Search of the attractive shears structure in atomic nuclei

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Abstract

The inclusion of attractive interaction potential generates the right decrease of rotational frequencies toward the experimental values. Thus, it may be inferred that the bands of interest are generated from the shears mechanism due to the attractive interaction potential, thereby, opens up a new and novel branch of the excitation mechanisms in weakly deformed nuclei.

Keywords: *Shears mechanism, nuclear interaction, particle-hole excitations, cranking model*

1. Introduction

It is noteworthy that a perfect sphere has no preferred direction in space against which a change in orientation can be measured, thereby quantum mechanically it cannot rotate. For a quantum system to rotate, the spherical symmetry in space must be broken. For example, a diatomic molecule can rotate about the axes perpendicular to its axis of symmetry. Similar concepts can be applied to the atomic nucleus. If the mass or charge distribution of the nucleus is non-spherical, the nucleus can rotate. The rotation is generally thought of as a collective behaviour because many nucleons contribute to it coherently [1-3].

"Shears Mechanism" is a general phenomenon by means of which higher angular momentum states are generated in weakly deformed systems. The signature of existing of Shears Mechanism is to observe band of strong M1 transitions in the level scheme of the particular nuclei. This kind of band is sometimes referred as "Magnetic Rotational (MR)" band. The band head configurations are favoured by the perpendicular coupling of the particle and hole angular momentum. The higher spins of a MR band generated via gradual closing of the angular momentum vectors and the MR band terminates when full closing is achieved. The presence of particle and hole in the high-j orbitals plays the crucial role for generation of a MR band. Presence of such MR bands along with core polarisation resulting from shears mechanism has been observed in several weakly nuclei in different mass region. The core deformation in shears mechanism is similar like reagent in chemical reaction. In order to quantify the core contribution, a dimensionless parameter (χ) is introduced and it has been observed that small values of χ favours shears mechanism whereas large χ (> 50 %) implies core contribution is dominating. Other than symmetric shears, large number of the asymmetric shears (unequal shears blades j_p and j_n produced by the particles and holes, respectively) have also been observed [1, 2, 4].

The Shears Mechanism with Principle Axis Cranking model (SPAC) is the widely used framework to interpret the intrinsic characters as well as interplay between the core rotation and the shears mechanism in case of a MR band. The present work is devoted to investigate the favourable region of the asymmetric and symmetric shears within the framework of hybrid shears mechanism with the SPAC model by introducing χ in the model for the weakly deformed nuclei near shell-closure [4].

2. Conventional Shears Mechanism

Here we take coupling occurs between two different types of nucleons. So interaction between them is repulsive. So the potential produced due to this type of interaction is also called repulsive interaction potential. We take this potential to be positive as it is repulsive.

$$E\text{ (shears)} = v_2\,(3\cos^2\theta - 1)/2$$

Where, v_2 is positive.

Now if we plot [Fig. 1] the shears energy versus shears angle we see that energy increases with decreasing shears angle that is with increasing spin. The left hand shaded region is energetically unfavourable as the energy decreases with increasing spin which is not possible.

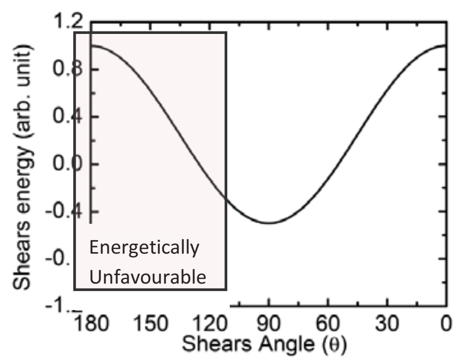

FIG 1: Shears Energy vs Shears angle Plot for Repulsive Interaction

3. Attractive shears

We stake similar type of nucleons that either particle-particle interaction or hol-hole interaction. Since they are similar type of nucleons, so we take interaction between them to be attractive. For this reason, we take the attractive interaction potential to be negative [1, 2].

$$E\text{ (shears)} = v_2\,(3\cos^2\theta - 1)/2$$

Where, v_2 is negative.

On plotting the shears energy versus shears angle we get this graph in Fig. 2. Here band-head occurs at 180˚ and band terminates at 90˚. The right hand shaded region is energetically unfavourable as the shears energy decreases with increasing spin which is not possible.

