Hossain et al. Journal of Theoretical and Applied Physics 2013, 7:46
http://www.jtaphys.com/content/7/1/46

Journal of Theoretical and Applied Physics
a SpringerOpen Journal

REVIEW Open Access

Ground-state energy band of even $^{104\text{-}122}$Cd isotopes under the framework of interacting boson model-1: a review

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Abstract

In this paper, the nuclear structure of ground-state bands of even-even $^{104\text{-}122}$Cd isotopes has been reviewed under the framework of interacting boson model-1 (IBM-1). The theoretical energy levels for $Z = 48$, even $N = 56$–74 up to 8^+ state have been obtained by using the PHINT computer program. The values of the parameters in the IBM-1 Hamiltonian yield the best fit to the experimental energy spectrum. The results are compared with the most recent experimental values where an acceptable degree of agreement is achieved. In this paper, the properties of even $^{104\text{-}122}$Cd isotopes have been considered to the U(5) ~ SO(6) transitional region of the IBM-1.

Keywords: Nuclear structure; $Z = 48$; $N = 56$–74; U(5); SO(6); Energy level

Review

Introduction

Atomic nuclei are known to exhibit changes of their energy levels and electromagnetic transition rates among them when the numbers of protons (or neutrons) are modified, resulting in the shape transition from one kind of collective behavior to another [1-3]. The even-mass cadmium isotopes have been extensively investigated both theoretically and experimentally in recent years with special emphasis on interpreting experimental data via collective models [4]. The collective character in medium-mass nuclei has been successfully described by Arima and Lachello using the interacting boson model-1 (IBM-1) [5]. There is no distinction of IBM-1 for proton and neutron degree of freedom. Recently, many researches on the structure of electromagnetic transition properties and energy levels of doubly even Cd isotopes have been investigated [6-10]. Cadmium isotopes are good examples of quadrupole vibration nuclei [7,11-13]. However, during the last few years, new experimental data and calculations have led to a modified picture on these nuclei. These descriptions with particular emphasis on describing the experimental data via collective models suggest these nuclei to be soft with regard to the γ deformation with an almost maximum effectivity trivially of $\gamma = 30°$ [14]. The even-even cadmium isotopes are part of an interesting region near the closed proton shell at $Z = 50$, while the number of neutrons in the open shell is larger, as such these nuclei have been commonly considered to exhibit vibration-like properties [4].

Longi et al. described the low-lying levels and high-spin states in ^{116,118,120}Cd the framework of interacting boson model [14]. Morrison and Smith described four separate constant boson interactions to explain the structure of $^{108\text{-}116}$Cd for states with L up to six [15,16]. Using in-beam and off-beam γ-ray and conversion electron spectroscopy, the low-lying (low-spin) collective states in even-even $^{106\text{-}112}$Cd and ^{116}Cd were investigated [17]. Octupole excitations in vibration nuclei with mass between 98 and 150 were studied by Pignanelli et al. and Kathryn et al. [18,19] using the interacting boson model. Recently, we have investigated the energy level of even-even $^{104\text{-}122}$Cd isotopes under the framework of IBM-1 [20,21]. Electromagnetic reduced transition properties of the ground-state band of even $^{102\text{-}106}$Pd and $^{104\text{-}112}$Cd isotopes were studied by means of IBM-1 [22,23]. At present, the review on interacting boson model is used to predict the ground-state energy bands up to 8^+ in doubly even isotopes $^{104\text{-}122}$Cd and to compare them with experimental

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results. Furthermore, even $^{104\text{-}122}$Cd isotopes in U(5)-O(6) transitional symmetry would be investigated and studied systematically, as well as the $R_L = E(L^+)/E(2_1^+)$ ratios of those nuclei in the ground-state band.

Energy levels

The IBM-1 provides theoretical level energies while including anharmonicities from residual interactions. The vibrational model uses a geometric approach, the IBM employs a severely truncated model space, and as such, calculations are possible for nuclei with N nucleons, providing a quantitative mechanism to compare experimental results and calculated values [21]. In the first approximation of IBM-1, only pairs with angular momentum $L = 0$ (called S bosons) and $L = 2$ (called d bosons) are considered [24]. The energy levels are calculated using the computer program PHINT [25].

