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NEW PARTICLE-HOLE SYMMETRIES AND THE EXTENDED INTERACTING BOSON MODEL

C. De Coster[1,3], J. De Beule[1], B. Decroix[1], K. Heyde[1,2] and A.M. Oros[1]

[1] *Dept. of Subatomic and Radiation Physics, Proeftuinstraat 86, B-9000 Gent*
[2] *present address : EP-ISOLDE, CERN CH 1211, Geneva 23*
[3] *Postdoctoral fellow of the Fund for Scientific Research-Flanders (Belgium)*

Abstract

We describe shape coexistence and intruder many-particle-hole (mp-nh) excitations in the extended interacting boson model EIBM and EIBM-2, combining both the particle-hole and the charge degree of freedom. Besides the concept of I-spin multiplets and subsequently $SU(4)$ multiplets, we touch upon the existence of particle-hole mixed symmetry states. We furthermore describe regular and intruder many-particle-hole excitations in one nucleus on an equal footing, creating (annihilating) particle-hole pairs using the K-spin operator and studying possible mixing between these states. As a limiting case, we treat the coupling of two IBM-1 Hamiltonians, each decribing the regular and intruder excitations respectively, in particular looking at the $U(5)$-$SU(3)$ dynamical symmetry coupling. We apply such coupling scheme to the Po isotopes.

(ISOLDE GENERAL)

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1 Introduction

The subject of shape coexistence and intruder particle-hole excitations has been addressed experimentally as well as theoretically using different approaches [1, 2]. Electromagnetic properties, collective band structure, α-decay hindrance factors and monopole properties contain clear indications for shape coexistence and shape mixing, supported by calculations of the total energy of the nucleus, starting from the liquid-drop model and Strutinsky shell and pairing corrections.

In addition, one and two-nucleon transfer reactions reveal the microscopic nature of the associated particle-hole intruder excitations, and the spherical shell model is able to reproduce at least qualitatively the energy behaviour of the proton (neutron) mp-mh intruder 0^+ band head throughout the neutron(proton) shell. The deformation driving quadrupole proton-neutron interaction is held responsible for the particular lowering in energy of the intruder excitation as one approaches midshell, which is an alternative way of looking at the more deformed structure which coexists with the regular collective excitations. For more details I refer to the talk by Kris Heyde at this conference.

We have addressed a third complementary method to describe particle-hole excitations accross the closed shell, starting from symmetry principles in an algebraic approach. The ideal framework for this purpose, keeping in mind that one aims at describing coexisting low-lying collective bands, is the interacting boson model (IBM) [3, 4].

In the IBM-1 the nucleus is described as an inert core and pairs of valence nucleons, described as s (L=0) and d (L=2) bosons, which is a reasonable assumption as pairing and quadrupole collectivity are dominant for the description of the low-energy spectrum of even-even nuclei away from the closed shells. It leads to an enormous truncation of the shell model space, still keeping track of the microscopy through a dependence of the observables on the total number of bosons. The corresponding algebraic structure is a $U(6)$ algebra, with three possible reduction schemes, each containing the $O(3)$ algebra, corresponding with rotational symmetry. These are the dynamical symmetry limits : the $U(5)$ or anharmonic vibrator limit, the $SU(3)$ or axial rotor limit and the $O(6)$ or γ-soft rotor limit.

A natural extension of the IBM-1 is the IBM-2, where one distinguishes between proton and neutron bosons. This additional degree of freedom and the associated reduction of the product algebra $U_\pi(6) \otimes U_\nu(6)$ into $U_{\pi+\nu}(6)$ leads to two-rowed representations which correspond to different symmetries of the boson wave functions. These can alternatively be labeled by the F spin quantum number, with $F = F_{max} = N/2$ corresponding with a totally symmetric state, whereas $F < F_{max}$ corresponds with non-symmetric or mixed-symmetry states. The so-called scissors 1^+ excitations, experimentally observed in rare-earth and actinide nuclei, are a nice example of this new class of collective excitations [5, 6].

