Back bending phenomena evaluation and energy band crossing of some deformed nuclei

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ABSTRACT

In the present work, the moment of inertia models(VMI,VAVM,GVMI)are used to study the nuclear structure of even-even nuclei ($^{56}_{26}Fe_{30}$, $^{74}_{34}Se_{40}$, $^{88}_{40}Zr_{48}$, $^{106}_{46}Pd_{60}$, $^{156}_{64}Gd_{92}$, $^{180}_{72}Hf_{108}$, $^{186}_{74}W_{112}$). These nuclei are belong to a dynamical symmetry O(6), SU(5)-O(6)-SU(3), SU(5), O(6)-SU(5), SU(3)-SU(5), SU(3), SU(3)-O(6) respectively, throw the study energy band crossing (energy level as a function of angular momentum), and back bending phenomena (moment of inertia ($2\vartheta/\hbar^2$) as a function of rotational energy squared $(\hbar\omega)^2$).

This study shows that the three moment of inertia models that are used here have no effect on the nuclear structure of the nucleus with the dynamical symmetry SU(3), but the nuclear structure of the other dynamical symmetries have been effected, because the back bending does appear in them .

حساب ظاهرة الانحناء الخلفي وظاهرة تقاطع حزم الطاقة لبعض الانوية المشوهة

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المستخلص

تم في هذا البحث استخدام ثلاثة نماذج من نماذج عزم القصور الذاتي هي (VMI,VAVM ,(GVMI لغرض دراسة التركيب النووي لبعض الانوية الزوجية-الزوجية $^{56}_{26}Fe_{30}$ $^{74}_{34}Se_{40}$ $^{88}_{40}Zr_{48}$ $^{106}_{46}Pd_{60}$ $^{156}_{64}Gd_{92}$ $^{180}_{72}Hf_{108}$ $^{186}_{74}W_{112}$ التي تنتمي الى التناظرات الديناميكية O(6),SU(5)-O(6)-SU(3),SU(5),O(6)-SU(5),SU(3)-SU(5), SU(3),

(6) O −(3)SU على التوالي من خلال دراسة ظاهرة تقاطع حزم الطاقة(مستويات الطاقة كدالة للزخم الزاوي) وظاهرة الانحناء الخلفي(عزم القصور الذاتي($2\vartheta/\hbar^2$) ومربع الطاقة الدورانية $(\hbar\omega)^2$. اظهرت الدراسة الحالية للنماذج الثلاثة المستخدمة انه لا تأثير لعزم القصور الذاتي على شكل الانوية الدورانية عند التناظر الديناميكي (3)SU لعدم ظهور الانحناء الخلفي في الحزم التي تنتمي الى هذا التناظر. أما بالنسبة للتناظرات الديناميكية الاخرى فقد تبين وجود تأثير لعزم القصور الذاتي على تركيبها النووي بسبب ظهور ظاهرة الانحناء الخلفي.

INTRODUCTION

Moment of inertia is an important subjects that are used to explain the energy band crossing, and back bending phenomena.

The nucleus extension due to the centrifugal force effect, which increases the value of moment of inertia, happened only for rotational nuclei if it is supposed that the nucleus is fluid, where the theoretical moment of inertia value (θ_{fluid}) is very small compared with that experimental .But this extension does not happen if we suppose that the nucleus is a rigid body and moment of inertia in this case (θ_{rigid}) is large [1].

The Back Bending Phenomena

This phenomenon has been discovered by Johnson A., et al. (1971) [2]. They found that moment of inertia at certain angular momentum significantly increases accompanied with a decrease of rotational energy value of some nuclear. It also occurs because rotational energy is greater than the stopping power of a pair of nucleons to couple [1].Where the single nucleons occupy different orbits which results in changing of the moment of inertia value for the nucleus.

The back bending is one feature of moment of inertia of deformed nuclei, in case of non appearance of back bending; this means that there is no effect of moment of inertia on the deformation of the nuclei .This can be attributed to:

(i): Energy Band Crossing

The band crossing means that the certain energy band like (β or γ) with high moment of inertia(ϑ_2)to replace or cross with another energy band as(g- band) state with lower moment of inertia (ϑ_1) (i.e. these two bands having same spin , and different in energy and moment of inertia will intersect with themselves) at a particular moment of inertia called (ϑ_c) where $\vartheta c = \vartheta cross$.

This phenomenon is considered an important feature of moment of inertia of deformed nuclei [3].

(ii): Corielis force effect

Corielis force effect increases with rotational motion at high spins for some nuclei; this increase in corielis force leads to depairing between numbers of nucleon pairs. The depairing of the first pair leads to the appearance of new band namely "*two quasi particles*" which probably intersects the ground state band at a certain angular momentum, while ground band remains completely paired. Where as the depairing of the second pair leads to the appearance of "*four-quasi particles*" band .This causes nuclear deformations and deviations at high angular momentum of some nucleus which causes back bending phenomena [4].

Habeeb N.A., et al. (1976)[5] explained the back bending phenomenon for $^{162}_{68}Er$ and $^{154}_{64}Gd$ nuclei depending on Corielis force effect.

Yu-Xin-Lin (1998) [6] have been calculated moment of inertia for high deformed nuclei using (IBM-1).

Hirsch, Jorge G., et al. (2005)[7] showed that the Pseudo SU(3) model and abnormal parity states in heavy deformed nuclei is based on the Pseudo spin symmetry, and is able to correctly predict the collective spectra and their transition amplitudes, and is also able to give nice description of the back bending phenomena.

THEORETICAL PART

1. Rotational and Vibration Energy Levels

The simple formula of the rotational or vibrational energy levels in even-even nuclei is determined by [8]:

$$E = \frac{1}{2}\vartheta\omega^2 = \frac{L^2}{2\vartheta} \quad \text{.......(1)}$$

Where ω is a rotational or vibrational frequency. The above equation is quantized to [9]:

$$E(L) = \frac{\hbar^2}{2\vartheta}L(L+1) \quad \text{.......(2)}$$

Mariscotti M., et al., (1969)[10] proposed another formula from this equation as:

$$E(L) = \frac{1}{2}\left[\frac{L(L+1)}{\vartheta(L)} + C(\vartheta(L) - \vartheta_o)^2\right] \quad \text{.......(3)}$$

Where

ϑ (L) is a moment of inertia as a function of angular momentum

C, ϑ_o are parameters which are suitable with fitted to the experimental data.

The physical meanings of these parameters are [11]:

ϑ_o is a moment of inertia for the ground state or (rotated nucleus).

C: is a meaning of "elasticity.

The derivative of equation (3) is

$$\frac{\partial E(L)}{\partial \vartheta(L)} = -\frac{1}{2}\frac{L(L+1)}{\vartheta^2(L)} + C(\vartheta(L) - \vartheta_o) \quad (4)$$

Moment of inertia ϑ(L) can be determined from the equilibrium condition [10, 11]:

$$\frac{\partial E(L)}{\partial \vartheta(L)} = 0 \quad (5)$$

$$\vartheta^3(L) - \vartheta^2(L)\vartheta_o - \frac{L(L+1)}{2C} = 0 \quad (6)$$

The solution of above equation is [12, 13]:

$$\vartheta(L) = (x+y)^{1/3} + (x-y)^{1/3} + \frac{1}{3}\vartheta_o \quad (7)$$

Where

$$x = \frac{L(L+1)}{4C} + \frac{\vartheta_o^3}{27}, y = \left[\frac{(L(L+1))^2}{16C^2} + \frac{\vartheta_o^3 L(L+1)}{54C}\right]^{1/2} \quad (8)$$

The nuclear softness coefficient (σ) can be written as [10]:

$$\sigma = \frac{1}{\vartheta(L)}\left(\frac{d\vartheta}{dL}\right)_{\vartheta=0} \quad (9)$$

σ can be written according to variable moment of inertia model as [10,12]

$$\sigma = \frac{1}{2C\vartheta_o^3} \quad (10)$$

2. The back bending phenomena

Rotational energy square $(\hbar\omega)^2$ and moment of inertia can be written as[14]

$$(\hbar\omega)^2 = \left[\frac{E(L)}{\sqrt{L(L+1)}}\right]^2 \quad (11)$$

$$\frac{2\vartheta}{\hbar^2} = \frac{L(L+1)}{E(L)} \quad (12)$$

Equation (11) can be written for g-band and β-band as following [12, 13]:

$$(\hbar\omega)^2 = \left[\frac{E(L\to L-2)}{\sqrt{L(L+1)}-\sqrt{(L-2)(L-2+1)}}\right]^2 \quad \text{.............................(13)}$$

$$(\hbar\omega)^2 = \left[\frac{E_\gamma}{\sqrt{L(L+1)}-\sqrt{(L-2)(L-1)}}\right]^2 \quad \text{.............................(14)}$$

and for γ-band is

$$(\hbar\omega)^2 = \left[\frac{E(L\to L-1)}{\sqrt{L(L+1)}-\sqrt{L(L-1)}}\right]^2 \quad \text{.......................................(15)}$$

