Observation of positive-parity bands in ^{109}Pd and ^{111}Pd: Enhanced γ softness

E. A. Stefanova,[1,*] S. Lalkovski,[2] A. Korichi,[3] T. Kutsarova,[1] A. Lopez-Martens,[3] F. R. Xu,[4] H. L. Liu,[4] S. Kisyov,[2] A. Minkova,[2] D. Bazzacco,[5] M. Bergström,[6] A. Görgen,[7,†] F. Hannachi,[3,‡] B. Herskind,[6] H. Hübel,[7] A. Jansen,[7] T. L. Khoo,[8] Zs. Podolyák,[9,§] and G. Schönwasser[7]

[1]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Science, 1784 Sofia, Bulgaria*
[2]*Faculty of Physics, University of Sofia "St. Kliment Ohridski," 1164 Sofia, Bulgaria*
[3]*CSNSM Orsay, IN2P3/CNRS, F-91405, France*
[4]*School of Physics, Peking University, Beijing 100871, China*
[5]*INFN, Sezione di Padova, I-35131 Padova, Italy*
[6]*The Niels Bohr Institut, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*
[7]*Helmholtz-Institut für Strahlen -und Kernphysik, Universität Bonn, Nussallee 14-16, D-53115 Bonn, Germany*
[8]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[9]*INFN, Laboratori Nazionali di Legnaro, I-35020 Padova, Italy*

(Received 28 March 2012; revised manuscript received 4 July 2012; published 1 October 2012)

The neutron-rich nuclei ^{109}Pd and ^{111}Pd were produced as fission fragments following the ^{30}Si + ^{168}Er reaction at 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 $\Delta I = 1$ 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 γ softness. The ground states of both nuclei are predicted by total Routhian surface calculations to be extremely γ soft with shallow triaxial minima. The first crossing in the new bands is proposed to be attributable to an alignment of $h^2_{11/2}$ neutrons.

DOI: 10.1103/PhysRevC.86.044302 PACS number(s): 23.20.Lv, 21.60.−n, 25.70.Jj, 27.60.+j

I. INTRODUCTION

The presently studied ^{109}Pd and ^{111}Pd belong to the region of mostly neutron-rich nuclei with $A \approx 100$ ($38, 40 \leqslant Z \leqslant 50$, $N > 56$). 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]. Owing to the scarcity of experimental information, the gradual character of the deformation development transition in the Pd isotopes is still under investigation. 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. Indeed, the $E(4^+_1)/E(2^+_1)$ ratios for ^{110}Pd and ^{112}Pd are close to the γ-soft O(6) limit of 2.5 of the IBM-2 model. Furthermore, the level-energy staggering behavior of the γ bands in the Pd and Ru isotopes was investigated in detail 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 chain of Pd isotopes. Moreover, both nuclei may be expected to form the region of maximum γ softness for 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 bases of this assumption were cranked Woods-Saxon and total Routhian surface (TRS) calculations [5]. The first band crossings in Pd isotopes heavier than ^{111}Pd were argued in the past to be attributable to a pair of $h_{11/2}$ neutrons or $g_{9/2}$ protons. The recent studies definitely agree on $h^2_{11/2}$ neutrons alignment. Indeed, these are the cases of the $h_{11/2}$ bands in ^{111,113,115}Pd [4–7] and the ground-state bands in ^{112,114,116,118}Pd [3,6,8].

Most of the nuclei in the discussed region are neutron rich and are not accessible by means of conventional fusion-evaporation in-beam techniques. Therefore, the experimental information is incomplete, even at low spin. Before the present study, the information on the positive-parity states in ^{109}Pd and ^{111}Pd was limited to a very few low-energy levels not connected in a band structure. Positive-parity bands built on the $5/2^+$ ground states were observed in ^{101,103}Pd [9,10], ^{105}Pd [11], ^{107}Pd [12], and ^{113,115}Pd [7], but not in ^{109}Pd and ^{111}Pd. Filling this gap of experimental information may shed light on

*elenas@inrne.bas.bg
†Present address: DAPNIA/SPhN, CEA-Saclay, Gif-sur-Yvette, France.
‡Present address: Centre d'Etudes Nuclaires de Bordeaux-Gradignan, Gradignan, France.
§Present address: Department of Physics, University of Surrey, Guildford GU27XH, UK.

the deformation evolution of the positive-parity ground-state bands through the transitional region. Considering that this is expected to be a region of maximum γ softness for the transitional Pd isotopes, the observation of these structures is important for understanding the whole transitional region.

In the present work, positive-parity bands in ^{109}Pd and ^{111}Pd are reported for the first time. They give a subject to investigate how these nuclei behave in a region where enhanced γ softness and prolate driving effects arising from an alignment of a pair of $h_{11/2}$ neutrons compete.

II. EXPERIMENT AND ANALYSIS

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. Excited yrast states of ^{98,100,102}Mo, produced also as fission fragments in the same experiment, were already studied and published [13]. 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 [14] multidetector array consisting 30 single High Purity Germanium (HpGe) Compton-shielded detectors and 26 clover [15] and 15 cluster [16] 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 2×10^9 three- and higher-fold events were recorded. In the off-line analysis, two E_γ-E_γ-E_γ cubes with energy ranges up to 4 MeV and up to 1 MeV, respectively, were sorted using the RADWARE package [17]. Triple γ-ray coincidence spectra were then produced by setting double gates on the E_γ-E_γ-E_γ cubes.

To search for new transitions in ^{109}Pd and ^{111}Pd, one can examine spectra double gated on low-lying transitions in the complementary fission fragments ^{84,82}Kr, respectively. The structures built on the ground states in the odd-mass Pd isotopes are expected to be populated weaker than the yrast $\nu(h_{11/2})^2$ bands [4]. Indeed, the data confirmed this expectation. In ^{109}Pd, only the 276-keV transition as well as 276- and 597-keV levels were known [18]. To identify the states above the known low-energy positive-parity levels, double gates on one of these transitions with the lowest-lying yrast transitions in the complementary Kr isotopes were created. A sample spectrum, double gated on the 276-keV transition from ^{109}Pd and on the 882-keV transition from ^{84}Kr, is shown in Fig. 1. Three transitions (230, 293, 523 keV) were observed previously [19] in ^{111}Pd. In this case, a double gate on 230- and 293-keV transitions, known to be in coincidence, was used in addition to cross-double gates on the known transitions in ^{111}Pd and on the transitions of Kr isotopes to identify new transitions in ^{111}Pd. Although the new transitions are weak and the spectra are contaminated, the coincidences were unambiguous and level schemes of the positive-parity structures in ^{109,111}Pd are constructed.

