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Beta decay of neutron-rich ^{116}Rh and the low-lying level structure of even-even ^{116}Pd

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Beta decay of neutron-rich ^{116}Rh has been studied at the IGISOL facility using β-γ and γ-γ coincidence spectroscopy. Online mass separated ^{116}Rh sources were produced by applying 25 MeV proton induced fission of natural uranium and the fission ion guide. Extended decay schemes have been constructed for the low- and high-spin states of ^{116}Rh, respectively. Two excited 0^+ states in ^{116}Pd at 1109.8 and 1732.9 keV are proposed as the quasi-β and intruder bandheads, respectively. New ^{116}Pd data support a different bandhead at 1809.9 keV for the recently reported negative-parity band. The systematics of low-lying collective and two-quasiparticle levels in even Pd nuclei has been extended substantially. The behavior of the quasi-γ band in ^{116}Pd reveals some deviation from a strict O(6) limit of the IBA model.

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I. INTRODUCTION

Neutron-rich transitional nuclei between Cd and Mo cover a wide variety of possible shapes ranging from nearly spherical to highly deformed, and provide very useful tests for comparisons of different nuclear models. Near the closed proton shell Sn isotopes, even Cd nuclei are often treated as vibrators [1–3], while Ru isotopes clearly exhibit softness against asymmetric γ deformation [4–8]. Pd isotopes situated between Cd and Ru are thus expected to show a structural transition from vibrational to γ-unstable nuclei. Stachel *et al.* [9] performed a detailed study of the phase transition between the SU(5) (anharmonic vibrator) and O(6) (γ-soft rotor) limit in the framework of the interacting boson model (IBM). From a comparison of the experimental excitation energies and $E2$ transition probabilities with the calculation, it has been established that even Pd nuclei follow the SU(5)$\rightarrow$O(6) transition. Recently, Kim *et al.* [10] carried out a new calculation for even Pd nuclei by using the proton-neutron interacting-boson model (IBM-II). The general agreement between the experimental excitation energies and model calculation is rather good from ^{102}Pd up to ^{116}Pd. They also presented predictions for heavier Pd isotopes up to ^{126}Pd. Newest theoretical calculations for even Pd nuclei can be found in Refs. [11–15], where microscopic approaches such as the cranked Hartree-Bogoliubov (CHB) [14] and the general collective Bohr model [15] have also been attempted.

Level structure of even Pd isotopes was extensively investigated from β decays of online mass separated Rh isotopes [16], where the systematics for the low-lying levels of $^{110-116}$Pd were revealed. Prompt γ-ray spectroscopy with spontaneous fission of ^{252}Cf source extended the ground state and γ bands to higher spin levels [17,18]. Coulomb excitation experiments for less neutron-rich $^{106-110}$Pd identified some other band structures [19,20]. Recently, very neutron-rich ^{118}Pd was studied both by β decay of ^{118}Rh [21], and by fusion-fission reaction [22]. As a matter of fact, two-quasineutron levels in even Pd nuclei are strongly fed by β decays of Rh isotopes, through fast $\nu 1g_{7/2}\rightarrow\pi 1g_{9/2}$ Gamow-Teller (GT) transitions. Sometime earlier, rotational bands based on two-quasineutron excitations were observed for the first time in neutron-rich ^{100}Zr and ^{102}Zr [23]. The obtained strength of the neutron pairing interaction turns out to be smaller than the values near stability in this region. According to Capote *et al.* [24], the pairing strength for neutron-rich $A\approx 100$ nuclei can be determined from the two-quasineutron bandhead energies, using a quantum Monte Carlo method.

By taking advantage of higher production yields than in Ref. [16], Lhersonneau *et al.* recently remeasured the β decays of ^{110,112}Rh and provided detailed decay schemes [25]. They also proposed two bands in ^{112}Pd built on excited 0^+ states [26] and suggested a systematics for two-quasiparticle levels in even $^{108-112}$Pd [25]. For more neutron-rich ^{116}Pd, the earlier prompt γ-ray spectroscopy studies established the ground state band up to 16^+ state and the γ band up to 9^+ state [17,18]. Moreover, three negative parity bands were reported during the completion of this work [27]. However, as mentioned above, there exists only one β-decay measurement conducted more than ten years ago [16], in which the level scheme was built up to 2450.0 keV. Because of the limited experimental sensitivity, only 9 excited levels and 13 γ transitions were placed. Since ^{116}Rh has two β-decaying states with spins of 1^+ and (6^-), ^{116}Pd levels with a large range of spins can be reached. Therefore, the current reinvestigation of the β decay of ^{116}Rh was motivated by exploration of the low-lying level structure in even daughter ^{116}Pd with much more intense sources. We report here the extended decay schemes for both low- and high-spin states in ^{116}Rh. The updated systematics for low-lying collective and quasiparticle levels in even Pd isotopes are also presented.

