Study of multiphonon $\gamma\gamma$-band in neutron-rich $^{112}$Ru nucleus and molybdenum isotopes

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Abstract
The structure of multiphonon $K=4$ $\gamma\gamma$-band of $^{112}$Ru, $^{104}$Mo, $^{106}$Mo, and $^{108}$Mo nuclei are investigated using the recently proposed modified soft rotor formula (MSRF). The positive values of the moment of inertia and small values of softness parameter are obtained. The calculated values of moment of inertia of $\gamma\gamma$-band are almost equal to the moment of inertia of $\gamma$-band, which indeed should be equal to the moment of inertia of ground band. The constant energy parameter $E_K$ in the MSRF is also illustrated for $K=4$ $\gamma\gamma$-band. The staggering pattern in the multiphonon $\gamma\gamma$-band is also discussed in detail. The study of one-phonon $K=2$ $\gamma$-band and two-phonon $K=4$ $\gamma\gamma$-band using MSRF yields good energy values.

Keywords: modified soft rotor formula, nuclear structure, one-phonon $\gamma$-band, two-phonon $\gamma\gamma$-band

1. Introduction
The neutron-rich Ru and Mo isotopes are a point of attraction both in theoretical and experimental studies. These nuclei lie in the mass region $A \approx 100$, which exhibits different kinds of nuclear structure varying from spherical symmetric nuclei to highly deformed nuclei. The structure of neutron-rich even–even Ru isotopes produced by the $\beta$-decay of $^{112}$Tc was studied by Stachel et al [1, 2]. In 1984, Sakai [3] illustrated a few excited energy levels for ground band, even fewer for $\gamma$-band, and none for $\gamma\gamma$-band in Ru and Mo isotopes. With advancement in the experimental techniques [4–9], the fission product was produced by a heavy nuclei source and the prompt $\gamma$-rays were studied using a large-detector array. Shannon et al [10] studied the prompt $\gamma$-rays from the fission of $^{248}$Cm source with EUROGAM array and proposed the levels with spin up to $10\hbar$ of $^{112}$Ru. Wang et al [11] significantly extended the study of Ru by introducing high spin states with two new side bands, one of them named the two-phonon $\gamma$-vibration band and other the two-quasiparticle band. The spectroscopy of $^{109–112}$Ru was studied by measuring the prompt $\gamma$-rays produced by the $^{238}$U($\alpha$, $f$) fusion–fission reaction [12]. The high spin levels in $^{104}$Mo, $^{106}$Mo, and $^{108}$Mo were observed by spontaneous fission of $^{252}$Cf with gammasphere detector array [13–15]. The two-phonon vibrational states are present in these neutron-rich Mo nuclei.

When the vibration of one phonon has no component of angular momentum along the symmetry axis, it is known as $\beta$-vibration ($K=0$). Similarly, the vibration of one phonon with a component of angular momentum along the symmetry axis ($K=2$) is known as $\gamma$-vibration. The two-phonon $\gamma$-vibration bands can be obtained by combination of parallel or antiparallel $K=2$ quanta, which lead to two bands, one with $K=0$ angular momentum and another with $K=4$ angular momentum. The two-phonon vibration bands i.e., $\beta\beta$ with $K=0$ and $\beta\gamma$ with $K=2$ are also observed in few nuclei [16–19]. The two-phonon vibration band i.e., $\gamma\gamma$ with $K=4$
was first observed in $^{168}$Er nucleus by Davidson et al [20, 21]. The study of $^{168}$Er nucleus using the interacting boson model (IBM) was completed by Warner et al [22]. Later on, the existence of a two-phonon $\gamma\gamma$ vibration band in $^{168}$Er nucleus was studied by Borner et al [23] using the absolute transition rate. Through a series of investigation of energy levels, interesting experimental data have been accumulated in the last decade for Ru and Mo isotopes. Further, the experimental results have been used in the studies by various nuclear models. Many authors have used the IBM, which was proposed by Iachello and Arima [24], to study the experimental data. In IBM-1, s-bosons and d-bosons are used as building blocks. The nucleus is characterized by the total boson number ($N_b$), which is equal to sum of half the number of valence protons ($N_p$) and valence neutrons ($N_n$) and there is no distinction between proton and neutron bosons in IBM-1. The isotopes of Ru were studied and it was concluded that they belong to a transition from U(5) and SU(6) limit of IBM [25]. However, in IBM-2, $N_p$ and $N_n$ are treated separately, which gives a deep understanding of collective interactions. The even–even Ru isotopes were discussed by using IBM-2 (see [26, 27]).

