EVOLUTION OF YRAST STATES AND $B(E2:\,8_1^+ \rightarrow 6_1^+)$ VALUES OF $^{114,116,118,120,122}Cd$ BY INTERACTING BOSON MODEL (IBM-1)

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In this paper we address the evolution of yrast levels of low-lying structure in the neutron-rich even-even $^{114-122}Cd$ nuclei within the framework of interaction boson model (IBM-1). The reduced transition probabilities $B(E2)\downarrow$ between 8_1^+ to 6_1^+ states of even-even neutron rich Cd nuclei for $N = 66, 68, 70, 72, 74$ have been calculated by IBM-1 and compared with the previous available experimental values. The calculated values of ^{114}Cd, ^{116}Cd, ^{118}Cd, ^{120}Cd, and ^{122}Cd, are $0.272\,e^2b^2$, $0.281\,e^2b^2$, $0.259\,e^2b^2$, $0.190\,e^2b^2$ and $0.149\,e^2b^2$ respectively. The ratio of the excitation energies of the first 4^+ and the first 2^+ excited states, $R_{4/2}$, were also calculated for those nuclei. The $^{114-122}Cd$ isotopes in $U(5)-O(6)$ transitional symmetry were investigated. We have studied the systematic $B(E2)$ values as a function of even neutrons from $N = 66$ to 74. Furthermore as a measure to quantify the evolution, we have studied systematically the ground state energy ratios $R_L = E(L^+)/E(2_1^+)$ and transition rate $R = B(E2:\,L^+ \rightarrow (L-2)^+)/B(E2:\,2^+ \rightarrow 0^+)$ of some of the low-lying quadrupole collective states in comparison to the available experimental data.

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1. INTRODUCTION

The interacting boson model (IBM-1) is an excellent interpretive model to understand the nuclear structure [1,2]. The cadmium nuclei, with two protons removed from a strong shell closure, exhibit intriguing aspects of nuclear structure at low excitation energies, namely the coexistence and mixing of vibrational with other collective degrees of freedom arising from the promotion of a proton pair across shell gap [3,4]. The structure of neutron-rich Cd isotopes has been studied the subject of many theoretical and experimental works in recent years. The yrast states up to $I^\pi = 8^+$ in $N = 48$ isotones were found two-hole states $\nu g_{9/2}^{-2}$ configurations for the $N = 50$ closed shell. The existences of structure of $\nu g_{9/2}^{-2}$ configurations indicate to find structure of the valance mirror nuclei $\pi g_{9/2}^{-2}$ configurations [5-8]. Therefore, it is interesting to study $\pi g_{9/2}^{-2}$ configurations, which suggest that $(\pi g_{9/2}^{-2})_I^\pi = 0^+, 2^+, 4^+, 6^+, 8^+$ configurations dominate the yrast states and their 8_1^+ states are very likely to become isomers.

Moreover $B(E2)$ of the yrast band between 8_1^+ to 6_1^+ plays important role in nuclear structure.

There are a number of theoretical works discussing intruder configuration and configuration mixing in the Cd isotopes. For instance, empirical spectroscopic study within the configuration mixing calculation in IBM [9-11], the IBM configuration mixing model in strong connection with shell model [12,13], conventional collective Hamiltonian approach [14,15] and the one starting from self-consistent mean-field calculation with microscopic energy density function[16]. Long et al. explained the low-lying levels and high-spin states of $^{116,118,120}Cd$ in the frame work of interacting boson model [17]. We have calculated the ground state energy band up to 8_1^+ levels [18] and reduced transition probabilities $B(E2)$ values from 6_1^+ to 4_1^+ and 4_1^+ to 2_1^+ levels in even-even $^{114-122}Cd$ isotopes by the framework of IBM-1[19]. In this work, we suggest an approach to search for the dynamical symmetries $U(5)$, $SU(3)$ and $O(6)$ and to calculate $B(E2)$ values between 8_1^+ to 6_1^+ states in even $^{114-122}Cd$ isotopes using IBM-1 model [2].

