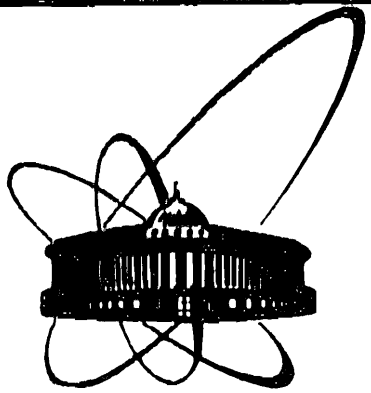

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NEW ASPECTS OF THE INTERACTING BOSON MODEL

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1. Development of the IBM

The interacting boson model (IBM), in its initial version called quadrupole phonon model [1,2], and later in its nowaday version IBM [3-6], has got a great development and has been used in many applications [7,8]. Its complete group structure has been derived in ref.[9], and the relation between the coefficients of both versions yielding their equivalence: in ref.[10], see also [11]. Its microscopic foundation has been discussed in a number of publications [7,12,13].

The model development has been performed, firstly, by several generalizations. Such one is the proton neutron IBM [14]. Farther comes its extension to the interacting boson fermion model for odd nuclei IBFM and odd-odd nuclei IBFFM including dynamic supersymmetries [15-19]. Moreover, configuration mixing IBM [20,10,21] and higher order IBM [7,22] have been proposed. And still farther, the continuous spectrum IBM [23-25] has been suggested. The necessity of introducing other degrees of freedom, besides the monopole-quadrupole one, has been realized immediately, and it has been performed by additional bosons [1-3,7], initially chosen empirically. About two years ago it was realized that definite boson combinations conserve at least the U(3) subgroup and thus the rotational limit [26-30]. We are going to show in section 2 in which way one can extend the boson space conserving a number of dynamic symmetries.

The IBM development has been performed, secondly, by developing methods minimizing the number of parameters and making them universal. Such is the consistent also extended Q formalism [31,32], showing that the transition between all three limit cases can be realized by three parameters only in the harmonic term and the quadrupole operator of the boson hamiltonian. Farther, the F spin projection on its maximal value [33,34], transforming the p n IBM-2 into the usual IBM-1 with less parameters. And finally, the N_pN_n systematics with respect to the product of valence proton N_p and neutron N_n numbers, showing that many tens of nuclei of several large regions can be described by 7 parameters only [35], and even by 5 parameters [36] if

other above mentioned methods are also applied. It is related to systematics with respect to the $P = N_p N_n/(N_p + N_n)$ parameter, representing the average number of interactions of each valence nucleon with those of the other type /37/.

The IBM development has been performed, thirdly, by developing methods of its hamiltonian diagonalization. The exact diagonalization is most efficient when based on group theory /38/. But recently three approaches have been applied, leading to simpler approximations. Such is the boson Hartree method /39.40/, the calculations of boson systems having turned out to be easier than those of fermion systems by the known for half a century fermion Hartree method. Farther, the hamiltonian separation /41,42/ into an "intrinsic" part determining the quasirotational bandheads, and a "collective" part, shifting, splitting and mixing the intrinsic states. And finally, the quasiqlassical coherent state method applied to boson models /43-45/, postulating an exponential dependence of the boson state on boson creation and annihilation operators.

2. Interacting multi boson model : IMBM

We have shown recently, in which way one can extend the boson space, conserving at the same time a number of dynamic symmetries. In this direction the above named generalization IMBM has been suggested /46/. It has been done by using generalized collective coordinates of any power, their momenta, boson creation and annihilation operators, and the generators of the group

$$U\left(n^2\right) \supset U\left(n(n-1)/2\right) \times U\left(n(n+1)/2\right) \qquad (1)$$

constructed of them (x means direct product of groups). Bosons with multipolarities $j = 0, 2, \ldots n-2\ (n-1)$ respectively space parity + for the first (second), and with $j = 1, 3, \ldots n-1\ (n-2)$ respectively - for the second (first) subgroup on the right-hand side of (1) have been included.

