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# Bands structure and electromagnetic transitions of O(6) nucleus $^{128}$Xe

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**Abstract**

An analysis of levels structure of $^{128}$Xe isotope within the framework of the proton-neutron interacting boson model is presented. Reduced electric quadrupole transition probabilities B(E2)and their ratios are reproduced. The mixing ratios for transitions with $\Delta I = 0$ or 1, $I \neq 0$ are compared with experiment. The presence of the mixed symmetry state in this isotope is discussed. Generally good agreement is obtained with a restricted number of adjustable parameters. Some predictions are presented for nucleus for which no experimental data are available.

**Key words**: Interacting boson model, Energy levels, electromagnetic transitions, mixing ratio, mixed symmetry states.

## 1. Introduction

The neutron-proton interaction is known to play a dominant role in structure of nuclei. As a consequence, the excitation energies of collective quadrupole excitations in nuclei near a closed shell are strongly dependent on the number of nucleons outside the closed shell. In the case of even- even Xe isotopes this interaction create a shape transition in the open shell region, due to the change of neutron number from isotope to other. The even-mass Xenon isotopes have been extensively investigated both theoretically and experimentally with special emphasis on interpreting experimental data via collective models [1-4]. Energy levels, electric quadrupole moments, B(E2) values of $^{114-120}Xe$ isotopes have been studied within the framework of the Interacting Boson Model-2[5-7]. Different nuclear models have been developed by many group and apply on this region in attempt of reproduction of nuclear properties and deformation parameters.[1,8]. The nucleus $^{128}Xe$ is of special interest because it is in the middle of the oblate- prolate shape coexistence which is predicted in even $^{124-132}Xe$ isotopes [9]. The works of Laquard *et. al* [9] and Mittal and Devi [10], concluded that the $^{128}Xe$ nucleus is a new example of the E(5) symmetry. A comparison of the energy value of the excited $0^+$, clearly indicates that there is problem in recognizing this state in its position. This means that there should be a coupling between oscillation and pairing vibration [11,12]. The work of Singh et al [13] on the nuclear deformation in Xe isotopes using ββ - decay process, produced B(E2) and Q($2^+$) and g factor of a series of isotopes. The excitation states of $^{128}$Xe were investigated in Ref. [14], where the levels were inferred from the $^{125}$Te (α,n) $^{128}$Xe reaction. As well as, the authors have investigated the symmetry character of the levels by calculated the F-spin and $n_d$ component of the wave function of the states.

Our aim in this study is to investigate $^{128}Xe$ isotope in O(6)-transitional region and calculate the energy levels, electromagnetic transition probabilities and δ(E2/M1) mixing ratios. However, the main task of this work is identify position of mixed symmetry states especially the scissors states and to study the influence of different values of Majorana parameters on the energies and decay probabilities.

## 2-The Proton-Neutron Interacting Boson Model (IBM-2)

The proton-neutron interacting boson model (IBM-2), Hamiltonian can be written [15-17]

$$H = H_\pi + H_\nu + H_{\pi\nu} \tag{1}$$

The Hamiltonian generally used in phenomenological calculations can be written as,

$$H = \varepsilon_d (n_{d\nu} + n_{d\pi}) + \kappa (Q_\nu . Q_\pi) + V_{\nu\nu} + V_{\pi\pi} + M_{\nu\pi} \tag{2}$$

The first term represents the single-boson energies for neutron and protons, $\varepsilon_d$ is the energy difference between s- and d- boson and $n_{d\rho}$ is the number of d-bosons, where $\rho$ correspond to $\pi$ (proton ) or $\nu$ (neutron) bosons. The second term denotes the main part of the boson-boson interaction, i.e. the quadrupole-quadrupole interaction between neutron and proton bosons with the strength $\kappa$. The quadrupole operator is

$$Q_\rho = [d_\rho^{\ +} s_\rho + s_\rho^{\ +} d_\rho]^{(2)} + \chi_\rho [d_\rho^{\ +} d_\rho]^{(2)} \tag{3}$$

where $\chi_\rho$ determines the structure of the quadrupole operator and is determined empirically. The terms $V_{\pi\pi}$ and $V_{\nu\nu}$, in equation (2) which correspond to interaction between like-boson, are sometimes included in order to improve the fit to experimental energy spectra. They are of the form

$$V_{\rho\rho} = \frac{1}{2} \sum_{L=0,2,4} C_L^{\ \rho} ([d^+{}_\rho d^+{}_\rho]^{(L)} . [d_\rho d_\rho]^{(L)} ). \tag{4}$$

However, their effects are usually considered minor and often neglected.

