ORIGINAL PAPER

THE PROBABILITY OF ELECTRIC TRANSITIONS; THE SQUARE OF ROTATIONAL ENERGY & THE MOMENT OF INERTIA FOR CM (A=246) ISOTOPE

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Abstract. *The interacting boson model (IBM-1) was used to study some properties for $^{246}_{96}Cm_{150}$ isotope, from important of these properties the probability of eelectric transitions B(E2), The B(E2) values for even-even $^{246}_{96}Cm_{150}$ isotope have been calculated and compared with the experimental data. The calculated B (E2) values are in good agreement with the experimental data. It has also been calculate reduced matrix elements $\langle L_f \| \hat{T}^{(E_2)} \| L_i \rangle$ relevant the probability of electric transitions values B(E2). Furthermore, calculate the electric quadrupole moments (Q_L) to clarify the shape of the nucleus.*

In addition, a study square of rotational energy $(\hbar^2\omega^2)$ and the moment of inertia $(\frac{2\vartheta}{\hbar^2})$ for each angular momentum and compared with experimental results and show that through drawing, where it was interpreted the change in the relationship between the moment of inertia (experimental and theoretical) as a function of angular momentum.

Keywords: *IBM-1, B(E2), Reduce matrix elements, Quadrapole moments, Square of rotational energy, The moment of inertia.*

1. INTRODUCTION

Interacting boson model (IBM) of nuclear structure was suggested by Arima and Iachello [1, 2]. The IBM has been applied widely to link the collective properties of even-even nuclei, and even-odd nuclei by pairing a single-particle (fermion) to the even-even core [3]. The IBM-1 does not distinguish between proton and neutron bosons. The number of bosons depend on the number of active nuclear particle (or hole) pairs outside a closed shell, while the total boson number (N) is calculated by adding the partial numbers i.e. $N = N_\pi + N_\nu$, where N_π and N_ν are the number of proton and neutron bosons respectively [4, 5].

The $^{246}_{96}Cm_{150}$ isotope is belong to the SU(3) – O(6) transition region, it has properties located between the SU(3) and O(6) dynamical symmetries [6]. Minkov *et al*. derived analytic expressions for the energies and the B(E2) transition probabilities in the ground state and the γ-bands of heavy deformed nuclei within a collective vector-boson model with SU(3) dynamical symmetry [7]. Saiqa S. *et al*. have studied of even – even curium isotopes, where show comparison between experimental and calculated values of B(E2), as show the quadrupole and hexadecupole deformation parameters to calculations for Cm (A=242-250) isotopes [8].

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2. THEORETICAL BASICS

2.1. ELECTRIC QUADRUPOLE TRANSITION OPERATORS ($T^{(E2)}$)

The electric quadrupole transition operator has a widespread applaction in the anylasis of gamma-ray transitions and can be obtained from equation (1) [9]:

$$\hat{T}^{(E2)} = \alpha_2 \left[\hat{d}^\dagger \times \hat{\tilde{S}} + \hat{S}^\dagger \times \hat{\tilde{d}}\right]^{(2)}_\mu + \beta_2 \left[\hat{d}^\dagger \times \hat{\tilde{d}}\right]^{(2)}_\mu = \alpha_2 \left(\left[\hat{d}^\dagger \times \hat{\tilde{S}} + \hat{S}^\dagger \times \hat{\tilde{d}}\right]^{(2)}_\mu + \chi \left[\hat{d}^\dagger \times \hat{\tilde{d}}\right]^{(2)}_\mu\right) = e_B \hat{Q} \quad (1)$$

The α_2 and β_2 are two parameters. The $\beta_2 = \chi\alpha_2, \alpha_2 = e_B$ (effective charge of boson).