A method of finding its group structure has been proposed /46/ in the sense of the subgroup lattice /47/ embedded in the initial unitary group $U(n^2)$ or in one of both its subgroups on the right-hand side of (1) with the usual rotational group $O(3)$ embedded at the end. It has been illustrated by the $n = 4$ s p d f boson model. The same has been done with constructing the boson hamiltonian and the (electromagnetic) transition operators. Methods of algebraic diagonalization have been developed, and the level spectra in both extreme vibrational and rotational limits have been derived. As it

has been shown, a number of levels and transitions appear, inaccessible to the usual model.

For the $U^{0,1,2,3}(16)$ s p d f boson model the first subgroup is the usual $U^{0,2}(6)$ group of the known s d boson model. The second one is the $U^{1,3}(10)$ p f boson group. Its subgroup lattice is as follows /46/ :

$$\begin{array}{ccccccc}
 & & \supset U^1(3)\times U^3(7) & & & & \\
 & & \vdots & \searrow & & & \\
 & \swarrow & & \supset O^1(3)\times O^3(7) & \supset & O^1(3)\times O^3(3) & \\
 & \vdots & & & & & \\
U^{1,3}(10) & \supset & O^{1,3}(10) & \cdots & & & \\
 & \vdots & & \searrow & & & \\
 & & \cdots & \supset U^{1,3}(5) & \supset & O^{1,3}(5) & \supset O^{1,3}(3) \\
 & & \vdots & \searrow & & & \\
 & & \cdots & \supset O^{1,3}(6) & & & \\
 & & \vdots & & \searrow & & \\
 & & \cdots & & \supset & U^{1,3}(3) &
\end{array} \qquad (2)$$

The generators of its subgroups have been obtained explicitly. Such group structure already means that in spite of extending the model, its main advantage of a simple description of transitional nuclei will be conserved.

For each of the six limits, an algebraic diagonalization of the corresponding hamiltonian, expressed in terms of the independent Casimir operators of the same row of (2), is possible. Denoting the first order Casimir operator of any $U^s(r)$ by $\hat{n}^s_r$, the second order one by $\hat{\nu}^s_r$, and the second order one of any $O^s(r)$ by $\hat{\omega}^s_r$, we obtain the limit hamiltonians as follows. They are special cases of the general p f hamiltonian /46/ of our model, $\hat{n} = \hat{n}^1_3 + \hat{n}^3_7$:

$$\begin{aligned}
H &= \varepsilon^3 \hat{n}^3_7 + \varepsilon^1 \hat{n}^1_3 + \alpha^{3,3} (\hat{n}^3_7)^2 + \alpha^{1,3} \hat{n}^1_3 \hat{n}^3_7 + \alpha^{1,1} (\hat{n}^1_3)^2 \\
&\quad + \beta^3_7 \hat{\omega}^3_7 + \beta^3_3 \hat{\omega}^3_3 + \beta^1_3 \hat{\omega}^1_3 + \beta^{1,3}_3 \hat{\omega}^{1,3}_3 \\
H &= \varepsilon \hat{n} + \alpha (\hat{n})^2 + \beta^{1,3}_{10} \hat{\omega}^{1,3}_{10} + \beta^3_7 \hat{\omega}^3_7 + \beta^3_3 \hat{\omega}^3_3 + \beta^1_3 \hat{\omega}^1_3 + \beta^{1,3}_3 \hat{\omega}^{1,3}_3 \\
H &= \varepsilon \hat{n} + \alpha (\hat{n})^2 + \beta^{1,3}_{10} \hat{\omega}^{1,3}_{10} + \beta^{1,3}_5 \hat{\omega}^{1,3}_5 + \beta^{1,3}_3 \hat{\omega}^{1,3}_3 \qquad (3) \\
H &= \varepsilon \hat{n} + \alpha (\hat{n})^2 + \alpha^{1,3}_5 \hat{\nu}^{1,3}_5 + \beta^{1,3}_5 \hat{\omega}^{1,3}_5 + \beta^{1,3}_3 \hat{\omega}^{1,3}_3 \\
H &= \varepsilon \hat{n} + \alpha (\hat{n})^2 + \beta^{1,3}_6 \hat{\omega}^{1,3}_6 + \beta^{1,3}_5 \hat{\omega}^{1,3}_5 + \beta^{1,3}_3 \hat{\omega}^{1,3}_3 \\
H &= \varepsilon \hat{n} + \alpha (\hat{n})^2 + \alpha^{1,3}_5 \hat{\nu}^{1,3}_5 + \beta^{1,3}_5 \hat{\omega}^{1,3}_5 .
\end{aligned}$$

