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Nuclear Structure and Properties Study of the Even-Even $^{106-116}$Pd Nuclei

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Abstract

Systematic evaluation of reduced electric quadruple transition probabilities $B(E2)$, provides critical insights in studying nuclear structural properties. The $B(E2)$ for the gamma transition 0^+ to 2^+, 2^+ to 4^+, 4^+ to 6^+, and finally 6^+ to 8^+ excited states for the even-even $^{106-116}$Pd isotopes have been computed in our present study by means of the global best fit (GBF) method. Then, the quadruple moment, Q_0 and the deformation parameter, β for low-lying quadruple collective states of the Pd nuclei with the even neutron numbers, $N = 60$ - 70 have also been calculated. The deviation of the spherical nuclear structure of the even-even $^{106-116}$Pd has been studied using those key parameters, namely, quadruple moment and deformation parameter. Moreover, the variable moment of inertia (VMI) model was employed to elucidate collective rotational behavior of Pd isotopes. Lastly, the estimated values of the first 4^+ to 2^+ excited states energy ratios of these even-even $^{106-116}$Pd isotopes exhibit excellent concordance with experimental data, which manifests γ-unstable O(6) symmetrical behavior during the transitions.

Keywords

Pd Isotopes, GBF Method, Deformation Parameter, Quadruple Moment, VMI Model

1. Introduction

Nuclear study focuses on the nuclear structure, especially for unstable nuclei, those found in the neutron-rich and heavy mass region. When the number of nucleons, namely, protons (neutrons), equals one of the 2, 8, 20, 28, 50, 82, and 126 (magic numbers), the nucleus attains a closed shell, known as an inert core, and is more stable [1]. Protons and neutrons are the two types of fermions present in atomic nuclei, and both can possess magic numbers [2]. Although a simple spherical harmonic oscillator potential can explain the clustering of the single-particle energy levels at the proton (neutron) numbers 2, 8, and 20, the appearance of heavier magic numbers like 28, 50, 82, and 126 is primarily attributed to the significant influence of the spin-orbit interaction [2]. If the nuclear shell is partly filled, the nuclei are assumed to be deviated from their spherical shape, resulting in a non-zero electric quadruple moment and an increase in moment of inertia [3]. Near closed shell, nuclei exhibit harmonic vibrations, while away from shell closures exhibit static deformation with rotational and vibrational dynamics [4]. A fundamental property of a nucleus $B(E2)$ transition probability between the low-lying states, which has been extensively employed to calculate quadruple moment and deformation parameter, β of the nucleus [5]. The collective quadruple excitations of the low-lying levels in even-even palladium (Pd) isotopes have been the subject of extensive theoretical and experimental investigations [6]-[10]. Within the framework of the Interacting Boson Model-1 (IBM-1), originally formulated by Iachello and Arima, the reduced electric quadruple transition probabilities for the even-even $^{104-112}$Cd, $^{100-102}$Ru, and $^{102-112}$Pd nuclei have been systematically analyzed [11] [12]. Correspondingly, the intrinsic quadruple moments (Q_0) and deformation parameters (β) of the Pd isotopes have been evaluated [13] [14]. Previous studies have also addressed various nuclear properties of the $^{72-78}$Ge isotopes [15]. Furthermore, Coulomb excitation measurements of the ^{106,108}Pd nuclei have demonstrated that vibrational degrees of freedom play a pivotal role in determining their low-spin level structures. Nonetheless, these vibrational effects alone do not fully account for the observed decay properties, underscoring the necessity of incorporating rotational motion and triaxiality to achieve a comprehensive description [4]. The study also reveals the excitation energy levels, and their g-factors follow the predictions of a simple vibrational model, but the non-zero static quadruple moment of the first excited state cannot be described without introducing rotational bands. The Doppler shifts lifetime measurements by E2 transition strengths for ^{106}Pd offer detailed insights into the quadruple collectivity of the low-spin states [4]. The ratio of the first two excited states ($R_{4/2}$), defined between the 4^+ and 2^+ levels, has been analyzed to probe the collective dynamics of even-even nuclei. The ratio, $R_{4/2}$ between the 4^+ and 2^+ levels have been calculated for ^{122}Te isotope that results $U(5)$ symmetry [16] [17], and $^{120-130}$Te isotopes [18]. The excitation energy ratio has also been calculated for ^{82}Se, ^{84}Kr and ^{86}Sr isotones [19]. Within the framework of the rotational model, the moment of inertia emerges as a key factor for characterizing deformed nuclei. Also, it is related to reduced transition probability through quadruple moment, which measures the nuclear deformation and mass distribution, and thereby affects the moment of inertia. Subsequently, Back-bending behavior was examined by studying the spin dependence of the moment of inertia within the framework of the variable moment of inertia (VMI) model [16] [20]. Furthermore, the nuclear moment of inertia at high rotational frequencies [21] and spin [22] had been extensively discussed in the literature.

