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SEARCH FOR MAGNETIC ROTATION IN ^{135}CE NUCLEUS

Amita[1], Veena Krishan Singh[1]

[1] Department of Physics, R.B.S. College, Agra, India

ABSTRACT

The observation of rotational bands in deformed and superdeformed nuclei is a well established phenomenon and researchers have been able to explain it completely. All the bands observed in these nuclei are mainly electric quadrupole (E2) in nature. However in 90's people observed regular sequences in nearly spherical nuclei, and to their surprise these bands are found to have strong magnetic dipole transitions with high B(M1) values. Frauendorf suggested a mechanism for the development of these bands known as the shears mechanism. An interesting point to note here is that all the M1 bands do not qualify as the shears bands. In the present work, we have chosen ^{135}Ce to test the validity of shears mechanism in all the three M1 bands in ^{135}Ce. We performed TAC calculations for the selected configurations for these bands and here we have discussed the results of our calculations and compared them with the experimental results.

KEYWORDS: Magnetic Rotation, Shears Mechanism, Mass-130 Region, 135Ce Nucleus, TAC Calculations, B(MI) values

INTRODUCTION

It is a well known fact that rotational bands in nuclei are obtained due to the existence of anisotropy or deformation in the system and this has been supported by non-obesrvation of regular rotational bands in weakly deformed or spherical nuclei. In 1992, H. Hubel in Germany and R. M. Clark in U.K., working independently, observed regular patterns of γ-rays in the spectra of 198Pb and 199Pb nuclei, which are nearly spherical in shape. After detailed study of their sequences, it was found that the intraband transitions were not electric quadrupole (E2) in nature but of magnetic dipole (M1) type [1]. Such bands have been termed as "Magnetic dipole" or "magnetic rotational" or "shears bands" in literature. The general characteristics shared by these magnetic rotational bands (MR) bands can be summarized as follows [2]:

1. The states in the bands (away from band crossings) have energies that follow the pattern of $E(I)-E \sim A(I-I)^2$. This is slightly different from the $I(I+1)$ relation due to the additional contribution I_0 to the total angular momentum that can be attributed to the intrinsic configuration (corresponding to the lowest energy state of the band).
2. The band consists of strong M1 (ΔI=1) transitions with very weak cross-overs resulting in large B(M1)/B(E2) ratios, $\geq 20\ \mu^2/(eb)^2$.
3. The M1 transitions have a reduced transition probability B(M1) ~ 2-10 μ^2 and B(E2) values may lie in the range of 1-0.01e^2b^2 or less.
4. The structures have small deformation ($|\varepsilon| \leq 0.1$).
5. The ratio of the dynamic moment of inertia ($\Im^{(2)}$) to the B(E2) is large, $\Im^{(2)}/B(E2) > 150\ MeV^{-1}(eb)^{-2}$ compared with well deformed [$\sim 10 MeV^{-1}(eb)^{-2}$] or superdeformed [$\sim 5 MeV^{-1}(eb)^{-2}$] structures.
6. The B(M1) values decrease with increasing angular momentum in a given MR band.

The ΔI=1 bands observed in the lead isotopes have been assigned weakly oblate configurations consisting of $K^{\pi}=11^{-}$ configurations coupled to low-Ω one/three quasineutrons (in odd-A nuclides) or two/four quasineutrons (in even-A nuclides). The active orbitals, in case of Pb isotopes are proton $h_{9/2}$ and $i_{13/2}$ orbitals and neutron holes in the $i_{13/2}$ subshell. At the bandhead, the proton angular momentum vector j_{π} (which arises from particles in the $h_{9/2}$ and $i_{13/2}$ orbitals) is nearly parallel to the symmetry axis (3) due to the torus like density distribution, while the neutron angular momentum j_{ν} (from holes in $i_{13/2}$ subshell) is nearly perpendicular to it due to dumb-bell like density distribution. Frauendorf [3-5] suggested that these two angular momenta are like the two blades of a pair of shears, and that the unusual properties of MR bands, like the generation of high angular momenta at such low deformation, predominance of regular M1 transitions, the lack of signature splitting etc., can be explained if the two blades simultaneously align towards the resultant total angular momentum to generate higher angular momentum states. This mechanism has therefore, been named as "shears mechanism".