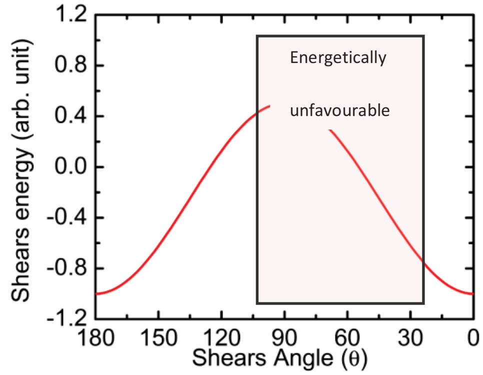

FIG 2: Shears Energy vs Shears angle Plot for Attractive Interaction

4. Framework of the Model

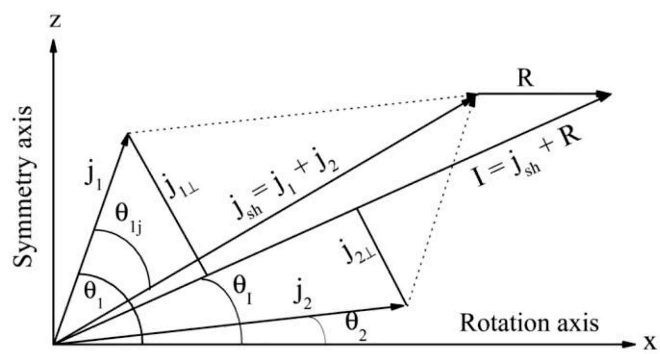

FIG 3: Coupling Scheme

In this model, total energy of an excited state E(I) can be expressed as [1, 2],

$$E(I) = \frac{R^2(I,\theta_1)}{2J(I)} + v_2 P_2\left(\cos(\theta_1)\right)$$

where, first and second terms of the equation represent the collective and quasi-particle (shears) interaction energy contribution. Here, θ_1 is the angle of j_1 with respect to the rotational axis (R) whereas the direction of j_2 is set along the rotational axis (R).

Calculations:

$$Now, \quad I = (J_1^2 + J_2^2 + 2I_1 J_2 \cos\theta)$$

$$So, \quad \cos\theta = \frac{I^2 - J_1{}^2 - J_2^2}{2J_1 J_2}$$

$$So, \quad \cos\theta = \frac{I(I+1) - J_1(J_1+1) - J_2(J_2+1)}{2\sqrt{(J_1+1)J_1}\sqrt{J_2(J_2+1)}}$$

Now putting it back in place of cosθ in E(I) eq^n.

$$E(I)\ \alpha\ v_2 P_2 \cos\theta$$

So, energy can be expressed in terms of I, J_1 and J_2

From the Fig 3 by applying parallelogram theorem we can get,

$$R = \sqrt{[I^2 - (j_1 \sin\theta_1 + j_2 \sin\theta_2)^2]} - (j_1 \cos\theta_1 + j_2 \cos\theta_2)$$

$$E(I) = \frac{R^2(I,\theta_1,\theta_2)}{2J} + \frac{V_2}{2}[3\{\cos(\theta_1 - \theta_2)\}^2] + constant$$

$$\frac{\partial^2 E(I,\theta_1,\theta_2)}{\partial\theta_1,\theta_2} = 0$$

$$B(M1) = \frac{3}{8\pi}[j_1 g_1^* \sin(\theta_1 - \theta_I) - j_2 g_2^* \sin(\theta_I - \theta_2)]^2$$

$$B(E2) = \frac{15}{128\pi} \times [Q_{eff} \sin^2\theta_{1j} + Q_{coll} \cos^2\theta_I]^2$$

$$where\ g_1^* = g_1 - g_R, g_2^* = g_2 - g_R\ and\ g_R = {}^{Z}/_{A}$$

And Q_{eff} and Q_{coll} are the quasiparticle and collective particle quadrupole moments respectively.

