Interpretation of the $A \approx 100$ transitional region in the framework of the interacting boson model

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A detailed study of the transition between the SU(5) and O(6) limit of the interacting boson model (IBA-1) has been performed in a schematic way. A comparison of the experimental excitation energies and $E2$ transition probabilities for neutron-rich Ru and Pd isotopes with this calculation shows that this mass region is well described in terms of this phase transition.

[NUCLEAR STRUCTURE Transition between the SU(5) and O(6) limit of IBA-1, energy levels, $B(E2)$, comparison with experimental data for $^{98-110}$Ru, $^{110-114}$Pd.]

I. INTRODUCTION

During the last decade there have been various theoretical investigations of the $A \approx 100$ region.[1–5] The predictions resulting from these calculations range from prolate and oblate deformation over shape coexistence between minima of different deformation towards strong asymmetric ground-state deformation for the neutron-rich nuclei of this mass region. All these calculations, however, agree in the prediction of β-deformed minima for the ground-state ($\beta \approx 0.2-0.3$) and pronounced softness with respect to γ deformation.

These predictions have been the motivation for systematic experimental investigations in this mass region. In the meantime, enough experimental information exists to start a detailed investigation of an eventual transition in nuclear shape in this mass region. In this paper the discussion will be restricted to the Ru and Pd isotopes. For these nuclei experimental data now cover the whole region of interest from the shell closure at $N=50$ up to the middle of the neutron shell at $N=66$. The treatment of such transitional regions in the framework of a usual geometrical model involves various competing degrees of freedom. In contrast, the interacting boson model[6–9] seems to be destined to do such systematic treatment, since even with a relatively small number of parameters it provides a consistent description of very different nuclei. In its simplest form, the so-called IBA-1, which makes no distinction between neutron and proton bosons, the Hamilton can be written as a multipole expansion in terms of boson creation and annihilation operators[10]:

$$H = \epsilon n_d + \kappa P \cdot P + \kappa' L \cdot L + \kappa'' Q \cdot Q + T_3 \left[(d^+ \tilde{d})^3 (d^+ \tilde{d})^3 \right]_0^0 + T_4 \left[(d^+ \tilde{d})^4 (d^+ \tilde{d})^4 \right]_0^0 . \quad (1)$$

Besides the three limiting symmetries SU(5), SU(3), and O(6), which have the anharmonic vibrator, the axial rotor, and the γ-soft rotor as geometrical analogs, this Hamiltonian contains all possible transitions between them. The symmetry triangle in Fig. 1 shows this in a symbolic way; the sides of the triangle represent direct transitions between the limiting cases, whereas all complex transition regions are contained in the area. The transition between SU(5) and SU(3) is realized, for instance, in the Sm and Nd nuclei,[11] whereas the Pt-Os region has been found to be a good example for the transition between SU(3) and O(6).[12]

The question now arises where on this triangle one can locate the Ru and Pd isotopes. From the excitation energy systematics (Fig. 2), one observes that, besides the systematic decrease in excitation

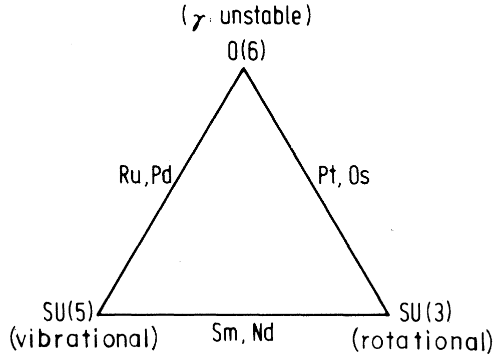

FIG. 1. Symmetry triangle, illustrating the three limiting symmetries of IBA-1, namely SU(5), SU(3), and O(6), corresponding to the vibrational, rotational, and γ-unstable geometrical limit, and the three direct transitions between them.

energy with increasing neutron number, the ratio $E_{4_1^+}/E_{2_1^+}$ reflects a transition from vibrator-like nuclei such as ^{98}Ru and ^{100}Pd to more deformed ones. Nevertheless this ratio stays clearly below the rotational value of 3.3 also for the heaviest known isotopes. It is important to note that there is no sharp onset of deformation as would be expected for a transition SU(5)→SU(3) (vibrator →axial-symmetric rotor[11]) and as is observed, for instance, in the Nd or Sm isotopes.