In the present study, the global best-fit (GBF) method was employed to estimate the reduced transition probabilities $B(E2)\uparrow$ for the even-even $^{106\text{-}116}$Pd isotopes. Using the same approach, the corresponding electric quadruple moments and deformation parameters were also evaluated. Furthermore, the nuclear structure and collective dynamics were analyzed through the ratio of the first 4^+ to 2^+ excitation energies, providing additional insights into the underlying collective motion. Eventually, rotational properties and deformation of the isotopes were explored through the inclusion of the moment of inertia in this study. These parameters play a vital role in elucidating collective structure and enriching nuclear data repository.

2. Methodology

2.1. Global Best Fit Method (GBF)

The global best-fit (GBF) method utilizes the excitation energy E (in keV) of the first 2_1^+ state to estimate the corresponding γ-ray lifetime τ_γ (in ps), which is subsequently used to determine the reduced transition probability $B(E2)\uparrow$ (in e^2b^2). Within the hydrodynamic model, under the assumption of irrotational flow, Bohr and Mottelson derived simplified expressions for τ_γ as follows [23]-[25]:

$$\tau_\gamma \approx 0.6\times10^{14} E^{-4} Z^{-2} A^{1/3} \tag{1}$$

For spherical nuclei undergoing small harmonic vibrations, the expression becomes:

$$\tau_\gamma \approx 1.4\times10^{14} E^{-4} Z^{-2} A^{1/3} \tag{2}$$

The $E^{-4}Z^{-2}$ dependence incorporated in these expressions was first introduced by Grodzins through empirical fits for even-even nuclei, in which $A^{1/3}$ was replaced by $A^{0.69}$. Subsequent analyses, treating the exponents of E and A as variable parameters, revealed that the optimal global fit to the experimental data is achieved with modified exponent values [26]-[29].

$$\tau_\gamma \approx 1.25\times10^{14} E^{-4} Z^{-2} A^{0.69} \tag{3}$$

Conversion of this relation into $(E2)\uparrow$ yields:

$$B(E2)\uparrow = 3.26E^{-1} Z^{2} A^{-0.69} \tag{4}$$

It has been noted that the dependence on E is more pronounced than on the precise value of the mass-number exponent. By adopting an exponent of −2/3 for A, instead of the previously used −0.69, a revised global best-fit expression is obtained that provides an improved description of the experimental data [30]:

$$B(E2)\uparrow = 2.6E^{-1} Z^{2} A^{-2/3} \tag{5}$$

Here, $B(E2)\uparrow$ denotes the reduced electric quadruple transition probability, E is the excitation energy, Z is the atomic number, and A is the nuclear mass number [23].

2.2. Electric Quadruple Moment

The deformation of a nucleus arises from the presence of an electric quadruple moment. As a result, its rotational spectrum is generated through electric quadruple transitions. The transition probability for γ-ray emission of a multiple of order l, is given by [31],

$$T(l) = \frac{8\pi(l+1)}{l[(2l+1)!!]^2}\frac{1}{\hbar}\left(\frac{\Delta E}{\hbar c}\right)^{2l+1} B(l) \quad (6)$$

Here, the $B(l)$, reduced transition probability, is written as,

$$B(l; l_i \to l_f) = \sum_{mMM'} \left|\left\langle I_f M' \middle| M'_{lm} \middle| I_i M \right\rangle\right|^2 \quad (7)$$

In particular, for an electric quadruple transition ($E2$) between two states of the same rotational band with quantum number K, the reduced transition probability is [31],

$$B(E2; IK \to I'K) = \frac{5}{16\pi} e^2 Q_0^2 \left|\left\langle I2K0 \middle| I'K \right\rangle\right|^2 \quad (8)$$