The reduce matrix elements $\langle L_f || \hat{T}^{(E_2)} || L_i \rangle$, one can calculate the electromagnetic transition rates and moments between the initial and the final stste. Electromagnetic transition rates are governed by B(E2) values, these are defined as [9, 10, 11]:

$$B(E2; L_i \rightarrow L_f) = \frac{1}{2L_i+1} \left|\langle L_f || \hat{T}^{(E_2)} || L_i \rangle\right|^2 \quad (2)$$

In the general case, the calculation has been done numerically. However, as in the case of the excitation energies, analytical expression can be found in the cases of the three dynamical symmetries [10, 11].

2.2. THE ELECTRIC QUADRUPOLE MOMENT BASIS

A measure of the deviation from spherical symmetry of the nuclear charge density distribution inside the nucleus is the electric quadrupole moment. The electric quadrupole (Q_L), has the dimensions of area and is measured in m^2 or barns. Then the (Q_L) is an important property of nuclei and from the quadrupole moment we can determine whether the nucleus is spherical $(Q_L = 0)$, deformed oblate $(Q_L < 0)$ or prolate $(Q_L > 0)$ shapes. The electric quadrupole moments of the nuclei can be derived from the $B(E2; L_i \rightarrow L_f)$ values according to equation (3) [9, 12, 13]:

$$Q_L = \left[\frac{16\pi}{5}\right]^{1/2} \left[\frac{L(2L-1)}{(2L+1)(L+1)(2L+3)}\right]^{1/2} \left[B(E2; L_i \rightarrow L_f\right]^{1/2} \quad (3)$$

The L is the angular momentum.

2.3. THE SQUARE OF ROTATIONAL ENERGY AND THE MOMENT OF INERTIA

The collective rotation motion for nucleus depends on the valence nucleons motion with nucleus motion, which causes rotation numeral of nucleons around axis different from nuclear symmetry axis. In some nuclei occurs a sudden change in the value of the moment of inertia at the high angular momentum relatively that leads to landing in the rotational energy of the nuclei. These sudden changes lead to occur (curvatures) like letter Z inverses [14].The formula for calculating all the moment of inertia and the square of rotational energy are [15, 16]:

$$\frac{2\vartheta}{\hbar^2} = \frac{4L-2}{E(L)-E(L-2)} = \frac{4L-2}{E_\gamma} (MeV)^{-1} \quad (4)$$

The ϑ is the moment of inertia and E_γ is the transition energy.

$$(\hbar\omega)^2 = \left(\frac{E(L)-(E(L-2)}{\sqrt{L(L+1)}-\sqrt{(L-2)(L-1)}}\right)^2 (MeV)^2 \tag{5}$$

3. RESULTS AND DISCUSSION

3.1. REDUCED MATRIX ELEMENTS & THE PROBABILITY OF QUADRUPOLE TRANSITIONS

To obtain an accurate description of the nuclear structure of any isotope axiomatic study the probability of electric transitions B(E2) as its represent the most important property of each isotope, (IBST.FOR) programe was used to calculate B(E2) theoretical values, and it must determinet value of effective charge e_B which represents (α_2). The value of effective charge e_B (α_2) was refferred to in the experimental result B(E2) and it is shown in table 1. As can through it find the value (β_2).

The values (E2SD, E2DD) represents the parameters was used in the program to obtain the theoretical results of B(E2).

Where: $E2SD = \alpha_2, E2DD = \sqrt{5}\beta_2 \Rightarrow \beta_2 = -\frac{\sqrt{7}}{2}\alpha_2$

Table 1. The values of the parameters (α_2, β_2) and (E2SD, E2DD) of the B(E2) and $\langle L_f||\hat{T}^{(E2)}||L_i\rangle$ for Cm (A=246) isotope by using (IBST.FOR) program.

Isotope	N_π	N_ν	N	$\alpha_2\ (eb)$	$\beta_2\ (eb)$	$E2SD(eb)$	$E2DD(eb)$
$^{246}_{96}Cm_{150}$	7	12	19	0.14760	-0.19525	0 .14760	0.43660

The comparison of the experimental data [17] with calculations of B(E2) values are given in table 2 for isotope under study. There is no available experimental transition data to many transitions in table 2. Therefore, it has been predicted by using IBM-1. This table shows that in general, there are a good agreement between the experimentally B(E2) values and the IBM-1 calculated ones.