The Majorana term, $M_{\nu\rho}$, which contains three parameters $\xi_1$ ,$\xi_2$ and $\xi_3$ written as

$$M_{\nu\pi} = \frac{1}{2}\xi_2([s_\nu{}^+ d_\pi{}^+ - d_\nu{}^+ s_\pi{}^+]^{(2)}.[s_\nu d_\pi - d_\nu s_\pi]^{(2)}) - \sum_{k=1,3}\xi_k([d_\nu{}^+ d_\pi{}^+]^{(k)}.[d_\nu d_\pi]^{(k)}).(5)$$

## 3. Calculation and Results

### *3.1.Energy levels*

The general feature of the systematic of low lying experimental energy level introduced in Figure-1, which contains the energy of $2_1^+,4_1^+,2_2^+$ and $0_2^+$ as a function of mass number **A**. We can see that all the energy increases with A, which is normal, due to the effect of the closed shell at N=82. The energies of the $2_2^+$ and $4_1^+$ states are close to each other in several Xe isotopes. It is a consequence of the fact that O(5) seniority is a good quantum number. The position of the nucleus under consideration $^{128}$Xe clearly market in the figure.

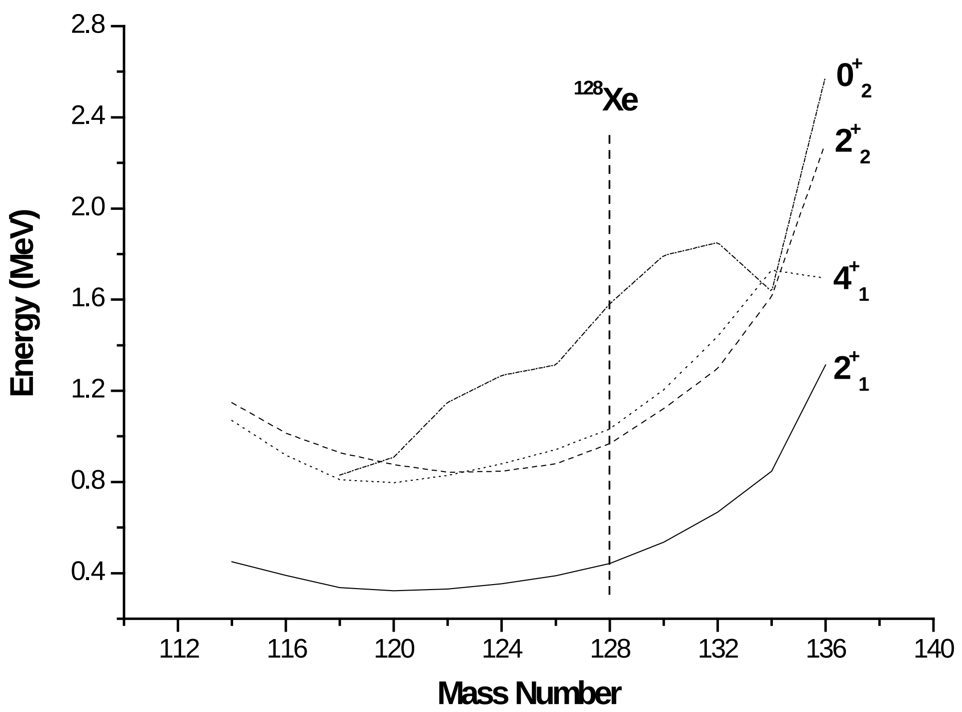


**Figure 1. The experimental [19] energy levels of selected states in Xe isotopes as a function of mass number A.**

parameters are approximately same as those in reference [5] and they are; $N_\pi = 2,\ N_\nu = 4,\ \varepsilon_d = 0.690, \kappa = -0.192, \chi_\pi = 0.87, \chi_\nu = -0.87, C_N^L = -0.100, 0.100, -0.050, \xi_1 = 0.450,$ $\xi_2 = 0.300, \xi_3 = -0.100.$