If one aims at describing particle-hole excitations across the closed shell, one needs to break up the inert core and introduce particle and hole bosons. This is the basis for the extended interacting boson model (EIBM) [7]. In section 2 we will briefly explain the basic features of the model and its extension EIBM-2, in which the charge and particle-hole degrees of freedom are combined [8]. In section 3 we establish the algebraic framework for the description of multi-particle-hole excitations within one nucleus on equal footing with regular collective excitations. We discuss the mixing of both types of excitations and apply the model to the Po isotopes in section 4.

2 The extended interacting boson model

In the extended IBM, the core is allowed to break up, and particle and hole pairs are now treated separately as particle and hole bosons, thus leading to a direct product algebra $U_p(6) \otimes U_h(6)$. Starting there, one can construct an embedding $U(12)$ algebra which can be reduced into the following two schemes [7]:

$$(i) \quad U(12) \supset \underset{[N_p]}{U_p(6)} \otimes \underset{[N_h]}{U_h(6)} \supset \underset{[N_p+N_h-i,i]}{U_{p+h}(6)} \tag{1}$$

and

$$(ii) \quad U(12) \supset U_{p+h}(6) \otimes SU_I(2) \otimes U_+(1) \quad . \tag{2}$$

The former reduction is analogous to the IBM-2 which distinguishes between proton and neutron bosons. The two-rowed representations of the algebra $U_{p+h}(6)$ with label $i \neq 0$ are said to correspond to configurations with mixed particle-hole symmetry character. The latter reduction contains the invariant of the system, the total number of bosons N in $U_+(1)$, and a spin object corresponding with the $SU_I(2)$ algebra, which we denote by I spin or intruder spin. We can then develop an I-spin formalism in analogy to F spin in the IBM-2 [9].

If one wants to combine the charge degree of freedom and the particle-hole degree of freedom, one can proceed by introducing particle and hole bosons in the IBM-2 [8]. One thus obtains four types of bosons, $(b_{\lambda\mu})_\alpha^{(\rho)}$, $\lambda = 0, 2$; $\mu = -\lambda, \ldots, +\lambda$; $\rho = \pi, \nu$; $\alpha = p, h$. These 24 single boson states are now subject to a unitary $U(24)$ group transformation. To obtain a classification of the many-boson states that can be constructed within the model space, one needs to determine the possible reductions of the associated $U(24)$ algebra. Thereby, we aim at recovering the quantum numbers L, F and I, respectively containing information about angular momentum, charge and particle-hole symmetry of the wave function. The only possible reduction reads

$$
U(24) \supset \begin{array}{l} U_L(6) \supset G_\lambda \supset O_L(3) \\ \otimes \\ SU_{IF}(4) \supset SU_I(2) \otimes SU_F(2) \quad , \end{array} \tag{3}
$$

where G_λ stands for the three dynamical symmetry limits obtained in the reduction of the $U(6)$ algebra (cf. IBM-1).

It is interesting to note that we can recover the EIBM by breaking the $SU(4)$ symmetry in an $SU_{I(\rho)}(2)$ symmetry, $\rho = \pi, \nu$ when describing proton or neutron particle-hole excitations respectively. So, the EIBM will have applications for nuclei at or near a single-closed proton (neutron) shell, where the neutrons (protons) act as a reference state [10]. The corresponding reduction scheme reads

$$
U(24) \supset U^{(\rho)}(12) \supset \begin{array}{l} U_L(6) \supset G_\lambda \supset O_L(3) \\ \otimes \\ SU_{I(\rho)}(2) \quad . \end{array} \tag{4}
$$

2.1 I-spin multiplets

If $U(12)$ is chosen as the dynamical algebra, the corresponding physical system contains states belonging to the representations $[N_p] \otimes [N_h]$ of $U_p(6) \otimes U_h(6)$ with $N_p + N_h = N$ constant. The "horizontal" classification of particle-hole excitations in terms of the resulting I-spin multiplet, as proposed in ref. [7] has been tested in the Z=50 and Z=82 regions [10, 11]. Data clearly point to the validity of I-spin dynamical symmetry. This will be illustrated for the Po isotopes in section 4.