Table 2 show that, probabilities of electric transitions (up and down) B(E2)↓, B(E2)↑ respectively, in $(eb)^2$ units, where: (eb) Electron barn.

The reduced matrix elements $\langle L_f||\hat{T}^{(E2)}||L_i\rangle$ the amaunt associated with the probability electric transitions B(E2), It can be found them by using equation (2), and for each electric transition for this isotope. It is measured in (eb) units.

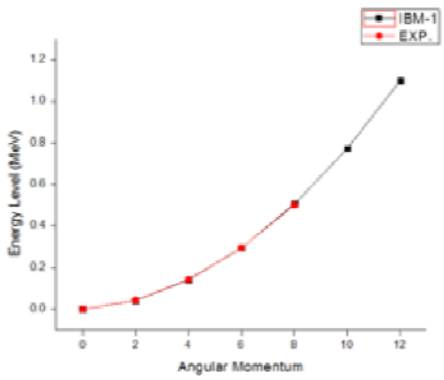
Table 2. Theoretical values of reduced matrix elements $\langle L_f||\hat{T}^{(E2)}||L_i\rangle$ and probabilities of electric transitions B(E2) for the Cm (A=246) isotope.

Isotope	Spin sequences $L_f^+ - L_i^+$	B(E2)↓ $(eb)^2$		B(E2)↑ $(eb)^2$		$\langle L_f\|\|\hat{T}^{(E2)}\|\|L_i\rangle$ eb
		IBM-1	EXP.[17]	IBM-1	EXP.[17]	
$^{246}_{96}Cm_{150}$ SU(3) – O(6)	$2_1^+ - 0_1^+$	2.9950	2.9940	14.9750	14.9700	3.8697
	$0_2^+ - 2_1^+$	0 .0085	-----	0.0425	-----	0.4610
	$0_2^+ - 2_2^+$	0 .0007	-----	0.0035	-----	0.1323
	$0_3^+ - 2_1^+$	0.0002	-----	0.0010	-----	0.0707
	$0_3^+ - 2_2^+$	1.2922	-----	6.4610	-----	5.6837
	$2_2^+ - 0_1^+$	0.2406	-----	1.2030	-----	1.0968