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2. THEORY AND METHOD OF CALCULATION

2.1. Yrast state energy band

The Hamiltonian of the interacting bosons in IBM-1 is given by [2,18].

$$H = \sum_{j=1}^{N} \varepsilon_j + \sum_{i<j}^{N} V_{i,j} \,, \tag{1}$$

where ε is the intrinsic boson energy and $V_{i,j}$ is the interaction between bosons i and j. In the multi pole form the Hamiltonian is given by [2,18,19].

$$H = \varepsilon n_d + a_0 PP + a_1 LL + a_2 QQ + a_3 T_3 T_3 + a_4 T_4 T_4 \,. \tag{2}$$

Here a_0, a_1, a_2, a_3 and a_4, are the strength of pairing, the angular momentum and multi pole terms. The Hamiltonian as given in Eq.(2) tends to reduce to three limits, the vibration $U(5)$, γ-soft $O(6)$ and the rotational $SU(3)$ nuclei, starting with the unitary group $U(6)$ and finishing with group $O(2)$. In $U(5)$ limit, the effective parameter is ε, in the γ-soft limit, $O(6)$, the effective parameter is the pairing a_0, and in the $SU(3)$ limit, the effective parameter is the quadrupole a_2. The eigenvalues for the three limits are given by [18].

$$U(5): \; E(n_d, \nu, L) = \varepsilon n_d + K_1 n_d (n_d + 4) + K_4 \nu(\nu + 3) + K_5 L(L + 1) \,. \tag{3}$$

$$O(6): \; E(\sigma, \tau, L) = K_3[N(N + 4) - \sigma(\sigma + 4)] + K_4 \tau(\tau + 3) + K_5 L(L + 1) \,. \tag{4}$$

$$SU(3): \; E(\lambda, \mu, L) = K_2[\lambda^2 + \mu^2 + 3(\lambda + \mu) + \lambda\mu] + K_5 L(L + 1) \,. \tag{5}$$

Here, K_1, K_2, K_3, K_4 and K_5 are other forms of strength parameters. Many nuclei have a transition property between two or three of the above limits and their eigenvalues for the yrast-line are given by [19].

$$U(5) - O(6): \; E(n_d, \tau, L) = \varepsilon n_d + K_1 n_d (n_d + 4) + K_4 \tau(\tau + 3) + K_5 L(L + 1) \,. \tag{6}$$

$$U(5) - SU(3): \; E(\varepsilon, \lambda, L) = \varepsilon n_d + K_2[\lambda^2 + 3(\lambda + \mu)] + K_5 L(L + 1) \,. \tag{7}$$

$$O(6) - SU(3): \; E(\tau, \lambda, L) = K_2[\lambda^2 + +3(\lambda + \mu)] + K_4 \tau(\tau + 3) + K_5 L(L + 1) \,. \tag{8}$$

2.2. Reduced transition probabilities $B(E2)$

The reduced transition probability in interaction boson model IBM-1 [20] is given by equation (9).

$$B(E2;\, J + 2 \to J) \downarrow = \alpha_2^2 \frac{1}{4} (J + 2)(2N - J) \,. \tag{9}$$

Where J is the state that the nucleus translates to it and N is the boson number, which is equal to half of the number of valence nucleons (proton and neutrons). The low-lying levels of even-even nuclei ($J_i = 2, 4, 6, 8, ...$) usually decay by $E2$ transition to the lower-lying yrast level with $J_f = J_i - 2$. From the given experimental value of transition ($2 \to 0$), one can calculate the value the parameter α_2^2 for each isotopes and use this value to calculate the transition ($8^+ \to 6^+$).