The $B(E2,2_1^+\rightarrow 0_1^+)$ values show a similar trend (Fig. 3). In comparison, the corresponding values for Nd isotopes, representing a transition from vibrational to rotational nuclei [SU(5)→SU(3) (Ref. 11)] and for Os isotopes, representing a transition from rotational to γ-unstable nuclei [SU(3)→O(6) (Ref. 12)] are shown. Although two different shells are compared, for the $A \approx 100$ region a transition between SU(5) and O(6) nuclei is suggested. A comparison of some experimental $B(E2)$ ratios with the model predictions for the three IBA-1 limits (Table I) confirms this suggestion; in any case a transition towards the SU(3) limit seems to be ruled out completely.

Since, until now, no examples are known for the SU(5)→O(6) transition, a more detailed discussion seems worthwhile. In the following section we will present a systematic investigation of the behavior of excitation energies and $E2$-transition-probabilities going from the SU(5) to the O(6) limit.

II. SYSTEMATIC STUDY OF THE SU(5)→O(6) TRANSITION

A. Outline of the procedure

For the three limiting situations different terms of the Hamiltonian (1) are important; in particular, the spectrum of SU(5) nuclei is dominated by values of ϵ, large in comparison with the other parameters, whereas O(6) nuclei are characterized by values of κ, large compared to ϵ. Hence for the investigation of the transition SU(5)→O(6) a systematic variation of κ/ϵ neglecting further terms

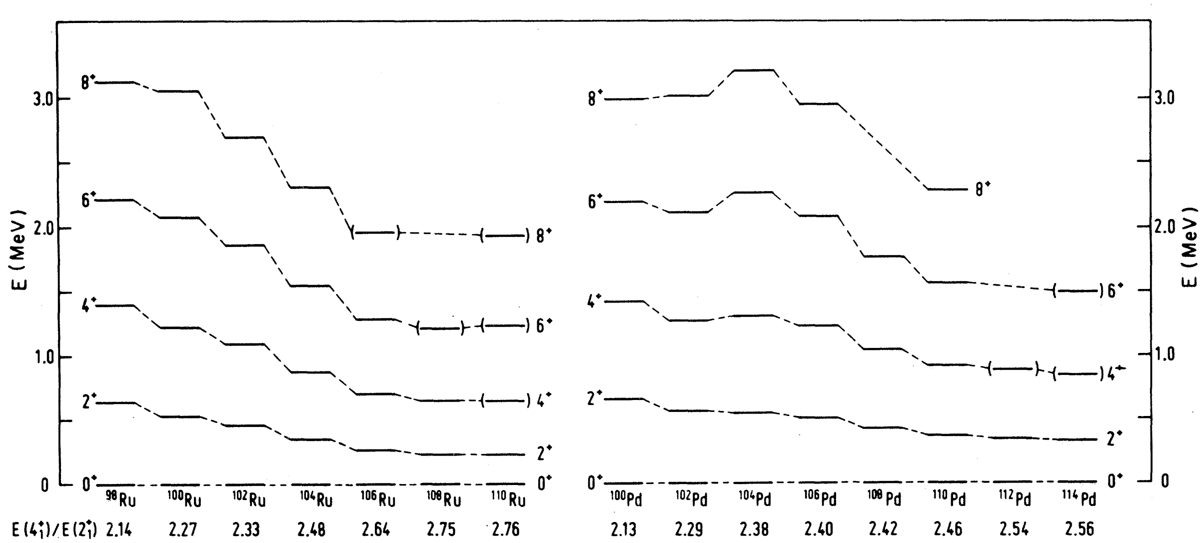

FIG. 2. The experimental excitation energy systematics for Ru and Pd isotopes; data are taken from Refs. 13–18. The energy ratio $E_{4_1^+}/E_{2_1^+}$ has to be compared with the corresponding vibrational and rotational value of 2.0 and 3.3, respectively.

