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Observation of Positive-Parity Bands in ^{109}Pd and ^{111}Pd

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Abstract. The neutron-rich nuclei ^{109}Pd and ^{111}Pd were produced as fission fragments following the ^{30}Si + ^{168}Er reaction at a beam energy of 142 MeV. Using the identification based on the coincidences with the complementary fission fragments, the only positive-parity bands observed so far in ^{109}Pd and ^{111}Pd emerged from this work. A band, built on top of the 5/2$^+$ ground state exhibiting ΔI = 1 energy-level staggering was observed in each of these nuclei. Both nuclei of interest, ^{109}Pd and ^{111}Pd, are suggested to lie in the transitional region of Pd isotopes of maximum γ-softness. The ground states of both nuclei are predicted by TRS calculations to be extremely γ-soft with shallow triaxial minima. The first crossing in the new bands is proposed to be due to an alignment of $h^2_{11/2}$ neutrons.

1 Introduction

The presently studied ^{109}Pd and ^{111}Pd belong to the region of mostly neutron-rich nuclei with $A \approx 100$ (38,40 $\leq Z \leq$ 50, $N > 56$). The nuclei in this region are known to exhibit a variety of structural phenomena and shapes and were for example a subject of detailed theoretical study by the Nilsson-Strutinski calculations with cranked Woods-Saxon average potential in Ref. [1]. They undergo a transition from nearly spherical vibrational to a deformed rotational character. This transition is known to be rather abrupt in Sr and Zr isotopes, but more gradual in Mo, Ru and Pd isotopes [2]. The calculations cited above [1] predict that the spherical-deformed shape transition goes through a region of γ-softness in the chain of Pd isotopes. The level-energy staggering behavior of the γ-bands in the Pd and Ru isotopes was investigated in details in Ref. [3]. It was concluded that ^{108,110,112}Pd are softer than ^{114,116}Pd and that Pd isotopes are softer than Ru isotopes [3]. The present study of ^{109}Pd and ^{111}Pd is intended to shed more light on the question of γ-softness in the Pd chain of isotopes.

Prior to the present work, a search for band structures in the neutron-rich nuclei ^{109}Pd and ^{111}Pd was performed using a fusion-fission reaction [4] and the negative-parity $\nu(h_{11/2})$ bands were identified. The first crossing was proposed to be a result of $\nu(h_{11/2})^2$ alignment, which stabilizes the prolate shape [4]. How to understand that in the light of the expected enhanced γ-softness? The situation was expressed in Ref. [5] as “a prolate, but still γ-soft shape is stabilized with increased rotational frequency” in ^{110,112,114,116}Pd isotopes. The basis of this assumption were cranked Woods-Saxon and total Routhian surface (TRS) calculations [5].

Most of the nuclei in the discussed region are neutron rich and are not accessible by means of conventional fusion-evaporation in-beam techniques. In the present work, positive-parity bands in ^{109,111}Pd are reported for the first time.

2 Experiment, Analysis and Experimental Results

Excited states in the neutron-rich nuclei ^{109}Pd and ^{111}Pd were populated via an induced fusion-fission channel of the ^{30}Si + ^{168}Er reaction. The beam of ^{30}Si at an energy of 142 MeV was provided by the XTU tandem accelerator at the Legnaro National Laboratory. Prompt γ rays emitted from the excited nuclei were detected with the EUROBALL III multidetector array consisting 30 single HpGe Compton-shielded detectors, 26 Clover and 15 Cluster composite Compton-shielded detectors. The ^{168}Er target foil of 1.15 mg/cm^2 thickness was evaporated on a 9 mg/cm^2 gold backing, in which the recoiling nuclei were slowed down and finally stopped. Events were collected with the requirement that at least five unsuppressed Ge detectors fired in coincidence. A total of about $2{\cdot}10^9$ three- and higher-fold events were recorded. In the off-line analysis, triple gamma-ray coincidence spectra were produced by setting double gates on the $E_\gamma - E_\gamma - E_\gamma$ cubes sorted.

