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Research Article

NUCLEAR SOFTNESS IN THE GROUND STATE ROTATIONAL BANDS IN EVEN-EVEN Yb 158-170 NUCLEI

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A R T I C L E I N F O

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A B S T R A C T

The ground state rotational band structures are studied under the aegis of Variable Moment of Inertia (VMI) Model in the even-even Yb isotopes. The nuclear softness parameter and ground state moment of inertia are obtained by applying least square fitting method. These parameters are used in VMI Model soft rotor formula. The level energies reproduced are in excellent agreement with experimental values. The magnitude of softness parameter (σ) is observed to decrease with increasing mass number. The nuclear matter does not rotate like classical rotor and moment inertia is observed to be far less than rigid rotor value. The reduction in moment of inertia is attributed to nuclear forces and paring correlations. In nutshell, the $2^+ \rightarrow 0^+$ transition energy is repertoire of vast nuclear information.

INTRODUCTION

Due to the developments in experimental techniques and high energy heavy ions particle accelerators [1], the study of nuclear structure at large energies has gathered momentum since the last few decades. Despite of so much wealth of information present about the nucleus, there is still much left to explore and understand many known & unknown aspects of fast rotating nuclei. The advent of large gamma ray detectors has made it possible to investigate the structure of nucleus up to very large momentum, thus resulting in huge wealth of spectroscopic data. This experimentally collected data can be used as a probe to look inside the fast spinning nucleus. The scrutiny of data may provide information about deformation of the nucleus, quadrupole moment, pairing correlations, softness, band termination and so on. The observation of these aspects have prompted considerable amount of experimental and theoretical effort to predict and observe exotic nuclear structure phenomena.

To excite the nucleus, a compound nucleus is formed by bombarding the target nucleus by fast moving projectile from accelerator. In general, high spin states are populated using (HI,xn) fusion-evaporation reactions. The residual nucleus – left after the evaporation of particles & fission, decays through the emission of Statistical Gamma-rays (Continuous γ Rays) and Yrast like transitions (Discrete γ rays). Observing Yrast γ - rays emitted from excited states can tell us about the energy (E), spin or angular momentum (I), parity (π) and lifetime (τ) of the state. In addition they can give use information on the quadrupole moment, magnetic moment, backbending and shape of the nucleus.

All even (Z) - even (N) nuclei have, as a consequence of pairing, a ground state spin and parity of $I^\pi = 0^+$. Closed-shell nuclei have a spherical shape and excited nuclear states can only be formed either by vibrations of the core or by breaking some of the nucleon pairs. Where the nucleus has a deformed shape, e.g. quadrupole or octupole, it can exhibit a regular rotational band structure. Rotating the nucleus to increasingly higher spin, forces the nucleus to adopt a configuration which has the lowest rotational energy. The spin is composed of a collective part and a contribution arising from single particles. Minimizing the energy can be achieved by reducing the collective part (pair breaking) or by increasing the nuclear moment of inertia. In this paper, the ground state rotational bands in even – even isotopes of Yb nucleus are discussed under the aegis of VMI Model and nuclear softness.

VMI Model – A Theoretical Approach

Nucleus is a simple as well as complex microscopic structure. In literature, we find that there are large numbers of Nuclear Models used to explain and understand a large gamut of nuclear properties. In the absence of any definite and precise theory to account for the complex inter-relationships between nucleons, a number of models have been formulated on the basis of which nuclear properties are studied. One such model is developed by Mariscotti [2] for even-even nuclei. The