2.2 SU(4) multiplets

The existence of F-spin and I-spin multiplets points to an underlying symmetry of the Hamiltonian describing the system. We can now similarly study the possible realization of the even more stringent $SU(4)$ symmetry conditions on the Hamiltonian We have found a possible candidate for $SU(4)$ symmetry in the Z=8 mass region. In the nucleus ${}^{16}_{8}O_8$ there is experimental evidence for a $K^\pi = 0^+$ band and a $K^\pi = 2^+$ band associated with 4p-4h excitations, featuring the properties of an asymmetric rotor [12, 13]. The microscopic structure associated herewith is a $\pi(2p - 2h)\nu(2p - 2h)$ excitation [14]. In the EIBM-2 context, this means that these levels belong to the $SU(4)$ multiplet with the total number of bosons $N = 4$. If the $SU(4)$ symmetry is a real symmetry for this multiplet, the same structure should be found in the nucleus ${}^{24}_{12}Mg_{12}$. Experimentally one indeed finds a similar structure in the groundband and $K^\pi = 2^+$ band of the latter [15].

2.3 Mixed symmetry states

Intuitively it is clear that within the EIBM-2 two types of mixed-symmetry states can occur: the proton-neutron mixed-symmetry states, which were also encountered in the IBM-2 and the particle-hole mixed-symmetry states. Since nothing is known so far about this latter class of states, neither experimentally, nor theoretically, it is interesting to study their basic properties, such as excitation energy and magnetic dipole transition probability to the ground state. The former is still under study, starting from the seniority scheme in the shell model [16]. Within the EIBM-2 it is possible to estimate the relative strength of the M1 transition to the ground state for a particle-hole mixed-symmetry 1^+ excitation with respect to the scissors excitation. This has been applied to neutron mid-shell nuclei in the Z=50 mass region [17].

3 Multi-particle-hole excitations : algebraic description and mixing

Besides the global behaviour of particle-hole intruder excitations in a certain mass region which can be well described in terms of I-spin multiplets, one needs to account for local perturbations in the energy systematics on top of the smooth behaviour, which can be attributed to the mixing between regular and intruder configurations. This has been demonstrated earlier by IBM-1 and IBM-2 mixing calculations [18]-[23], in which electromagnetic properties which are more wave function sensitive observables, were studied as well.

3.1 The K-spin formalism

To describe such mixing in a consistent way using the framework of the extended IBM, one introduces operators that increase the number of particle and hole bosons by one, keeping $N_p - N_h$ constant. The resulting non-compact algebraic structure $U(6,6)$ can be further reduced as [7]

$$U(6,6) \supset U_{p-h}(6) \otimes SU_K(1,1) \otimes U_-(1) \quad . \tag{5}$$

The non-compact $SU_K(1,1)$ algebra corresponds with generators that can be seen as three components of an object K spin, where the ladder operators $\hat{K}_+(\hat{K}_-)$ create (annihilate) a particle-hole pair. As a consequence of the non-compactness, however, this object obeys different commutation rules and therefore does not correspond to a general angular momentum, as does I spin.

In fig. 1 an overview of both the horizontal and vertical classification schemes for intruder particle-hole excitations in the EIBM is given.

