Neutron configurations in ^{113}Pd

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Excited states in ^{113}Pd, populated in β^- decay of ^{113}Rh and in spontaneous fission of ^{248}Cm and ^{252}Cf have been studied by means of γ spectroscopy at the IGISOL facility of Jyväskylä University and using large arrays of Ge detectors Eurogam2 and Gammasphere, respectively. The position of the $11/2^-$ yrast excitation in ^{113}Pd, proposed recently at 166.1 keV by other authors, have been corrected to 98.9 keV. The decay of this level has been discussed, to explain the observed transition intensities. The $7/2^-$ member of the yrast, unique-parity configuration has been identified at 84.9 keV and a band on top of this level proposed. On top of the 1/2+, first excited state a band has been built and a new 3/2+ band head has been proposed at 151.9 keV. A possible oblate-shape origin of these low-energy bands heads has been discussed.

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I. INTRODUCTION

The $\nu h_{11/2}$ neutron shell plays a crucial role in defining the near-yrast excitations in the neutron-rich nuclei of the A$\sim$ 100 region. In a theoretical study of neutron-rich nuclei from this region it has been suggested that in nuclei, where the Fermi level approaches high-Ω orbitals of the $\nu h_{11/2}$ shell, one may expect oblate-deformed configurations as ground states [1]. However, subsequent experimental studies of neutron-rich palladium isotopes indicated that up to neutron number $N = 72$ the deformation is of a prolate type [2]. Such a discrepancy may be due to a still incomplete knowledge of excitation patterns in these nuclei. While the $\Omega \leq 5/2$ orbitals of the $\nu h_{11/2}$ parentage are well documented, the properties of high-Ω orbitals are less certain. Therefore, their proper identification is of importance.

In our study of odd-A, neutron-rich Pd isotopes [3] we have proposed new spins for isomers in ^{115}Pd and ^{117}Pd, lower than the $11/2^-$ values proposed previously [2, 4–6]. The observed splitting of the $\nu h_{11/2}$ shell indicates some degree of deformation deformation in the the neutron-rich Pd isotopes. These nuclei have been further reinvestigated in Ref. [7] and in our recent work [8] where have confirmed the $1/2^+$ spin and parity for the ground state and the $7/2^-$ spin and parity for the isomer in ^{115}Pd, proposed in Ref. [7] and determined the excitation energy of the $9/2^-$ level in the ^{115}Pd nucleus to be 127.9 keV. In Ref. [8] we proposed a new type of systematics, where a clear dependence on the population of subshells of the $\nu h_{11/2}$ shell is seen. This new systematics works well for deformed, neutron-rich Mo and Ru isotopes, but is less clear in Pd chain, especially in case of ^{113}Pd, when using the energy of the $11/2^-$ level reported in Ref. [7].

In the present work we report on a detailed reinvestigation of the low-energy excitations in ^{113}Pd. The aim of this study is to verify the position of the $11/2^-$ level proposed in Ref. [7] and to determine the position of the $7/2^-$ orbital originating from the $\nu h_{11/2}$ shell. Of particular interest is the identification of other low-energy, positive-parity configurations in this nucleus, expected near the Fermi level, which may tell about the tendency towards oblate deformation in Pd isotopes.

In the next Section we describe briefly the experiments. The third Section describes experimental results and their interpretation and in Section IV the study is summarized.

II. EXPERIMENTS

The data presented in this work results from two different mechanisms populating excited states in the ^{113}Pd, the spontaneous fission of ^{248}Cm and ^{252}Cf and β^- decay of ^{113}Rh.

To search for near-yrast neutron configurations, we used multiple-gamma coincidence data from measurements of γ radiation following spontaneous fission of ^{248}Cm and ^{252}Cf. High-fold coincidences between prompt-γ rays were measured using the EUROGAM2 [9–11] and Gammasphere [12] arrays, respectively. In the analysis we used triple-γ coincidences, which in most cases allow the unique assignment of γ lines to nuclei, as well as their unique placement in the scheme. More details on the data analysis from these experiments can be found in Refs. [13, 14], describing new advanced software used to search for weak decay branches.

The β^- decay experiment was carried out at the Ion Guide Isotope Separator On-Line (IGISOL) facility of the Jyväskylä Accelerator Laboratory (Finland). A target of natural ^{238}U was bombarded with 25 MeV protons from the K-130 cyclotron. The neutron–rich fission products of mass $A = 113$ were on-line mass separated and implanted at a movable collection tape surrounded by a β plastic scintillator and two Ge γ-ray detectors. Details of the experimental setup at IGISOL are described in Ref. [15]. Although the experiment was optimized for the β decay of ^{113}Ru it was also suited for the study of ^{113}Rh which decays to ^{113}Pd with a few times longer half-life. The results on the more exotic $A = 113$ isobars ^{113}Ru and ^{113}Rh were published in Refs. [15, 16].

III. RESULTS AND DISCUSSION

In this Section we show and discuss the results obtained in the present work. In the first subsection the results for the negative-parity levels in ^{113}Pd are presented, which are obtained in all the measurements performed, though predominantly in fission experiments. In the second subsection we present the results for positive-parity excitations in ^{113}Pd populated in β^- decay. Then in the third subsection we interpret the observed negative-parity and positive-parity levels in terms of single-particle configurations in ^{113}Pd. Finally we discuss properties of other levels observed in β^- decay, which are not assigned to the previous two groups.

A. Negative-parity excitations

In ^{113}Pd Houry *et al.* [2] has reported a decoupled band based on the $11/2^-$ neutron excitation, which consisted of two branches, the favored one based on the $11/2^-$ level located at 99 keV and the unfavored based on the $9/2^-$ level at 81 keV. The $9/2^-$ level was previously found to be a 0.3 s isomer [17]. The $11/2^-$ level has been placed by Houry *et al.* [2] at 99 keV due to the observation of the 407 keV transition linking both cascades (unfortunately, the assignment of the unfavored cascade to ^{113}Pd has not been discussed in Ref. [2]). The $11/2^-$ band has been later reported in Refs.[5, 6] but the band-head energy was not provided there.

In the most recent study of ^{113}Pd [7] the $11/2^-$ level has been proposed at 166.1 keV, i.e. 85.1 keV above the $9/2^-$, 81 keV isomer. This change was based on the observation of a 85.1 keV transition, assumed to be a M1+E2 mixture, which according to Ref. [7] deexcites the $11/2^-$ level to the $9/2^-$ isomer at 81 keV. The new result challenges the result of Ref. [2] as well as the systematics of the relative positions of the $9/2^-$ and $11/2^-$ presented in our study of Pd isotopes [3].

In Fig. 1 we show a fragment of a γ-spectrum, doubly-gated on the 383.1- and 570.8-keV lines of the yrast cascade in ^{113}Pd. The picture is analogous to Fig. 3 (upper panel) of Ref. [7]. Both data sets were obtained from fission of ^{252}Cf. In Fig. 1 clearly seen is a line at 84.9(1) keV (85.1 in Ref. [7]) as well as lines from the Te complementary fragments. The number of counts in the 84.9-keV peak in Fig. 1 is 4900(300) while the number of counts in the 85.1-keV peak shown in Fig. 3 (upper panel) in Ref. [7] can be estimated to be 6500(500). Both numbers are comparable, which justifies our quantitative verification of the data of Ref. [7], as described below.

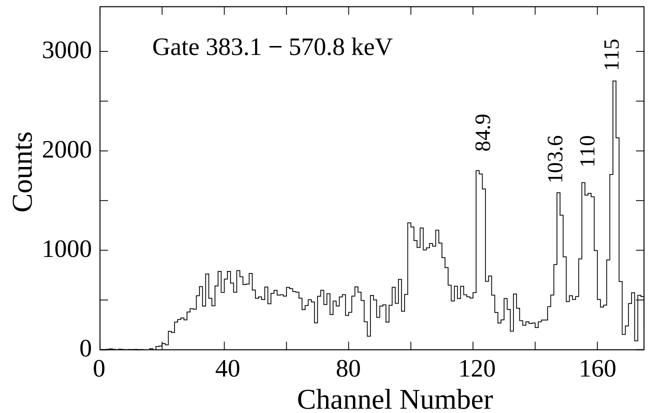

FIG. 1: Low-energy part of a γ spectrum from fission of ^{252}Cf, doubly gated on the 383.1- and 570.8-keV lines of ^{113}Pd, measured using the Gammasphere array. Peaks are labeled with their energies in keV.

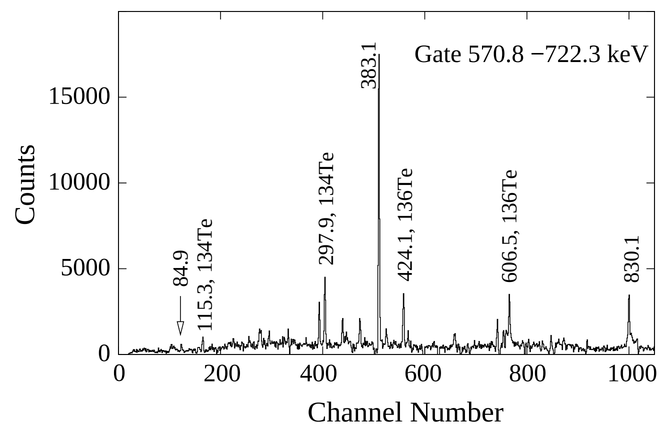

FIG. 2: A spectrum of γ rays following fission of ^{252}Cf, doubly gated on the 570.8- and 722.3-keV lines of ^{113}Pd, measured using the Gammasphere array. Peaks are labeled with their energies in keV.

In Fig. 2 we show a spectrum, doubly-gated on the 570.8- and 722.3-keV lines of the yrast cascade in ^{113}Pd, where both the 84.9- and 383.1-keV lines are seen. In this spectrum the 84.9-keV line corresponds, according to the Ref. [7], to the $11/2^- \rightarrow 9/2^-$, M1+E2 transition and should bear the same total intensity as the 383.1-keV transition. However, in Fig. 2 the 84.9-keV line is barely visible and the difference in the number of counts in the 84.9- and 383.1-keV lines is dramatic. The peak at 84.9 keV has 900(200) counts while the peak at 383.1 keV has 50500(500) counts. Part of this difference can be attributed to different conversion coefficients and different detector efficiencies at both energies, as shown in Table I, but these corrections are by far insufficient. While the total intensity of the 383.1-keV transition (in

TABLE I: Intensities (in relative units) of γ transitions in ^{113}Pd, populated in spontaneous fission of ^{252}Cf and ^{248}Cm in doubly-gated γ spectra analogous to the spectrum shown in Fig. 2.