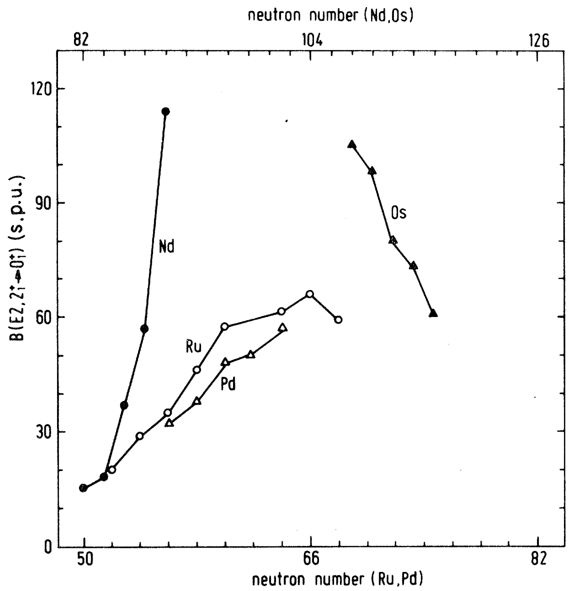

FIG. 3. Experimental $B(E2,\, 2_1^+ \rightarrow 0_1^+)$ values (in single-particle units) for Ru (open circles) (Refs. 19–22), Pd (open triangles) (Refs. 23-26), Nd (filled circles) (Ref. 29), and Os isotopes (filled triangles) (Refs. 27, and 28).

of the Hamiltonian (1) seems appropriate. The corresponding Hamiltonian is

$$H = \epsilon(d^\dagger \cdot \tilde{d}) + \kappa(d^\dagger \cdot d^\dagger - s^\dagger s^\dagger)(\tilde{d} \cdot \tilde{d} - ss) \; . \qquad (2)$$

This is also the treatment chosen by Dieperink *et al.*[33] in their investigation of the shape phase transitions of ground state properties (binding energy, $\langle n_d \rangle_{\text{g.s.}}$).

In the following we will also choose their parametrization in ξ and η, with

$$\xi = \frac{\eta}{1+\eta} \text{ and } \eta = \frac{4\kappa}{\epsilon}(N-1) \; . \qquad (3)$$

Here N denotes the total number of bosons. Note that in this parametrization the phase transition occurs at exactly $\xi = 0.5$ for $N \rightarrow \infty$. The variation of ξ is done in nine equidistant steps between 0.1 and 0.9 with ϵ constant at 600 keV, corresponding roughly to the excitation energy of the 2_1^+ state. For the calculation of $E2$ properties we take a constant quadrupole operator, independent of ξ, which is of the form

$$T^{(E2)} = e_2 \left[(s^\dagger d + d^\dagger s)^{(2)} + (d^\dagger d)^{(2)} \right] \; . \qquad (4)$$

The calculations were performed numerically, using the program PHINT.[34]

The change in the level scheme corresponding to this variation of ξ for $N = 14$ is shown in Fig. 4. Only the lowest excited states are shown. Together with the continuous lowering of the excitation energies with increasing ξ, a characteristic change in the spacing of the multiplets equidistant in SU(5) is observed, which will be discussed in detail later. Note that some of the states leave the multiplets they belong to in the SU (5) limit. This is connected with a dramatic change in decay properties, also discussed later on.

B. Comparison with experimental data for Ru and Pd isotopes

To explore whether and where in this transitional region between the two limits SU(5) and O(6) each of the Ru and Pd isotopes can be placed, in the following several properties of different excited

TABLE I. $B(E2)$ ratios for low-lying excited states in the three IBA-1 limits; in comparison the corresponding experimental values for $^{102-108}$Ru are shown. (Refs. 14, 16, 19, 20, and 30–32.)

	$\frac{B(E2,2_2^+\rightarrow 0_1^+)}{B(E2,2_2^+\rightarrow 2_1^+)}$	$\frac{B(E2,2_2^+\rightarrow 2_1^+)}{B(E2,2_1^+\rightarrow 0_1^+)}$	$\frac{B(E2,3_1^+\rightarrow 2_1^+)}{B(E2,3_1^+\rightarrow 4_1^+)}$	$\frac{B(E2,4_2^+\rightarrow 4_1^+)}{B(E2,4_2^+\rightarrow 2_2^+)}$	$\frac{B(E2,4_1^+\rightarrow 2_1^+)}{B(E2,2_2^+\rightarrow 2_1^+)}$
SU(5)	0.011	1.40	0.06	0.72	1.0
SU(3)	0.70	0.02	2.50	0.03	6.93
O(6)	0.07	0.79	0.12	0.75	1.84
^{102}Ru	0.036 (3)	0.71 (7)	0.18 (2)	0.51	1.62 (21)
^{104}Ru	0.045 (4)	0.86 (7)	0.10 (2)	0.54 (5)	1.57 (17)
^{106}Ru	0.087 (11)		0.16 (7)		
^{108}Ru	0.103 (11)		0.21 (6)		

