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Symmetry character of collective states in ^{104}Pd populated in the EC-β^+ decay of ^{104}Ag

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Abstract. The states of ^{104}Pd, populated in the EC-β^+ decay of the ground ($J^\pi = 5^+$) and metastable ($J^\pi = 2^+$) states of ^{104}Ag, have been investigated in the framework of the proton-neutron interacting boson model, extending a previous analysis to take into account the newly appeared experimental data. All positive-parity states up to an excitation energy of 3 MeV and spin in the range $J = 1$–6, fed by more than 0.3% in the decay of the parent nucleus, have been considered. As a result, strong evidence has been found for interpreting most of these states as states of collective nature having a quite pure full- or mixed-symmetry character and, in particular, for identifying the 1^+ level at 2276 keV as the lowest 1^+ mixed-symmetry state.

PACS. 21.60.Fw Collective models – 21.10.Re Collective levels – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The symmetry concept has been very fruitful in investigating the properties of nuclei and providing a simple interpretation of phenomena like, *e.g.*, regularities or peculiar features in excitation energy patterns. One of the most remarkable results of the symmetry-based interacting boson model, in the version which distinguishes proton- and neutron-bosons (IBA-2) [1], was the prediction of states non symmetric in the proton and neutron degrees of freedom, the so-called mixed-symmetry (MS) states [2,3]. The lowest MS state was predicted to have $J^\pi = 1^+$ in deformed nuclei [4] and $J^\pi = 2^+$ in spherical nuclei [5]. After the identification of the 1^+ MS in ^{156}Gd [6] in the early eighties an extensive amount of data has been collected on this state in different rotational regions and its features have also been carefully investigated from the theoretical point of view (see, *e.g.*, [7,8]). The identification of the 2^+ MS state in nuclei having a structure close to the $U(5)$ and $O(6)$ limits of the model was achieved shortly after and in the following years experimental evidence for this state was obtained by several groups [9–20]. Recently, a noticeable experimental effort has been devoted to the identification of the 1^+ MS state in γ-soft nuclei, in particular in the mass region around $A = 130$ [17,18,21,22].

In the last years we have investigated whether it was possible, through a phenomenological analysis performed in the framework of the IBA-2 model, to achieve a systematic identification of MS states, possibly not limited to the lowest-lying ones, in nuclei having quasi-spherical structure. In particular, we have focused on the $Z \simeq 50$ region and have performed a detailed analysis of excitation energy patterns and electromagnetic properties of positive-parity levels in even $^{98\text{-}114}$Ru ($Z = 44$) [23,24], $^{100\text{-}116}$Pd ($Z = 46$) [25,24], $^{110\text{-}114}$Cd ($Z = 48$) [10,26]. In these analyses the model parameters vary smoothly along a particular isotopic chain and among isotones in neighboring isotopic chains, as required by the collective character of the states under study.

An IBA-2 analysis of the palladium chain has recently been performed also by Kim *et al.* [27] paying special attention to the identification of the lowest 2^+ and 3^+ MS states.

In a recent experimental work [28] we have studied the nucleus ^{104}Pd populated through the EC-β^+ decay of the ground ($J = 5^+$) and metastable ($J = 2^+$) states of ^{104}Ag. The measurements of γ-γ coincidences, angular correlations and K-conversion coefficients have provided new information on spin parity, branching ratios of levels up to about 3.6 MeV as well as on $\delta(E2/M1)$ mixing ratios of several transitions and allowed the identification of the lowest 1^+ state at 2276 keV. These results led us to extend the analysis of ^{104}Pd performed in [25] where, by comparing experimental and calculated energies, branching ratios and $B(E2)$ values, a group of fully symmetric (FS) states (0_1^+, 2_1^+, 4_1^+, 2_2^+, 0_2^+, 6_1^+, 4_2^+, 8_1^+) and, below

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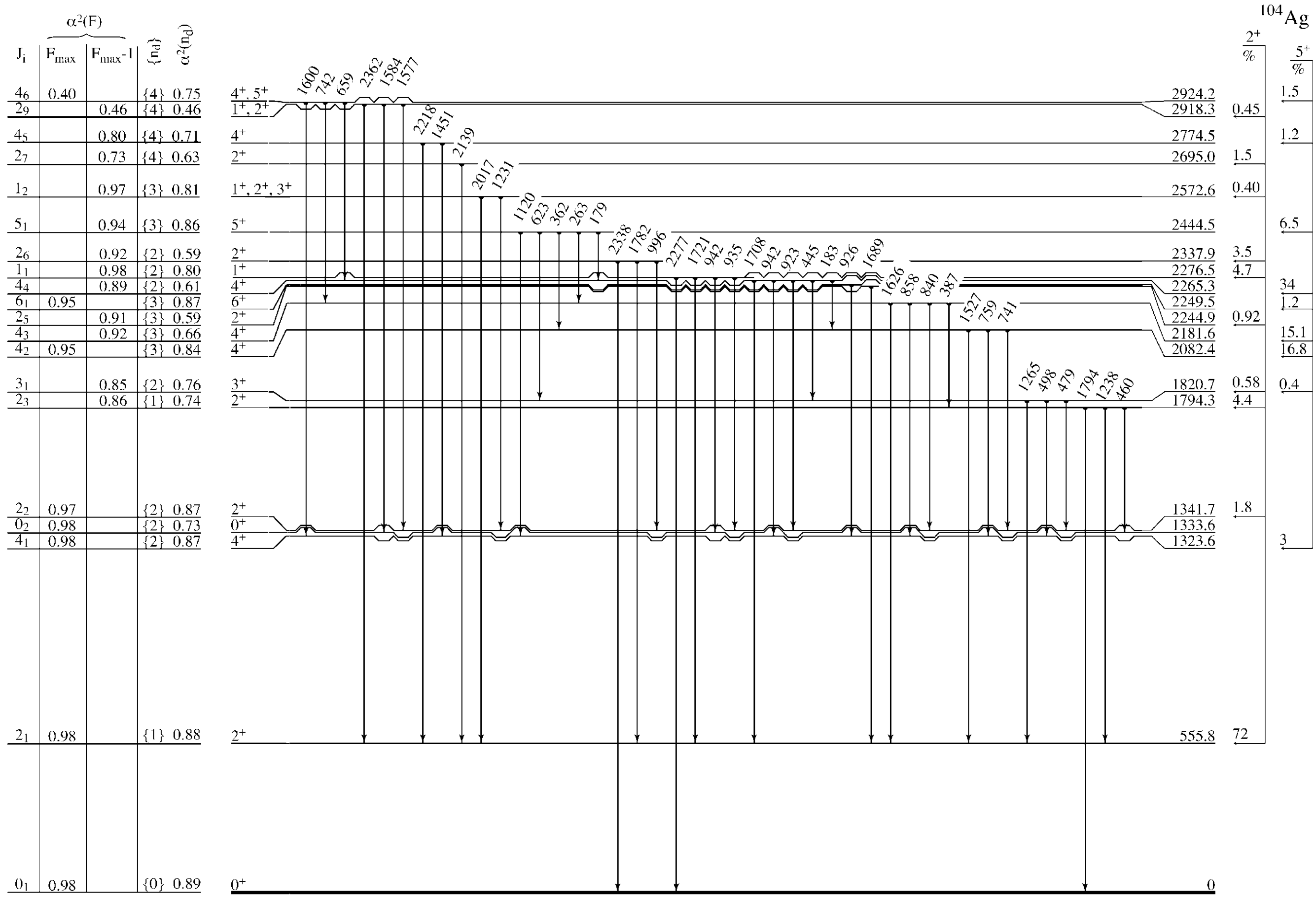