Gates (keV)	γ−line (keV)	Number of counts	Eff. (rel.)	I_γ (rel.)	I_{cc} [18]	I_{tot} (rel.)
	^{113}Pd,	fission of	^{252}Cf			
570.8-722.3	383.1	50400(500)	72(4)	700(40)	0.04(E2)	730(41)
570.8-722.3	84.9	900(200)	27(3)	33(8)	0.6 (M1) 2.5 (E2)	53(13) 116(28)
	^{113}Pd,	fission of	^{248}Cm			
570.8-722.3	383.1	7400(200)	72(4)	103(3)	0.04	107(5)
570.8-722.3	84.9	180(70)	40(3)	5(2)	0.6 (M1) 2.5 (E2)	8(3) 18(7)

arbitrary relative units) yields I_{tot}=730(41), the total intensity of the 84.9-keV transition is between 53 and 116 units depending on the conversion coefficient for the 84.9-keV transition (limits on I_{tot} include the uncertainty of the I_γ). On average, factor eight is missing in the intensity balance. A similar conclusion is obtained from the analysis of the same transitions in ^{113}Pd observed in spontaneous fission of ^{248}Cm, as shown in Table I, where, on average, again factor eight is missing in the intensity balance. Of other effects, which might produce such an imbalance, we can exclude a possible cut in intensity due to a long half-life of the $11/2^-$ level. The time window in the measurement with Gammasphere was 900 ns, which is much longer than any expected half-life of a M1+E2 transition of 85 keV. Summarizing the above observations we conclude that the location of the 84.9-keV transition in ^{113}Pd proposed in Ref. [7] can not be correct.

Unfortunately, the Ref. [7] does not comment on the cascade on top of the $9/2^-$ isomer and, in particular, on the presence of the 407-keV decay branch, which links the positions of the $11/2^-$ level and $9/2^-$ isomer according to Ref. [2]. In Fig. 3 we show a γ spectrum doubly gated on the 576.1- and 717.6-keV lines of the cascade proposed in Ref. [2] on top of the $9/2^-$ isomer. In the spectrum there are lines at 425.0, 819.5 and 407.4 keV and lines from the complementary Te isotopes. Further spectra doubly-gated on the 425.0-576.1-keV lines and 407.4-576.1-keV lines are shown in Figs. 4 and 5, respectively. Here again lines from the discussed cascade, proposed in Ref. [2], are consistently present. In Figs. 3 and 4 there is a doublet of 425.0- and 423.4-keV lines, because these lines, emitted from ^{113}Pd and ^{136}Te complementary fragments produced in fission of ^{252}Cf, are in coincidence. However, in Fig. 6, where we show a spectrum doubly gated on the 407.4- and 576.1-keV lines using the data from ^{248}Cm

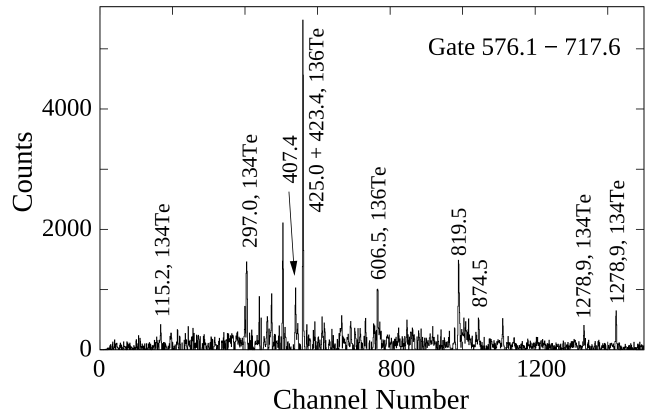

FIG. 3: A spectrum of γ rays following fission of ^{252}Cf, doubly gated on 576.1- and 717.6-keV lines, measured with Gammasphere array. Peaks are labeled with their energies in keV.

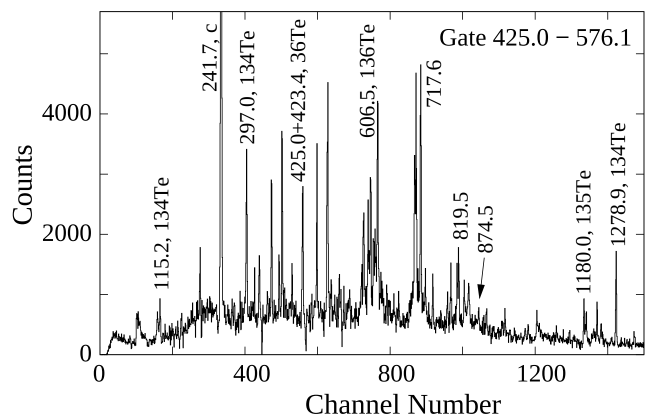

FIG. 4: A spectrum of γ rays following fission of ^{252}Cf, doubly gated on 425.0- and 576.1-keV lines, measured with Gammasphere array. Peaks are labeled with their energies in keV.

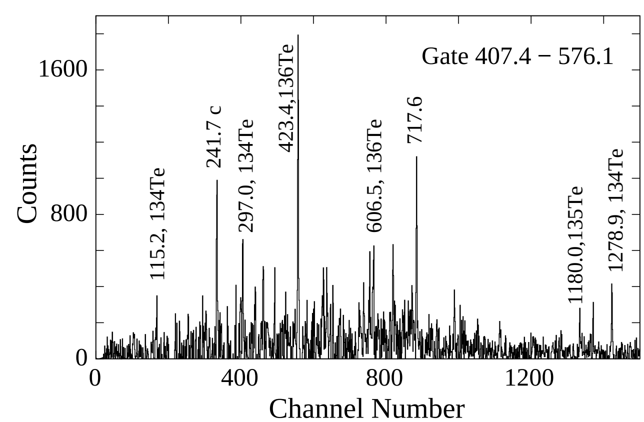

FIG. 5: A spectrum of γ rays following fission of ^{252}Cf, doubly gated on 407.4- and 576.1-keV lines, measured with Gammasphere array. Peaks are labeled with their energies in keV.

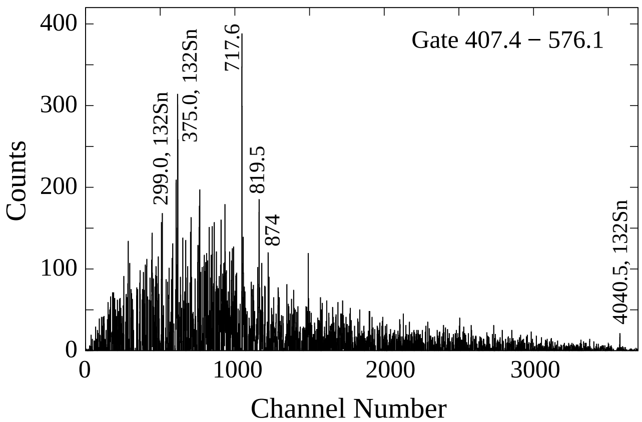

FIG. 6: A spectrum of γ rays following fission of ^{248}Cm, doubly gated on 407.4- and 576.1-keV lines, measured with Eurogam2 array. Peaks are labeled with their energies in keV.

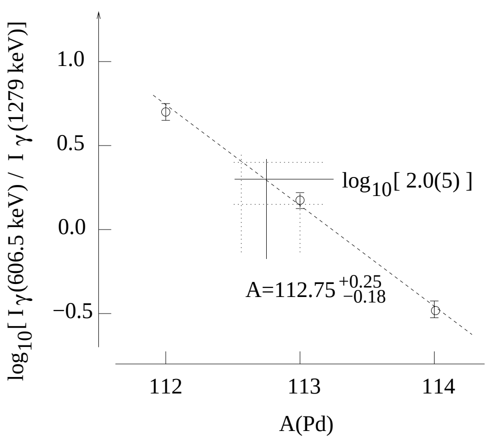

FIG. 7: Mass correlation diagram for Pd and Te complementary fission fragments populated in fission of ^{252}Cf. See text for further explanation.

fission, the 425.0- and 423.4-keV doublet is not present.

The observed coincidences indicate that in the discussed cascade the 407.4-keV transition depopulates the same level as the 425.0-keV transition. Therefore, we support the decay scheme proposed in Ref. [2]. We note that the cascade on top of the $9/2^-$ isomer proposed in Ref. [2] has not been reported in any other medium-spin study of ^{113}Pd [5–7]. Therefore, it is of interest to verify the identification of the discussed cascade with the ^{113}Pd nucleus.

Figures 3, 4 and 5 indicate that the cascade comprising the 425.0-. 576.1- and 717.6-keV lines should belong to a Pd isotope because it is in coincidence with more than one Te complementary fragment. In Fig. 7 we show a mass correlation diagram of a type used in several other works (see for example Ref. [19]). It has been observed that the ratio of intensities of γ lines from two different complementary fragments (here the 606.5-keV line from ^{136}Te and the 1278.9-keV line from ^{134}Te), observed in a spectrum gated on the given isotope (here a Pd isotope) depends strongly on the mass of this isotope (here ^{112}Pd, ^{113}Pd and ^{114}Pd). When displayed on a logarithmic scale, such ratios follow approximately a straight line dependence. This is also true for the case of Pd-Te complementary fragments populated in fission of ^{252}Cf, as shown in Fig. 7. The three data points, shown as open circles, represent intensity ratios of the 606.5-and 1278.9-keV lines as observed in spectra doubly gated on the yrast cascades in ^{112}Pd, ^{113}Pd and ^{114}Pd, respectively (in ^{113}Pd the gate was set on the 383.1- and 570.8-keV lines).

In a spectrum gated on the cascade comprising the 407.4-, 425.0-, 576.1- and 717.6-keV transitions, the intensity ratio of the 606.5- to 1278.9-keV line is 2.0(5). The intersection of the $\log_{10}[2.0(5)]$ value with the calibration line (the dashed line in Fig.7) indicates the mass $A = 112.8^{+0.25}_{-0.18}$ of the Pd isotope to which the discussed cascade belongs. This result uniquely assigns the cascade to the ^{113}Pd nucleus.

