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THEORETICAL DESCRIPTION OF EVEN-EVEN PLATINUM Pt-186 NUCLEUS USING IBM AND (VMI) MODELS[†]

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The aim of this study, is to investigate, in a phenomenological way, the backbending effect in platinum Pt-186 nucleus, in order to get a good description of the bends by using new parameters. VMI model and interacting boson model IBM-1 have been used to perform this research for a heavy mass nucleus (Z = 78). Energy ratios and arrangement of the bands show that the platinum Pt-186 have O(6)-SU(3) dynamical symmetry. Our current calculations gave results that are reasonably consistent with the most recent experimental data, especially the results calculated according to the VMI-model. Variable moment of inertia has been applied to describe successfully the effect of backbending in deformed even-even Pt-186 nucleus. Backbending was observed in the ground and β-bands, due to the change of the moment of inertia but not for (γ_1, γ_2) bands, because no changing in the moment of inertia.
Keywords: *Nuclear structure; IBM; nuclear physics; VMI model; back-bending*
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1. INTRODUCTION

There are two nuclear collections particles: protons, and neutrons so called nucleons, separately divided over certain energy level subjected to the restrictions of the Pauli exclusion principle. All nuclei have ground and excited states, and the nucleons in excited states can be removed from, or added to, nuclei. The nuclear structure gained by studying these phenomena [1]. The IBM-1 was used to description the nuclear collective motion suggested firstly, by Iachello and Arima in order to study the collective states in e-e positive parity nuclei. This model does not distinguish between neutron bosons and proton bosons [2,3]. This research, aims to calculate energy levels, gamma transition and study the backbending phenomena, using the IBM-1 and VMI models.

Backbending has been observed experimentally in the band of the ground state [4,5] or in the rotational band of some deformed nuclei. The effect occurs because, the moment of inertia ($\mathcal{J}$) rapidly increases with the rotational frequency (ω) towards the solid value [6]. When the rotational energy ħω is greater than the energy needed to separate a pair of protons or neutrons S_{2por2n}, the separated proton or neutron moves to another orbit, which result in change of the moment of inertia [7]. An explanation of this effect is attributed to a disappearance of the pairing by band crossing of two rotational energy and Corielis force effect [8,9], this effect of Corielis force increases with rotational frequency at high angular momentum for some bands, leads to depairing nucleon pairs, the first pair depairing called "two quasi particles". the case where the depairing of two quasi particles, which may couple with the collective rotation to produce a new band, this effect leads to back-bending phenomena [10]. Many researchers have been interested in studying the phenomenon of backbending using different methods, including Regan(2003) [10] who used the E-Gos method by drawing the relation between the transitional energy E_γ over spin ($\frac{E_\gamma}{J}$) for two successive levels and the spin (J).Some theoretical researchers have recently focused on studying the nuclear properties of platinum isotopes, including N. Ashok and A.Joseph(2019)[11] studied the ground state properties of Pt isotopes with the help of Skyrme-Hartree-Fock-Bogoliutov (HFB)theory by using harmonic oscillator H.O. and transformed harmonic oscillator T.H.O. to calculate S_{2n} (separation energy of 2-neutrons) and r.m.s radii of proton and neutron. The results obtained are in good agreement with the practical data.

M. Khalil et al (2019) [12] studied the platinum isotopes properties using particle rotor model VMI and IBM to calculate the energies of single particle spectrum and investigated the phenomena of the back-bending. S.H. Al-Fahdawi, A.K. Aobaid (2021) [13] used the first model of interacting bosons and the generalized moment of inertia model to study some of the nuclear properties of deformed heavy nuclei and obtained acceptable results compared to the experimental values and concluded the success of these two models for the study of heavy nuclei. E.A. Al-Kubaisi, A.K. Aobaid (2021) [14] also used the first model of the interacting bosons and vibrator moment of inertia (VAVM) model to calculate the energy levels, the quadrupole moment for even-even Dy-162 nucleus and showed that the (VAVM) model are better than the results calculated by (IBM-1).