In the present IBM-2 fitting, the program code NPBOS [18] have been used. The

All parameters are in MeV unit except $\chi_\pi$ and $\chi_\nu$ which are dimensionless. The model parameters of Mara *et al* [6], who limited their calculation to A=114-120, could not tell any systematic specially the value of $\varepsilon_d$, which is vibrate from one isotope to other. While the parameters of Ref. [5], have a smooth systematic for whole series of isotopes. The choice of the parameters $\chi_\pi = -\chi_\nu$ in order to reproduced the O(6) structure of this nucleus. The result of calculations is presented in Figure 2. As we can see that the agreement between experimental and theoretical is very good regarding their values and systematic as well.

The ratio $E4_1^+ / E2_1^+$ indicates that this isotopes belong to the O(6) limit of the IBM, which equal to 2.33 experimental and 2.47 theoretical. The $0_2^+$ level pushed up away from the rest of the two phonon triplet $2_2^+$ and $4_1^+$ gives clear low lying gamma band ,and this other indication of the O(6). The ratio $E0_3^+ / E0_2^+$ can be a useful indicator soft nuclei [7] according to the quantum number of O(6), which is 2,07 in the SU(3) and less in the O(6). In our case the ratio is 1.19.

By calculated the quantities $R_{2,o,\beta,g}, R_{4,2,\beta,g}$ and $R_{4,2,\gamma,g}$ [20] one can see how much collectivity in the experimental levels and the model prediction. These quantities are shown in Table 1. It is clear from the table that the agreement between theory and experiments are good, which means that these levels are

are collective. The calculated energy of the $6_1^+$ and $8_1^+$ states equal to 1.778 and 2.673 MeV in a good agreement with experimental ones equal to.737 and 2.512 MeV, respectively.

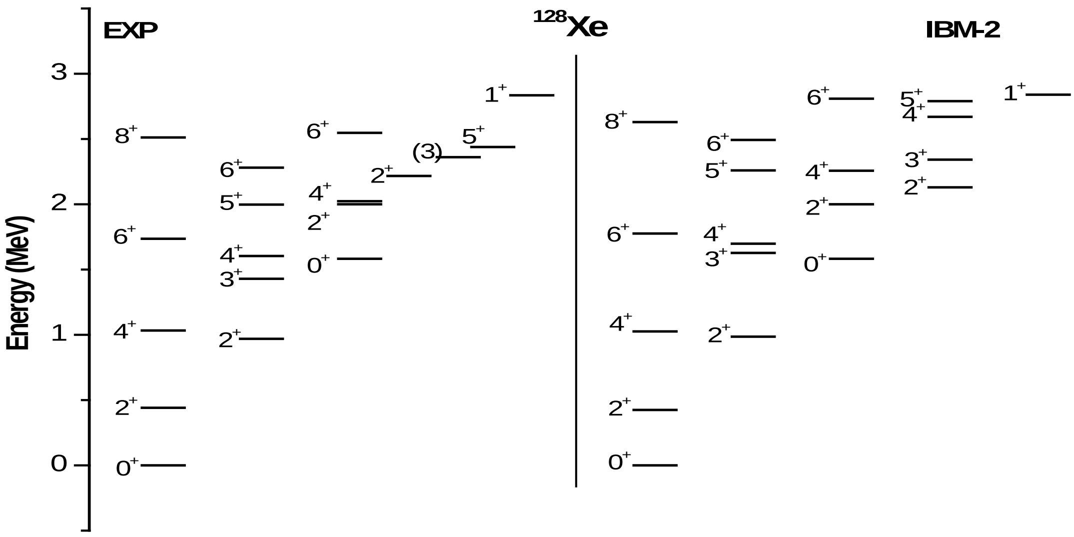


**Figure 2. Comparison of levels [128]Xe isotope predicted by IBM-2 calculation with experimental data [19].**

**Table-1 A comparison between the IBM-2 predictions of quantities** $R_{2,o,\beta,g}, R_{4,2,\beta,g}$ *and* $R_{4,2,\gamma,g}$ **and their experimental values**