II. EXPERIMENTAL SETUP AND ANALYSIS

The neutron-rich β-decaying ^{116}Rh sources were produced by using 25 MeV proton induced fission of natural uranium at the ion-guide on-line isotope separator (IGISOL)

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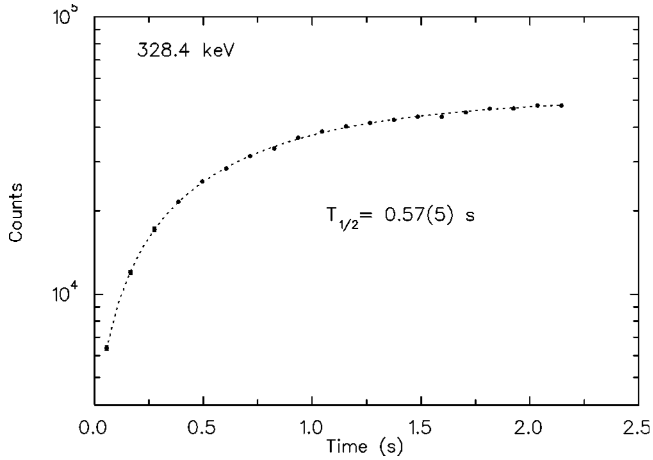

FIG. 1. Growth curve of the activity for ^{116}Rh high-spin isomer; the time bins are of 0.11 s.

[28–30] of the University of Jyväskylä. Since fission fragments are emitted more or less isotropically, the 15 mg/cm^2 thick ^{nat}U target was tilted to a 7° angle with respect to the beam axis, resulting in an effective target thickness of 120 mg/cm^2. The proton beam was delivered by the K130 cyclotron as 50 MeV H_2^+ ions with intensities about 6–10 μA. In the ion guide, the fission products recoiling out of the target are thermalized in helium gas of 200 mb pressure, transported by the gas flow through a differential pumping system and then injected directly into the acceleration stage of the isotope separator, where the singly charged positive ions are accelerated to 40 keV. The $A=116$ isobaric beam is then separated from other fission products through a suitable field setting of a 55° magnet. The mass resolution of the system is typically 300 (FWHM) in this mass region. The latest development of ion guide technique enables the mass-separated beams of fission products with an intensity of 2700 ions/s per mb cross section [31]. In this experiment, the average production rates for 1^+ and high-spin states of ^{116}Rh are about 1100 and 1300 ions/s, respectively. The yields of ^{116}Pd and ^{116}Ag are about one order of magnitude higher.

The mass separated $A=116$ beam was implanted into a collection tape, which was periodically moved at preset time interval to reduce the activities of long-lived isobaric contaminants. For ^{116}Rh, a collection cycle of 2.2 s was applied. After each cycle, the acquisition system was blocked while the tape moved forward about 20 cm in 0.3 s. In the detection setup, a 2 mm thick BC408 cylindrical plastic scintillator was used for detection of β particles with the total efficiency of about 60%. Four large volume Eurogam phase-I germanium detectors with relative efficiency of 70% in each, were used to detect γ rays. The energy and absolute detection efficiency of the Ge detectors were calibrated with a set of standard γ sources. Coincident β-γ or γ-γ events were recorded with the VENLA multiparameter data acquisition system [32]. In offline analysis of the data, a symmetric γ-γ energy matrix was created from the energy pairs regardless of the detectors which fired, by using a gain-matching algorithm from the EUROGAM software [33]. The γ-γ energy matrix was then analyzed with conventional projection techniques to establish the γ-γ coincidence relationships. The γ-ray intensities were obtained mainly from the β-gated γ spectrum. In several cases, when the specific γ ray was too weak, γ-γ coincidence spectra were also used to get the intensity.

