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Description of positive and negative parity dipole bands within the extended coherent state model

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Abstract

The extended coherent state model is further extended as to describe two dipole bands of different parities. The formalism provides a consistent description of eight rotational bands. A unified description for spherical, transitional and deformed nuclei is possible. Projecting out the angular momentum and parity from a sole state, the $K^\pi = 1^+$ band acquires a magnetic character, while the electric properties prevail for the other band. New signatures for a static octupole deformation are pointed out. Interesting features concerning the decay properties of the two bands are found. For illustration the formalism was applied to ^{172}Yb and results are compared with the available data.

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The field of negative parity bands became very attractive when the first suggestions for a static octupole deformation were advanced by Chassman [1] and Moller and Nix [2]. Since a nuclear shape with octupole deformation does not exhibit a space reflection symmetry and on the other hand a spontaneously broken symmetry leads to a new nuclear phase, one expects that the octupole deformed nuclei have specific properties. The main achievements of this field have been reviewed in Refs. [3–5].

Identifying the nuclei which have static octupole deformation seems to be a difficult task. Indeed, because there is no measurable quantity for the octupole deformation, some indirect information about this variable should be found. Several properties are considered as signatures for octupole deformation: (a) In some nuclei like ^{218}Ra, the state 1^-, the head of the $K^\pi = 0^-$ band, has a very low position and this is an indication that the potential energy has a flat minimum, as a function of the octupole deformation. (b) The parity alternating structure in ground and the lowest 0^- bands suggests that the two bands may be viewed as being projected from a sole deformed intrinsic state, exhibiting both quadrupole and octupole deformations. (c) A nuclear surface with quadrupole and octupole deformations might have the center of charge in a different position than the center of mass, which results in having an electric dipole moment which may excite the state 1^- from the ground state, with a large probability. The list is not complete and thereby any new signature for this new nuclear phase deserves a special attention.

Few years ago we considered this subject within a phenomenological framework. Thus, in Refs. [6–9] we extended the coherent state model (ECSM) [10] to the negative parity bands. To the lowest positive parity bands, named ground (g^+), beta (β^+) and gamma (γ^+), one associates three negative bands, g^-, β^-, γ^-, respectively. The six bands are obtained by projecting out the angular momentum and the parity from three orthogonal functions which exhibit both quadrupole and octupole deformations The intrinsic function for the ground as well as for the $K^\pi = 0^-$ bands is a product of coherent states with respect to the zero components of the quadrupole ($b^\dagger_{2\mu}$) and octupole ($b^\dagger_{3\mu}$) bosons. The other two pairs of different parity bands are

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generated by polynomial quadrupole boson excitations of the ground band. The excitations are chosen such that the resulting functions are orthogonal before and after projecting the angular momentum and parity.

Thus, the intrinsic states for ground, beta and gamma bands are:

$$\Psi_g = e^{f(b_{30}^\dagger - b_{30})} e^{d(b_{20}^\dagger - b_{20})} |0\rangle_{(3)} |0\rangle_{(2)},$$
$$\Psi_\beta = \Omega_\beta^\dagger \Psi_g, \qquad \Psi_\gamma = \Omega_\gamma^\dagger \Psi_g, \tag{1}$$

where the excitation operators have the expressions:

$$\Omega_\beta^\dagger = \left(b_2^\dagger b_2^\dagger b_2^\dagger\right)_0 + \frac{3d}{\sqrt{14}}\left(b_2^\dagger b_2^\dagger\right)_0 - \frac{d^3}{\sqrt{70}},$$
$$\Omega_\gamma^\dagger = \left(b_2^\dagger b_2^\dagger\right)_{22} + d\sqrt{\frac{2}{7}} b_{22}^\dagger. \tag{2}$$

The notation $|0\rangle_{(k)}$ stands for the vacuum state of the 2^k-pole boson operators. Obviously, the states (1) do not have good space reflection symmetry. Since in the laboratory frame this symmetry is valid, it should be restored by a projection procedure. Thus, one generates six sets of mutually orthogonal states:

$$\varphi_{JM}^{(i,k)} = \mathcal{N}_J^{(i,k)} P_{MK_i}^J \Psi_i^{(k)}, \quad k = \pm; i = g, \beta, \gamma, \tag{3}$$

