Shape changes in Odd-Even Osmium Isotopes

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Abstract. The electromagnetic spectrum of the gamma rays resulting for the excited nucleus in high-spin always for studying of nuclear structure, especially, for neutron-rich heavy deformed nuclei in the rare-earth region with $180 < A < 200$, was important. In this paper, the energy levels of $^{185-187}^{189}$Os isotopes using the projected shell model (PSM) have been calculated. Yrast Spectrum, nucleus rotation frequency and the ratio of reduced electromagnetic transition probabilities, $B(E2)/B(M1)$ plots versus spin for understanding the structure of multi-quasiparticle band up to the spins 47/2$, 33/2$ and $31/2$ for these isotopes, are plotted, respectively. It was found that in spins 35/2$, 31/2$ and $27/2$ due to 3-quasiparticle band-crossing, simultaneously by increasing rotational inertia of the nucleus, nucleus rotation frequency decreases greatly and as an important result, $B(E2)/B(M1)$ ratio, the electrical properties of nucleus in these spins increase. Indeed, in these isotopes, observed that by increasing neutron number, the deformation parameter, $\varepsilon_2$ decreases as well and by increasing spin in especial spins, due to nucleon alignment phenomenon, the nucleus rotational behavior decreases invers the vibration mode.

Keywords. Yrast Spectrum, Alignment Phenomenon, Electromagnetic Transition Probability, Projected Shell Model.

Introduction

In this work, by the projected shell model (PSM) that was carried for the first time by Nilsson in 1955 [1] for considering the deformed shape of the nucleus was presented. In 1995, this model was formulated as a shell model projected on the nuclear symmetry axis known as the PSM model by Hara and Sun [2]. Finally, in 1997, the FORTRAN code of the PSM for PCs was written and published [3] and has been quietly successful and is still used today.

The PSM is a truncated spherical shell model projected on axial symmetry of deformed nuclei and most commonly is used to study medium and heavy-rare-earth mass nuclei. The most important of the PSM model is the formation of a quasi-particle structure by combining the single-particle deformed states from the Nilsson model with the BCS calculations based on the vacuum quasi-particle, |0> [4]. The configuration space of the PSM model generally consists of three major shells for protons and neutrons. In this model, Computations are done with three major shells N= 3, 4, 5 (N=4, 5, 6) with active shell N=5 (N=6) for protons (neutrons). Nilsson parameters $\varepsilon_2$ (Quadrupole deformation) and $\varepsilon_4$ (Hexadecupole deformation) are chosen from reference [6] and are listed in Table 1. By projecting a set of multi-quasiparticle states |$\Phi_x>$ that includes single and three-particle states for the odd-even nuclei in the form of the Equation 1 on a suitable angular momentum such as I, quasi-particle states of deformed shell model are constructed.

$$|\Phi_x> = \{a_+ | 0 >, a^+_x a^+_y a^+_z | 0 > \}$$ (1)

Where $|0>$ the vacuum state and $a^+$ are the quasi particle (qp) creation operators and the index (n) stands for neutrons (protons). Then by defining the angular momentum image operator $\hat{p}^I_{MK}$ as [2]:

$$\hat{p}^I_{MK} = \frac{2i+1}{8\pi^2} \int d\Omega d_k\Omega R(\Omega)$$ (2)

So that $R(\Omega)$ is the rotational operator, $\Omega$ the Euler angle and $d_k\Omega(\Omega)$ the function –D, which forms a complete set of functions in the parametric space $\Omega$ and by affecting the nucleon-like pairs. |$\Phi_x>$, the wave function form of the PSM model is obtained.

$$|\Psi^I_{IM}> = \sum_K f^I_{MK} |\Phi^K_x>$$ (3)

Coefficients $f^I_{MK}$ by solving the Schrodinger equation $H |\Psi^I_{IM}> = E |\Psi^I_{IM}>$ and simultaneous Hamiltonian diagonalization are determined at the bases $\{\hat{p}^I_{MK}|\Phi^K_x>\}$.