The cascade comprising the 407.4-, 425.0-, 576.1- and 717.6-keV transitions does not show any coincidence relation with other known lines of ^{113}Pd. Therefore, one can conclude that this cascade populates either the ground state or the 81.1-keV isomer. The former option can be excluded, because otherwise a 425.0-keV (or a 407.4-keV) level with spin 7/2 or $9/2^+$ should exists and be fed in β^- decay, which is not the case (see Ref. [17] and the discussion below). We thus conclude that this cascade populates the 0.3 s isomer at 81.1 keV.

The fact that this cascade is less intense that the cascade comprising the 383.1-, 570.8- and 722.3-keV transitions indicates its unfavored character and is consistent with spin $9/2^-$ assignment to the 81.1-keV isomer. Consequently, the $11/2^-$ level should be placed above the isomer. How high above remains to be shown.

In Ref. [2] it has been proposed that the more intense, 425.0-keV line represents an “in-band” E2 transition and feeds the $9/2^-$ isomer while the weaker 407.4-keV branch populates the $11/2^-$ level at 98.9 keV. However in Ref. [7] the $11/2^-$ level was elevated to 166.1 keV. Our results support in two ways the former solution. First, we confirm the presence of the 407.4-keV link between the favored and the unfavored cascades and, second, we show that the 84.9-keV transition does not follow immediately the 383.1-keV decay. The solution is proposed in Fig. 8, where we show a partial level scheme of ^{113}Pd, comprising the negative-parity excitations, as observed in this work. In the scheme we show the two cascades based on the $9/2^-$ isomer and on the $11/2^-$ level, linked by the 407.4-keV transition. In the scheme we also propose an (unobserved) M1+E2 decay of 17.8 keV from the $11/2^-$ level to the $9/2^-$ isomer as well as an (unobserved) E2 decay of 14.0 keV from the $11/2^-$ level to a new level at 84.9-keV.

Properties of γ lines in ^{113}Pd, observed in this work following fission of ^{252}Cf, are listed in Table II where we included lines shown in Fig. 8 (except 119.5-, 135.0- and

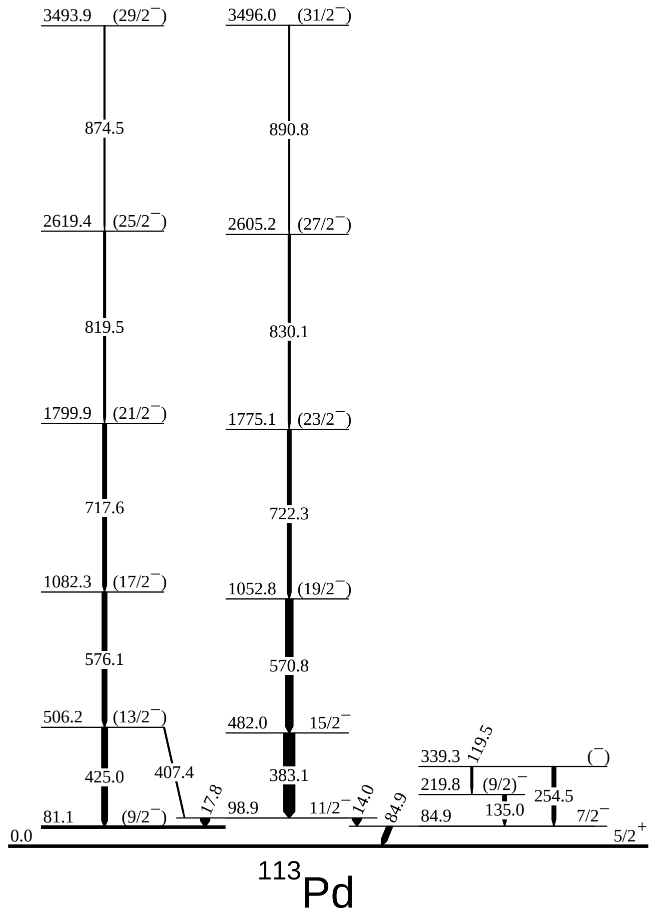

FIG. 8: Scheme of negative-parity excitations in ^{113}Pd, as determined in the present work.

254.5-keV lines observed solely in β-decay measurement). In Table II we also report transitions in the positive-parity, ground-state band seen in our fission measurement and reported previously in Refs. [6, 7].

In this work we do not confirm the presence of the 717.1- and 731.6-keV transitions reported in Ref. [6] (these transitions were not reported in Ref. [7], either). Concerning the energies of excited levels in ^{113}Pd, in this work we confirm and determine more precisely excitation energies reported by Houry *et al.* [2]. Because of the changed placement of the 84.9-keV transition the excitation energies above spin $9/2^-$ proposed in Ref. [7] are changed. The positive-parity, ground-state band will be discussed in more detail further in the text.

The new placement of the 84.9-keV level and transition proposed in Fig. 8 accounts for the coincidence of the 84.9-keV transition with the favored cascade and explains the strongly suppressed coincidence rate between the 84.9-keV and the 383.1-keV transitions. Most of the intensity of the yrast, favored cascade may funnel towards the 81.1-keV isomer via the M1+E2, 17.8-keV transition and only part towards the 84.9-keV level via

TABLE II: Energies and intensities (in relative units) of γ lines in ^{113}Pd, populated in spontaneous fission of ^{252}Cf, as observed in this work.

E_γ (keV)	I_γ (^{252}Cf)	$E_{init.}$ (keV)	E_γ (keV)	I_γ (^{252}Cf)	$E_{init.}$ (keV)
14.0	-	98.9	570.8(1)	85(5)	1052.8
17.8	-	98.9	576.1(2)	27(5)	1082.3
84.9(1)	35(5)	84.9	576.9(1)	15(4)	1031.6
189.8(1)	39(4)	189.6	630.1(1)	12(2)	1346.5
261.7(1)	4(1)	716.4	647.0(1)	12(3)	1678.6
265.1(1)	19(3)	454.7	657.9(2)	2(1)	3000.1
311.3(2)	0.6(3)	2342.2	663.6(2)	5(1)	2342.2
315.0(2)	2(1)	1346.5	676.6(2)	3(1)	2707.6
315.1(2)	5(1)	1031.6	684.4(3)	2(1)	3392.0
332.2(3)	9(3)	1678.6	684.5(1)	6(1)	2031.0
352.5(2)	2(1)	2031.0	722.3(1)	35(4)	1775.1
365.3(3)	0.4(2)	2707.6	717.6(2)	8(2)	1799.9
383.1(1)	100(4)	482.0	819.5(3)	3(1)	2619.4
407.4(2)	11(2)	506.2	830.1(3)	8(2)	2605.2
425.0(2)	55(9)	506.2	874.5(5)	0.7(4)	3493.9
454.7(1)	15(3)	474.7	890.8(5)	2(1)	3496.0
526.7(2)	20(3)	716.4			

the E2, 14.0-keV transition. It is of high interest to confirm the presence of the 84.9-keV level and to determine its spin and parity in order to check whether the 14.0-keV, E2 transition is possible.

A short cascade comprising 84.9-, 135.0-, 119.5- and 254.5-keV lines has been reported in Ref. [20] but not placed in the level scheme of ^{113}Pd [17, 20]. In the measurement of γ radiation following β^- decay of ^{113}Rh, performed in the present work at the IGISOL facility, we clearly observe a line at 84.8(2) keV, which is in coincidence with the lines of 135.0-, 119.5- and 254.5-keV as illustrated in Fig. 9 (a). We have now placed these four lines in the level scheme of ^{113}Pd as shown in Figs. 8 and 10, based on our β^- decay data presented in Tables III - VI. Tables III - V contain energies, relative intensities, positions and coincidence relations of γ transitions and Table VI contains beta feedings and log ft values of the excited levels populated in the β^- decay of ^{113}Rh.

The fact that the 84.9 keV line feeds the ground state is established by its coincidence relations with many other gamma lines from low to high energies as shown in Fig. 9. In Tables III - V there are over 20 coincidence relations between 84.9 keV and other transitions in ^{113}Pd fed by the β^- decay of ^{113}Rh. Altogether those coincidence relations fix the position of 84.9 keV line as a ground-state transition. The order of lines in the cascade is established by coincidence relations observed in β^- decay data presented.

The multipolarity of 84.9 keV transition was determined in Ref. [17] to be E1 based on the experimental internal conversion coefficient $\alpha_K = 0.12(3)$. Our results are in accordance with the E1 multipolarity given in Ref. [17].

Due to the E1 multipolarity of the 84.9-keV transi-

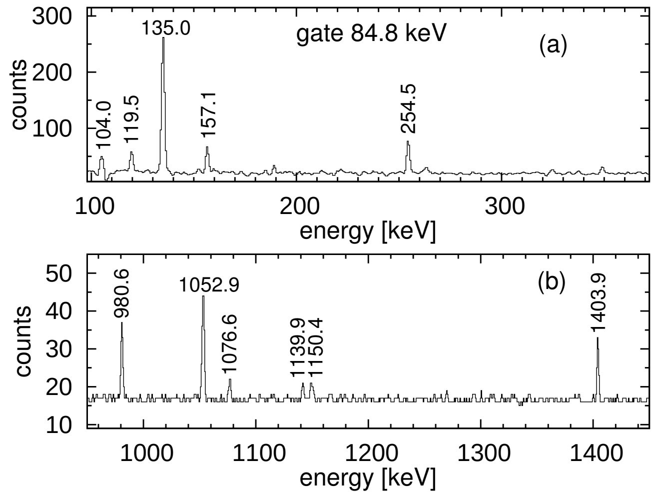

FIG. 9: A spectrum of γ rays following β^- decay of ^{113}Rh measured in the mass $A = 113$ separated with the IGISOL facility. The gate is set on the 84.8-keV line. The panels a) and b) present the low- and high-energy part of the spectrum, respectively. Peaks are labeled with their energies in keV.

tion, the 84.9-keV level in Figs. 8 and 10 has negative parity and the spin of this level is restricted to $3/2^-$, $5/2^-$ or $7/2^-$, considering the $5/2^+$ spin and parity of the ground state of ^{113}Pd. The prompt character of the 84.9-383-keV coincidence relation excludes the $3/2^-$ and the $5/2^-$ options (unless an extra level is introduced between the $11/2^-$, 98.9-keV level and the 84.9-keV level). The remaining $7/2^-$ spin and parity assignment for the 84.9-keV level is consistent with all the observations. In this case the 14.0-keV decay has an E2 character. Due to a very high total conversion coefficient, α_{tot}=361, this decay may compete with the the M1+E2, 17.8-keV decay to the $9/2^-$ isomer (at E_γ=17.8 keV, α_{tot} yields 8.0 for a pure M1 multipolarity and 111 for a pure E2 multipolarity). The non-observation of any half-life for the $11/2^-$ level indicates that they should both have prompt character. Furthermore, one may expect that the 14.0-keV decay branch is less intense than the 17.8-keV branch, which could explain the unbalanced intensities observed in the 383.1-84.9-keV cascade, discussed above.