$\mathcal{N}_J^{(i,k)}$ are renormalization factors, while $P_{MK_i}^J$ is the angular momentum projection operator for $K_i = 2\delta_{i,\gamma}$. The function $\Psi_i^{(k)}$ is the component of parity k of the intrinsic state Ψ_i. Within the boson space spanned by the projected states, one considers the following effective quadrupole and octupole boson Hamiltonian

$$H = \mathcal{A}_1\left(22\hat{N}_2 + 5\Omega_{\beta'}^\dagger \Omega_{\beta'}\right) + \mathcal{A}_2 \Omega_\beta^\dagger \Omega_\beta + \mathcal{A}_J \vec{J}^2 + \mathcal{B}_3 \hat{N}_3$$
$$+ \mathcal{B}_1 \hat{N}_3\left(22\hat{N}_2 + 5\Omega_{\beta'}^\dagger \Omega_{\beta'}\right) + \mathcal{A}_{(J23)} \vec{J}_2 \vec{J}_3. \tag{4}$$

The angular momentum carried by the 2^k-pole bosons is denoted by $\hat{J}_k$. If $\vec{J}^2$ is restricted to $\vec{J}_2^2$, the first three terms from Eq. (4) define the Hamiltonian used by the coherent state model (CSM) for ground, beta and gamma bands. Here $\hat{N}_k$, $k = 2, 3$ denotes the 2^k-pole boson number operators and $\Omega_{\beta'}^\dagger$ stands for the following second order invariant: $\Omega_{\beta'}^\dagger = (b_2^\dagger b_2^\dagger)_0 - d^2/\sqrt{5}$. Arguments supporting this choice for the model Hamiltonian are given in Refs. [6,9].

As shown in Ref. [10], the projected states are linear superposition of states with definite K-quantum number. However, in the asymptotic limit of the deformation parameter, a single K component is prevailing for each set. Assigning to each band its major K, one may say that the set of projected states given by Eq. (3) comprises two $K^\pi = 0^+$, two $K^\pi = 0^-$, one $K^\pi = 2^+$ and one $K^\pi = 2^-$ subsets. In the boson basis of projected states, the only nonvanishing matrix elements of the effective Hamiltonian are relating g^k and γ^k $(k = \pm)$ states. The eigenvalues of H depend on the structure coefficients and two deformation parameters d and f. The eight parameters were fixed by a least square procedure in order to fit the available experimental excitation energies. The interpretation of these parameters is given in Ref. [11].

The procedure is interesting not only because is able to describe a relatively large volume of data with a relatively small number of parameters but also because it provides a consistent description of the rotational degrees of freedom. Indeed, all formalisms based on quadrupole and octupole boson interaction overestimate the rotational degrees of freedom contribution. That happens since in the intrinsic frame the Eulerian angles associated to the quadrupole and octupole coordinates are independent variables. Such a redundancy is automatically removed in the present formalism due to the projection operation. Another salient feature of the coherent state formalism consists of that it represents the ideal framework for the description of the semiclassical aspects of the collective motion. In particular it provides a suitable description for the high spin states, where the nuclear system behaves semiclassically, as well as for the quadrupole and octupole deformed systems. Moreover, the mechanism for a static octupole deformation is different [11] from the traditional one where a fourth order octupole boson term is necessary [12]. As we mentioned before an octupole shaped system may have nonvanishing electric dipole moment. Also, due to the fact that the angular momentum is built up by both quadrupole and octupole bosons one expects that the magnetic properties in a given state depend on its boson composition. Such properties are expected to be met in dipole bands.