Also from equation (12) can be evaluating moment of inertia for g-band and β-band as [15]:

$$\frac{2\vartheta}{\hbar^2} = \frac{L(L+1)-(L-2)(L-2+1)}{E(L\to L-2)} = \frac{4L-2}{E(L_i)-E(L_f)} \quad \text{..............(16)}$$

and for γ-band is:

$$\frac{2\vartheta}{\hbar^2} = \frac{L(L+1)-L(L-1)}{E(L\to L-1)} = \frac{2L}{E_\gamma} \quad \text{...(17)}$$

Where E(L→L-2) is the energy difference between any two states which have angular momentum L and (L-2) for g-band and β-band while E(L→L-1) is the energy difference between any two states having angular momentum L and (L-1) for γ-band

RESULTS AND DISCUSSION

In the present study we can evaluate the following calculations by programming (VMI, VAVM, and GVMI) model using FORTRAN 77language:

1. Theoretical energy levels $E_{cal.}$ Using equation (3).
2. Moment of inertia as a function of angular momentum using equation (7).
3. Rotational energy square $(\hbar\omega)^2$ and $(2\vartheta/\hbar^2)$ as a function of angular momentum.
4. Chi-squared which can be calculated from the following equation [16]:

$$\chi^2 = \frac{(E_{cal}-E_{\exp})^2}{E^2_{cal}} \quad \text{...(18)}$$

5. Nuclear softness parameters (σ) from equation (10).

6. Standard deviation (Root Mean Square Deviation) from the following equation [11, 16]:

$$deviation(\Delta) = \left[\frac{1}{N} \sum_{i=1}^{N} (E_{cal} - E_{\exp})^2 \right]^{1/2} \quad ....(19)$$

Table (1) shows the parameters ($\vartheta_o/\hbar^2$, C, Y, E_k) which are used in (VMI, VAVM,GVMI) program to calculate the above results.

1. The Energy Band crossing

The increasing of rotational energy between any two excited states due to reduce moment of inertia at large angular momentum. Here, Corielis force effect will increase with the increase of rotational energy between these bands. This effect leads to reducing the energy of two nucleons, which occupy these states because, the depairing of the nucleon pairs. In this case, the direction of angular momentum of these nucleons is in same direction with the rotational axis with low rotational energy and maximum angular momentum. The unstable of these two excited states leads to crossing band with any other band at certain angular momentum called "L_{cross}.".

Figure (1) indicates the energy band crossing as a function of angular momentum for all chosen nuclei using (VMI) model.

It is noticed in this figure that the (g,β_2),(g,β_3),(β_1, β_2,γ_2 ,γ_3) of the ${}^{56}_{26}Fe_{30}$ nucleus will intersect at angular momentum L_c=(14,7,5) respectively, while the band crossing would happened at L_c =(6,7,11,14,22) for ${}^{74}_{34}Se_{40}$ nuclei. This figure also shows that the bands of ${}^{88}_{40}Zr_{48}$ and ${}^{156}_{64}Gd_{92}$ are not crossing between them, while, all bands of ${}^{106}_{46}Pd_{60}$ are crossing at L_c=(5,7,11), while, it happened at L_c=13 in ${}^{180}_{72}Hf_{108}$ and at L_c=(5,7) of ${}^{186}_{74}W_{112}$.

Figure(2) shows the energy band crossing for the same nuclei using (VAVM).This figure shows the bands(g, β_3),(g,γ_1), (β_1,β_2,γ_2,γ_3) of ${}^{56}_{26}Fe_{30}$ intersect at angular momentum L_c=(15,7,5) respectively , while it happened at L_c =(4,8,17) in ${}^{74}_{34}Se_{40}$, L_c= (4,5,7,12,17,21) in ${}^{106}_{46}Pd_{60}$, L_c=14 in ${}^{180}_{72}Hf_{108}$ and L_c =(10,20,22) in ${}^{186}_{74}W_{112}$, while in the bands of ${}^{156}_{64}Gd_{92}$ there are no crossing between them .

Figure(3) shows the band crossing using (GVMI) model for all selected nuclei.

In this figure we noticed that the (g, β_3, γ_1),(β_1,β_2,γ_2,γ_3) bands crossing at L_c =(14,6) in ${}^{56}_{26}Fe_{30}$ respectively, L_c=(4,7,9,12) in ${}^{74}_{34}Se_{40}$. This figure also shows that the band crossing happened between (β_1,β_2) bands at L_c=18, L_c=(5,6,8,11) in ${}^{106}_{46}Pd_{60}$, L_c=14 in ${}^{180}_{72}Hf_{108}$,and L_c=(4,6,10) in ${}^{186}_{74}W_{112}$,while, there is no band crossing in ${}^{156}_{64}Gd_{92}$.

2. The Back Bending Phenomenon

In order to study the back bending phenomenon, we must calculated and drawn the values of moments of inertia($2\vartheta/\hbar^2$) and rotational energy squared $(\hbar\omega)^2$ as a function of angular momentum (L) by using (VMI,VAVM, and GVMI) model using the parameters(ϑ_o, C. E_K, Y) in table(1) for the ground state, and the excited state bands.

Figure (4) indicates that the back bending (moment of inertia ($2\vartheta/\hbar^2$) as a function of rotational energy squared $(\hbar\omega)^2$ using VMI model for chosen nuclei . This figure shows that the back bending occurs in γ_1 –band of ${}^{56}_{26}Fe_{30}$ and ${}^{74}_{34}Se_{40}$ at angular momentum L_c=9,12 respectively, and no effect of moment of inertia on nuclear structure of other nuclei , due to the back bending not occurs .

Figure (5) shows the same plot but for (VAVM) model. It is noticed in this figure that the back bending occurs in γ_1-band of ${}^{106}_{46}Pd_{60}$ at angular momentum L_c=9, while it is not occurs in the other band.

Figure (6) also shows the back bending using (GVMI) model. This figure noticed that the back bending occurs in (g, β_1,β_3) ,(β_3,β_4), (g, β_1,β_2), (β_1,β_3,β_4) ,(β_1) bands of the nuclei ${}^{56}_{26}Fe_{30}$, ${}^{74}_{34}Se_{40}$, ${}^{88}_{40}Zr_{48}$, ${}^{106}_{46}Pd_{60}$, ${}^{186}_{74}W_{112}$ at angular momentum L_c=(8,8,18), (16,12), (10,10,6), (8,8,10),(12) respectively, while it is not happened in ${}^{156}_{64}Gd_{92}$, ${}^{180}_{72}Hf_{108}$ nuclei .

We noticed from these figures in which the back bending appearance, the moment of inertia ($2\vartheta/\hbar^2$) increases with rotational energy squared $(\hbar\omega)^2$, but at certain angular momentum (L_c) the rotational energy squared$(\hbar\omega)^2$ decreases, while the moment of inertia ($2\vartheta/\hbar^2$) increases ,causing the back bending phenomena .This reason belonging to *“Corielis antipiring effect”* .In this case the moment of inertia will effect on nuclear structure of these nuclei .

The figures in which no back bending appearance; this means that there is no effect of moment of inertia on nuclear structure of these nuclei. Such, that these nuclei are belonging to dynamical symmetry SU(3) as in ${}^{180}_{72}Hf_{108}$ nuclei .

Table (1): The corresponding parameters of (VMI), GVMI, VAVM) model for even-even nuclei.

Nuclei	band	parameter / Model	ϑ_0/h^2 $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ'	Standard deviation	χ^2
$^{56}_{26}Fe_{30}$ O(6)	g	VMI	1.8100	0.0470	0.0000	———	1.7941	0.0709	0.0068
		GVMI	0.0280	0.044	0.0000	0.4680	51.78	0.0763	0.0075
		VAVM	24.1800	0.01000	0.0000	0.4280	-0.0141	0.0603	0.0054
	β 1	VMI	6.0000	5.0000	2.9417	———	0.0005	0.3956	0.1605
		GVMI	9.1200	7.8800	2.9417	1.0000	-0.0002	0.1666	0.0278
		VAVM	7.9000	18.0000	2.9417	0.0280	-0.0002	0.0464	0.0019
	β 2	VMI	13.0000	8.8000	3.5992	———	0.0003	0.1305	0.0132
		GVMI	54.0000	0.0020	3.5992	5.2000	-0.0298	0.0198	0.0003
		VAVM	10.1600	12.0000	3.5992	0.0016	-0.0001	0.0004	0.0000
	β 3	VMI	27.9000	0.08000	4.3002	———	0.0003	0.0529	0.0019
		GVMI	93.4000	0.0110	4.3002	3.9900	-0.0008	0.0010	0.000001
		VAVM	23.2000	11.0000	0.0096	4.3002	-0.00001	0.0007	0.00000
	γ1	VMI	12.4000	2.0160	2.3800	———	0.00001	0.1960	0.0632
		GVMI	17.9000	3.9800	2.6575	0.8400	-0.00003	0.1879	0.05950
		VAVM	0.2800	0.0008	2.6460	0.00588	-0.00004	0.6688	06776

Table (1): To be continued (2/8).

