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Symmetry character of positive-parity bands in neutron-rich even palladium isotopes

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Abstract. The new data provided by recent experiments on ^{118}Pd, a nucleus not previously investigated, and on the high-spin states of the yrast band in even $^{110-116}$Pd isotopes have been analyzed in the framework of the IBA-2 model, extending a former study. A correct description of the properties of ^{118}Pd has been obtained by using model parameters equal or very close to those of the neighbouring isotopes. The importance of mixed-symmetry components for a satisfactory description of the states of $J \geq 10$ in $^{110-118}$Pd is pointed out.

PACS. 21.60.Fw Models based on group theory – 21.10.Re Collective levels – 27.60.+j $90 \leq A \leq 149$

1 Introduction

In the last few years a noticeable effort has been devoted to the experimental study of neutron-rich even palladium isotopes. They have been produced through the β-decay of on-line mass-separated Rh isotopes [1–5], in the spontaneous fission of ^{252}Cf [6–8] and in fusion-fission reactions [9,10]. Of particular interest are the very recent results on ^{118}Pd, which, at the moment, is the heaviest palladium isotope whose excitation energy pattern has been investigated [4,7,9].

Different theoretical approaches have been used to describe neutron-rich palladium isotopes, based on microscopic models (cranked shell model [11], cranked HB [12] and cranked HFB calculations [9]), on collective vibrational-rotational models [6] and on the algebraic interacting boson model (IBA), in both the IBA-1 [11,13, 14] and IBA-2 versions [15–18]. In the latter version, where neutron and proton degrees of freedom are explicitly taken into account, the symmetry of a state (in the well-known limiting cases) is characterized by the F-spin value [19]. Fully symmetric (FS) states have the maximum value of the F-spin while mixed-symmetry (MS) states are characterized by quantum numbers $F = F_{\max} - 1$, $F_{\max} - 2, \dots$.

The analyses performed in the framework of the IBA-2 model were limited to states of $J \leq 8$ in [15,16]. In [17,18] all the available experimental data concerning the states up to the maximum spin allowed by the model in even $^{100-116}$Pd were compared to the calculated ones. It turned out that it was possible to obtain a satisfactory description of the properties of the states identified as having collective nature once mixed-symmetry components were taken into account.

Similar analyses performed in the Kr [20] and Ru [21, 18] chains led to analogous conclusions. In particular, it was found that the energies predicted for the states of the yrast band in the Ru ($Z = 44$) and Pd ($Z = 46$) chains, which turned out to have large or predominant MS components for $J \geq 10$, compared well with the experimental data available at that time [18].

Aim of the present work was, on the one hand, to test the capability of the model to reproduce the experimental data on the newly studied ^{118}Pd by adopting model parameters equal or close to those of the neighbouring isotopes and, on the other hand, to check whether the new experimental information on $^{110-118}$Pd is consistent with our proposed interpretation [18] of the $J \geq 10$ states in the palladium chain as states of predominant mixed-symmetry character.

2 Data analysis

In the study of even $^{100-116}$Pd we used the Hamiltonian [17]

$$H = \varepsilon \left(\hat{n}_{d_\pi} + \hat{n}_{d_\nu}\right) + \kappa \, \hat{Q}_\pi[\chi_\pi] \cdot \hat{Q}_\nu[\chi_\nu] + w_{\pi\nu} \, \hat{L}_\pi \cdot \hat{L}_\nu + \hat{M}_{\pi\nu}[\xi_1, \xi_2, \xi_3], \quad (1)$$

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and the standard expressions [19] of the $\hat{T}(E2)[e_\pi, e_\nu]$ and $\hat{T}(M1)[g_\pi, g_\nu]$ transition operators; six $(\chi_\pi, \xi_1, e_\pi, e_\nu, g_\pi, g_\nu)$ out of the twelve model parameters were kept fixed all along the isotopic chain.