Here, we enlarge the number of bands treated by ECSM, considering the dipole parity partner bands. A possible solution for the intrinsic state generating the dipole bands is

$$\Psi^{(1,\pm)} = \Omega_3^\dagger b_{31}^\dagger \Psi_g^{(\pm)}, \quad \Omega_3^\dagger = \left[b_3^\dagger b_3^\dagger\right]_0 + \frac{f^2}{\sqrt{7}}. \tag{5}$$

From these states, two sets of angular momentum projected states are obtained, which are hereafter denoted by $\phi_{JM}^{1,\pm}$. These states are weakly coupled to the states of other bands by the $\mathcal{B}_1$ and $\mathcal{B}_3$ terms. Moreover, these terms give large contribution to the diagonal matrix elements involving the projected dipole states. Aiming at describing quantitatively the properties of the dipole states two terms are added to the model Hamiltonian

$$\Delta H = \mathcal{C}_1 \Omega_3^\dagger \Omega_3 + \mathcal{C}_2 \Omega_3^\dagger \hat{N}_2 \Omega_3. \tag{6}$$

The new terms affect only the diagonal matrix elements of the dipole states. Their strengths are fixed as follows: $\mathcal{C}_2$ is determined so that the corresponding contribution to a particular state energy, in the negative dipole band, cancels the one coming from the $\mathcal{B}_1$ term. $\mathcal{C}_1$ is fixed so that the measured excitation energy of the state 1^- is reproduced. With the parameters determined in this way, the effect of the off diagonal terms, caused by $\mathcal{B}_1$ and $\mathcal{B}_2$, on the energies of the two dipole bands, amounts to few keV. Due to this feature, the energies of the two dipole bands are obtained as the corresponding average values of the model Hamiltonian $H + \Delta H$.

Here we give the results for ^{172}Yb were members of the $K^\pi = 1^-$ band up to spin 14^- have been identified with the $^{170}\mathrm{Er}(\alpha, 2n)^{172}\mathrm{Yb}$ reaction in Ref. [13]. Also few energy levels from the $K^\pi = 1^+$ band are available [14]. The option for this isotope is justified by the fact that by contrast to the other nuclei where only very few $K^\pi = 1^-$ states are identified and moreover in most cases the positive dipole states are missing, here the energies of a reasonable large number of dipole states are known and also data for the branching ratios of the E1 transitions to the ground band states are available. To conclude, we consider this isotope the best candidate to test the formalism proposed. Concerning the nature of the dipole states our comments are as follows. Many authors believe that the states of nonvanishing K cannot be of collective nature. To give an example, the authors of Ref. [13] invoke the arguments from Ref. [15] and interpret the dipole states of negative parity as two quasi-neutron states. As one of us (A.F.) concluded in Ref. [16], based on microscopic studies with surface delta interaction, the $K^\pi = 1^-, 2^-$ bands of some actinides have, however, a collective nature. On the other hand the microscopic interpretation of the negative parity states, as two or four quasiparticle states seems not to be unique. For example the double bending, one back and one forward, seen in the ground and 0^- bands of ^{218}Ra, interpreted in Ref. [17] as caused by successive intersections of a collective band, a two neutron and a two neutron plus two proton quasiparticle bands, are fairly well reproduced by the phenomenological description provided by ECSM [9]. Although the dipole states for ^{172}Yb are considered in Ref. [13] as two quasi-neutron states, the branching ratios of the $K^\pi = 0^-, 1^-$ low lying states are realistically described within an IBA-sdf formalism in Ref. [18]. In the examples mentioned above the effect of single particle degrees of freedom is simulated by the competition between various anharmonic terms involved in the model Hamiltonian or in the transition operator. Since the head states of the negative parity bands are high in energy, one expects that at least the first states in the bands do not exhibit octupole deformation. This does not matter at all our investigation since ECSM is able to describe the negative parity states for both octupole deformed and octupole nondeformed nuclei[8]. Actually, the mentioned expectation is confirmed by the behavior of the second order energy displacement function for the $g^\pm$ and $\beta^\pm$ pairs of bands, respectively [19]. However this function, considered for the γ bands, vanish for $J = 11^-$ and 11^+ which suggests that the energies of these states have identical $A[J(J+1)]^2$ pattern. This feature might infer that the two states correspond to the same intrinsic function exhibiting both quadrupole and octupole deformation. Of course, the mentioned intrinsic state might generate, by projecting out the angular momentum and parity, two bands which are different from the $\gamma^\pm$ bands. It clearly results that bands intersection does not exclude the settlement of the octupole deformation. In this respect it is worth investigating the behavior of the first and second order energy displacement function associated to the two dipole bands.