Nuclei	band	parameter / Model	ϑ_0/h^2 $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ'	Standard deviation	χ^2
$^{56}_{26}Fe_{30}$ O(6)	γ2	VMI	6.4000	0.6920	3.0000	———	0.0028	0.1626	0.0233
		GVMI	83.0200	0.9900	3.3697	7.9960	-0.00003	0.1579	0.0198
		VAVM	8.2000	6.6000	3.2600	0.0020	-0.0005	0.1278	0.0137
	γ3	VMI	8.8600	0.6900	3.5400	———	0.0010	0.0956	0.0070
		GVMI	99.8800	1.0000	3.7480	7.6000	-0.00001	0.0944	0.0066
		VAVM	11.0000	8.8800	3.6900	0.0010	-0.0002	0.0741	0.0042
	γ4	VMI	8.8800	4.0900	3.6800	———	0.00002	0.0550	0.0022
		GVMI	85.0400	1.0000	3.8303	7.4800	-0.00002	0.0517	0.0019
		VAVM	11.0000	4.8800	3.7200	0.0360	-0.0003	0.0392	0.0011
$^{74}_{34}Se_{40}$ SU(5) - O(6) - SU(3)	g	VMI	1.0000	0.0090	0.0000	———	55.5556	0.0561	0.0089
		GVMI	3.1642	1.0600	0.0000	0.0710	0.0255	0.0186	0.0011
		VAVM	72.9200	0.4990	0.0000	0.3162	-0.00001	0.0071	0.0002
	β 1	VMI	6.5500	0.0452	0.8538	———	0.0394	0.0053	0.00006
		GVMI	4.6000	1.1880	0.8538	0.2220	0.0048	0.0171	0.0006
		VAVM	23.0000	0.2990	0.8538	0.2200	-0.0005	0.0194	0.0009
	β 2	VMI	7.5000	0.0110	2.1300	———	0.1077	0.1459	0.0272
		GVMI	5.7000	5.6000	2.1300	0.1600	0.0006	0.1358	0.0235
		VAVM	28.3200	0.4990	2.1300	0.1526	-0.0002	0.1232	0.0208

Table (1): To be continued (3/8).

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ'	Standard deviation	χ^2
$^{74}_{34}Se_{40}$ SU(5) - O(6) - SU(3)	β 3	VMI	6.4400	0.0087	2.7180	------	0.2152	0.1470	0.0211
		GVMI	12.7000	0.8000	2.7180	1.0000	-0.0006	0.0340	0.0012
		VAVM	10.5580	0.4990	2.7180	0.0505	-0.0034	0.0012	0.000001
	β 4	VMI	6.6000	0.0053	2.9180	------	0.3281	0.0794	0.0058
		GVMI	4.4600	0.7000	2.9180	0.00006	0.0161	0.0152	0.0002
		VAVM	98.0000	0.0480	2.9160	0.2000	-0.00004	0.0395	0.0014
	γ1	VMI	9.0000	0.0200	1.6600	------	0.0343	0.3310	0.2229
		GVMI	20.0000	1.0000	1.7400	1.3700	-0.0002	0.1900	0.0683
		AVMV	74.0000	0.4400	0.8300	0.4250	-0.00001	0.1732	0.0714
$^{88}_{40}Zr_{48}$ SU(5)	g	VMI	1.0000	0.01000	0.0000	------	50.0000	0.4674	0.9331
		GVMI	1.0000	02860	0.0000	0.0290	3.2934	0.2740	0.1656
		VAVM	99.8000	0.3288	0.0000	0.3720	-0.000006	0.4316	0.5778

Table (1): To be continued (4/8).

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ'	Standard deviation	χ^2
$^{88}_{40}Zr_{48}$ SU(5)	β 1	VMI	9.2800	0.8900	1.5214	------	0.0007	0.0170	0.0004
		GVMI	2.8000	0.4000	1.5214	0.0180	0.1098	0.3597	0.1828
		VAVM	48.0000	0.0088	1.5214	0.2200	-0.0020	0.1339	0.0257
	β 2	VMI	7.4400	0.9990	2.2250	------	0.0012	0.0339	0.0013
		GVMI	3.0000	0.0820	2.2250	0.0320	0.4227	0.4908	0.2423
		VAVM	0.7000	0.00038	2.2250	0.1900	3836	0.0891	0.0088
$^{106}_{46}Pd_{60}$ O(6)- SU(5)	g	VMI	2.0000	0.0077	0.0000	------	8.1169	0.7749	0.8603
		GVMI	2.2800	0.1000	0.0000	0.08200	0.7053	0.1395	0.0793
		VAVM	99.6000	0.1660	0.0000	0.2610	-0.00001	0.2968	0.2094
	β 1	VMI	6.2000	0.0090	1.1338	------	0.2331	0.0419	0.0033
		GVMI	4.6500	1.0000	1.1338	0.0610	0.0087	0.0020	0.000007
		VAVM	91.0000	0.00238	1.1338	0.2138	-0.0011	0.0005	0.000000

Table (1): To be continued (5/8).

Nuclei	band	Model \ parameter	$\vartheta_0/\hbar^2$ $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ'	Standard deviation	χ^2
$^{106}_{46}Pd_{60}$ O(6)-SU(5)	B 2	VMI	4.2000	0.0020	1.7064	------	3.3744	0.1636	0.0374
		GVMI	2.6000	0.0135	1.7064	0.0000	4.2145	0.0100	0.0134
		VAVM	99.6000	0.1860	1.7064	0.1590	-0.00001	0.1496	0.0316
	β 3	VMI	5.6000	0.00019	2.0015	------	14.9848	0.0882	0.0108
		GVMI	7.6000	0.0070	2.0015	0.0260	0.3085	0.0594	0.0046
		VAVM	99.6000	0.1860	2.0015	0.0900	-0.00001	0.0855	0.0098
	β 4	VMI	5.0000	0.0002	2.2781	------	19.9005	0.0013	0.000002
		GVMI	12.1700	0.0500	2.2781	0.0790	0.0093	0.0010	0.000001
		VAVM	99.6000	0.1860	2.2781	0.0742	-0.00001	0.0081	0.00008
	γ1	VMI	7.8000	1.9800	0.7700	------	0.0005	0.0709	0.0094
		GVMI	21.5000	2.0000	1.0600	2.0560	-0.0001	0.0566	0.0074
		AVMV	29.0000	0.2000	0.4000	0.3500	-0.0004	0.0859	0.0137

Table (1): To be continued (6/8).

Nuclei	band	Model \ parameter	$\vartheta_0/\hbar^2$ $(MeV)^{-1}$	C $(MeV)^3$	E_{bl} (MeV)	Y (MeV)	σ'	Standard deviation	χ^2
$^{156}_{64}Gd_{92}$ SU(3)-SU(5)	g	VMI	32.7580	0.0025	0.0000	------	0.0057	0.0079	0.0003
		GVMI	21.7600	0.0057	0.0000	0.3307	0.0057	0.0079	0.0003
		VAVM	94.4000	0.0040	0.0000	0.0534	-0.0006	0.0399	0.0098
	β 1	VMI	40.8000	0.00223	1.0495	------	0.0033	0.0133	0.0006
		GVMI	23.6000	1.0600	1.0495	0.2250	0.00004	0.0074	0.0002
		VAVM	98.9900	0.0640	1.0495	0.0384	-0.00003	0.0132	0.0007
	β 2	VMI	30.6000	0.0016	1.1682	------	0.0109	0.0213	0.0016
		GVMI	16.8800	0.01400	1.1682	0.2020	0.0088	0.0158	0.0010
		VAVM	99.2000	0.0740	1.1682	0.0583	-0.00003	0.0223	0.0017
	β 3	VMI	46.0000	0.09988	1.7152	------	0.0001	0.0234	0.0011
		GVMI	31.9000	0.0380	1.7152	0.3640	0.0002	0.0219	0.0009
		VAVM	68.0000	0.0740	1.7152	0.0200	-0.00008	0.0131	0.0004
	γ1	VMI	30.6000	0.0016	1.0660	------	0.0109	0.0117	0.0007
		GVMI	52.2000	0.000356	1.1300	1.1080	-0.0240	0.0133	0.0007
		AVMV	81.0000	0.0040	1.0700	0.0460	-0.0009	0.0182	0.0014
	γ2	VMI	20.0000	0.0016	1.6000	------	0.0391	0.1198	0.0337
		GVMI	47.0000	0.8000	1.7660	1.0000	-0.00001	0.0676	0.0102
		VAVM	62.0000	0.0080	1.6900	0.0520	-0.0010	0.0730	0.0119

Table (1): To be continued (7/8).

Nuclei	band	parameter / Model	$\vartheta_0/\hbar^2$ $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{180}_{72}Hf_{108}$ SU(3)	g	VMI	32.0540	0.01370	0.0000	——	0.0011	0.0002	0.00000
		GVMI	21.5800	0.0280	0.0000	0.3400	0.0011	0.0009	0.00001
		VAVM	70.4800	3.8800	0.0000	0.0490	-0.000001	0.0087	0.0005
	β_1	VMI	44.6000	0.8800	1.1073	——	0.0000	0.0228	0.0015
		GVMI	30.8000	1.8820	1.1073	0.3540	0.000005	0.0221	0.0014
		VAVM	73.6000	1.8800	1.1073	0.0256	-0.000003	0.0192	0.0011
	β_2	VMI	0.0600	0.0020	1.3157	——	1162	0.1643	0.0443
		GVMI	4.4000	0.4800	1.3157	0.0000	0.0244	0.1386	0.0301
		VAVM	99.8800	0.0800	1.3157	0.2000	-0.00002	0.1620	0.0426
	γ_1	VMI	0.9990	0.0003	1.0600	——	1671	0.05147	0.0095
		GVMI	42.2000	1.2800	1.1998	0.6800	-0.000004	0.0357	0.0049
		VAVM	99.0000	0.1801	1.1000	0.0640	-0.00001	0.0325	0.0039

Table (1): To be continued (8/8).