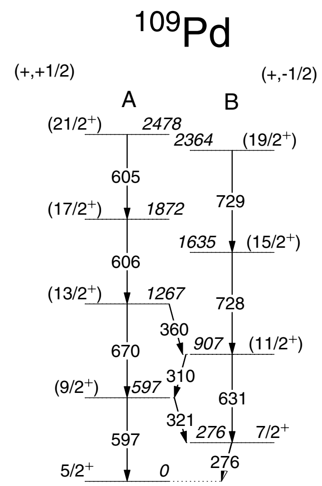

Figure 1. The positive-parity ground-state band of ^{109}Pd deduced from the present work. The energies are given in keV. The experimental uncertainties of the energies are less than 1 keV. Only the 7/2^{+} state at an energy of 276 keV with the 276 keV transition depopulating it to the ground state and the 597 keV level (the transition depopulating the 597 keV level was not observed) were observed in previous studies [6].

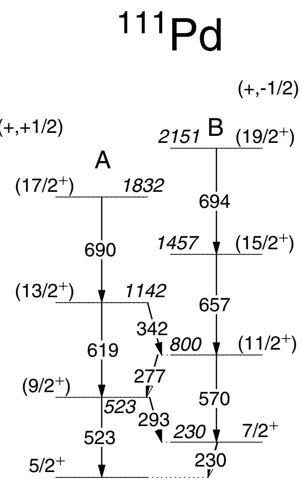

Figure 2. The positive-parity ground-state band of ^{111}Pd deduced from the present work. The energies are given in keV. The experimental uncertainties of the energies are less than 1 keV. The levels at 230 keV and 523 keV as well as the 230, 293 and 523 keV transitions were previously known [7].

In order to search for new transitions in ^{109}Pd and ^{111}Pd, one can examine spectra double gated on low-lying transitions in ^{109,111}Pd and on low-lying transitions in the complementary fission fragments ^{84,82}Kr, respectively. Positive-parity rotational (quasi-rotational) bands were observed for the first time in ^{109}Pd and ^{111}Pd in the present work and are shown in Figures 1 and 2. Low-lying negative-parity yrast bands in both nuclei were previously observed in [4] and are given for completeness in Figure 3.

No band structures built on the two known low-lying positive-parity states were observed in ^{109}Pd before the present study. The first 7/2$^+$ and (9/2$^+$) states at energies of 276 keV and 597 keV, respectively, were observed previously as single not connected levels [6]. Based on these previous experiments, a positive parity can be assigned to the newly observed band structure. The 597 keV transition was not observed before the present study. We assign (9/2$^+$) to the 597 keV state due to the newly observed transitions of 321 and 597 keV connecting this state with the previously known 7/2$^+$ state at 276 keV and with the 5/2$^+$ ground state, respectively. Similarly, a ΔI = 2 ($E2$) character can be assigned as most probable for the transitions within both signature partners and ΔI = 1 ($M1$ or $M1/E2$) character can be expected for the transitions connecting both signature partners of the band. The spin and parity assignments are given in brackets on the level scheme as no direct experimental measurement exists.

No positive-parity rotational band has been observed in ^{111}Pd before the present experimental study. Only two excited positive-parity states (at 230 keV

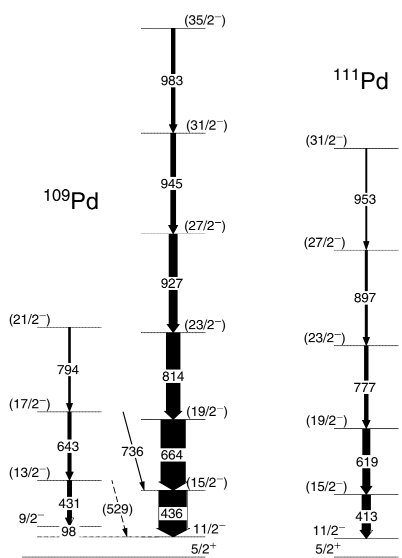

Figure 3. Level scheme of ^{109}Pd and ^{111}Pd for which only negative-parity bands were known so far [4].

and 523 keV) were known in ^{111}Pd prior to the present study [7]. Based on the observed rotational (quasi-rotational) band structure (with ΔI = 2 and ΔI = 1 transitions as most likely), on the previously existed experimental data and on the systematics of the ground-state bands in the region, the spins and parities of the observed states can be proposed.