The Hamiltonian of the IBM-1 [26] is given as

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

where ε is the intrinsic boson energy and V_{ij} is the interaction between bosons i and j. The multipole form of the Hamiltonian [6] is given as

$$H = \varepsilon \hat{n}_d + a_0(\hat{P}.\hat{P}) + a_1(\hat{L}.\hat{L}) + a_2(\hat{Q}.\hat{Q}) + a_3(\hat{T}_3.\hat{T}_3) + a_4\hat{T}_4.\hat{T}_4. \tag{2}$$

The $\hat{n}_d$ operator gives the number of d boson, p is the pairing operator for the S and d bosons, J is the angular momentum operator, Q is the quadrupole operator, and T_3 and T_4 are the octupole and hexadecapole operators, respectively. And the interaction parameters in the PHINT program are given below:

Table 1 Boson number and calculated parameters (in keV) for $^{104\text{-}122}$Cd even-even isotopes [20,21]

A	*N*	ε	κ_1	κ_4	κ_5
104	4	495.34	50.78	−19.57	−2.16
106	5	707.99	31.61	−35.76	2.81
108	6	772.58	14.63	−39.52	9.15
110	7	878.79	−23.72	−22.63	14.79
112	8	891.99	−46.67	−14.61	16.89
114	9	768.71	−33.62	−16.40	15.69
116	8	483.66	26.22	−34.54	14.14
118	7	484.78	26.29	−30.35	9.17
120	6	292.83	66.94	−29.95	5.72
122	5	521.45	55.09	−40.52	1.52

Table 2 Experimental and IBM-1 calculation of ground-state energy band (in keV) for $^{104\text{-}122}$Cd [29-39]

Nucleus	J^{π}_{gsb}	E^{ex}_{gsb} [14]	E^{th}_{gsb}	Δ%
^{104}Cd	0^+	0	0	0
	2^+	658 (20)	658.0	0
	4^+	1,492.1 (4)	1,361.2	8.7
	6^+	2,370.2 (4)	2,109.5	10.9
	8^+	2,903.1 (4)	2,903.0	0.003
^{106}Cd	0^+	0	0	0
	2^+	632.64 (4)	561.5	9.37
	4^+	1,493.78 (5)	1,493.8	0.003
	6^+	2,491.66 (6)	2,261.9	9.2
	8^+	3,044.13 (7)	3,044.13	0
^{108}Cd	0^+	0	0	0
	2^+	632.98 (16)	742.5	17.3
	4^+	1,508.46 (23)	1,508.5	0.002
	6^+	2,994.1 (2)	2,397.8	19.9
	8^+	3,110.49 (10)	3,110.6	0.003
^{110}Cd	0^+	0	0	0
	2^+	776.55 (14)	758.4	2.3
	4^+	1,637.9 (3)	1,542.4	0.05
	6^+	2,230.8 (3)	2,352.1	−5.4
	8^+	2,718.6 (3)	3,187.3	−17.2
^{112}Cd	0^+	0	0	0
	2^+	617.52 (10)	701.5	−13.5
	4^+	1,415.58 (12)	1,415.6	−0.001
	6^+	2,168.03 (15)	2,142.2	1.19
	8^+	2,881.26 (16)	2,881.3	0.001
^{114}Cd	0^+	0	0	0
	2^+	558.5 (2)	629.1	12.64
	4^+	1,283.9 (3)	1,283.7	0.015
	6^+	1,990.6 (4)	1,963.8	1.35
	8^+	2,668.8 (4)	2,669.3	0.019
^{116}Cd	0^+	0	0	0
	2^+	513.4 (2)	561.5	9.37
	4^+	1,219.4 (3)	1,219.5	0.81
	6^+	2,026.6 (4)	1,973.9	2.60
	8^+	2824.8 (4)	2,824.9	0.004
^{118}Cd	0^+	0	0	0
	2^+	487.77 (8)	549.8	12.72
	4^+	1,164.94 (9)	1,164.9	0.003
	6^+	1,935.94 (13)	1,845.3	4.68
	8^+	2,590.9 (10)	2,590.9	0

Table 2 Experimental and IBM-1 calculation of ground-state energy band (in keV) for $^{104\text{-}122}$Cd [29-39] *(Continued)*

^{120}Cd	0^+	0	0	0
	2^+	505.94 (17)	542.0	7.13
	4^+	1,203.7 (3)	1,203.7	0
	6^+	2,033.7 (4)	1,985.1	2.39
	8^+	2,886.2 (10)	2,886.2	0
^{122}Cd	0^+	0	0	0
	2^+	569.45 (8)	643.9	13.07
	4^+	1,329.15 (12)	1,329.2	0.04
	6^+	2,178.02 (25)	2,055.6	5.62
	8^+	2,823.4 (4)	2,823.4	0

ε = EPS, a_0 = 2PAIR, a_1 = ELL/2, a_2 = $QQ/2$, a_3 = 5OCT, and a_4 = 5HEX.