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rotational structures observed in even-even deformed nuclei in rare earth region of periodic table could be described with the help of semi—classical rigid rotor formula [2,3]:

$$E(I) = \frac{\hbar^2}{2\tau_o} I(I+1) \qquad (1)$$

where, I is the spin of the state and τ_o is ground state moment of inertia. I can take 0, 2, 4, 6, … values. However, there are large deviations from the observed experimental values at large spins. There are several theories and modifications introduced from time to time to account for these differences in order to understand the behavior of the nucleus. With increase in the volume of experimental data, many new parameters are introduced to account for the observed nuclear features. In the present paper, the effect of variation in the moment of inertia of nuclear matter is explored in the even-even isotopes of Yb nucleus. The slow change in the moment of inertia is incorporated in the above expression through "softness parameter – σ " which measures the relative initial variation of Γ with respect to I. Therefore, the moment of inertia of the rotating nucleus is given as:

$$\Gamma = \tau_o(1 + \sigma I) \qquad (2)$$

where τ_o is static moment of inertia and it is calculated from the $2^+ \rightarrow 0^+$ transition energy. Hence, the energy for deformed nucleus rotor is written as:

$$E(I) = \frac{\hbar^2}{2\Gamma} I(I+1) \qquad (3)$$

Nuclear softness parameter is defined as

$$\sigma = \left[\Gamma^{-1}\frac{d\Gamma}{dI}\right]_{I=0} \qquad (4)$$

The moment of inertia of the nucleus is computed using equation (1) for different energy levels of the rotational band. It is observed that observed moment of inertia is far less than rigid body moment of inertia. It also increases with spin. This variation in MI results in the introduction of nuclear softness i.e. stretching out of nucleus as it rotates. Such behavior of nucleus is represented by equation (2). Technically, this is called VMI Model of the deformed nucleus. Sometimes, a correction term is applied to equation (3). This is called rotation- vibration interaction energy. With its introduction, the deviations in the results could be minimized. On its addition, the resulting expression becomes:

$$E(I) = \frac{\hbar^2}{2\Gamma} I(I+1) + \frac{1}{2}C(\Gamma - \tau_o)^2 \qquad (5)$$

C and τ_o are parameters, characteristic for each nucleus. C is called stiffness parameter.

RESULTS AND DISCUSSION

By using the experimentally observed level energies of ground state bands in the even-even isotopes of Yb nuclei [4-10], the moment of inertia is computed using the expression (1) – the semi classical rotor formula. The results of calculations are shown in Figure 1. The variation in MI is almost linear and the lines are nearly parallel to each other with larger isotope lying at the top. However, these experimental values are 20-50% lower than rigid body value throughout the spin range (up to 24 $\hbar$). For τ_{rigid} moment of inertia, this is a good enough approximation given by:

$$\tau_{rigid} = 0.01253A^{\frac{5}{3}}(1 + 1/2\sqrt{5/4\pi\beta) + 0.068225A} \qquad (6)$$

The deformation (β) is taken to be the ground state deformation as given by Möller [11].

This reduction in moment of inertia is generally attributed due to nucleon-nucleon pairing correlations. The rise in MI with spin does indicate that the effect of pairing correlations reduces at higher spins and may be this effect could be the result of CAP – Coriolis Anti Pairing phenomenon. The small value of MI is an indicator that the nuclear matter is somewhat different from classical description.

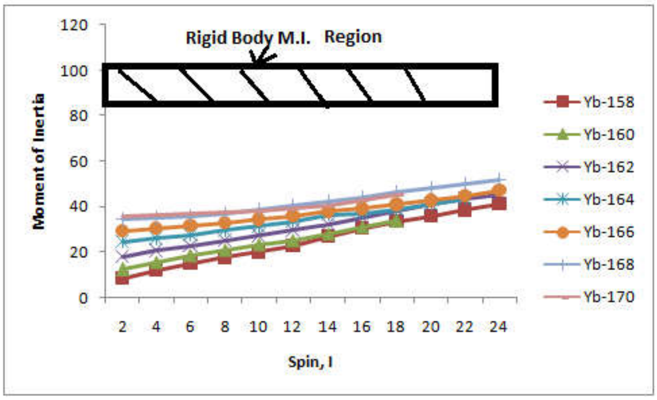

Figure 1 Moment of Inertia ($\hbar^2/MeV$) as a function of spin ($\hbar$) for even-even Yb nuclei.