2. THEORETICAL ASPECT

2.1. IBM-1 Basis

The interacting b3oson model-1 is an important model used to study the low-lying collective states structure in deformed e-e nuclei, and has been considered as systems composed of interacting (s –d) bosons, which described in terms of monopole boson with $s_{\ell=0}$ and quadrupole boson with $d_{\ell=2}$ [15]. The formula of the Hamiltonian operator can be written by [16]:

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$$\hat{H}=\sum_{i=1}^{N}\varepsilon_i+\sum_{i<j}^{N}V_{ij}. \quad (1)$$

Where ε_i is the energy of bosons i, V_{ij} is the potential energy between the bosons i and j.

General formula for Hamiltonian operator in Eq. 1 assumed by Iachello and Arima can be written as [16,17]:

$$\begin{aligned}\hat{H} &= \varepsilon_s(s^{\dagger}.\tilde{s})+\varepsilon_d(d^{\dagger}.\tilde{d})+\sum_{\ell=0,2,4}\frac{1}{2}(2\ell+1)^{\frac{1}{2}}C_\ell\left[(d^{\dagger}\times d^{\dagger})^{(\ell)}\otimes\left(\tilde{d}\otimes\tilde{d}\right)^{(\ell)}\right]^{(0)}\\ &+\frac{1}{\sqrt{2}}U_2[(d^{\dagger}\otimes d^{\dagger})^{(2)}\times\left(\tilde{d}\otimes\tilde{s}\right)^{(2)}+(d^{\dagger}\otimes s^{\dagger})^{(2)}\otimes\left(\tilde{d}\otimes\tilde{d}\right)^{(2)}]^{(0)}\\ &+\frac{1}{2}U_0[(d^{\dagger}\otimes d^{\dagger})^{(0)}\otimes(\tilde{s}\otimes\tilde{s})^{(0)}+(s^{\dagger}\otimes s^{\dagger})^{(0)}\times\left(\tilde{d}\otimes\tilde{d}\right)^{(0)}]^{(0)}\\ &+V_2\,[(d^{\dagger}\otimes s^{\dagger})^{(2)}\otimes\left(\tilde{d}\otimes\tilde{s}\right)^{(2)}]^0+\tfrac{1}{2}V_0[(s^{\dagger}\otimes s^{\dagger})^{(0)}\otimes(\tilde{s}\otimes\tilde{s})^{(0)}]^{(0)}.\end{aligned} \quad (2)$$

Where: ($s^{\dagger}$,$d^{\dagger}$), ($\hat{s}$, $\hat{d}$) are creation and annihilation operators respectively, $C_{\ell=0,2,4}$, $U_{\ell=0,2}$, $V_{\ell=0,2}$ describes the bosons interactions with each other, $\varepsilon = \varepsilon_d - \varepsilon_S$ represent the bosons energy. The energy of the boson s (ε_S) was considered to be zero, therefore: $\varepsilon = \varepsilon_d$. The other formulas of Hamiltonian operator in equation (2) can be written as multipole expansion mutual into equation of various boson-boson interactions [18]:

$$\widehat{H}=\varepsilon\hat{n}_d+\alpha_0\hat{P}\hat{P}+\alpha_1\hat{L}\hat{L}+\alpha_2\hat{Q}\hat{Q}+\alpha_3\widehat{T_3}\widehat{T_3}+\alpha_4\widehat{T_4}\widehat{T_4}. \quad (3)$$

Where the parameters($\alpha_0,\alpha_1,\alpha_2,\alpha_3,\alpha_4$) represents the strength of the pairing, angular momentum,quadrupole, octupole and hexadecapole interactions between bosons respectively.

2.2. VMI Model Basis

The (VMI) model proposed firstly, by M. Mariscotti et al. 1969 [19] to calculate the energy states values for any band as:

$$E_J(\mathcal{J})=\frac{1}{2}C(\mathcal{J}-\mathcal{J}_0)^2+\frac{1}{2}\,[J(J+1)]/\mathcal{J} \quad (4)$$

Moment of inertia can be determined from equilibrium condition [19,20]:

$$\frac{\partial E(\mathcal{J})}{\partial\mathcal{J}}=0 \quad (5)$$

Determines $\mathcal{J}_J$ (in $\hbar^2$ unit) as a function of (J).