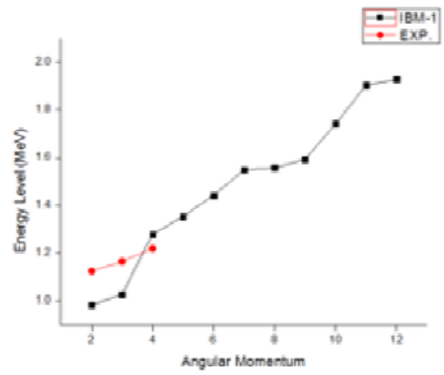
	$2_3^+-0_1^+$	0.0017	-----	0.0085	-----	0.0922
	$2_3^+-0_2^+$	2.5576	-----	12.7880	-----	3.5760
	$2_4^+-0_1^+$	0 .0000	-----	0.0000	-----	0.0000
	$2_4^+-0_2^+$	0.0117	-----	0.0585	-----	0.2419
	$2_4^+-0_3^+$	1.7455	-----	8.7275	-----	2.9542
	$2_2^+-2_1^+$	0.3704	-----	1.8520	-----	3.0430
	$2_3^+-2_1^+$	0.0026	-----	0.0130	-----	0.2549
	$2_3^+-2_2^+$	0.0003	-----	0.0015	-----	0.0866
	$2_4^+-2_1^+$	0.0001	-----	0.0005	-----	0.0500
	$2_4^+-2_2^+$	0.3345	-----	1.6725	-----	2.8918
	$2_4^+-2_3^+$	0.0170	-----	0.0850	-----	0.6519
	$2_2^+-4_1^+$	0.0224	-----	0.1120	-----	1.0040
	$2_3^+-4_1^+$	0.0044	-----	0.0220	-----	0.4450
	$2_4^+-4_1^+$	0.0001	-----	0.0005	-----	0.0671
	$2_4^+-4_2^+$	0.3111	-----	1.5555	-----	3.7416
	$2_4^+-4_3^+$	0.0395	-----	0.1975	-----	1.3332
	$3_1^+-2_1^+$	0.4249	-----	2.1245	-----	3.2592
	$3_1^+-2_2^+$	4.0707	-----	20.3535	-----	10.0880
	$3_2^+-2_1^+$	0.0015	-----	0.0075	-----	0.1936
	$3_2^+-2_2^+$	0.0036	-----	0.0180	-----	0.3000
	$3_2^+-2_3^+$	0.3590	-----	1.7950	-----	2.9958
	$3_1^+-4_1^+$	0.2039	-----	1.0195	-----	3.0291
	$3_2^+-4_1^+$	0.0006	-----	0.0030	-----	0.1643
	$3_2^+-4_2^+$	0.0038	-----	0.0190	-----	0.4135
	$4_1^+-2_1^+$	4.0385	-----	20.1925	-----	10.0480
	$4_2^+-2_1^+$	0.1273	-----	0.6365	-----	1.7840
	$4_2^+-2_2^+$	1.2388	-----	6.1940	-----	5.5651
	$4_2^+-2_3^+$	0.0005	-----	0.0025	-----	0.1118
	$4_3^+-2_1^+$	0.0024	-----	0.0120	-----	0.2449
	$4_3^+-2_2^+$	0 .0000	-----	0.0000	-----	0.0000
	$4_3^+-2_3^+$	3.4168	-----	17.0840	-----	9.2423
	$4_2^+-3_1^+$	3.0368	-----	15.1840	-----	10.3096
	$4_3^+-3_1^+$	0.0001	-----	0.0005	-----	0.0592
	$4_4^+-3_1^+$	0.3726	-----	1.8630	-----	3.6112
	$4_2^+-4_1^+$	0.4433	-----	2.2165	-----	4.4664
	$4_3^+-4_1^+$	0.0026	-----	0.0130	-----	0.3420
	$4_3^+-4_2^+$	0.0000	-----	0.0000	-----	0.0000
	$4_2^+-6_1^+$	0.0523	-----	0.2615	-----	1.8438
	$4_3^+-6_1^+$	0.0038	-----	0.0190	-----	0.4970
	$5_1^+-3_1^+$	1.9089	-----	9.5445	-----	8.1738
	$5_1^+-4_1^+$	0.3494	-----	1.7470	-----	3.9652
	$5_1^+-4_2^+$	2.1838	-----	10.9190	-----	9.9132
	$5_1^+-6_1^+$	0.2658	-----	1.3290	-----	4.1566
	$7_1^+-5_1^+$	2.4138	-----	12.0690	-----	11.5221
	$7_1^+-6_1^+$	0.2999	-----	1.4995	-----	4.4151
	$7_1^+-6_2^+$	1.2506	-----	6.2530	-----	9.0160
	$7_1^+-8_1^+$	0.2957	-----	1.4785	-----	5.0134
	$6_1^+-4_1^+$	4.1629	-----	20.8145	-----	13.6869
	$6_2^+-4_1^+$	0.0926	-----	0.4630	-----	2.0413
	$6_2^+-4_2^+$	2.2505	-----	11.2525	-----	10.0634
	$6_3^+-4_1^+$	0.0025	-----	0.0125	-----	0.3354
	$6_3^+-4_2^+$	0.0001	-----	0.0005	-----	0.0671
	$6_2^+-5_1^+$	1.6205	-----	8.1025	-----	9.4407
	$6_2^+-6_1^+$	0.4414	-----	2.2070	-----	5.3564
	$6_3^+-6_1^+$	0.0031	-----	0.0155	-----	0.4489
	$6_3^+-6_2^+$	0.0002	-----	0.0010	-----	0.1140
	$6_2^+-8_1^+$	0.0726	-----	0.3630	-----	2.4841