The parameters $d, f, \mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_J, \mathcal{B}_1$ are kept the same as in Ref. [9] while the remaining ones are given in Table 1. The strengths of the ΔH terms were determined as explained before while $A_{J23}, \mathcal{B}_3$ were slightly varied around the values obtained in the above quoted reference, in order to improve the agreement in the negative parity dipole band. Energies of the $K^\pi = 1^+$ band are free of adjustable parameters.

The term ΔH given by Eq. (6) produces an energy shift of -3.562 and -3.801 MeV for the band-head states 1^- and 1^+, respectively.This energy shift compensates the excessive contribution to the excitation energies of the two dipole states caused by the harmonic octupole term $\mathcal{B}_3$. Calculated energies for $g^\pm, \beta^\pm, \gamma^\pm$ are practically the same as in Ref. [9] and therefore are not given here. As shown in Fig. 1, the energy levels of negative parity dipole bands are staggered in doublets $(J^-, (J+1)^-)$ with J-even. The staggering is present also in the $K^\pi = 1^+$ band with the difference that the doublets are of (odd, even) type. Excitation energies in the two dipole bands are used to calculate the dynamic moment of inertia which is presented in Fig. 2 as a function of angular momentum. The available experimental data are also given. Below $J = 22$, $\mathcal{J}^{(2)}$ has a saw-teeth structure for both dipole bands. For the 1^+ band the moments of inertia of odd and even spins are lying on smooth curves, respectively. The curve of odd spins lies above

Table 1
The coefficients involved in the model Hamiltonian given in units of keV

A_{J23}	$\mathcal{B}_3$	$\mathcal{C}_1$	$\mathcal{C}_2$
4.70	8328	−8853	594.45

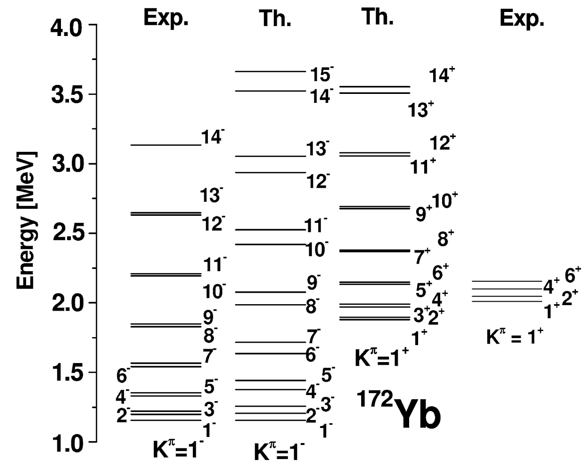

Fig. 1. Theoretical (Th.) and available experimental (Exp.) excitation energies for the $K^\pi = 1^-$ and $K^\pi = 1^+$ in ^{172}Yb. Experimental data are from Refs. [13,14].

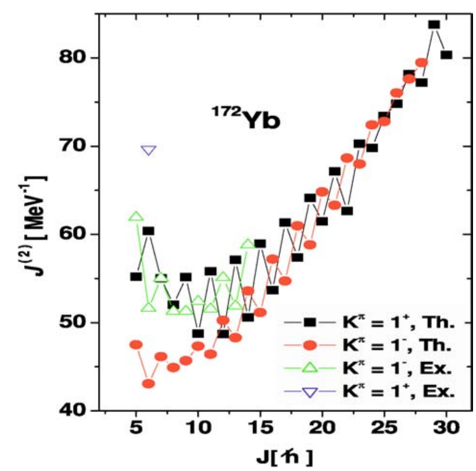

Fig. 2. The dynamic moment of inertia for the dipole bands of positive and negative parity corresponding to the calculated and experimental energies respectively, is plotted as function of the angular momentum.