Fig. 1. Positive-parity levels of ^{104}Pd populated in the β^+-EC decay of $^{104\mathrm{g,m}}$Ag by more than 0.3% and interpreted as collective states in the IBA-2 model. Their percent feeding is reported on the right. The calculated levels associated with the experimental ones are shown on the left. For each predicted state the spin and ordinal i, the squared amplitude α^2 of the predominant F-spin and n_d components together with the value $\{n_d\}$ of the dominant component are displayed.

2.3 MeV, two groups of MS states (the first one consisting of the 2_3^+, 4_4^+, 0_4^+ states and the second one of the 3_1^+, 4_3^+, 2_4^+ states) were identified.

In this work we report the results of the new analysis where all positive-parity states up to 3 MeV populated to an extent $> 0.3\%$ in the EC-β^+ decay of $^{104\mathrm{g,m}}$Ag have been taken into account.

2 Symmetry character of states in ^{104}Pd

The calculations performed in [25] have been extended keeping the same values of the parameters appearing in the Hamiltonian and in the $E2$ and $M1$ transition operators, except for the Majorana parameter ξ_1, which strongly affects only the energies of a group of MS states having the 1^+ state as the lowest one.

Since at the time of our previous analyses no 1^+ state was definitely identified below 2 MeV in any of the above-mentioned nuclei, the value of ξ_1 was kept fixed at 1 MeV, so as to push the 1_1^+ state at an energy $\geq$ 2 MeV. In particular, in ^{104}Pd its energy was predicted at 2.902 MeV. It was also checked that the possibility of reproducing the properties of all the states identified in these analyses as having MS character was practically independent of ξ_1.

The $J = 1$ assignment to the 2276 keV positive-parity level in ^{104}Pd [28] led us to investigate whether this state could be identified with the lowest 1^+ MS state (we recall that no 1^+ FS state is predicted by the IBA-2 model). We therefore decreased the value of ξ_1 to 0.3 MeV so that the calculated energy of the lowest 1^+ state could match that of the experimental one. As a consequence, three additional levels of spin 1, 2, and 3 are predicted below 3 MeV as compared to [25]. The change in the ξ_1 value does not significantly affect the predicted properties of the other states of ^{104}Pd up to 3 MeV. Indeed, *e.g.*, the maximum variation in the excitation energies is less than 1% and the changes in the values of calculated mixing ratios lie well within the typical experimental uncertainty.

The calculations have been performed by using the NPBOS code [29] which diagonalizes the Hamiltonian in a $U(5)$ basis and provides as outputs, in addition to the standard quantities, the F-spin and n_d (d-boson number) components of the wave functions of the states. In the $U(5)$ limit, FS states are characterized by the maximum F-spin value ($F_{\max} = N/2$, where N is the total number of bosons) and MS states by the quantum numbers $F_{\max}-1$, $F_{\max}-2$ .., etc.

In our previous analyses we found that the mixing of the F-spin components induced by the use of a realistic Hamiltonian was, in most cases, sufficiently limited to allow a clear cut distinction between states of FS and MS character.

The number of positive-parity states in ^{104}Pd up to 3 MeV, with spin in the range $J = 1$–6, populated in the decay of $^{104\mathrm{g,m}}$Ag amounts to 33 and their feeding varies over more than four orders of magnitude. The states in this spin range already identified in [25] as having collective nature are strongly populated in the β^+ decay, with an intensity varying from 72% to about 1% [30]. In the present analysis we have considered all the positive-parity states (21) up to 3 MeV fed with an intensity larger than 0.3%.

To establish a possible correspondence between the experimental states (not already taken into account in [25]) and the calculated ones we have compared excitation energies and branching ratios of the levels and mixing ratios of the de-exciting gamma transitions. For each experimental level of spin J, we have considered as possible theoretical candidates those of the same spin having an excitation energy differing from the experimental one by less than 10%. This constraint was suggested by our previous results where the agreement between experimental and predicted excitation energy was generally well within this limit. For the states at 2572, 2918, 2924 keV, whose spin have different possible values, an enlarged set of candidates was considered.

No predicted state could be associated to the 2^+, 2533 keV and 4^+, 2571 keV levels. In almost all other cases only one theoretical candidate was clearly favored by the decay mode, leading to the association shown in fig. 1. Here, on the right are reported the experimental levels populated by more than 0.3% from the 2^+ and 5^+ states of ^{104}Ag together with their feeding, on the left the corresponding predicted states identified in the present or in our previous analysis. For the latter, spin and ordinal i, squared amplitudes (α^2) of the predominant $F_{\max}$ or $F_{\max}-1$ component and of the predominant n_d components are shown. The detailed structure of the 4^+ states is displayed, as an example, in fig. 2. This point will be further considered in the subsect. 2.2.

The experimental and predicted data concerning the energies of the states first taken into account in the present work and the decay properties of all the levels for which new spectroscopic data became recently available [28] are compared in fig. 3.

