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CONFIGURATION MIXING FOR Po ISOTOPES WITHIN THE INTERACTING BOSON MODEL-2

We analyze a sequence of $^{194-204}$*Po isotopes, using the Configuration Mixing (CM) Interacting Boson Model 2 (IBM-2). We set the parameters of Hamiltonian using a least-square fit for the known energy levels, electrical transition rates* $B(E2)$*, and quadruple moments* $Q(2_1^+)$ *for the first excited states. We have a good agreement with the experimental values for all the observables tested, and we infer that the feature of the shape coexistence is concealed in the isotopes of Po, just as in the isotopes of Os and Pt.*

Keywords: Interacting Boson Model (IBM-2), configuration mixing, $B(E2)$, $Q(2_1^+)$.

1. Introduction

The concept of shape coexistence is very well known in the area of lead isotopes, as well as in a variety of other shell closures, and was examined by Wood *et al.*, [1]. However, the clear practical evidence of the texture and evolution of existing configurations around the shape is mostly limited to the isotopes of Pb, Hg, and Pt. The Pt and Hg isotopes were analyzed in [2, 3] and [4], respectively, and Yb–Pt nuclei with $N = 108$ were considered in [5]. Oros *et al.* [6] used the particle-core model to study the shape coexistence in light Po isotopes, and García-Ramos and Heyde [7] considered the nuclear shape coexistence in Po isotopes within the interacting boson model.They found that the lead zone, Po, Pb, Hg, and Pt have coexisting structures with different deformations and correspond to different shell-model particle-hole configurations. If the 0_2^+ states in the polonium isotopes arise from a second configuration ($N_\pi = 3$), we can assume that the IBM-2 with the configuration mixing formalism describes the nuclear structure of Po isotopes. This model implies that the medium and heavy even-even nuclei can be represented by the inert core of valence nucleons whose pairs interact weakly with each other. The purpose of this work is to assess the importance of the configuration mixing in comprehending the nuclear structure of Po isotopes within IBM-2 CM, where the phenomena of shape coexistence is not sufficiently clear.

2. Theoretical Framework

The IBM-2 [7, 8] is a rather complex ideology in the physics of nuclear structure. It focuses on group theory principles and the classification of coupled nucleons as bosons. The second incarnation of the theory labeled IBM-2, in which protons and neutrons are distinguished, is discussed in what follows. In the context of IBM-2, nucleons with a spin of either 0 or 2 are categorized as s and d-bosons and are considered to be coupled into bosons. In the group theory language, the key collective nucleus motions are characterized using the sets, U(5) (anharmonic vibrator), SU(3) (symmetric rotor), and O(6) (γ-soft

rotor). The IBM-2 Hamiltonian is given by [8]:

$$H = \varepsilon(\hat{n}_{ds} + \hat{n}_{d\nu}) + KQ_\pi Q_\nu + K(Q_\nu.Q_\pi + Q_\pi.Q_\nu) + \\ + V_{\pi\pi} + V_{\nu\nu} + M_{\pi\nu}, \quad (1)$$

where Q_ρ is the operator of quadrupole moment:

$$Q_\pi = [d^+ \times S^\sim + S^+ \times d^\sim]^{(2)} + \chi_\pi [d^+ \times d^\sim]$$

and

$$Q_\nu = [d^+ \times S^\sim + S^+ \times d^\sim]^{(2)} + \chi_\nu [d^+ \times d^\sim], \quad (2)$$

ρ is the energy of a d-boson, k is the strength of the quadrupole-quadrupole interaction between neutron bosons and proton bosons, and χ_ρ is the quadrupole deformation parameter for bosons that determines the sign of the operator of quadrupole moment. The term $V_{\pi\pi}$ is the interaction of proton bosons, and $V_{\nu\nu}$ is the interaction of neutron bosons only. They are given by [8]:

$$V_{\pi\pi} = \frac{1}{2}\sqrt{2L+1} \sum_{L=0,2,4} C_{L\pi} \left[(d_\pi^+ d_\pi^+)^{(L)} (d_\pi^+ d_\pi^\sim) \right]^{(0)}$$

and

$$V_{\nu\nu} = \frac{1}{2}\sqrt{2L+1} \sum_{L=0,2,4} C_{L\nu} \left[(d_\nu^+ d_\nu^+)^{(L)} (d_\nu^+ d_\nu^\sim) \right]^{(0)}. \quad (3)$$