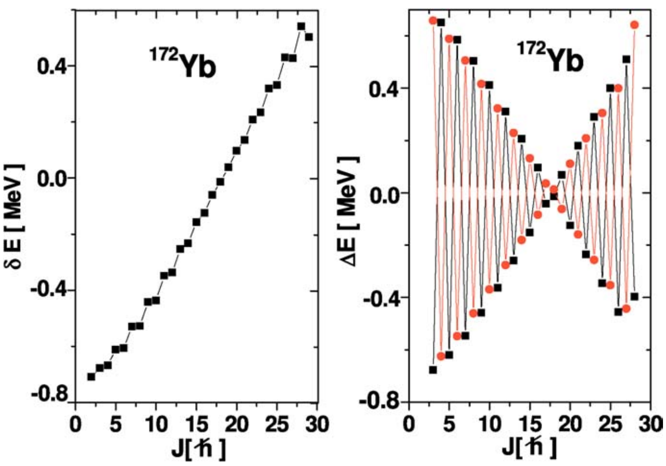

Fig. 3. The energy displacement functions δE (left panel) and ΔE (right panel), given by Eq. (7), are plotted as functions of J.

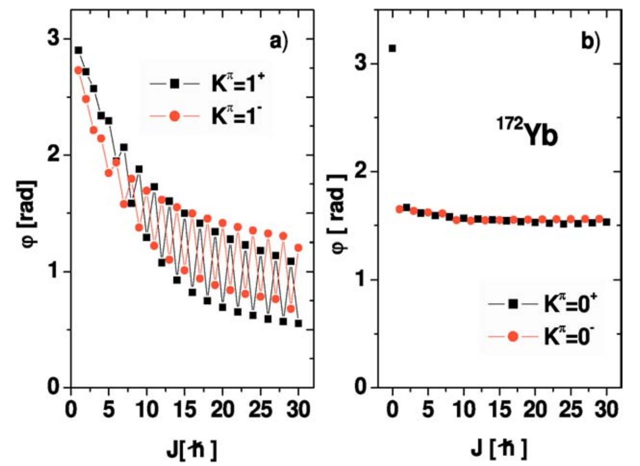

Fig. 4. The angle between the angular momenta carried by the quadrupole and octupole bosons respectively, in the states of dipole (a) and $g^{\pm}$ (b) bands, vs. angular momentum.

that of even spins. The same is true for the negative band with the difference that here the even spin states have larger moments of inertia than the odd-spin ones. Starting with $J = 19$ the odd spin states of positive parity and even spin states with negative parity have an interleaved structure. The remaining states have also an interleaved structure and moreover the two interleaved curves approach each other, when J is increased. The question is whether this interleaved structure suggests that the octupole deformation is set on. In order to answer this question we plotted in Fig. 3 the first and second order energy displacement functions defined as

$$\delta E(J^-) = E(J^-) - \frac{(J+1)E((J-1)^+) + JE((J+1)^+)}{2J+1},$$
$$\Delta E_{1,\gamma}(I) = \frac{1}{16}\big[6E_{1,\gamma}(I) - 4E_{1,\gamma}(I-1) - 4E_{1,\gamma}(I+1) + E_{1,\gamma}(I-2) + E_{1,\gamma}(I+2)\big],$$
$$E_{1,\gamma}(I) = E(I+1) - E(I). \tag{7}$$

The two functions vanish or almost vanish for $J = 18, 19$. Thus, one may say that a static octupole deformation shows up only for one state in each dipole band. However the E1 transition to the ground band does not show a jump for these angular momenta since the final state exhibits no deformation. It is worth mentioning that for $J^{\pi} = 19^+$, the M1 branching ratio to the $K^{\pi} = 0^-$ states gets the largest value in the band. In the right panel of Fig. 3, two sets of data were plotted, one having 1^+ as the lowest state (black square) while for the other one, 1^- is the lowest state (full circle). The parity assignment in the expression of ΔE is as follows. The states whose angular momenta differ by two units have the same parity while those which differ by unity are of different parities. We note that ΔE exhibits a node and a beat pattern with a large period.