As is well known [31,32,27,33] even palladium isotopes display an $U(5) \to O(6)$ transitional character in going from the lighter to the heavier isotopes. This has been confirmed by the analysis performed in [25] where, in particular, it was found that the collective states in ^{100,102,104}Pd display a structure very close to that of the $U(5)$ limit of the model, *i.e.*, characterized by a quite pure $F_{\max}$ or $F_{\max}-1$ character and a single n_d component clearly overwhelming the other ones. From the present work and our

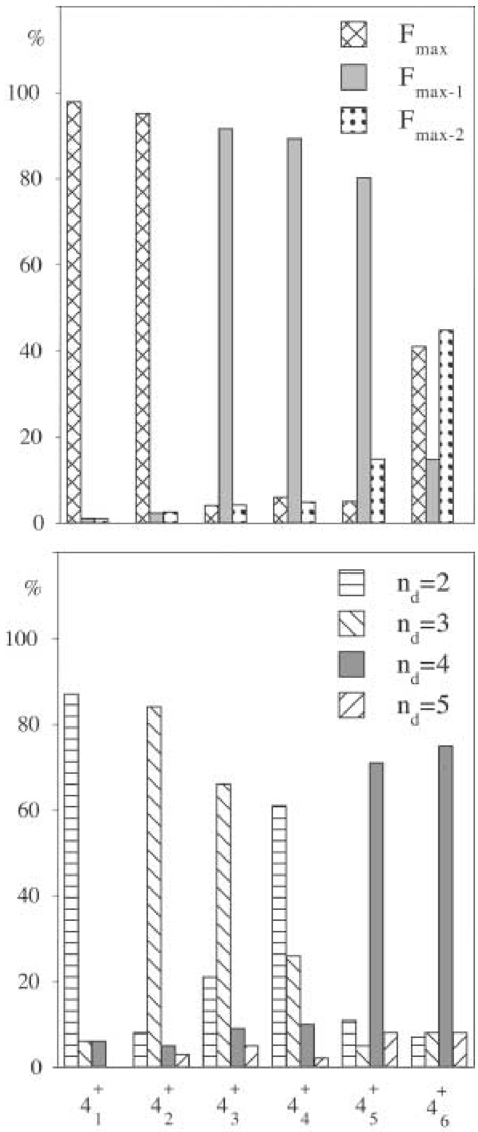

Fig. 2. Squared amplitudes (given as percentage) of the F-spin and of the four largest n_d components for the 4^+ states.

previous study it turns out that this is just the structure of all the states reported in fig. 1 , apart from a few levels above 2.8 MeV, whose wave functions have different F-spin (n_d) components of comparable squared amplitudes. As displayed in fig. 4, these states can be rearranged in different groups resembling the pattern reported in the inset of the same figure where the eigenstates of the simplest $U(5)$ Hamiltonian ($H = \epsilon \hat{n}_d + \hat{M}$, where $\hat{M}$ is the Majorana operator) are shown. Here the FS states are reported in column (a), the $F = F_{\max}-1$ states in the three columns (b), (c), (d) according to the different dependence of their excitations energies on the Majorana parameters ξ_1, ξ_2, ξ_3 [34,25]; we remark that the parameter ξ_1 affects only the energy of the states in column (d). The correspondence of the four columns in which are arranged the states of ^{104}Pd with those in the $U(5)$ limit is stressed by the use of the same labels (a), (b), (c), and (d). On the

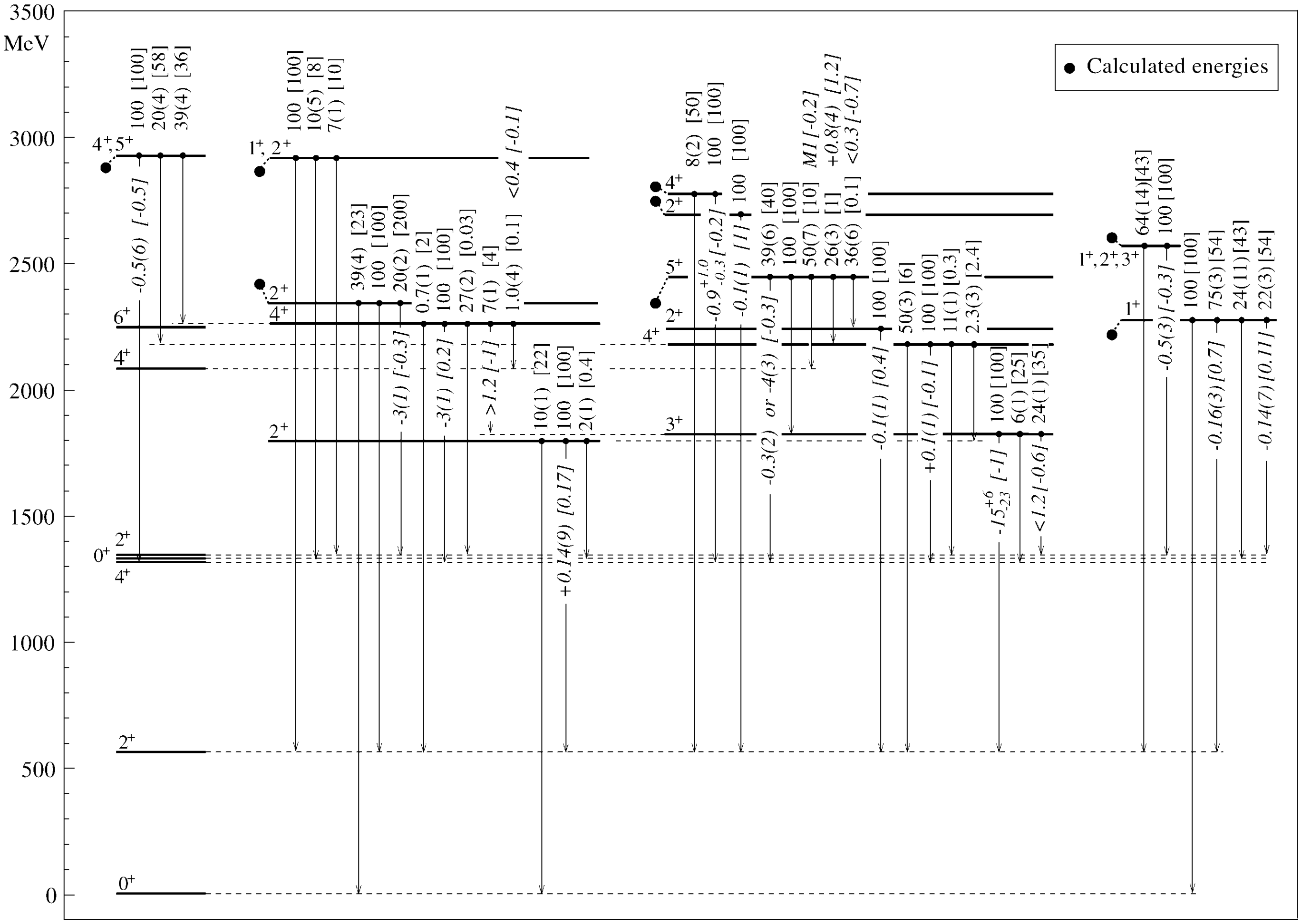

Fig. 3. Comparison of experimental and calculated energies (full circles) for the states first taken into account in the present work and decay properties of all the levels for which new spectroscopic data have become recently available [28]. The relative intensities of the de-exciting transitions are reported above each level, the $E2/M1$ mixing ratios (in italics) are normally reported along the arrow representing the transition. Limits for δ refer to absolute values. The calculated quantities are reported in square brackets.

right-hand side of fig. 4 are shown the positive-parity experimental states up to $\simeq 3$ MeV in ^{106}Pd which, on the basis of the analysis performed in [25], can be grouped in three columns (a), (b), and (c) having the same meaning as for ^{104}Pd.