Many other nuclear models have also been used for the calculation of excitation energies and transition strengths of Ru isotopes, for example, the rotation–vibration model [5], cranked shell model [28], generalized collective model [29], and rigid triaxial rotor model [30] (RTRM). Stefanescu et al [30] carried out the calculations using a Hamiltonian with a three-body term of IBM-1 and also examined the relation between IBM and RTRM.

The present approach of the work is to discuss the important aspects of an even–even $^{112}$Ru nucleus and Mo isotopes such as excitation energies and odd–even staggering patterns both in one-phonon $\gamma$-band ($K = 2$) and two-phonon $\gamma\gamma$-band ($K = 4$) by using the MSRF and experimental data, respectively. The calculations of the present work are also compared with the latest experimental information taken from [13–15, 28], which includes a new band-like structure on band head of $4^+_1$ state ($K = 4$) proposed as $\gamma\gamma$-band in $^{104}$Mo, $^{106}$Mo, $^{108}$Mo, and $^{112}$Ru nuclei.

2. **Theory**

For good rotors, Bohr–Mottelson [31] proposed the energy formula:

$$E(I) = \frac{\hbar^2}{2\theta}(I + 1),$$  

(1)

where $I$ is the spin of each state and $\theta$ is the moment of inertia (MoI) of the nuclei. For shape transitional nuclei, this ideal formula deviates and therefore a more extended form of the rotor formula was proposed. The soft rotor formula (SRF) proposed by Gupta [32] used the concept that with increasing spin $I$, MoI also increases because of centrifugal stretching and Coriolis effects. The SRF [33] was found to be successful in calculations of excitation energies. The SRF is given as:

$$E(I) = \frac{\hbar^2}{2\theta}(I + 1) + \frac{C(\theta_1 - \theta_0)^2}{2},$$  

(2)

where $\sigma$ is the variable of MoI parameter (also known as softness parameter). Bihari et al [34] used the SRF to evaluate the MoI and softness parameter $\sigma$ for $\gamma$-band. They obtained both the positive and negative values of MoI in many nuclei. However, Gupta et al [35] pointed out that it is difficult to justify the negative values of MoI and large values of $\sigma$. The variable moment of inertia model (VMI) [36] used for high spins is expressed as:

$$E(I) = \frac{\hbar^2}{2\theta_1(1 + s\theta)} + \frac{C(\theta - \theta_0)^2}{2},$$  

(3)

where $\theta_1$ is the MoI parameter at spin $I$, $\theta_0$ is the MoI at ground state ($I = 0$), and $C$ is the stiffness parameter. A combination of SRF and VMI is known as the VMINS3 model [37] and it was found that the value of $\sigma$ for ground state in all nuclei is smaller i.e., less than 1. However, Bihari et al [34] found the value of $\sigma$ to be large in some cases. Gupta et al [35] resolved the anomaly of negative MoI and large values of $\sigma$ by modifying the SRF for $\gamma$-band ($K = 2$).

We further extend the search of MSRF by applying this formula to multiphonon $\gamma\gamma$-band, MSRF expression:

$$E(I) = EK + \frac{\hbar^2}{2\theta_1(1 + s\theta)} + \frac{C(\theta - \theta_0)^2}{2},$$  

(4)

where $EK$ is constant energy term.

The constant term $EK$ can be eliminated and the parameters $\sigma$ and MoI can be evaluated, by using the substraction method. In $\gamma$-band, there is a problem of odd–even spin staggering, therefore the even and odd spins are taken separately in order to determine the MoI and $\sigma$ parameters. The equations for even spin members to find $\sigma$ and MoI are:

$$E_4 - E_2 = \frac{1}{\theta_1} \left[ \frac{21}{1 + 6\sigma} - \frac{3}{1 + 2\sigma} \right],$$  

(5)

$$E_6 - E_4 = \frac{1}{\theta_1} \left[ \frac{36}{1 + 8\sigma} - \frac{10}{1 + 4\sigma} \right],$$  

(6)

by dividing equations (5) and (6), a quadratic equation in terms of $\sigma$ is obtained. Then the positive root of sigma is used to find $\theta$ from equation (5). Using the value of $\sigma$ and $\theta$, the excitation energies of $\gamma$-band can be calculated.