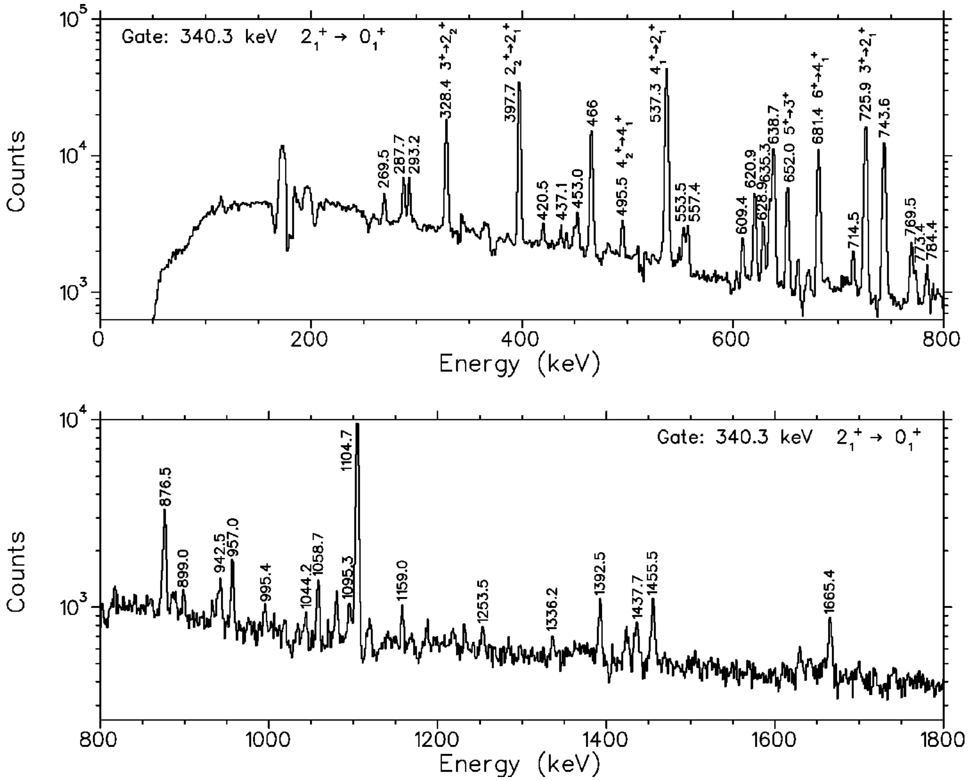

FIG. 2. Gamma spectrum in coincidence with the 340.3 keV $2_1^+ \rightarrow 0^+$ ground state transition of ^{116}Pd. This spectrum was projected from the γ-γ energy matrix which was created by making use of events from all four Ge detectors.

TABLE I. List of γ rays from the decay of the 1^+ state of ^{116}Rh. 100 γ-intensity units correspond to a β feeding of 45%.

E_γ [keV]	I_γ	E_i	E_f	I_i^π	I_f^π
340.3 (1)	100.0	340	0	2_1^+	0_1^+
397.7 (1)	32.6 (41)	738	340	2_2^+	2_1^+
737.8 (1)	22.4 (26)	738	0	2_2^+	0_1^+
769.5 (2)	7.7 (9)	1110	340	(0_2^+)	2_1^+
995.4 (5)	3.3 (2)	1733	738	(0_3^+)	2_2^+
1336.2 (4)	2.1 (2)	2074	738	(2_3^+)	2_2^+
1392.5 (3)	3.7 (5)	1733	340	(0_3^+)	2_1^+
1665.4 (4)	5.4 (4)	2006	340		

TABLE II. Levels in ^{116}Pd fed in the decay of 1^+ state of ^{116}Rh. Ground state β-feeding value is taken from Ref. [16]. Log *ft* values are calculated with $Q_\beta = 8.0$ MeV and $T_{1/2} = 0.68$ s [16,34]. The typical error for log *ft* is 0.2.

Energy [keV]	β feeding [%]	log *ft*	I^π
0.0	45.0 (22.0)	5.4	0^+
340.3 (1)	22.7 (92)	5.6	2^+
737.9 (1)	22.3 (90)	5.5	2^+
1109.8 (2)	3.5 (15)	6.2	(0^+)
1732.9 (3)	3.2 (13)	6.1	(0^+)
2005.7 (4)	2.4 (10)	6.1	
2074.1 (4)	0.9 (4)	6.5	(2^+)

III. RESULTS

A. Half-life of ^{116}Rh

The β decay half-life of ^{116}Rh was determined by analysis of the growth of activity during collection. For the decay of high-spin ^{116}Rh state, some intense γ rays have been analyzed. Figure 1 gives the growth curve for 328.4 keV γ ray in this decay. This curve has been fitted with a single half-life of 0.57(5) s. This value is in agreement with the previously reported 0.9(5) s in Ref. [16], while the uncertainty is greatly reduced. For the 1^+ ^{116}Rh state, only several rather weak γ rays, such as 769.5, 1392.5, 1665.4 keV transitions could be purely attributed to this decay. These weak γ rays have been analyzed in the same way, and yield a half-life which agrees with the value of 0.68(6) s in Ref. [16].

B. Decay schemes

The construction of the level schemes is mainly based on γ-γ coincidence relationships. As an example, Fig. 2 shows the γ-ray spectrum gated by the 340.3 keV $2_1^+ \rightarrow 0^+$ ground state transition of ^{116}Pd. It is known that ^{116}Rh has two β-decaying states [16], but the very close lifetimes make it impossible to assign all the γ transitions to either of the decaying parents by observing the half-life difference. However, as these two states have spins of 1^+ and 5–7 [16], it is possible to distribute the levels, by assuming that the 1^+ decay directly populates only states with $I \leqslant 2$. This argument is supported by the intensity balance for the 1066.2 keV 3^+ level indicating no direct β feeding. Accordingly, only the 340.3 keV 2_1^+ and 737.9 2_2^+ levels are populated in both β decays. The intensities of 340.3, 397.7, and 737.8 keV γ transitions are then separated, as the β feedings must be negligible to the 340.3 and 737.9 keV levels in the decay of high-spin isomer.