In the next subsections we will discuss in detail the arguments to assign a given state to a particular group in fig. 4 . To this aim also the signatures provided by the decay properties of the states in the $U(5)$ limit will be exploited. In this limit, $M1$ and $E2$ transitions satisfy the selection rules $\Delta n_d = 0$ and $\Delta n_d = 0$ or ± 1, respectively. $M1$ transitions are forbidden between FS states whereas they are enhanced between $F = F_{\max} - 1$ and $F = F_{\max}$ states [9]. Proton and neutron $E2$ transition matrix elements between $F_{\max} - 1$ and $F_{\max}$ states have equal absolute values and opposite sign so that, for close values of effective proton and neutron charges, $B(E2)$ values are small. Hence one of the most important features for the identification of MS states is that they can decay to FS state having the same n_d component via strong $M1$ transitions, *i.e.*, via transitions having a small $E2/M1$ mixing ratio.

In the following, to help the reader in the discussion, the predicted states will be reported in square brackets.

2.1 States in column (a)

The experimental states of ^{104}Pd reported in column (a) and represented by a full line have been interpreted in [25] as states of FS character.

The level at 2924 keV ($J = 4^+$ or 5^+) is tentatively associated to the $[4_6]$ state at 2880 keV; it is represented in column (a) by a dashed line since its wave function has a largely predominant $n_d = 4$ component, as expected for a state belonging to the $n_d = 4$, FS "multiplet", but comparable $F_{\max}$ and $F_{\max} - 2$ components (see fig. 2). To account for such a structure we observe that the calculations predict at about 2.9 MeV a second 4^+ state ($[4_7^+]$ at 2897 keV) which also has a predominant $n_d = 4$ component and comparable $F_{\max}$ and $F_{\max} - 2$ components. The

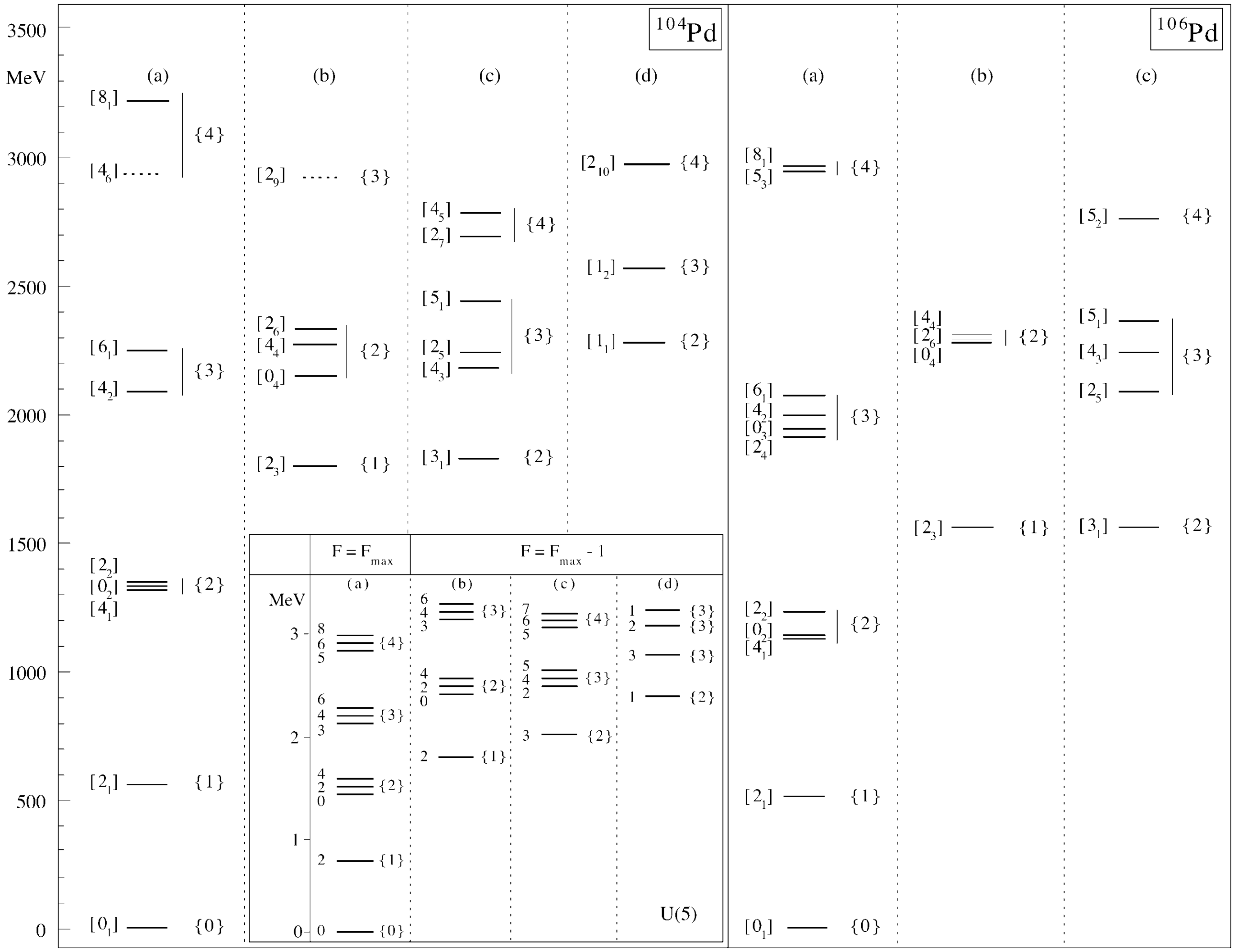

Fig. 4. Experimental levels up to 3 MeV in ^{104}Pd and ^{106}Pd which are interpreted as having collective character. Close to each experimental state is reported the label J_i of the corresponding predicted one. A vertical line defines a group of states having the same predominant $\{n_d\}$ component. In the panel at the bottom of the figure the $F = F_{\max}$ and $F = F_{\max} - 1$ states in the $U(5)$ limit are schematically represented. States in columns (a), (b), (c) belong to degenerate n_d-multiplets, displayed slightly splitted for the sake of clarity. The states in ^{104}Pd and ^{106}Pd are analogously reported in separate columns to stress their correspondence with the $U(5)$ states.

structure of these two states can be traced back to that of the two 4^+ states which, in the $U(5)$ limit, belong to the $n_d = 4$ FS multiplet and $F_{\max} - 2$ triplet (see [24] for the latter). The value of δ reported in fig. 3 for the transition to the 4_1^+ state is that deduced in [28] in the hypothesis of $J = 4$.