3 Discussion

The nuclei ^{109}Pd and ^{111}Pd lie in the transitional region between vibrational and rotational nuclei. It is known that this transition from sphericity to deformation in the Pd isotopes is more gradual than the ones in the Sr and Zr isotopes [2]. Nilsson-Strutinski calculations with cranked Woods-Saxon average potential [1] predict that this transition in palladium goes rather through γ-softness than just through softness to axial quadrupole deformation. In agreement, TRS calculations using Woods-Saxon potential as well as Ultimate Cranker predict γ-softness at low-rotational frequencies for the even-even Pd isotopes from ^{110}Pd to ^{116}Pd [5]. The ratios of $E(4_1^+)/E(2_1^+)$ for ^{110}Pd and ^{112}Pd are also very close to the ones predicted by the IBM-2 model value of 2.5 for a γ-soft $O(6)$ rotor. The energy-level staggering in γ-bands in the chain of the Pd isotopes was analyzed in Ref. [3]. The levels of the γ-bands in ^{108}Pd [3], ^{110}Pd [3], ^{112}Pd [8] are grouped as 2^+, (3^+,4^+), (5^+,6^+) and etc., which is consistent with γ-soft behavior accordingly to the model of Wilets and Jean [9]. While the γ-bands are not so well developed in ^{102,104,106}Pd as in the heavier Pd isotopes, the amplitude of the staggering effect decreases in ^{114}Pd and ^{116}Pd with respect to that in ^{108,110,112}Pd, where it reaches its maximum [3]. It was concluded that ^{108}Pd, ^{110}Pd and ^{112}Pd are the most γ-soft Pd isotopes [3].

Thus, one may expect a significant degree of γ-softness at low energies and angular momenta for the nuclei of interest, ^{109}Pd and ^{111}Pd. Moreover, according to the behavior of the γ-bands in the even-even Pd isotopes, one may suggest that both nuclei lie in the region of maximum γ-softness. This suggestion is also supported by the TRS calculations [10] reported below.

3.1 Negative-Parity Bands in ^{109}Pd and ^{111}Pd

The only rotational-like structures in ^{109}Pd and ^{111}Pd observed before the present study were the negative-parity bands built on the low-lying 11/2$^-$ isomer [4] (see Figure 3). They were interpreted as built on an orbital in the middle of $h_{11/2}$ neutron subshell with a prolate deformation [4]. Analogous bands were observed in the neighboring odd-mass Pd isotopes as for example in ^{105,107,113,115}Pd. The alignment of $h_{11/2}^2$ neutrons was proposed to be the nature of this crossing in the odd-mass Pd isotopes as well as in the even-mass Pd isotopes. It is known that the alignment of $h_{11/2}^2$ neutrons drives the nucleus towards prolate shape. Indeed, prolate driving force is predicted by the CSM [11] and cranked-HFB models [12] for the aligned pair of $h_{11/2}$ neutrons. At the same time, Nilsson-Strutinski calculations [1] predict quite a γ-soft potential for the transitional Pd