The low statistics does not allow the deduction of relative γ-ray intensities with reasonable precision for the observed transitions in ^{109,111}Pd. To study the level decay branches further experiments are needed.

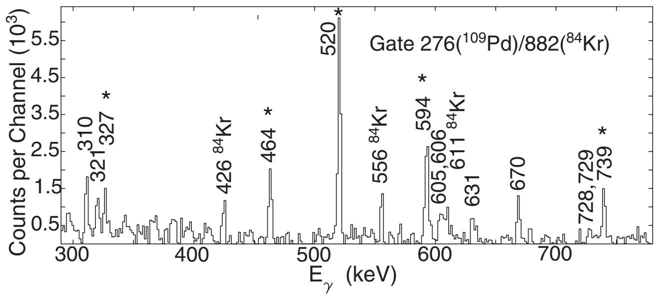

FIG. 1. Spectra, double gated on the 276-keV transition from ^{109}Pd and the 882-keV transition from ^{84}Kr. Contaminant lines are marked with asterisks (∗).

The spin and parity assignments are based on the previously known adopted values for the lowest-lying excited positive-parity states [18,19], the systematics of the neighboring nuclei, and the fact that well-defined band structures, with most likely $\Delta I = 2$ and $\Delta I = 1$ transitions, are developed on top of them.

III. EXPERIMENTAL RESULTS

Positive-parity rotational (quasirotational) bands were observed for the first time in ^{109}Pd and ^{111}Pd in the present work and are shown in Figs. 2 and 3. Low-lying negative-parity yrast

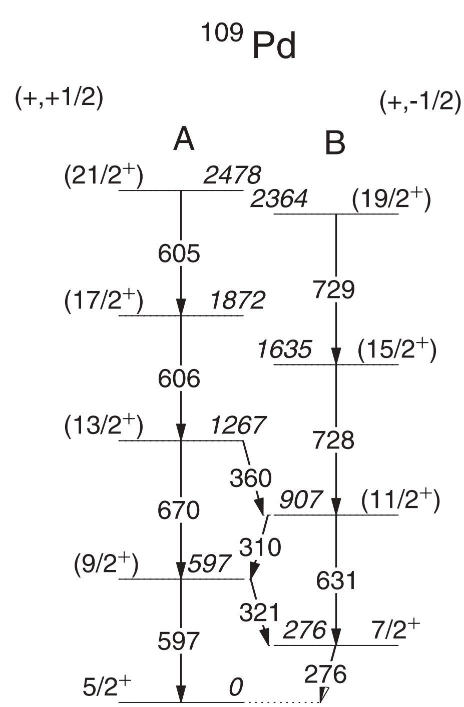

FIG. 2. The positive-parity ground-state band of ^{109}Pd deduced from the present work. The energies are given in keV. The experimental uncertainties of the energies are less than 1 keV. Only the $7/2^+$ state at an energy of 276 keV with the 276-keV transition depopulating it to the ground state and the 597-keV level (the transition depopulating the 597-keV level was not observed) were observed in previous studies [18].

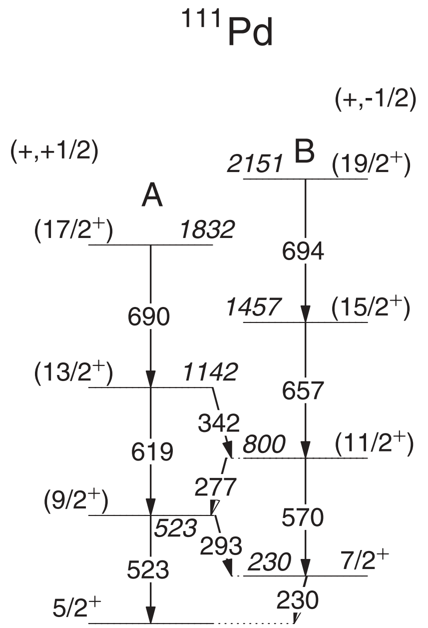

FIG. 3. The positive-parity ground-state band of ^{111}Pd deduced from the present work. The energies are given in keV. The experimental uncertainties of the energies are less than 1 keV. The levels at 230 and 523 keV as well as the 230-, 293-, and 523-keV transitions were previously known [19].

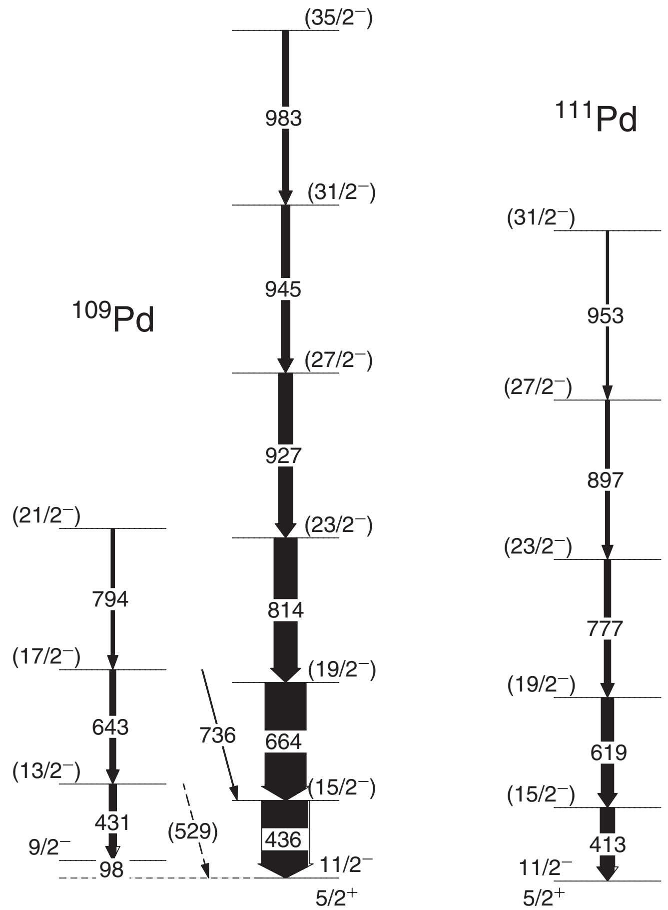

FIG. 4. Level scheme of ^{109}Pd and ^{111}Pd for which only negative-parity bands were known so far [4].