| $R_{2,0,\beta,g} = \dfrac{E(2^+_\beta)-E(0^+_\beta)}{E(2^+_g)}$ | | $R_{4,2,\beta,g} = \dfrac{E(4^+_\beta)-E(2^+_\beta)}{E(4^+_g)-E(2^+_g)}$ | | $R_{4,2,\gamma,g} = \dfrac{E(4^+_\gamma)-E(2^+_\gamma)}{E(4^+_g)-E(2^+_g)}$ | |
|---|---|---|---|---|---|
| Exp. | IBM-2 | Exp. | IBM-2 | Exp. | IBM-2 |
| 0.941 | 1.331 | 0.280 | 0.429 | 1.073 | 1.183 |

## 3.2. Electromagnetic Transition and Quadrupole moment

### *3.2.1. E2 transition probability*

The general one body E2 transition probability operator in the IBM-2 is written as

$$T^{(E2)} = e_\pi Q_\pi + e_\nu Q_\nu \qquad (6)$$

where the quadrupole operator $Q_\rho$ is defined in Eq. 3, $e_\pi$ and $e_\nu$ are boson effective charges depending on the boson number $N_\rho$. The effective boson charges $e_\pi$ and $e_\nu$ were calculated, using the method used in Ref. [21], by plotting Y against $N_\pi / N_\nu$ where

$$Y = \frac{1}{N_\pi}\left[\frac{5N}{N+4} B(E2;2^+_1 - 0^+_1)\right]^{1/2} eb \qquad (7)$$

The best fitted straight line was obtained, Figure-3, from which

$e_\pi = 0.0856\, eb$ (interception) and

$e_\nu = 0.121\, eb$ (slope) were found.

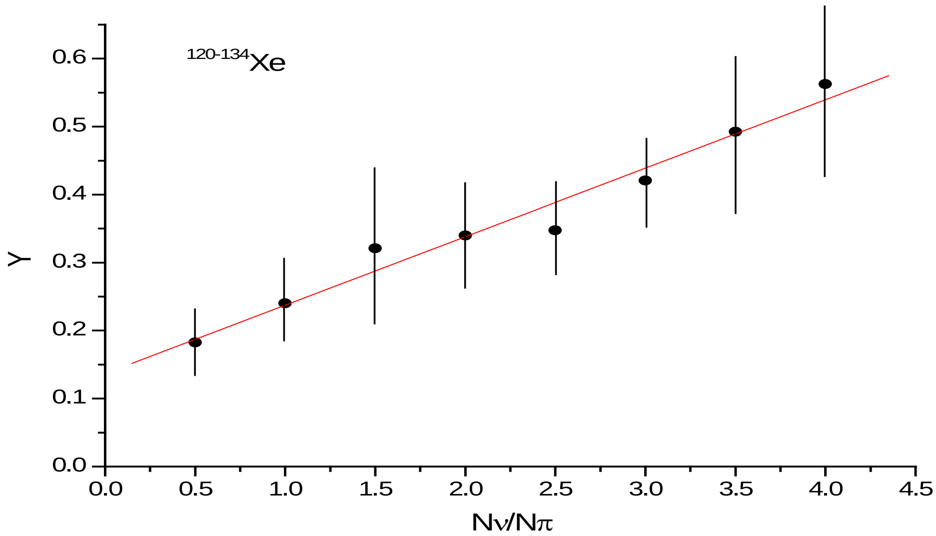


**Figure 3. The Y values as a function of the $N_\pi / N_\nu$ , B(E2) experimental values taken from [13] and references sited in.**

These two values were used in the calculation of the transition probability using the NPBEM code. The results are presented in Table 2.