The new experimental data on the yrast bands in the even $^{110-116}$Pd have been compared with those predicted by using in eq. (1) the same model parameters given in [17], apart from the Majorana parameters ξ_2 and ξ_3, which were slightly varied in ^{114,116}Pd. These parameters, which affect only the excitation energies of states having mixed-symmetry components, were determined in our previous calculations on Pd isotopes focusing on the properties of groups of states not belonging to the yrast band. It turns out that the $J = 12_1$, 14_1 experimental states in $^{110-116}$Pd can be associated to calculated states in $^{110-116}$Pd which have predominant or large MS components and display a strong dependence of their excitation energies on ξ_2 and ξ_3. This last property has been exploited for the final adjustment of the Majorana parameters in ^{114,116}Pd.

In the present work the analysis of the even Pd isotopes has been extended to ^{118}Pd. Beside excitation energies and branching ratios, the stretched character of the transitions connecting the states considered has been taken into account. The parameters not varied along the isotopic chain were kept at the same values adopted in [17] and the remaining ones were deduced so as to reproduce as closely as possible the available experimental data, having as starting point the values of the corresponding parameters in the neighbouring isotopes. In ^{118}Pd two different bands up to $J = 14$, based on the 6^+_1 state, have been observed [7,9]. In this analysis only the band observed by Houry *et al.* [9] has been considered since it has been populated in the same reaction (induced fission of ^{238}U) as the yrast bands in $^{110-116}$Pd isotopes, which suggests a similar structure of the states. In fact, its excitation energy pattern is close to the corresponding ones in the neighbouring isotopes (see fig. 2 below), whereas that of the band observed by Zhang *et al.* [7], in the spontaneous fission of ^{252}Cf, has a much reduced energy spacing and no counterpart in the lighter isotopes (8^+, 10^+, 12^+ states at 2211, 2623, 3094 keV, respectively).

The comparison between experimental and calculated data has been considered only up to states of spin 12 (see fig. 1). Indeed, it has already been shown in [18] that the IBA-2 model fails to reproduce the excitation energy of the state having the maximum spin allowed by the finite number of bosons, for which a unique state is predicted which has a fully symmetric character. In ^{118}Pd there are seven bosons available ($N_\pi = 2$, $N_\nu = 5$), which implies a maximum spin $J = 14$; the predicted energy is 6.97 MeV, which is to be compared to the experimental one of 4.68 MeV.

The calculated states corresponding to the experimental ones are yrast with the exception of the 10^+ state. The association of the calculated 10^+_2 state at 3292 keV, instead of the 10^+_1 state at 2918 keV, to the experimental level at 3337 keV is based not only on the better agreement on the excitation energy but also on the argument that the calculations predict a strongly preferential

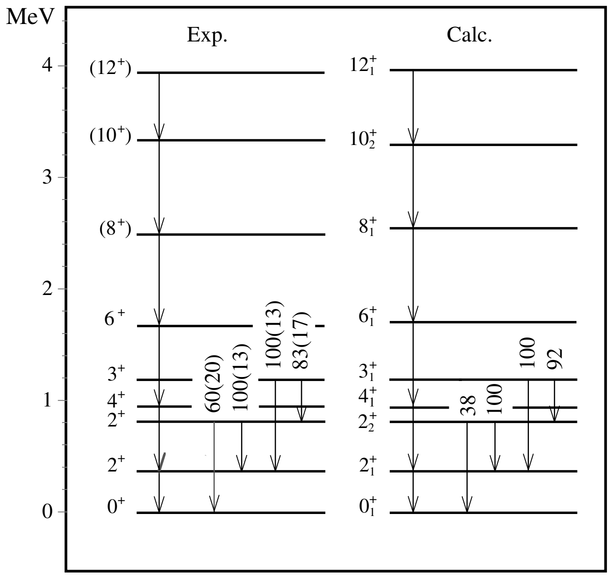

Fig. 1. Experimental [4,7,9] and calculated excitation energies and branching ratios in ^{118}Pd. For the association of the calculated 10^+_2 state with the experimental one [9] see text.