bands in both nuclei were previously observed in Ref. [4] and are given for completeness in Fig. 4.

A. Positive-parity band in ^{109}Pd

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 and 597 keV, respectively, were observed previously as single unconnected levels. A band with two signature partners developing on both these states was observed in the present experiment as presented in Fig. 2. The $7/2^+$ state at 276 keV, as well as the one at 597 keV assumed to be with spin and parity of $7/2^+$ or $9/2^+$, were first observed by Kanazawa *et al.* [20] in β^--decay experiment. The $7/2^+$ state together with the 276-keV transition depopulating it to the ground state were also observed by Casten *et al.* [21] in (n,γ) experiment, while a 596(4)-keV state was observed in (d,t) experiment [22] with an assignment of $7/2^+$. 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 owing 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. Indeed, considering that a rotational-like structure is observed and the ground-state band systematics in the region, $\Delta I = 1$ ($M1$ or $M1/E2$) and $\Delta I = 2$ ($E2$) characters can be safely proposed for the 321- and 597-keV transitions, respectively. To go further in the argumentation, one can add that because both signature partners are built on known positive-parity states ($5/2^+$ and $7/2^+$), the possibility of an octupole band with an alternating-parity level structures can be ruled out. The combination of $E1$ and $M2$ transitions can also be excluded as unlikely. Similarly, a $\Delta I = 2\,(E2)$ character can be assigned as most probable for the transitions within both signature partners and $\Delta I = 1$ ($M1$ 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. Three sample spectra double gated on the 276- and 321-keV, 276- and 728-keV, and on the 310- and 728-keV transitions are shown in Fig. 5.

B. Positive-parity band in ^{111}Pd

No positive-parity rotational band has been observed in ^{111}Pd before the present experimental study. Only two excited positive-parity states were known in ^{111}Pd prior to the present study. A rotational band, with two signature partners developing on the two known levels, was extracted from the present experimental data and presented in Fig. 3. The state at 230 keV was previously observed in (d,p), β^- decay and (n,γ) experiments with possible spin and parity assignments of $7/2^+$ or $9/2^+$ [19]. Considering the rotational-like new band