The nuclear softness parameter is obtained by least square fitting method. The experimentally observed data is fitted in the equation (2). The τ_o static moment of inertia is extracted from the $2^+ \rightarrow 0^+$ transition energy. These values are presented in Table 1.

Table 1 Fitting Parameters (τ_o and σ).

Mass Number, A	**#Quadrupole Deformation, β**	$\tau_o(\hbar^2/MeV)$	**σ**	**0==>2 Transition (MeV)[4-10]**
158	0.183	9.0	0.150	0.357
160	0.206	12.3	0.090	0.243
162	0.239	18.2	0.065	0.166
164	0.262	24.3	0.034	0.123
166	0.274	29.3	0.025	0.102
168	0.286	34.2	0.020	0.087
170	0.287	35.6	0.012	0.084

 # The data is taken from references [11].

The invetigative plot in Figure 2 shows the variation of σ and $0^+ \rightarrow 2^+$ energy with mass number A. It is observed that the behaviour of σ and $0^+ \rightarrow 2^+$ energy is similar. This finding suggests the functional dependence of σ on mass number A and $0^+ \rightarrow 2^+$ transition energy is an indicator of softness of deformed nucleus.

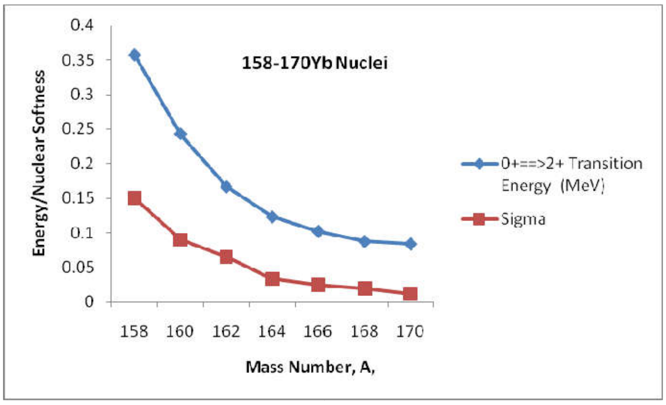

Figure 2 β and $0^+ \rightarrow 2^+$ energy plotted as a function of Mass Number, A.

The ground atate moment of inertia (τ_o) as shown in Table 1 (Figure 3), shows a definite relation with nuclear defromation. It also tends to stabilise much like deformation (β). The smaller values means the particular nucleus is not far away from spherically closed structure.

The above mentioned parameters are also employed in VMI model to estimate the level energies for the ground state bands of even even deformed Yb nuclei. These plots are shown in Figure 4. There energies are reproduced theoreticallaly and it is noticed that there are very small deviations from the experimental values thus exhibiting the almost pure rotational behaviour. In VMI model, only two parameter approach is employed. With the proper selection of τ_o and σ , the $^{158-170}$Yb nuclei ground state band behaviour is investigated and there is excellent aggrement with experimentally observed energy levels. The minimum deviations between experimental and calculated energies predicts small interaction between rotation and vibration states or in other words we can say that rotation-vibration interaction is almost absent in heavly deferomed Yb nuclei.

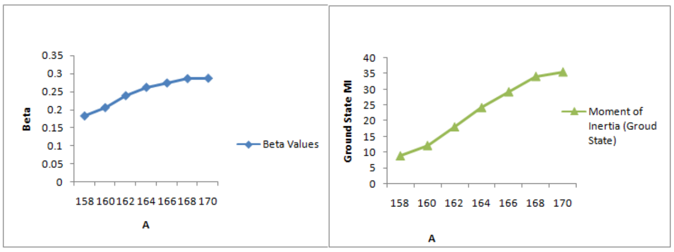

Figure 3 τ_o and β plotted as a function of mass number, A.