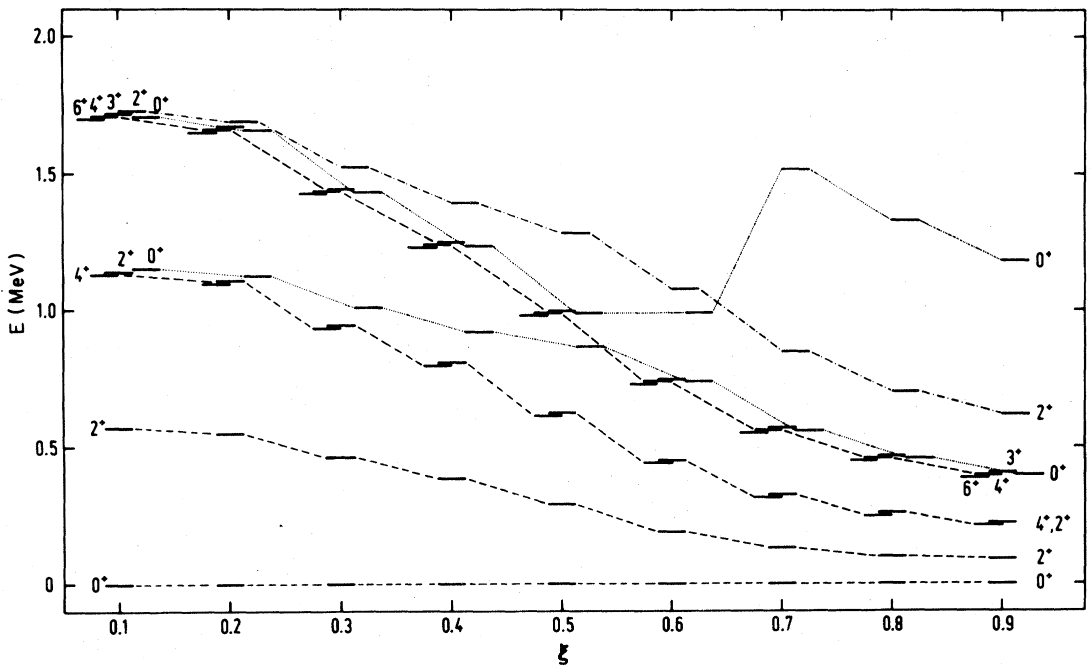

FIG. 4. Calculated excitation energies for low-lying excited states in the SU(5)→O(6) transitional region as a function of ξ for $N=14$.

states will be discussed. Figure 5(a) shows the ratios $E_{4_1^+}/E_{2_1^+}$ and $E_{2_2^+}/E_{2_1^+}$ for three different boson numbers as a function of ξ. One can observe how the phase transition, sharp for $N\rightarrow\infty$, becomes diffuse for decreasing boson number. The experimental excitation energies for the Ru and Pd isotopes are marked on or interpolated in between the theoretical curves with the corresponding total