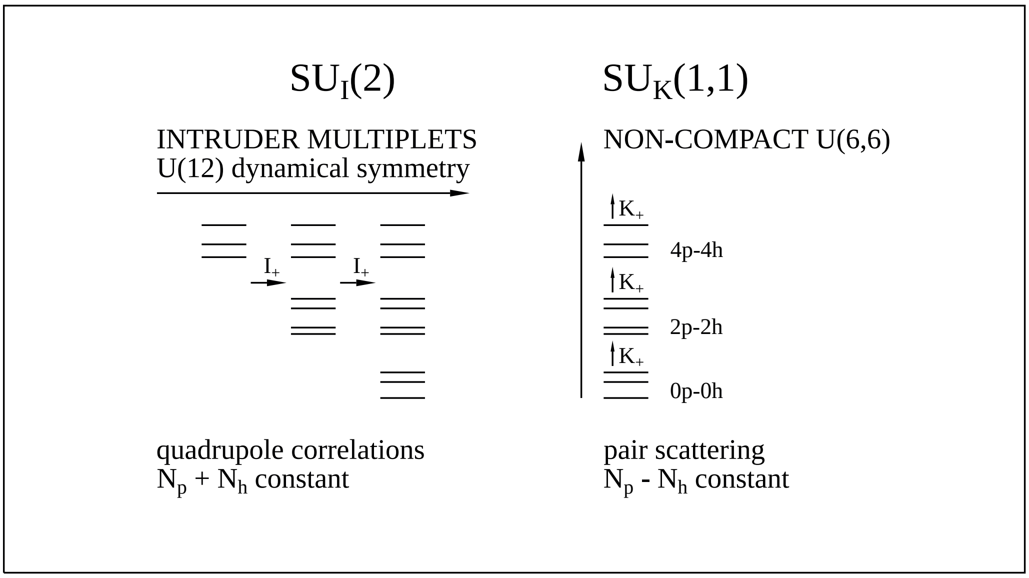

Figure 1: Horizontal and vertical classification of particle-hole excitations, respectively realized within a $U(12)$ algebra, using I spin, and a non-compact $U(6,6)$ algebra, using K spin. While multi-particle-multi-hole states within one nucleus are realized through pair scattering, quadrupole correlations are the driving force for the global behaviour of such excitations throughout a multiplet.

3.2 IBM-1 mixing calculations

One can show that an IBM-1 calculation as performed in ref. [23] is a limiting case in this general framework, when no distinction is made between particle and hole bosons. This is allowed since all low-lying intruder bands have maximum I-spin, i.e. they have totally symmetric wave functions, as if all bosons were identical. More limiting cases have been studied recently, coupling dynamical symmetries $U(5)$-$O(6)$ and $O(6)$-$SU(3)$ with applications in the Z=50 and Z=82 region [10, 11, 20].

In such calculations, one assumes that the regular collective excitations can be described by an IBM-1 Hamiltonian $\hat{H}_{reg}$ in an N-boson space, with the number of bosons counted in the usual way, i.e. from the nearest closed shells. Furthermore the 2p-2h excitations are described by an IBM-1 Hamiltonian $\hat{H}_{intr}$ in an N+2-boson space, with the two extra bosons accounting for the particle and hole pair respectively. By diagonalizing the Hamiltonians, one obtains the pure, unperturbed regular and intruder excitations, for which the I-spin symmetry concept should be applicable. Therefore, one can use regular bands from neigbouring I-spin multiplet partners to fit the parameters for $\hat{H}_{intr}$. This is extremely useful, since it increases the amount of available data appreciably. One can then study the mixing between both structures by diagonalizing the matrix

$$\left(\begin{array}{c|c} E_N & \langle \Phi_N | H_{mix} | \Phi_{N+2} \rangle \\ \hline \langle \Phi_{N+2} | H_{mix} | \Phi_N \rangle & E_{N+2} + \Delta \end{array} \right) \quad , \tag{6}$$

where $E_N(\Phi_N)$ and $E_{N+2}(\Phi_{N+2})$ are the eigenvalues (eigenstates) for the corresponding Hamiltonian and where

$$H_{mix} \ = \ \alpha \ [s^\dagger s^\dagger + ss]^{(0)} + \beta \ [d^\dagger d^\dagger + \tilde{d}\tilde{d}]^{(0)} \quad , \tag{7}$$

mixes the N-boson regular and N+2-boson intruder excitations. The parameter Δ is used to shift the intruder excitations in energy with respect to the regular excitations and accounts for those contributions to this relative energy which cannot be explicitly accounted for in the IBM, i.e., the energy needed to promote two particles accross the closed shell and the pairing energy gain [24].