**Table-2 The absolute B(E2) values measured in $e^2b^2$, compared with the available experimental data.**

| $E_\gamma$ [MeV] | $I_f^+ \to I_i^+$ | EXP | IBM-2 |
|---|---|---|---|
| 0.443 | $2_g \to 0_g$ | 0.1632(245) | 0.1619 |
| 0.590 | $4_g \to 2_g$ | 0.2433(199) | 0.2214 |
| 0.527 | $2_\gamma \to 2_g$ | 0.1919(371) | 0.2325 |
| 0.969 | $2_\gamma \to 0_g$ | 0.0025(3) | 0.0012 |
| 0.696 | $3_\gamma \to 4_g$ | 0.1218(226) | 0.0710 |
| 0.460 | $3_\gamma \to 2_\gamma$ | 0.3486(613) | 0.1819 |
| 0.987 | $3_\gamma \to 2_g$ | 0.0055(9) | 0.0017 |
| 0.613 | $0_\beta \to 2_\gamma$ | 0.2023(291) | 0.0990 |
| 1.140 | $0_\beta \to 2_g$ | 0.0141(22) | 0.0395 |
| 0.570 | $4_\gamma \to 4_g$ | 0.1157(122) | 0.1177 |
| 0.634 | $4_\gamma \to 2_\gamma$ | 0.1134(111) | 0.0928 |
| 1.160 | $4_\gamma \to 2_g$ | 0.0019(2) | 0.0014 |
| 0.704 | $6_g \to 4_g$ | 0.4061(498) | 0.2541 |
| 0.908 | $0_{\beta\beta} \to 2_\gamma$ | 0.0850(176) | 0.1650 |
| 1.434 | $0_{\beta\beta} \to 2_g$ | | 0.1619 |
| 0.416 | $2_\beta \to 0_\beta$ | | 0.2214 |

### *3.2.2 The B(E2) ratios*

One delicate test of the O(6) feature, are the ratios $R_1$, $R_2$ and $R_3$ and $R_4$ which are written as [22,23]

$$R_1 = \frac{B(E2;4_g - 2_g)}{B(E2;2_g - 0_g)} = \frac{10}{7}\frac{(N-1)(N+5)}{N(N+4)}, \qquad R_2 = \frac{B(E2;2_\gamma - 2_g)}{B(E2;2_g - 0_g)} = \frac{10}{7}\frac{(N-1)(N+5)}{N(N+4)}$$

$$R_3 = \frac{B(E2;0_\beta - 2_g)}{B(E2;2_g - 0_g)} = 0, \qquad R_4 = \frac{B(E2;2_\gamma - 0_g)}{B(E2;2_\gamma - 2_g)} = 0\, in\ U(5) = \frac{10}{7}\ in\ SU(3)$$

**Table-3: The B(E2) ratios**

| Ratio | Exp. | O(6) | IBM-2 |
|---|---|---|---|
| $R_1$ | 1.46 | 1.31 | 1.36 |
| $R_2$ | 1.20 | 1.31 | 1.15 |
| $R_3$ | - | 0.0 | 0.018 |
| $R_4$ | 0.013 | $1.4 \geq R_4 \geq 0$ | 0.024 |

As one can see from the table 3 , the results of IBM-2 is very closed to the experimental values and O(6) symmetry, bearing in mind that the effective charges estimated from O(6) plot. From the table, one can see that the $2^+_\gamma$ state has a strong branch to the $2^+_g$.This feature reflects the O(6) limit in the IBM [24,25] as well..

. The quadrupole moment of $2^+_g$ state was calculated, using the relation [22].

$$B(E2;0^+_g \rightarrow 2^+_g) = \frac{5}{16\pi}Q_0^2$$
$$Q(2^+_g) = -\frac{2}{7}Q_o \qquad (8)$$

where $Q_o$ is the static quadrupole moment.
The calculated value is -0.436 *eb*, compared with experimental value -0.355 *eb*.

### *3.2.3.* $\delta(E2/M1)$ *mixing ratios*

The IBM-2 M1 operator can be written as

$$T^{(M1)} = \left[\frac{3}{4\pi}\right]^{1/2}(g_\pi L_\pi{}^{(1)} + g_\nu L_\nu{}^{(1)}) \qquad (9)$$

where $g_\pi, g_\nu$ are the proton and neutron boson g-factors in units $\mu_N$ and $L^{(1)} = \sqrt{10}(d^+ x\tilde{d})^{(1)}$. This operator can be written as

$$T^{(M1)} = \left[\frac{3}{4\pi}\right]^{1/2}\left[\tfrac{1}{2}(g_\pi + g_\nu)(L_\pi{}^{(1)} + L_\nu{}^{(1)}) + \tfrac{1}{2}(g_\pi - g_\nu)(L_\pi{}^{(1)} - L_\nu{}^{(1)})\right] \qquad (10)$$