The parameter C is the hardness coefficient and $\mathcal{J}_0$ is the moment of inertia of the ground state (for $\mathcal{J}_0 > 0$).

From equations (4,5) can obtained:

$$\mathcal{J}_J^3-\mathcal{J}_0\mathcal{J}_J^2=[J(J+1)]/2C \quad (6)$$

Eq. 6 contains one real root for any value when ($\mathcal{J}_0$,C) finite and positive.

The lest fit-to-square (l.s.f.) procedure has been applied to all measured E_J values for any state.

The energy of the J-level according to the rotational model is given by the relation [21]:

$$E_J=\frac{\hbar^2}{2\mathcal{J}}J(J+1) \quad (7)$$

As for the transition energy between levels J → J-2 is given by the relationship [22,23]:

$$\Delta E_\gamma=E_J-E_{J-2}=\frac{\hbar^2}{2\mathcal{J}}(4J-2)\ \text{ for (g, β) band} \quad (8)$$

$$\Delta E_\gamma=\frac{E2_1^+}{4}(J+2)\qquad \text{for } \gamma \text{ –unstable O(6)} \quad (9)$$

In order to study the phenomenon of backbending, the moment of inertia ($2\mathcal{J}/\hbar$^2) must be calculated from the Eq. 8 and the square of the rotational energy $(\hbar\omega)^2$ as:

$$\frac{2\mathcal{J}}{\hbar^2}=\frac{4J-2}{\Delta E_\gamma}\qquad \text{for (g, β) band} \quad (10)$$

Where $\Delta E_\gamma=E_J-E_{J-2}$

$$\frac{2\mathcal{J}}{\hbar^2}=\frac{2J}{\Delta E_\gamma}\qquad \text{for gamma band} \quad (11)$$

Equation (8) can be written for harmonic oscillator as:

$$E_\gamma(J\to J\text{-}2)=\hbar\omega \quad (12)$$

While the rotational energy squared $(\hbar\omega)^2$ can be written as [22,23]:

$$(\hbar\omega)^2=(J^2-J+1)\left[\frac{\Delta E_\gamma}{2J-1}\right]^2 \quad (13)$$

The nuclear stiffness parameter σ was introduced, which measures the initial variation of moment of inertia w.r.t. angular momentum, can be calculated from equation (6) as [19,24]:

$$\sigma = \left[\frac{1}{\mathcal{J}}\frac{d\mathcal{J}}{dJ}\right]_{J=0} = \frac{1}{2C\mathcal{J}_0^3} \tag{14}$$

3. HAMILTONIAN INTERACTION PARAMERERS

The Hamiltonian parameters in the IBM computer program "PHINT COD" [25] was used to make the Hamiltonian diagonal. The equivalent program for PHINT code is (IBM1.For) and the input file called "Bos.inp.". All parameters can be changed indepently fitting with the experimentally energy spectrum for the nucleuos, and from these calculations, we find the nuclear structure of the Pt-186 spectra by the Hamiltonian interaction paramerers values, These coefficients that have reasonable agreement with the experimental data were shown in Table 1. These chosen parameters depended on number of proton bosons N_π and neutron bosons number N_ν were calculated from the nearst closed shell, and the number of total bosons N = $N_\pi + N_\nu$. The nucleuos of even-even Pt-186 have atomic number equel 78 protons ,so there are 4 holes (2 protons bosons) to fill the shell Z = 82, and neutrons number equel 108, so there are 18 holes to fill the shell N = 126 or 9 neutrons bosons. The total numbers of bosons N=11.

While the results of VMI model were calculated using VMI. For program from file "Par.input" this file depends on ($\frac{\mathcal{J}_0}{\hbar^2}$, C, E_k) parameters, where: $\frac{\mathcal{J}_0}{\hbar^2}$ moment of inertia for ground state, C is constant parameter fitted with experimental data, E_k is the head of the band energy.

The other files called "Enr. out" and "Enr1.out" these files calculated the following:

1 – Theoretical energy $E_{cal.}$

2 – Rotational energy square $(\hbar\omega)^2$ and $(\frac{2\mathcal{J}}{\hbar^2})$.