Nuclei	band	parameter / Model	$\vartheta_0/\hbar^2$ $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{186}_{74}W_{112}$ SU(3)-O(6)	g	VMI	12.0000	0.0010	0.0000	——	0.2894	0.1126	0.0739
		GVMI	13.2400	9.0000	0.0000	0.2000	0.00003	0.0242	0.0081
		VAVM	57.3440	0.0096	0.0000	0.06420	-0.0011	0.0059	0.0004
	β_1	VMI	0.0400	0.0008	0.8820	——	9803	0.0768	0.0141
		GVMI	7.4000	0.4900	0.8820	0.2600	0.0024	0.1471	0.0535
		VAVM	98.0000	0.0640	0.8820	0.1420	-0.00003	0.0806	0.0156
	β_2	VMI	10.0000	0.0006	1.1530	——	0.8333	0.1086	0.0265
		GVMI	3.0000	0.0040	1.1530	0.0300	8.7037	0.5383	0.0057
		VAVM	99.6000	0.0740	1.1530	0.1158	-0.00003	0.0935	0.0179
	γ_1	VMI	20.0000	0.8800	0.6600	——	0.00007	0.0527	0.0096
		GVMI	30.4000	0.0080	0.7100	1.4500	-0.0084	0.0493	0.0077
		VAVM	70.0000	0.0001	0.4400	0.1600	-0.0583	0.0346	0.0038

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Table (1): The corresponding parameters of (VMI), GVMI, VAVM) model for even-even nuclei.

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ (MeV)$^{-1}$	C (MeV)^3	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{56}_{26}Fe_{30}$ O(6)	g	VMI	1.8100	0.0470	0.0000	———	1.7941	0.0709	0.0068
		GVMI	0.0280	0.044	0.0000	0.4680	51.78	0.0763	0.0075
		VAVM	24.1800	0.01000	0.0000	0.4280	-0.0141	0.0603	0.0054
	β_1	VMI	6.0000	5.0000	2.9417	———	0.0005	0.3956	0.1605
		GVMI	9.1200	7.8800	2.9417	1.0000	-0.0002	0.1666	0.0278
		VAVM	7.9000	18.0000	2.9417	0.0280	-0.0002	0.0464	0.0019
	β_2	VMI	13.0000	8.8000	3.5992	———	0.0003	0.1305	0.0132
		GVMI	54.0000	0.0020	3.5992	5.2000	-0.0298	0.0198	0.0003
		VAVM	10.1600	12.0000	3.5992	0.0016	-0.0001	0.0004	0.0000
	β_3	VMI	27.9000	0.08000	4.3002	———	0.0003	0.0529	0.0019
		GVMI	93.4000	0.0110	4.3002	3.9900	-0.0008	0.0010	0.000001
		VAVM	23.2000	11.0000	0.0096	4.3002	-0.00001	0.0007	0.00000
	γ_1	VMI	12.4000	2.0160	2.3800	———	0.00001	0.1960	0.0632
		GVMI	17.9000	3.9800	2.6575	0.8400	-0.00003	0.1879	0.05950
		VAVM	0.2800	0.0008	2.6460	0.00588	-0.00004	0.6688	06776

Table (1): To be continued (2/8).

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ (MeV)$^{-1}$	C (MeV)^3	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{56}_{26}Fe_{30}$ O(6)	γ_2	VMI	6.4000	0.6920	3.0000	———	0.0028	0.1626	0.0233
		GVMI	**83.0200**	0.9900	3.3697	7.9960	-0.00003	0.1579	0.0198
		VAVM	8.2000	6.6000	3.2600	0.0020	-0.0005	0.1278	0.0137
	γ_3	VMI	8.8600	0.6900	3.5400	———	0.0010	0.0956	0.0070
		GVMI	**99.8800**	1.0000	3.7480	7.6000	-0.00001	0.0944	0.0066
		VAVM	**11.0000**	8.8800	3.6900	0.0010	-0.0002	0.0741	0.0042
	γ_4	VMI	8.8800	4.0900	3.6800	———	0.00002	0.0550	0.0022
		GVMI	**85.0400**	1.0000	3.8303	7.4800	-0.00002	0.0517	0.0019
		VAVM	**11.0000**	4.8800	3.7200	0.0360	-0.0003	0.0392	0.0011
$^{74}_{34}Se_{40}$ **SU(5) - O(6) - SU(3)**	g	VMI	1.0000	0.0090	0.0000	———	55.5556	0.0561	0.0089
		GVMI	3.1642	1.0600	0.0000	0.0710	0.0255	0.0186	0.0011
		VAVM	**72.9200**	0.4990	0.0000	0.3162	-0.00001	0.0071	0.0002
	β_1	VMI	6.5500	0.0452	0.8538	———	0.0394	0.0053	0.00006
		GVMI	4.6000	1.1880	0.8538	0.2220	0.0048	0.0171	0.0006
		VAVM	**23.0000**	0.2990	0.8538	0.2200	-0.0005	0.0194	0.0009
	β_2	VMI	7.5000	0.0110	2.1300	———	0.1077	0.1459	0.0272
		GVMI	5.7000	5.6000	2.1300	0.1600	0.0006	0.1358	0.0235
		VAVM	2**8.3200**	0.4990	2.1300	0.1526	-0.0002	0.1232	0.0208

Table (1): To be continued (3/8).

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ (MeV)$^{-1}$	C (MeV)^3	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{74}_{34}Se_{40}$ SU(5) - O(6) - SU(3)	β_3	VMI	6.4400	0.0087	2.7180	———	0.2152	0.1470	0.0211
		GVMI	12.7000	0.8000	2.7180	1.0000	-0.0006	0.0340	0.0012
		VAVM	10.5580	0.4990	2.7180	0.0505	-0.0034	0.0012	0.000001
	β_4	VMI	6.6000	0.0053	2.9180	———	0.3281	0.0794	0.0058
		GVMI	4.4600	0.7000	2.9180	0.00006	0.0161	0.0152	0.0002
		VAVM	98.0000	0.0480	2.9160	0.2000	-0.00004	0.0395	0.0014
	γ_1	VMI	9.0000	0.0200	1.6600	———	0.0343	0.3310	0.2229
		GVMI	20.0000	1.0000	1.7400	1.3700	-0.0002	0.1900	0.0683
		AVMV	74.0000	0.4400	0.8300	0.4250	-0.00001	0.1732	0.0714
$^{88}_{40}Zr_{48}$ SU(5)	g	VMI	1.0000	0.01000	0.0000	———	50.0000	0.4674	0.9331
		GVMI	1.0000	02860	0.0000	0.0290	3.2934	0.2740	0.1656
		VAVM	99.8000	0.3288	0.0000	0.3720	**-0.000006**	0.4316	0.5778

Table (1): To be continued (4/8).

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ (MeV)$^{-1}$	C (MeV)^3	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{88}_{40}Zr_{48}$ SU(5)	β_1	VMI	9.2800	0.8900	1.5214	———	0.0007	0.0170	0.0004
		GVMI	2.8000	0.4000	1.5214	0.0180	0.1098	0.3597	0.1828
		VAVM	48.0000	0.0088	1.5214	0.2200	-0.0020	0.1339	0.0257
	β_2	VMI	7.4400	0.9990	2.2250	———	0.0012	0.0339	0.0013
		GVMI	3.0000	0.0820	2.2250	0.0320	0.4227	0.4908	0.2423
		VAVM	0.7000	0.00038	2.2250	0.1900	3836	0.0891	0.0088
$^{106}_{46}Pd_{60}$ O(6)-SU(5)	g	VMI	2.0000	0.0077	0.0000	———	8.1169	0.7749	0.8603
		GVMI	2.2800	0.1000	0.0000	0.08200	0.7053	0.1395	0.0793
		VAVM	99.6000	0.1660	0.0000	0.2610	-0.00001	0.2968	0.2094
	β_1	VMI	6.2000	0.0090	1.1338	———	0.2331	0.0419	0.0033
		GVMI	4.6500	1.0000	1.1338	0.0610	0.0087	0.0020	0.000007
		VAVM	91.0000	0.00238	1.1338	0.2138	-0.0011	0.0005	0.000000

Table (1): To be continued (5/8).