4 Application to the $^{192-200}$Po isotopes

More recently, measurements on the Po isotopes led to some controversy on the interpretation of the data [25]-[27]. We believe that the predictions of several models corroborated with the trend in the experimental data support the interpretation of the systematics of the Po isotopes in terms of shape coexisting configurations [28, 29].

In fig. 2 we show the regular $[\pi(2p)]$ excitations, as well as the intruder $[\pi(2h-4p)]$ excitations. The systematics is locally disturbed by mixing between regular and intruder configurations, as indicated by the arrows on fig. 2. This becomes even more clear when looking at the I=3/2 multiplet involving the Os $[\pi(6h)]$ regular and Po $[\pi(2h-4p)]$ intruder excitations. In fig. 3 we show the comparison of the data and a two-state model calculation, where the unperturbed intruder energies have been reconstructed [28, 29]. It is very clear that the I-spin dynamical symmetry is restored when de-mixing regular and intruder configurations. The most striking example are the 2^+ excitations in ^{196}Po, indicated by dashed lines, which energies deviate both substantially from the 2^+ energy in ^{188}Os. For ^{192}Po, where the intruder band is most probably becoming the ground band, as supported by PES calculations [31], the picture is worse. However here, no de-mixing was possible since no excited states are known experimentally. The de-mixing of the ground state as deduced from α-decay hindrance factors leads to a 60 keV shift of the energy, as indicated by the dashed line.

In the framework of the IBM-1, we have performed mixing calculations: (i) We describe the regular states by a $U(5)$ Hamiltonian

$$\hat{H} \ = \ \epsilon \hat{n}_d + \kappa' \hat{L} \cdot \hat{L} \quad , \tag{8}$$

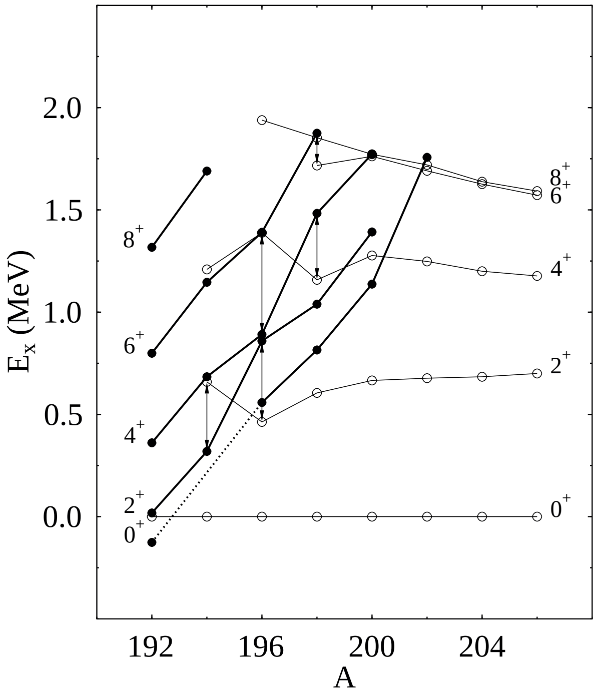

Figure 2: Systematics of the Po isotopes, interpreted in terms of shape coexisting configurations. Regular (intruder) excitations are indicated by thin (thick) lines and $\circ(\bullet)$. Data are taken from ref. [27]. The dotted line is used to indicate the predicted lowering of the intruder 0^+ state following PES calculations. [29].

where the parameters $\epsilon = 0.68$ MeV and $\kappa' = -4$ keV have been fitted to the yrast and yrare $J^\pi = 0^+, 2^+, 4^+$ states of $^{202-208}$Po, and have been kept constant for the description of the whole series of $^{192-208}$Po isotopes. The regular yrast $6^+, 8^+$ states have a rather pure $(\pi h_{9/2})^2$ character, although, as the neutron number decreases, the 6^+ state becomes more vibrational[1]. Thus, when restricting the calculation to the lighter $^{192-200}$Po isotopes, where the intruder excitations really start to play an important role in the low-energy spectrum, one can assume the $U(5)$ description of the regular excitations to be satisfactory up to angular momentum 6.