3 – Nuclear softness (σ)from equation (12)

4 – Deviation (Δ) [26,27] which determined the deviation between calculate energy states $E_{cal.}$ and experimental values $E_{exp.}$ from equation:

$$\Delta = [\frac{1}{k}\sum_{i=1}^{k}(E_{cal.} - E_{exp.})^2]^{1/2}, \tag{15}$$

where k is the number of levels.

5 – Chi-squared (χ^2) from equation [19]:

$$\chi^2 = (\frac{E_{cal.} - E_{exp.}}{E_{exp.}})^2 \tag{16}$$

Where all calculations for VMI model were chosen from the smallest (χ^2) as in Table.1.

Table 1. Best fitted interaction parameters for the energies of IBM-1 and VMI model

The parameters used for IBM-1 in MeV units except CHI and SO6 unless units								
N	ε	α_0	α_1	α_2	α_3	α_4	CHI	SO6
11	0.0000	0.0399	0.0041	0.0000	0.1206	0.0010	0.0000	1.0000
The parameters used for VMI model parameters σ, Δ and χ^2 unless units								
Band		$\frac{\mathcal{J}_0}{\hbar^2}$ (MeV)$^{-1}$	C (MeV)^3	E_k (MeV)		σ	Δ	χ^2
g-band		10.881000	0.0010200	0.001020		0.380508	0.039794	0.006069
β-band		8.8810008	0.000820	0.471000		0.870504	0.114324	0.071045
γ_1- band		34.000000	0.011100	1.000000		0.001146	0.130298	0.130763
γ_2- band		7.832500	90.500500	0.770000		0.000011	0.095356	0.015812

The ratios of the excitation energies 4_1^+, 6_1^+ and 8_1^+ dividing on the energy level of the first exited 2_1^+ for Pt-186 nucleus using IBM-1 and VMI have been calculated and compared with the identical values for the three limits, SU(5),SU(3) and O(6) as in Table 2, these calculations shows that the platinum-186 has Gamma unstable O(6) dynamical symmetry, but the arrangement of the bands according to their appearance (g, β, γ_1, γ_2) bands shows that the nucleus under study belong to rotational dynamic SU(3)limit.

Table 2. Ideal energy ratios of three chains [18] compared with experiment [28,29] and theoretical (IBM-1 and VMI) values

Energy Ratios R	**$E4_1^+/E2_1^+$**	**$E6_1^+/E2_1^+$**	**$E8_1^+/E2_1^+$**	**Dynamical symmetry**
Identical values [18]	2.0	3.0	4.0	SU(5)
	3.33	7	12	SU(3)
	2.500	4.500	7	O(6)
Experimental data [28,29]	2.565	4.592	7.026	O(6)
IBM-1 Model	2,290	3.881	5.761	O(6)
VMI Model	2,623	4.623	6.916	O(6)

4. RESULTS AND DISCUSSION

4.1. Energy levels

The ideal, practical, and theoretically calculated energy ratios in Table 2 show that the platinum nucleus belongs to gamma unstable O(6) limit, while the arrangement of the band (g, β, γ) indicates that it belongs to rotational SU(3) limit, because the level (0_2^+) appeared before (2_2^+) level this means that a beta band (β) had appeared and therefore the nucleus understudy had O(6)-SU(3) dynamical symmetry.

The calculated of energy levels values for IBM-1 and VMI are compared with the experimental values [28,29] for all bands are shown in Table 3.