The first term on the right hand side ,in the above equation, is diagonal and therefore for M1 transitions the previous equation may be written as

$$T^{(M1)} = 0.77\left[(d^+\tilde{d})_\pi^{(1)} - (d^+\tilde{d})_\nu^{(1)}\right](g_\pi - g_\nu) \qquad (11)$$

The direct measurement of B(M1) matrix elements is difficult normally, so the M1 strength of gamma transition may be expressed in terms of the multipole mixing ratio which can be written as [26]

$$\delta(E2/M1) = 0.835\,E_\gamma(MeV).\Delta \qquad (12)$$

where $\Delta = \dfrac{\langle I_f \,\|\, T^{E2} \,\|\, I_i \rangle}{\langle I_f \,\|\, T^{M1} \,\|\, I_i \rangle}$ $in\ \ eb/\mu N$

The $g_\pi$ and $g_\nu$ have to be estimated, using the experimental value of g=0.41(7) and the fact that g =Z/A=0.42, with Sambataro et.al. [27] relation

$$g = g_\pi \frac{N_\pi}{N_\pi + N_\nu} + g_\nu \frac{N_\nu}{N_\pi + N_\nu} \qquad (13)$$

Taking $N_\pi = 2$ and $N_\nu = 4$, we have got $g_\pi + 2g_\nu = 1.23$ and the estimated values are; $g_\pi = 0.681\ \mu_N$ and $g_\nu = 0.293\,\mu_N$. These values are the same as in reference[5]. These values were used to calculate the ratio $\Delta(E2 \setminus M1)$ and then the mixing ratio $\delta(E2 \setminus M1)$. The ratios were calculated for some selected transitions and listed with the available experimental data in Table 4. A very good agreement with the experimental data obtained, even those with a minuses sign, when we look to the experimental errors they will be in agreement with theory.

**Tabl1-4. The calculated mixing ratios for selected transitions according to available Experimental data [28,29].**

| $I_i \rightarrow I_f$ | $E_\gamma$ (MeV) | This work | Experimental |
|---|---|---|---|
| $2_\gamma \rightarrow 2_g$ | 0.527 | +3.21 | $5.7^{+24}_{-17}$ |
| $2_\beta \rightarrow 2_g$ | 1.999 | +4.42 | - |
| $2_\beta \rightarrow 2_\gamma$ | 1.029 | +0.676 | +3.4(2) |
| $2_{\beta\beta} \rightarrow 2_g$ | 1.829 | +1.179 | - |
| $2_{\beta\beta} \rightarrow 2_\gamma$ | 1.302 | +3.519 | - |
| $3_\gamma \rightarrow 4_g$ | 0.396 | +1.050 | +2.8(3) |
| $4_\beta \rightarrow 4_\gamma$ | 0.419 | +0.23 | $-1.1^{+3}_{-4}$ |
| $4_\beta \rightarrow 3_\gamma$ | 0.594 | +0.86 | $3.9^{+6}_{-4}$ |
| $4_\beta \rightarrow 4_g$ | 0.990 | +13.22 | $-1.1^{+1}_{-2}$ |
| $3_\gamma \rightarrow 2_g$ | 0.987 | +0.514 | +1.7(1) |
| $3_\gamma \rightarrow 2_\gamma$ | 0.460 | +2.13 | +7.8(8) |
| $4_\gamma \rightarrow 4_g$ | 0.570 | +1.4 | $+1.9^{+3}_{-5}$ |

All the experimental and theoretical mixing ratios for isotopes indicate a small M1 components which means that in the band-mixing transitions, M1 components is almost forbidden. In the calculation of $\delta(E2/M1)$ it is found that there is a great effect of the Majorana parameter $\xi_2$ on the value and sign of E2 and M1 matrix elements.