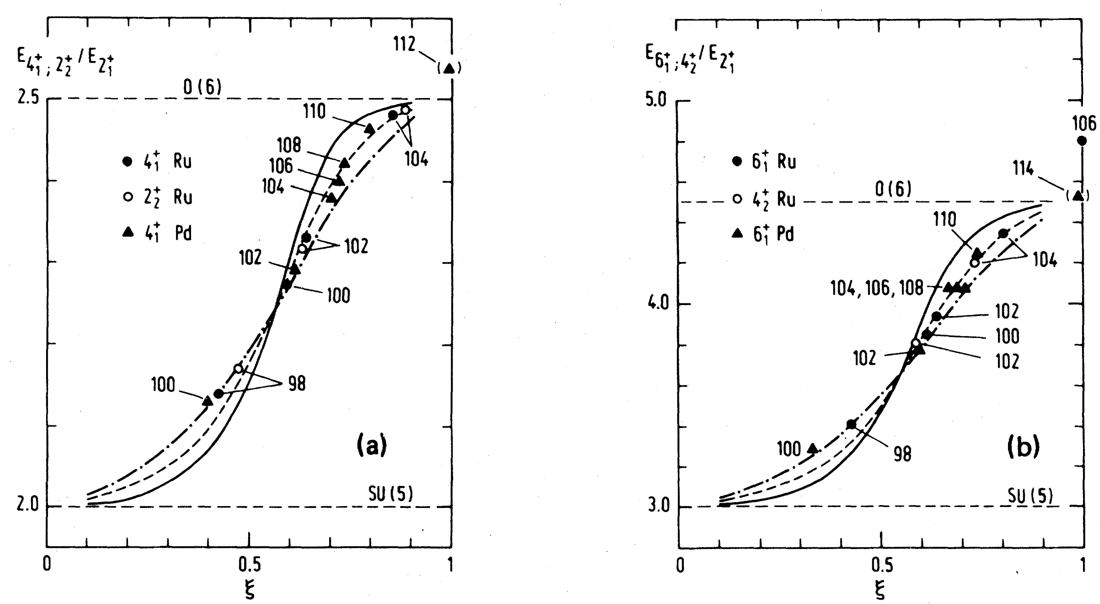

FIG. 5. (a),(b) Calculated excitation energy ratios $E_{4_1^+,2_2^+}/E_{2_1^+}$ and $E_{6_1^+,4_2^+}/E_{2_1^+}$ for different total boson number N as a function of ξ. The notation here and in the following figures will be: full line for $N=14$, dashed line for $N=8$, dashed-dotted line for $N=5$. The experimental values for the Ru and Pd isotopes (Refs. 13, 14, and 16–18) are marked on the corresponding curves or interpolated between them.

boson number N. The splitting of the 4_1^+ and 2_2^+ state observed in the Pd isotopes[13] is not reproduced with this dramatically simplified Hamiltonian; as a consequence, the 2_2^+-energies are not considered in this figure. One can see that with increasing neutron number an almost continous increase in ξ is correlated. This is also observed for ratios $E_{6_1^+}/E_{2_1^+}$ and $E_{4_2^+}/E_{2_1^+}$ [Fig. 5(b)]; from a value of ≈ 0.4 for ^{98}Ru and ^{100}Pd ξ increases to ≈ 1.0 for ^{104}Ru and ^{108}Pd. The corresponding value for ^{106}Ru is even above what one would expect for the pure O(6) limit. In none of the nuclei under consideration is the 3_1^+ state degenerate with the 6_1^+ and 4_2^+ state,[13-15] as would be predicted by this simplified calculation.

For the $E2$-transition probabilities, the situation appears to be more complex. Some transition probabilities do not change very characteristically over the whole transition region between SU(5) and O(6); that is, their ξ dependence is of the order of the experimental uncertainties or the N dependence. As an example, Fig. 6 shows the ratio $B(E2,\, 4_1^+ \rightarrow 2_1^+)\,/B(E2,\, 2_1^+ \rightarrow 0_1^+)$. The resulting ξ values lie around $\xi \approx 0.5$, but further conclusions cannot be reached in this case.

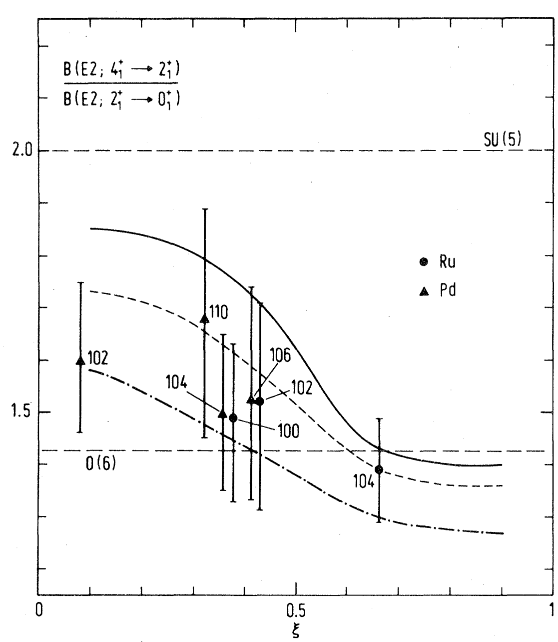

FIG. 6. The ratio $B[(E2,\, 4_1^+ \rightarrow 2_1^+)]\,/[B(E2,\, 2_1^+ \rightarrow 0_1^+)]$ as resulting from calculations with $N=14$, 8, 5, as a function of ξ. The experimental values are taken from Refs. 16, 19, 20, 23, 24, 26, 31, and 35. The values of this ratio in the SU(5) and O(6) limit (2 and $\frac{10}{7}$, respectively) are only valid in the limit $N \rightarrow \infty$.