The Hamiltonian as given in Equation 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) [27]. In the 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 as follows [28]:

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

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

$$SU(3): \quad E(\lambda, \mu, L) = K_2\left(\lambda^2 + \mu^2 + 3(\lambda+\mu) + \lambda\mu\right) + K_5 L(L+1) \tag{5}$$

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 [28] by the following:

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

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

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

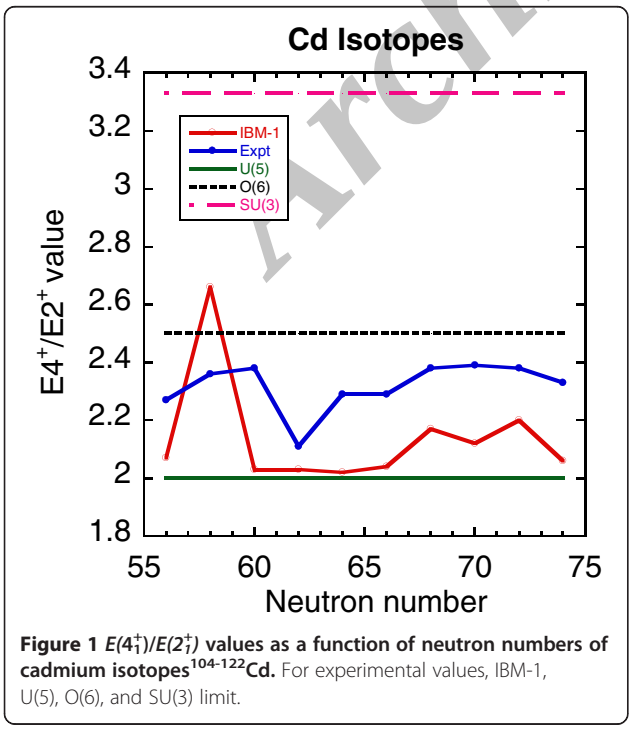

Figure 1 $E(4_1^+)/E(2_1^+)$ values as a function of neutron numbers of cadmium isotopes$^{104\text{-}122}$Cd. For experimental values, IBM-1, U(5), O(6), and SU(3) limit.

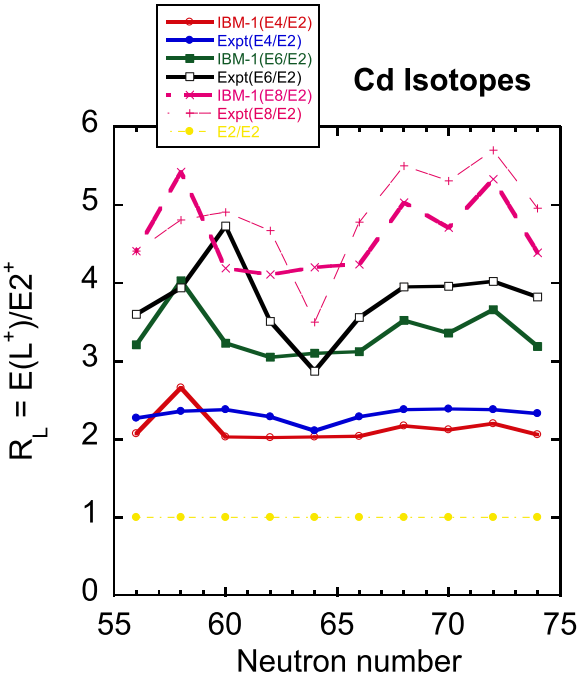

Figure 2 The yrast sequences of ground-state band of $R_L = E(L^+)/E(2_1^+)$. As a function of neutron numbers (normalized to the energy of their respective 2_1^+ levels) in $^{104\text{-}122}$Cd isotopes.

Results and discussion

Boson numbers

A simple correlation exists between the nuclei showing identical spectra and their valence neutron proton (N_p) and neutron number (N_n). The identification of such a correlation scheme provided the clue to understand the identical band phenomena. It is natural to assume that the nuclei with equal total boson number $N_b = N_p + N_n$ should have the same deformation and identical spectra. 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. The boson number and calculated parameters (in keV) for $^{104\text{-}122}$Cd even-even isotopes are presented in Table 1. Experimental and IBM-1 calculations of ground-state energy band (in keV) for $^{104\text{-}122}$Cd are presented in Table 2.