In the rotational model for even-even nuclei, the reduced electric quadrupole transition probability is expressed as [31],

$$\begin{aligned} B(E2; I \to I+2) &= \frac{5}{16\pi} e^2 Q_0^2 \left|\left\langle I200 \middle| I+2,0 \right\rangle\right|^2 \\ &= \frac{15}{32\pi} e^2 Q_0^2 \frac{(I+1)(I+2)}{(2I+1)(2I+3)} \end{aligned} \quad (9)$$

For deformed nuclei, rotational excitations are characterized by large quadrupole transition strengths, $B(E2; I \to I')$, which increase with the intrinsic quadrupole moment Q_0 [31].

Experimentally, Q_0 is determined via Coulomb excitation, in which the target nucleus is excited by the electromagnetic field of an impinging charged particle (protons, deuterons, α-particles, or heavier ions). The de-excitation occurs through γ-ray emission, allowing extraction of transition strengths. In cases where higher-lying states are not accessible through Coulomb excitation, γ-decays from radioactive nuclei may be utilized.

For the ground-state to first excited state transition ($0^+ \to 2^+$) in even-even nuclei, the reduced transition probability takes the form,

$$B(E2)\uparrow = \frac{5}{16\pi} e^2 Q_0^2 \quad (10)$$

which leads to the standard relation,

$$Q_0 = \left[\frac{16\pi B(E2)\uparrow}{5e^2}\right]^{1/2} \quad (11)$$

Thus, experimental values of $B(E2)\uparrow$ provide direct information on the intrinsic quadrupole moment and, by extension, nuclear deformation.

2.3. Quadruple Deformation Parameter

The reduced electric quadruple transition probability, $B(E2)\uparrow$, corresponding to the transition from the 0^+ ground state to the first excited 2^+ state, represents a key observable in nuclear structure studies. This quantity provides critical information that complements the characterization of low-lying excitation energies and offers direct insight into collective nuclear behavior. The magnitude of $B(E2)\uparrow$ reflects the degree of quadruple deformation in nuclei and is commonly evaluated using the global best-fit (GBF) relation [23]:

$$B(E2)\uparrow = 2.6E^{-1}Z^2A^{-2/3} \tag{12}$$

where E is the γ-ray transition energy (in keV), Z is the atomic number, and A is the nuclear mass number. The quadruple deformation parameter (β) provides a measure of the departure of nuclei from spherical symmetry and is defined as [5],

$$\beta = \left(4\pi/3ZR_0^2\right)\left[B(E2)\uparrow/e^2\right]^{1/2} \tag{13}$$

where Z is the proton number, $B(E2)\uparrow$ is the reduced transition probability, and R_0 represents the mean nuclear radius. The latter can be evaluated using the relation,

$$R_0^2 = 0.0144A^{2/3}b \tag{14}$$

where A denoting the mass number and b is a constant.

Nuclear deformation occurs, when the numbers of protons (Z) and neutrons (N) deviate from closed-shell configurations. Nuclei with magic numbers (2, 8, 20, 28, 50, 82, and 126) are known to possess enhanced stability, whereas those with partially filled proton and neutron shells are prone to deformation. This effect arises from the distribution and interaction of valence nucleons in unfilled shells [32]. According to the liquid-drop model, nuclei exhibit softness and flexibility, allowing their shapes to deviate considerably from spherical symmetry. Experimental investigations have indeed confirmed that many nuclei display significant deformation, particularly in regions of the nuclear chart where both N and Z differ substantially from magic numbers. Such deformations reflect the redistribution of nuclear charge over a wide range of proton and neutron numbers, highlighting the complex interplay between shell structure and collective behavior.

3. Result and Discussion

The excitation energy of different states has been collected from the nuclear data sheets [33]-[38] for even-even $^{106-116}$Pd isotopes and is presented in **Table 1**. The electric quadruple reduced transition probabilities, quadruple moment, and deformation parameter for various transition levels are also included in **Table 1**. These are the crucial factors to study the nuclear structure and its deviation from an ideal shape. **Table 2** shows the relative data presentation for electric quadruple reduced transition probabilities that demonstrates a comparison of the calculated $B(E2)$ values against available experimental data for selected Pd isotopes. **Figures 1-5** illustrate the interrelations among the mentioned parameters. These graphical representations help to visualize and correlate the theoretical artifacts of these nuclear structure parameters.