3. RESULTS AND DISCUSSIONS

The transition from the first excited state to the ground state is assumed to be a pure $E2$, ($2^+ \to 0^+$) transition. The best parameters for ground-state band in even-even isotopes $^{114-122}Cd$ are presented in Table 1. A summary of boson number, 8^+ energy level, gamma-ray transitions 8^+ to 6^+, experimental $B(E2) \downarrow$ between 2^+ to ground-state and reduced transition probabilities between 8^+ to 6^+ level of even even nuclei from ^{112}Cd to ^{122}Cd, are presented in Table 2. The calculated results using frame work of IBM-1 are compared with the previous available experimental results.

Table 1. *Parameters in (keV) for even-even $^{114-122}Cd$ isotopes [18]*

A	ε	K_1	K_4	K_5
114	768.71	-33.62	-16.40	15.69
116	483.66	26.22	-34.54	14.14
118	484.78	26.29	-30.35	9.17
120	292.83	66.94	-29.95	5.72
122	521.45	55.09	-40.52	1.52

3.1. Boson numbers (N)

A boson represents the pair of valence nucleons and the boson number is counted as the number of collective pairs of the valence nucleons. A simple correlation exists between the nuclei showing identical spectra and their valence neutron proton (N_p), neutron number (N_n). The number of valance proton N_p and neutron (N_n) has a total $N = (N_p + N_n)/2 = n_\pi + n_\nu$ bosons At present ^{132}Sn doubly-magic nucleus is taken as an inert core to find boson number of ^{114}Cd to ^{122}Cd nuclei and they are presented in Table 2.

Table 2. *Reduced transition probability* $B(E2)\downarrow$ *from level* $8_1^+ \to 6_1^+$

Nucl.	Boson num. $N = n_\pi + n_\nu$	8^+ level* in keV	γ Energy $(8^+ \to 6^+)$ keV	$^\star B(E2)$ $(2^+ \to 0^+)$ $W.U.$	$B(E2)$ $(2^+ \to 0^+)$ e^2b^2	$B(E2)_{IBM-1}$ $(8^+ \to 6^+)$ e^2b^2	$^\star B(E2)$ $(8^+ \to 6^+)$ e^2b^2
^{114}Cd	9=1+8	2669	678	31(19)	0.102	0.272	0.279(71)
^{116}Cd	8=1+7	2824	798	33.5(12)	0.113	0.281	
^{118}Cd	7=1+6	2591	771	33(3)	0.113	0.259	
^{120}Cd	6=1+5	2886	853	27	0.095	0.190	
^{122}Cd	5=1+4	3062	849	26(14)	0.093	0.149	

*Ref. [6,21-28]

3.2. The $R_{4/2}$ classification

In the collective dynamics of energies of even-even nuclei are grouped into classes, within each class the ratio: $R_{4/2} = E(4_1^+)/E(2_1^+)$ of excitation energies of the first 4^+ and the first 2^+ excited states. As pointed out by other similar ratios were characteristics of different collective motions of the nucleus. An harmonic vibrator has $E(4_1^+)/E(2_1^+) = 2.00$, an axially symmetric rotor should have $E(4_1^+)/E(2_1^+) = 3.33$, while $X(5)$ behavior should have $E(4_1^+)/E(2_1^+) = 2.91$. The variation of the $E(4_1^+)/E(2_1^+)$ values as a function of even neutron numbers of Cadmium isotopes for experimental values, IBM-1, $U(5)$, $O(6)$ and $SU(3)$ limits are presented in Fig.1. We identified $U(5) - O(6)$ transitional symmetry in even-even nuclei with $Z = 48$ and $N = 66, 68, 70, 72, 74$ with a range $2.04 < R_{4/2} < 2.20$. But they are near to $U(5)$ symmetry.