(ii) A first more schematic calculation starts from the description of the intruder states by an $SU(3)$ Hamiltonian ($\chi = -\sqrt{7}/2$)

$$\hat{H} \;=\; \kappa \hat{Q} \cdot \hat{Q} + \kappa' \hat{L} \cdot \hat{L} + \Delta \quad , \tag{9}$$

where the parameters $\kappa = -8$ keV and $\kappa' = 22$ keV have been fitted to the ground and γ band of ^{190}Os, and kept constant throughout the whole series

[1]This is more clear when looking at the whole systematics of the $^{194-210}$Po isotopes [26].

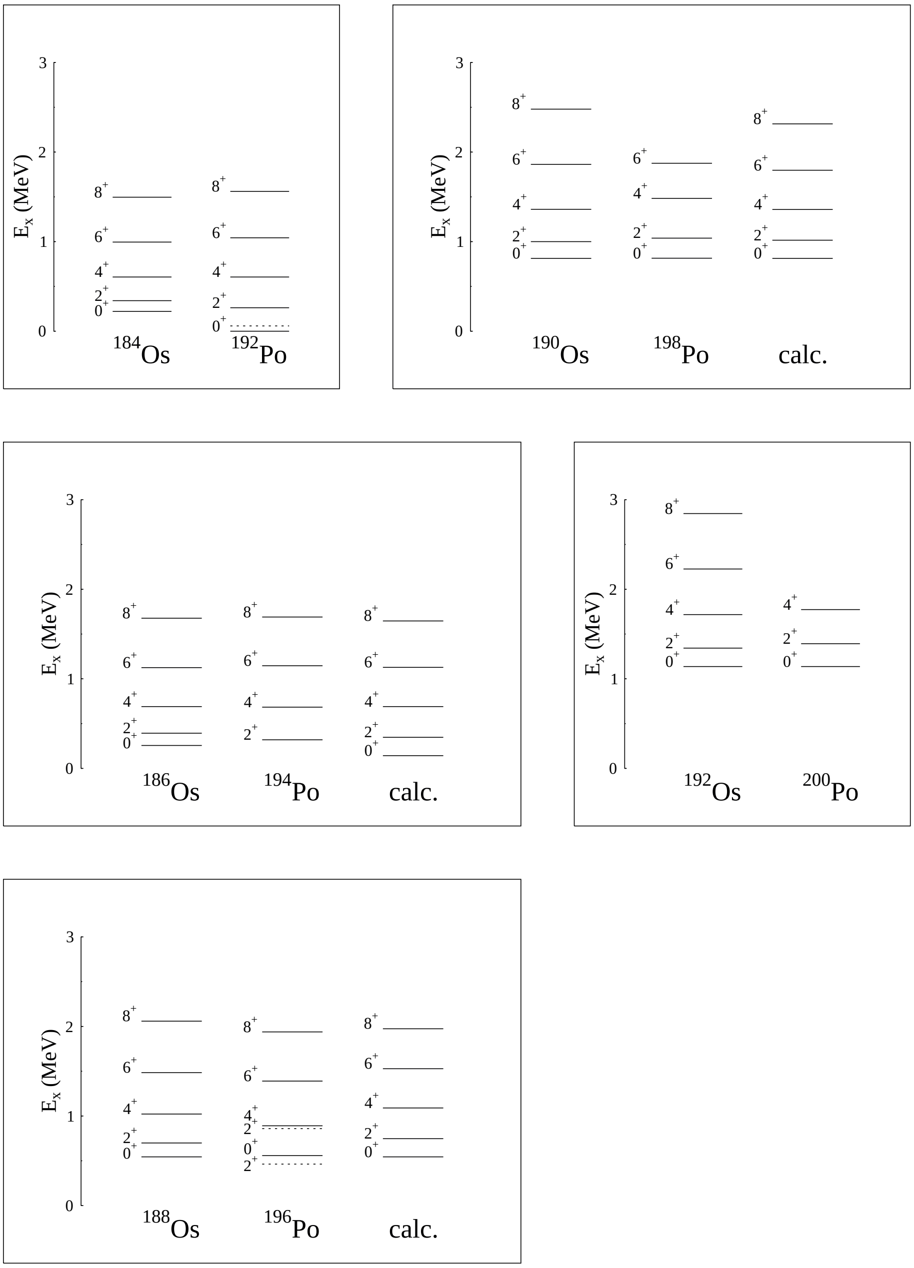

Figure 3: I=3/2 multiplet involving $[\pi(6h)]$ excitations in $^{184-192}$Os and $[\pi(2h-4p)]$ excitations in $^{192-200}$Po. Details are explained in the text. Data are taken from refs. [27, 29] for Po and ref. [32] for Os. The Os band has been normalized to the unperturbed 0^+ energy, which is very little affected by mixing, as is clear from the comparison with the Po data, except for ^{192}Po, where from α-decay the 0^+ is known to be mixed, and ^{194}Po, where the experimental 0^+ energy is unknown, and the 4^+ energy is nearly unaffected by mixing and hence used for normalization of the Os band.

of $^{192-200}$Po isotopes. The parameter Δ was fitted to the excitation energy of the known intruder 0^+ levels and also kept constant for all isotopes considered, in accordance with its physical meaning. As a result, the intruder 0^+ configuration becomes the ground state in ^{192}Po.

In a second calculation we start from the I-spin concept and adapt for the description of the intruder states in the Po isotopes a more general Hamiltonian, suitable for the description of the corresponding Os isotopes,

$$\hat{H} = \epsilon \hat{n}_d + \kappa \hat{Q} \cdot \hat{Q} + \kappa' \hat{L} \cdot \hat{L} + \Delta \quad , \tag{10}$$

and which is similar to the one used for an earlier calculation of $^{174-180}$Os [33]. The parameters $\epsilon = 0.22$ MeV and $\chi = -0.8$ are kept constant for all isotopes, while κ, κ' are smoothly varying from $^{184-192}$Os ($^{192-200}$Po) in the ranges -14 to -9 keV and 11.3 to 16.7 keV respectively. These values are in line with those used in [33]. The parameter Δ was again fitted to the excitation energy of the known intruder 0^+ levels and also kept constant for all isotopes considered. As a result the intruder 0^+ configuration becomes nearly degenerate with the regular ground state in ^{192}Po.