Table 1. Data of excitation energy, square of nuclear radius, reduced transition probabilities, $B(E2)\uparrow$, deformation parameter, and quadruple moment for even-even $^{106-116}Pd$ nuclei for different energy states.

Nuclei	Energy State (I)	Excitation Energy (E) (KeV)	Square of nuclear radius $R_0^2(b)$	$B(E2)\uparrow$ (e^2b^2)	Deformation parameter β	Quadrupole moment $Q_0(b)$
^{106}Pd	2^+	511.850	0.32252	0.47989	0.19559	2.1965
	4^+	1229.30		0.34237	0.16520	1.8552
	6^+	2077.01		0.28976	0.15198	1.7067
	8^+	2963		0.27724	0.14866	1.6695
^{108}Pd	2^+	433.94	0.32657	0.55904	0.20849	2.3707
	4^+	1048.25		0.39490	0.17523	1.9925
	6^+	1771.16		0.33557	0.16153	1.8367
	8^+	2548.42		0.31211	0.15578	1.7713
^{110}Pd	2^+	373.80	0.33059	0.64109	0.22055	2.5387
	4^+	920.78		0.43812	0.18232	2.0987
	6^+	1574		0.36686	0.16684	1.9204
	8^+	2296		0.33191	0.15869	1.8267
^{112}Pd	2^+	348.79	0.33458	0.67886	0.22424	2.6124
	4^+	883.56		0.44277	0.18110	2.1098
	6^+	1550		0.35529	0.16223	1.8899
	8^+	2318		0.30831	0.15112	1.7605
^{114}Pd	2^+	332.6	0.33855	0.70355	0.22561	2.6595
	4^+	852.37		0.45020	0.18047	2.1274
	6^+	1500.5		0.36104	0.16162	1.9051
	8^+	2215.7		0.32718	0.15385	1.8136
^{116}Pd	2^+	340.26	0.34250	0.67979	0.21921	2.6142
	4^+	877.58		0.43048	0.17444	2.0803
	6^+	1559		0.33944	0.15490	1.8473
	8^+	2343		0.29503	0.14441	1.7222

Table 2. Calculated and experimental data of electric quadruple reduced transition probabilities $B(E2)\uparrow$.

Nuclei	Energy states	Calculated values (GBF)	Expt. [39]
^{106}Pd	4^+	0.34237	0.396 ± 0.054
^{108}Pd	4^+	0.39490	0.504 ± 0.072
^{110}Pd	4^+	0.43812	0.558 ± 0.072
^{112}Pd	2^+	0.67886	0.630 ± 0.01

In Figure 1, variations of upward transition probabilities of even-even $^{106-116}Pd$ nuclei have been shown for various energy states. The graph represents that, upward transition probabilities of even-even $^{106-116}Pd$ nuclei decreases exponentially as the energy state of even-even $^{106-116}Pd$ nuclei increases. The figure reportedly depicts the lower electric quadruple transition probabilities for isotopes close to magic number. Figure 2 shows the variations of quadruple moments of even-even $^{106\text{-}116}$Pd nuclei for various energy states. The graph shows that, quadruple moment of even-even $^{106\text{-}116}$Pd nuclei decreases as homogenous configuration of the $B(E2)\uparrow$ as the energy state of even-even $^{106\text{-}116}$Pd nuclei increases. Variations of deformation parameter β of even-even $^{106\text{-}116}$Pd nuclei for various energy states presented in Figure 3. The graph shows that, deformation parameter of even-even $^{106\text{-}116}$Pd nuclei decreases in the similar pattern of the exponential decay as the transition levels of even-even $^{106\text{-}116}$Pd nuclei increases. Overall, the nuclear deformation increases at higher energy states. The conclusion can be drawn for Figures 1-3 that for the transition 0^+ - 2^+ the reduced transition probabilities, quadruple moment, and deformation parameter exhibits its highest values across all studied isotopes. As the transition levels increase, a consistent decreasing trend is observed. This suggests that the degree of nuclear deformation, as reflected by the electric quadruple reduced transition probability, quadruple moment, and deformation parameters are more prominent at lower spin states.