Table 3. Comparision of experimental and calculated results for IBM-1 and VMI model

${}^{186}_{78}Pt$		E_J (MeV)			E_γ (MeV) J → J − 2			$\frac{2\vartheta}{\hbar^2}$ $(MeV)^2$	$(\hbar\omega)^2 exp.$ $(MeV)^2$
band	J_i^+	Exp. [28,29]	IBM-1	VMI	Exp. [28,29]	IBM-1	VMI		
G--band	0_1^+	0.000	0.000	0.000	----	----	-----	-----	-----
	2_1^+	0.191	0.193	0.191	0.191	0.193	0.191	20.942	0.034
	4_1^+	0.490	0.442	0.501	0.299	0.249	0.310	26.755	0.088
	6_1^+	0.877	0.749	0.883	0.367	0.307	0.382	31.007	0.149
	8_1^+	1.342	1.112	1.321	0.465	0.363	0.438	34.408	0.215
	10_1^+	1.858	1.532	1.803	0.516	0.420	0.482	38.759	0.265
	12_1^+	2.336	2.008	2.324	0.478	0.476	0.521	50.209	0.228
	(14_1^+)	2.825	2.542	2.879	0.489	0.534	0.555	57.259	0.238
	(16_1^+)	3.394	3.133	3.465	0.569	0.591	0.586	56.239	0.323
	(18_1^+)	4.051	3.782	4.079	0.657	0.649	0.614	54.794	0.431
	(20_1^+)	4.788	4.488	4.719	0.737	0.706	0.640	54.274	0.542
β1 - band	0_2^+	0.471	0.482	0.471	---	---	---	---	---
	2_2^+	0.607	0.555	0.670	0.136	0.073	0.199	5.012	0.017
	4_2^+	0.991	0.925	0.976	0.384	0.370	0.306	37.974	0.145
	(6_2^+)	1.470	1.233	1.346	0.479	0.308	0.370	30.075	0.227
	(8_2^+)	2.004	1.597	1.766	0.534	0.364	0.420	71.428	0.284
	(10_2^+)	2.108	2.018	2.226	0.104	0.421	0.460	50.420	0.010
	(12_2^+)	2.611	2.498	2.722	0.503	0.480	0.496	69.651	0.252
	(14_2^+)	3.192	3.035	3.249	0.581	0.537	0.527	49.689	0.337
	(16_2^+)	3.664	3.630	3.805	0.472	0.595	0.556	114.64	0.222
	(18_2^+)	4.258	4.285	4.385	0.594	0.655	0.580	75.757	0.352
	(20_2^+)	4.956	5.943	4.990	0.698	0.605	0.605	---	---
γ1- band	2_3^+	0.798	0.675	0.954	---	---	---	---	---
	3_1^+	0.956	0.909	1.047	0.158	0.234	0.093	---	---
	4_3^+	1.222	0.926	1.172	0.266	0.017	0.125	---	---
	(5_1^+)	1.362	1.349	1.328	0.140	0.423	0.156	---	---
	(6_3^+)	1.600	1.353	1.604	0.238	0.004	0.276	---	---
	(7_1^+)	1.801	1.765	1.735	0.201	0.412	0.131	---	---
	(8_3^+)	2.123	1.837	1.984	0.322	0.072	0.249	---	---
	(9_1^+)	2.280	2.038	2.266	0.157	0.201	0.282	---	---
	(10_3^+)	2.544	2.378	2.578	0.264	0.340	0.312	---	---
	11_1^+	---	2.669	2.922	---	0.291	0.344	---	---
	(12_3^+)	2.864	2.916	3.296	---	0.247	0.374	---	---
γ2- band	2_4^+	1.175	1.038	1.153	---	---	---	---	---
	3_2^+	1.417	1.474	1.535	0.242	0.436	0.382	---	---
	4_4^+	2.159	1.632	2.046	0.742	0.158	0.511	---	---
	5_2^+	---	1.934	2.684	---	0.302	0.638	---	---
	6_4^+	---	1.963	3.450	---	0.029	0.766	---	---
	7_2^+	---	2.452	4.343	---	0.489	0.893	---	---

In Table 3 The values of the energy levels are calculated theoreticaly for the spins ($11_1^+, 5_2^+, 6_4^+, 7_2^+$) respectively which are not determined experimentally, especially in γ_2 –band. Theoretical calculations also showed that the value of the uncertain practical energy, which is equal to (2.825MeV)for the spin{(14_1^+)}, is more probable to the confirmed value, especially for VMI model (2.879 MeV) also at the spin {(16_1^+),(18_1^+), (20_1^+),(14_2^+), (20_2^+),(5_1^+), (6_3^+), (9_1^+), (10_3^+)}.

