation $\epsilon_2 = -0.1$ (left panel) and for large oblate deformation $\epsilon_2 = -0.25$ (right panel).

and $7/2[604]$ for a small oblate deformation ($\epsilon_2 = -0.1$). We also show the results for a deformation aligned (DAL) proton particle in $9/2[514]$ and a neutron hole in $7/2[604]$ for deformation ($\epsilon_2 = -0.25$); we find no signature splitting in the case of normal deformation as shown by long dashed line in figure 2. However, for ($\epsilon_2 = -0.1$), a strong signature splitting develops at $I > 15$ in all the cases. This is clearly an effect of enhanced Coriolis mixing due to small deformation. It is therefore not surprising that many bands in Pb nuclei exhibit signature splitting. The bands however remain quite regular from $I = 9$ to 15.

In figure 3, we show the geometry of angular momenta at $I = 8$ and 16 for both small as well as large oblate deformations. It may be noted that signature splitting just sets in at $I = 16$ and therefore both the angular momenta correspond to situations where splitting is minimum. We show the proton and neutron alignments and their resultant vectors. The 1- and 3-axis correspond to rotation and symmetry axis respectively. The resultant $\vec{j}$ combines with a small rotational angular momentum along 1-axis to give the total angular momentum $\vec{I}$. The tilt angle of the total angular momentum is therefore basically decided by the tilting of $\vec{j}$. In case of small oblate deformation (left panel) we find that as I increases along a band, the proton and neutron alignments tilt towards their resultant $\vec{j}$ thereby increasing its magnitude and there is no appreciable change in the tilt angle which the resultant $\vec{j}$ makes with the 3-axis. This is as expected in the 'shears mechanism'. On the other hand in case of large deformation (right panel), the tilting of the proton and neutron alignments with increasing I ceases and the resultant $\vec{j}$ does not increase with I and therefore the angular momentum is generated by the rotational angular momentum R. It may therefore be concluded that a small deformation is necessary for shears mechanism to occur and particle rotor model can describe this mechanism quite well.

In figure 4, we show similar results for three consecutive angular momenta $I = 20$, 21 and 22 which lie in the region of signature splitting. The angular momenta $I = 20$ and 22 correspond to signature $\alpha = 0$ and $I = 21$ corresponds to signature α=1. We find that the tilt angle of the resultant $\vec{j}$ is significantly different for the two signatures. Further, only proton alignment appears to be closing with no change in the neutron alignment. The 'shears mechanism' is therefore not active that strongly once the signature splitting sets in.

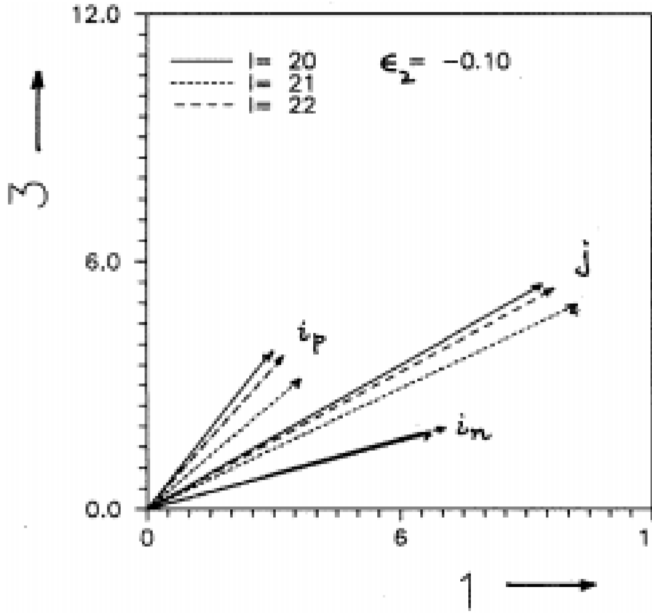

Figure 4. Geometry of particle angular momenta for three consecutive angular momenta $I = 20$, 21 and 22 which lie in the region of signature splitting for small oblate deformation $\epsilon_2 = -0.1$.

6. Conclusions

We therefore conclude that the observation of signature splitting in many bands identified as MR bands is in line with the results of TQPRM calculations. The shears mechanism appears to be valid only for small deformation and weakens significantly after the signature splitting sets in the bands. More detailed calculations along these lines including the calculation of transition probabilities are in progress.

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