An interesting point to note here is that as we go up along a band, the angle between the proton and neutron angular momentum blades decreases and as a result, the $\mu_{\perp}$ decreases, since the B(M1) values are proportional to $(\mu_{\perp})2$ [6], the shears mechanism predicts decreasing B(M1) values with increasing spin along the band. The decreasing B(M1) values with increasing angular momentum is, therefore, the most important signature of the shears mechanism. This mechanism was earlier observed in neutron deficient lead nuclei only, but, later investigation in other mass regions revealed that a similar mechanism was observed in the A=80, 110 and 130 mass regions, although different orbitals are involved. The data table prepared by Amita and co-workers [7, 8] lists 178 MR bands in 76 nuclides. The table contains 11 bands in A=80 mass region, 39 in A=110 region, 49 in A=135 mass region and 79 in the A=195 mass region.

In the mass-130 region, the nuclei are predicted to show γ softness [9 – 11], and the prolate and oblate nuclear shapes are only a few hundred keV apart. The high spin states in these nuclei receive a major contribution from the $h_{11/2}$ proton orbitals and/or $h_{11/2}$ neutron orbitals. As is common with the high-j orbitals, the low-Ω $h_{11/2}$ orbitals favour prolate shapes whereas the high-Ω $h_{11/2}$ neutron orbiatals drive the nucleus towards an oblate shape. This is the reason of observing the coexistence of prolate and oblate excited bands in the mass-130 region and the nuclear shape can be stabilized at different specific values of γ deformation by the occupation of various high-j quasiparticle orbitals [12]. Because of the combination of low-Ω protons and high-Ω neutron orbitals in high-j bands of mass-130 region, these constitute a good testing ground for the shears mechanism in this mass region. Several $\Delta I=1$ bands have been observed in the mass-130 region. In the present work we have chosen odd-N ^{135}Ce for our calculation to test the bands whether they are shears bands or not.

$\Delta I=1$ bands in ^{135}Ce

The ^{135}Ce nucleus, having Z=58, N=77 has three $\Delta I=1$ bands at high spin [7, 13, 14]. These bands are majorly characterized by [15-17]:

1. The intraband transitions are predominantly $\Delta I=1$ (M1) with none or weak E2 crossover transitions.
2. Large B(M1)/B(E2) ratios (≥ 10 (μN/ /eb)^2).
3. High excitation energy (band 1 at 3.23 MeV, band 2 at 4.18 MeV and band 3 at 4.5 MeV, respectively.
4. High spin (11.5 ħ, 13.5 ħ and 13.5 ħ for bands 1, 2 and 3 respectively.

These bands are therefore, expected to be built upon multi quasiparticle configurations. Whereas, the levels in band 1 have positive parity, bands 2 and 3 have negative parity. Ref. [13] assigns configuration to these bands based on a comparison with similar bands in the N=75 isotones. In order to test the role of shears mechanism in these bands, we perform tilted axis cranking calculations using the hybrid version [18] for our purpose. Since the proton and neutron fermi surfaces lie in the middle of the shells, pairing is an important parameter. The pairing parameters Δ_p and Δ_n for both protons and neutrons have been calculated as 80% of the odd-even mass difference Δ_{oe} [19] with the binding energies taken from [20]. The calculated values for Δ_p and Δ_n for ^{135}Ce come out to be 0.87 and 0.91 MeV, respectively. The Fermi level λ for both proton and neutron in all the calculations has been taken to reproduce the correct particle numbers. The results and conclusions drawn from our calculations for each band are discussed in the following subsections.