**4- A comparison between $^{128}Xe$ and the O(6) like $^{196}pt$**

At the early beginning of the IBM , it has been pointed out that the nucleus $^{196}pt$ is one of the best examples of O(6) nuclei [27], and a lot of discussions still wandering around it [ see 25]. Table-5 contains a summary of range of parameters for both $^{128}Xe$ and $^{196}pt$. As one can see, it is hard to choose between which nucleus corresponds closest to $\gamma$ - unstable (O(6)) description. Actually the i $^{128}Xe$ s closer rather than the Pt in many parameters.

**Table-5. A comparison between the traditional O(6) nucleus $^{196}$Pt and the new $^{128}$Xe**

| Parameter | O(6) | $^{196}pt$ Exp. | $^{196}pt$ IBM-2 | $^{128}Xe$ Exp. | $^{128}Xe$ IBM-2 |
|---|---|---|---|---|---|
| $E4_g^+ \ / E2_g^+$ | 2.5 | 2.47 | 2.46 | 2.33 | 2.51 |
| $E2_\gamma^+ \ / E4_g^+$ | 1.0 | 0.78 | 0.85 | 0.94 | 0.91 |
| $E0_\beta^+ / E2_g^+$ | 4.5 | 3.19 | 3.7 | 3.57 | 3.61 |
| $* E6_g^+ / E2_g^+$ | 4.5 | 4.3 | 4.26 | 3.92 | 4.54 |
| $\frac{B(E2;2^+_\gamma \to 0^+_g)}{B(E2;2^+_g \to 0^+_g)}$ | 0.0 | $10^{-6}$ | $2\times10^{-6}$ | 0.016 | 0.028 |
| $\frac{B(E2;0^+_\beta \to 2^+_g)}{B(E2;0^+_\beta \to 0^+_g)}$ | 0.0 | 6.25 | 18.6 | -- | 0.018 |
| $Q_{2g} / Q_o$ | 0.0 | -0.51 | -0.25 | -0.286 | -0.352 |

* from reference [21] and the rest from reference [22]

**5. The mixed symmetry state**

Neither of the completely symmetric model can reproduce, so called mixed symmetry state. This state creates by a mixture of two wave functions, one for proton and other for neutron. The mixed symmetry
state has two characteristics, strong M1 branch and a weak or unobservable decay to the ground state. The IBM-2 additional degree of freedom associated with the distinction between proton and neutron allow mixed symmetry states to occur naturally in the low lying states. The raising or lowering the energy of such states is made by altering the Majorana parameters, which leaves the energy of totally symmetric states unchanged. Figure 4 shows the influences of Majorana's parameter on the energy of $J = 2^+$ and $1_1^+$ states. The first six $J = 2^+$ states are close to experimental ones. The theoretical calculation of the

energy of these states is in very good agreement with experimental data. It is well known, that the Majorana parameters influence the energy of the mixed levels without much affecting the energy of the full symmetric states

In $^{128}$Xe, near 2 MeV excitation energy, there are two existences $J = 2^+$ states, namely $2_3^+$ and $2_4^+$. They are separated by only 128 KeV in energy. The investigation of these states is quite important in clarifying the nature of the lowest mixed symmetry state. The energy is well reproduced by the calculation, where the choice of the Majorana parameters plays a crucial role. It is found that the $J = 2_4^+$ level is very sensitive to the strength of Majorana term, confirm its identity with a mixed symmetry level in the nucleus under consideration. The calculated result predicts that the $F_{max} - 1$ character is the main component in the wave function of this state as shown in figure 5