B. Positive-parity excitations

The positive-parity excitations at 189.8 and 454.5 keV were first proposed in Refs. [17, 20]. The ground-state band in ^{113}Pd has been later extended by Zhang *et al.* [6] up to spin $25/2^+$ in a measurement of γ rays following fission of ^{252}Cf. In our measurement of ^{252}Cf fission we confirm the ground-state band reported in Ref. [6], except the 656.4-keV transition and the 1110.9-keV level reported there. The results of our analysis are included in Table II. The ratio of γ intensities of the 606.5- to 1278.9-keV lines from the respective ^{136}Te and ^{134}Te complementary fission fragments in a spectrum doubly gated on the 189.8- and 264.7-keV lines yields 1.7(2). This value determines mass $A = 112.85^{+0.14}_{-0.10}$, when using the mass calibration of Fig. 7, confirming the assignment of the discussed cascade to ^{113}Pd.

We further confirm and enrich the ground-state band using the data from fission of ^{248}Cm. To illustrate the quality of the data we show in Fig. 11 a fragment of a doubly-gated γ spectrum, where the first gate is set on the 189.8-keV line and the second coincidence condition corresponds to summed gates set on all lines, which are in cascade with the 189.8-keV line. In the spectrum there are all the lines reported previously and new lines at 311.3-, 315.0-, 332.2-, 352.5- and 365.3-keV. These new lines connect levels in the two signature cascades of the ground-state bands, as summarized in Table II. Furthermore, our coincidence data indicate that there is a new line at 684.4 keV (in addition to the 684.5 keV decay from the 2031.0-keV level). The new 684.4 keV line feeds the 2707.6-keV level and defines a new level in the ground-state band at 3392.0 keV.

The g.s. band is observed up to spin $11/2^+$ in our measurement of γ rays following β^- decay of ^{113}Rh, as shown in Fig. 10, however the $11/2^+$ level is practically not fed by β decay. This is consistent with the $7/2^+$ spin and parity assignment to the ground state of ^{113}Rh, proposed tentatively in Refs. [17, 21].

One may interpret the $7/2^+$, 189.8 keV level in ^{113}Pd as a member of a rotational band built on the $5/2^+$ ground state thus providing a way to estimate the ground-state feeding in beta decay of ^{113}Rh. The intensity rule, known as Alaga rule [22], for the beta transition to rotational states in our case is $I_\beta(7/2^+ \rightarrow 7/2^+) = 0.25 \times I_\beta(7/2^+ \rightarrow 5/2^+)$. Consequently one may estimate the ground state feeding in ^{113}Pd as 17.5 units (see Table VI).

On top of the 35.1-keV level, reported previously in Ref. [17] we observe in our β decay measurement a short cascade, as shown in Fig. 10. The coincidence spectrum in Fig. 12 supports the existence of the 35.1 keV level. For the 35.1-keV level spin and parity $1/2^+$ have been proposed in Ref. [17]. This is consistent with the lack of β decay to this level, as shown in Table VI. In Ref. [17] it was mentioned that the half life of this level is much longer than 1 μs. In the present β^- decay measurement we do observe a 35.1-keV line in singles γ spectrum (see Fig. 13 (b)). However, this line is not present in β-gated γ spectrum (see Fig. 13(a)). This observation supports long half-life reported in Ref. [17].

The 172.6-keV level, reported previously in Ref. [17], decays only to the 35.1-keV level. Therefore, we propose that it is a member of a band on top of the 35.1-keV head. The M1 multipolarity reported in Ref. [17] for the 137.5-keV decay, and the low energy and prompt character of this decay, all indicate spin $3/2^+$ for the 172.6-keV level, considering the non zero feeding in β decay to this level (see Table VI).

The 151.9-keV level decays by low-energy transitions to the ground state and to the 35.1-keV level. For the

TABLE III: Energies, relative intensities I_γ and coincidence relations of γ lines observedin the β^- decay of ^{113}Rh.

E_γ[keV]		I_γ [%]	from	to	coincident γ lines
35.1(2)		0.66(2)[s]	35	0	96, 117, 175, 198, 213[a], 221, 1245[d]
79.5(1)		1.52(7)	252	172	97, 121, 138, 157, 322, 358, 399[d], 451, 487, 567, 609, 756, 814, 886, 1117
81.1(1)		7.6(2)[s]	81	0	
84.8(1)		5.1(1.0)	85	0	104[d], 120, 135, 157, 220[d], 255, 263, 311, 324, 349, 433, 454, 522, 527, 568, 646, 665, 669, 672, 684[a], 734, 777, 817, 846, 918, 924, 981, 1053, 1077, 1142, 1150, 1270, 1343, 1404, 1479, 1525[a], 1720, 1752, 1870[a]
97.0(1)		1.12(5)	349	252	80, 117, 175, 198, 213[a], 221, 1245[d]
100.3(1)		0.45(6)	252	151	98[d], 117, 121, 124[d], 152, 157, 358, (399, 567)[d], 1346
104.0(1)		0.09(2)	189	85	85, 123, 128[a], 158, 220
116.8(1)		8.0(2)	151	35	35[d], 97, 100, 121, 124[d], 157, 197, 221, 257, 349, 358, 401, 455, 488, 500, 508[a], 564, 579, 609, 653[a], 693, 696[a], 709, 740[a], 749, 857, 913, 934, 997, 986, 1219, 1265, 1338
119.5(1)		0.38(2)	339	219	85, 135, 522, 1077, 1149
120.8(1)		1.8(1)	373	252	21.3, 80, 85, 117, 135, 138, 217, 252, 358, 693
127.9(1)		0.30(8)	500	373	20.3, 117, 221, 337[c]
135.0(1)		2.5(2)	219	85	85, 120, 433, 522, 544[a], 608, 649[a], 770[c], 846, 863, 918, 1077, 1104[a], 1150, 1194[a], 1270, 1343, 1721
137.5(1)		6.4(4)	172	35	80, 97, 121, 124, 157, 176, 236, 321, 358, 400, 452, 552, 567, 609, 688, 756, 814, 836, 885, 892, 1118, 1245, 1317
151.9(1)		6.4(2)	151	0	97[d], 101, 121, 157, 197, 221, 257, 349, 358, 401, 500, 565, 579, 692, 709, 749, 757, 885, 913, 987, 998, 1264
157.1(1)		5.0(4)	409	252	21.3, 80, 85, 100[d], 117, 138, 217, 252, (350, 856)[d], (961[a], 970[b])[d]
160.0(1)		3.6(3)	349	189	16.0, 21.4, (84, 161[b])[d], 190, (933, 768[a])[d]
176.4(1)		0.22(2)	349	172	21.3, 97[d], 138
189.6(1)		45(1)	189	0	125[d], 160, 220, 265, 311, 321, 349, 452, 462, 527, 541, 630, 665, 668, 672, 712, 821, 876, 933, 1094, 1140, 1181, 1227, 1300, 1906[a]
197.1(1)		0.8(2)	349	151	98[b], 117, 152
217.1(1)		9.4(2)	252	35	97, 121, 124[d], 157, 321, 358, 400, 444[c], 451, 567, 609, 693, 727[a], 756, 814, 830, 885, 1118
219.6(1)		10.3(3)	409	189	21.4, 24.0, 117, 152, 190
221.2(1)		4.6(4)	373	151	14.6[d], 21.4, 117, 128[a], 152, 189, 358, 488[d], 693
236.7(1)		1.30(5)	409	172	21.2, 137, 173[a]
252.2(1)		6.3(2)	252	0	97, 121, 157, 358, 400, 489[d], 509, 553, 609, 757, 814, 886, 1118
254.5(1)		1.16(4)	339	85	85, 522, 1076
257.4(1)		3.2(2)	409	151	21.2, 117, 152
263.2(3)	Ru	0.21(2)	349	85	(85, 934)[d] and other in Table 1 [15]
265.1(1)		3.2(2)	454	189	190, 668
310.9(1)		1.54(5)	500	189	85[d], 190
321.6(2)		0.73(6)	730	409	162[ad], 409[d], 669
323.9(2)		0.18(4)	409	85	
349.0(2)	T	100(3)	349	0	117, 152, 190, (381, 474)[a], 539, 543[a], 552, 560[c], 1067, 1076, 1140, (1240, 1400)[a]
349.0(2)	T	2.8(4)	500	151	as above
349.0(2)	T	1.9(1)	538	189	as above
357.9(2)		4.9(3)	730	373	21.2, 80, 87[c], 116, 121, 152, 212[c], 217, 221, 252, 337[c], 373[d]
373.3(2)		0.69(6)	373	0	349, 359
399.4(3)		0.40(6)	651	252	
409.2(3)		42.3(1.3)	409	0	20.3, 21.2, 80, 88[c], 190, 217, 263, 322, 349, 384[a], 409, 452[d]
432.7(3)		0.55(6)	651	219	85, 88[c], 135
451.8(3)		0.81(5)	861	409	409
453.8(3)		0.18(2)	538	85	
454.7(3)		2.7(2)	454	0	85[d], 88[c], 117, 137, 668
462.2(3)		0.33(4)	651	189	189[d]
488.0(3)		0.33(8)	861	373	(121, 190, 151)[d]

[a] Not placed in decay scheme, [b] decay of ^{97}Y, [c] decay of ^{113}Ru, [d] weak coincidence, [D] doublet, [T] triplet, [s] intensity from singles spectrum