1. Decay of 1^+ state of ^{116}Rh

Transitions assigned to the decay of 1^+ state of ^{116}Rh are listed in Table I. The ^{116}Pd levels fed in this decay are listed in Table II, while the decay scheme is shown in Fig. 3. Six excited levels are placed in this level scheme, the upper four are new ones. In analogy with the decays of less neutron-rich ^{110,112,114}Rh [16,25], several low-lying 0^+ states are expected to be populated in ^{116}Pd. The level at 1109.8 keV is tentatively assigned as 0^+, following the systematics of the β band found in even $^{108-114}$Pd (Ref. [26], and references therein). The experimental facts are in no contradiction with this assignment. There is no transition to the ground state [$I_\gamma(1109.8)/I_\gamma(769.5) < 0.07$], nor feeding to or from levels with $I > 2$ could be detected in our measurement. Theoretical calculation with the IBM-II model predicts a 0^+ level slightly above 1110 keV [10], in good agreement with our interpretation. In addition, spins 0^+ and 2^+ are tentatively assigned to 1732.9 and 2074.1 keV levels as well, based on the level energy systematics of intruder band in even Pd nuclei [26].

2. Decay of high-spin state of ^{116}Rh

For the decay of high-spin isomer of ^{116}Rh, the assigned transitions are listed in Table III, the ^{116}Pd levels are listed in

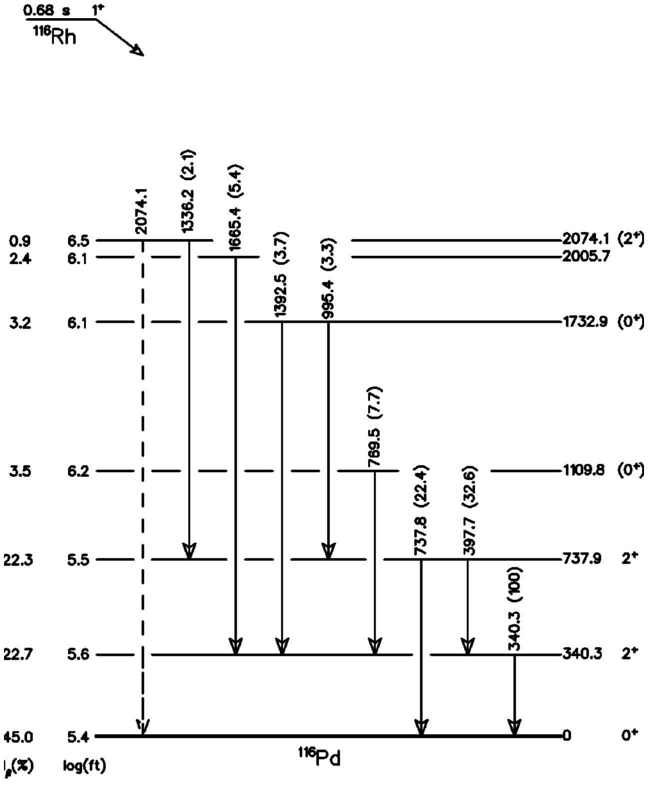

FIG. 3. Decay scheme of the low-spin state of ^{116}Rh.

TABLE III. List of γ rays from the decay of high-spin isomer of ^{116}Rh. 100 γ-intensity units correspond to a β feeding of 88%.

E_γ [keV]	I_γ	E_i	E_f	I_i^π	I_f^π
172.4 (2)	1.1 (2)	1982	1810	5^-	4^-
269.5 (2)	1.5 (1)	2718	2449		(6_2^-)
287.7 (2)	3.5 (2)	2603	2316		
293.2 (3)	3.3 (2)	2276	1982	(6_1^-)	5^-
328.4 (1)	19.1 (12)	1066	738	3^+	2_2^+
340.3 (1)	100.0	340	0	2_1^+	0^+
397.7 (1)	19.2 (27)	738	340	2_2^+	2_1^+
420.5 (2)	1.0 (1)	2869	2449		(6_2^-)
437.1 (2)	1.2 (2)	1810	1373	4^-	4_2^+
453.0 (2)	2.7 (4)	2435	1982	(7_1^-)	5^-
465.8 (2)	3.9 (6)	2276	1810	(6_1^-)	4^-
466.1 (1)	12.8 (11)	2449	1982	(6_2^-)	5^-
495.5 (2)	2.9 (2)	1373	878	4_2^+	4_1^+
537.3 (1)	52.9 (40)	878	340	4_1^+	2_1^+
553.5 (2)	2.0 (1)	2869	2316		
557.4 (2)	2.5 (2)	2276	1718	(6_1^-)	5^+
609.4 (2)	3.0 (2)	1982	1373	5^-	4_2^+
620.9 (2)	8.2 (5)	2316	1695		$(3^-,4^+)$
628.9 (2)	8.7 (6)	1695	1066	$(3^-,4^+)$	3^+
635.3 (2)	8.3 (10)	1373	738	4_2^+	2_2^+
638.7 (1)	19.4 (14)	2449	1810	(6_2^-)	4^-
652.0 (1)	11.1 (10)	1718	1066	5^+	3^+
681.4 (1)	15.9 (14)	1559	878	6_1^+	4_1^+
714.5 (2)	1.9 (5)	2433	1718		5^+
725.9 (1)	27.9 (20)	1066	340	3^+	2_1^+
728.0 (3)	1.2 (3)	2101	1373	(6_2^+)	4_2^+
737.8 (1)	13.2 (16)	738	0	2_2^+	0^+
743.6 (1)	25.5 (18)	1810	1066	4^-	3^+
773.4 (3)	1.2 (1)	2492	1718	7^+	5^+
784.4 (3)	1.1 (1)	2343	1559	(8^+)	6_1^+
876.5 (2)	9.6 (7)	2435	1559	(7_1^-)	6_1^+
886.5 (3)	0.6 (1)	2869	1982		5^-
889.5 (4)	0.6 (2)	2449	1559	(6_2^-)	6_1^+
899.0 (3)	1.4 (1)	2617	1718		5^+
942.5 (2)	1.4 (1)	2316	1373		4_2^+
957.0 (2)	4.9 (4)	1695	738	$(3^-,4^+)$	2_2^+
1044.2 (4)	1.2 (3)	2603	1559		6_1^+
1058.7 (3)	1.3 (4)	2869	1810		4^-
1095.3 (4)	0.8 (1)	2654	1559	(7_2^-)	6_1^+
1104.7 (2)	22.7 (16)	1982	878	5^-	4_1^+
1159.0 (3)	1.4 (1)	2718	1559		6_1^+
1253.5 (4)	0.7 (1)	2813	1559		6_1^+
1437.7 (6)	1.0 (3)	2316	878		4_1^+
1455.5 (4)	2.1 (6)	2333	878		4_1^+