	$6_3^+-8_1^+$	0.0035	-----	0.0175	-----	0.5454
	$8_1^+-6_1^+$	4.0421	-----	20.2105	-----	16.2091
	$8_2^+-6_1^+$	0.0735	-----	0.3675	-----	2.1857
	$8_2^+-6_2^+$	2.4733	-----	12.3665	-----	12.6793
	$8_2^+-6_3^+$	0.0046	-----	0.0230	-----	0.5468
	$8_2^+-7_1^+$	0.9965	-----	4.9825	-----	8.6451
	$8_2^+-8_1^+$	0.4225	-----	2.1125	-----	5.9927
	$8_2^+-10_1^+$	0.0891	-----	0.4455	-----	3.0587
	$9_1^+-7_1^+$	2.4672	-----	12.3360	-----	13.6029
	$9_1^+-8_1^+$	0.2597	-----	1.2985	-----	4.6983
	$9_1^+-8_2^+$	0.8160	-----	4.0800	-----	8.3283
	$10_1^+-8_1^+$	3.8145	-----	19.0725	-----	18.0064
	$10_2^+-8_1^+$	0.0605	-----	0.3025	-----	2.2677
	$10_2^+-8_2^+$	2.4244	-----	12.1220	-----	14.3553
	$12_1^+-10_1^+$	3.5305	-----	17.6525	-----	19.2536
	$12_2^+-10_1^+$	0.0507	-----	0.2535	-----	2.3073
	$12_2^+-10_2^+$	2.2627	-----	11.3135	-----	15.4137

Fig. 1 illustrates the relationship between energy levels (expermintal and theoretical) and the angular momentum of the energy band $(g, \gamma_1, \beta_1, \beta_2, \gamma_2)$ for the isotope in the present work [6, 17, 18].



(a)



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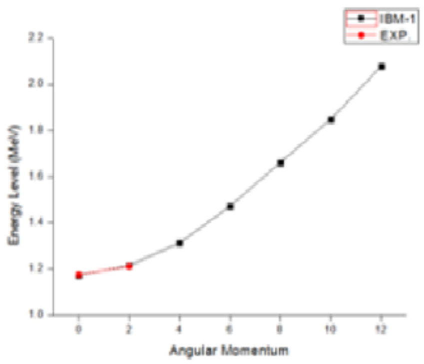

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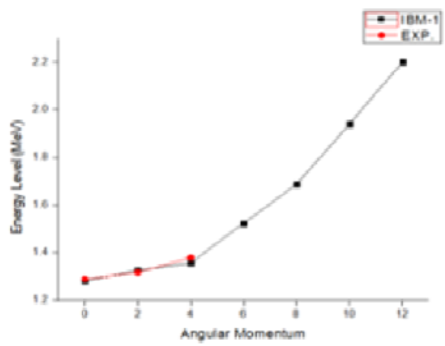

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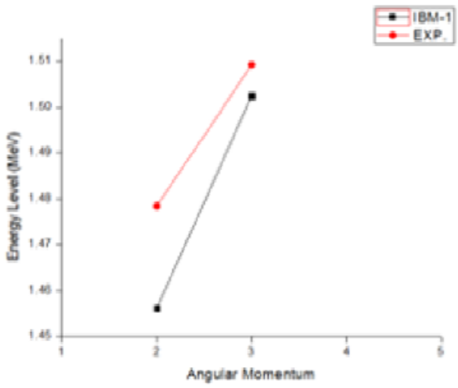

(e)

Figure 1. The relation between energy level as a function of angular momentum of the energy band $(g, \gamma_1, \beta_1, \beta_2, \gamma_2)$ respectively for $^{246}_{96}Cm_{150}$ isotope.