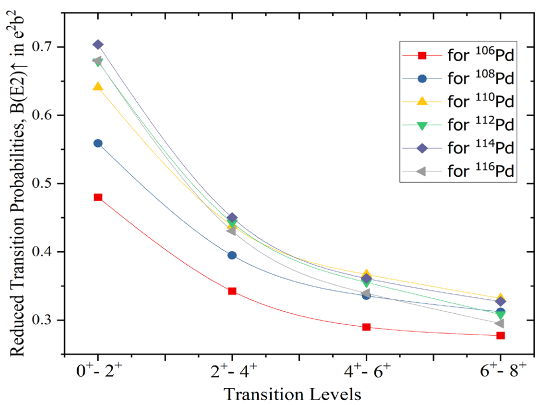

Figure 1. Variation of the reduced transition probabilities $B(E2)\uparrow$ with transition states for the even-even $^{106\text{–}116}$Pd isotopes.

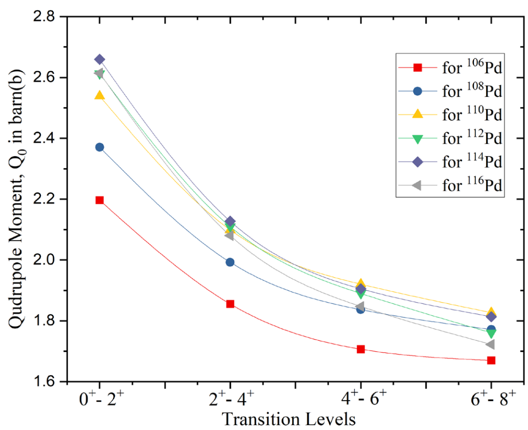

Figure 2. Variation of the quadrupole moments with transition levels for the even-even $^{106\text{–}116}$Pd isotopes.

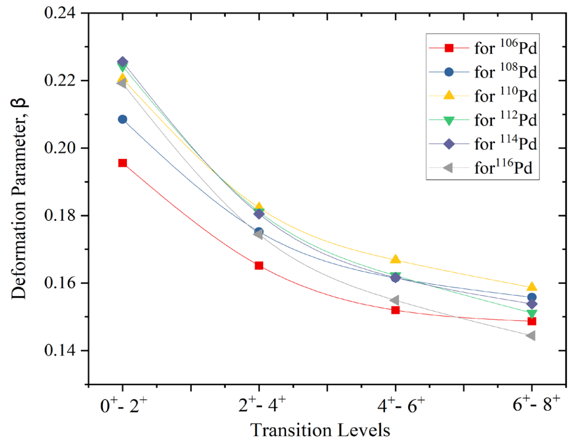

Figure 3. Variation of the deformation parameter (β) with transition levels for the even-even $^{106-116}$Pd isotopes.

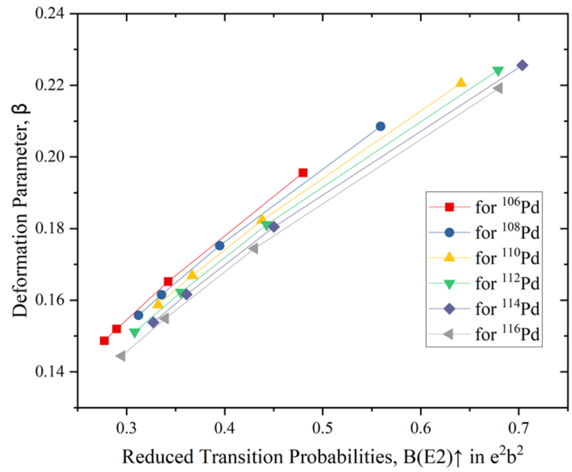

Figure 4. Deformation parameter (β) versus reduced transition probabilities $B(E2)\uparrow$ for the even-even $^{106-116}$Pd isotopes.