TABLE IV. Levels in ^{116}Pd fed in the decay of high-spin isomer of ^{116}Rh. $\log ft$ values are calculated with Q_β=8.0 MeV [16,34] and $T_{1/2}$=0.57 s. The typical error for $\log ft$ is 0.1.

Energy [keV]	β feeding [%]	$\log ft$	I^π
0.0			0^+
340.3 (1)			2^+
737.9 (1)			2^+
877.6 (1)	7.3 (38)	5.9	4^+
1066.2 (1)			3^+
1373.1 (2)	3.9 (10)	6.0	4^+
1559.0 (2)	0.4 (14)	6.9	6^+
1695.0 (2)	4.8 (8)	5.8	$(3^-,4^+)$
1718.2 (1)	3.6 (10)	5.9	5^+
1809.9 (2)	0.9 (21)	6.5	4^-
1982.4 (2)	6.5 (18)	5.6	5^-
2101.1 (3)	1.1 (3)	6.3	(6^+)
2275.7 (2)	8.6 (9)	5.4	(6^-)
2315.7 (2)	4.5 (7)	5.6	
2333.1 (4)	1.9 (5)	6.0	
2343.4 (4)	1.0 (1)	6.3	(8^+)
2432.7 (2)	1.7 (5)	6.0	
2435.4 (2)	10.9 (11)	5.2	(7^-)
2448.5 (1)	26.8 (25)	4.8	(6^-)
2491.6 (3)	1.1 (1)	6.2	7^+
2603.4 (2)	4.2 (5)	5.6	
2617.2 (3)	1.2 (1)	6.1	
2654.3 (4)	0.7 (1)	6.3	(7^-)
2718.0 (2)	2.6 (3)	5.7	
2812.5 (4)	0.6 (1)	6.3	
2869.0 (1)	4.3 (5)	5.5	

Table IV, and the decay scheme is displayed in Fig. 4. Altogether 25 levels are placed in this level scheme with 46 γ transitions. The decay scheme is remarkably improved due to much higher experimental sensitivity. The previously observed γ transitions in Ref. [16] are confirmed except the weak 607.4 keV one. The new data also support the existence of a 2448.5 keV level. However, the order of 1104.7 and 466.1 keV γ rays in the cascade depopulating the 2448.5 to 877.6 keV (4_1^+) levels should be reversed. In addition, the order of 743.6 and 638.7 keV γ rays in the cascade decaying from the same 2448.5 state to 1066.2 keV (3_1^+) level should also be reversed. Thus, the previous 1345.5 and 1706.1 keV levels are replaced by the 1982.4 and 1809.9 keV levels, respectively. The vanishing of the previous 1345.5 and 1706.1 keV levels also means that they cannot be the 4^+ and 5^+ members of the γ band as suggested in Ref. [16]. New 495.5 and 635.3 keV transitions are found which support the existence of a 4_2^+ level at 1373.1 keV, consistent with the result of prompt γ-ray spectroscopy [18,27]. Moreover, the 1718.2 keV level has already been proved to be the 5^+ member [18,27].

The information on spin and parity of ^{116}Pd levels revealed in Ref. [27] is very helpful to verify our distribution of the levels to either of the decay parents. In the present β-decay work, the ground-state band is observed up to the 8^+ level, and the γ band up to the 7^+ state at 2491.6 keV. In addition, two negative-parity bands which are labeled by C and D in Ref. [27], are both observed up to their (7^-) states at energies of 2435.4 and 2654.3 keV, respectively. For the newly proposed negative-parity band B, our data support a different bandhead at the energy of 1809.9 keV. Namely, the 743.6 keV γ ray should be the transition to 1066.2 keV 3_1^+