The energy spectram of platinum Pt-186 for (g, $\beta, \gamma_1, \gamma_2$) bands as a comparison of IBM-1 and VMI calculations with experimental data were plotted in Figure 1.

The experimental data and calculated of energy bands for the ground and β-bands were plotted in Figure 2. Good agreements from the comparison of the IBM-1 and VMI model calculations (energies, spin and parity) with the experimental data. But in $\gamma_1 -$ band, the agreements were acceptable in the low-lying states, while it is deviated in the high spin (energies)of the experimental data because, the calculations of IBM-1 have been performed with no distinction made between neutron and proton bosons.

In $\gamma_2 -$ band VMI calculations were in agreements with experimental data while, the calculations of IBM-1 were not good with experimental data because the interacting boson model does not distinguish between neutron and proton bosons, there were no experimental values for the energy states for band.

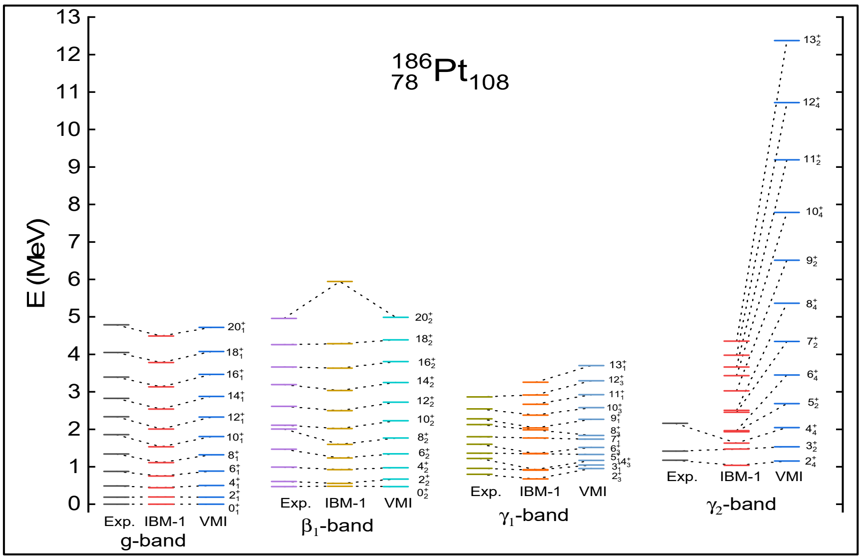

Figure 1. The energy spectra for Pt-186 nucleus as a comparison of IBM-1 and VMI calculations with the available experimental data [28,29]