Recently, the intrinsic character as well as interplay between the core rotation and the shears mechanism of the magnetic rotational (MR) bands has been well explained within the framework of the shears mechanism with the principal axis cranking (SPAC) model for the nuclei of A ~100, 140 and 200 mass regions. It is noteworthy that the shears bands in weakly deformed atomic nuclei are the consequences of interplay of the repulsive potential (χ = -ve) between the particles and holes outside the core of the nucleus. It would be possible to the shears band-like structure in these nuclei due to the attractive potential (χ = +ve) created by the similar types of nucleons i.e. either particles or holes. At the band-head configuration the angular momentum vectors will be anti-aligned to each other, thereby producing the minimum energy for the same. This band will terminate when the angular momentum vectors are orthogonal resulting the maximum energy for the structure of interest. The intrinsic characters of this band are not yet investigated in details both theoretically and experimentally. Thus, the present work has been motivated to explore the intrinsic character of the shears bands due to the attractive potential produce by the similar type of nucleons i.e. either particles or holes in atomic nuclei near shell closure, also search for the same exists in the level structure of these nuclei. To achieve the goal, the SPAC model has been modified by introducing the dimensionless parameter χ in its energy expression. The intrinsic signatures i.e. nature of the rotational frequency and transition strengths along the spin of the states in the attractive shears band have been extracted and have been compared with the existing structures, that are predicted to be as attractive shears in nature, in the weakly deformed nuclei all over the periodic table.

5. Evidence of the attractive shears

As, the shears mechanism has been observed in the weakly deformed nuclei near shell closure all over the periodic table, this new form would also be expected in these nuclei. To explore this new mode of shears mechanism the level structure of the different weakly deformed nuclei near shell closure all over the periodic chart exists in the literature have been reviewed. The overall scanning of these nuclei along with the modified SPAC calculation provides several candidates of the islands of the attractive shears bands.

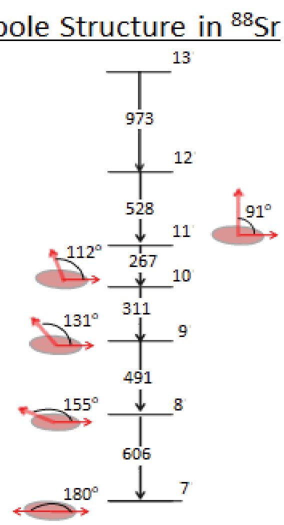

FIG 4: Energy band diagram of Strontium atom in different energy states (data from Ref. [5]).

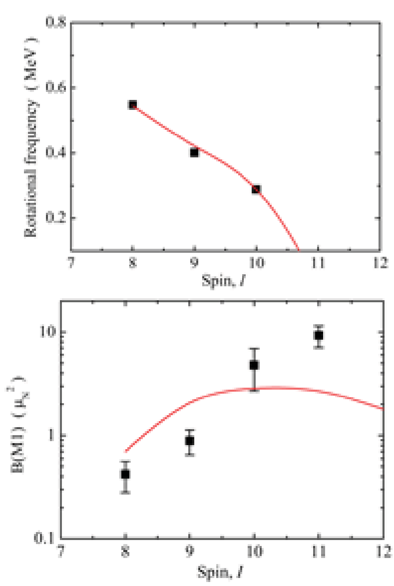

FIG 5: Frequency and M1 Transition Probability vs Spin for ^{88}Sr (data from Ref. [5]).

6. Applications:

In A ~ 90 mass region, the weakly deformed atomic nuclei having proton and neutron particles outside the Z > 40 sub shell and N > 50 shell closures, respectively, are expected to exhibit the shears bands due to the attractive potential. In the level scheme of ^{88}Sr exhibits a band-like structure consisting of the dipole transitions of energies 605, 490, 311, and 267-keV above the (7^{-}) 6234-keV excited state [5]. The modified SPAC model calculation has been performed with the configuration $\pi g^{1}_{9/2} p^{1}_{3/2} \otimes \nu g_{9/2}$ to explore the intrinsic character of the band of interest. The decreasing nature of the experimental ω values for the structure is well reproduced within the calculations shown in Figs. 4 and 5. This is indeed indicating that the band structure of interest in ^{88}Sr may be generated by the shears mechanism due to the attractive potential.

7. Conclusion

The semi-classical calculations of shears mechanism within the modified SPAC model framework reveal the possibility of presence of the shears band resulting from the attractive interaction for weakly deformed nuclei all over the periodic chart. The decreasing trend of the experimental frequency are found to be in agreement with the modified SPAC calculations for the band containing dipole transitions in ^{88}Sr thereby demand the candidature of the attractive shears. Other interesting consequence of the modified SPAC calculations is the increase of the B(M1) and B(E2) transition strengths. Thus measurement of the transition probability has been required on urgent basis to validate the strong candidature of such an extreme excitation mechanism in the weakly deformed nuclei.

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