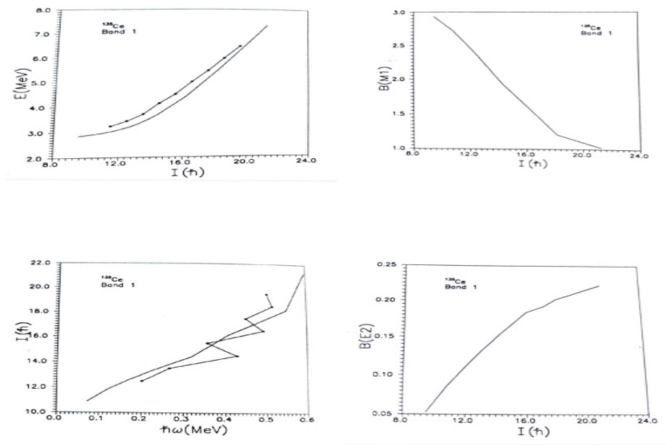
Section A: Band 1

The lowest lying band 1 in ^{135}Ce is an irregular band having high excitation energy (3.23 MeV) and high spin (11.5 ħ). For deformation $\varepsilon_2 \leq 0.2$, the high-j orbital close to the fermi surface for both protons and neutrons for nuclei in mass-130 region is $h_{11/2}$. Since the band possess positive parity and the positive parity orbital close to the Fermi surface is $g_{7/2}$, the lowest lying positive parity three quasiparticle configuration turns out to be

$$\pi\,(h_{11/2}g_{7/2}) \otimes \nu\,(h_{11/2})$$

We have performed calculations for band 1 using this configuration. The deformation parameters obtained by minimizing the total energy in the lab frame at $\hbar\omega$=0.2 MeV are nearly prolate ε_2=0.15 and γ=2^o. We present the results of our calculations in Fig. (1), wherein, we plot the experimental and theoretical level energies as a function of total angular momentum I in the upper left panel. We find that the slope of the curves in both the cases is the same; this supports our choice of configuration. Since the rotational frequencies give us more information about a band, we plot the total angular momentum as a function of rotational frequencies in the lower left panel. We see here, that the band exhibits strong odd-even effect, which is quite large (~ 200 keV) at the beginning. We find that, on an average, the calculations agree with the experiment but the TAC calculations cannot reproduce the odd-even staggering.

Figure 1: In the right panels-- Dotted lines are from experiment and solid lines are from the TAC calculations.



The electromagnetic transition probabilities have also been shown in the figure wherein we plot the B(M1) values on the upper right panel and the B(E2) values in the lower right panel as a function of total angular momentum I from our TAC calculations. The experimental values are not available and hence, we could not make a comparison between the theory and the experiment. The B(M1) values are large (> 1.0 μN^2) and are found to decrease sharply with increasing angular momentum. Also, the B(E2) values are small and exhibit a rising trend with increasing angular momentum. Both these plots indicate a small quadrupole collectivity.

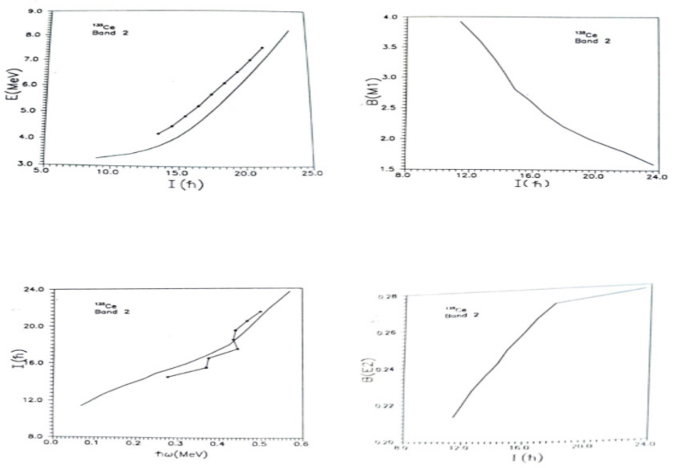
Section B: Band 2

The negative parity band, band2, in ^{135}Ce is also high lying (excitation energy = 4.18 MeV) band with bandhead spin = 13.5 ħ. As we know, the high-j negative parity orbital close to the Fermi surface for both protons and neutrons is h11/2 and therefore, the three quasiparticle configuration that may give rise to shears mechanism and can produce such a high spin in the system would be

$$\pi (h_{11/2}^{2}) \otimes \nu (h_{11/2})$$

We have chosen this configuration for our TAC calculations for band 2. This configuration has also been assigned to band 2 in Ref [13] by comparison with the neighbouring N=75 isotones. The corresponding deformation parameters from our calculations come out to be nearly prolate ε_2=0.16 and γ=3^o at ħω=0.2 MeV. The level energies as a function of total angular momentum from both theory and experiment are shown in the upper left panel of Fig.(2). The theoretical curve exactly follows the experimental curve. The zero point in the theoretical curve is chosen arbitrarily. The results are again supportive of our chosen configuration. In the lower left panel, we plot the total angular momentum as a function of rotational frequency ħω. The band exhibits an odd-even staggering in the beginning which cannot be explained by the TAC; the calculated curve, however, very closely follows the trend of experimental results.