2.2 States in column (b)

The identification of the lowest MS state in ^{104}Pd with the 2_3^+ state at 1794 keV was proposed by Kim *et al.* [27] who, in the analysis of even palladium isotopes (performed in the framework of the IBM-2 model by using parameters consistent with microscopic calculations) identify also the lowest 2^+ MS state in ^{106}Pd.

The same conclusions were independently drawn by our group [35]. In [25] we further associate the states 4^+ at 2265 keV and 0^+ at 2138 keV of ^{104}Pd to the $[4_4^+]$, $[0_4^+]$ states whose structure is close to that of the $[4^+]$, $[0^+]$ states belonging to the 2d-boson MS triplet in the $U(5)$ limit (column (b) in the inset of fig. 4).

As to the relevance of the new experimental data on ^{104}Pd [28], we first note that the small value deduced for $\delta(2_3^+ \to 2_1^+)$ provides further support to the identification of the 2_3^+ state as the lowest 2^+ MS state and, secondly, that its value allows to deduce a lower limit for $B(E2; 2_3^+ \to 0_1^+)$, $B(E2; 2_3^+ \to 2_1^+)$ and $B(M1; 2_3^+ \to 2_1^+)$ when combined with the upper limit [30] of the half-life ($T_{1/2} < 1.4$ ps) and the known branching ratios of the 2_3^+ level.

The experimental data on the $B(E2)$ and $B(M1)$ of the transitions de-exciting the 2_3^+ state and on $\delta(2_3^+ \to 2_1^+)$ in ^{104}Pd and ^{106}Pd are compared in table 1 with those calculated in [27] for both isotopes, in the present work for

Table 1. Comparison of experimental and calculated values of $B(E2)$ (in e^2b^2), $B(M1)$ (in μ_N^2) and δ for the indicated transitions and of the dipole magnetic moment of the 2_1^+ state (in μ_N) in ^{104,106}Pd. The experimental values of $B(E2; 2_1^+ \rightarrow 0_1^+)$ and $\mu(2_1^+)$ in ^{104}Pd and ^{106}Pd are from [36] and [37], respectively. In ^{106}Pd the experimental $B(E2)$ values of the transitions de-exciting the 2_3^+ state are from [38] whereas the experimental value of $B(M1; 2_3^+ \rightarrow 2_1^+)$ is deduced from that of the $B(E2; 2_3^+ \rightarrow 2_1^+)$ and from the value of $\delta(2_3^+ \rightarrow 2_1^+)$ reported in [37]. The values for the effective charges and gyromagnetic factors adopted in [27] are $e_\pi = 0.12$ eb, $e_\nu = 0.10$ eb and $g_\pi = 1\ \mu_N$, $g_\nu = 0\ \mu_N$ while those adopted in [25] and in the present work are $e_\pi = 0.095$ eb, $e_\nu = 0.11$ eb and $g_\pi = 0.51\ \mu_N$, $g_\nu = 0.28\ \mu_N$ (the values of $g_{\pi,\nu}$ are the same as in the ruthenium chain [23]). The values of $\delta(2_3^+ \rightarrow 2_1^+)$ in column (4) and (7) are deduced from the calculated $B(E2)$ and $B(M1)$ values reported in the same column.

	^{104}Pd			^{106}Pd		
	Experiment	Present work	[27]	Experiment	[25]	[27]
$B(E2; 2_1^+ \rightarrow 0_1^+)$	0.105(6)	0.096	0.116	0.137(9)	0.122	0.142
$B(E2; 2_3^+ \rightarrow 2_1^+)$	$> 3 \times 10^{-4}$	4×10^{-4}	1×10^{-4}	$16(3) \times 10^{-4}$	4×10^{-4}	10^{-8}
$\mu(2_1^+)$	0.82(6)	0.74	0.84	0.80(4)	0.72	0.78
$B(M1; 2_3^+ \rightarrow 2_1^+)$	> 0.008	0.017	0.568	0.021(4)	0.011	0.361
$\delta(2_3^+ \rightarrow 2_1^+)$	+0.14(9)	+0.17	±0.01	+0.24(1)	+0.17	$\pm 10^{-4}$

^{104}Pd and in [25] for ^{106}Pd. In the same table is also reported the comparison of $B(E2; 2_1^+ \rightarrow 0_1^+)$, to give an idea of the kind of agreement obtained for allowed $E2$ transitions, and on $\mu(2_1^+)$, whose value depends on both the effective gyromagnetic factors (instead those of $B(M1)$'s depend only on their difference).

Both the calculated values reported in columns (3) and (4) for $B(E2; 2_3^+ \rightarrow 2_1^+)$ and $B(M1; 2_3^+ \rightarrow 2_1^+)$ are consistent with the experimental limits. However, this is not the case for the corresponding quantities in ^{106}Pd which are better reproduced by the calculations in [25]. Since an abrupt change in the properties of corresponding states of collective nature in neighboring isotopes is very unlikely, one can reasonably assume that the values of $B(E2)$ and $B(M1)$ in ^{104}Pd, for which only lower limits are known, are close to those measured in ^{106}Pd. The values predicted in the present work for the reduced transition probabilities of the transitions de-exciting the $[2_3^+]$ state in ^{104}Pd would then have at least the right order of magnitude. This is confirmed by the good agreement found between experimental and calculated value of $\delta(2_3^+ \rightarrow 2_1^+)$.

As to the 4_4^+ state at 2265 keV, its preferential decay to the 4_1^+ state is just that expected for the lowest 4^+ state of column (b). However, the values predicted for the branching to the $[2_2^+]$ state and for $\delta([4_4^+] \rightarrow [4_1^+])$ are smaller than the experimental values. At the same time, the predicted value [−10] of $\delta([4_2^+] \rightarrow [4_1^+])$ is overestimated with respect to the experimental one [−0.8(2)] [25]. Taking into account the detailed structure of the $[4_2^+]$ and $[4_4^+]$ states (see fig. 2), the above-mentioned selection rules and the small difference in the excitation energy of the corresponding experimental states it is apparent that some stronger mixing of these states would be needed.

The "missing member" of the $n_d = 2$ "triplet" is here identified with the 2^+, 2338 keV level, associated to the $[2_6^+]$ state. The experimental and calculated energies differ by less than 3.5% and the branching ratios to the 0_1^+ and 2_1^+ states are correctly reproduced. However, the intensity of the transition to the 2_2^+ state, predicted to have predominant $M1$ character, is overestimated and the value of $\delta([2_6^+] \rightarrow [2_2^+])$ turns out to be small with respect to the experimental one. Analogously to the case of the $[4_4^+]$ state, it seems that the calculations predict a too pure $F = F_{\max} - 1$, $n_d = 2$ structure for the $[2_6^+]$ state, which reflects in a too strong $M1$ transition towards the $[2_2^+]$ state which has a quite pure $F = F_{\max}$, $n_d = 2$ structure.