3.2. B(E2) RATIO

A basic requirement to represent each dynamical symmetry depends on the ratio of the probability of electric quadrupole transitions B(E2).

$$R = \frac{B(E2;4_1^+ \to 2_1^+)}{B(E2;2_1^+ \to 0_1^+)}, R' = \frac{B(E2;2_2^+ \to 2_1^+)}{B(E2;2_1^+ \to 0_1^+)}, R'' = \frac{B(E2;0_2^+ \to 2_1^+)}{B(E2;2_1^+ \to 0_1^+)} \quad (6)$$

Since Curium isotope ($^{246}_{96}Cm_{150}$) belongs to transitional region SU(3) – O(6) in IBM-1[6], therefore, table 3 show the B(E2) ratio by using IBM-1, and the B(E2) ratio for SU(3), O(6) dynamical symmetries.

From table 3 note that, the B(E2) ratio for isotope under study ranging between the B(E2) ratio for SU(3) and (O6) dynamical symmetry.

Also from this table, we can see that the theoretical values of B(E2) ratio for this isotope in a good agreement with two limits (SU3), (O6).

Table 3. The IBM-1 and SU(3), O(6) dynamical symmetry[9, 19] values of B(E2) ratios for the Cm (A=246) isotope.

Isotope		$^{246}_{96}Cm_{150}$
N		19
IBM-1	R	1.3484
	R′	0.1237
	R″	0.0028
SU(3)	R	$< \frac{10}{7}$
	R′	0
	R″	0
O(6)	R	$< \frac{10}{7}$
	R′	$< \frac{10}{7}$
	R″	0

3.3. QUADRUPOLE MOMENTS

3.3.1. INTRINSIC QUADRUPOLE MOMENT AND DEFORMATION PARAMETER

The intrinsic quadrupole moment Q_0 considered one of the important quantities to determinet the shape of nuclei, and can be derived from the transition rate B(E2)↑ values according to equation (7).

$$Q_0 = [(16\pi/5)B(E2)\uparrow/e^2]^{1/2} barn \tag{7}$$

where:

$$B(E2\uparrow; L-2 \rightarrow L) = \frac{2L+1}{2(L-2)+1} B(E2\downarrow; L \rightarrow L-2) \tag{8}$$

In addition to, there are other quantities dependent on the value of B(E2) called the doformation parameter β , and it can be calculated by the following equation:

$$\beta = \left(4\pi/\left(3ZR_0{}^2\right)\right)[B(E2)\uparrow/e^2]^{1/2} \tag{9}$$

where:

$$R_0{}^2 = 0.144A^{2/3} barn \tag{10}$$

Note that $Q_0, R_0{}^2$ measured with barn unit.

Table 4 presents the calculations of intrinsic quadrupole moment Q_0 and deformation parameter β with in framework of IBM-1 for the even – even ${}^{246}_{96}Cm_{150}$ isotope. The presented result for Q_0 is consistent with the expectations and from phenomenological systematic, and is compared with experimental result [17].

Table 4. The IBM-1 values and the experimental data [17] of Q_0 and β for Cm (A=246) isotope.

Isotope		${}^{246}_{96}Cm_{150}$
$Q_0(b)$	IBM-1	12.2665
	EXP.	12.2645
β	IBM-1	0.0298
	EXP.	0.0298

3.3.2. ELECTRIC QUADRUPOLE MOMENTS

The values of electric quadrupole moments (Q_L) are one of the most important properties for measuring the nuclear deformation. The deformed nuclei of prolate shape have a positive electric quadrupole moment $(Q_L > 0)$, the nuclei of oblate shape have a negative electric quadrupole moment $(Q_L < 0)$, and $(Q_L = 0)$ for the isotopes belong to O(6) limit. Table 5 shows the IBM-1 electric quadrupole moments measuring with (eb) unit of the ground state $(Q_{2_1^+})$ and the excited states $(Q_{2_2^+}, Q_{2_3^+})$ according to the dynamical symmetry.