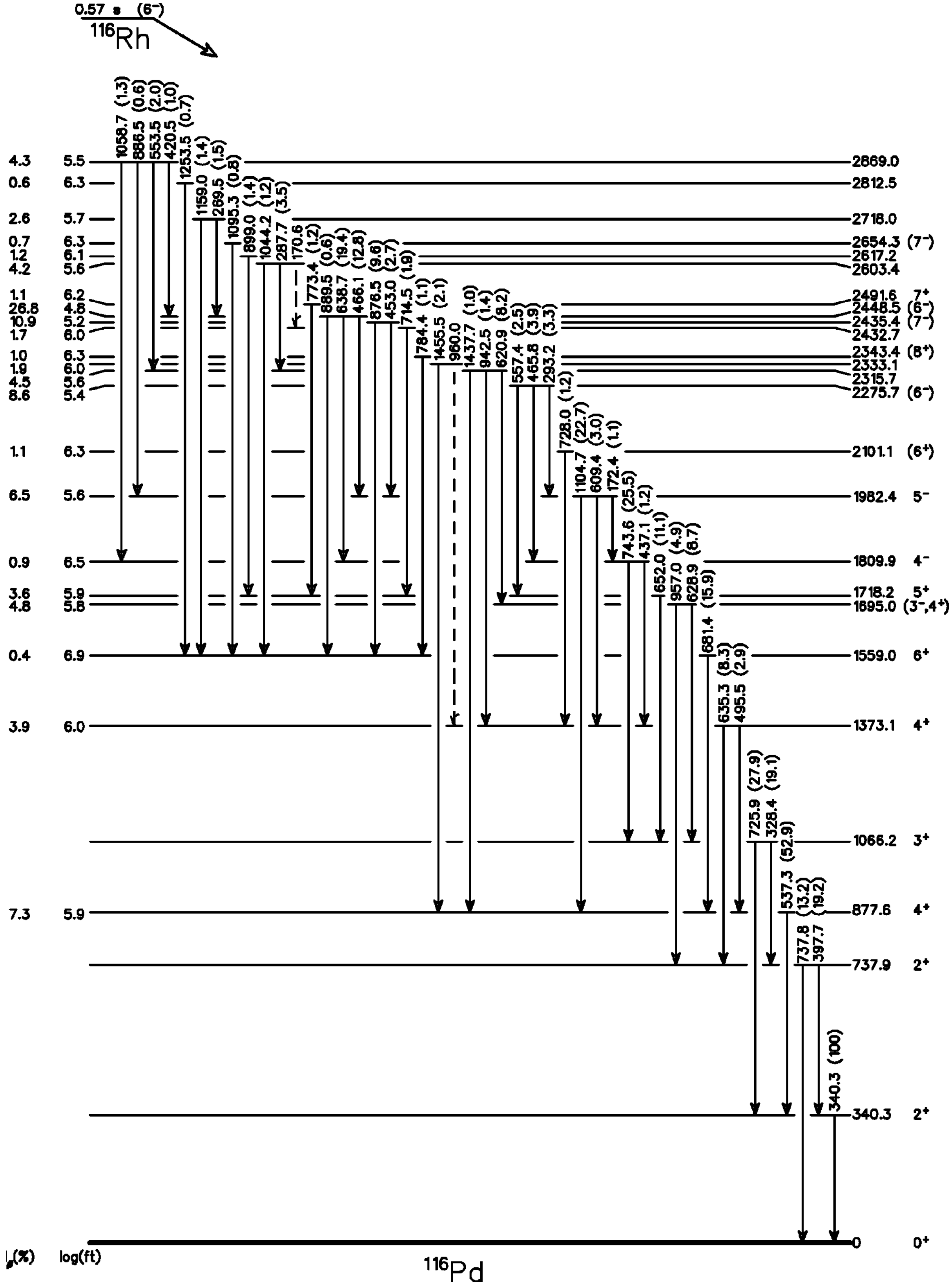

FIG. 4. Decay scheme of the high-spin state of ^{116}Rh.

level, while the 465.8 keV γ ray is the lowest $E2$ transition within the band. The 4^- assignment of spin and parity to this bandhead is based on systematics [25] and the presence of the identical band in ^{114}Pd [27]. The puzzling coincidence relationship between the 466 and 1104.7 keV γ transitions in Ref. [27] is resolved by our observation of two γ transitions