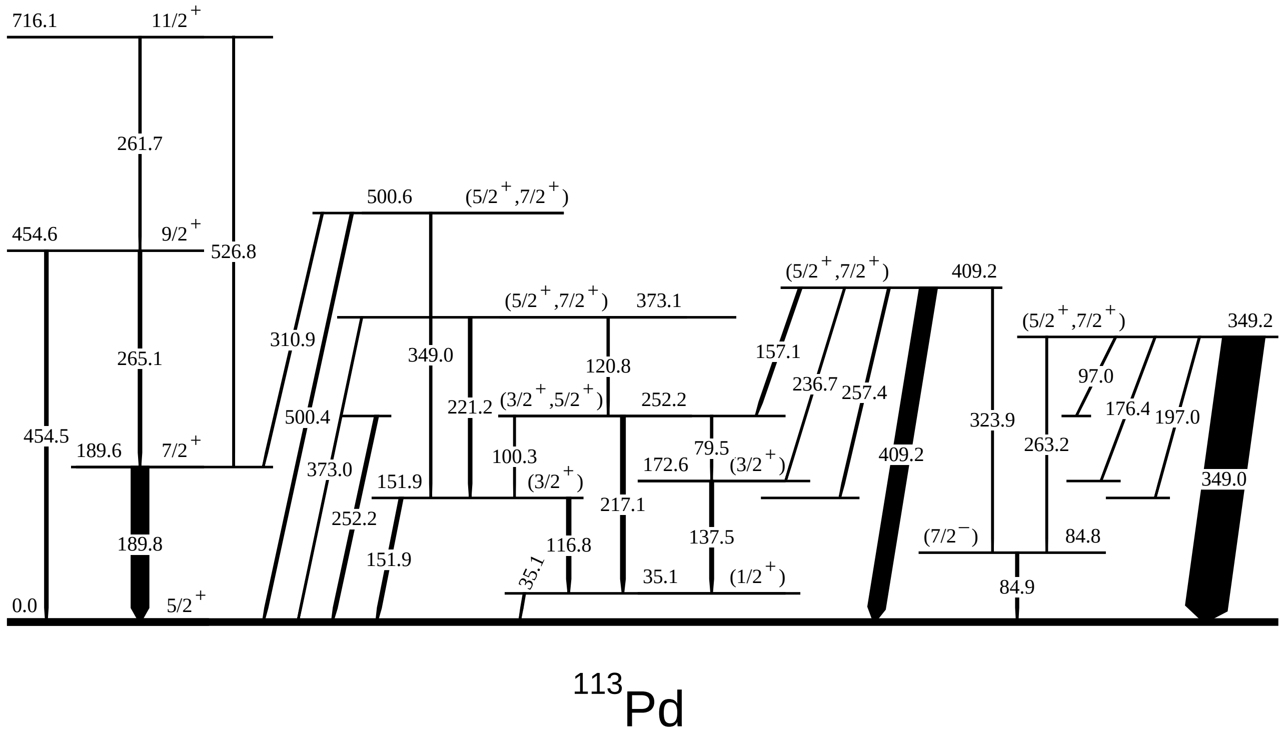

FIG. 10: Partial level scheme of positive-parity excitations in ^{113}Pd, populated in β^- decay of ^{113}Rh, as observed in the present work. Note that 84.9 keV line belongs to the negative-parity scheme shown in Fig. 8. The 97.0-, 252.2-, 176.4-, 1970- and 257.4-keV transitions populate (or depopulate), respective levels at 252.2, 172.6 and 151.9 keV.

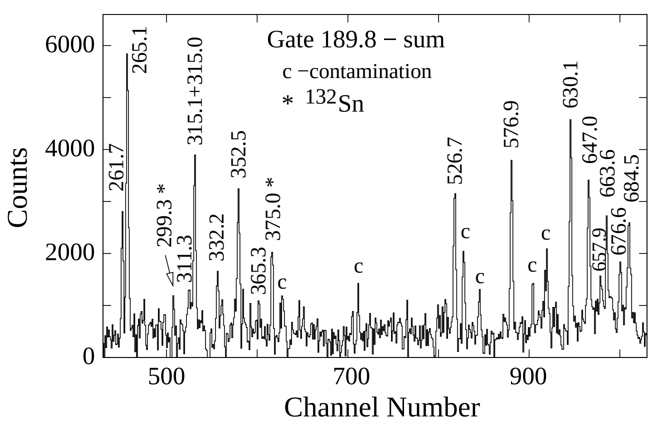

FIG. 11: A doubly-gate spectrum of γ rays following fission of ^{248}Cm, measured with Eurogam2 array. The first gate is set on the 189.8-keV line and the second gate is set on all other lines in the cascade. Peaks are labeled with their energies in keV.

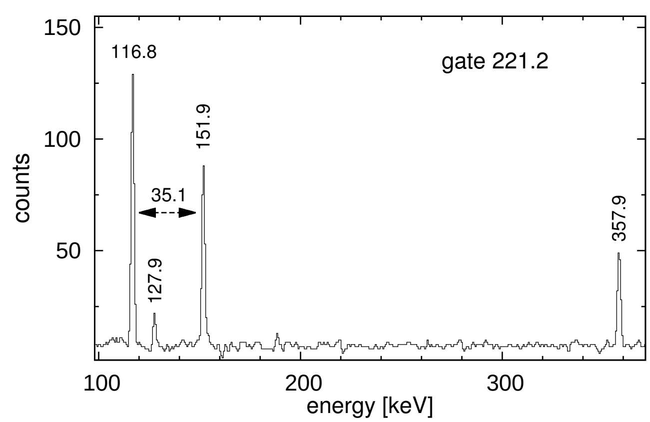

FIG. 12: A spectrum of γ rays following β^- decay of ^{113}Rh measured in the mass $A = 113$ separated with the IGISOL facility. The gate is set on the 221.2-keV line. Peaks are labeled with their energies in keV.

151.9-keV level we propose spin and parity $3/2^+$, considering that it decays by low-energy transitions to both the the $5/2^+$ ground state and the $1/2^+$, 35.1-keV level.

Two levels at 252.2 and 373.0 keV decay to the 151.9-keV level and could be members of a band built on top of the 151.9-keV band head. We note that the 252.2-keV level, which is a candidate for the $5/2^+$ member of this band, decays also to the $1/2^+$, 35.1-keV level and it is not clear to which band it belongs. Low feeding in β decay to the 252.2-keV level is at odds with the $5/2^+$ spin assignment, another possibility is spin $3/2^+$. Spin and parity assignment $5/2^+$ or $7/2^+$ to the 373.0-keV level is consistent with the observed γ branchings, and the observed moderate feeding in β decay.

In Fig. 10 we show two levels at 349.0 and 409.2 keV, which are strongly populated in β^- decay of ^{113}Rh. We note that both levels decay to the 84.9-keV level with the

TABLE IV: Energies, relative intensities I_γ and coincidence relations of γ lines observed in the β^- decay of ^{113}Rh.

E_γ[keV]	I_γ [%]	from	to	coincident γ lines
500.4(2)[D]	0.8(1)	651	151	21.4[d], 76[a], 117, 152, 263, 1194[c]
500.4(2)[D]	2.8(2)	500	0	as above
522.2(3)	1.30(8)	861	339	85, (138, 120)[d]
526.8(3)	0.69(6)	716	189	(21.4, 85)[d], 190, 204[a], 262
538.4(3)	6.0(3)	538	0	137[d], 148[a], 161[b], 348[d], 971[b d]
541.1(3)	1.16(8)	730	189	162[d], 190
552.0(7)	0.43(8)	901	349	138[d]
567.2(3)[D]	0.5(1)	819	252	80, 85[d], 138
567.2(3)[D]	0.2(1)	651	85	80, 85[d], 138
578.7(3)[Ru]	0.98(0.16)	730	151	117, 349
608.8(3)	4.0(4)	861	252	21.2, 80, 100, 138, 189, 217, 252, 348
629.8(3)	0.22(4)	819	189	190[d]
646.2(3)	0.27(5)	730	85	
651.6(3)	1.1(2)	651	0	117[d]
665.3(4)	0.3(2)	855	189	190
668.1(3)	2.7(3)	1122	454	21.3, 85, 88[c], 117, 152, 160[d], 161[b], 163[a], 190, 263, 265, 322
671.5(3)	1.5(2)	861	189	190
688.5(3)	0.34(5)	861	172	138
692.4(3)	0.93(6)	1065	373	21.5, 117, 121, 222[d]
709.4(3)[Ru]	1.70(0.14)	861	151	88, 117, 152
711.5(3)	0.71(0.12)	901	189	190
730.9(2)	4.6(2)	730	0	161[d]
734.2(3)	0.09(2)	819	85	
749.3(2)	1.5(1)	901	151	85, 117, 152
756.3(2)	2.1(1)	1008	252	21.4, 80, 138, 217, (252, 263)[d], 375[a]
776.5(3)	0.23(5)	861	85	
813.3(2)	1.26(0.13)	1065	252	21.3, 80, 138, 217, 252[d]
816.7(4)	0.29(3)	901	85	
820.3(3)[D]	0.40(6)	819	0	190
820.3(3)[D]	0.40(6)	1008	189	190
830.1(5)	0.63(9)	1082	252	
836.0(2)	1.2(1)	1008	172	138, 162[d]
845.8(3)	0.40(5)	1065	219	85, 135
856.0(4)	0.40(0.14)	1008	151	117[d]
861.2(2)	3.7(2)	861	0	160[d]
862.8(5)	0.13(6)	1082	219	
876.0(2)	1.28(8)	1065	189	190
885.8(4)	0.60(2)	1137	252	217[d]
892.8(3)	0.38(7)	1065	172	(138, 263)[d]
901.4(2)	0.43(5)	901	0	
913.2(3)	0.24(7)	1065	151	163[a], 322[d]
917.9(2)	0.38(6)	1137	219	85, 135
923.8(2)	0.58(6)	1008	85	85
933.4(2)[D]	1.3(4)	1282	349	85[d], 117, 160, 190, 263
933.4(2)[D]	1.3(4)	1122	189	85[d], 117, 160, 190, 263
980.6(2)	1.03(9)	1065	85	85
985.7(3)	0.38(7)	1137	151	117[d]
996.2(4)	0.55(0.14)	1369	373	88[c d]

[a] Not placed in decay scheme, [b] decay of ^{97}Y
[c] decay of ^{113}Ru, [d] weak coincidence, [D] doublet,
[Tc] also in Tc, [Ru] also in Ru, [Rh] also in Rh

TABLE V: Energies, relative intensities I_γ and coincidence relations of γ lines observed in the β^- decay of ^{113}Rh.