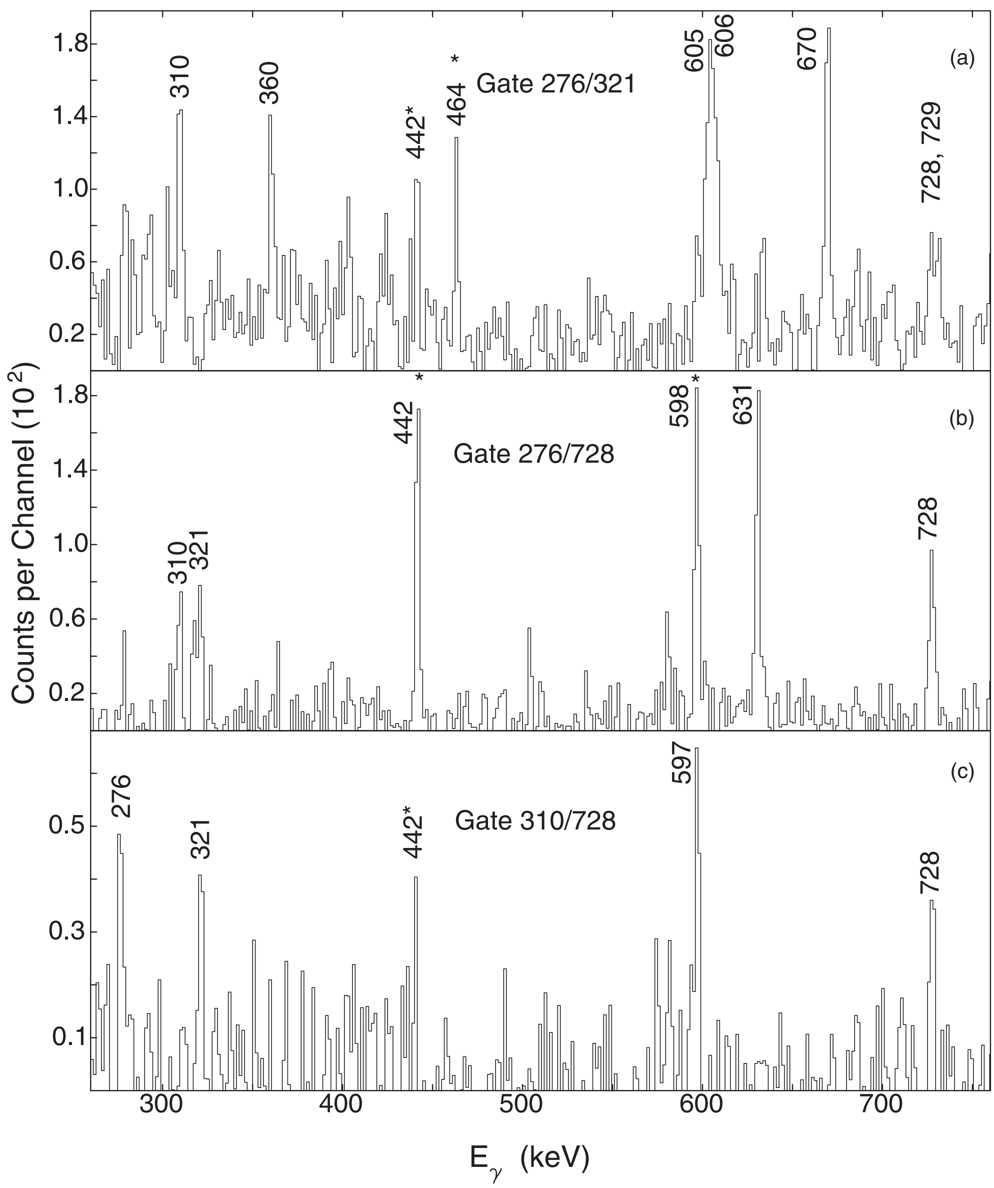

FIG. 5. Sample spectra double gated on the 276- and 321-keV (a), 276- and 728-keV (b), and 310- and 728-keV (c) transitions in ^{109}Pd. The lines marked with asterisks (∗) are from contaminants.

structure observed and comparing it with the very similar one in ^{109}Pd, an assignment of $7/2^+$ was adopted for the 230-keV state. The 230-keV transition depopulating this state to the ground state was also previously observed [19]. The level at 523 keV was observed before in β^--decay experiments [19]. However, no spin assignment was adopted for it [19]. The 293- and 523-keV transitions depopulating the state at 523 keV to the 230-keV level and to the ground state, respectively, were also known [19]. The previously known positive parity for the state at 230 keV makes it possible to assign positive parity for the newly observed band structure. Based on the observed rotational (quasirotational) band structure (with $\Delta I = 2$ 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. Two sample spectra double gated on the 230- and 570-keV transitions and on the 277- and 657-keV transitions are shown in Fig. 6.

IV. DISCUSSION

A. A region of γ softness

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

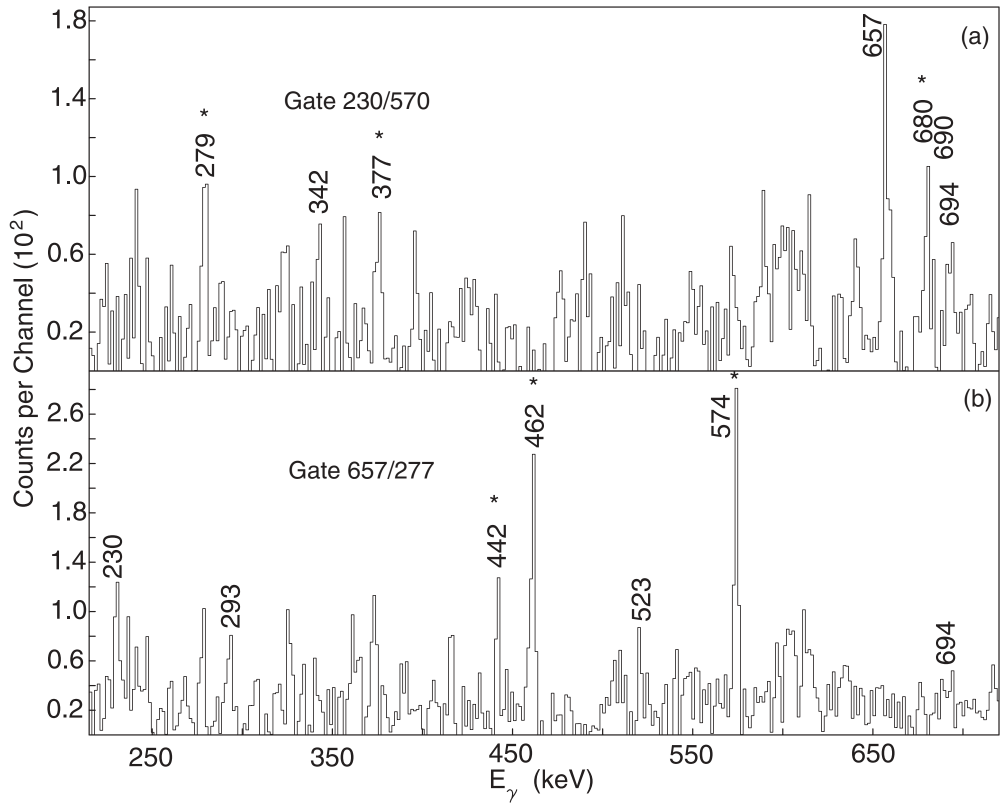

FIG. 6. Sample spectra double gated on the 230- and 570-keV (a) and on the 277- and 657-keV (b) transitions in ^{111}Pd. The lines marked with asterisks (∗) are from contaminants.

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. Also, an odd-even energy-level staggering in a γ band is known to be a sign of a nonaxial shape (soft or rigid) [23]. 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 [24] are grouped as 2^+, (3^+,4^+), (5^+,6^+), etc., which is consistent with γ-soft behavior accordingly to the model of Wilets and Jean [25]. 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 [26] reported below.

B. 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 Fig. 4). 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}Pd [11], ^{107}Pd [12], ^{113}Pd [5–7,27], and ^{115}Pd [5–7,27]. They appear as quasirotationally aligned except for the ones in ^{109}Pd [4] and ^{113}Pd [6], where the signature partner was observed. The $\Delta I = 1$ staggering of the level energies of the signature partners suggests kind of semidecoupled or so called Coriolis-distorted structures. It has not been possible so far to investigate on the origin of the different band behavior observed in ^{109}Pd and ^{113}Pd and in the other odd-even isotopes.