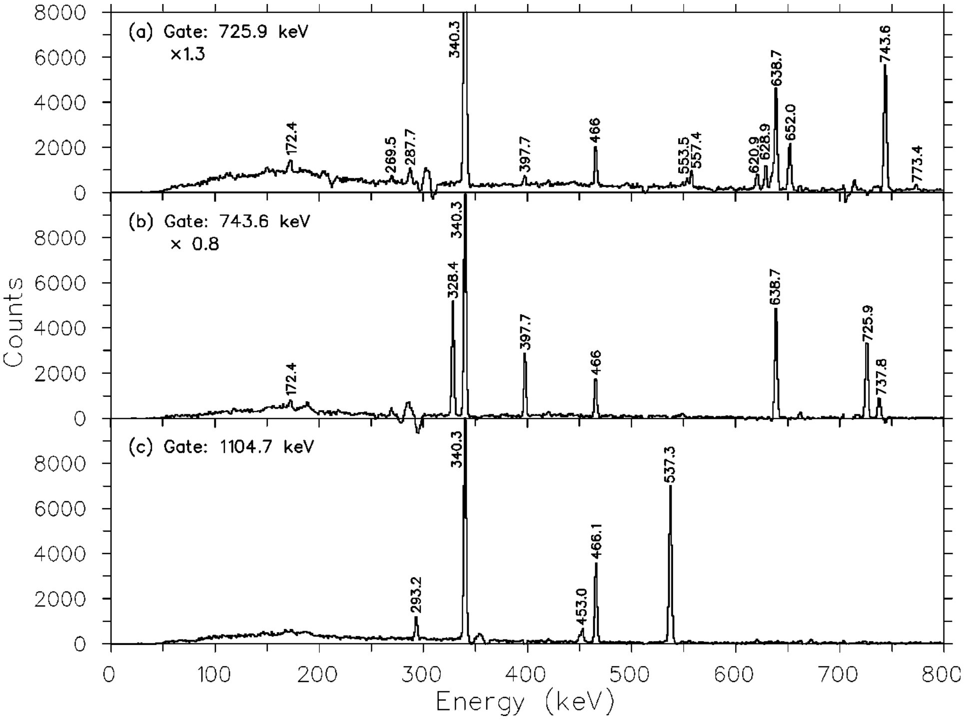

FIG. 5. Gamma spectra gated by the 725.9 keV $3^+\rightarrow 2_1^+$, 743.6 keV $4^-\rightarrow 3^+$ and 1104.7 keV $5^-\rightarrow 4_1^+$ transitions of ^{116}Pd. The 397.7 keV peak seen in (a) is due to the 728.0 keV γ ray. See text.

of 466.1 and 465.8 keV. However, our 465.8 keV γ-ray transition is identified as their 466.1 keV one. As a unique feature of the present β-decay measurement, the strongest direct β feeding to the 2448.5 keV level leads to a well-established coincidence relationship between the 466.1 and 1104.7 keV transitions, with comparable strength to that between 638.7 and 743.6 keV γ-ray transitions, and thus ensures the placement of these intense γ rays. Although the 465.8 keV γ-ray transition cannot be resolved from the more intense 466.1 keV partner, the observed intensities of the 172.4 and 466 keV γ transitions in the 743.6 keV gated spectrum give a firm indication of its existence, and the means to obtain the relative intensity of the 465.8 keV γ ray after correction for the contribution of the 466.1 keV γ transition.

To illustrate the above arguments, spectra gated by the 725.9 keV $3^+\rightarrow 2_1^+$, 743.6 keV $4^-\rightarrow 3^+$, and 1104.7 keV $5^-\rightarrow 4_1^+$ transitions are shown in Fig. 5. Note the 466 keV peak in Fig. 5(a) which is the sum of 466.1 and 465.8 keV γ transitions. The existence of 465.8 keV γ transition is indicated in Fig. 5(b), in which the intensity difference between the 466 and 172.4 keV γ transitions is very evident. In addition, note the 638.7 keV peak in Fig. 5(b) and the 466.1 keV peak in Fig. 5(c) which are the two main transitions depopulating the 2448.5 keV level.

The new level at 1695.0 keV is found to correspond to 1714.9 keV (3^-, 4^+) in ^{112}Pd [25,27]. From the observed β feeding in our measurement, the spin and parity of 4^+ is more favorable. It lies at an energy of about 2.3 times that of the γ vibration (2_2^+), and decays to the 1066.2 keV 3^+ and 737.9 keV 2_2^+ levels of the γ band. Therefore, it is likely to associate this level with the $K^\pi=4^+$ two-phonon γ-vibrational state. Such two-phonon γ-vibrational states have been recently identified in well-deformed ^{166}Er [35,36], as well as in neutron-rich transitional region nucleus ^{106}Mo [37]. Similarly to even $^{108-114}$Pd [16,25], the 2448.5 keV ^{116}Pd level is the most strongly fed one, with a log *ft* value of 4.8. It is therefore interpreted as a two-quasiparticle state. The tentative assignment of 6^- to this level is implied by the existence of a 6^- two-quasiparticle level at 2622.6 keV in ^{114}Pd [16,27]. As levels with spin and parity of 5^-, 6^-, and 7^- have the strongest β feedings, it is very tempting to assign $I^\pi=6^-$ to the high-spin decay isomer. However, the nonzero β feedings to 4^+ levels may suggest another β decaying isomer with positive parity, or mean that some intensity to balance the feedings to the 4^+ has not been observed.

IV. DISCUSSION

The systematics of low-lying levels in neutron-rich even Pd isotopes is shown in Fig. 6. The obvious contribution of this work is the extension of both the β and intruder bands. Furthermore, it is also worth mentioning the correction of 4^+ and 5^+ members of the γ band in ^{116}Pd. Turning to the systematic behavior, as a rule for neutron-rich even Ru and Pd nuclei, the excitation energy minimum of both the ground state and γ bands occur at $N=68$, two neutrons more than the middle between the $N=50$ and 82 shells. The gradual decrease of energies indicates the trend of increase in deformation until $N=68$, and then a smooth transition towards diminishing deformation in ^{116}Pd and ^{118}Pd. Nevertheless, further examination of the deformation deduced from the half-lives of 2_1^+ levels shows some difference, as displayed in Table V, all even Pd nuclei from 104 up to 116 have $\beta_2 \sim 0.2$, while ^{110}Pd ($N=64$) seems to have the largest deformation with $\beta_2=0.24$ (1). This systematics versus neutron number N is similar to even Ru, where ^{108}Ru ($N=64$) is the most deformed with $\beta_2=0.28$ (1) [41].