The embedding of the irreducible representations (IR) of all

U(r) : $[h_1 \geq h_2 \geq \ldots h_r \geq 0]$ and all O(r) : $(\bar{h}_1 \geq \bar{h}_2 \geq \ldots \bar{h}_{[r/2]} \geq 0)$ can be found as described in ref./46/. In particular, in the $[r/2]$ IR $[h]$ of the initial unitary group $U^{1,3}(10)$ are embedded the IR of its first subgroups of (2) according to the following rules given in (4). There: $[..] \times [..]$ denotes outer product of representations, $\textcircled{x}$: outer plethysm, $\sim$: local isomorphism, $[t]$: the integer part of t .

$$
\begin{aligned}
[h] &= \sum_{k=0}^{h} [k] \times [h-k] && : U^1(3) \times U^3(7) \\
[h] &= \sum_{k=0}^{[h/2]} (h - 2k) && : O^{1,3}(10) \\
U^{1,3}(10) : [h] &= [1,1] \textcircled{x} [h] && : U^{1,3}(5) \qquad (4) \\
[h] &= [2] \textcircled{x} [h] && : U^{1,3}(4) \ , \ SU^{1,3}(4) \sim O^{1,3}(6) \\
[h] &= [3] \textcircled{x} [h] && : U^{1,3}(3) .
\end{aligned}
$$

Thereafter, the eigenvalues n_r , ν_r ; ω_r of the Casimir operators $\hat{n}_r$, $\hat{\nu}_r$; $\hat{\omega}_r$ in (3) of all subgroups U(r) and O(r) in (2) are known /46/ :

$$
\begin{aligned}
n_r &= \sum_{k=1}^{r} h_k \\
\nu_r &= \sum_{k=1}^{r} h_k (h_k + r + 1 - 2k) \qquad (5) \\
\omega_r &= \sum_{k=1}^{[r/2]} \bar{h}_k (\bar{h}_k + r - 2k) .
\end{aligned}
$$

In the following we will exchange the second order Casimir operator $\hat{\nu}_r$ of U(r) for the corresponding $\hat{\bar{\nu}}_r$ of SU(r) , which will lead to the exchange of ν_r in (5) for $\bar{\nu}_r$ in (6) :

$$
\bar{\nu}_r = \nu_r - (n_r)^2 / r . \qquad (6)
$$

In this way, the hamiltonians' (3) level energies have been found algebraically.

3. Reflection asymmetric nuclear shapes

Let us consider this actual nuclear structure problem which appeared about five years ago, in order to do the first application of the model developed in ref./46/ and in section 2 of this work.

In a number of nuclei of the actinide and later the lanthanide region, low lying negative parity collective states have been observed, e.g. 1^- at about 300 keV in even-even nuclei, connected by relatively enhanced E1 transitions with the positive parity states. It turned out to be difficult to ascribe a vibrational origin to all of them.

Two alternative interpretations have been proposed, based on a number of physical arguments. Firstly, alpha clustering, or dinuclear system molecular modes /48-50/. Secondly, octupole dynamic and/or static deformation /51-53,45/, a dipole deformation of protons with respect to neutrons being related /54/. Experimental information has recently appeared, weakening the evidence in favour of the first /55/ and yielding additional evidence in favour of the second one /56/.

Let us apply the s p d f boson model in a concise form: without d bosons, without Coriolis type interactions, and with a minimal number of parameters, in one of the limit hamiltonians (3). This means realization of the octupole plus dipole (f plus p) dynamic and/or static deformation interpretation. We are going to describe the positive and negative parity yrast lines of actinide region nuclei with sufficient experimental information. We choose three groups of isotones $^{218}_{88}Ra_{130}$ /57,58/ , $^{220}_{90}Th_{130}$ /59/ for which nearly vibrational spectra are observed shown in figure 1 , $^{220}_{88}Ra_{132}$ /60,61/ , $^{222}_{90}Th_{132}$ /59/ with transitional type spectra shown in figure 2 , and $^{226}_{88}Ra_{138}$ /62-64/ . $^{228}_{90}Th_{138}$ /65,64/ . $^{230}_{92}U_{138}$ /64/ with nearly rotational spectra shown in figure 3 .