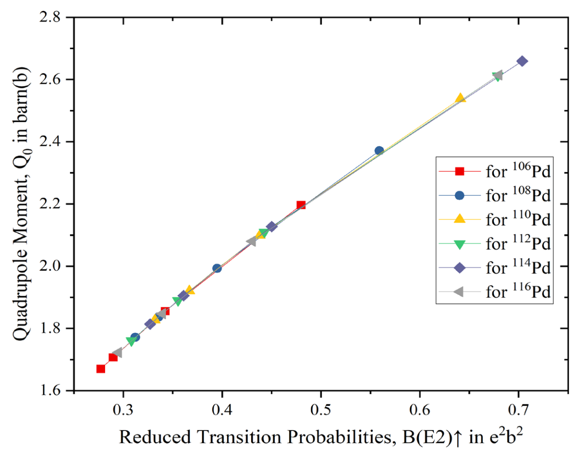

Figure 5. Quadrupole moment as a function of reduced transition probabilities of even-even $^{106-116}$Pd isotopes.

In **Figure 4**, variations of deformation parameter of even-even $^{106\text{-}116}$Pd nuclei have been shown for various upward transition probabilities. The graph shows that deformation parameter of even-even $^{106\text{-}116}$Pd nuclei increases about linearly as the upward transition probability of even-even $^{106\text{-}116}$Pd nuclei increases. In **Figure 5**, variations of quadruple moment of even-even $^{106\text{-}116}$Pd nuclei have been shown for various upward transition probabilities. The graph shows that, initially quadruple moment of even-even $^{106\text{-}116}$Pd nuclei increases exponentially as the upward transition probability increases after the transition probability 0·3 e^2b^2 they become linear. At lower values of $B(E2)\uparrow$ the deformation parameter and quadruple moment for all isotopes remains closely aligned. The positive values of Q_0, *i.e.*, $Q_0 > 0$, correspond to a prolate deformation, and this intrinsic shape is growing with neutron number. However, as the transition probabilities increase the values of β and Q_0 begin to diverge, reflecting increasing differences in nuclear deformation among the isotopes.

3.1. The $R_{4/2}$ Classifications

Even-even nuclei are classified based on the ratio of excitation energy between the initial 4^+ and initial 2^+ excited states [11].

$$R_{4/2} = \frac{E\left(4_1^+\right)}{E\left(2_1^+\right)}$$

where, the $R_{4/2}$ energy ratio is a key parameter for understanding the nuclear structure. **Table 3** represents the $R_{4/2}$ values for $^{106\text{-}116}$Pd isotopes. An axially symmetric rotor $SU(3)$ should have $E\left(4_1^+\right)/E\left(2_1^+\right) = 3.0 - 3.3$, a harmonic vibrator $U(5)$ consumes limit $E\left(4_1^+\right)/E\left(2_1^+\right) = 2.0 - 2.4$, and transitional nuclei have $E\left(4_1^+\right)/E\left(2_1^+\right) => 2.7 \text{ to} < 3.0$ and γ-unstable $O(6)$ should have $E\left(4_1^+\right)/E\left(2_1^+\right) => 2.4 - 2.7$ [14]. The study of even-even nuclei containing 46 protons and 62, 64, or 66 neutrons exhibit a certain sort of symmetry known as $O(6)$ [14]. Recent investigations on entanglement entropy in palladium isotopes (from $^{102}Pd_{56}$ to $^{110}Pd_{64}$) shows that entanglement entropy increases from $^{104}Pd_{58}$ to $^{110}Pd_{64}$, implying that these nuclei exhibit more pronounced $O(6)$ symmetry as the neutron number increases [14] [40].

Table 3. $R_{4/2}$ values for $^{106\text{-}116}$Pd isotopes.

Pd isotopes	^{106}Pd	^{108}Pd	^{110}Pd	^{112}Pd	^{114}Pd	^{116}Pd
$R_{4/2}$	2.40	2.41	2.46	2.53	2.56	2.57

Figure 6 describes for the $^{106\text{-}116}$Pd isotopes, all energy ratio values qualify the expected limits for $O(6)$ symmetry, which characterizes triaxial deformation of γ-unstable nuclei [40].