Similarly for $\gamma\gamma$-band, we treat the even and odd spins separately; the equations for even spin members are as follows:

$$E_6 - E_4 = \frac{1}{\theta_1} \left[ \frac{21}{1 + 6\sigma} - \frac{10}{1 + 4\sigma} \right],$$  

(7)

$$E_8 - E_4 = \frac{1}{\theta_1} \left[ \frac{36}{1 + 8\sigma} - \frac{10}{1 + 4\sigma} \right],$$  

(8)

by dividing these two equations, $\theta$ is eliminated and the resulting expression yields a quadratic equation in $\sigma$. Then the positive root of $\sigma$ is taken to find MoI from equation (7). Using the value of MoI and $\sigma$ in equation (4), the value $EK$ and then the excitation energies of $\gamma\gamma$-band can be calculated.
3. Results and discussions

The softness parameter $\sigma$ and $\text{MoI} \theta$ of MSRF are fitted to excitation energies of ground-band, $\gamma$-band ($K = 2$), and $\gamma\gamma$-band ($K = 4$). First, the MSRF as described earlier is applied to study the positive parity bands of even–even $^{112}$Ru nucleus and Mo isotopes. The comparison of experimental values with theoretical values using MSRF are presented in figures 1–4 for $^{112}$Ru nucleus and isotopes of Mo. For ground-state band, the levels up to spin $12^+$ are taken in the calculations, and we find that the theoretical data match excellently with experimental data. For $\gamma$-band, the levels up to spin $10^+$ are included in the fitting. For $\gamma\gamma$-band, the calculated data have been extended up to spin $11^+$, whereas experimental data are available only up to spin $9^+$ in $^{112}$Ru and $^{104}$Mo nuclei. The theoretical data show very good agreement with experimental data for all the three bands.

3.1. Comparison with rotor model values

The rotor model values of MoI for all $K$-bands serve as the reference points. For ground-band, it is given by $\text{MoI} = \frac{3}{E(2^+)}$. For $\gamma$-band $\text{MoI} = \frac{3}{E(3^+)-E(2^+)}$ and for $\gamma\gamma$-band $\text{MoI} = \frac{5}{E(5^+)-E(4^+)}$.

It was proven [38] that the MoI of $\gamma$-band is almost equal to the value of MoI of ground-band for the same nucleus. If we check this statement for MoI of $\gamma\gamma$-band, we find that the derived MoI of $\gamma\gamma$-band is almost equal to the derived MoI of $\gamma$-band and ground-band for the same nucleus. The values of $\theta$, $\sigma$, and $EK$ for ground-band using MSRF are shown in table 1. The values of the MoI using the rotor model are also listed for comparison. The parameters $R_{4\theta/2\theta}$, $R_{2\gamma/2\gamma}$, and $R_{4\gamma/2\gamma}$ are also written in table 1 to find the nature of the nucleus. The value of fitted parameters $\theta$, $\sigma$, and $EK$ have been calculated for $\gamma$-band and $\gamma\gamma$-band are listed in tables 2 and 3, respectively.
Table 1. The values of fitted parameters \( \theta, \sigma, \) and \( EK \) for ground-band from MSRF has been listed. The value of \( R_{4g/2g}, R_{2g/2g}, \) and \( R_{4g/2g} \) are also listed. The value of \( \text{MoI} \left( = \frac{1}{E_{K(3g)}} \right) \) using the rotor model for ground-band are also listed for comparison.

| Nuclei | \( A \) | \( \frac{1}{E_{K(3g)}} \) | \( \theta \) | \( \sigma \) | \( EK \) | \( R_{4g/2g} \) | \( R_{2g/2g} \) | \( R_{4g/2g} \) |
|--------|-------|----------------|------|------|------|------|------|------|
| Ru     | 112   | 0.012          | 0.012 | 0.075 | 28   | 2.72 | 2.21 | 2.70 |
| Mo     | 104   | 0.016          | 0.015 | 0.046 | 14.23| 2.92 | 4.23 | 1.95 |
| Mo     | 106   | 0.017          | 0.018 | 0.028 | 10.27| 3.04 | 4.13 | 2.02 |
| Mo     | 108   | 0.015          | 0.016 | 0.042 | 14.23| 2.77 | 3.04 | 2.43 |