E_γ[keV]	I_γ [%]	from	to	coincident γ lines
1008.7(2)[Ru]	1.59(0.13)	1008	0	
1052.9(3)	3.0(2)	1137	85	21.3, 85, 88[c d]
1066.9(3)	0.81(0.12)	1416	349	349[d]
1076.6(3)	0.51(6)	1416	339	85, 135
1093.1(3)	0.31(7)	1282	189	190[d]
1117.2(4)	0.67(0.12)	1369	252	21.3[d], 80, 138, 217
1122.6(4)[Ru]	0.47(0.11)	1122	0	211[d]
1139.9(3)	3.2(2)	1489	349	85, 190[d], 349
1150.4(4)	0.39(6)	1489	339	21.0[d], 85, 135[d]
1179.9(4)[Ru]	1.5(2)	1369	189	88, 190, (211[c], 263)[d]
1218.5(8)	0.09(4)	1369	151	
1226.1(4)[Ru]	1.99(0.14)	1416	189	88[c d], 190
1264.1(5)	0.61(0.11)	1416	151	117, 152[d]
1269.9(6)	0.14(5)	1489	219	85[d]
1299.4(6)	1.2(2)	1489	189	88[c d], 190, 211[c d]
1317.7(6)	0.68(8)	1489	172	
1336.8(6)	0.59(7)	1489	151	117
1343.0(9)	0.18(6)	1563	219	
1403.9(8)	1.1(1)	1489	85	21.3[d], 85
1415.6(8)	1.75(0.11)	1416	0	138
1477.3(9)	0.24(6)	1563	85	(85, 211[c], 263)[d]
1488.2(1.0)	0.53(8)	1489	0	
1718.6(1.6)	0.45(8)	2058	339	(20.8, 85)[d]
1751.1(1.7)	0.31(6)	1837	85	85
1837.3(2.0)	0.6(2)	1837	0	
2058.4(2.7)[Ru]	0.18(5)	2058	0	

[a] Not placed in decay scheme, [b] decay of ^{97}Y
[c] decay of ^{113}Ru, [d] weak coincidence, [Ru] also in Ru,

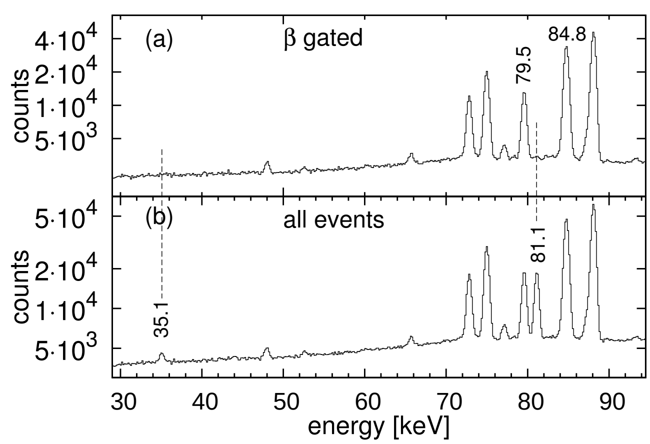

FIG. 13: Low-energy part of a γ spectrum from the mass chain $A = 113$ separated by IGISOL. Spectrum in a) was gated by β events in the plastic scintillator. Spectrum in b) shows all recorded γ events. As one expects, the isomeric transitions 35.1 and 81.1 keV are not present in the β-gated spectrum. Transitions in ^{113}Pd are labeled with their energies in keV.

TABLE VI: Beta feedings and $\log ft$ values of excited levels in ^{113}Pd populated by the β^- decay of ^{113}Rh. The values of internal conversion coefficients were taken from [20]. All the γ lines leaving each level are listed in the last column.

E_{lev}[keV]	I_β[%]	$\log ft$	γ lines leaving the level
0.0	17.5(38)	5.4	
35.1	–	–	35.1
81.1	–	–	81.1
84.8	0.0	0.0	84.8
151.9	0.0	0.0	116.8, 151.9
172.6	0.21(12)	7.3	137.5
189.6	4.38(42)	6.0	104.0, 189.7
219.8	0.21(6)	7.3	135.0
252.2	0.21(21)	7.3	79.5, 100.3, 217.1, 252.2
339.3	0.0	0.0	119.5, 254.5
349.2	30.4(15)	5.1	97.0, 160.0, 176.4, 197.1, 263.2, 349.0
373.1	0.54(18)	6.8	120.8, 221.2, 373.3
409.2	18.2(8)	5.3	157.1, 219.6, 236.7, 257.4 323.9, 409.2
454.6	0.95(12)	6.5	265.1, 454.7
500.6	1.55(13)	6.3	310.9, 349.0, 500.4
538.4	2.42(13)	6.1	349.0, 453.8, 538.4
652.0	1.70(11)	6.2	399.4, 432.7, 462.2, 500.4, 567.2, 651.6
716.1	0.21(3)	7.1	526.8
730.9	3.76(18)	5.8	321.6, 357.9, 541.1, 578.7, 646.2, 730.9
819.7	0.27(3)	6.9	567.2, 629.8, 734.2, 820.3
854.6	0.09(6)	7.4	665.3
861.2	4.11(21)	5.7	451.8, 488.0, 522.2, 608.8, 671.5, 688.5, 709.4, 776.5, 861.2
901.3	1.01(7)	6.3	552.0, 711.5, 749.3, 816.7, 901.4
1008.6	1.85(11)	6.0	756.3, 820.3, 835.8, 856.0, 923.8, 1008.7
1065.4	1.64(9)	6.0	692.4, 813.3, 845.8, 876.0, 892.8, 913.2, 980.6
1082.4	0.24(3)	6.8	830.1, 862.8
1122.6	1.31(16)	6.1	668.1, 933.1, 1122.6
1137.6	1.28(10)	6.1	885.1, 917.9, 985.7, 1052.9
1282.1	0.48(12)	6.4	933.1, 1093.1
1369.4	0.86(7)	6.1	996.2, 1117.2, 1179.9, 1218.5
1415.8	1.70(9)	5.8	1066.9, 1076.6, 1226.1, 1264.1, 1415.6
1489.2	2.33(13)	5.7	1139.9, 1150.4, 1269.9, 1299.4, 1317.7, 1336.8, 1403.9, 1488.2
1562.5	0.12(3)	6.9	1343.0, 1477.3
1836.5	0.27(6)	6.4	1751.1, 1837.3
2058.0	0.18(3)	6.4	1718.6, 2058.4

proposed spin and parity $7/2^-$. The decays to the $7/2^-$ level exclude spin 1/2 or $3/2^+$ for the 349.0- and 409.2-keV levels. Considering other decay branchings and the strong population in β decay of the $7/2^+$ ground state of ^{113}Rh, spins and parities for the two levels are limited to $5/2^+$ and $7/2^+$. We note that if any of these two levels has spin $7/2^+$ then the $3/2^+$ spin of the 252.2-keV level is unlikely, because of the low-energy feeding from the 349.0 and 409.2 keV levels.

The remaining excited levels, populated in the β^- decay of ^{113}Rh and their decays are listed in Table VI. Spin and parity assignments to these levels are proposed based on the logft values shown in Table VI and on their observed decay branchings and are discussed in Section III.C.3.

C. Discussion

1. Negative-parity levels

In the weakly deformed ^{113}Pd nucleus the $h_{11/2}$ neutron shell splits into subshells. At the neutron number $N = 67$ the negative-parity excitations are most likely due to the population of the $5/2^-[532]$ and $7/2^-[523]$ Nilsson orbitals, which are near the Fermi level in this nucleus. This is clearly observed in the ^{111}Ru nucleus, the $N = 67$ isotone of ^{113}Pd, where two negative-parity bands are observed on top of the $5/2^-[532]$ and $7/2^-[523]$ configurations, respectively [23, 24] (though the $5/2^-$ band head is pushed up in energy by the Coriolis interaction). In ^{113}Pd, which exhibits lower deformation than ^{111}Ru, the Coriolis interaction perturbs positions of low-spin, negative-parity levels even more, probably pushing up the $5/2^-$ band-head to high energy (this level has not been identified in this work).

The negative-parity band in ^{113}Pd is a decoupled band characteristic of the $h_{11/2}$ neutron configuration. In Fig. 14 we draw, for the negative parity bands in Pd, Ru and Mo nuclei, the so-called staggering, which measures the departure of the in-band excitation energies from the rigid-rotor formula and is defined as $\Delta E = E_\gamma(I+1 \rightarrow I) - E_\gamma(I \rightarrow I-1)$. For a rigid rotor ΔE is constant as a function of spin, i.e. does not differentiate between favored and unfavored states in a strongly coupled band. However, in the decoupled band the staggering values for the favored states are positive and are significantly higher than for the unfavored states, which are negative. Because ΔE may grow quickly with spin, in Fig. 14 we show value of ΔE/I.

In ^{109}Pd [2] and ^{113}Pd, the only two Pd isotopes where both favored and unfavored states are known for the $h_{11/2}$ neutron level, the values of ΔE/I shown by open and filled circles, respectively, have the same sign and similar amplitude. They have also the same sign as for the known, negative-parity bands in ^{111}Ru [23] and ^{109}Mo [25] nuclei, the $N = 67$ isotones of ^{113}Pd. This observation supports the $11/2^-$ spin-parity assignment to the 98.9-keV level in ^{113}Pd.

In Fig. 15 we show the total aligned angular momentum, I_x for the two signature branches of the negative-parity band in ^{113}Pd and compare it to the I_x values for the ground-state band in ^{112}Pd core nucleus [26]. The I_x values have been calculated as a function of the rotational frequency, ω, from the formula $I_x = \sqrt{(I_a + 1/2)^2 - K^2}$, where I_a=(I_i-I_f)/2 and $\hbar\omega$=$(E_i - E_f)/2$. Calculating I_x

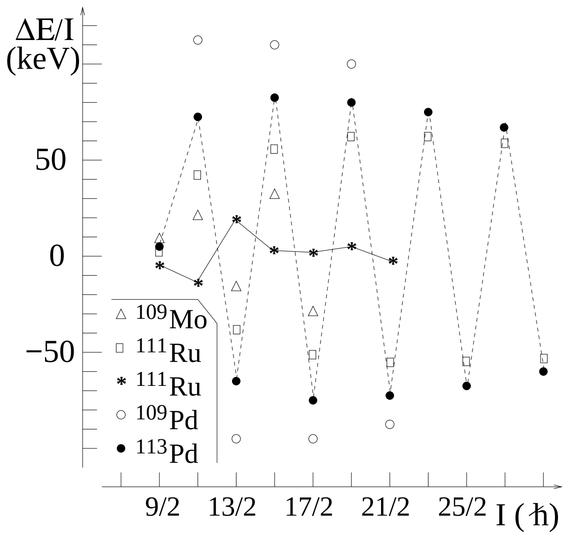

FIG. 14: Staggering in the yrast, negative-parity band of ^{109}Pd, ^{113}Pd, ^{111}Ru and ^{109}Mo nuclei. Star symbols represent staggering for the $5/2^{-}[532]$ configuration in ^{111}Ru. The data are taken from Refs. [2, 23, 25] and the present work. See text for more explanations.