On the other hand, there exist transitions which are strongly forbidden in the SU(5) limit as crossover transitions with $\Delta n_d = 2$, but increase several orders of magnitude in going towards the O(6) limit. This is valid, for instance, for the transitions $2_1^+ \rightarrow 0_1^+$, $3_1^+ \rightarrow 2_1^+$, and $4_2^+ \rightarrow 2_1^+$. The corresponding theoretical branching ratios are shown in Figs. 7(a)–(c) together with the experimental ones. Here again the resulting ξ values vary between 0.4–1.0. For the Ru isotopes ξ increases with increasing neutron number; in the case of the Pd isotopes either no neutron number dependence or even the opposite trend shows up. Partly, this might be due to experimental uncertainties. Another possibility could be that ^{102}Pd already has a predominant O(6) character, which stays about the same also for the neutron-rich isotopes. Finally a transition path different from the straight line connecting the SU(5) and O(6) limit is possible, which would hence require additional terms in the Hamiltonian to produce a different neutron number dependence.

A very characteristic signature of the SU(5) $\rightarrow$O(6) transition is the behavior of low-lying 0^+ states.[9] Figure 8 shows the energies for the first excited 0^+ state. A comparison of calculated and experimental excitation energies yields ξ values significantly lower than those resulting from the previously discussed excited states. For the decay properties of this state one has to expect a very dramatic change. In the SU(5) limit the 0_2^+ state is a member of the two-phonon triplet with the number of d bosons $n_d = 2$ and the $\Delta n_d = 1$ selection rule allows only a decay to the 2_1^+ state.[7] With the transition to the O(6) limit the 0_2^+ state becomes the head of a band with $\tau = 3$ and $\sigma = \sigma_{\max}$. Now the $\Delta\sigma = 0$ and $\Delta\tau = 1$ selection rules allow only a decay to the 2_2^+ state ($\sigma = \sigma_{\max}$, $\tau = 2$).[9] This variation is shown in Fig. 9. On one hand, none of the 0_2^+ states in the Ru or Pd isotopes decays to the 2_2^+ state. On the other hand, the experimental ratio $B(E2, 0_2^+ \rightarrow 2_1^+)\,/B(E2,\, 2_1^+ \rightarrow 0_1^+)$ (Refs. 16, 19, 20, and 23) is about a factor of 2–3 smaller than the SU(5) prediction. This suggests that these states might be of other than a simple collective nature. There exist in this mass region different sources for low-lying 0^+ states, which may become rather complex. In the Zr or Cd and Sn isotopes these states can be understood in terms of excitation of pairs of protons over subshell or shell gaps, a description which is equivalent to shape coex-