Table 1. Hamiltonian parameters as given in [17] apart from those reported in italics. All parameters are in MeV, except χ_ν (dimensionless). The values of the parameters kept fixed along the isotopic chain are $\chi_\pi = -0.90$ and $\xi_1 = 1.0$ MeV.

A	ε	κ	χ_ν	$w_{\pi,\nu}$	ξ_2	ξ_3
108	0.678	−0.08	−0.50	0.040	0.12	−0.25
110	0.624	−0.08	−0.40	0.050	0.11	−0.20
112	0.604	−0.10	0.10	0.060	0.00	−0.19
114	0.547	−0.10	0.20	0.060	*0.03*	*−0.20*
116	0.550	−0.10	0.20	0.060	*0.07*	*−0.21*
118	*0.580*	*−0.095*	*0.20*	*0.060*	*0.12*	*−0.23*

$12^+_1 \to 10^+_2 \to 8^+_1$ decay (see table 2 in sect. 3); actually, no branching from the experimental 12^+ and 10^+ states shown in fig. 1 has been reported.

The 2^+_2 and 3^+_1 states observed in the β-decay of ^{118}Rh [4] and in the spontaneous fission of ^{252}Cf [7] have also been considered in the analysis. Their experimental energies follow the trend of the corresponding states along the isotopic chain. Their identification is of great interest since they could be the bandhead of bands similar to those recently observed in ^{112,114,116}Pd whose high-spin states turn out to have MS character [22].

The Hamiltonian parameters deduced for ^{118}Pd are reported in table 1, together with those of $^{108-116}$Pd. It is seen that their values

– are very close to those of the neighbouring isotopes;
– make it possible to recognize the trend of the parameters, as a function of A, past the neutron mid-shell at $N = 66$ (^{112}Pd), thereby allowing to make confident predictions for still heavier palladium isotopes.