The $h_{11/2}$ bands in the odd-mass Pd isotopes from ^{107}Pd to ^{115}Pd show the first band crossing at a frequency of about 0.47 MeV [4–7,12], suggesting similar crossing nature for all of them. It is at about 0.56 MeV in ^{105}Pd [11], which was proposed to be a result of its smaller deformation [11,12]. The crossing in the odd-mass isotopes is delayed with respect to the first crossing (≈0.35 MeV) in the neighboring even-mass Pd isotopes, which was explained to be attributable to a blocking effect caused by the $h_{11/2}$ neutron. Therefore, the alignment of $h_{11/2}^2$ neutrons rather than $g_{9/2}^2$ protons, which was the alternative interpretation, was proposed to be the nature of this crossing in the odd-mass Pd isotopes (see, e.g., [4–7,12]) and in the even-mass Pd isotopes ^{108}Pd [3,12,28], ^{110}Pd [3,6], and ^{112,114,116,118}Pd [6,8]. Additional arguments supporting the $h_{11/2}^2$ neutron alignment comes for example from Cranked Shell Model

(CSM) calculations [28] and TRS calculations [12] performed for ^{108}Pd and cranked Hartree-Fock-Bogoliubov (HFB) for ^{112}Pd [6].

It is known that the alignment of $h^2_{11/2}$ neutrons drives the nucleus towards prolate shape. Indeed, prolate driving force is predicted by the CSM [28] and cranked-HFB models [6] 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 nuclei. The TRS calculations for ^{108}Pd [12] also show a shallow prolate minimum, soft with respect to γ and β deformation, at $\hbar w = 0$ MeV. With an increase of the rotational frequency the minimum moves towards soft nonaxial deformation. Then, the alignment of $h_{11/2}$ pair of neutrons stabilizes the prolate shape, but the potential surface is still quite soft towards β and γ deformation [12]. The performed TRS calculations for ^{110}Pd (not shown) revealed that the potential is more γ soft than that in ^{108}Pd. 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 Fig. 7, TRS calculations [26] 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 $\alpha = +1/2$ signature partner in ^{109}Pd is calculated with a shallow minimum at $\gamma = +24^\circ$ [see Fig. 7(a)], while the $\alpha = -1/2$ signature partner is at $\gamma = -21^\circ$ [see Fig. 7(c)]. Both surfaces reveal a pronounced γ and β softness. It must be noted that both minima lie within a shallow γ-soft valley between $\gamma \approx +30^\circ$ to $\gamma \approx -30^\circ$. Interpreting the calculations one shall consider that the minima are very shallow and the energy potential surface is predicted to be quite γ soft and they may be sensitive to the calculation parameters. Indeed, the average γ deformation of both minima is $\gamma \approx 0^\circ$, which corresponds to a prolate shape. However, a nonaxial 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 $\gamma = 0^\circ$ for both signatures. The relatively low barrier between them would easily allow a change of the γ deformation. Although only the $\alpha = -1/2$ signature was observed in ^{111}Pd, calculations for both band signatures are presented in Fig. 7. A pronounced γ deformation is predicted for both signatures and, especially for the $\alpha = -1/2$ one, at $\hbar w = 0.100$ MeV with $\gamma = -28^\circ$ and $\beta_2 = 0.248$ [see Fig. 7(g)]. 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, for example, ^{107}Pd. While the TRS calculations predict γ-soft prolate minima for this band in ^{107}Pd (not presented),