Within ECSM it is possible to calculate the angle between the angular momenta carried by the quadrupole and octupole bosons respectively, in a dipole state.

$$\cos\varphi = \frac{\langle\phi_{JM}^{(k)}|\vec{J}_2.\vec{J}_3|\phi_{JM}^{(k)}\rangle}{\sqrt{\langle\phi_{JM}^{(k)}|\hat{J}_2^2|\phi_{JM}^{(k)}\rangle\langle\phi_{JM}^{(k)}|\hat{J}_3^2|\phi_{JM}^{(k)}\rangle}}, \quad k = 1, \pm. \tag{8}$$

Similarly, one may define the angle characterizing the other parity partner bands. In Fig. 4 we plot the angle vs. angular momentum for the dipole (left panel) as well as for $g^{\pm}$ bands. It is remarkable the fact that for the ground bands, excepting the state 0^+ which is characterized by an angle equal to π, the function is almost constant and quite close to $\pi/2$. This feature suggests that adding a third component (e.g., a set of particles) to the present Hamiltonian, the new system may exhibit a chiral symmetry [20]. Similar J-dependence for the angles in $\beta^{\pm}$ and $\gamma^{\pm}$ bands was obtained. A saw-teeth structure for the angle characterizing the dipole states is to be noticed. Again the function restricted to odd or even spins have a smooth decreasing behavior. The two components $\vec{J}_2$ and $\vec{J}_3$ are orthogonal for $J^{\pi} \approx 10^-, 11^+$. The angle characterizing the states J^-, $J =$ even decreases slowly reaching the value of 72° for $J = 30$. For the J^+ states with $J =$ odd, the angle decreases faster and reaches the value 60° for $J = 29$. The angle lower limits for J^- with J-odd and J^+ with J-even are about 30° and 40°, respectively. For $J^{\pi} = 18^+, 19^-$ where the static octupole deformation is settled, the $(\vec{J}_2, \vec{J}_3)$ angle is about $\pi/3$.

Concerning the decay properties of these bands, our analysis leads to the following conclusions. The $K^{\pi} = 1^+$ band may decay by M1 to g^+. Transition is caused by an anharmonic term of the transition operator

$$M_{1\mu}^{\text{anh}} = \sqrt{\frac{3}{4\pi}}g_2'\big[J^{(2)}\big(b_3^{\dagger}b_3^{\dagger}\big)_2\big]_{1\mu}. \tag{9}$$

The branching ratio $(J \to (J+1))/(J \to (J-1))$, with $J =$ odd, has an oscillating behavior as a function of J. For $J = 1$ the ratio's value is $0.369\mu_N^2$, then it decreases to the value $0.02\mu_N^2$ achieved for $J = 9$ and again increases up to $1443\mu_N^2$ for $J = 19$. We recall that for this spin the energy displacement function vanishes, which suggests that a static octupole deformation is settled. Increasing J the ratio decreases and attains the value $37.3\mu_N^2$ for $J = 29$. Intraband transitions are mainly determined by the lowest order boson expansion of the transi-

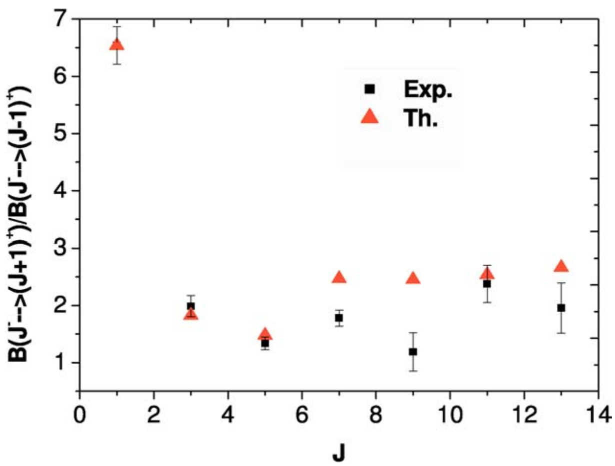

Fig. 5. Results for the branching ratios characterizing the transitions of $K^\pi = 1^-$ states to the ground band states (triangle), are compared with the corresponding experimental data (square) taken from Ref. [14]. The transition operator used is $T_{1\mu} = T_{1\mu}^{\mathrm{h}} + T_{1\mu}^{\mathrm{anh}}$ with the anharmonic term defined by Eq. (11). All ratios correspond to the relative effective charge $q_{\mathrm{anh}}/q_1 = -1.722$ where q_1 denotes the strength of the harmonic term.