Table 2. The fitted parameters \( \theta, \sigma, \) and \( EK \) both for even and odd spin members of \( \gamma \)-band are listed here. The value of \( \text{MoI} \left( = \frac{1}{E_{K(3g)} + E_{K(2g)}^{\sigma}} \right) \) using the rotor model for \( \gamma \)-band are also listed for comparison.

| Nuclei | \( A \) | \( \frac{1}{E_{K(3g)}} \) | \( \theta_{\text{even}} \) | \( \theta_{\text{odd}} \) | \( \sigma_{\text{even}} \) | \( \sigma_{\text{odd}} \) | \( EK_{\text{even}} \) | \( EK_{\text{odd}} \) |
|--------|-------|----------------|------|------|------|------|--------|--------|
| Ru     | 112   | 0.013          | 0.010 | 0.012 | 0.100 | 0.075 | 278.03 | 350.46 |
| Mo     | 104   | 0.014          | 0.011 | 0.014 | 0.116 | 0.068 | 588.78 | 668.61 |
| Mo     | 106   | 0.017          | 0.018 | 0.018 | 0.055 | 0.034 | 534.00 | 573.86 |
| Mo     | 108   | 0.015          | 0.013 | 0.016 | 0.068 | 0.044 | 387.90 | 442.86 |

Table 3. The fitted parameters \( \theta, \sigma, \) and \( EK \) both for even and odd spin members of \( \gamma \gamma \)-band are listed. The value of \( \text{MoI} \left( = \frac{1}{E_{K(5g)} - E_{K(3g)}^{\sigma}} \right) \) using the rotor model for \( \gamma \gamma \)-band are also listed for comparison.

| Nuclei | \( A \) | \( \frac{1}{E_{K(5g)} + E_{K(3g)}^{\sigma}} \) | \( \theta_{\text{even}} \) | \( \theta_{\text{odd}} \) | \( \sigma_{\text{even}} \) | \( \sigma_{\text{odd}} \) | \( EK_{\text{even}} \) | \( EK_{\text{odd}} \) |
|--------|-------|----------------|------|------|------|------|--------|--------|
| Ru     | 112   | 0.021          | 0.011 | 0.014 | 0.107 | 0.057 | 758.34 | 837.88 |
| Mo     | 104   | 0.021          | 0.015 | 0.015 | 0.061 | 0.060 | 1035.62| 1050.19|
| Mo     | 106   | 0.022          | 0.020 | 0.020 | 0.023 | 0.018 | 967.38 | 984.67 |
| Mo     | 108   | 0.018          | 0.013 | 0.022 | 0.070 | 0.015 | 823.57 | 1054.45|

3.2. Staggering indices

Staggering indices \( S(I) \) are defined as relative displacement of odd spin levels w.r.t even spin levels. For the experimental energy levels of \( \gamma \)-band, \( S(I) \) can be expressed as [39]:

\[
S(4\gamma) = \frac{(E_{4\gamma} - 2E_{3\gamma}) - (E_{2\gamma})}{E(2^+_1)}. \tag{9}
\]

For \( \gamma \gamma \)-band, we can use this formula:

\[
S(6\gamma\gamma) = \frac{(E_{6\gamma\gamma} - 2E_{5\gamma\gamma}) - (E_{4\gamma\gamma})}{E(2^+_1)}. \tag{10}
\]

\( S(I) \) show alternative behavior with spin \( I \) for \( \gamma \)-soft and \( \gamma \)-rigid nuclei. For the case of \( \gamma \)-rigid nuclei, \( S(I) \) have positive values for even spin levels and negative for odd spin levels. In the case of an axially symmetric rotor, the \( S(I) \) does not show any variation in phase but increases with increasing spin \( I \). We also find the staggering feature in \( \gamma \gamma \)-band (see equation (10)), observe the changes in \( S(I) \), and try to predict the nature of nuclei in \( \gamma \gamma \)-band.

In \( ^{112}\text{Ru} \) nucleus, the \( S(I) \) describe interesting behavior in \( \gamma \gamma \)-band. In figure 5, the \( S(I) \) of \( \gamma \gamma \)-band have a positive value for even spin members and negative \( S(I) \) value for odd spin members; this is the nature of \( \gamma \)-rigid nuclei in \( \gamma \)-band. Therefore, by using the same concept for \( \gamma \gamma \)-band, we can say that the neutron-rich \( ^{112}\text{Ru} \) nucleus show \( \gamma \)-rigid triaxial behavior both in \( \gamma \)-band and \( \gamma \gamma \)-band.