Table 5. The IBM-1 values of electric quadrapole moments Q_L (pw) for Cm (A=246) isotope.

Isotope	Electric Quadrapole Moments		
	$Q_{2_1^+}(eb)$	$Q_{2_2^+}(eb)$	$Q_{2_3^+}(eb)$
${}^{246}_{96}Cm_{150}$	-4.7403	4.1249	-4.4074

3.4. THE SQUARE OF ROTATIONAL ENERGY AND THE MOMENT OF INERTIA

The rotational motion is very complicated because it represents the body rotation hardwood and each surface of the rotation warped includes N of free particles. The rotational motion leads to the formation of large deformation quadrupole for cases of excited low-lying nuclei and the spin should not be a body rotation hardwood, the spherical surface of the nucleus will rotate and orbital levels for all nucleons spin too.

The square of rotational energy ($\hbar^2\omega^2$) can be found through the equation (5) with $(\text{MeV})^2$ units which are the same energy units as it is shown in table 6 (expermintal and theoretical) and each angular momentum. Fig. 2 represents the relation between ($\hbar^2\omega^2$) (expermintal & theoretical) and angular momentum for isotope under study. We find good agreement with the IBM-1 and experimental results.

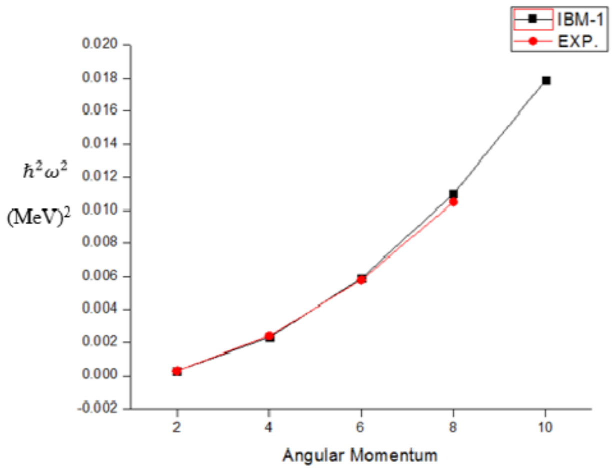

Figure 2. The relation between $\hbar^2\omega^2$as a function of angular momentum for ${}^{246}_{96}Cm_{150}$ isotope.

It was found that the moment of inertia, which must be used to obtain agreement with the experimental results is less than the moment of inertia of the body hard by a factor of 2 to 4 as the nucleons drift with the surface during the rotational motion, and has been found experimintaly that the moment of inertia increases constant deformation β increase.

The moment of inertia ($\frac{2\vartheta}{\hbar^2}$) can be found through the equation (4) with $(\text{MeV})^{-1}$ units and as it is shown in table 6 (expermintal and theoretical) and each angular momentum.

Table 6. Comparison between the IBM-1 and experimental [17, 18] values for square of rotational energy & moment of inertia for Cm (A=246) isotope.

L	$\hbar^2\omega^2$		$\frac{2\vartheta}{\hbar^2}$	
	IBM-1	EXP.	IBM-1	EXP.
2	0.0003	0.0003	142.8571	140.0233
4	0.0023	0.0024	142.7260	141.1290
6	0.0059	0.0058	142.4963	143.3225
8	0.0110	0.0105	142.1733	146.3415
10	0.0179	----	141.7434	----

Fig. 3 represents the relationship between $(\frac{2\vartheta}{\hbar^2})$ (expermintal & theoretical) and angular momentum for isotope under study.

From this figure, note that, there recursive difference increases with increasing excitement energy and this difference can be explained as a result of the increased moment of inertia increase the angular momentum of the rotation, and that the impact centrifugal force.