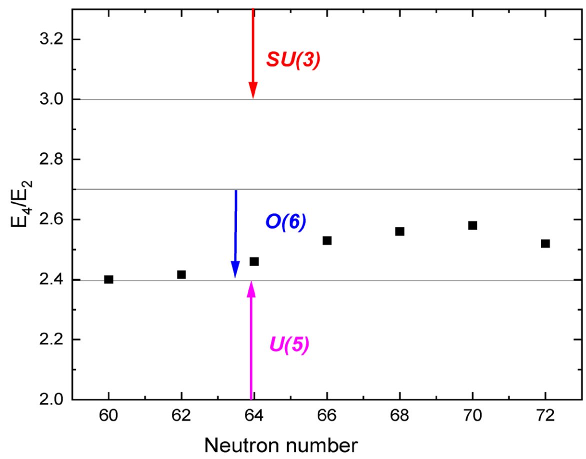

Figure 6. $E\left(4_1^+\right)/E\left(2_1^+\right)$ values, $U(5)$, $O(6)$, and $SU(3)$ limit of $^{106\text{-}116}$Pd isotopes.

3.2. Kinematic of Moment of Inertia

The moment of inertia is a crucial element in studying the structural characteristics of even-even nuclei like palladium. The moments of inertia are calculated utilizing this equation [41]:

$$\frac{2v}{\hbar^2}=\frac{2(2I-1)}{E(I)-E(I-2)}=\frac{4I-2}{E_\gamma}$$

Here, $\frac{2v}{\hbar^2}$ represents the moment of inertia, I denote the nuclear spin, and E_γ refers to the γ-ray transition energy. The moment of inertia is vital for understanding the properties of even-even palladium nuclei. Investigations on $^{100\text{-}110}$Pd isotopes have demonstrated the relationship between moment of inertia and rotational energy, recognizing a phenomenon such as back-bending and the steady transition from vibrational to rotational properties [42].

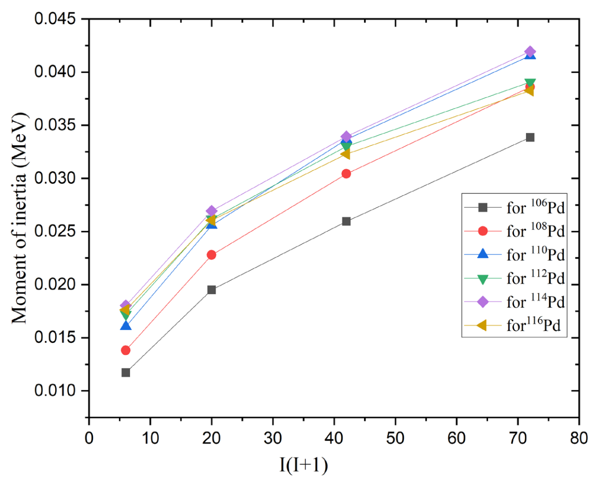

Figure 7. Moment of inertia v/s $I(I+1)$ of $^{106\text{-}116}$Pd.

Figure 7 depicts the moment of inertia for $^{106-116}$Pd are plotted as the function of $I(I+1)$. According to VMI model, the plot of $\frac{2\nu}{\hbar^2}$ vs $I(I+1)$ in terms of the lowest order provides a straight line. Furthermore, the moment of inertia $\frac{2\nu}{\hbar^2}$ increases as the value of $I(I+1)$ rises. It indicates that even-even $^{106-116}$Pd isotopes exhibit rotational pattern, which is known as collective behavior [14] [43] [44]. Increased centrifugal stretching as well as deformation of the nuclei [45] by reducing the pairing correlations due to Coriolis anti-pairing, that soften the nucleus and enable deformation to occur with spin rather than acting like a rigid rotor [46].

4. Conclusion

The present analysis demonstrates that the electric quadruple transition probabilities $B(E2)\uparrow$, quadruple moments, and deformation parameter systematically decrease with increasing excitation energy and are notably reduced near neutron magic numbers. Besides, the evaluated values of $R_{4/2}$ ratios for $^{106-116}$Pd isotopes confirm $O(6)$ symmetry, consistent with previous IBM-1 studies, thereby placing these nuclei in the transitional region between the vibrational $U(5)$ and rotational $SU(3)$ limits, characterized by dominant γ-unstable behavior. The observed increase in the moment of inertia with rising excitation energy indicates a progressive shape evolution from near-spherical to more deformed configurations, consistent with earlier reports. In addition, the study indicates that nuclear deformation from a spherical shape increases with increasing energy states. Collectively, these results provide valuable contributions to the refinement of nuclear data tables.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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