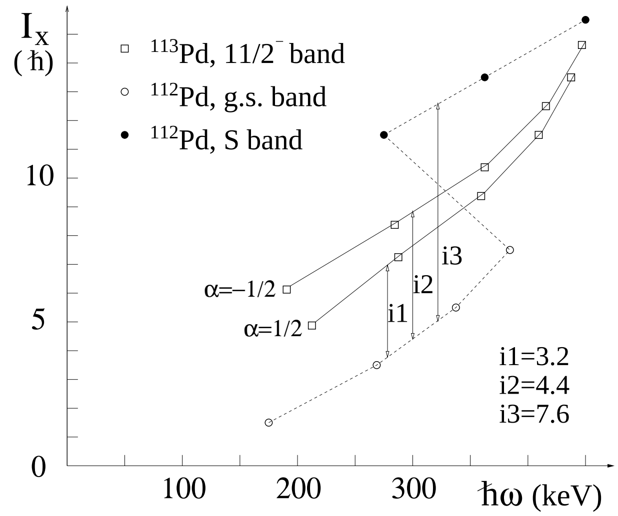

FIG. 15: Total angular momentum alignment, I_x, for the negative-parity band in ^{113}Pd and the g.s. band in ^{112}Pd. The data are taken from Ref. [26] and the present work. Lines are drawn to guide the eye. See text for more explanation.

for this band we assumed $K = 7/2$.

One clearly sees a difference of about one unit in alignment between the two signature branches of the negative-parity band in ^{113}Pd, which is a characteristic feature of a decoupled band. The alignment in the two branches, $\alpha = +1/2$ and $\alpha = -1/2$, relative to the g.s. band of ^{112}Pd, measured at the rotational frequency $\hbar\omega \approx 0.3$ MeV is i1=3.2$\hbar$ and i2=4.4$\hbar$ respectively. Their sum is equal the alignment gain of i3=7.6$\hbar$ in the g.s. band of ^{112}Pd, where a pronounced backbending is observed at the rotational frequency $\hbar\omega \approx 0.34$ MeV. Such a high gain in the total alignment of ^{112}Pd is possible by aligning a pair of $h_{11/2}$ neutrons or a pair of $g_{9/2}$ protons. We note that in ^{113}Pd the backbending at $\hbar\omega \approx 0.34$ MeV is not seen. This is consistent with the neutron pair alignment in ^{112}Pd, which is blocked in the odd-N nucleus ^{113}Pd.

The lowest negative-parity spin identified in this work, is $7/2^{-}$, assigned to the 84.9-keV level, which may correspond to the the $7/2^{-}[523]$ Nilsson orbital but it also could be an excitation in a band based on top of a $5/2^{-}[532]$ band head. In the presence of strong Coriolis decoupling it is difficult to assign the observed $7/2^{-}$ level to a particular band. This is illustrated in Fig. 14, where the staggering value at spin $I = 9/2$ clearly deviates from a regular trend. This is probably caused by the “improper” energy of the $7/2^{-}$ level. It is likely that there are two $7/2^{-}$ levels (the other not identified in this work), which interacts and repel each other.

The two levels at 219.8- and 339.3-keV could represent collective excitations on top of the $5/2^{-}[532]$ orbital, though we do not know the spin of the 339.4-keV level and have not identify the $5/2^{-}$ and the second $7/2^{-}$ levels in ^{113}Pd. Further studies are needed to answer whether the 219.9- and 339.4-keV levels in ^{113}Pd belong to the $5/2^{-}[532]$ band. In ^{111}Ru such an irregular band has been identified and in Fig.14 we show staggering for this band (star symbols). One may notice an opposite sign of staggering, as compared to the staggering in $7/2^{-}[523]$ bands.

2. Positive-parity levels

As pointed in Ref. [27], in the $A \approx 110$ region one observes an allowed β^{-} decay between spin-orbit partners, $\nu 1g_{7/2} \rightarrow \pi 1g_{9/2}$, which strongly populates levels with neutron $\nu g_{7/2}$ component in their wave functions. In addition, in odd-A Pd isotopes this decay can populate positive-parity states arising from the $2d_{5/2}$, $3s_{1/2}$ and $2d_{3/2}$ neutron orbitals, which are near the Fermi surface.

In the weakly deformed nucleus ^{113}Pd, which has 67 neutrons the odd neutron at its lowest excitation is expected to populate the $5/2^{+}[402]$ orbital, (see e.g. the Nilsson diagram in Ref. [28]). This orbital is a natural candidate for the ground-state configuration of ^{113}Pd. In Fig. 16 we show staggering in the $5/2^{+}$, ground-state band of ^{113}Pd and compare it to the staggering in the $5/2^{+}$, ground-state band of the $N = 67$ isotone, ^{111}Ru. The picture for both nuclei is almost identical, indicating that both bands have the same structure.

The structure of the $5/2^{+}$ g.s. band in ^{111}Ru has been explained in Refs. [23, 24] as due to the $5/2^{+}[413]$ and $5/2^{+}[402]$ neutron configurations. As seen in Fig. 16 the staggering observed in both $5/2^{+}$ g.s. bands at low spins indicates the signature $\alpha = -1/2$. Such a signature corresponds to the favored band based on the $5/2^{+}[402]$ configuration, which should then dominate the structure

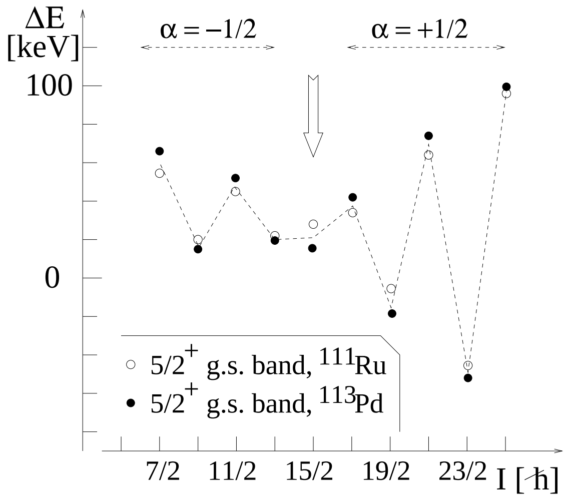

FIG. 16: Staggering in the positive-parity band of ^{111}Ru and ^{113}Pd nuclei. The data are taken from Ref. [23] and the present work. See text for more explanations.

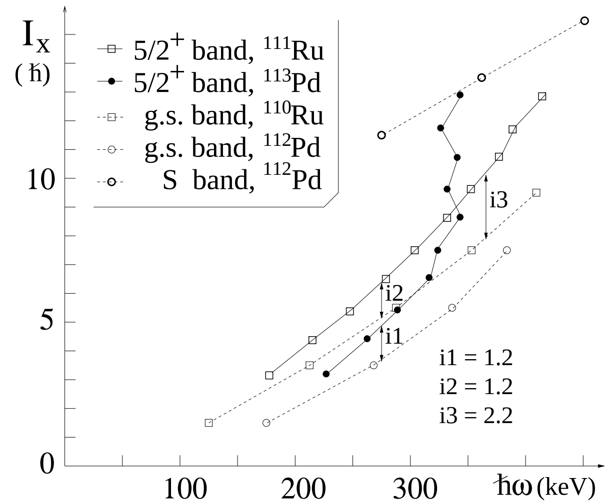

FIG. 17: Total angular momentum alignment, I_x, for the g.s. bands in ^{113}Pd and ^{111}Ru. The data are taken from Ref. [23, 26, 38] and the present work. Lines are drawn to guide the eye. See text for more explanation.

of ground states in both ^{111}Ru and ^{113}Pd. At higher excitations, around spin $I = 15/2$ marked by a thick arrow in Fig. 16, the staggering changes sign and indicates signature $\alpha = +1/2$ for the band. This corresponds to the dominating of $5/2^+[413]$ configuration in the band above spin $I = 15/2$.

One expects that due to the interaction of the $5/2^+$ subshells of the neutron $2d_{5/2}$ and $1g_{7/2}$ shells the $5/2^+[402]$ Nilsson orbital, resulting from this mixing, will bear properties of the $2d_{5/2}$ spherical shell while the $5/2^+[413]$ Nilsson orbital, resulting from this mixing, will bear properties of the $1g_{7/2}$. The $5/2^+[402]$ neutron orbital ($2d_{5/2}$ shell with some admixture of the $1g_{7/2}$ shell), as candidate for the structure of the ground state in ^{113}Pd, is consistent with the $\log ft = 5.4$ estimated in this work for the ground state of ^{113}Pd.

It is instructive to look at the angular-momentum alignment process in the g.s. band. In Fig. 17 we show the total angular momentum, I_x, for the g.s. bands in ^{111}Ru and ^{113}Pd and compare it to the total angular momentum in their respective core nuclei, ^{110}Ru and ^{112}Pd. The alignment in the bottom part of the g.s. band in ^{113}Pd is i1=1.2$\hbar$ at the rotational frequency $\hbar\omega \approx$0.28 MeV, for each of the two signature branches. This is the same as i2=1.2$\hbar$ observed in ^{111}Ru [23] and is consistent with the $5/2^+[402]$ configuration proposed for ground states in both nuclei.

In ^{111}Ru the alignment in the g.s. band grows slowly with spin and at the frequency $\hbar\omega \approx$0.38 MeV yields i3=2.2$\hbar$, which is consistent with the $5/2^+[413]$ structure of the band at higher excitations. Judging from the nearly identical staggering in ^{111}Ru and ^{113}Pd, one may expect that a similar alignment effect is also observed in ^{113}Pd. However, in ^{113}Pd this is masked by a more pronounced alignment of about 6$\hbar$ observed at the frequency $\hbar\omega \approx$0.34 MeV. This alignment is similar to the alignment observed in the negative-parity band and one can propose that it is due to a pair of $h_{11/2}$ neutrons. It is an interesting question why the $h_{11/2}$ alignment is not observed in the ground-state band of ^{111}Ru.

A possible explanation is that the $h_{11/2}$ neutron pair, which aligns in ^{112}Pd, is more strongly bound in ^{110}Ru. Such an extra binding could be due to higher collective effects in ^{110}Ru, as compared to ^{112}Pd. Indeed in this region there are particularly strong triaxial correlations, evolving from γ softness and triaxiality in neutron-rich Mo isotopes [29–33], via triaxial effects in Tc isotopes [19, 34–37], towards triaxial deformation in Ru isotopes [23, 24, 38]. As summarized in Ref. [39], the effect of triaxial deformation on nuclear binding energy is at its maximum over the whole periodic table in ^{108}Ru. This effect is very localized and in Pd isotopes is significantly lower than in Ru, Tc and Mo isotopes.