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{106}_{46}Pd_{60}$ O(6)-SU(5)	B_2	VMI	4.2000	0.0020	1.7064	———	3.3744	0.1636	0.0374
		GVMI	2.6000	0.0135	1.7064	0.0000	4.2145	0.0100	0.0134
		VAVM	99.6000	0.1860	1.7064	0.1590	-0.00001	0.1496	0.0316
	β_3	VMI	5.6000	0.00019	2.0015	———	14.9848	0.0882	0.0108
		GVMI	7.6000	0.0070	2.0015	0.0260	0.3085	0.0594	0.0046
		VAVM	99.6000	0.1860	2.0015	0.0900	-0.00001	0.0855	0.0098
	β_4	VMI	5.0000	0.0002	2.2781	———	19.9005	0.0013	0.000002
		GVMI	12.1700	0.0500	2.2781	0.0790	0.0093	0.0010	0.000001
		VAVM	99.6000	0.1860	2.2781	0.0742	-0.00001	0.0081	0.00008
	γ_1	VMI	7.8000	1.9800	0.7700	———	0.0005	0.0709	0.0094
		GVMI	21.5000	2.0000	1.0600	2.0560	-0.0001	0.0566	0.0074
		AVMV	29.0000	0.2000	0.4000	0.3500	-0.0004	0.0859	0.0137

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ (MeV)$^{-1}$	C (MeV)^3	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{156}_{64}Gd_{92}$ SU(3)-SU(5)	g	VMI	32.7580	0.0025	0.0000	———	0.0057	0.0079	0.0003
		GVMI	21.7600	0.0057	0.0000	0.3307	0.0057	0.0079	0.0003
		VAVM	94.4000	0.0040	0.0000	0.0534	-0.0006	0.0399	0.0098
	β_1	VMI	40.8000	0.00223	1.0495	———	0.0033	0.0133	0.0006
		GVMI	23.6000	1.0600	1.0495	0.2250	0.00004	0.0074	0.0002
		VAVM	98.9900	0.0640	1.0495	0.0384	**-0.00003**	0.0132	0.0007
	β_2	VMI	30.6000	0.0016	1.1682	———	0.0109	0.0213	0.0016
		GVMI	16.8800	0.01400	1.1682	0.2020	0.0088	0.0158	0.0010
		VAVM	99.2000	0.0740	1.1682	0.0583	-0.00003	0.0223	0.0017
	β_3	VMI	46.0000	0.09988	1.7152	———	0.0001	0.0234	0.0011
		GVMI	31.9000	0.0380	1.7152	0.3640	0.0002	0.0219	0.0009
		VAVM	68.0000	0.0740	1.7152	0.0200	***-0.00008***	0.0131	0.0004
	γ_1	VMI	30.6000	0.0016	1.0660	———	0.0109	0.0117	0.0007
		GVMI	52.2000	0.000356	1.1300	1.1080	-0.0240	0.0133	0.0007
		AVMV	81.0000	0.0040	1.0700	0.0460	-0.0009	0.0182	0.0014
	γ_2	VMI	20.0000	0.0016	1.6000	———	0.0391	0.1198	0.0337
		GVMI	47.0000	0.8000	1.7660	1.0000	-0.00001	0.0676	0.0102
		VAVM	62.0000	0.0080	1.6900	0.0520	-0.0010	0.0730	0.0119

Table (1): To be continued (6/8).

Table (1): To be continued (7/8).

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ (MeV)$^{-1}$	C (MeV)^3	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{180}_{72}Hf_{108}$ SU(3)	g	VMI	**32.0540**	0.01370	0.0000	———	**0.0011**	0.0002	0.00000
		GVMI	**21.5800**	0.0280	0.0000	0.3400	**0.0011**	0.0009	0.00001
		VAVM	**70.4800**	3.8800	0.0000	0.0490	**-0.000001**	0.0087	0.0005
	β_1	VMI	**44.6000**	0.8800	1.1073	———	**0.0000**	0.0228	0.0015
		GVMI	**30.8000**	1.8820	1.1073	0.3540	**0.000005**	0.0221	0.0014
		VAVM	**73.6000**	1.8800	1.1073	0.0256	**-0.000003**	0.0192	0.0011
	β_2	VMI	**0.0600**	0.0020	1.3157	———	**1162**	0.1643	0.0443
		GVMI	**4.4000**	0.4800	1.3157	0.0000	**0.0244**	0.1386	0.0301
		VAVM	**99.8800**	0.0800	1.3157	0.2000	**-0.00002**	0.1620	0.0426
	γ_1	VMI	**0.9990**	0.0003	1.0600	———	**1671**	0.05147	0.0095
		GVMI	**42.2000**	1.2800	1.1998	0.6800	**-0.000004**	0.0357	0.0049
		VAVM	**99.0000**	0.1801	1.1000	0.0640	**-0.00001**	0.0325	0.0039

Table (1): To be continued (8/8).

Nuclei	band	parameter / Model	$\vartheta_o/\hbar^2$ $(MeV)^{-1}$	C $(MeV)^3$	E_k (MeV)	Y (MeV)	σ	Standard deviation	χ^2
$^{186}_{74}W_{112}$ SU(3)-O(6)	g	VMI	12.0000	0.0010	0.0000	———	0.2894	0.1126	0.0739
		GVMI	13.2400	9.0000	0.0000	0.2000	0.00003	0.0242	0.0081
		VAVM	57.3440	0.0096	0.0000	0.06420	-0.0011	0.0059	0.0004
	β_1	VMI	0.0400	0.0008	0.8820	———	9803	0.0768	0.0141
		GVMI	7.4000	0.4900	0.8820	0.2600	0.0024	0.1471	0.0535
		VAVM	98.0000	0.0640	0.8820	0.1420	-0.00003	0.0806	0.0156
	β_2	VMI	10.0000	0.0006	1.1530	———	0.8333	0.1086	0.0265
		GVMI	3.0000	0.0040	1.1530	0.0300	8.7037	0.5383	0.0057
		VAVM	99.6000	0.0740	1.1530	0.1158	-0.00003	0.0935	0.0179
	γ_1	VMI	20.0000	0.8800	0.6600	———	0.00007	0.0527	0.0096
		GVMI	30.4000	0.0080	0.7100	1.4500	-0.0084	0.0493	0.0077
		VAVM	70.0000	0.0001	0.4400	0.1600	-0.0583	0.0346	0.0038

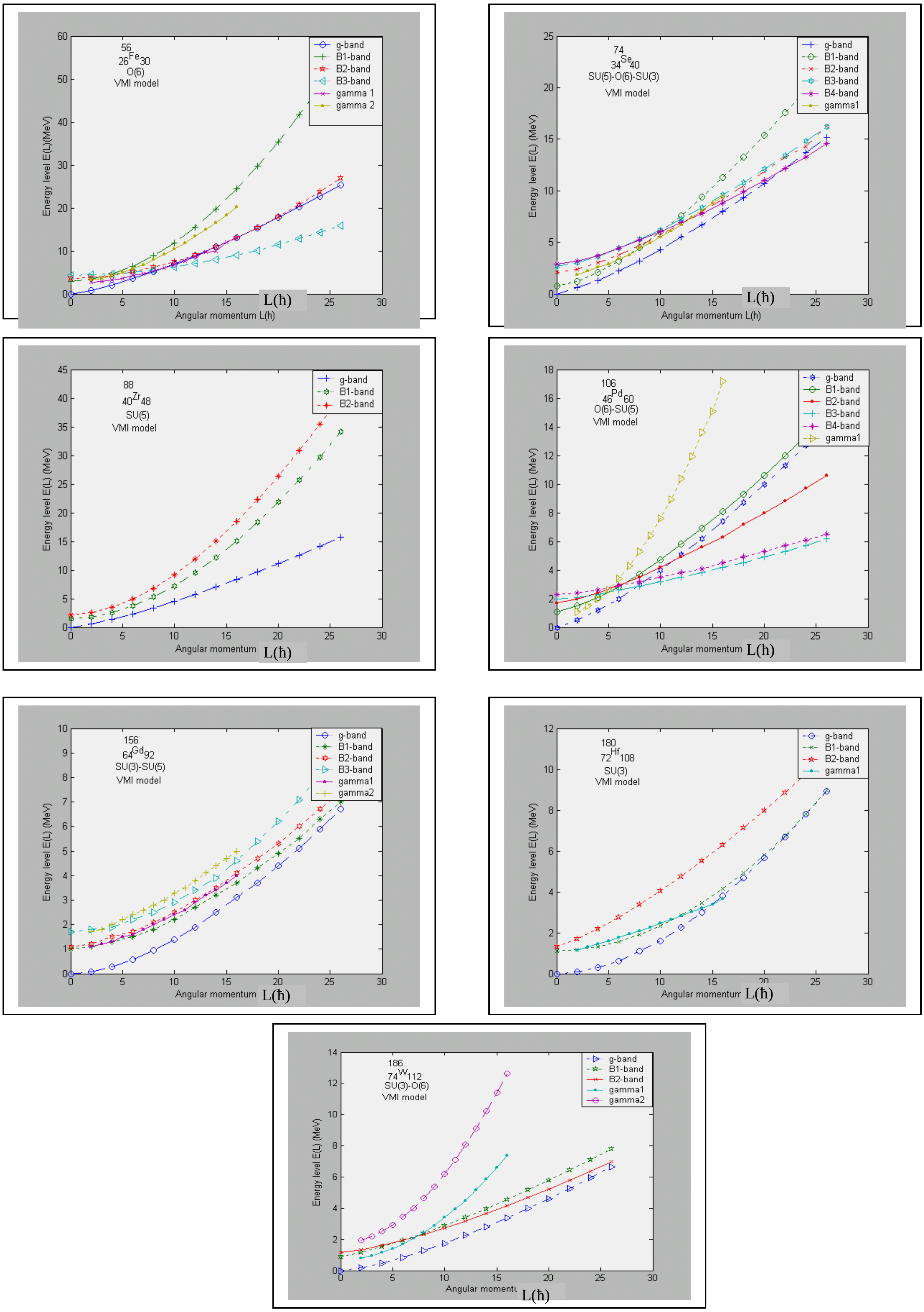


Figure (1): The energy band crossing E(L) as a function of angular momentum L for chosen nuclei using (VMI) model. The parameters used for calculations are in table (1).