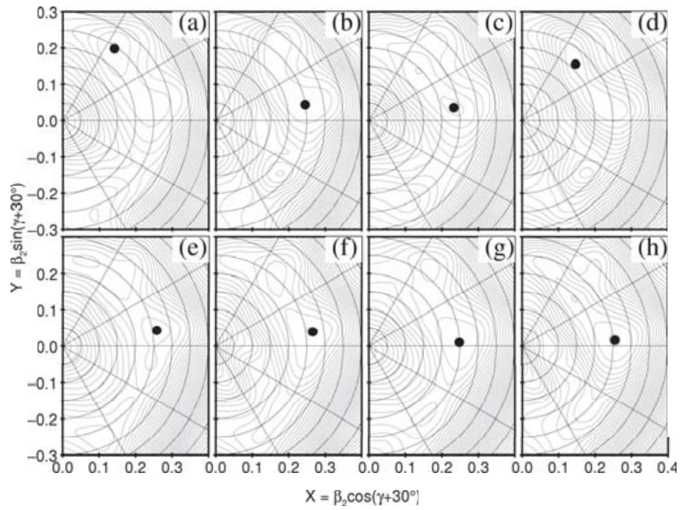

Figure 4. Total Routhian surface calculations for the negative-parity bands in ^{109}Pd and ^{111}Pd. Contour lines are in 200 keV increment. a) ^{109}Pd, (-,+1/2), $\hbar w$ = 0.100 MeV, β_2 = 0.243, γ = +24°; b) ^{109}Pd, (-,+1/2), $\hbar w$ = 0.400 MeV, β_2 = 0.249, γ = -20°; c) ^{109}Pd, (-,-1/2), $\hbar w$ = 0.100 MeV, β_2 = 0.236, γ = -21°; d) ^{109}Pd, (-,-1/2), $\hbar w$ = 0.400 MeV, β_2 = 0.215, γ = +17°; e) ^{111}Pd, (-,+1/2), $\hbar w$ = 0.100 MeV, β_2 = 0.262, γ = -20°; f) ^{111}Pd, (-,+1/2), $\hbar w$ = 0.350 MeV, β_2 = 0.269, γ = -21°; g) ^{111}Pd, (-,-1/2), $\hbar w$ = 0.100 MeV, β_2 = 0.248, γ = -28°; h) ^{111}Pd, (-,-1/2), $\hbar w$ = 0.350 MeV, β_2 = 0.255, γ = -26°

nuclei. The TRS calculations for ^{108}Pd [13] also show a shallow prolate minimum, soft with respect to γ- and β-deformation, at $\hbar w = 0$ MeV. Kruecken et al. [5], reported on TRS calculations for the even-even isotopes ^{110,112,114,116}Pd. They predict very γ-soft minima at low rotational frequency. After the alignment of the $h_{11/2}$ pair of neutrons, the prolate but otherwise γ-soft shape is going towards stabilization [5]. Will a shallow prolate minimum of a very γ-soft potential be the case of ^{109}Pd and ^{111}Pd as well?

In Figure 4, TRS calculations [10] for the negative-parity bands built on the 11/2$^-$ states in ^{109}Pd and ^{111}Pd are shown. The calculations were performed separately for both signatures in both nuclei. At $\hbar w = 0.100$ MeV, the α = +1/2 signature partner in ^{109}Pd is calculated with a shallow minimum at γ = +24° (see Figure 4a), while the α = -1/2 signature partner is at γ = -21° (see Figure 4c). Both surfaces reveal a pronounced γ- and β-softness. It must be noted that both minima lie within a shallow γ-soft valley between $\gamma \approx$ +30° to $\gamma \approx$ -30°. Interpreting the calculations one shall consider that the minima are very shallow and the energy potential surface is predicted quite γ-soft and they may be sensitive to the calculation parameters. Indeed, the average γ-deformation of both minima is $\gamma \approx 0°$, which corresponds to a prolate shape. On the other hand, a non-axial considerably γ-soft shape is predicted for the branches itself.

This behavior can be described as two different shallow potential wells almost symmetrically displaced from $\gamma = 0°$ for both signatures. The relatively low barrier between them would easily allow a change of the γ-deformation. Although only the α = -1/2 signature was observed in ^{111}Pd, calculations for both band signatures are presented in Figure 4. A pronounced γ-deformation is predicted for both signatures and, especially for the α = -1/2 one, at $\hbar w = 0.100$ MeV with γ = -28° and β_2 = 0.248 (see Figure 4g). Independent of the softness of the potential with considerably shallow minima and of the uncertainties of the present calculations, the TRS calculations reveal a different picture for ^{109}Pd and ^{111}Pd than for, e.g., ^{107}Pd. While the TRS calculations predict γ-soft prolate minima for this band in ^{107}Pd (not presented), ^{109}Pd and ^{111}Pd are predicted to be quite γ-soft with non-axial minima.

The TRS calculations do predict a band crossing with $h^2_{11/2}$ neutrons in agreement with the above discussion. The alignment of the $h_{11/2}$ pair of neutrons in ^{109}Pd moves the minimum in the α = +1/2 signature branch from γ = +24° to γ = -20° (see Figures 4a and 4b), while the opposite (minimum moves from γ = -21° to γ = +17°, Figures 4c and 4d) is predicted for the α = -1/2 signature. The potential is still very γ-soft. In ^{111}Pd, on the other hand, the $\gamma \approx$ -28° minimum of the $\alpha =$ -1/2 signature persists through the alignment of the $h^2_{11/2}$ neutrons (see Figure 4h). The TRS calculations predict both signatures in ^{111}Pd with similar γ-deformation, less γ-softness and a stronger β_2 deformation due to the alignment of $h^2_{11/2}$ neutrons. Thus, the alignment of $h^2_{11/2}$ neutrons stabilizes the triaxial minimum at negative γ-deformation in ^{111}Pd. Prolate and not so soft shapes are calculated for both nuclei at higher frequency ($\hbar w = 0.600$ MeV) and angular momentum.

