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 ground state bands in $^{109}$Pd and $^{111}$Pd were found. They are the only positive-parity bands observed so far in $^{109}$Pd and $^{111}$Pd. A band, built on top of the $5/2^+$ ground state exhibiting $\Delta I = 1$ 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 $\gamma$-softness. The ground states of both nuclei are predicted by TRS calculations to be extremely $\gamma$-soft with shallow triaxial minima. The first crossing in the new bands is proposed to be due to an alignment of $h_{11/2}$ neutrons.

1. Introduction

The neutron-rich nuclei in the $A \approx 100$ ($38 \leq Z \leq 50$, $N > 50$) 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]. The calculations predict that the expected spherical-deformed shape transition goes through a region of $\gamma$-softness in the chain of Pd isotopes. The present study of $^{109}$Pd and $^{111}$Pd is intended to shed more light on the question of $\gamma$-softness in the chain of Pd 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 [2] 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 [2]. How to understand that in the light of the expected $\gamma$-softness?

The situation was expressed in Ref. [3] as “a prolate, but still $\gamma$-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 [3]. 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 $\gamma$ rays emitted from the excited nuclei were detected with the EUROBALL III multidetector array. 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.

In order to search for new transitions in $^{109}$Pd and $^{111}$Pd, we examined 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.

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 [4]. 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. No positive-parity rotational band has been observed in $^{111}$Pd prior to the present experimental study. Only two excited positive-parity states (at 230 keV and 523 keV) were known in $^{111}$Pd prior to the present study [5]. Based on the observed rotational (quasi-rotational) band structure (with $\Delta J = 2$ and $\Delta I = 1$ 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 [6]. Nilsson-Strutinski calculations with cranked Woods-Saxon average potential [1] predict that this transition in palladium goes rather through $\gamma$-softness than just through softness to axial quadrupole deformation. 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 $\gamma$-soft $O(6)$ rotor. The energy-level staggering in $\gamma$-bands in the chain of the Pd isotopes was analyzed in Ref. [7]. The levels of the $\gamma$-bands in $^{108}$Pd [7], $^{110}$Pd [7], $^{112}$Pd [8] are grouped as $2^+$, $(3^+, 4^+)$, $(5^+, 6^+)$ and etc., which is consistent with $\gamma$-soft behavior accordingly to the model of Wilets and Jean [9]. While the $\gamma$-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 [7]. It was concluded that $^{108}$Pd, $^{110}$Pd and $^{112}$Pd are the most $\gamma$-soft Pd isotopes [7].

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

In the present experiment, the ground-state positive-parity bands were observed in $^{109}$Pd and in $^{111}$Pd. While $^{107}$Pd is predicted to be moderately $\gamma$-soft at its ground state, but still around prolate deformation by the TRS calculations, the TRS plots presented in Figure 3 for $^{109}$Pd and $^{111}$Pd draw a long valley from $\gamma = 60^\circ$ till $\gamma = -120^\circ$ revealing extreme $\gamma$-softness (especially for $^{111}$Pd). Indeed, the nucleus $^{109}$Pd looks considerably $\gamma$-soft at its ground state with a minimum at $\gamma = -20^\circ$ (see Figure 3a) and extreme $\gamma$-softness with a minimum at $\gamma = -30^\circ$ (see Figure 3c) 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 3. The signature partners have almost the same deformation up to the crossing.

A band crossing in $^{109}$Pd occurs at around 0.35 MeV (the figure is not shown), 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. In agreement, an alignment of $h_{11/2}^2$ neutrons is predicted by the TRS calculations for these bands in $^{109}$Pd and $^{111}$Pd. The calculations predict that the alignment of $h_{11/2}^2$ neutrons ($\hbar \omega \approx 0.300 \text{ MeV}$) forces the $\alpha = -1/2$ signature partners in $^{109}$Pd (see Figure 3d) and $^{111}$Pd (see Figure 3h) towards more $\gamma$-stable near prolate shape. However, the $\alpha = +1/2$ signature partners in both nuclei are predicted to preserve and actually to stabilize the triaxial deformation (see Figures 3b and 3f). 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.
4. Conclusion

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, together with $^{111}$Pd, lie in the transitional Pd region where maximum $\gamma$-softness is expected to occur. The first band crossing in the observed positive-parity bands of this work is proposed to be due to the alignment of the $h_{11/2}$ neutrons. The calculations predict that this alignment drives one of the band signatures in both nuclei to a less $\gamma$-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.

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