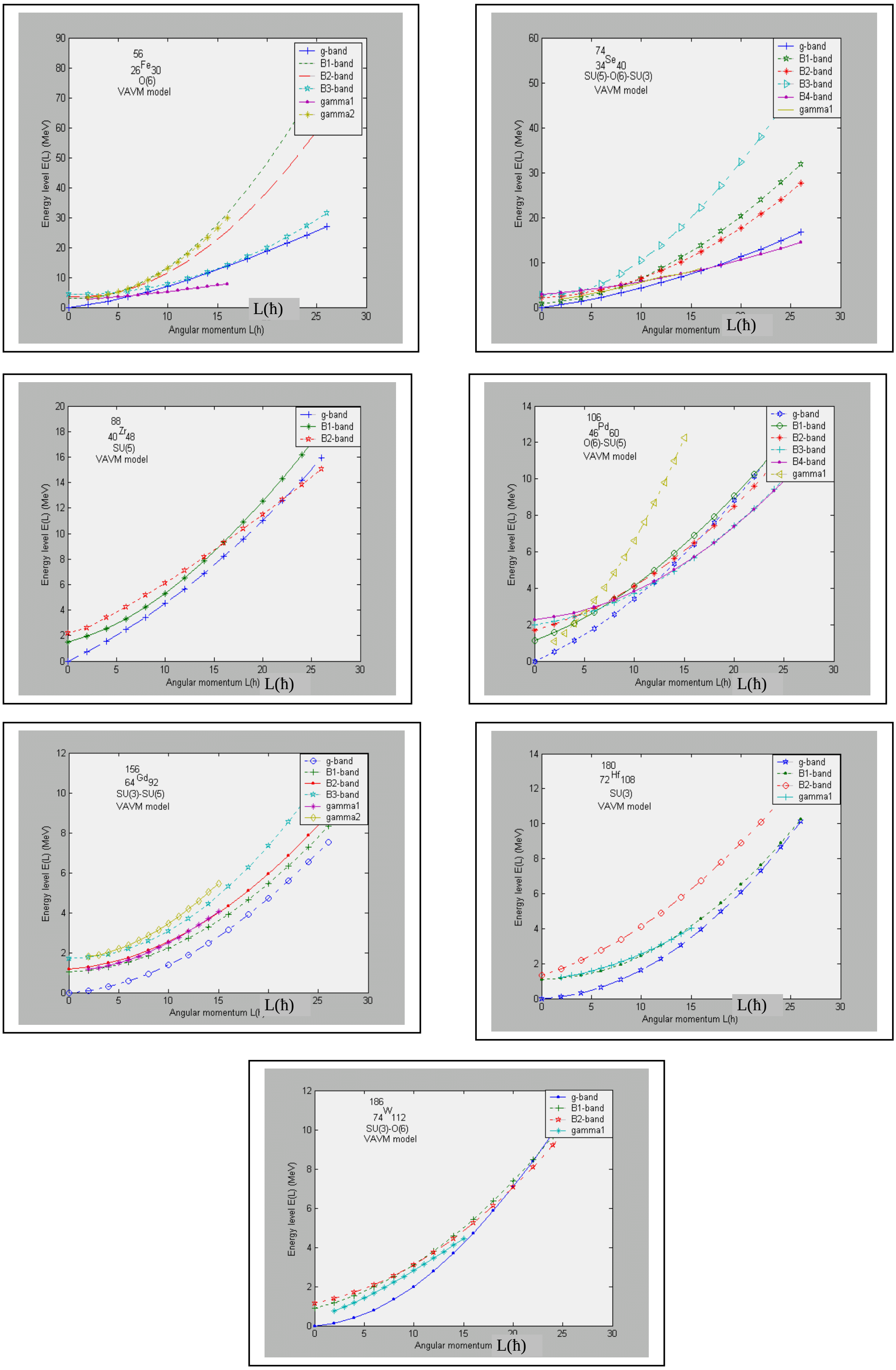
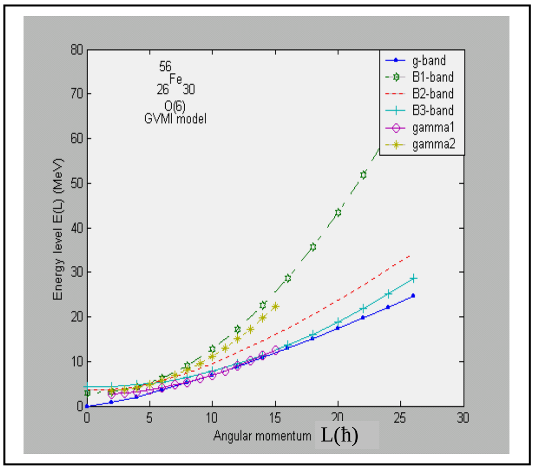
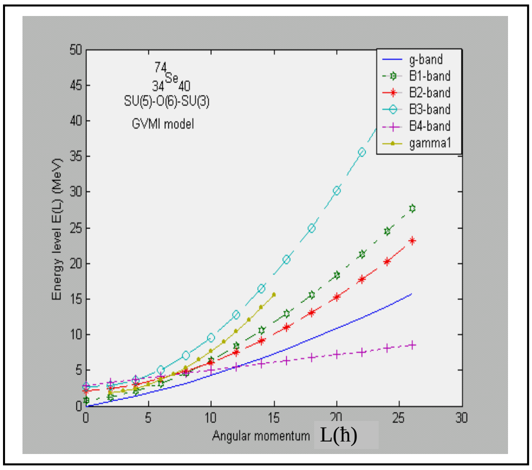
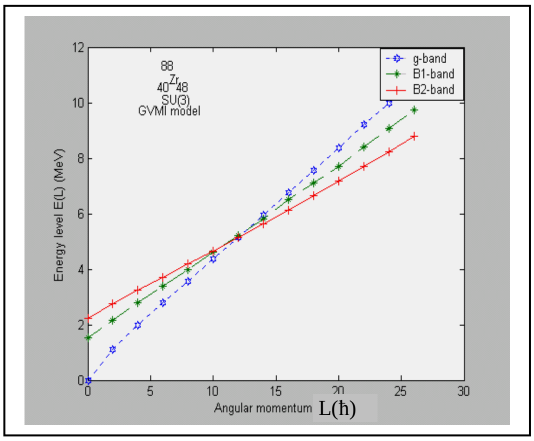
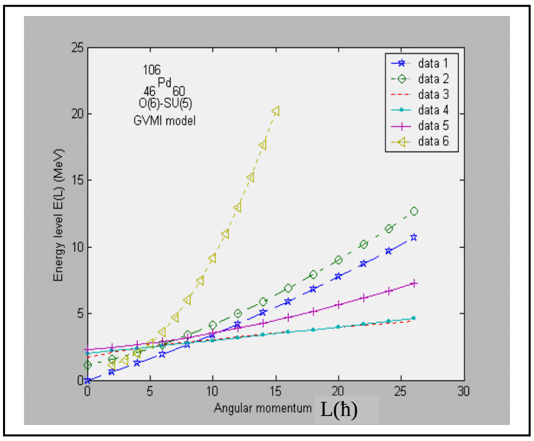


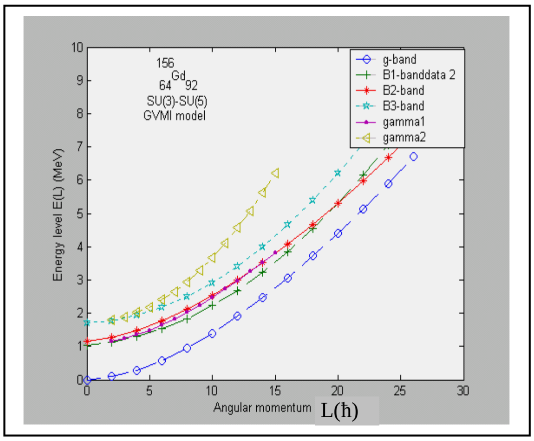
Figure (2): The energy band crossing E(L) as a function of angular momentum L for chosen nuclei using (VAVM) model. The parameters used for calculations are in table (1).