Figure 2: In the right panels-- Dotted lines are from experiment and solid lines are from the TAC calculations.



The B(M1) values as a function of I(ħ) are shown in the upper right panel. The values are large (lying between 1.5 and 4 μ_N^2 and decrease sharply with increasing spin. The B(E2) values show opposite trend. These are small and are found to increase slowly with rising spin.

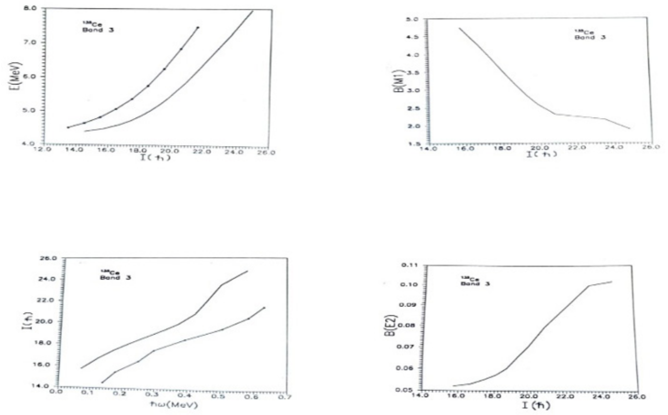
Section C: Band 3

Band 3 also has negative parity and the same bandhead spin (13.5 ħ) as band 2 but it is lying higher in energy (4.5 MeV). The three quasiparticle configuration chosen for band 2 is not therefore is not adequate for this band. This band has been termed in literature [13] as a collectively rotating oblate structure and the configuration assigned to this band is:

$$\pi (h_{11/2} g_{7/2}) \otimes \nu (h_{11/2}^{2} s_{1/2})$$

This assignment has been made by comparison with a similar band in neighbouring ^{136}Ce and no deformation parameters and calculations are given. The band does not have any E2 crossover transitions. In order to confirm the nature of this band and the configuration and the deformation assignments, we have performed TAC calculations using the hybrid version. For this configuration, the deformation of the band comes out to be near oblate (ε_2=0.15 and γ=50^o) at ħω=0.15 MeV. We compare the results of our calculations with those of experimental ones in Fig. 3 where we find that the calculated curves are similar to the experimental ones in both the level energies vs. I (upper left panel) and I vs. ħω (lower left panel) plots.

Figure 3: In the right panels: Dotted lines are from experiment and solid lines are from the TAC calculations.



The calculated reduced transition probabilities B(M1) and B(E2) vs. I are shown in the right panels of Fig.[3]. We find that the B(M1) values are large (ranging from 4.7 to 1.8 μ_N^2) and are decreasing with increasing spin. The band therefore, appears to be a good candidate for magnetic rotation. The B(E2) values are small and increase slightly with rise in angular momentum.

CONCLUSION

There are three ΔI=1 bands in ^{135}Ce. The first two bands exhibit a signature splitting. Our calculations, however, reproduce the overall behaviour of both these bands except the odd-even staggering which is beyond the scope of TAC. We could assign configurations to all the bands. Bands 1 and 2 are found to be built on near prolate three quasiparticle configurations whereas the configuration assigned to band 3 has slightly oblate deformation. The calculations exactly follow the experimental data for band 3. The reduced transition probabilities for magnetic dipole transitions B(M1) are large in all the cases and do exhibit a decreasing trend with increasing angular momentum. All the bands have small B(E2) values and therefore, the B(M1)/B(E2) ratios are high in all the bands. The shears mechanism therefore seems to play an active role in generating the angular momentum in all the bands.

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