3.2 Positive-Parity Bands in ^{109}Pd and ^{111}Pd

In the present experiment, the ground-state positive-parity bands were observed in ^{109}Pd and in ^{111}Pd. They exhibit energy-staggered ΔI = 1 transitions and thus, appear as semi-decoupled bands. Reasons for an energy-staggering of a band can be due to a band mixing, Coriolis distortion due to high-j orbital, γ-softness, triaxiality. The observed bands pattern may be explained by the γ-softness of the nuclei ^{109}Pd and ^{111}Pd. While ^{107}Pd is predicted to be moderately γ-soft at its ground state, but still around prolate deformation by the TRS calculations, the TRS plots presented in Figure 5 for ^{109}Pd and ^{111}Pd draw a long valley from $\gamma = 60°$ till $\gamma =$ -120° revealing extreme γ-softness (especially for ^{111}Pd). Indeed, the nucleus ^{109}Pd looks considerably γ-soft at its ground state with a minimum at $\gamma = -20°$ (see Figure 5a) and extreme γ-softness with a minimum at $\gamma = -30°$ (see Figure 5e) is seen for the ground state of ^{111}Pd. Calculations were performed separately for both signature partners of these bands in ^{109}Pd and ^{111}Pd as shown in Figure 5. The signature partners have almost the same deformation up to the crossing.

The alignments, i_x, of the newly observed positive-parity bands in ^{109}Pd and

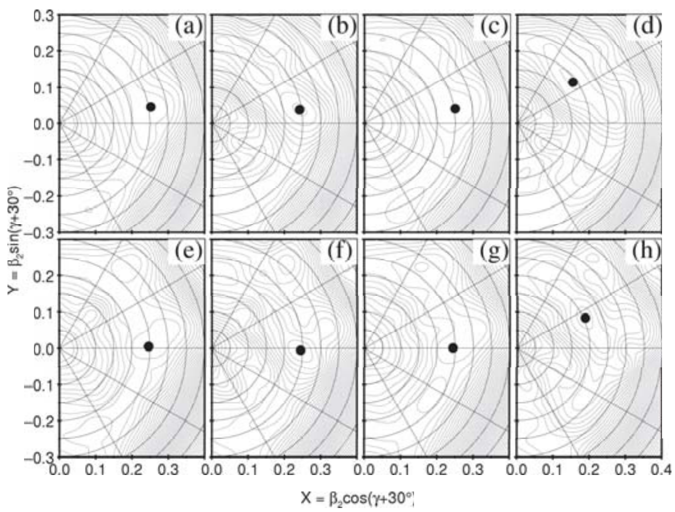

Figure 5. Total Routhian surface calculations for the positive-parity bands in ^{109}Pd and ^{111}Pd. Contour lines are in 200 keV increment. a) ^{109}Pd, (+,+1/2), $\hbar w$ = 0.100 MeV, β_2 = 0.256, γ = -19°; b) ^{109}Pd, (+,+1/2), $\hbar w$ = 0.350 MeV, β_2 = 0.245, γ = -21°; c) ^{109}Pd, (+,-1/2), $\hbar w$ = 0.100 MeV, β_2 = 0.253, γ = -20°; d) ^{109}Pd, (+,-1/2), $\hbar w$ = 0.350 MeV, β_2 = 0.191, γ = +7°; e) ^{111}Pd, (+,+1/2), $\hbar w$ = 0.100 MeV, β_2 = 0.246, γ = -29°; f) ^{111}Pd, (+,+1/2), $\hbar w$ = 0.350 MeV, β_2 = 0.244, γ = -31°; g) ^{111}Pd, (+,-1/2), $\hbar w$ = 0.100 MeV, β_2 = 0.244, γ = -30°; h) ^{111}Pd, (+,-1/2), $\hbar w$ = 0.350 MeV, β_2 = 0.204, γ = -9°.