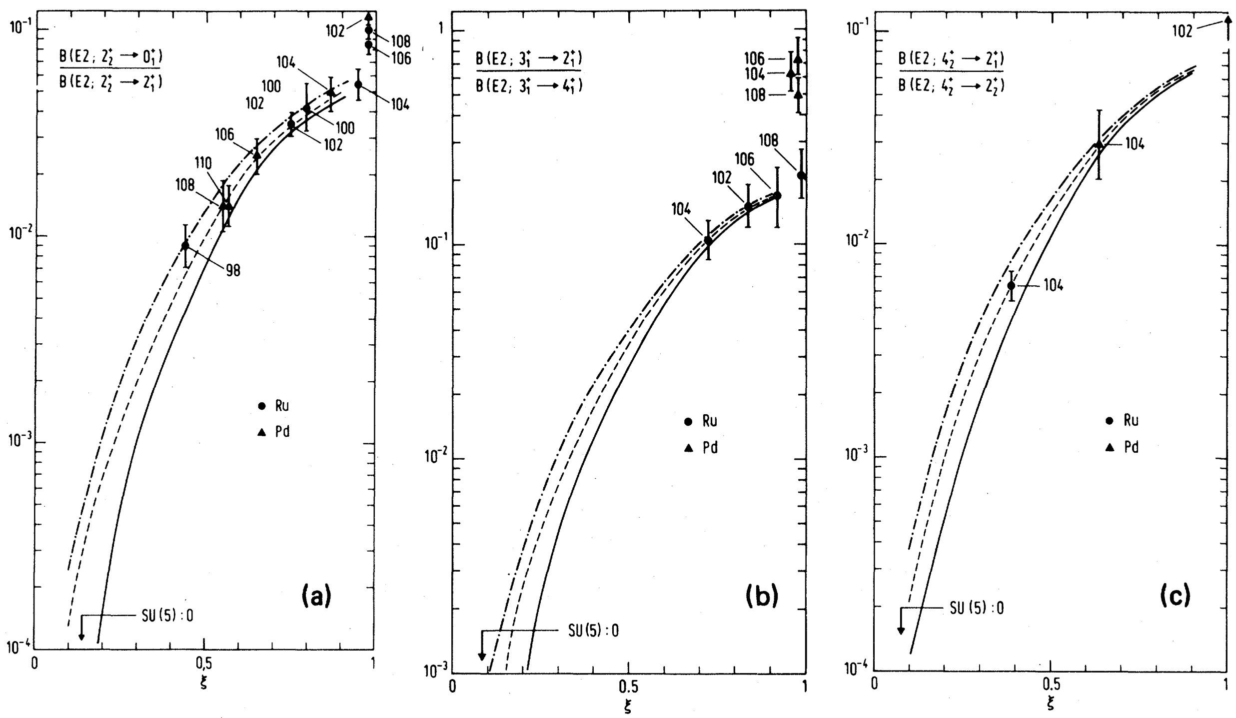

FIG. 7 (a)—(c) Calculated $E2$ branching ratios for the 2_2^+, 3_1^+, and 4_2^+ state in the SU(5)→O(6) transitional region as compared with the corresponding experimental values for Ru and Pd isotopes (Refs. 15, 16, 14, 19, 20, 36, 30, and 31 and 23, 26, 35, and 37—42, respectively).

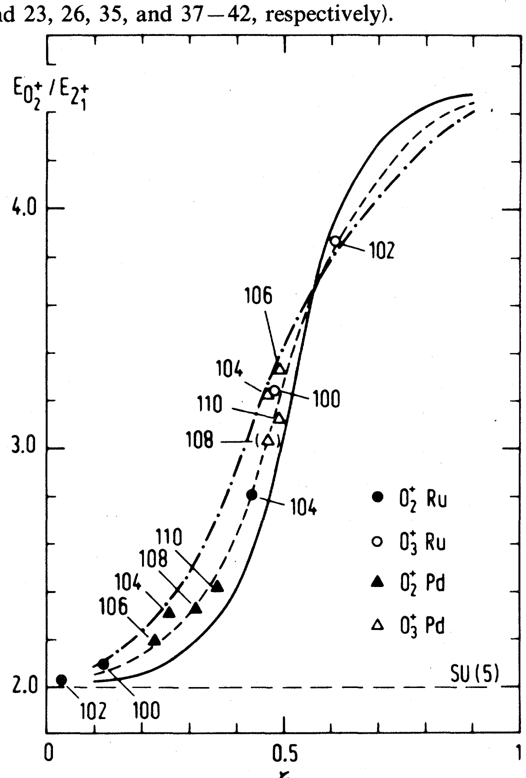

FIG. 8. The excitation energy ratio $E_{0_2^+}/E_{2_1^+}$ as compared to experimental values for low-lying excited 0^+ states in Ru and Pd isotopes (Refs. 13—15).

istence between states of different deformation.[45] An attempt to study the corresponding states in Ru and Pd isotopes as intruder states in the framework of the interacting boson model seems to be worthwhile.

For some Ru and Pd isotopes second excited 0^+ states (0_3^+) are known. The ratio $E_{0_3^+}/E_{2_1^+}$ fits much better in the picture resulting from the other low-lying excited states and gives similar values for ξ (Fig. 8). For these states an increasing $B(E2, 0_3^+ \to 2_2^+)$ value with increasing neutron number consistent with these calculations is also observed (Fig. 9).