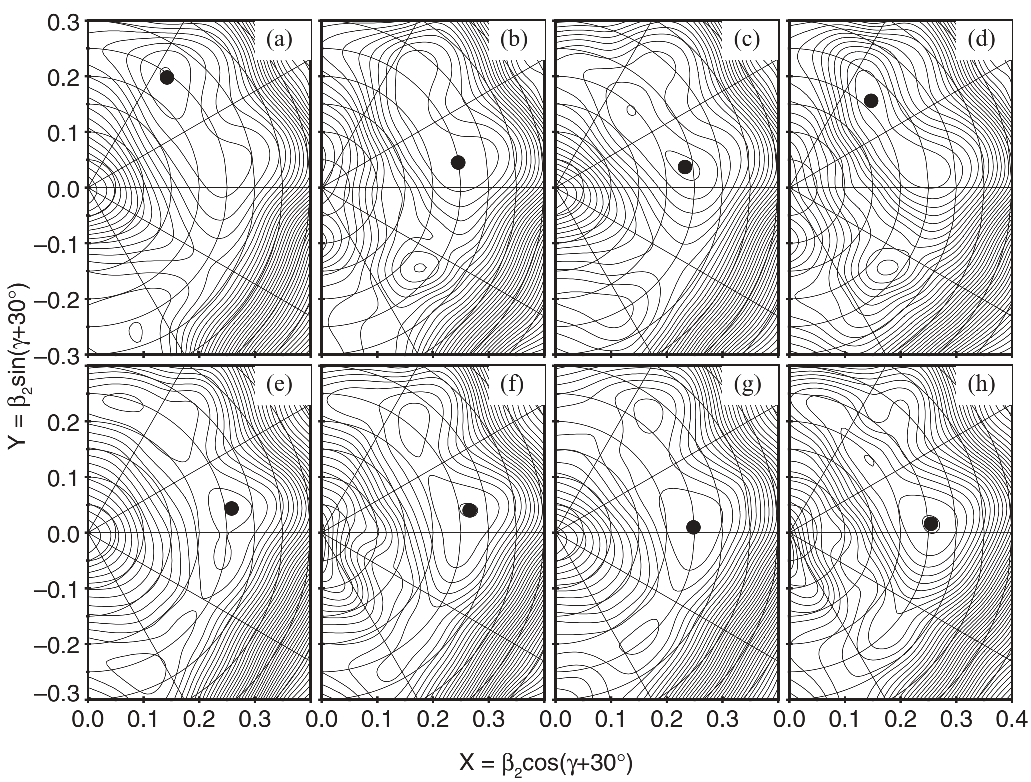

FIG. 7. Total Routhian surface calculations for the negative-parity bands in ^{109}Pd and ^{111}Pd. Contour lines are in 200-keV increments. (a) ^{109}Pd, $(-,+1/2)$, $\hbar w = 0.100$ MeV, $\beta_2 = 0.243$, $\gamma = +24^\circ$; (b) ^{109}Pd, $(-,+1/2)$, $\hbar w = 0.400$ MeV, $\beta_2 = 0.249$, $\gamma = -20^\circ$; (c) ^{109}Pd, $(-,-1/2)$, $\hbar w = 0.100$ MeV, $\beta_2 = 0.236$, $\gamma = -21^\circ$; (d) ^{109}Pd, $(-,-1/2)$, $\hbar w = 0.400$ MeV, $\beta_2 = 0.215$, $\gamma = +17^\circ$; (e) ^{111}Pd, $(-,+1/2)$, $\hbar w = 0.100$ MeV, $\beta_2 = 0.262$, $\gamma = -20^\circ$; (f) ^{111}Pd, $(-,+1/2)$, $\hbar w = 0.350$ MeV, $\beta_2 = 0.269$, $\gamma = -21^\circ$; (g) ^{111}Pd, $(-,-1/2)$, $\hbar w = 0.100$ MeV, $\beta_2 = 0.248$, $\gamma = -28^\circ$; (h) ^{111}Pd, $(-,-1/2)$, $\hbar w = 0.350$ MeV, $\beta_2 = 0.255$, $\gamma = -26^\circ$.

^{109}Pd and ^{111}Pd are predicted to be quite γ soft with nonaxial 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 $\alpha = +1/2$ signature branch from $\gamma = +24^\circ$ to $\gamma = -20^\circ$ [see Figs. 7(a) and 7(b)], while the opposite [minimum moves from $\gamma = -21^\circ$ to $\gamma = +17^\circ$; Figs. 7(c) and 7(d)] is predicted for the $\alpha = -1/2$ signature. The potential is still very γ soft. In ^{111}Pd, however, the $\gamma \approx -28^\circ$ minimum of the $\alpha = -1/2$ signature persists through the alignment of the $h^2_{11/2}$ neutrons [see Fig. 7(h)]. The TRS calculations predict both signatures in ^{111}Pd with similar γ deformation, less γ softness, and a stronger β_2 deformation owing 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.

C. 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 $\Delta I = 1$ transitions and thus, appear as semidecoupled bands. Reasons for an energy-staggering of a band can be attributed to a band mixing, Coriolis distortion owing 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. However, analogous bands, on top of the $5/2^+$ ground state with two energetically staggered signature partners, were also observed in ^{101}Pd [9], ^{103}Pd [10], ^{105}Pd [11], ^{113}Pd [7], and ^{115}Pd [7]. The $\Delta I = 1$ staggering of these bands in ^{101}Pd [9], ^{103}Pd [10], and ^{105}Pd [11] cannot be explained by γ softness as these nuclei are expected to be more β soft rather than γ soft. For instance, it may be rather attributable to a band mixing. In the level schemes of these nuclei bands and levels causing a possible mixing have, indeed, been observed. In the heavier ^{113}Pd, however, the positive-parity band may be explained by γ softness. Again, we have performed TRS calculations for the ground state of ^{113}Pd and they predict that this nucleus is considerably γ soft. The TRS calculations for the ground state band in ^{107}Pd (not shown) reveal a γ-soft prolate minimum for the $\alpha = -1/2$ signature and a nearly prolate γ-soft minimum with $\gamma = 10^\circ$ for the $\alpha = +1/2$ signature. Thus, a signature splitting may be suggested. In agreement, a strongly populated band (band 4) looking like a quasirotationally aligned was observed in ^{107}Pd [12]. A more detailed theoretical study is needed to explain the behavior of the positive-parity ground-state bands in the chain of the odd-A Pd isotopes.