For the $1^+, 2^+$, 2918 keV state we propose the association to the $[2_9^+]$, 2875 keV state. The squared amplitudes of its predominant components are $\alpha^2(F_{\max}) = 0.40$, $\alpha^2(F_{\max} - 1) = 0.46$, $\alpha^2(n_d = 3) = 0.41$, and $\alpha^2(n_d = 4) = 0.46$. It has been reported in column (b) of fig. 4 (because of its largest F-spin component) with a dashed line to mean that its structure is almost equally shared between the 2^+ states belonging to $n_d = 4$ "multiplet" of column (a) and $n_d = 3$ "multiplet" of column (b).

2.3 States in column (c)

In the search performed by Kern *et al.* [39], in the framework of the IBA-1 model, for nuclei exhibiting the $U(5)$ dynamical symmetry it was apparent that the main problem for ^{104}Pd was related to the 3_1^+ state at 1820 keV. The identification of this state as the lowest 3^+ MS state in ^{104}Pd was proposed by Kim *et al.* [27] and, independently, by our group [35].

Further support to this identification is provided by the compatibility of the predicted value of $\delta([3_1^+] \rightarrow [2_2^+])$ with the experimental upper limit for its absolute value [28]. In the light of what stated at the beginning of sect. 2, this is particularly significant since, in our interpretation, the $[3_1^+] \rightarrow [2_2^+]$ transition would be a "$\Delta F = 1$" transition connecting two states having the same predominant $n_d = 2$ component. On the other hand, the new experimental value of δ $[-15^{+6}_{-23}]$ [28] (which is at variance with that reported in [36] but compatible with the lower limit $|\delta| >$

13 given in [40]) is not sufficiently precise to allow a useful comparison with the predicted one.

In [25] we have associated the levels 4^+ at 2182 keV and 2^+ at 2245 keV in ^{104}Pd to the $[4_3^+]$, $[2_5^+]$ states whose structure is similar to that of the $[4^+]$, $[2^+]$, 3d-boson states of column (c) in the inset of fig. 4. The new experimental data [28] on the mixing ratios of the transitions de-exciting the two states and the branching ratio of the $4_3^+ \rightarrow 2_3^+$ transition confirm the model predictions; this meaning that the structure of these states is predicted correctly.

In the $U(5)$ limit the third member of the 3d-boson triplet has spin 5 and its decay is characterized by a strong transition to the 2d-boson $[3^+]$ MS state and by a large $M1$ component in the transition to the 3d-boson $[4^+]$ FS state. The 2444 keV state, to whom has been assigned spin 5 in [28], displays just these decay features and has therefore been associated to the $[5_1^+]$ state at 2343 keV of quite pure $n_d = 3$ and $F = F_{\max} - 1$ structure. We remark that the attempt to identify the 2444 keV level with the lowest 5^+ FS state would fail not only on the basis of the excitation energy (predicted at 2989 keV) but also because no important branching to the 3^+ MS state is predicted and, in any case, the transition to the 4_2^+ state would have a quite strong $E2$ component.

The 2^+, 2695 keV and 4^+, 2774 keV levels have been identified with the $[2_7^+]$ and $[4_5^+]$ states, which are members of the 4d-boson "multiplet" of column (c), respectively. Indeed, the experimental excitation energies are reproduced to better than 2%; moreover, the 2695 keV state de-excites only via a transition to the 2_1^+ level and it has been checked that the $[2_7^+] \rightarrow [2_1^+]$ transition is the strongest one among the nine calculated transitions taken into account in evaluating the branching ratios from the $[2_7^+]$ state. Finally, the $[4_5^+]$ state is predicted to decay mainly to the $[4_1^+]$, $[2_1^+]$ states, as observed experimentally.

2.4 States in column (d)

The identification of the 1^+ MS state in non deformed nuclei was first achieved in ^{200}Hg, which has an $U(5) \rightarrow O(6)$ transitional structure [41]. The search for the 1^+ MS state in γ-soft nuclei has led to its identification in ^{196}Pt [21], in some nuclei of the $A \simeq 130$ region [11,22,17,42] and in ^{94}Mo [17,18]. The vibrational ^{112}Cd nucleus has recently been investigated by Lehman *et al.* [43] who propose positive parity for the state of spin 1 at 2931 keV and its identification as the 1^+ MS state.

As to ^{104}Pd, in view of a possible identification of the level at 2276 keV as the lowest 1^+ MS state we have considered the signatures [32,44] characterizing the decay of the 2d-boson 1^+ MS state in the $U(5)$ limit: the $M1$ transitions to $[0_1^+]$ and $[2_1^+]$ states are forbidden whereas those to the 0_2^+ and 2_2^+ are enhanced and a strong $E2$ transition is predicted to the lowest 2^+ MS state. Ratios of $B(E2)$, $B(M1)$ and $\Delta(E2/M1)$ reduced mixing ratios $[\Delta = \langle J_f \| \hat{T}(E2) \| J_i \rangle / \langle J_f \| \hat{T}(M1) \| J_i \rangle]$ of transitions de-exciting the 1^+ state with respect to a proper reference transition turn out to be independent of the model parameters [45] since their analytical expressions contain only the boson numbers. These quantities are reported in column (1) of table 2 by using the symbols 1_M^+, 2_M^+ to indicate the lowest 1^+ and 2^+ MS states in the $U(5)$ limit and the $[1_1^+]$ and $[2_3^+]$ states in ^{104}Pd. The values of the ratios reported in column (2) have been calculated in the $U(5)$ limit for a nucleus having the same neutron- and proton-bosons as ^{104}Pd $[N_\pi = 2,\ N_\nu = 4]$. It is seen that the $B(M1)$ values of the transitions connecting the $[1_M^+]$ state to the $[2_2^+]$ and $[0_2^+]$ states are comparable to that of the $B(M1; [2_M^+] \rightarrow [2_1^+])$ and that the value of the $B(E2; [1_M^+] \rightarrow [2_M^+])$ is comparable to that of the $B(E2; [2_1^+] \rightarrow [0_1^+])$. The ratios of $B(E2)$ and $B(M1)$ for the corresponding transitions in ^{104}Pd, obtained from the realistic calculations performed in the present work, are reported in column (3) of table 2; it is apparent that their values are rather close to those evaluated in the $U(5)$ limit.

In the decay of the 2276 keV level all the transitions corresponding to those reported in table 2 as de-exciting the 1^+ MS state have been observed, apart from that to the lowest 2^+ MS state. However, even though the $[1_1^+] \rightarrow [2_3^+]$ transition is predicted to have a $B(E2)$ value [0.079 e^2b^2] comparable to that of the $[2_1^+] \rightarrow [0_1^+]$ transition, its calculated branching ratio amounts only to 5% of the most intense transition de-exciting this level.

