MAGNETIC ROTATION (MR) BAND-CROSSING AT HIGH SPIN STATES: Role of nucleons in this crossing in N = 78 odd-Z isotones.

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Abstract. Magnetic-dipole rotational (MR) bands were discovered about 15 years ago, and have been explained using shears mechanism. The theoretical understanding of these bands has been provided using tilted axis cranking (TAC). At present, magnetic rotation has been seen in whole nuclear landscape and about 180 bands in 80 nuclides has been observed in mass regions A = 20, 60, 80, 110, 135 and 195 respectively. The crossing of these bands (\(\Delta I = 1\)) is very much similar to normal band crossing (\(\Delta I = 2\)) and already exhibited in different mass regions. We have observed new MR bands and their crossing in the A = 130 mass region in \(^{135}\text{La}\), \(^{137}\text{Pr}\) and \(^{139}\text{Pm}\) nuclei. The systematic evolution of this phenomenon in N=78 odd-Z isotones leads us to understand the role on nucleons in this crossing.

1. Introduction

The observation of regular rotational-like bands of strongly enhanced M1 transitions in the near spherical Pb region was very surprising [1]. To explain the observation of rotational bands in near spherical nuclei, a new type of nuclear excitation called ‘magnetic rotation (MR)’ was discovered. In this rotation, the total angular momentum is generated by step-by-step alignment of the particle and hole spins in the direction of total angular momentum. Theoretically TAC has been used extensively to interpret the bands. MR phenomenon has been explored in several mass regions like A = 20, 60, 80, 110, 135 and 195 [2, 3, 4, 5]. Some of the features of MR bands are:

(i) Typically observed in near-spherical nuclei.
(ii) Strong intraband M1 transitions with weak or absent E2 crossover transitions.
(iii) The M1 transitions have a reduced transition probability B(M1) \(\sim 2-10 \mu_N^{-2}\).
(iv) Decrease in B(M1) and B(M1)/B(E2) values with increasing angular momentum.

In the rare-earth region (A \(\approx 135\)), several nuclei have been investigated to explore MR bands. For these nuclei, the proton \(g_{7/2}, d_{5/2}, h_{11/2}\) spherical single states are originating from the particle orbitals and neutron \(h_{11/2}\) spherical states from hole orbitals. In the present experimental study, \(^{135}\text{La}\) was studied for MR phenomenon. The observed \(\Delta I = 1\) bands were compared with other odd-mass N=78 isotones namely \(^{137}\text{Pr}\), \(^{139}\text{Pm}\) and \(^{141}\text{Eu}\). Apart from the observation of MR bands, band crossing between the MR bands has been observed for \(^{135}\text{La}\). A systematic comparision of band crossings across N = 78 isotones has been done.
Bandcrossing between rotational bands arises due to rotation alignment of certain pairs of nucleons under the influence of coriolis force. Alignment gain $\Delta i$, crossing spin and band crossing frequency $\bar{h}\omega$ characterise a band crossing. The rotational frequency at which band crossing occurs is called the band crossing frequency ($\bar{h}\omega$).

2. Experimental details
High spin states in $^{135}$La were populated by the reaction $^{128}$Te($^{11}$B,4n)$^{135}$La using a $^{11}$B beam of 50.5 MeV from the Pelletron Linac Facility at Tata Institute of Fundamental Research (TIFR), Mumbai. The target consisted of 1.02 $mg/cm^2$ $^{128}$Te on 4 $mg/cm^2$ $^{197}$Au backing. The gamma rays were detected using INGA [10, 11]. In the current experiment, the array consisted of 16 Compton-suppressed clover detectors arranged in spherical geometry with 3, 2, 2, 4, 2 and 3 number of clover detectors placed at $157^\circ$, $140^\circ$, $115^\circ$, $90^\circ$, $65^\circ$ and $40^\circ$ with respect to the beam direction respectively. The detectors are placed at a distance of 25 cm from the target. The online data was collected via XIA based triggerless Digital Data AcQuision (DDAQ) system [10]. A total of about $3.9 \times 10^9$ two and higher fold events were recorded. The data were sorted using Multi pARameter time-stamped based COincidence Search program (MARCOS) to generate double and triple gamma coincidence matrices. The RADWARE software package was used for analysis of these matrices [12].
Figure 2. Plot of $I(\hbar)$ vs $\hbar \omega$ of MR bands in $^{135}\text{La}$, $^{137}\text{Pr}$, $^{139}\text{Pm}$ and $^{141}\text{Eu}$.

Table 1. Configurations, deformation parameter $\varepsilon_2$ and triaxiality parameter $\gamma$ obtained from TAC calculations across some $N = 78$ isotones.

| Nucleus | 3qp, Band 1 in Fig. 1 | 5qp, Band 2 in Fig. 1 |
|---------|----------------------|----------------------|
| $^{135}\text{La}$ | $\pi(\frac{h_{11/2}}{2})^1 \otimes \nu(\frac{h_{11/2}}{2})^{-2}$ | $\pi(\frac{h_{11/2}}{2})^1(\frac{g_{7/2}}{2}/d_{5/2})^2 \otimes \nu(\frac{h_{11/2}}{2})^{-2}$ |
| $^{137}\text{Pr}$ | $\pi(\frac{h_{11/2}}{2})^1 \otimes \nu(\frac{h_{11/2}}{2})^{-2}$ | $\pi(\frac{h_{11/2}}{2})^1(\frac{g_{7/2}}{2})^2 \otimes \nu(\frac{h_{11/2}}{2})^{-2}$ |
| $^{139}\text{Pm}$ | $\pi(\frac{h_{11/2}}{2})^1 \otimes \nu(\frac{h_{11/2}}{2})^{-2}$ | $\pi(\frac{h_{11/2}}{2})^1 \otimes \nu(\frac{h_{11/2}}{2})^{-4}$ |
| $^{141}\text{Eu}$ | $\pi(\frac{h_{11/2}}{2})^1 \otimes \nu(\frac{h_{11/2}}{2})^{-2}$ | $\pi(\frac{h_{11/2}}{2})^1 \otimes \nu(\frac{h_{11/2}}{2})^{-4}$ |