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 Fig. 8 for ^{109}Pd and

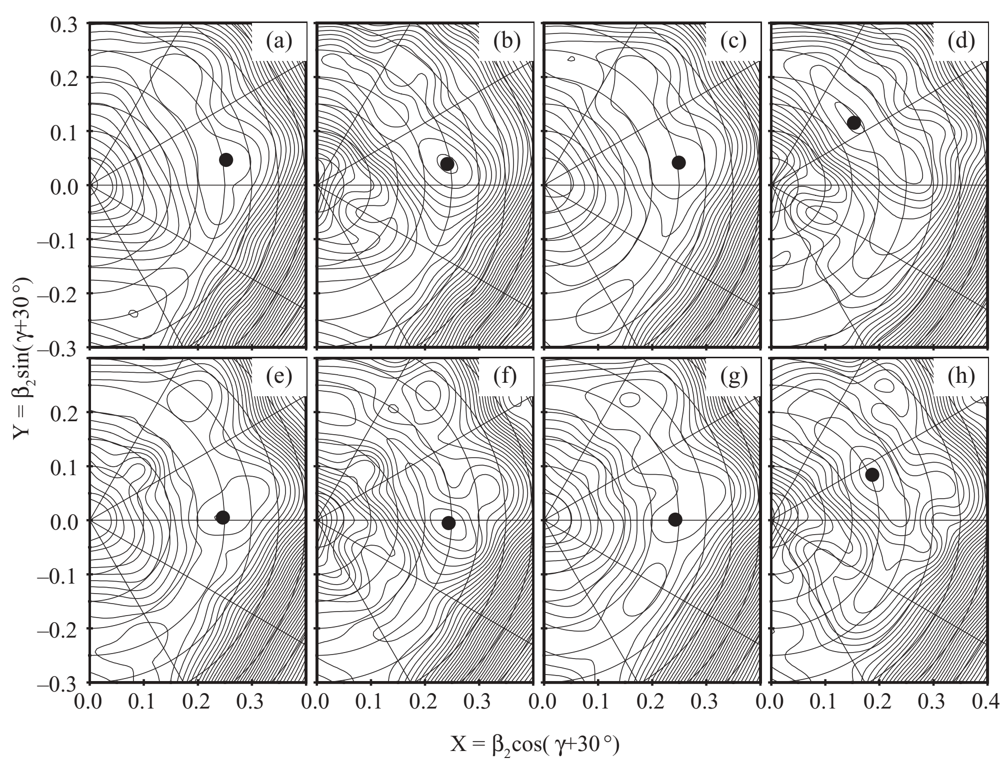

FIG. 8. Total Routhian surface calculations for the positive-parity bands in ^{109}Pd and ^{111}Pd. Contour lines are in 200-keV increments. (a) ^{109}Pd, (+, +1/2), $\hbar w = 0.100$ MeV, $\beta_2 = 0.256$, $\gamma = -19^\circ$; (b) ^{109}Pd, (+, +1/2), $\hbar w = 0.350$ MeV, $\beta_2 = 0.245$, $\gamma = -21^\circ$; (c) ^{109}Pd, (+, −1/2), $\hbar w = 0.100$ MeV, $\beta_2 = 0.253$, $\gamma = -20^\circ$; (d) ^{109}Pd, (+, −1/2), $\hbar w = 0.350$ MeV, $\beta_2 = 0.191$, $\gamma = +7^\circ$; (e) ^{111}Pd, (+, +1/2), $\hbar w = 0.100$ MeV, $\beta_2 = 0.246$, $\gamma = -29^\circ$; (f) ^{111}Pd, (+, +1/2), $\hbar w = 0.350$ MeV, $\beta_2 = 0.244$, $\gamma = -31^\circ$; (g) ^{111}Pd, (+, −1/2), $\hbar w = 0.100$ MeV, $\beta_2 = 0.244$, $\gamma = -30^\circ$; (h) ^{111}Pd, (+, −1/2), $\hbar w = 0.350$ MeV, $\beta_2 = 0.204$, $\gamma = -9^\circ$.

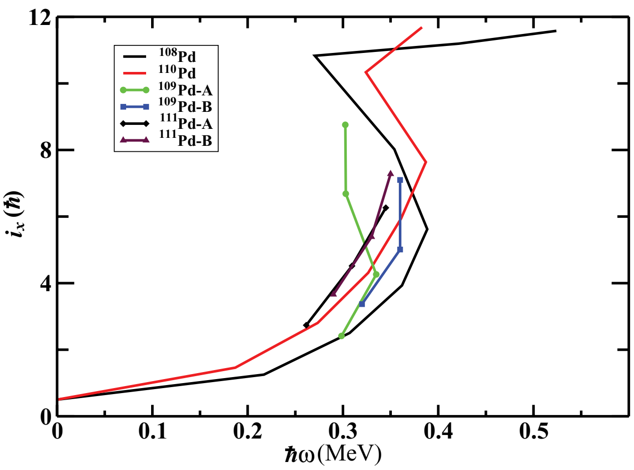

FIG. 9. (Color online) Experimental alignments i_x for the ground-state positive-parity bands in ^{109}Pd and ^{111}Pd and compared to the i_x for the ground-state positive-parity bands in the neighboring even-even ^{108}Pd and ^{110}Pd isotopes. The Harris parameters used were $J_0 = 5\hbar^2/\mathrm{MeV}$ and $J_1 = 16\hbar^4/\mathrm{MeV}^3$. 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.

^{111}Pd draw a long valley from $\gamma = 60^\circ$ until $\gamma = -120^\circ$ 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 $\gamma = -20^\circ$ [see Fig. 8(a)] and extreme γ softness with a minimum at $\gamma = -30^\circ$ [see Fig. 8(e)] is seen for the ground state of ^{111}Pd. The corresponding predominant configurations are calculated to be $d_{5/2}$ neutrons for ^{109}Pd and $g_{7/2}$ neutrons for ^{111}Pd. These minima in both nuclei persist up to around the crossing with a pair of $h_{11/2}$ neutrons. Calculations were performed separately for both signature partners of these bands in ^{109}Pd and ^{111}Pd as shown in Fig. 8. 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 ^{111}Pd and for those in the neighboring isotopes ^{108}Pd and ^{110}Pd, are presented in Fig. 9. The staggering pattern of the levels within the bands suggests that K changes within the bands. However, the behavior of the i_x does not change strongly with K and $K = 5/2$ 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 [12] and ^{113}Pd [7] 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 a pair of $h_{11/2}$ neutrons is predicted by the TRS calculations for the positive-parity bands in ^{109}Pd and ^{111}Pd. The calculations predict that the alignment of a pair of $h_{11/2}$ neutrons ($\hbar w \approx 0.300$ MeV) forces the $\alpha = -1/2$ signature partners in ^{109}Pd [see Fig. 8(d)] and ^{111}Pd [see Fig. 8(h)] towards more γ-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 Figs. 8(b) and 8(f)]. Thus, a more stable triaxiality is predicted at higher spins. Experimental observation of the bands at higher spins in future experiments may make it possible to test this predictions. A negative-parity band with two signature partners connected with staggered $M1$ transitions was observed at higher excitation energies in ^{112}Pd [24]. The performed TRS calculations also predict possibly a triaxial shape for this band [24].

Thus, basically all experimental observables, calculations, and arguments suggest that ^{109}Pd and ^{111}Pd, probably together with ^{113}Pd, lie in the region of maximum γ softness. The TRS calculations predict that the alignment of an $h_{11/2}$ pair of neutrons drives these nuclei towards more stable deformation, prolate or even triaxial.

V. SUMMARY

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. Indeed, the nuclei ^{109}Pd and ^{111}Pd are predicted to be γ soft with shallow triaxial minima for the lowest-lying states of the observed negative parity as well as positive-parity bands by the TRS calculations. An extreme γ softness is predicted for ^{111}Pd. 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 nonaxial behavior.

The observed positive-parity bands in ^{109}Pd and ^{111}Pd appear like semidecoupled bands, with a $\Delta I = 1$ level-energy staggering, which can be consistent with a γ-soft potential [23]. The analogous band in ^{107}Pd has a rotationally aligned behavior, while an odd-even level-energy staggering is revealed for the analogous bands in lighter Pd isotopes ($^{101-105}$Pd). Detailed theoretical studies are needed to explain the behavior of the positive-parity ground-state bands in the chain of Pd isotopes. The first band crossing in the observed positive-parity bands of this work is proposed to be caused by 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 to test for these predictions.