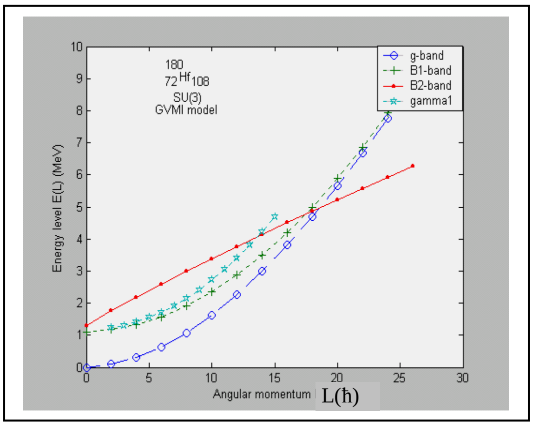

56
Fe
26 30
O(6)
GVMI model
g-band
B1-band
B2-band
B3-band
gamma1
gamma2
Energy level E(L) (MeV)
Angular momentum L(h)


74
Se
34 40
SU(5)-O(6)-SU(3)
GVMI model
g-band
B1-band
B2-band
B3-band
B4-band
gamma1
Energy level E(L) (MeV)
Angular momentum L(h)


88
Zr
40 48
SU(3)
GVMI model
g-band
B1-band
B2-band
Energy level E(L) (MeV)
Angular momentum L(h)


106
Pd
46 60
O(6)-SU(5)
GVMI model
data 1
data 2
data 3
data 4
data 5
data 6
Energy level E(L) (MeV)
Angular momentum L(h)


156
Gd
64 92
SU(3)-SU(5)
GVMI model
g-band
B1-banddata 2
B2-band
B3-band
gamma1
gamma2
Energy level E(L) (MeV)
Angular momentum L(h)


180
Hf
72 108
SU(3)
GVMI model
g-band
B1-band
B2-band
gamma1
Energy level E(L) (MeV)
Angular momentum L(h)

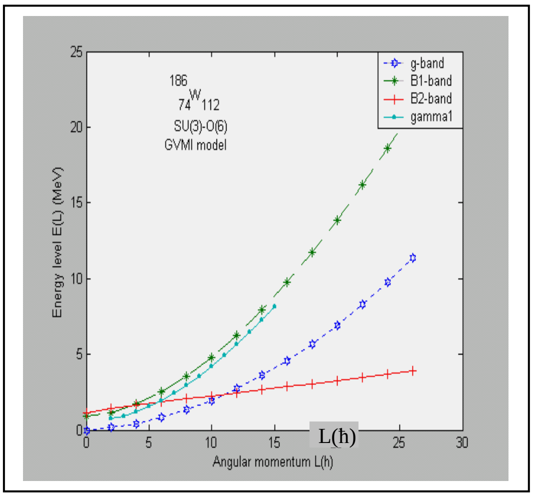


Figure (3): The energy band crossing E(L) as a function of angular momentum L for chosen nuclei using (GVMI) model .The parameters used for calculations are in table (1) .

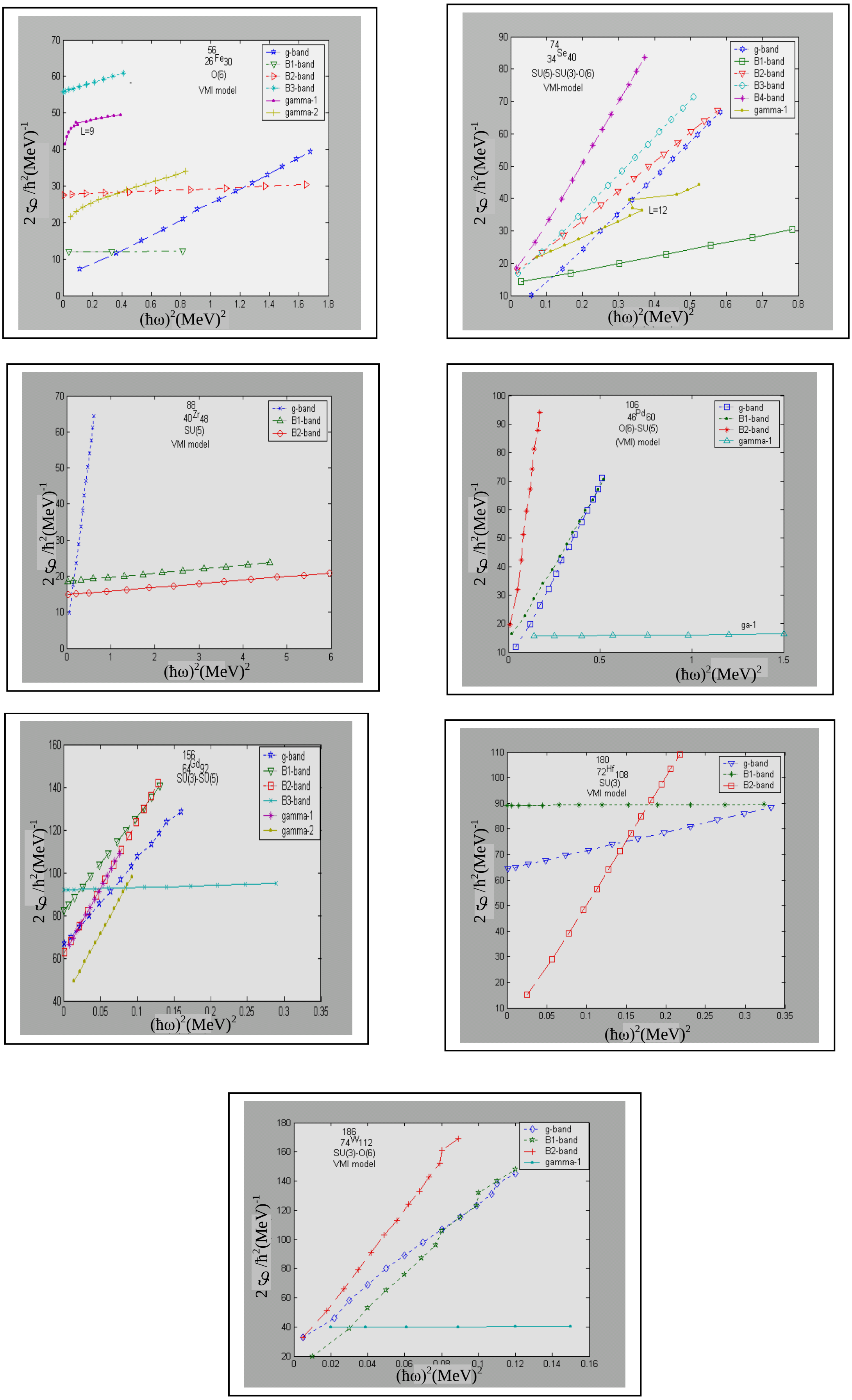


Figure (4): The back bending ($2\vartheta/\hbar^2$) versus $(\hbar\omega)^2$ plot for chosen nuclei using (VMI) model . The parameters used for calculations are in table (1).

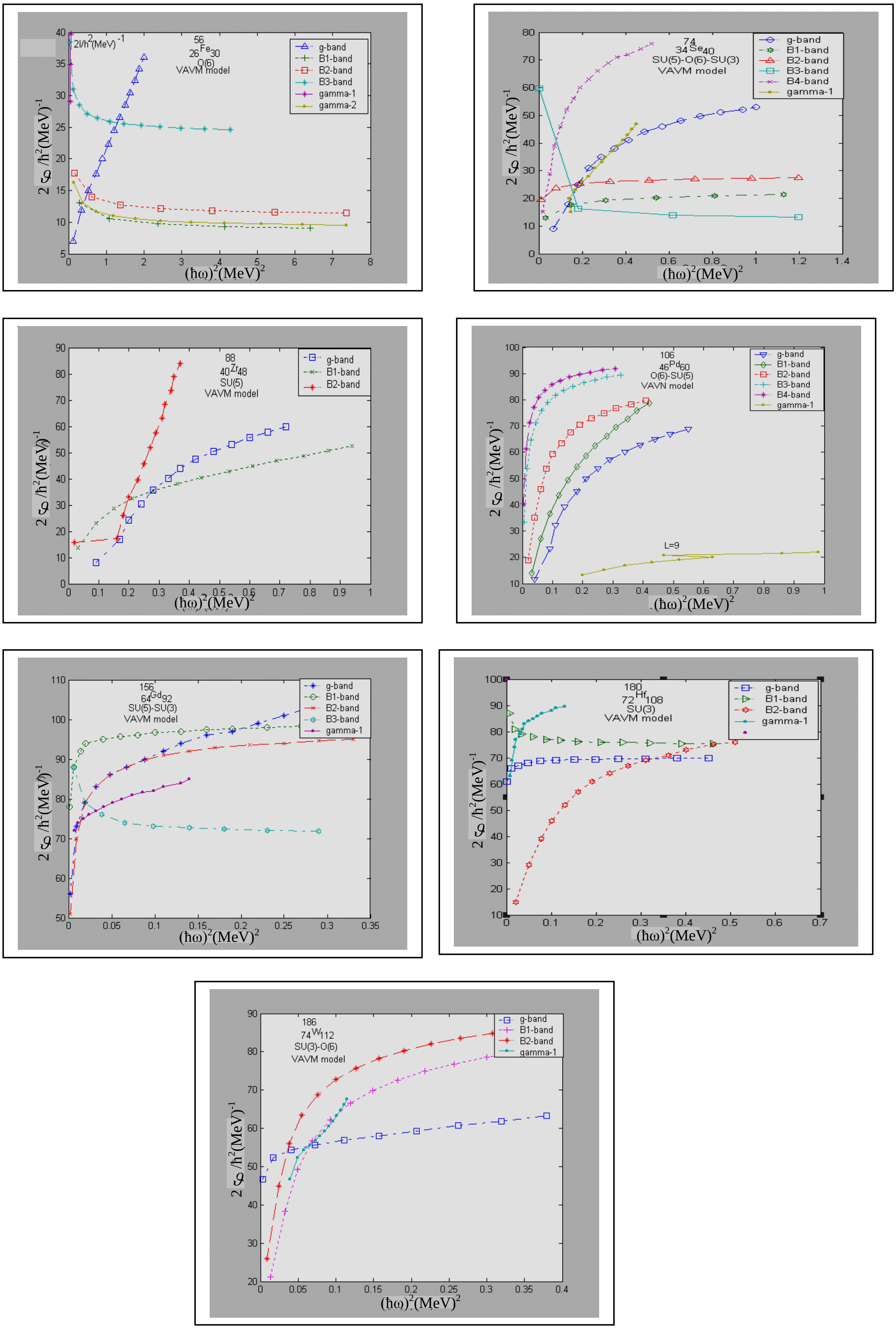


Figure (5): The back bending $(2\vartheta/\hbar^2)$ versus $(\hbar\omega)^2$ plot for chosen nuclei using (VAVM) model. The parameters used for calculations are in table (1).