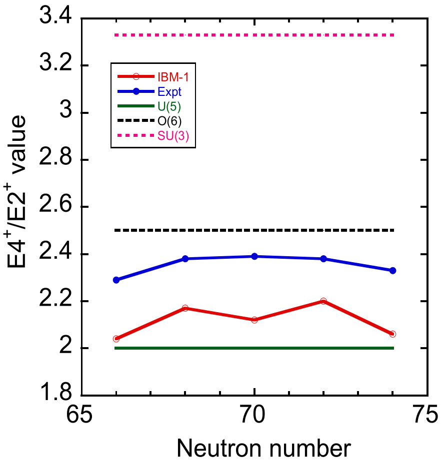

Fig.1. $E(4_1^+)/E(2_1^+)$ *values as a function of neutron numbers of Cadmium isotopes* $^{114-122}Cd$ *for experimental values, IBM-1,* $U(5)$, $O(6)$ *and* $SU(3)$ *limit*

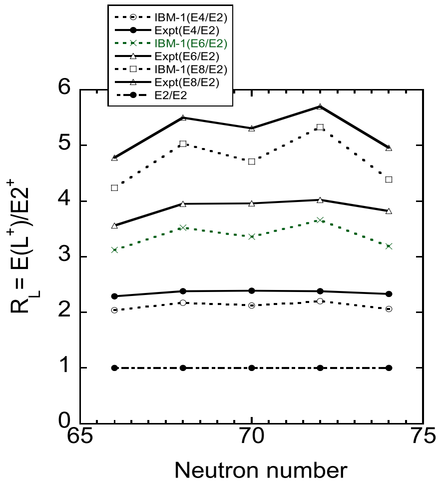

Fig.2. *The yrast sequences of ground state band of* $R_L = E(L^+)/E(2_1^+)$ *as a function of neutron numbers (normalized to the energy of their respective* 2_1^+ *levels) in* $^{114-122}Cd$ *nuclei*

In Fig.2, we present the energies of the yrast sequences of ground state band using IBM-1 (normalized to the energy of their respective 2 levels) in these nuclei and compared them with previous experimental values [6, 21-28]. We present the comparisons of the ratios $R_L = E(L^+)/E(2_1^+)$ in the ground-state band (a usually adopted measure of nuclear collectivity), using the neutron numbers $N = 66, 68, 70, 72, 74$. From Figs.1 and 2, we can see that IBM-1 calculation fit the $U(5) - O(6)$ predictions generally. However, we find that the R_L values are consistently smaller in the IBM calculations than in experimental values.

3.3. Reduced transition probabilities $B(E2)$

The values of the reduced transition probabilities have been fitted the calculated absolute strengths $B(E2)$ of the transitions within the ground state band to the experimental ones. The value of the effective charge α_2 of the IBM-1 was determined by normalizing to the experimental data $B(E2; 2_1^+ \to 0_1^+)$ of each isotope by using Eq.(1). From the given experimental value of the transitions $(2 \to 0)$, we calculated value of the parameter α_2^2 for each isotope and used this value to calculate the transition $(8^+ \to 6^+)$. The $B(E2)$ values are presented in Table 2, where the experimental data is compared with the present calculations and other previous work [6, 21-28]. The theoretical and experimental values of B(E2) values are plotted as a function of even neutrons represented in Fig.3.

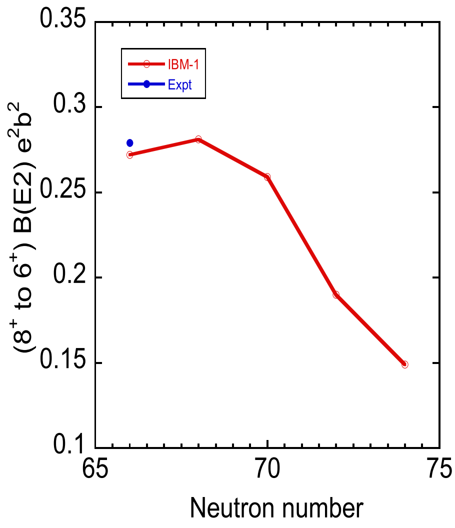

Fig.3. *Reduced transition probabilities $B(E2 : 8^+ \to 6^+)$ as a function of even neutron numbers of $^{114-122}Cd$ isotopes*