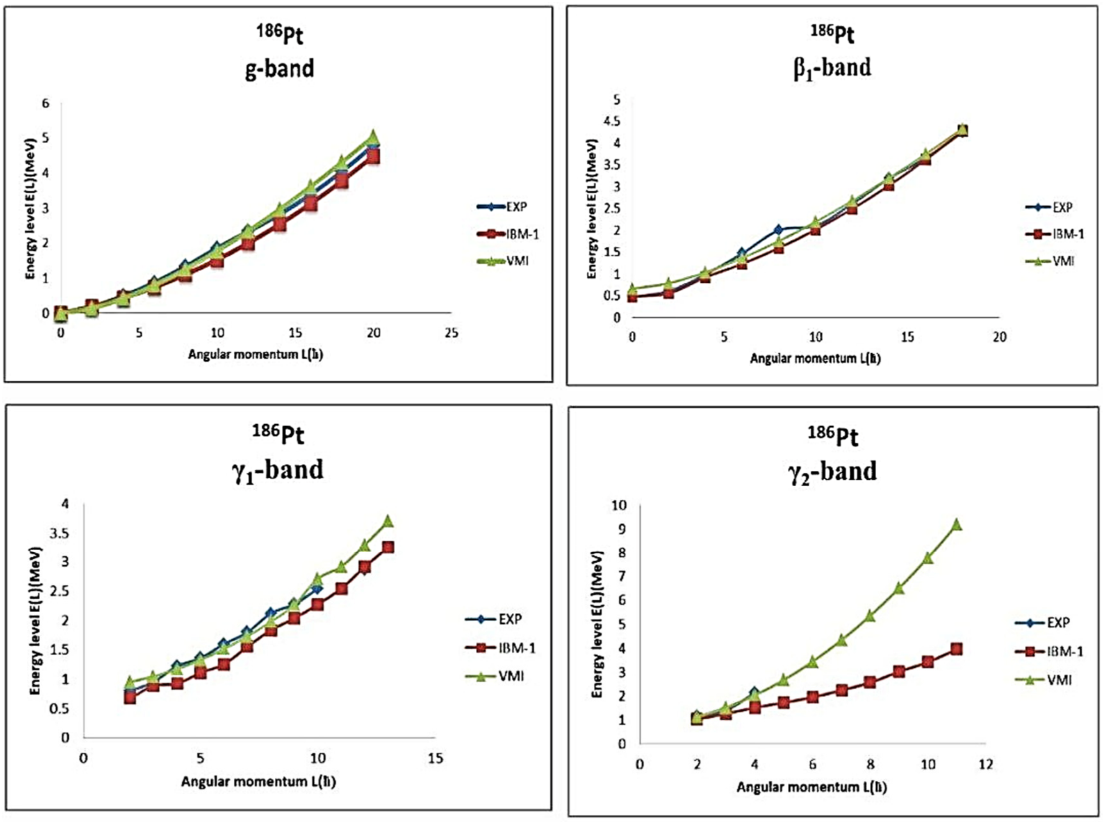

Figure 2. The experimental [28,29] and theoretical results IBM-1, VMI, E(L) versus L for g, β, γ,-bands

4.2. Backbending phenomena

For the purpose of identifying the properties of the nuclei and studying the possibility of backbending in them, the moment of inertia $(\frac{2\mathcal{J}}{\hbar^2})$ and Rotational energy squared$(\hbar\omega)^2$ were calculated using equations (10 and 12) respectively, these values are shown in Table 3. The relation between $(\frac{2\mathcal{J}}{\hbar^2})$ and $(\hbar\omega)^2$ was drawn for the ground and beta bands in which a backbending appeared in it, and shown in Figures 3 and 4. The backbending of these bands occur, due to the change in the moment of inertia and β-band lies in SU(3) limit, and no backbending was observed in the (γ_1,γ_2) bands, because the moment of inertia does not change ,also these bands belonging to γ-unstable limit.

The drawing of the ground state band Figure 3 had a backbending between the levels 12_1^+, and (18_1^+), due to the deformation of these levels, also, the backbending occurs due to the rapid increase in the moment of inertia at relatively high spin than the expected value according to the rotational motion model of some nuclei, which causes a decrease in the expected energy value at these cases result in a backbending in the moment of inertia curve as a result of the disengagement of one or two pairs of nucleons and their re-engagement, which reduces the expected energy value that causes the backbending.

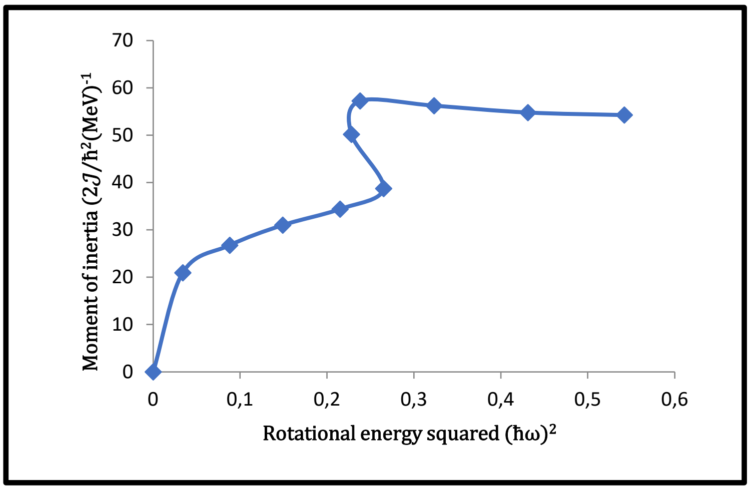

Figure 3. Moment of inertia $(2\mathcal{J}/\hbar\text{^}2)$ as a function of Rotational energy squared $(\hbar\omega)^2$ for g-band experimental