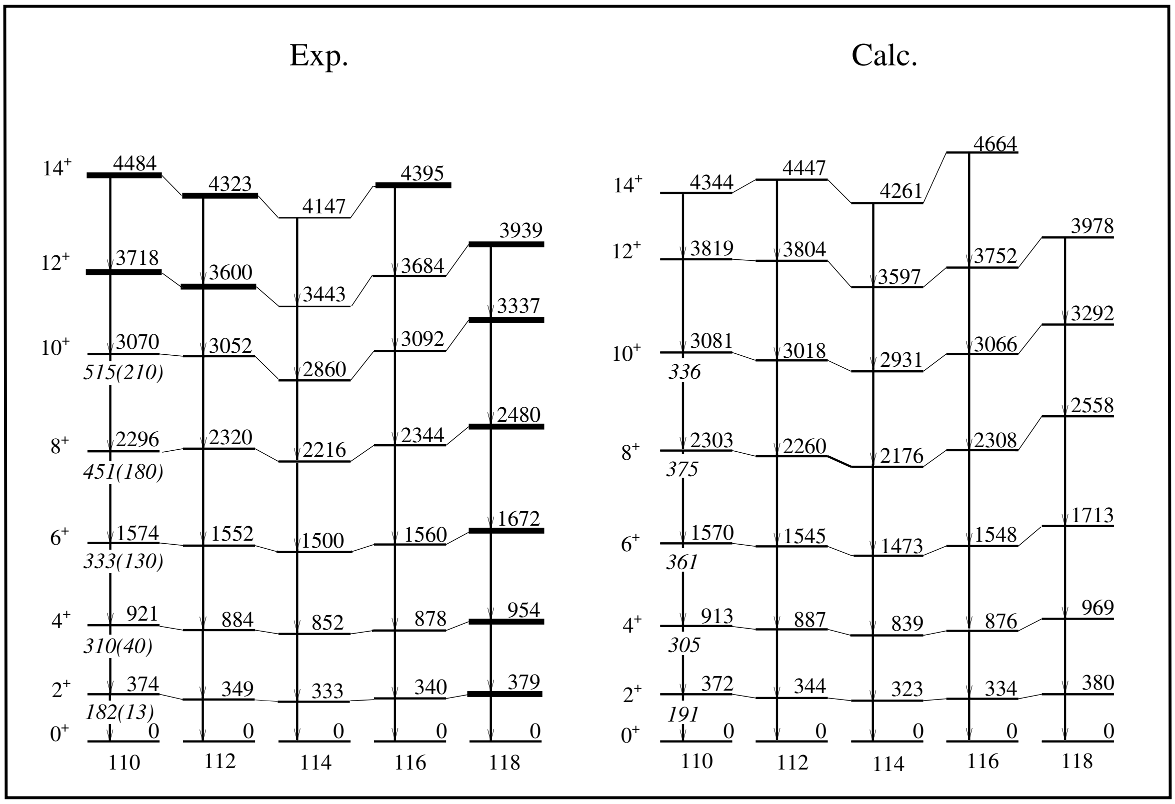

Fig. 2. Experimental excitation energies of the yrast bands in $^{110-116}$Pd and of the band reported in [9] in ^{118}Pd are compared to the predicted ones. New levels are shown by a thick line. The experimental [23] and calculated [17] $B(E2)$ values reported (in italics) for ^{110}Pd are given in 10^{-3} e^2b^2 units. The new experimental data on $^{110-116}$Pd are from [6,9,10]. A preliminary result on the 12^+ state in ^{110}Pd was reported in [24].

The agreement obtained with such a choice of the parameters between experimental and calculated data is shown in fig. 1.

3 Discussion

Different interpretations have been provided for the decrease of the spacing near $J = 10$ in the yrast band of neutron-rich even palladium isotopes. In microscopic models this phenomenon is explained on the basis of a band built on a non-collective state crossing the ground-state band. As to the structure of this non-collective state, the interpretation is not unique. For example, in the cranked shell model the backbending in heavy palladium isotopes is considered as due to an oblate-driving alignment of two $g_{9/2}$ protons in [11], whereas the new high-spin data seem to be more consistent with a $\nu(h_{11/2})^2$ pair alignment and prolate deformation [6–9]. Calculations performed by Butler-Moore *et al.* [6] in a simple collective vibrational-rotational model were not able to reproduce the experimental data for the higher-spin states.

In our interpretation the reduced spacing at higher energies would be determined by the presence of states having mixed-symmetry character.

In order to discuss this point, the experimental yrast bands in $^{110-116}$Pd and the band observed by Houry *et al.* [9] in ^{118}Pd are shown in fig. 2 together with the calculated ones. It is seen that the high-lying experimental levels display, as a function of the mass number, a regular trend, similar to that of the low-lying states, with a minimum for A close to the neutron mid-shell, as expected for states of collective nature. No further transition besides those reported in the figure has been observed from the states shown on the left of the figure apart from a $10^+ \to 8^+$ transition of unknown branching in ^{110}Pd [10]. $B(E2)$ values along a band have only been measured in ^{110}Pd [23]; they are shown in fig. 2 together with the predicted values.

Two requirements were imposed to the calculated states in order to be associated to the experimental ones:

i) their excitation energies should reproduce the experimental ones to better than 10%;

ii) to belong to a strongly connected sequence of states in each isotope.

It turns out that the calculated states associated to the experimental ones are yrast up to $J = 8$ (see also [18]). For $J \geq 10$ the identification of the states has been based on the data reported in table 2. Here, are shown the energies of the experimental levels of $J \geq 8$, the calculated ones of the possible candidates, the squared amplitudes (α^2) of the F-spin and n_d (d-boson number) components of their wave functions and the calculated $B(E2)$ values of the de-exciting transitions.

Table 2. Energies (in keV), squared amplitudes of the F-spin and n_d components of high-spin states, and $B(E2;\, J \to J-2)$ values (in 10^{-3} $e^2\text{b}^2$ units) in $^{110-118}$Pd. Calculated results concerning states not associated to the experimental ones are reported in italics.