(iii) We then introduce the mixing as described in eqs. (6) and (7), with mixing parameters $\alpha = \beta \simeq 0.04$MeV, which is again in line with the values used earlier in this mass region [21, 23]. In the case of a pure $U(5)$-$SU(3)$ dynamical symmetry coupling, the systematics and the general features of the spectra of the $^{192-200}$Po isotopes are reproduced qualitatively, but the mixing is underestimated quantitatively, especially in ^{194,196}Po. Moreover, the ground state in ^{192}Po is almost purely 4p-2h in nature, in accordance with the PES predictions [31], but in disagreement with α-decay hindrance factors [30] which point to mixing. For the more general Hamiltonian of eq. (10), the mixing results in a fair overall agreement with experimental data, as can be seen from fig. 4. The ground state in ^{192}Po is now mixed, but with the regular configuration as the dominant one. The disagreement between the experimental and calculated yrast 8^+ level as neutron number increases, is linked with the dominant regular nature of this state, which, as a $(\pi h_{9/2})^2$ configuration, is outside the IBM model space.

5 Conclusions

We have illustrated how the introduction of particle and hole bosons in the IBM leads to a number of new concepts, such as I-spin and $SU(4)$ symmetry, mixed-symmetry particle-hole excitations, which are the merits of this complementary approach to the description of shape coexistence and intruder states. We have furthermore established a general framework in which regular and intruder excitations can be treated on equal footing, allowing for the study of mixing between the two classes of excitations. The coupling of two IBM-1 Hamiltonians as a limiting case is then applied to the $^{192-200}$Po isotopes with considerable success.