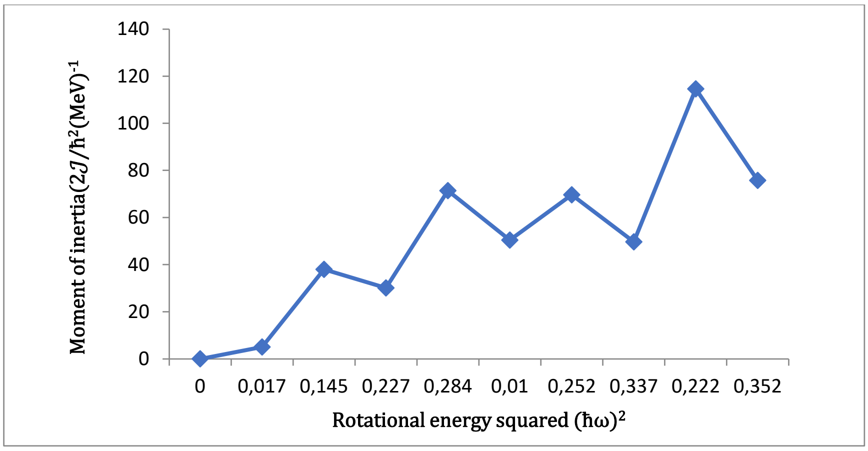

Figure 4. Moment of inertia $(2\vartheta/\hbar\text{^}2)$ as a function of Rotational energy squared $(\hbar\omega)^2$ for β-band experimental

5. CONCLUSIONS

In the present work, the IBM-1and VMI model have been applied successfully in description deformed e-e Pt-186 nucleus and I got:

1. The results of state bands show reasonable agreement with empirically but had been found a little difference in high states, due to the interacting boson model do not distinguish between proton and neutron bosons.

2. The IBM-1 calculations show that the currently results of the energy states were in good agreement with practical calculations for the g-band and in reasonable agreement with the beta band and high in (γ_1, γ_2) band, also some of the energy states calculated in my current research did not calculate empirically, especially in γ_2 – band.

3. The results of VMI successfully investigated energy bands in low and high spin levels, and the predictions of this model gave a good description of the occurrence of backbending in the ground and beta bands due to the small rotational frequency (ω) of nucleons, and thus, the nucleon pair behavior at high angular momentum appears to be crucial for this an effect, and either the lack of backbending in the gamma bands may be attributed to the presence the deformation of an octupole or a hexadecabol in these bands.

4. From the curves of the backbending of the energy bands is clear that the β-band lies in SU(3) limit, and this is confirmed by the arrangement of the energy bands and the appearance of the backbending in them. while the energy ratios shows that the platinum Pt-186 has Gamma unstable O(6) limit.

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ТЕОРЕТИЧНИЙ ОПИС ПАРНО-ПАРНОГО ЯДРА ПЛАТИНИ Pt-186 З ВИКОРИСТАННЯ МОДЕЛЕЙ IBM ТА (VMI)

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Метою цього дослідження є феноменологічне дослідження backbending ефекту в ядрі платини Pt-186, з метою отримати покращений опис вигинів за допомогою нових параметрів. Модель VMI та модель взаємодіючого бозона IBM-1 використовувалися для виконання цього дослідження для ядра важкої маси (Z = 78). Енергетичні співвідношення та розташування смуг показують, що платина Pt-186 має O(6)-SU(3) динамічну симетрію. Наші поточні розрахунки дали результати, які досить узгоджуються з останніми експериментальними даними, особливо тими, що розраховані відповідно до VMI-моделі. Змінний момент інерції був застосований для успішного опису back-bending ефекту в деформованому парно-парному ядрі Pt-186. Backbending спостерігався в основному та β-смугах через зміну моменту інерції, але не для (γ_1, γ_2) смуг, оскільки не змінювався момент інерції.

Ключові слова*:* *структура ядра; IBM; ядерна фізика; модель VMI; backbending*