A	E_{exp}	E_{calc}	J_i	$F_{\max}$	$F_{\max}-1$	$F_{\max}-2$	$n_d=4$	$n_d=5$	$n_d=6$	$n_d=7$	$n_d=8$	$n_d=9$	$B(E2)$
110	2296	2303	8_1	**0.80**	0.16	0.03	**0.62**	0.18	0.16	0.03	0.01		375
	3131	3081	10_1	**0.60**	**0.31**	0.09		**0.51**	**0.30**	0.15	0.04		336
	3716	3819	12_1	0.21	**0.41**	**0.38**			0.18	**0.44**	**0.35**	0.03	197
	4483	4344	14_1	0.02	0.20	**0.78**				0.01	0.17	**0.82**	86
112	2318	2260	8_1	**0.72**	0.22	0.06	**0.55**	0.11	0.27	0.04	0.03		432
	3049	3018	10_1	**0.57**	**0.33**	0.10		**0.55**	0.16	0.23	0.04	0.02	411
	3597	3804	12_1	**0.35**	**0.43**	0.22			**0.41**	**0.35**	0.16	0.06	331
	4321	*4447*	*14_1*	*0.01*	*0.17*	*0.82*				*0.00*	*0.03*	*0.92*	*10*
		4546	14_2	0.08	**0.41**	**0.51**				0.03	**0.82**	0.02	144
114	2216	2176	8_1	**0.70**	0.24	0.06	**0.58**	0.11	0.26	0.03	0.02		350
	2860	2931	10_1	**0.46**	**0.38**	0.16		**0.44**	**0.31**	0.16	0.08		288
	3443	*3437*	*12_1*	*0.01*	*0.19*	*0.80*			*0.00*	*0.07*	*0.85*	*0.08*	*0.3*
		3597	12_2	0.08	**0.46**	**0.46**			0.01	**0.75**	0.08	0.16	86
	4147	*3825*	*14_1*	*0.01*	*0.14*	*0.85*				*0.00*	*0.04*	*0.96*	*83* [→ *12_1*]
													2.6 [→ 12_2]
		4261	14_2	0.03	**0.32**	**0.65**				0.03	**0.95**	0.02	0.1 [→ *12_1*]
													100 [→ 12_2]
116	2345	2308	8_1	**0.50**	**0.45**	0.05	**0.62**	0.14	0.20	0.03	0.01		272
	3093	*2975*	*10_1*	*0.02*	*0.22*	*0.75*		*0.00*	*0.07*	*0.85*	*0.08*		*10^{-5}*
		3066	10_2	**0.50**	**0.45**	0.05		0.06	**0.73**	0.05	0.16		81
	3685	*3327*	*12_1*	*0.01*	*0.16*	*0.83*			*0.00*	*0.03*	*0.97*		*69* [→ *10_1*]
													1.7 [→ 10_2]
		3752	12_2	0.28	**0.64**	0.08			0.02	**0.97**	0.01		10^{-3} [→ *10_1*]
													88 [→ 10_2]
	4394	4664	14_1	0.01	0.02	**0.97**				0.00	**1.00**		1.1 [→ *12_1*]
													9.2 [→ 12_2]
118	2480	2503	8_1	**0.56**	**0.31**	0.13	**0.50**	**0.36**	0.08	0.06			166
	3337	*2909*	*10_1*	*0.01*	*0.19*	*0.80*		*0.00*	*0.03*	*0.97*			*0.4*
		3300	10_2	0.08	**0.40**	**0.52**		0.01	**0.94**	0.05			47
	3939	3943	12_1	0.01	0.02	**0.97**				**1.00**			1.8 [→ *10_1*]
													22 [→ 10_2]

It is evident that

- the 10_1^+ state in ^{118}Pd does not satisfy neither of the requirements i), ii);
- the 10_1^+ state in ^{116}Pd, the 12_1^+ states in ^{114,116}Pd, and the 14_1^+ states in ^{112,114}Pd satisfy requirement i) but not requirement ii);
- the 10_2^+ state in ^{116,118}Pd, the 12_2^+ states in ^{114,116}Pd, and the 14_2^+ states in ^{112,114}Pd satisfy both requirements i) and ii) and have therefore been associated to the experimental ones.