From an experimental point of view our attention is called to two points. Firstly, when changing Z and keeping N constant (isotones) the spectra are very similar, but when changing N and keeping Z (isotopes) or even A constant (isobars) they are rather different. This should be considered as evidence in favour of the prevailing role of neutrons for the appearance of octupole-dipole deformation in actinides. Secondly, level spins are observed, exceeding the allowed ones by the simple ad hoc rule applied in the IBM, according to which the total boson number is equal to the number of valence nucleon pairs.

From a theoretical point of view we are going to note the following points. Different total s, p, f boson numbers $N = n_1^0 + n_3^1 + n_7^3$ reproduce the low spin part in an almost identical way, higher N just increasing the number of high spin levels and the maximal spin I ; therefore everywhere N = 6 has been chosen. Two parameters are sufficient to reproduce the yrast line of each isotones group if no

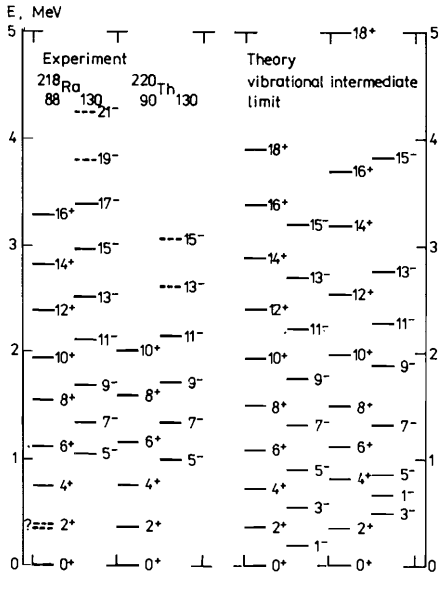

Figure 1. Reproducing the yrast line of actinide isotones with nearly vibrational spectra. Experiment from refs.[57-59]. Theory in the vibrational limit: from the first hamiltonian (3) with $\varepsilon^3 = 3\varepsilon^1 = 540$ keV, $\beta^3_7 = 10$ keV; theory in the intermediate limit: from the third, fourth or fifth hamiltonian (3) with $\beta^{1,3}_{5,3}$ = 118 keV, $\beta^{1,3}_{5,3} = -18.5$ keV; all other parameters equal to 0.

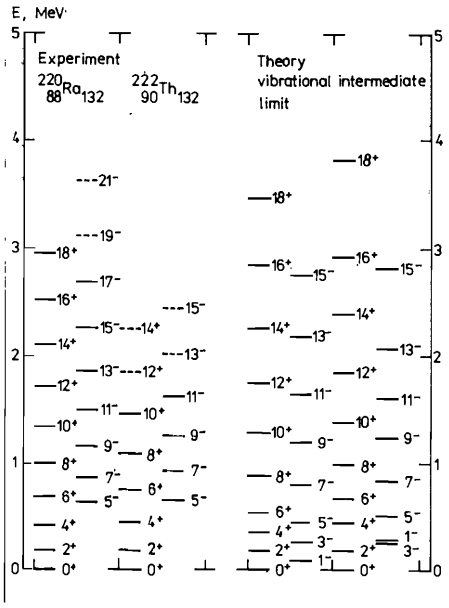

Figure 2. Reproducing the yrast line of actinide isotones with nearly transitional spectra. Experiment from refs.[59-61]. Theory in the vibrational limit: from the first hamiltonian (3) with $\varepsilon^3 = 3\varepsilon^1 = 270$ keV, $\beta^3_7 = 28$ keV; theory in the intermediate limit: from the third, fourth or fifth hamiltonian (3) with $\beta^{1,3}_{5,3} = 49$ keV, $\beta^{1,3}_{5,3} = -2.6$ keV; all other parameters equal to 0.