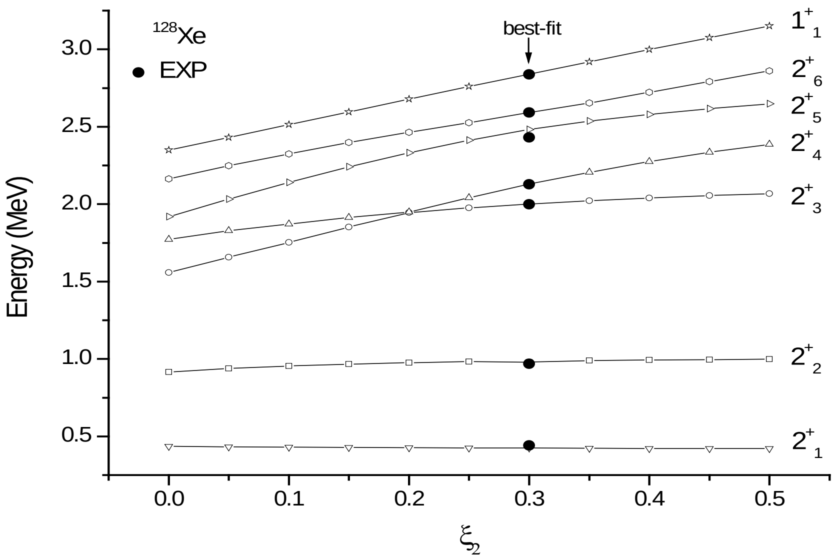


**Figure 4: The variation in energy levels $J = 2_i^+$ $i = 1,6$ and $1_1^+$ states of $^{128}$Xe as a function of $\xi_2$, all the other parameters were kept at their best-fit values.**

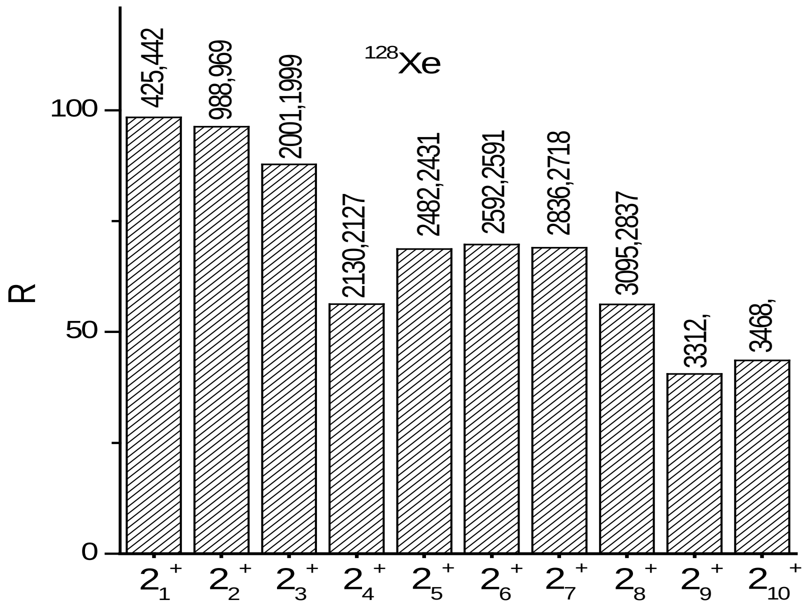


**Figure – 5 The R-values of the $2^+$ states in IBM-2. Upper numbers denote the calculated and experimental energies (KeV unit), lower numbers denote the order of the states.**

## 6- Conclusion

The structure of $^{128}$ Xe isotope has been investigated using IBM-2, a detailed description of energy levels and electromagnetic transition has been preformed. The obtained results show that this isotope is a good example of O(6) limit nuclei. The results indicate that the energy levels of all different quasiband can be reproduced quite well by the model. The theoretical calculations and experimental data indicate the existence of the mixed symmetry states in this nucleus in the 2 MeV. By inspecting the wave function and electromagnetic transitions, the $2_4^+$ is the first mixed symmetry $2^+$ state. It would be very useful to have monopole transition predication from this model.

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# التركيب الحزمي والانتقالات الكهرومغناطيسية لنواة التحديد O(6) $^{128}$Xe

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*البصرة – العراق*

**الخلاصة**

تم دراسة مستويات الطاقة لنواة $^{128}$Xe باستخدام أنموذج البوزنات المتفاعلة الثاني . حسبت احتمالية الانتقالات رباعية القطب الكهربائي ونسب التفرع . تم كذالك حساب نسب الخلط للمستويات $I \neq 0$ ,$\Delta I = 0$ or $1$ . تم تحديد مستويات الطاقة ذات التماثل المختلط . قورنت النتائج المستخلصة مع القيم العملية وأظهرت تطابقا" جيدا" . أدرجت جميع القيم المحسوبة لاستفادة منها في تحديد القيم العملية مستقبلا.