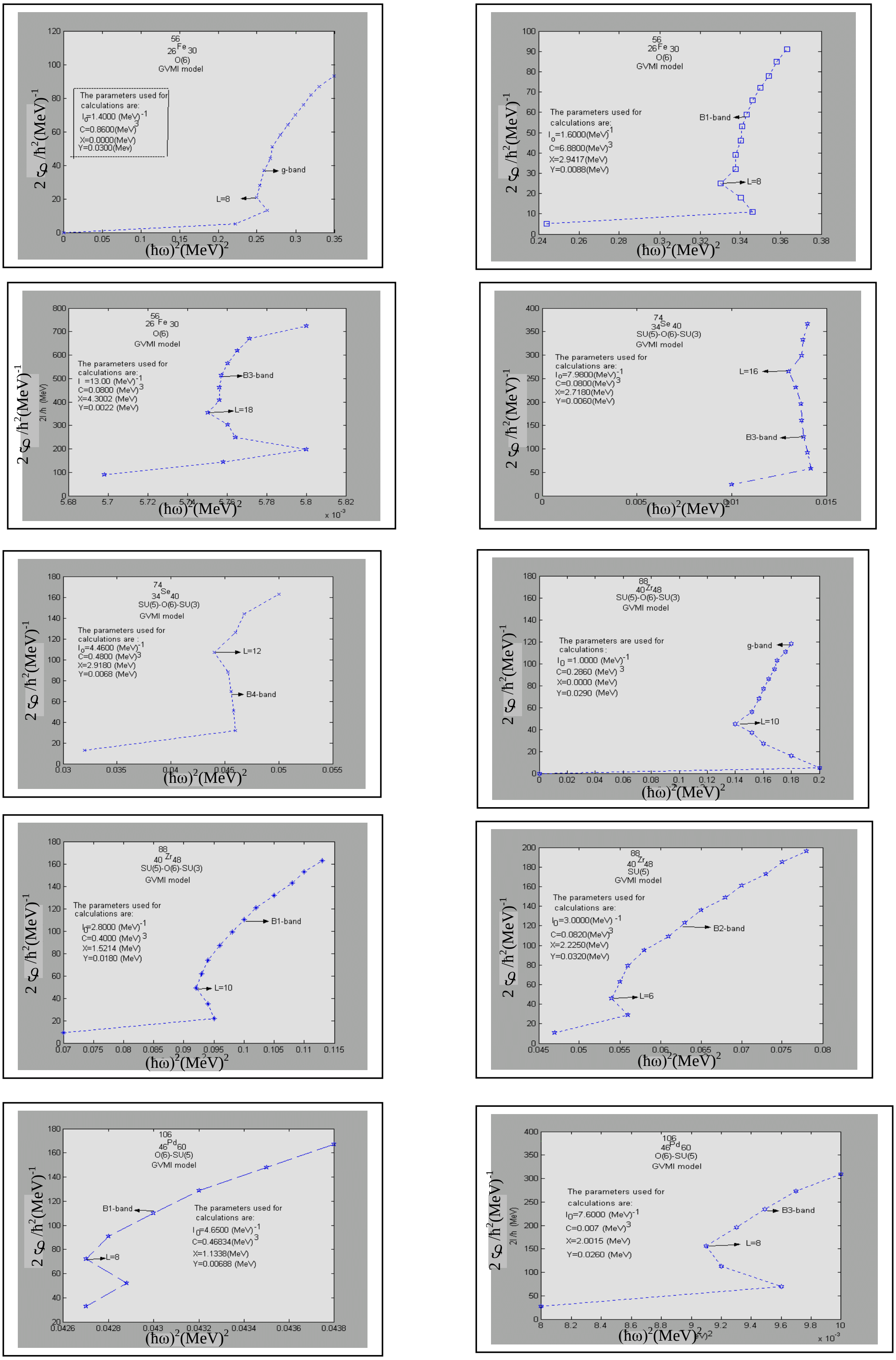


Figure (6): The back bending $(2\vartheta/\hbar^2)$ versus $(\hbar\omega)^2$ plot for chosen nuclei using (GVMI)model.

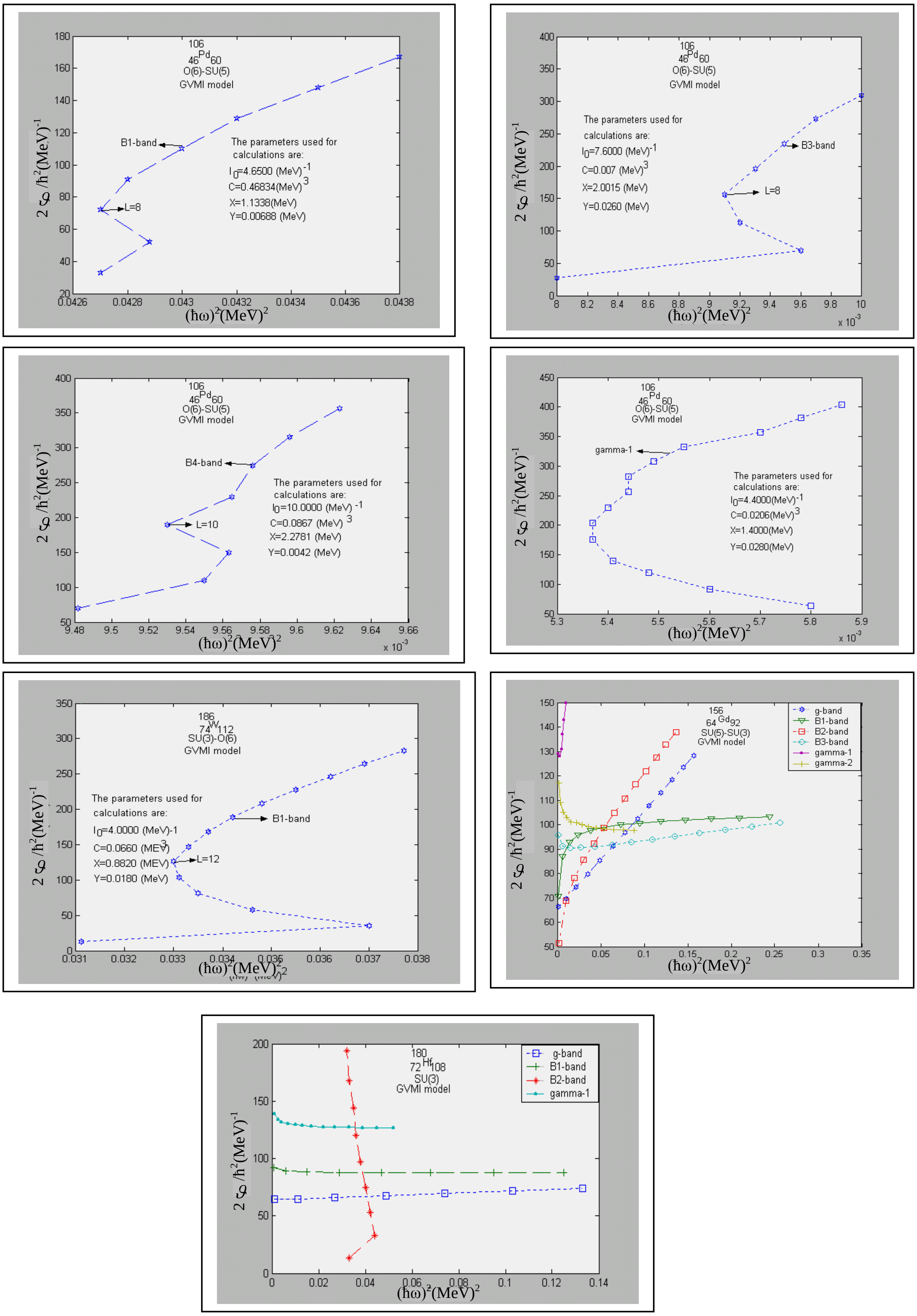


Figure (6): To be continued (2/2). The parameters used for calculations ^{156} Gd and ^{180}Hf nuclei are in table (1).