detailed coincidence is required. The vibrational spectra in figure 1 are better reproduced by the vibrational limit, the transitional in figure 2 : by the intermediate, and the rotational spectra in figure 3 : by the rotational limit (if mainly the low spin parts are compared), as one should expect. The p plus f boson combination yields the possibility to reproduce the 0^+, 1^-, 2^+, 3^- .... line in all limits, at variance with the f boson case alone: compare figure 1 of this work with figure 1a of ref.[46]. And finally, one

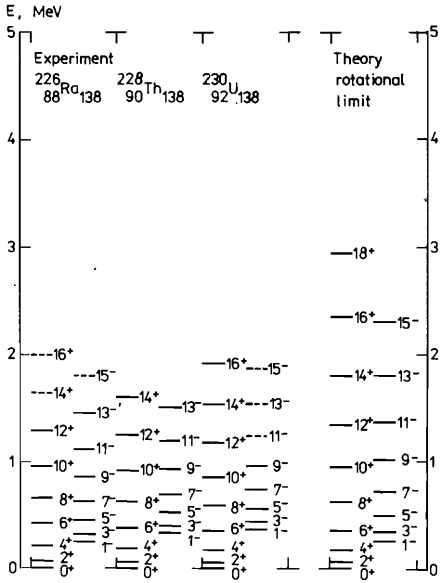

Figure 3. Reproducing the yrast line of actinide isotones with nearly rotational spectra. Experiment from refs.[62-65]. Theory in the rotational limit from the sixth hamiltonian (3) with $\varepsilon = 1000$ keV, $\alpha^{1,3}_{3} = -2\beta^{1,3}_{3} = -17.2$ keV; all other parameters equal to 0.

can see everywhere that the distorted high spin part is poorly reproduced, which is a general IBM feature [10] without taking Coriolis interactions into account. However, in the IMBM they exist at variance with IBM (see section 4), and this gives the possibility for a better description of this spectrum part as well.

4. Foundation, application and development of the IMBM

It is interesting to note that after the preprint in ref.[46] was published, two articles independent of it appeared [66,67]. They show the significance of the collective nucleon pairs 1^-P and 3^-F, besides the generally applied 0^+S and 2^+D. Thus these articles can be considered as a microscopic foundation of the IMBM of ref.[46] and section 2 of this work in its s p d f version.

Such a model can find a number of applications to problems of nuclear structure, e.g. to the appearance and alteration of various nuclear shapes, to the question whether quasirotational band termination exists and where it is, to a better description of high spin states with Coriolis interaction and/or exit out of the unitary scheme framework (see below), and to the recently revealed isovector vibrational modes in nuclei of different shape (see [68] and references therein): 1^+ at about 3 MeV, 2^+ at about 2 MeV. The last ones have been considered in the p n IBM as mixed symmetry states [69], but in principle similar states can appear in any two-component

system [70], e.g. in our case of a system with s d and p f components.

In the framework of the IMBM, its development includes numerical diagonalization of its general or concise hamiltonian [46], in particular with Coriolis type terms taken into account. The last ones will appear in this model due to the existence of three types p, d, f boson angular momenta and scalar products in the general hamiltonian, at variance with the only d boson one type angular momentum in the usual model. This interaction must improve the high spin part description due to the fact that it alignes the boson angular momenta [45]. Such a development includes farther an algebraic or numerical description of transition rates by applying one of the methods mentioned in section 1 . Moreover, it includes the possibility to create an s p d f g h boson model on the basis of the U(36) group that should improve the known s d g boson model based on the U(15) group [27,28].

Out of the framework of the IMBM, its development might take place by an extension of the compact unitary $U(n^2)$ group to the noncompact symplectic $Sp(2n^2,R)$, as it was suggested for the extension of U(6) to Sp(12,R) in refs.[9,10], and as it was shown how this can be performed without a substantial increase in the number of parameters in ref.[10]. This will mean total boson number nonconservation, appearance of infinite bands, and inclusion of the well-known rotation-vibration Greiner model with limited power static interaction as a particular case. It should influence the problems of quasirotational band termination, as well as their high spin states description.

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