As mentioned above, the wave function of the Nilsson orbital labeled by the $5/2^+[413]$ asymptotic numbers has a substantial contribution from the $1g_{7/2}$ spherical shells and should be, therefore, strongly populated in β^- decay of ^{113}Rh. One of the 349.0- and 409.2-keV levels, with $\log ft$ values of 5.1 and 5.3, respectively, is a good candidate for such a configuration. The other one of the two levels could correspond to the $7/2^+[404]$ orbital. At present there is no evidence allowing to determine which of the two levels corresponds to the $5/2^+[413]$ orbital and which to the $7/2^+[404]$ orbital. One may suggest that the 409.2-keV level, which receives in β^- decay a similar feeding as the ground state, may correspond to the $5/2^+[413]$ orbital, which is a mixture of the $1g_{7/2}$ and the $2d_{5/2}$ shells, similarly as the $5/2^+[402]$ ground-state configuration. The $7/2^+[404]$ orbital, which is pure $g_{7/2}$ shell, should receive the highest feeding in β^-, which is observed for the 349.0-keV level.

The 1/2+, 35.1-keV level, with negligible feeding in β^- decay, is a good candidate for the $1/2^+[411]$ neutron configuration. The 35.1-keV decay of this level to the ground state should correspond to a single-particle E2 transition between $3s_{1/2}$ and $2d_{5/2}$ neutron orbits.

The 151.9-keV level may correspond to the $3/2^+[402]$ neutron orbital, originating from the $2d_{3/2}$ shell. We note that the $3/2^+[411]$ resulting from the mixture of $3/2^+$ subshells of the $2d_{5/2}$ and $1g_{7/2}$ shells is less likely, because the 151.9-keV level has negligible feeding in β^- decay. The close proximity of the 172.6-keV level with the same $3/2^+$ spin and parity may raise a question why these two levels do not interact. This could happen if the 172.6-keV level corresponds to a collective excitation on top of the 1/2+ band head at 35.1 keV, having a wave function rather different from the $3/2^+[402]$ neutron configuration proposed for the 151.9-keV level. The two discussed bands are strongly mixed, as indicated by their decays to each other. A similar mixing has been discussed in ^{111}Ru for the $1/2^+$ band based on the 9.7-keV level. There the alignment in the $1/2^+$ band has been interpreted as an argument in favor of such a mixing. In ^{113}Pd the data is, at present, too limited to extract either the staggering or alignment for the $1/2^+$ band. It is of interest to study in the future the discussed $1/2^+$ and $3/2^+$ bands at medium spins, to see if there is any crossing with the $g_{7/2}$ neutron configuration, as discussed in ^{111}Ru [23].

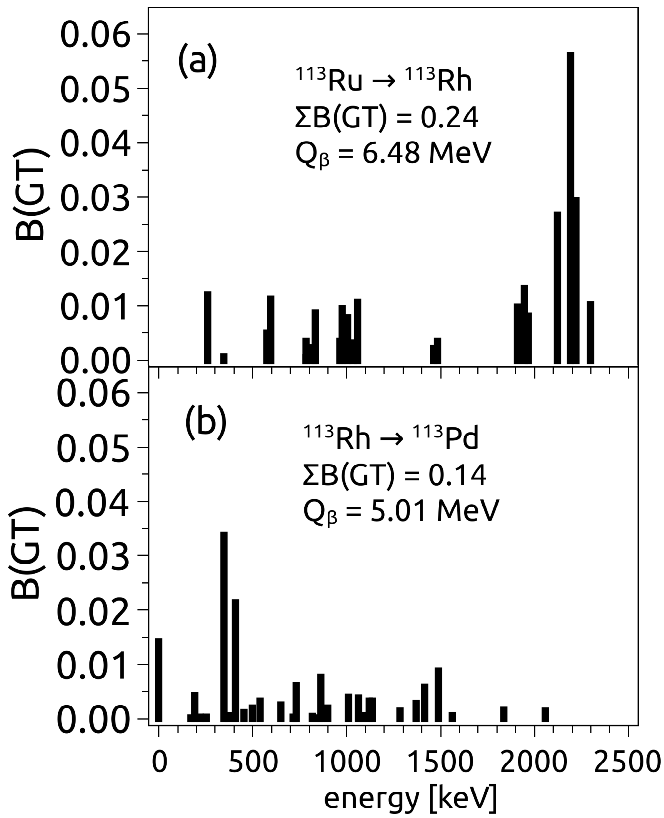

FIG. 18: Panel a) shows B(GT) strength distribution for decay of the ^{113}Ru ground state to ^{113}Rh [15] and panel b) shows the same for decay of the ^{113}Rh ground state to ^{113}Pd as found in this work.

3. *Other observations*

The ground state, the 35.1-, 151.9-, 349.0- and 409.2-keV positive-parity levels and the 81.1-, 84.9- and 98.9-keV negative-parity levels, observed in this work, exhaust the list of possible neutron configurations expected at low excitations in ^{113}Pd. Several other levels, seen in this work and shown in Figs. 8 and 10 have been assigned as collective excitations on top of the these neutron configurations. However there is a number of other levels observed in this work in β^- decay of ^{113}Rh, listed in Table VI, which do not belong to these bands. Moreover, their excitation energies are too low for them being three-quasi-particle (3qp) excitations, which prompts questions about their origin.

To shed some light on their possible nature we display in Fig. 18 the B(GT) function for levels in ^{113}Pd, in comparison with an analogous function for ^{113}Rh. The comparison of the two functions is enhanced by the fact that both nuclei have been studied with the same detector setup.

The B(GT) function for ^{113}Rh shows a characteristic pattern, observed in many nuclei with feeding of band heads at low excitation energies and 3qp excitations above 2 MeV. The B(GT) function for ^{113}Pd is quite different in that the feeding to any 3qp is not seen and the observed strength extends to 1.5 MeV, only. There is almost 40% feeding to the levels between 0.5 and 1.5 MeV. Such a substantial population of these levels in β^- decay of ^{113}Rh suggests a contribution of the $1g_{7/2}$ configuration in their wave functions. In fact, most of these 'unclassified' levels decay to the ground-state band and 'bands' based on the 35.1- and 151.9-keV levels. One may, therefore, suggest that excited states in ^{113}Pd located between 0.5 and 1.5 MeV correspond to the same single-particle excitations as observed below 0.5 MeV but now coupled to another (excited) core. It is possible that such an excited core could correspond to a promotion of a pair of neutrons between closely spaced orbitals, for example, from the $3/2^+[411]$ to the $1/2^+[411]$ orbital or, as already proposed for levels in ^{111}Ru from $5/2^+[413]$ to the $5/2^+[402]$ orbital. Further studies are needed to explain the structure of the states above 0.5 MeV in ^{113}Pd.

The last remaining question concerns the structure of the low-spin bands based on the 35.1-keV and 151.9-keV levels. As discussed above the two band heads may correspond to the $1/2^+[411]$ and $3/2^+[411]$ neutron configurations, respectively. However, in ^{111}Ru the $1/2^+$ band is unusual in that it has too high alignment as for the $1/2^+[411]$ configuration. This observation remains unexplained. As mentioned, in ^{113}Pd the data is to scarce for any detailed alignment analysis. Assuming that the

500.6-keV level is a quadrupole excitation on top of the 151.9-keV level and taking $K = 3/2$ for the 151.9-keV band head, one obtains a very high alignment of $3.2\hbar$ in the favored branch which suggests the alignment of about $6\hbar$ in the band. Such high alignment for the positive-parity band in ^{113}Pd is only possible when a low-Ω orbital of the $1g_{7/2}$ shell is involved.

It has been discussed in previous works that there exists a tendency for oblate configurations in neutron-rich Pd isotopes [40]. A theoretical proposition [1] of an oblate shape in the ground state was not supported by the experiment [2]. However, one may ask whether oblate configurations appear as excited states. If so, one might expect in ^{113}Pd a low-energy excited state corresponding to the $1/2^+[420]$ orbital originating from the $g_{7/2}$ spherical shell.

IV. SUMMARY

In the present work we measured prompt-γ radiation following fission of ^{248}Cm and ^{252}Cf and β-decay of ^{113}Rh to obtain new information on excited states and transitions in neutron-rich, even-odd nucleus ^{113}Pd. The study provided rich, new information on excited levels in ^{113}Pd.

We have proposed a new $7/2^-$ level at 84.9 keV in ^{113}Pd. The level decays by the 84.9-keV transition, which was previously located elsewhere. Consequently we set the $11/2^-$ yrast excitation at 98.9 keV and propose two low-energy (unobserved) transitions 17.8 and 14.0 keV linking the $11/2^-$ level to the $9/2^-$, 81.1 keV and $7/2^-$, 84.9 keV levels, respectively. The cascade of favored character comprising of the 383.1-, 570.8- and 722.3 keV transitions is proposed to populate the $11/2^-$ level at 98.9 keV. We confirmed the unfavoured cascade comprising the 407.4-, 425.0-, 576.1- and 717.6 keV transitions, which populates the $9/2^-$ isomeric state at 81.1 keV. Both cascades are linked by the 407.4 keV transition. A short cascade including 135.0-, 119.5- and 254.5 keV transitions has been placed on the top of the $7/2^-$ level at 84.9 keV, interpreted as the $7/2^-[523]$ Nilsson orbital.

In the level scheme of the positive-parity excitations we propose the $5/2^+[402]$ Nilsson configuration for the ground state of ^{113}Pd and add two new band heads 35.1 and 172.6 keV with spins $1/2^+$ and $3/2^+$, respectively, which may correspond to the $1/2^+[411]$ and $3/2^+[411]$ Nilsson configurations, respectively. However, these configurations are analogous to levels in ^{111}Ru, which may correspond to Nilsson configurations in an oblate potential.

Finally we note a striking difference in the pattern of B(GT) strength distribution observed in the β^- decays of ^{113}Ru and ^{113}Rh. We propose that excited states in ^{113}Pd located between 0.5 and 1.5 MeV may correspond to the same single-particle excitations as observed below 0.5 MeV but now coupled to an excited core. This excitation may correspond to promotion of a pair of neutrons between closely spaced neutron orbitals, as $5/2^+[413]$ the $5/2^+[402]$.

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