Finally, the term $M_{\pi\nu}$ is the Majorana force parameter:

$$M_{\pi\nu} = -\sum_{k=1-3} 2\xi_k (d_\pi^+ \times d_\pi^+)^{(k)} (d_\pi^\sim \times d_\pi^\sim)^{(k)} + \\ + \xi_2 (d_\pi^+ \times S_\nu^+ - S_\pi^\sim \times d_\nu^\sim)^{(2)} (d_\pi^\sim \times S_\nu^\sim - S_\pi^\sim \times d_\pi^\sim)^{(2)}. \quad (4)$$

The IBM-2 treats the configuration mixing by using the technique developed by Duval and Barrett [10]. The calculations within IBM-2 CM are separated for two configurations, and the results are then mixed using their interaction.

The Interacting Boson Model (IBM-2) [8] describes the nuclear shape coexistence phenomenon and considers that the excitation levels of the isotope are characterized by the number of bosons. The bosons are coupled with the angular momentum $L = 0$ or $L = 2$ for a given nucleus, where N is constant. The IBM-2 system of configurations with $N, N+2, N+4, N+6, ...$ corresponds to the configuration mixing in the shell model "$0p-0h$, $2p-2h$, $4p-4h$, $6p-6h, ...$". The IBM-2 has ability to treat this case in the configuration mixing (IBM-2 CM) [11]; the application of this model was pointed out by Fossion *et al.*, [12] for Pb nuclei.

The two configurations are connected in the Hamiltonian called a mixing Hamiltonian, which is given in the form [10]:

$$H_{\rm mix} = H_1 + H_2 + V_{\rm mix}, \quad (5)$$

where H_1 is the Hamiltonian of IBM-2 for the first configuration ($N_\pi = 1$), H_2 is the Hamiltonian of IBM-2 for the second configuration ($N_\pi = 3$), which is given in Eq. (1), and $V_{\rm mix}$ is the interaction mixing parameter for two configurations:

$$V_{\rm mix} = \alpha (S_\pi^+ \times S_\pi^+ + S_\pi^\sim \times S_\pi^\sim)^{(0)} + \\ + \beta (d_\pi^+ \times d_\pi^+ + d_\pi^\sim \times d_\pi^\sim)^{(0)}. \quad (6)$$

The normal configuration consists of two protons (one boson $N_\pi = 1$), while the intruder configuration (second configuration) is represented by $N_\pi = 3$ with the excitations across the major shell ($Z = 82$). The parameters α and β are called the mixing strength parameters. The third parameter Δ is the pair excitation energy of the bosons across the major shell and gives the relative energy of two configurations [10]. The transition operators in IBM-2 are defined as [8]:

$$T^{(l)} = T_\pi^{(l)} + T_\nu^{(l)}. \quad (7)$$

The operator of electric quadrupole transition takes the form:

$$T^{(E2)} = e_\pi Q_\pi^{\chi\pi} + e_\nu Q_\nu^{\chi\nu}, \quad (8)$$

where e_π (e_ν) are effective charges for proton (neutron) bosons, respectively. In the configuration mixing, the effective charges for the proton and neutron bosons are often considered equal for simplicity: $e_\pi = e_\nu = e$. Therefore, Eq. (8) becomes as:

$$T^{(E2)} = e(Q_\pi + Q_\nu). \quad (9)$$

The electric quadrupole transition operator for two configurations is given by [11]:

$$T^{(E2)} = e_1 \left[(Q_{1\pi} + Q_{1\nu}) + \left(\frac{e_3}{e_2}\right) (Q_{3\pi} + Q_{3\pi}) \right]. \quad (10)$$

To evaluate the effective charges for proton and neutron bosons, we used the method in Ref. [13] and performed the fitting of the the experimental value of

Table 1. **IBM-2 variables of the Hamiltonian used in the calculations of Po isotopes. The χ and s parameters are dimensionless; the other parameters are given in MeV**