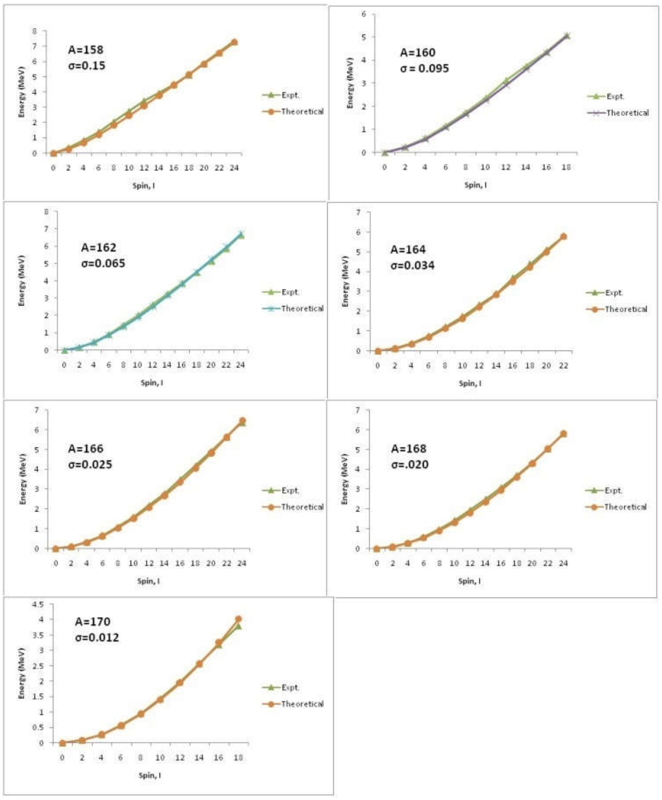

Figure 4 Calculated and experimentally observed level energies in different isotopes of Yb nucleus.

The plot in Figure 5 displays the variations in σ and β with respect to mass number A. As we know that quadrupole deformation β represents the deviation from spherical symmetry, similarly magnitude of σ can be percieved as an indicator of deformed nuclear shape. However, both these parameters behave in opposite manner with respect to mass number A i.e. one increases and other decreases. Therefore smaller magnitude of σ means more deormed the nucleus is.

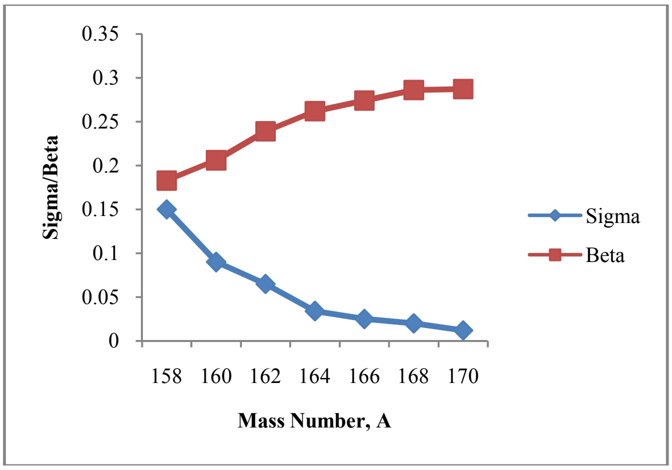

Figure 5 σ and β as a function of Mass Number, A in Yb Nuclei.

CONCLUSIONS

From the above study it is concluded that nucleus is not like a rigid classical spherical object. Its moment of inertia is substantially less than rigid body value. This reduction could be attributed to nuclear forces or pairing forces existing between paired nucleons. As nucleus rotates faster, its kinetic moment of inertia approaches towards rigid value, implying rotation does reduce the effect of pairing correlations. The excellent agreement between experimental level energies and theoretically computed values using the concept of nuclear softness strengthens the VMI model. To complete the study of VMI, this approach should be used in other even-even nuclei in rare earth region of the periodic table.

In nutshell, $0^+ \rightarrow 2^+$ transition energy is found to be dependent on mass number and with proper choice of empirical mathematical relation other nuclear parameters can be extracted from it.

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