Bizzeti and Bizzeti-Sona [40] suggested that the \( ^{104}\text{Mo} \) nucleus has the characteristics of X(5) critical point symmetry [41, 42]. Later, Hutter et al [43] contributed that the ground-state band energy of \( ^{104}\text{Mo} \) has good agreement with the X(5) predictions but the \( B(E2) \) values of the ground-band follow the rotational behavior not the X(5) predictions. In \( ^{104}\text{Mo} \), the energy ratio \( R_{0^+1/2^-} \) is 4.67, while X(5) symmetry requires...
5.67. The energy states $E(6^+)$ and $E(0^+_2)$ should be nearly degenerate for X(5) symmetry and this is not followed by $^{104}$Mo nucleus. The energy ratio $R_{0^+_2/2^+_1}$, and experiment $B(E2)$ values of $^{104}$Mo do not show the features of X(5) critical point symmetry. The $S(I)$ show an oscillatory pattern with the small negative values of even spin members and positive values of odd spin members in $\gamma$-band of $^{104}$Mo. This shows that $^{104}$Mo may be an axially symmetric rotor nucleus in $\gamma$-band. This is also accepted by Li-Ming et al [13] and Guessous et al [44]. However, because all the spin members have a positive $S(I)$ value, this implies that the $^{104}$Mo nucleus is axially symmetric in nature for $\gamma\gamma$-band (see figure 6).

For the $^{106}$Mo nucleus, because all spins have positive $S(I)$ values both in $\gamma$-band and $\gamma\gamma$-band, as shown in figure 7, this clearly illustrates that it is an axially symmetric deformed nucleus both in $\gamma$-band and $\gamma\gamma$-band: this is also proposed by Guessous et al [45] for $\gamma$-band.

In the case of $^{108}$Mo nucleus (see figure 8), the staggering grows with increasing spin and it appears axially symmetric in nature at low spin, but at high spin it changes. This shows the triaxial behavior both in $\gamma$-band and $\gamma\gamma$-band (also observed by Hui-Bo et al [15] for $\gamma$-band).

4. Constant energy term $E_K$

The constant energy term $E_K$ is equivalent to an extrapolated energy value of the $K = 2$ band for $I = 0$. For the $\gamma$-band, the energy difference $(E(2^+_1) - E_K)$ should be related to the ground-band energy $E(2^+_1)$. A plot of this energy difference versus ground-band energy is shown in figure 9.

The value of $E_K$ in MSRF is equivalent to an extrapolated energy value of the $K = 4$ $\gamma\gamma$-band for $I = 0$. This energy difference $(E(4^+_1) - E_K)$ should be related to the ground band energy $E(4^+_1)$. A plot of the energy difference $(E(4^+_1) - E_K)$ versus $E(4^+_1)$ is shown in figure 10. The data lie near the diagonal line for $\gamma$- and $\gamma\gamma$-bands, which illustrates the validity and usefulness of the MSRF for multiphonon bands.

5. Conclusion

The excitation energies of $^{112}$Ru, $^{104}$Mo, $^{106}$Mo, and $^{108}$Mo nuclei have been calculated with the MSRF for ground, $\gamma$-,
obtain a softness parameter \( \sigma \). Here, we deal with multiphonon \( \gamma \gamma \)-bands. An excellent fit is obtained in all these nuclei, as shown in figures 1–4. The MSRF yields a positive value for the MoI \( \theta \) and softness parameter \( \sigma \) for all the bands studied here of Ru, Mo nuclei. In these nuclei, the derived \( \theta \) for the \( \gamma \gamma \)-band is almost equal to the derived \( \theta \) for the \( \gamma \)-band and the case is similar for ground-band, which is also true for the corresponding rotor model values (see tables 1–3). It has been studied that for the ground band, the softness parameter \( \sigma \) is less than 0.5 in most nuclei with \( R_{42} > 2.5 \) (see [33]). For \( \gamma \)-band, the same statement has been proven true by Gupta et al [35]. Here, we deal with multiphonon \( \gamma \gamma \)-band and we obtain a softness parameter \( \sigma \) less than 0.2 using MSRF for \(^{112}\)Ru, \(^{104}\)Mo, \(^{106}\)Mo, and \(^{108}\)Mo nuclei.

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