Isotopes	$\varepsilon^{1\pi}$	$K^{1\pi}$	$\chi^{1\pi}$	$\chi^{1\nu}$	$C_{0\nu}^{1\pi}$	$C_{2\nu}^{1\pi}$	$\xi_2^{1\pi}$	$\xi_1^{1\pi} = \xi_3^{1\pi}$	$\varepsilon^{3\pi}$	$\xi_1^{3\pi} = \xi_3^{3\pi}$	$\alpha = \beta$	Δ
^{192}Po	1.00	–0.16	0.4	–0.8	0.30	0.102	0.25	0.02	0.0.33	–0.085	0.125	4.20
^{194}Po	1.62	–0.15	0.4	–1.0	0.28	0.102	0.25	0.02	0.0.33	–0.085	0.125	4.20
^{196}Po	1.15	–0.14	0.4	–1.0	0.16	0.102	0.25	0.02	0.0.33	–0.085	0.125	4.20
^{198}Po	0.90	–0.14	0.4	–1.2	–0.28	0.102	0.25	0.02	0.0.33	–0.085	0.125	4.20
^{200}Po	0.80	–0.15	0.4	–1.1	–0.15	0.102	0.25	0.02	0.0.33	–0.085	0.125	4.20
^{202}Po	0.70	–0.155	0.4	–1.1	–0.12	0.102	0.25	0.02	0.0.33	–0.085	0.125	4.20
^{204}Po	0.60	–0.16	0.4	–1.0	–0.10	0.102	0.25	0.02	0.0.33	–0.085	0.125	4.20

$C_{0\nu}^{3\pi} = C_{2\nu}^{3\pi} = C_{4\nu}^{3\pi} = 0.0$ MeV, $C_{0\nu}^{3\pi} = C_{0\nu}^{1\pi} = 0.0$ MeV, $\xi_2^{3\pi} = 0.0$ MeV.

$B(E2; 2_1^+ \to 0_1^+)$. The reduced electric transition rate can be written as [14]:

$$B(E2; I_i^+ \to I_f^+) = \frac{|\langle I_f||T^{(E2)}||I_i\rangle|}{2I_i + 1}. \tag{11}$$

r The quadrupole moment for the fist excited state is as follows [14]:

$$Q(2_1^+) = \left(\frac{32\pi}{175}\right)^{1/2} \langle 2_1^+||T^{(E2)}||2_1^+\rangle. \tag{12}$$

3. Results and Discussion

3.1. Energy levels

The parameters of the Hamiltonian for two configurations are given in Table 1. One can observe that the ε, k, χ_ν and $C_{o\nu}$ parameters in two configurations vary from isotope to isotope with increasing the neutron number; these parameters are free parameters. The Majorana force parameters $\xi_1 = \xi_2$ are constants for all isotopes in two configurations. The other parameters are remaining fixed or give negligible contributions into the calculations. The pair excitation energy Δ is a function of the neutron number or the number of neutron bosons. Our Δ parameter values used in calculations for Po isotopes are larger than the values in [15], because we assume that the second configuration is based on one proton pair of $Z = 82$ shell within the same valence space. The mixing parameters are taken $\alpha = \beta$ for all isotopes.

In Table 2, we show excitations of the first configuration $N_\pi = 1$, as well as the intruder excitations. The systematic is locally disturbed by the mixing between regular and intruder configurations. This becomes even more clear, when looking at the $I = 2$ multiple involving the regular or normal configuration of $^{184-192}$Os isotopes ($N_\pi = 3$) and $^{192-204}$Po isotopes ($N_\pi = 3$) intruder excitations. In Table 1, Po isotopes for $N_\pi = 1$ lie in vibrational nuclei near the spherical shape, and these isotopes tend to a deformed shape.

In Table 3, we show the comparison of the data for $^{192-204}$Po isotopes (intruder configuration $N_\pi = 3$) and $^{184-192}$Os isotopes (normal configuration $N_\pi = = 3$), where the intruder energies have been reconstructed [16–20]. It is clear that the Po isotopes in the intruder configuration $N_\pi = 3$ have the same behavior as $^{184-192}$Os isotopes.

There are, however, emerging discrepancies near the paring gap at $N_\pi = 3$ which may be the asymptotics of the admixture of non-collective excitations which are outside the IBM-2 space, In particular, the highest spin states (higher band) is too high in energy. In addition, our calculations predict the band $K^\pi = 4^+$ at about 3.0 MeV for ^{200}Po. The experimental behavior of 0+ states is consistent with this IBM-2 CM picture. The energy of the 0_2^+ states (intruder states) increases, in fact, with the number of neutrons and goes up in two configurations, although few experimental information about intruder 0_2^+ states is available [22, 23].