A few additional states in the isotopes considered, which satisfy requirement i) but not requirement ii), have not been reported in the table for the sake of simplicity.

It is seen that in each isotope the $F_{\max}$ component of the chosen states rapidly reduces in going from the $J=8$ state to the state of highest spin, which displays a quite pure mixed-symmetry character.

By looking at fig. 2 one can observe that the energies of the experimental states of spin ≥ 10 are typically reproduced to within a few percent with a maximum discrepancy of $\simeq 6\%$. In each isotope, the arrows connecting the calculated states are shown to emphasize that they belong to a stretched cascade. The possibility of reproducing such a behaviour, in spite of the changing character of the states, is related to the slowly changing structure of the wave functions in going from the lower- to the higher-spin states and to the fact that $E2$ transitions satisfy the selection rules on F-spin ($\Delta F = 0, \pm 1$ [25,26]) and on d-boson number ($\Delta n_d = 0, \pm 1$ [19]). The largest $\langle \hat{T}(E2) \rangle$ values are those between components of the initial and final states having a sizeable α^2 value, the same F-spin and differing by one in n_d [27]. As shown in table 2, in a given isotope each pair of the selected states of spin $(J, J-2)$ has large components of the same F-spin and a d-boson number differing by one. To stress this point the F-spin and n_d component having squared amplitudes larger than 0.30 (an arbitrarily chosen value) are reported in bold face character.

We now briefly discuss the changing symmetry character of the states along the bands just mentioned in the example of ^{118}Pd, by referring to the $U(5)$ limit. In this limit, the eigenvalues of the generalized Hamiltonian for