As seen in fig. 3, the realistic calculations are able to reproduce the branching ratios of the 2276 keV level whose de-exciting transitions have $M1$ multipolarity (to the 0_1^+ and 0_2^+ states) or a strongly predominant $M1$ component (to the 2_1^+ and 2_2^+ states, as deduced from the measured mixing ratios). This basically means that they are able to reproduce the $B(M1)$ ratios of the transitions de-exciting this state. In addition, the present calculations predict the magnitude of $\Delta([1_1^+] \rightarrow [2_2^+])$ to be close to that of $\Delta([2_3^+] \rightarrow [2_1^+])$; indeed the corresponding experimental values turn out to be $-0.18(9)$ and $0.13(9)$, respectively [28].

Table 2. The values of the ratios indicated in column (1), predicted in the $U(5)$ limit for a nucleus having the same proton- and neutron-bosons as ^{104}Pd, are given in column (2). Those obtained from the realistic calculations performed in the present work are reported in column (3).

	$U(5)$	Present work
$B(E2; 1_M^+ \rightarrow 2_1^+)/B(E2; 2_M^+ \rightarrow 0_1^+)$	1	0.91
$B(E2; 1_M^+ \rightarrow 2_2^+)/B(E2; 2_M^+ \rightarrow 2_1^+)$	0.78	0.97
$B(E2; 1_M^+ \rightarrow 2_M^+)/B(E2; 2_1^+ \rightarrow 0_1^+)$	1	0.82
$B(M1; 1_M^+ \rightarrow 0_1^+)/B(M1; 2_M^+ \rightarrow 2_1^+)$	0	0.15
$B(M1; 1_M^+ \rightarrow 2_1^+)/B(M1; 2_M^+ \rightarrow 2_1^+)$	0	0.12
$B(M1; 1_M^+ \rightarrow 0_2^+)/B(M1; 2_M^+ \rightarrow 2_1^+)$	0.80	0.91
$B(M1; 1_M^+ \rightarrow 2_2^+)/B(M1; 2_M^+ \rightarrow 2_1^+)$	1.40	1.15
$\Delta(1_M^+ \rightarrow 2_2^+)/\Delta(2_M^+ \rightarrow 2_1^+)$	0.65	0.92

To summarize, the decay properties of the 2276 keV level are closely matched by those of the $[1_1^+]$ state (which displays the signatures characterizing the $[1_M^+]$ state in the $U(5)$ limit) so that we propose the identification of this state as the lowest $[1^+]$ MS state. However, in the absence of any systematic information on the 1^+ MS state in nuclei close to the $U(5)$ limit, a word of caution is in order and any definite conclusion on the nature of this state can only be drawn from the measurement of absolute transition strengths for the de-exciting transitions. From our analyses of the ruthenium and palladium chains [23, 25] and from the discussion on the 2_3^+ states in ^{104,106}Pd given above it turns out that the $B(M1)$ strength should have values of $\simeq 10^{-2}\mu_N^2$ for "allowed" transitions.

We note that the properties of the 2276 keV level differ considerably from those observed for the $[1^+]$ MS states in γ-soft nuclei, one of the most striking differences being related to the decay to the ground state. Indeed, in nuclei having a structure close to the $O(6)$ limit (where, as is well known, the $1_M^+ \to 0_1^+$ transition is allowed) the lowest 1^+ MS state, which appears normally to be fragmented, has a summed $B(M1; 1_M^+ \to 0_1^+)$ strength of $\simeq 0.1$–$0.2\ \mu_N^2$ (see, *e.g.*, [46]).

The calculations predict for the $[1_2^+]$ state an excitation energy of 2603 keV, very close to that of the $J^\pi = 1^+, 2^+, 3^+$ state at 2573 keV. Since the branching ratios are well reproduced and the value of the mixing ratio for the transition to the 2_2^+ state (deduced in [28] in the hypothesis of $J = 1$) compares well with the predicted one we propose to identify the 2573 keV state with the second excited state of column (d).

3 Conclusions

The study we have performed [25] in the framework of the IBA-2 model of low-lying states in ^{104}Pd has led to the identification of the lowest 2^+ and 3^+ MS states at about 1.8 MeV (independently proposed by Kim *et al.* [27]) and of four more MS states at about 2.2 MeV. The new experimental information that we have recently obtained [28] on spin parity and decay properties of the levels of this nucleus, populated in the EC-β^+ decay of $^{104\mathrm{g,m}}$Ag, led us to extend the calculations to higher energies. In the analysis, the same model parameter as in [25] have been used, apart from the Majorana parameter ξ_1 whose value has been changed to investigate whether the positive-parity state at 2276 keV, to which we assigned spin 1, could be identified as the lowest 1^+ MS state.

On the basis of the comparison of experimental and predicted properties, eight additional levels up to 3 MeV of spin $J = 1$–5 have been identified or proposed as states of collective nature.

The organizing ability of the model is evident from fig. 4 where all the states of fig. 1 are sorted in four separated groups that correspond to those in which can be arranged the $F_{\max}$ and $F_{\max} - 1$ states in the $U(5)$ limit. In the same figure are also reported the states of ^{106}Pd identified as collective ones in [25], analogously arranged in groups to stress the similarity in the structure of the two isotopes. One can observe that

i) all the members of the $n_d = 2$ and $n_d = 3$ "triplets" have been identified in both ^{104}Pd and ^{106}Pd;
ii) complementary information for the $n_d = 4$ "multiplets" are provided by the states in the two isotopes;
iii) the average energy of the corresponding n_d "multiplets" decreases from ^{104}Pd to ^{106}Pd, as expected for states of collective nature when the neutron number increases toward the middle of the shell (50–82);
iv) altogether, forty collective states have been proposed or identified in the two isotopes. As to ^{104}Pd, strong indications for the identification of the lowest 1_1^+ MS state with the 2276 keV state are provided.

In conclusion, it appears that about 60% of the states up to 3 MeV populated in the decay of ^{104}Ag can be interpreted as collective ones and that the β decay is very effective in populating MS states. How this could happen has been first illustrated by Iachello [47] for nuclei having a structure close to the $U(5)$ limit; as an example he considered the decay of the 1^+, ground state of ^{100}Tc to the 2_3^+ state in ^{100}Ru, identified in [15] as the lowest 2^+ MS state. The detailed description of a process like the EC-β^+ decay of ^{104}Ag, where several FS and MS states are populated, is a major challenge for the otherwise well-tested interacting boson- and fermion-boson models.