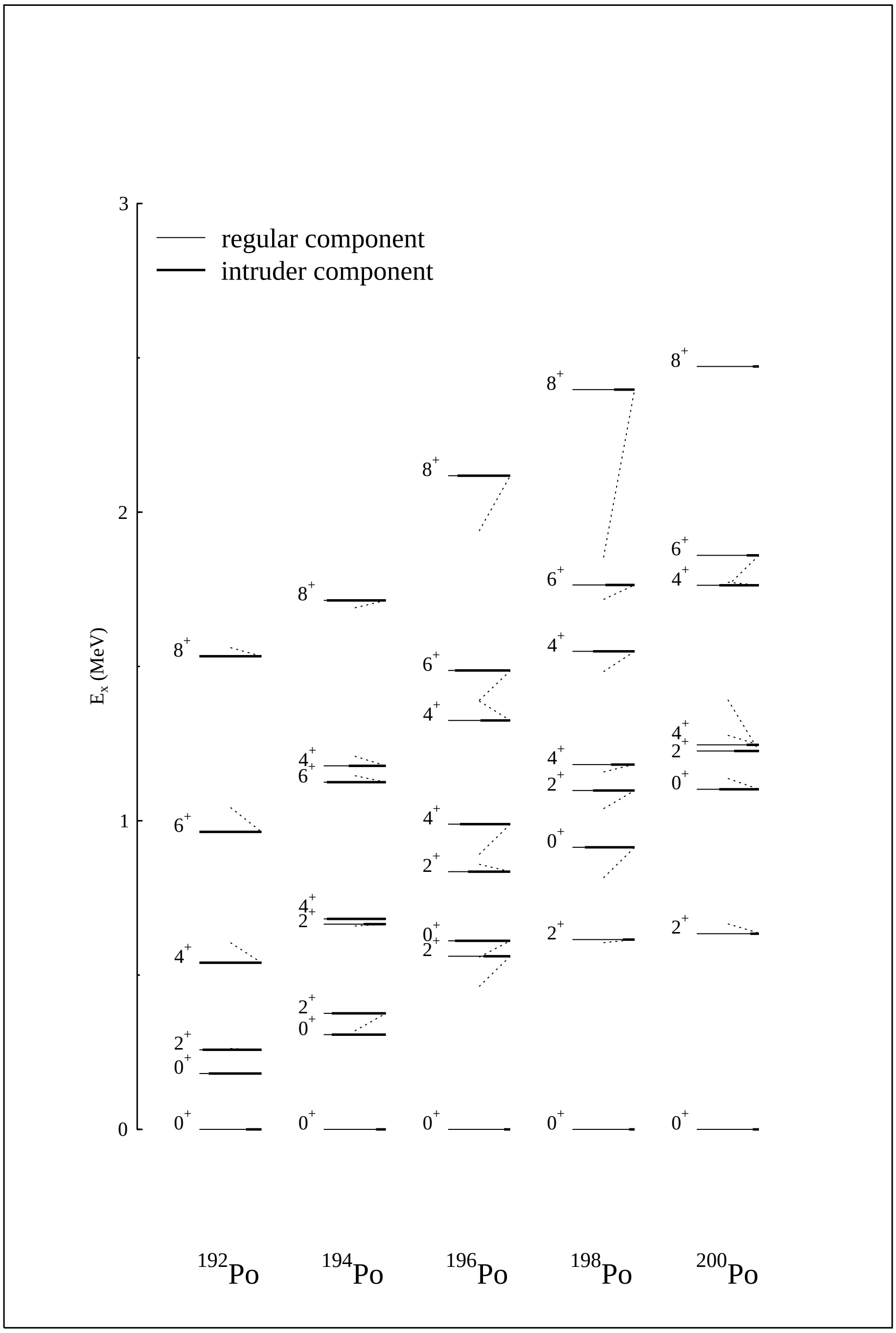

Figure 4: Calculated systematics for the $^{192-200}$Po isotopes, as described in the text. The relative contribution of regular (intruder) components to the wave functions is indicated by the thin (thick) parts of the respective levels. The discrepancy with experimental data is indicated by the dotted line, of which the endpoint corresponds to the experimental value.

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