tion operator

$$M_{1\mu}^{\mathrm{h}} = \sqrt{\frac{3}{4\pi}}\left[g_2 J_\mu^2 + g_3 J_\mu^{(3)}\right]. \tag{10}$$

The gyromagnetic factors have the same values as in Ref. [21]. In the band $K^\pi = 1^+$, the transitions $J \to (J-1)$ with J-even dominate those for J-odd. Moreover the $B(\mathrm{M1})$ values increases with J from $0.258\mu_N^2$ for $J = 2$ up to $4.2\mu_N^2$ when $J = 30$. In the $K^\pi = 1^-$ band, the M1 transitions $J \to (J-1)$ with J-odd prevail. They are also increasing functions of J, the values for $J = 3$ and $J = 29$ being $0.39\mu_N^2$ and $1.923\mu_N^2$, respectively. The $B(\mathrm{E1})$ values for the $K^\pi = 1^+$ to the g^- band transitions, have been calculated by using the lowest order boson expression for the E1 transition operator. The ratio $(J \to J+1)/(J \to J-1)$ with J-even is a monotonic function of J in the interval 4–28 varying from 1.3 to 10.13. For $J = 2$ the ratio value is 2.64. Concerning the E1 decay of the negative dipole band to the ground band the results are as follows. The E1 branching ratio $(J \to J+1)/(J \to J-1)$ with J-odd, is increasing monotonically with J in the interval 9-29, from 7.197 to 14.234. For $J = 1, 3, 5, 7$ the values are 28.7; 2.06; 1.31 and 8.28, respectively. Comparing the results obtained with a harmonic transition operator with the corresponding data one notices that except for the ratios corresponding to $J^\pi = 3^-, 5^-$ where the agreement is very good, the other theoretical results exceed the data by a factor varying from 3 to 6. In order to improve the agreement with the data we added to the harmonic term $T_{1\mu}^{\mathrm{h}}$, defined as in Ref. [11], an anharmonic term involving the quadrupole and octupole like angular momenta:

$$T_{1\mu}^{\mathrm{anh}} = q_{\mathrm{anh}}\left\{\left[b_3^\dagger(\hat{J}_3\hat{J}_2)_2\right]_{1\mu} + \left[(\hat{J}_2\hat{J}_3)_2 b_{\tilde{3}}\right]_{1\mu}\right\}. \tag{11}$$

As shown in Fig. 5 the results of our calculations agree reasonable well with the experimental data [14].

Concluding, the merit of the present formalism consists of that it provides a consistent description of spectroscopic properties of eight rotational bands grouped in four pairs. The members of each pair have different parities otherwise exhibit the common feature of originating from a single intrinsic state. Letting the deformation parameters go to zero the description for the quasi-rotational bands in the vibrational nuclei is readily obtained. Thus, one may say that the present formalism is suitable for a unified description of vibrational, transitional and deformed nuclei. Here the focus falls on the dipole bands. Specific properties concerning excitation energies, E1 and M1 transition probabilities are pointed out. The inter and intra-band M1 transitions can be discussed in terms of the $(\vec{J}_2, \vec{J}_3)$ angle. Signatures for static octupole deformation are tentatively attributed only to one positive and one negative parity dipole state. The positive parity state having static octupole deformation exhibits large M1 branching ratio to the ground band. One of the major points made in this Letter asserts that the parity projection operation separates the magnetic and electric properties. Indeed, the M1 transition probabilities prevail for the 1^+, while the E1 transitions associated to the 1^- band, are dominant. The numerical application shows that the ECSM provides a consistent description of both energies and the E1 branching ratios characterizing the electric dipole band in ^{172}Yb. More experimental data for excitation energies as well as for transition probabilities for both octupole deformed and spherical nuclei are needed in order to draw definite conclusions about possible fingerprints of octupole deformation in the dipole bands.

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