The calculated reduced transition probabilities using IBM-1 as a function of neutrons number slowly increase from $0.272\,e^2b^2$ to $0.282\,e^2b^2$ in the neutron number from 66 to 68, and then decrease to $0.149\,e^2b^2$ for up to neutron number 74. In Fig.3, results of the present work are compared with the available previous experimental values and shows good agreement for $N = 66$. Moreover, the general agreement between the calculation and their previous experimental values for $B(E2; 8^+ \to 6^+)$ transition in Cd isotopes show a little different for $N = 66$. Using IBM-1 in Fig.3, $B(E2)$ values for the transition 8^+ to 6^+ decrease smoothly after the neutron number $N = 68$. The $B(E2)$ values of the $Z = 48$ isotopes with $N < 68$ differ significantly from those with $N > 68$. This difference probably originates from the orbital occupied by valance neutron; in the ground state with $Z = 48$, the valence protons occupy hole-like states in the $Z = 50$ closed shell, with a main configuration $\pi g_{9/2}^{-2}$. The valence neutrons occupy mainly particle-like states in the $50 - 82$ shells. Due to the proton-neutron interaction, the nucleus is deformed. In $^{114}Cd_{66}$ and $^{116}Cd_{68}$ isotopes the valance neutrons occupy in the $2d_{3/2}$ orbitals while for $^{118,120,122}Cd$ isotopes, the valance neutrons occupy in the $3S_{1/2}1h_{11/2}$ orbitals. The nuclei ^{114}Cd by IBM-1 model nicely reproduced the experiment data and were fit satisfactory.

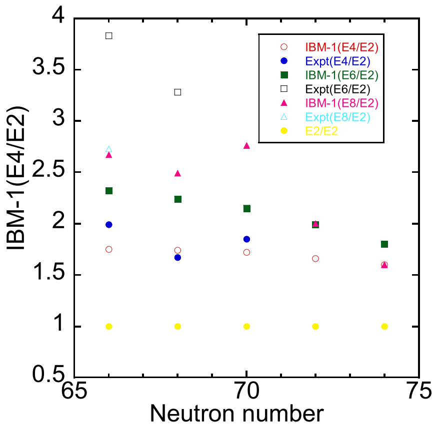

Fig.4. *Comparison of the $B(E2)$ values in IBM-1 and experimental value. The ratio $R = B(E2 : L^+ \to (L-2)^+)/B(E2 : 2^+ \to 0^+)$ in the ground state bands (normalized to the $B(E2 : 2^+ \to 0^+)$) in these nuclei*

In Fig.4, we compare the ratio $R = B(E2 : L^+ \to (L-2)^+)/B(E2 : 2^+ \to 0^+)$ of IBM-1 and the previous experimental values in the ground state bands (normalized to the $B(E2 : 2^+ \to 0^+)$) as a function of even neutron number in these nuclei. We found that the R values were consistently smaller in the IBM calculations than in the experimental values. However, we could see that the best agreement is closed to the calculations with neutron number $N = 66$. Actually, in IBM-1 the proton and neutron bosons are not distinguishable as long as valence protons and neutrons are both hole-like or both particle-like [2]. The large $B(E2)$ values in ^{114}Cd and ^{116}Cd nuclei are the main indicator of vibration characters.

4. CONCLUSIONS

The evolution of nuclear low-lying yrast states in the even neutron-rich $^{114-122}Cd$ isotopes were investigated within the interaction boson model (IBM-1). As a measure to quantify the evolution, we calculated the energy ratios of yrast states and the $B(E2)$ transition rates of some of the low-lying quadrupole collective states in comparison to the available experimental data. It is seen that ground state band up to 8^+ levels and electric quadrupole reduced transition probability of those nuclei are in good agreement with the previous experimental results. The even-even $^{114-122}Cd$ isotopes in $U(5) - O(6)$ transitional symmetry were also investigated.