ACKNOWLEDGMENTS

The authors would like to acknowledge the useful discussions with N. Minkov. This work was partly supported from the Bulgarian National Science Fund, Contract No. DMU02/1, the collaboration agreement between Bulgarian Academy of Sciences-CNRS under Contract No. 4847, and by the German BMBF under Contract No. 06BN109.

[1] J. Skalski, S. Mizutori, and W. Nazarewicz, Nucl. Phys. A **617**, 282 (1997).
[2] M. A. C. Hotchkis, J. L. Durell, J. B. Fitzgerald, A. S. Mowbray, W. R. Phillips, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore *et al.*, Nucl. Phys. A **530**, 111 (1991).
[3] S. Lalkovski, A. Minkova, M.-G. Porquet, A. Bauchet, I. Deloncle, A. Astier, N. Buforn, L. Donadille, O. Dorvaux, B. P. J. Gall *et al.*, Eur. Phys. J. A **18**, 589 (2003).
[4] T. Kutsarova, A. Minkova, M.-G. Porquet, I. Deloncle, E. Gueorguieva, F. Azaiez, S. Bouneau, C. Bourgeois, J. Duprat, B. J. P. Gall *et al.*, Phys. Rev. C **58**, 1966 (1998).
[5] R. Krücken, Z. Wang, S. J. Asztalos, J. A. Becker, L. A. Bernstein, R. M. Clark, M. A. Deleplanque, R. M. Diamond, P. Fallon, N. Fotiades *et al.*, Phys. Rev. C **60**, 031302 (1999).
[6] M. Houry, R. Lucas, M.-G. Porquet, Ch. Theisen, M. Girod, M. Aiche, M. M. Aleonard, A. Astier, G. Barreau, F. Becker *et al.*, Eur. Phys. J. A **6**, 43 (1999).
[7] X. Q. Zhang, J. H. Hamilton, A. V. Ramayya, S. J. Zhu, J. K. Hwang, C. J. Beyer, J. Kormicki, E. F. Jones, P. M. Gore, B. R. S. Babu *et al.*, Phys. Rev. C **61**, 014305 (1999).
[8] X. Q. Zhang, J. H. Hamilton, A. V. Ramayya, S. J. Zhu, J. K. Hwang, C. J. Beyer, J. Kormicki, E. F. Jones, P. M. Gore, B. R. S. Babu *et al.*, Phys. Rev. C **63**, 027302 (2001).
[9] F. A. Rickey and P. C. Simms, Phys. Rev. Lett. **31**, 404 (1973).
[10] B. M. Nyako, J. Gizon, A. Gizon, J. Timar, L. Zolnai, A. J. Boston, D. T. Joss, E. S. Paul, A. T. Semple, N. J. O'Brien *et al.*, Phys. Rev. C **60**, 024307 (1999).
[11] F. A. Rickey, J. A. Grau, L. E. Samuelson, and P. C. Simms, Phys. Rev. C **15**, 1530 (1977).
[12] K. R. Pohl, P. H. Regan, J. E. Bush, P. E. Raines, D. P. Balamuth, D. Ward, A. Galindo-Uribarri, V. P. Janzen, S. M. Mullins, and S. Pilotte, Phys. Rev. C **53**, 2682 (1996).
[13] S. Lalkovski, S. Ilieva, A. Minkova, N. Minkov, T. Kutsarova, A. Lopez-Martens, A. Korichi, H. Hübel, A. Görgen, A. Jansen *et al.*, Phys. Rev. C **75**, 014314 (2007).
[14] J. Simpson, Z. Phys. A **358**, 139 (1997).
[15] G. Duchene, F. A. Beck, P. J. Twin, G. de France, D. Curien, L. Han, C. W. Beausang, M. A. Bentley, P. J. Nolan, and J. Simpson, Nucl. Instrum. Methods Phys. Res. A **432**, 90 (1999).
[16] J. Eberth, P. von Brentano, W. Teichert, T. Mylaeus, R. M. Lieder, W. Gast, G. Hebbinghaus, H. Jäger, K. H. Maier, H. Grawe *et al.*, Nucl. Phys. A **520**, 669c (1990).
[17] D. C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).
[18] J. Blachot, Nucl. Data Sheets **107**, 355 (2006).
[19] J. Blachot, Nucl. Data Sheets **110**, 1239 (2009).
[20] M. Kanazawa, T. T. S. Ohya, Z.-I. Matumoto, and N. Mutsuro, J. Phys. Soc. Jpn. **44**, 25 (1978).
[21] R. F. Casten, G. J. Smith, M. R. Macphail, D. Breitig, W. R. Kane, M. L. Stelts, S. F. Mughabghab, J.A.Cizewski, H. G. Borner, W. F. Davidson *et al.*, Phys. Rev. C **21**, 65 (1980).
[22] R. C. Diehl, B. L. Cohen, R. A. Moyer, and L. H. Goldman, Phys. Rev. C **1**, 2086 (1970).
[23] R. F. Casten, *Nuclear Structure from a Simple Perspective* (Oxford Science, Oxford, 2000), 2nd ed.
[24] R. Krücken, S. J. Asztalos, R. M. Clark, M. A. Deleplanque, R. M. Diamond, P. Fallon, I. Y. Lee, A. O. Macchiavelli, G. J. Schmid, F. S. Stephens *et al.*, Eur. Phys. J. A **10**, 151 (2001).
[25] L. Wilets and M. Jean, Phys. Rev. **102**, 788 (1956).
[26] R. Wyss, J. Nyberg, A. Johnson, R. Bengtsson, and W. Nazarewicz, Phys. Lett. B **215**, 211 (1988).
[27] D. Fong, J. K. Hwang, A. V. Ramayya, J. H. Hamilton, Y. X. Luo, P. M. Gore, E. F. Jones, W. B. Walters, J. O. Rasmussen, M. A. Stoyer *et al.*, Phys. Rev. C **72**, 014315 (2005).
[28] P. H. Regan, T. M. Menezes, C. J. Pearson, W. Gelletly, C. S. Purry, P. M. Walker, S. Juutinen, R. Julin, K. Helariutta, A. Savelius *et al.*, Phys. Rev. C **55**, 2305 (1997).