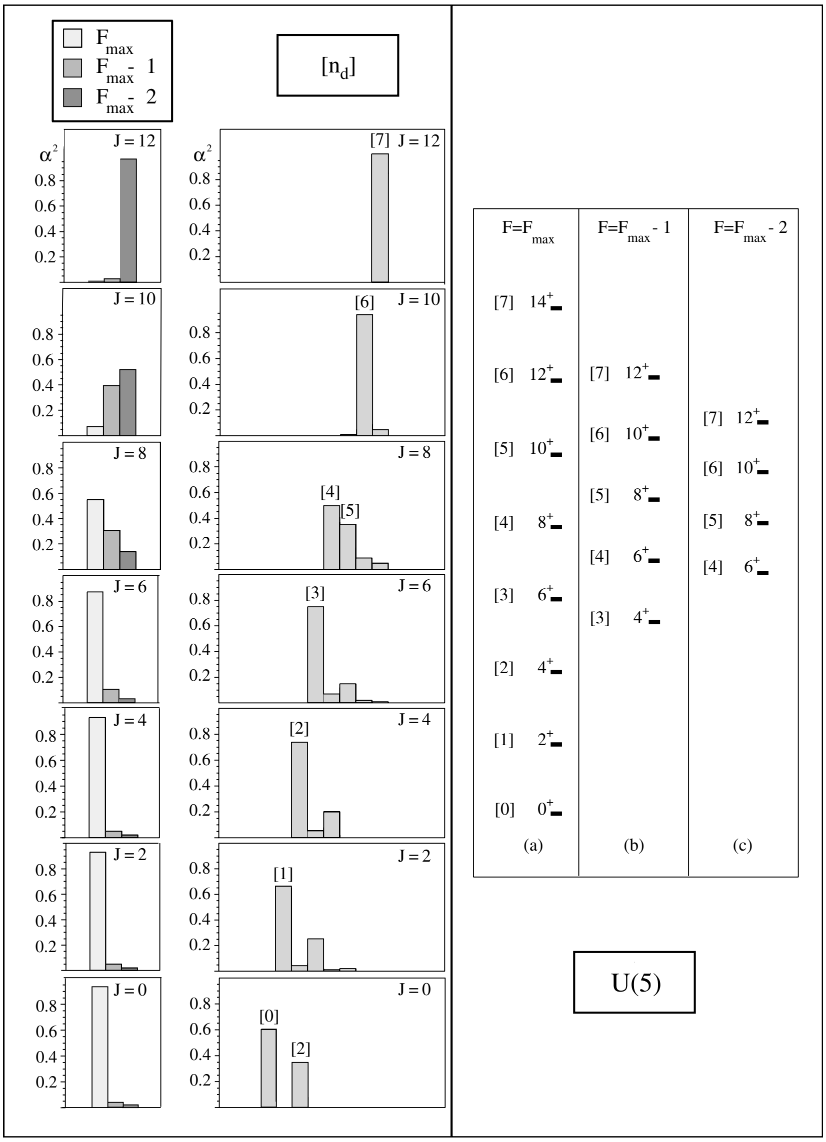

Fig. 3. Left: squared amplitudes (α^2) of the F-spin and n_d components of the wave functions of the band in ^{118}Pd resulting from the present calculations. For each J, the d-boson number is reported on top of the strongest n_d component. Right: relevant bands in the $U(5)$ limit. Close to each state is reported the n_d component in square brackets.

the MS states having $F = F_{\max} - 1$ and $F = F_{\max} - 2$ are known in analytic form [17,18,28] and it turns out that, when the Majorana parameter ξ_2 is positive and ξ_3 negative (as in the present analysis), the excitation energies of states belonging to MS bands can appear at an energy very close or even lower than that of states of the same J in the FS band, so that some MS states become yrast [18]. In fig. 3 the squared amplitude of the F-spin and n_d components of the wave functions of ^{118}Pd are reported on the left, the bands most relevant to the present example predicted by the IBA-2 model in the $U(5)$ limit on the right. It is evident a close correspondence of the states of ^{118}Pd up to $J = 6$ with the states of band (a) of the $U(5)$ limit, for which F-spin and n_d are good quantum numbers. The large mixing of F-spin and n_d components in the $J = 8$ state is related to the small energy spacing predicted by the realistic Hamiltonian (1) for the three $J = 8$ states corresponding to those of bands (a), (b), and (c) in the figure. The $J = 10$ state has comparable $F_{\max} - 1$ and $F_{\max} - 2$ components and the largest d-boson component for $n_d = 6$. Its structure can be traced to the mixing of states corresponding to those of the same spin in bands (b) and (c) , whereas the state of spin 12, which turns out to have $\alpha^2(F_{\max} - 2) = 0.97$ and $n_d = 7$, can be associated to the $J = 12$ state in band (c).

4 Conclusions

The experimental information on the newly studied isotope ^{118}Pd has been satisfactorily reproduced by the calculations without performing an *ad hoc* tuning of the model parameters, which are equal or very close to the corresponding ones in the neighbouring isotopes, respecting the general trend along the isotopic chain. Such a result supports the capability of the model to correctly describe the even isotopes of the Pd chain.

The new experimental data on neutron-rich palladium isotopes are consistent with our interpretation of a symmetry changing structure in the bands considered in the present work. Unfortunately, the transition probabilities between the high-spin states have not been measured yet; only in ^{110}Pd the $B(E2)$ values are known up to the $J = 10$ state. A crucial test for the different interpretations would be provided by a measurement of the $B(E2)$ value between the first pair of levels showing a reduced energy spacing (*e.g.*, the $12_1^+ \rightarrow 10_1^+$ transition in ^{110}Pd). Indeed, its value would be dramatically reduced should the de-exciting state be of non-collective character, whereas in our interpretation this should not happen.

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