3.2. Electric Transition Probability B(E2)

The reduced electric transition rates which are given in Eq. (10) depend on the effective charges for bosons, e_π and e_v. From the energy levels in Table 2, the ratio $E(4_1^+)/E(2_1^+)$ for $^{194-202}$Po isotopes equals about 2, which means that the Po isotopes are characterized by the U(5) vibrational symmetry and possess an almost spherical shape. Therefore, we use this sym-

Table 2. **Energy levels for Po isotopes in MeV units for the configuration $N_\pi = 1$**

$2^* J_i^+$	^{194}Po		^{196}Po		^{198}Po		^{200}Po		^{202}Po		^{204}Po	
	Exp.	IBM-2	Exp.	IBM-2	Exp.	IBM-2	Exp.	IBM-2	Exp.	IBM-2	Exp.	IBM-2
0_1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2_1	0.319(3)	0.319	0.463(6)	0.464	0.605(10)	0.605	0.666(14)	0.665	0.677(20)	0.665	0.684(20)	0.684
4_1	0.684(4)	0.683	0.891(12)	0.889	1.158(13)	1.160	–	1.179	1.248(3)	1.249	1.200(3)	1.202
2_2	0.659(4)	0.670	0.859(11)	0.844	1.039(14)	1.002	–	1.032	–	1.143	1.255(3)	1.267
3_1	–	0.789	–	0.983	–	0.997	–	–1.001	–	1.110	–	1.230
0_2	–	0.543	0.558(1)	0.600	0.815(10)	0.845	1.137(9)	1.198	–	1.201	–	1.254
4_2	1.209(5)	1.30	0.891(13)	0.901	1.483(16)	1.532	1.277(19)	1.340	1.773(3)	1.821	1.552(6)	1.590
6_1	1.146(5)	1.160	1.390(13)	1.397	1.717(18)	1.632	1.762(10)	1.776	1.691(4)	1.700	1.626(4)	1.720
2_3	1.146(3)	1.231	1.039(2)	1.00	–	1.380	1.392(9)	1.420	–	1.521	–	1.610
8_1	1.690(6)	1.567	1.939(19)	1.889	1.835(18)	1.929	–	1.998	1.772(5)	1.802	1.683(5)	1.731
4_3	–	1.228	1.388(2)	1.301	–	1.420	1.773(12)	1.860	–	1.875	–	1.899

Experimental data are given from Refs [24–26].

Table 3. **Energy levels for Po isotopes in MeV units for the configuration $N_\pi = 3$**

$2^* J_i^\pi$	$N_\nu = 9$		$N_\nu = 8$		$N_\nu = 7$		$N_\nu = 6$		$N_\nu = 5$	
	^{184}Os	^{192}Po	^{186}Os	^{194}Po	^{188}Os	^{196}Po	^{190}Os	^{198}Po	^{192}Os	^{200}Po
0_1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2_1	0.334	0.267	0.379	0.359	0.671	0.791	0.793	0.851	1.119	1.172
0_2	0.732	0.742	0.567	0.889	0.632	0.921	0.932	1.393	1.321	1.407
4_1	0.997	0.998	0.681	1.191	1.036	1.324	1.402	1.862	1.738	1.824
6_1	1.479	1.530	1.136	1.474	1.500	1.637	1.885	2.1191	2.209	2.456
8_1	1.493	2.187	1.672	2.270	2.081	2.229	2.541	2.750	2.881	3.889

Table 4. **Electric transition probabilities (in e^2b^2 units) and quadrupole moments (in eb units) for Po isotopes**

$2^* B(E2; J_i^+ \to J_f^+)$	^{194}Po	^{196}Po	^{198}Po	^{200}Po	^{202}Po	^{204}Po
	IBM-2	IBM-2	IBM-2	IBM-2	IBM-2	IBM-2
$B(E2; 2_1^+ \to 0_1^+)$	0.00203	0.00345	0.00520	0.00723	0.00951	1.21
$B(E2; 4_1^+ \to 2_1^+)$	0.0121	0.0325	0.0342	0.0431	0.0987	0.0994
$B(E2; 2_2^+ \to 2_1^+)$	0.0166	0.0283	0.0406	0.0500	0.0478	0.0470
$B(E2; 2_3^+ \to 2_1^+)$	0.0012	0.0023	0.0498	0.0550	0.760	0.0610
$Q(2_1^+)$	1.633	1.543	1.420	1.38	1.242	1.145