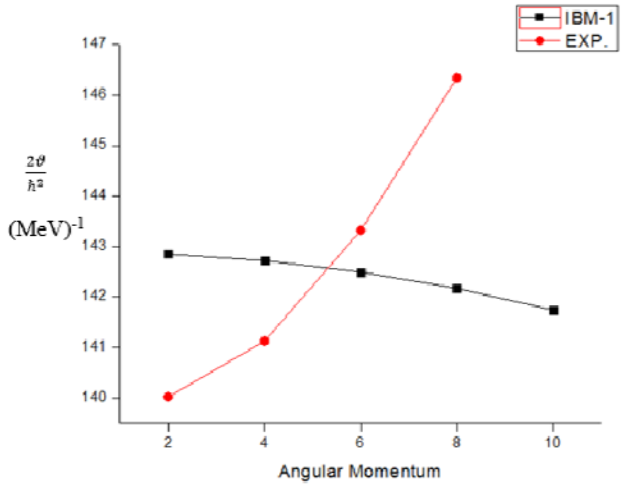

Figure 3. The relation between $\frac{2\vartheta}{\hbar^2}$ as a function of angular momentum for $^{246}_{96}Cm_{150}$ isotope.

Fig. 4 shows the relation of the moment of inertia $(\frac{2\vartheta}{\hbar^2})$ as a function of the square of the energy $(\hbar^2\omega^2)$ of the emitted photon for $^{246}_{96}Cm_{150}$ isotope. When the nucleus transform from the (L) state to the (L-2) state, the even-even $^{246}_{96}Cm_{150}$ isotope does not suffer from any curvature which indicates the absence of change in their properties. The comparison between the theoretical and the experimental values [17, 20] for all square rotational energy and the moment of inertia are shown in Fig. 4.

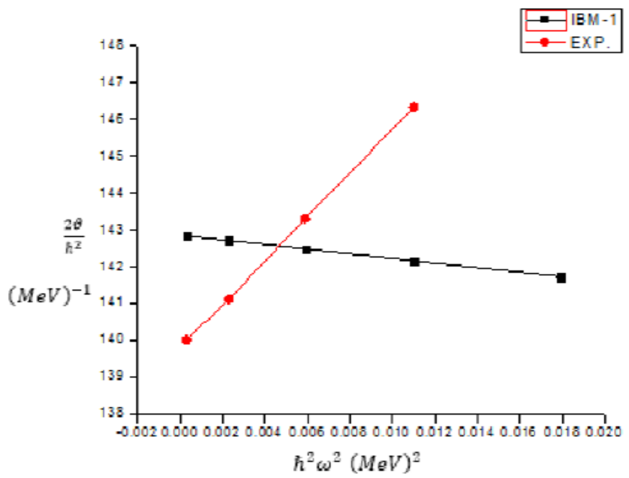

Figure 4. The calculated and observed moment of inertia $\frac{2\vartheta}{\hbar^2}$ vs. $\hbar^2\omega^2$ for yrast levels of $^{246}_{96}Cm_{150}$ isotope. The experimental data are taken from [17, 20].

4. CONCLUSIONS

From all calculations, it was concluded to study some of the nuclear properties for $^{246}_{96}Cm_{150}$ isotope, it was used IBM-1 of this study, and these properties:

- Calculate the probability of electric transitions B(E2) values and compared with the experimental results if applicable.
- Study the reduce matrix elements $\langle L_f || \hat{T}^{(E_2)} || L_i \rangle$ the associated with the probability electric transitions B(E2).
- Calculate the B(E2) ratio (R, R', R'') for ${}^{246}_{96}Cm_{150}$ isotope and comparing with B(E2) ratio for SU(3), O(6) dynamical symmetries.
- Determine the value of electric quadrupole moment for detemiation the shape of the nucleus and the amount of deformation happening in it.
- A study the square of rotational energy and the moment of inertia for each nucleolus contributes to reaching the basic concepts of nuclear structure.

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