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ЭВОЛЮЦИЯ YRAST-СОСТОЯНИЙ И ВЕЛИЧИНЫ ПЕРЕХОДОВ $B(E2:8_1^+\to 6_1^+)$ $^{114,\,116,\,118,\,120,\,122}Cd$ В МОДЕЛИ ВЗАИМОДЕЙСТВУЮЩИХ БОЗОНОВ (IBM-1)

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Представлена эволюция yrast-уровней низколежащей структуры в богатом нейтронами четно-четном ядре $^{114-122}Cd$ в рамках модели взаимодействующих бозонов (IBM-1). Вероятности измененных (reduced) переходов $B(E2)\downarrow$ между состяниями 8_1^+ и 6_1^+ в богатом нейтронами четно-четном ядре Cd для $N = 66$, 68, 70, 72, 74 были расчитаны с помощью IBM-1 и сравнены с ранее известными экспериментальными величинами. Рассчитанные величины ^{114}Cd, ^{116}Cd, ^{118}Cd, ^{120}Cd и ^{122}Cd равны $0.272\,e^2b^2$, $0.281\,e^2b^2$, $0.259\,e^2b^2$, $0.190\,e^2b^2$ и $0.149\,e^2b^2$, соответственно. Отношение энергий возбуждения первого 4^+ и первого 2^+ возбужденных состояний $R_{4/2}$ были рассчитаны для этих ядер. $^{114-122}Cd$ изотопы в $U(5)-O(6)$ симметрии переходов были исследованы. Мы исследовали систематику $B(E2)$ величин, как функцию четных нейтронов от $N = 66$ до 74. Кроме того, изучая количественно эволюцию, мы систематически изучили отношения энергий основных состояний $R_L = E(L^+)/E(2_1^+)$ и величину $R = B(E2:\,L^+\to(L-2)^+)/B(E2:\,2^+\to 0^+)$ для переходов нескольких низколежащих квадрупольных коллективных состояний и сравнили с доступными экспериментальными данными.

ЕВОЛЮЦІЯ YRAST-СТАНІВ ТА ВЕЛИЧИНИ ПЕРЕХОДІВ $B(E2: 8_1^+ \to 6_1^+)$ $^{114,\,116,\,118,\,120,\,122}Cd$ У МОДЕЛІ ВЗАЄМОДІЮЧИХ БОЗОНІВ (IBM-1)

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Представлена еволюція yrast-рівнів низьколежачої структури в багатому нейтронами парно-парному ядрі $^{114-122}Cd$ у рамках моделі взаємодіючих бозонів (IBM-1). Вірогідності змінених (reduced) переходів $B(E2)\downarrow$ між станами 8_1^+ і 6_1^+ у багатому нейтронами парно-парному ядрі Cd для $N =$ 66, 68, 70, 72,

74 були розраховані за допомогою IBM-1 і порівняні з раніше відомими експериментальними величинами. Розраховані величини ^{114}Cd, ^{116}Cd, ^{118}Cd, ^{120}Cd і ^{122}Cd дорівнюють $0.272\,e^2b^2$, $0.281\,e^2b^2$, $0.259\,e^2b^2$, $0.190\,e^2b^2$ та $0.149\,e^2b^2$, відповідно. Співвідношення енергій збудження першого 4^+ та першого 2^+ збуджених станів $R_{4/2}$ були розраховані для цих ядер. $^{114-122}Cd$ ізотопи в $U(5)-O(6)$ симетрії переходів були досліджені. Ми дослідили систематику $B(E2)$ величин, як функцію парних нейтронів від $N = 66$ до 74. Крім того, вивчаючи кількісно еволюцію, ми систематично вивчили співвідношення енергій основних станів $R_L = E(L^+)/E(2_1^+)$ та величину $R = B(E2:\, L^+ \to (L-2)^+)/B(E2:\, 2^+ \to 0^+)$ для переходів кількох низькорозміщених квадрупольних колективних станів та порівняли з наявними експериментальними даними.