C. Comparison with an IBA-2 calculation

In Fig. 10 we plot the expectation value of the number of d bosons in the ground state $\langle n_d \rangle_{\text{g.s.}}$ divided by the total number of bosons N as a function of ξ, again for the three cases $N=5$, $N=8$, and $N=14$. We also show $\langle n_d \rangle_{\text{g.s.}}/N$ in the limit $N \to \infty$, as it is derived in Ref. 33. Recently the Ru and Pd isotopes were studied[46] in the framework of the IBA-2. This version of the interacting boson model distinguishes between proton and neutron bosons. The values $\langle n_d \rangle_{\text{g.s.}}/N$ resulting from Ref. 46 are again marked on or between the

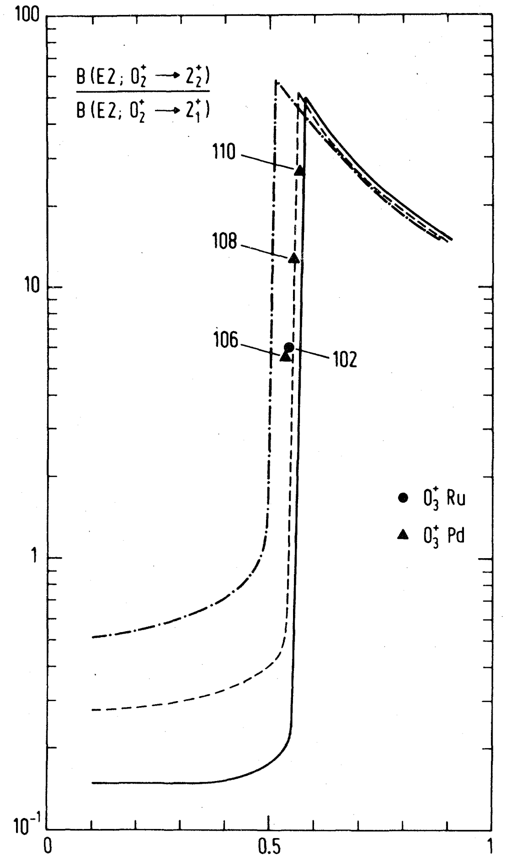

FIG. 9. The calculated $E2$ branching ratio for the first excited 0^+ state (0_2^+). Since in the Ru and Pd isotopes no $0_2^+ \rightarrow 2_2^+$ transition is observed, the corresponding experimental values (Refs. 30, 43, 44, 38, and 41) for the second excited 0^+ state (0_3^+) are shown here.

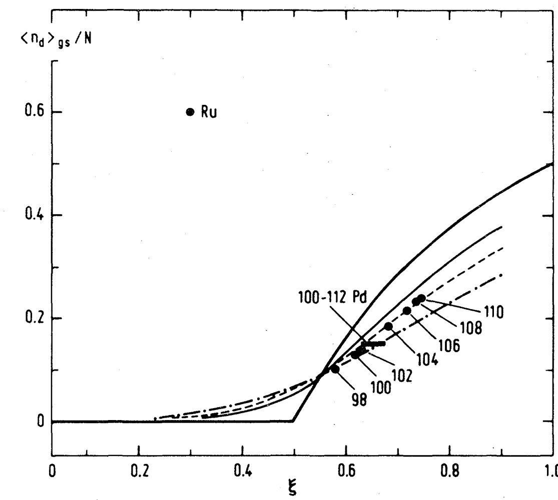

FIG. 10. The quantity $\langle n_d \rangle_{\text{g.s.}}/N$ as a function of ξ. The full, dashed, and dashed-dotted curves represent the result of our schematic calculation for $N=14$, 8, and 5, respectively. The thick full curve is the result in the classical limit $N \rightarrow \infty$ (Ref. 33). The corresponding values for the Ru and Pd isotopes result from a IBA-2 calculation (Ref. 46).

theoretical curves with corresponding N. The resulting ξ values between $0.5-0.8$ show that the result of the schematic calculation presented here agrees rather well with the result of the detailed fit performed in IBA-2. For $^{100-112}$Pd the IBA-2 fit gives nearly constant values for $\langle n_d \rangle_{\text{g.s.}}/N$ around 0.15 and a value of ξ around 0.65 results. This supports a localization of these nuclei in the transitional region between SU(5) and O(6). But, in contrast to the Ru isotopes, one cannot observe a clear evolution as a function of the neutron number for the Pd isotopes.

In conclusion, we have given, in a schematic way, a detailed account of the properties of the SU(5)→O(6) transition in the framework of the interacting boson model. Evidence has been presented that the Ru isotopes, and to a lesser extent the Pd isotopes, follow this schematic transition. However, it is clear that the extremely simplified Hamiltonian presented here cannot account for all observed nuclear properties of the Ru and Pd isotopes. Therefore, this SU(5)→O(6) transition calculation should be viewed only as a guideline, and not as the ultimate theoretical calculation, when comparing it to the experimental data in the Ru and Pd nuclei.

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