3. Discussion
In Fig. 1, the partial level schemes for different nuclei are shown for the interested part of the nuclear structure. It is very much clear that all the nuclei have $\Delta I = 1$ bands which can be interpreted as arising from 3qp and 5qp configurations using Tilted Axis Cranking (TAC) calculations [6, 7, 13, 14]. The 3qp configuration is built on the $\pi(\frac{h_{11/2}}{2})^1 \otimes \nu(\frac{h_{11/2}}{2})^{-2}$ configuration. 5qp configuration can be understood by considering different alignments of proton/neutron pair as given in Table 1. For $^{135}\text{La}$ and $^{137}\text{Pr}$, $g_{7/2}/d_{5/2}$ proton pair particles decouple and align their angular momentum along the axis of rotation to produce a 5qp configuration at a particular rotational frequency. At this band crossing frequency, a band crossing occurs between the 3qp and 5qp configuration. However, for $^{139}\text{Pm}$, band crossing occurs due to the alignment of neutron pair holes. Thus all the nuclei exhibit $\Delta I = 1$ band crossing from 3qp to 5qp configuration. The experimental features of 5qp configuration suggest different configurations for $^{135}\text{La}$, $^{137}\text{Pr}$ nuclei as compared to $^{139}\text{Pm}$, $^{141}\text{Eu}$ nuclei. In Fig. 2 is given a plot of angular momentum/spin $I(\hbar)$ as a function of rotational frequency which is taken as $\hbar \omega = E_\gamma$ for dipole transitions. All the nuclei show band crossing at $\hbar \omega \approx 0.40$ MeV. The behaviour of $I$ vs $\hbar \omega$ plot is very similar for all nuclei for lower bands before band crossing.
Figure 3. Experimental band crossings shown by the behaviour of excitation energy \( E(\text{MeV}) \) vs spin \( I(\hbar) \). The fitted lines are guide to see band crossing (E vs I fit).

However, after the band crossing \(^{135}\text{La},^{137}\text{Pr}\) nuclei behave in similar way as compared to \(^{139}\text{Pm},^{141}\text{Eu}\) nuclei which show similar features. Also \( \Delta i \) in \(^{135}\text{La},^{137}\text{Pr}\) is \( 3.5\hbar \) as compared to \( 4.5\hbar \) for \(^{139}\text{Pm},^{141}\text{Eu}\) nuclei. The systematic comparison for excitation energy \( E(\text{MeV}) \) vs spin \( I(\hbar) \) provides the information of crossing spin. It is clear from Fig. 3 that band crossing took place between \( 33/2\hbar \) to \( 37/2\hbar \) (\( \approx 35/2\hbar \)). The trends of \( E \) vs \( I \) also show different crossing behaviour for \(^{135}\text{La},^{137}\text{Pr}\) as compared to \(^{139}\text{Pm},^{141}\text{Eu}\).

Electromagnetic properties for \( \Delta I=1 \) bands, which play an important role in the understanding of nuclear structure of these bands, can be obtained from the absolute values of the reduced M1 and E2 transition probabilities, \( B(M1) \) and \( B(E2) \) respectively. The \( B(M1) \) values are sensitive to the details of the nucleon configuration, coupling scheme of the nucleons angular momenta and their contribution to net perpendicular magnetic moment. Lifetime measurements are not carried in all the nuclei of interest. In such a situation, the \( B(M1)/B(E2) \) ratios are very useful to get insight into the details of nuclear structure. Therefore, the \( B(M1)/B(E2) \) values have been compared for the \( \Delta I=1 \) bands for different nuclei and plotted in Fig. 4. The \( B(M1)/B(E2) \) behaviour again supports the argument made above for the change in configuration as one moves from \(^{137}\text{Pr}\) to \(^{139}\text{Pm}\). Apart from this, very interesting observation can be seen for inter-mixing between two bands and the role played by pair of nucleons responsible for band crossing by observing \( B(M1)/B(E2) \) values as function of angular momentum. It can be seen from the Fig. 4 that the behaviour of \( B(M1)/B(E2) \) vs \( I \) is very similar in \(^{135}\text{La},^{137}\text{Pr}\) than \(^{139}\text{Pm},^{141}\text{Eu}\) nuclei, and hence justifies the effect of nucleon pair on the band crossing of \( \Delta I=1 \) bands.
Figure 4. Variation of $B(M1)/B(E2)$ as a function of $I(h)$ for the negative parity MR bands.

The MR band crossing has been explored systematically for $N = 78$ odd-Z isotones. The influence of nucleon pair alignment in such band crossing provide the information of role of nucleons. The systematic study of different experimental properties of band crossing gives insight on the participating aligning nucleons. In future, lifetime measurements will be necessary to provide information on $B(M1)$ transition strengths and hence the role of nucleons in MR band crossing.

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