^{111}Pd and for those in the neighboring isotopes ^{108}Pd and ^{110}Pd, are presented in Figure 6. $K = 5/2$ is used for both nuclei. A band crossing in ^{109}Pd occurs at around 0.35 MeV, which is at about the same frequency as in the even-even Pd neighbors. This behavior is consistent with an alignment of a pair of $h_{11/2}$ neutrons, as no blocking is expected in these bands. The first crossing cannot be seen in ^{111}Pd in the present data. Similarly, the first crossings in the bands on top of the 5/2$^+$ ground states in ^{107}Pd [13] and ^{113}Pd [14] are observed at $\hbar w \approx 0.32$ MeV. In both nuclei, the crossing was interpreted as caused by the alignment of $h^2_{11/2}$ neutrons. In agreement, an alignment of $h^2_{11/2}$ neutrons is predicted by the TRS calculations for these bands in ^{109}Pd and ^{111}Pd. The calculations predict that the alignment of $h^2_{11/2}$ neutrons ($\hbar w \approx$ 0.300 MeV) forces the α = -1/2 signature partners in ^{109}Pd (see Figure 5d) and ^{111}Pd (see Figure 5h) towards more γ-stable near prolate shape. However, the α = +1/2 signature partners in both nuclei are predicted to preserve and actually to stabilize the triaxial deformation (see Figures 5b and 5f). Thus, a more stable triaxiality is predicted at higher spins. Experimental observation of the bands at higher spins in future experiments may allow to test this predictions.

Thus, basically all experimental observables and calculations suggest that ^{109}Pd and ^{111}Pd, probably with ^{113}Pd, lie in the region of maximum γ-softness.

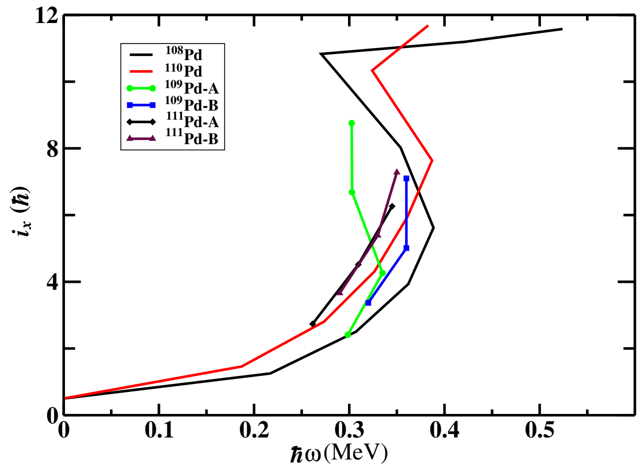

Figure 6. Experimental alignments i_x for the ground-state positive-parity bands in ^{109}Pd and ^{111}Pd and compared to the i_x for the ground-state positive-parity bands in the neighboring even-even ^{108}Pd and ^{110}Pd isotopes. The Harris parameters used were J_0 = 5$\hbar^2$/MeV and J_1 = 16$\hbar^4$/MeV^3. For the bands in ^{109}Pd and ^{111}Pd, K = 5/2 was used. The letters A, B correspond to the band signature partners labels used on the level schemes.

The TRS calculations predict that the alignment of an $h^2_{11/2}$ neutrons drives these nuclei towards more stable deformation, prolate or even triaxial.

4 Conclusion

The neutron-rich nuclei ^{109}Pd and ^{111}Pd were produced as fission fragments at high-excitation energies and angular momentum through the induced fusion-fission reaction ^{30}Si + ^{168}Er at a beam energy of 142 MeV. The beam of ^{30}Si was provided by the XTU tandem accelerator at the Legnaro National Laboratory. Although few low-lying positive-parity states were known before the present study, no band structures built on them were observed. Positive-parity bands in ^{109}Pd and ^{111}Pd were observed for the first time in this work.

It was concluded that ^{109}Pd and ^{111}Pd, together with ^{113}Pd, lie in the transitional Pd region where maximum γ-softness is expected to occur. The TRS calculations do confirm the proposed alignment of $h^2_{11/2}$ neutrons [4] for the negative-parity bands built on the $11/2^-$ states in both nuclei. However, the stabilization towards prolate shape is predicted in these negative-parity bands at higher frequencies than the crossing, while the crossing itself goes through γ-soft non-axial behavior.

The observed positive-parity bands in ^{109}Pd and ^{111}Pd appear like semi-decoupled bands, with a ΔI = 1 level-energy staggering, which can be consistent with a γ-soft potential. The first band crossing in the observed positive-parity bands of this work is proposed to be due to the alignment of the $h^2_{11/2}$ neutrons. The calculations predict that this alignment drives one of the band signatures in both nuclei to a less γ-soft, near-prolate shape, while a stabilization of the triaxial shape is predicted for the other signature in both nuclei. Further experiments are definitely needed in order to test for these predictions.

Acknowledgements

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