metry to estimate the effective charges for bosons [22]. These effective charges for bosons are normalized to experimental values of $B(E2; 2_1^+ \to 0_1^+)$. For simplicity, we use $e_\pi = e_v = e_1$, where $e_1 = 0.29eb$ and $e_3 = 0.128eb$; these values are kept constants for all isotopes. The IBM-2 CM values are tabulated in Table 3. The $B(E2)$ values of Po increase smoothly with the neutron number. The $B(E2; 2_1^+ \to 0_1^+)$ and $B(E2; 4_1^+ \to 2_1^+)$ values are of the same behavior which is typically increasing toward the end of the

shell. The transition $B(E2; 2_2^+ \to 2_1^+)$ is weak and has a small value because of the M1 mixing. The values of $B(E2; 2_3^+ \to 2_1^+)$ are small, bacause it is the transition from the mixed symmetric state 2_3^+ to the symmetric state 2_1^+, i.e., the transition from the gamma band to *gs*-band. The quadrupole moment for the excited first state $Q(2_1^+)$ is given in Table 3. It is seen that these values are positive. This indicates that the Po isotopes take an oblate shape in 2_1^+ states. The values of $Q(2_1^+)$ decrease smoothly, as the neutron number increases, because the nucleus acquires the spherical shape, by approaching the closed shell $N = 126$.

4. Conclusions

We have studied the nuclear structure and the reduced probability of the electrical transitions $B(E2)$ and $Q(2_1^+)$ in $^{194-204}$Po isotopes within the Interacting Boson Model Configuration Mixing (IBM-2 CM). The polonium isotopes in the normal configuration $N_\pi = 1$ take a vibrational shape (near spherical shape), i.e., they are characterized by the U(5) symmetry. Based on the results concerning the energy states, we considered normal excitations of the configuration $N_\pi = 1$, as well as the intruder excitations for $N_\pi = 3$. The systematic is locally disturbed by the mixing of the regular and intruder configurations. This becomes even more clear, when looking at the $I = 2$ multiple involving the $^{184-192}$Os isotopes ($N_\pi = 3$) in the regular or normal configuration and $^{192-204}$Po isotopes ($N_\pi = 3$) intruder excitations. In Table (1), Po isotopes in $N_\pi = 1$ lie in the vibrational region near the spherical shape, and these isotopes tend to a deformed character in the intruder configuration $N_\pi = 3$. The shape of Po isotopes is vibrational in the $N_\pi = 1$ configuration. But, in the $N_\pi = 3$ [$(2p - 2h)$ across the major shell] configuration, they take a rotational shape like Os nuclei. In the present research, we performed a detailed analysis of the $^{194-204}$Po series of isotopes using the IBM-2, involving double boson excitations through the proton-closed shell (called the intruder configuration zone) and their contact with the normal configuration space within the IBM-2 CM. We have identified the Hamiltonian and the $E2$ operator describing this interacting boson system and have made a least-square fit to the known experimental data.

In addition, we have evaluated the effective charges for bosons which are normalized to the experimental value of $B(E2; 2_1^+ \to 0_1^+)$. For simplicity, we use $e_\pi = e_v = e_1$, where $e_1 = 0.29eb$ and $e_3 = 0.128eb$; these values are kept constants for all isotopes. The electric transition probabilities $B(E2)$ are given in Table 3. The values of quadrupole moments for the first excited state decrease smoothly, as the neutron number increases. This is due to approaching the closed shell $N = 126$; i.e., the shape of a Po nucleus become close to spherical.

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ЗМІШУВАННЯ КОНФІГУРАЦІЙ ДЛЯ ІЗОТОПІВ Po В МОДЕЛІ-2 ВЗАЄМОДІЮЧИХ БОЗОНІВ

Аналізується послідовність ізотопів $^{194-204}$Po в рамках Моделі-2 Взаємодіючих Бозонів зі змішуванням конфігурацій. Параметри гамільтоніана знайдено шляхом підгонки за методом найменших квадратів по відомих рівнях енергії, константам швидкості електричних переходів $B(E2)$ і квадрупольним моментам $Q(2_1^+)$ перших збуджених станів. Отримано добре узгодження з експериментом для всіх розглянутих величин. Зроблено висновок, що властивість співіснування форм є прихованою для ізотопів Po, як і для ізотопів Os і Pt.

Ключові слова: Модель-2 Взаємодіючих Бозонів, змішування конфігурацій, $B(E2)$, $Q(2_1^+)$.