The Hamiltonian used in these calculations by the equation as below, Eigen energies of quasi particles were obtained. More details of the PSM theory calculations are defined in ref. [2]:

$$H = H_0 - \frac{1}{2} \sum_\nu \hat{\Omega}_\nu \hat{Q}_\nu - G_\nu \hat{P}^+ \hat{P} - G_\Omega \sum_\mu \hat{P}^+ \hat{P}$$

$H_0$ is a harmonic oscillator single-particle Hamiltonian containing a proper spin-orbit force. The second, third, and fourth expressions which form the non-spherical Hamiltonian, represent quadrupole-quadrupole, monopole, and quadrupole-pairing interactions, respectively. The Coefficients...
of χ, G_M, and G_0 are called strength of interactions. The value of strength, χ can be calculated self-consistently using the deformation parameter ε_2. The monopole paring strengths, G_M can be expressed by equation 8:
\[ G_M = |21.20 ± 13.90 \frac{A^{-\frac{3}{2}}}{A}| \quad (5) \]
where the (-) sign is for neutrons and the (+) sign for protons. The G_0 quadrupole coupling power is assumed to be proportional to G_M and is considered to be a constant 0.16 [5]. In the present work, systematic study of high spin states of $^{185,187,189}$Os isotopes have been investigated using the PSM model.

Table 1. Quadrupole and Hexadecupole deformation parameters used for $^{185,187,189}$Os isotopes.

<table>
<thead>
<tr>
<th>Os</th>
<th>185</th>
<th>187</th>
<th>189</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε_2</td>
<td>0.2</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>ε_4</td>
<td>0.07</td>
<td>0.08</td>
<td>0.08</td>
</tr>
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Results and discussion

Yrast line and Nucleon Alignment phenomenon

As it was shown in Figure 1, the Yrast line has a slight slope change concerning spin. Since the rotation frequency in terms of spin represents a major quantity to describe the nucleon alignment with the nucleus is known as “alignment phenomenon” and is defined by the following relation:
\[ \omega = \frac{E(I) - E(I-\Delta I)}{\Delta I} (h^1 \text{ MeV}) \quad (6) \]
Where for double-odd isotopes ΔI=1.

Reduced Electromagnetic Transition Probability

Another important quantity related to the band diagram and alignment phenomenon in nuclei are the reduced electric quadrupole and magnetic dipole transition probabilities, B (E2) and B (M1) that can be calculated using PSM wave functions Eq. (1), from the initial state (I=I) to the final states (I=I-1) and (I-I-1), respectively, is given by the ratio [6]:
\[ \frac{B(E2)}{B(M1)} = 1 \cdot 44 \cdot \frac{1}{\mu_N^2} \frac{e^4h^2}{\epsilon N} \mu_N^2 \quad (7) \]
μ_N is the nuclear magnetron given as $\mu_N = \frac{e\hbar}{2m_e c} = 0.105 \text{ efm}$. This electromagnetic ratio for each of $^{185,187,189}$Os isotopes for the Yrast line has been calculated and is shown in Figure 3.

In summary, the structures of $^{185,187,189}$Os isotopes have been studied by two important quantity including nucleon alignments and ratios of reduced transition probabilities, B (E2)/B (M1), up to spins 47/2, 33/2, and 31/2 using the projected shell model, respectively. It was shown in spins 35/2, 31/2, and 27/2, a pair of protons were aligned by the nucleus, and alignment phenomenon occurs.

As result, nucleus rotation frequency decreases and it has a direct effect on B(E2)/B(M1) ratio.

Fig 3. B(E2)/B(M1) ratio, as a function of spin for $^{185,187,189}$Os. Experimental data are taken from Ref. [7,8].

Conclusion

In these isotopes under discussion, observed that by increasing neutron number, the deformation parameter, ε decreases as well. This means that the shape of isotopes changes from non-spherical to spherical and the rotational behavior change to a vibrational one, thus the rotation alignment happens at upper spins.

References