The $R_{4/2}$ classification

Collective dynamics of energies in even-even nuclei are grouped into classes; within each class, the ratio of excitation energies of the first 4^+ and the first 2^+ excited states is $R_{4/2} = \frac{E(4_1^+)}{E(2_1^+)}$. A 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 $E(4_1^+)/E(2_1^+)$ values as a function of even neutron numbers of cadmium isotopes for experimental values, IBM-I, U(5), O(6), and SU(3) limits are presented in Figure 1. We identify U(5)-O(6) transitional symmetry in even-even nuclei with atomic number $Z = 48$ and even neutron number $N = 56$–74, and most of them are near the U(5) symmetry.

In Figure 2, we present energies of the yrast sequences of ground-state band using IBM-1 (normalized to the energy of their respective 2_1^+ levels) in these nuclei and have compared them with previous experimental values [29-39]. We have compared ratios $R_L = E(L^+)/E(2_1^+)$ in the ground-state band (a usually adopted measure of nuclear collectivity) as a function of even neutron number $N = 56$–74. From Figures 1 and 2, we can see that the IBM-1 calculation fits the U(5)-O(6) predictions generally. However, we find that the R_L values are consistently smaller in the IBM calculations than in the experimental values.

In order to achieve the low-lying energy levels of Cd isotopes in the mass region $A = 104$–122 by IBM-1, it is important to specify the shape symmetry of a nucleus, which can be predicted from the energy ratio $R = E4_1^+/E2_1^+$, where $E4_1^+$ is the energy level at 4_1^+ and $E2_1^+$ is the energy level at 2_1^+. R has a limit value of 2 for the vibration nuclei U(5), 2.5 for the γ-unstable nuclei O(6), and finally 3.33 for rotational nuclei SU(3).

IBM-1 calculated the energy of different states (i.e., 0^+, 2^+, 4^+, 6^+, 8^+) for doubly even $^{104\text{-}122}$Cd isotopes. Considering one parameter to vary and keeping constant the others until an overall best fit was archived for the ground-state bands of doubly even $^{104\text{-}122}$Cd isotopes. A suitable free parameter was determined to find the close excitation energy of all positive parity levels (2^+, 4^+, 6^+, 8^+) for which a good indication of the spin value exists [20,21]. Each nucleus at the evolving states is determined using Equation3. Table 1 shows the values of these parameters that were used to calculate the energy of the yrast states for the isotopes $Z = 48$ and $N = 66$–76 under this study. The energy level fits with IBM-1 are presented in Table 2. During the calculation, PHINT code [25] was used and we made a comparison with experimental levels [29-39]. The agreement between the calculated theory and experiment is excellent and reproduced well. The values of the first excited state $E2_1^+$ and the ratio $R = E4_1^+/E2_1^+$ show that $^{104\text{-}122}$Cd isotopes are vibration nuclei.

Conclusions

We have reviewed the ground-state energy band for even-even $^{104\text{-}122}$Cd isotopes within the framework of interacting boson model approximations. The energy levels 0^+, 2^+, 4^+, 6^+, and 8^+ of even $^{104\text{-}124}$Cd nuclei were obtained by the best fitted values of the parameters in the Hamiltonian of the IBM-1. The validity of the presented parameters in IBM-1 formulations has been investigated, and it is seen that there is an existence of a satisfactory agreement between IBM-1 results and previous experimental data [29-39]. We have concluded that the general characteristics of the Cd isotopes are well accounted in this review, and the idea of shape coexistence in this region is supported. It is established that the framework of interacting boson approximations showed that the Cd isotopes under study are considered as vibration nuclei and close to the U(5) ~ SO(6) transitional region of IBM-1.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

IH carried out the confirmation of the calculation and writing of the paper. HYA collected all papers included in the sequence alignment and drafted the manuscript. IMA participated in the sequence alignment. MAS participated in the IBM-1 calculation. All authors read and approved the final manuscript.

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Acknowledgements

The authors thank King Abdulaziz University for providing the fund to complete the projects.

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Received: 16 May 2013 Accepted: 2 September 2013
Published: 11 September 2013

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doi:10.1186/2251-7235-7-46
Cite this article as: Hossain *et al.*: Ground-state energy band of even $^{104\text{-}122}$Cd isotopes under the framework of interacting boson model-1: a review. *Journal of Theoretical and Applied Physics* 2013 **7**:46.