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References

1. F. Iachello, A. Arima, *The Interacting Bosons Model* (Cambridge University Press, Cambridge, 1987).
2. A. Arima, T. Otsuka, F. Iachello, I. Talmi, Phys. Lett. B **66**, 205 (1977).
3. T. Otsuka, A. Arima, F. Iachello, I. Talmi, Phys. Lett. B **76**, 139 (1978).
4. F. Iachello, Nucl. Phys. A **358**, 89c (1981).
5. F. Iachello, Phys. Rev. Lett. **53**, 1427 (1984).
6. D. Böhle, A. Richter, W. Steffen, A.E. L. Dieperink, N. Lo Iudice, F. Palumbo, O. Scholten, Phys. Lett. B **137**, 27 (1984).
7. A. Richter, Prog. Part. Nucl. Phys. **34**, 261 (1995).
8. U. Kneissl, H.H. Pitz, A. Zilges, Prog. Part. Nucl. Phys. **37**, 349 (1996).
9. P.O. Lipas, P. von Brentano, A. Gelber, Rep. Prog. Phys. **53**, 1353 (1990) and references therein.
10. A. Giannatiempo, G. Maino, A. Nannini, A. Perego, P. Sona, Phys. Rev. C **44**, 1508 (1991).
11. B. Fazekas, T. Belgya, G. Molnár, A. Veres, R.A. Gatenby, S.W. Yates, T. Otsuka, Nucl. Phys. A **548**, 249 (1992).
12. T.F. Fazzini, A. Giannatiempo, A. Nannini, A. Perego, D. Cutoiu, Z. Phys. A **346**, 21 (1993).
13. J.R. Vanhoy, J.M. Anthony, B.M. Haas, B.M. Benedict, B.T. Meehan, S.F. Hicks, B.M. Davoren, C.L. Lundstedt, Phys. Rev. C **52**, 2387 (1995).
14. P.E. Garret, H. Lehmann, C.A. McGrath, Minfang Yeh, S.W. Yates, Phys. Rev. C **54**, 1 (1996).

15. A. Giannatiempo, A. Nannini, P. Sona, D. Cutoiu, Phys. Rev. C **53**, 2770 (1996).
16. I. Wiedenhöver, A. Gelberg, T. Otsuka, N. Pietralla, J. Gableske, A. Dewald, P. von Brentano, Phys. Rev. C **56**, R2354 (1997).
17. N. Pietralla *et al.*, Phys. Rev. C **58**, 796 (1998).
18. N. Pietralla *et al.*, Phys. Rev. Lett. **83**, 1303 (1999).
19. A. Gade, I. Wiedenhöver, J. Gableske, A. Gelberg, H. Meise, N. Pietralla, P. von Brentano, Nucl. Phys. A **665**, 268 (2000).
20. C. Doll, H. Lehmann, H.g. Börner, T. von Egidy, Nucl. Phys. A **672**, 3 (2000).
21. P. von Brentano *et al.*, Phys. Rev. Lett. **76**, 2029 (1996).
22. H. Maser, N. Pietralla, P. von Brentano, R.D. Herzberg, U. Kneissl, J. Margraf, H.H. Pitz, A. Zilges, Phys. Rev. C **54**, R2129 (1996).
23. A. Giannatiempo, A. Nannini, P. Sona, D. Cutoiu, Phys. Rev. C **52**, 2969 (1995).
24. A. Giannatiempo, A. Nannini, P. Sona, Phys. Rev. C **58**, 3335 (1998).
25. A. Giannatiempo, A. Nannini, P. Sona, Phys. Rev. C **58**, 3316 (1998).
26. A. Giannatiempo, A. Nannini, A. Perego, P. Sona, Phys. Rev. C **44**, 1844 (1991).
27. K.H. Kim, A. Gelberg, T. Mizusaki, T. Otsuka, P von Brentano, Nucl. Phys. A **604**, 163 (1996).
28. M.E. Bellizzi, A. Giannatiempo, A. Nannini, A. Perego, P. Sona, Phys. Rev. C. **63**, 064313 (2001)
29. T. Otsuka, N. Yoshida, program NPBOS Japan Atomic Energy Research Institute report JAERI-M85-094, 1985.
30. R.B. Firestone, *Table of Isotopes*, edited by V.S. Shirley (John Wiley & Sons Inc., 1996).
31. J. Stachel, P. Van Isacker, K. Heyde, Phys. Rev. C **25**, 650 (1982).
32. O. Scholten, K. Heyde, P. Van Isacker, J. Jolie, J. Moreau, M. Waroquier J. Sau, Nucl. Phys. A **438**, 41 (1985).
33. Feng Pan, J.P. Draayer, Nucl. Phys. A **636**, 156 (1998).
34. I. Talmi, Phys. Lett. B **405**, 1 (1997).
35. A. Giannatiempo, A. Nannini, P. Sona, *Ninth International Symposium on Capture Gamma-ray Spectroscopy and Related Topics, Budapest, October 1996* (Springer, Budapest, 1997) p. 35.
36. J. Blanchot, Nucl. Data Sheets **64**, 1 (1991).
37. D. De frenne, E. Jacobs, Nucl. Data Sheets **72**, 1 (1994).
38. L.E. Svensson, C. Fahlander, L. Hasslgren, A. Bäcklin, L. Westerbeerg, D. Cline, T. Czosnyka, C.Y. Wu, R.M. Diamond, H. Kluge, Nucl. Phys. A **584**, 547 (1995).
39. J. Kern, P.E. Garret, J. Jolie, H. Lehmann, Nucl. Phys. A **593**, 21 (1995).
40. J.A. Grau, L.E. Samuelson, F.A. Rickey, P.C. Simms, G.J. Smith, Phys. Rev. C **14**, 2297 (1976).
41. S.T. Ahmad, W.D. Hamilton, P. Van Isacker, S.A. Hamada, S.J. Robinson, J. Phys. G: Nucl. Part. Phys. **15**, 93 (1989).
42. T. Eckert *et al.*, Phys. Rev. C **56**, 1256 (1997); **57**, 1007 (1998).
43. H. Lehmann *et al.* Phys. Rev. C **60**, 024308 (1999).
44. P. Van Isacker, K. Heyde, J. Jolie, A. Sevrin, Ann. Phys. (N.Y.) **171**, 253 (1986).
45. A. Giannatiempo, A. Nannini, P. Sona, Phys. Rev. C **48**, 2657 (1993).
46. P. von Brentano *et al.*, *International Conference on Nuclear Structure, Gatlinburg, 1998*, edited by C. Baktash (Woodbury, New York, 1999) p. 449.
47. F. Iachello, *International Conference on Perspectives for the Interacting Boson Model on the Occasion of its 20th Anniversary, Padua, June 1994* (World Scientific, London) p. 1.