The systematics of the energy ratios in the yrast band

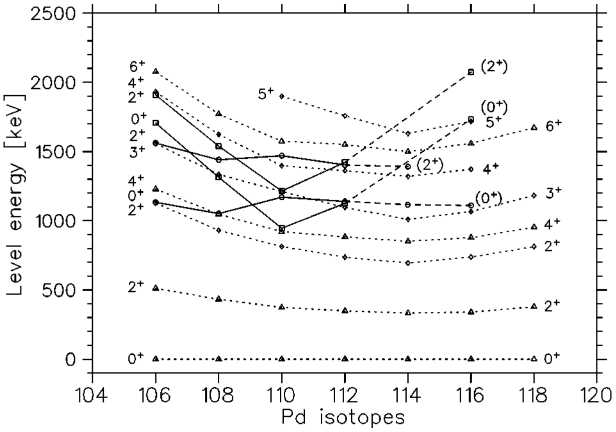

FIG. 6. Systematics of low-lying excitation levels in even-mass Pd isotopes. The ground-state band (open triangle) and γ-band (open diamond) are only displayed to some extent for clarity. The β-band (open circle) and intruder-band (open square) are preliminarily extended to ^{116}Pd in this work. See text.

$E(4^+)/E(2^+)$ and $E(6^+)/E(2^+)$ in even $^{104-118}$Pd indicate that the O(6) symmetry reaches its maximum at $A=116$ ($N=70$), and then a transition back to SU(5) symmetry occurs between $A=116$ and 118 [21]. Since the proton-neutron interaction is of primary importance for the development of collectivity and deformation in heavy nuclei, a N_pN_n scheme was introduced to describe the collectivity in heavy nuclei in terms of the parameter $P=N_pN_n/(N_p+N_n)$ [42]. According to this scheme, even Pd nuclei have the same P values as their Xe isotones, i.e., the same number of boson pairs in the IBA model, therefore the collective energy levels of even Pd isotopes are often compared with their Xe isotones. Table VI lists some properties of ^{116}Pd in comparison with its ^{124}Xe isotone. According to Ref. [44], ^{124}Xe belongs to an extensive region of O(6)-like nuclei near $A\sim130$. In general, the properties of ^{116}Pd are close to those of ^{124}Xe. As shown in the table, for both ^{116}Pd and ^{124}Xe, the E_{4_1}/E_{2_1} and E_{6_1}/E_{2_1} energy ratios are very close to 2.5 and 4.5, respectively. These two values are well known for an O(6) nucleus in the IBA model. However, the energy spacings of γ band $(E_{4_2}-E_{3_1})/E_{2_1}$ and $(E_{4_2}-E_{3_1})/(E_{4_2}-E_{2_2})$ are larger than predicted [44,46]. According to the model, the energy staggering between the odd- and even-spin members of the γ-band should lead to the degeneracy of the 3^+ and 4^+ states at the O(6) limit. Therefore, the observed less staggerings for both ^{116}Pd and ^{124}Xe reflect the deviations from a strict O(6) γ-soft limit. From this point of view, ^{116}Pd is farther from a strict O(6) nucleus than ^{124}Xe. In addition, we can also compare the $B(E2)$ ratios with the predictions of IBA [9,44,45]. The $2_2^+\rightarrow0_1^+$ and $3_1^+\rightarrow2_1^+$ are forbidden for $E2$ transition according to the O(6) selection rules, so the first two $B(E2)$ ratios in the table become 0 at O(6) limit, while the observed values are of the order 10^{-2} for both ^{116}Pd and ^{124}Xe. The $B(E2)$ ratio between the two allowed transitions from the 4_2^+ level is consistent with O(6) for ^{124}Xe. A little larger value for ^{116}Pd may arise from a possible $M1$ mixture of $4_2^+\rightarrow4_1^+$ transition. On the whole, the properties of ^{116}Pd are not in full agreement with an O(6) nucleus.

TABLE V. Deformation of even-Pd nuclei with respect to the half-life of 2_1^+ level

Nucleus	$E_\gamma(2_1^+\rightarrow0^+)$ [MeV]	$T_{1/2}$(ps)[a]	β_2[b]
^{104}Pd	0.556	9.9(5)	0.20(1)
^{106}Pd	0.512	12.1(3)	0.21(1)
^{108}Pd	0.434	23.4(6)	0.23(1)
^{110}Pd	0.374	43(3)	0.24(1)
^{112}Pd	0.349	84(14)	0.20(2)
^{114}Pd	0.333	200(60)	0.15(2)
^{116}Pd	0.340	106(30)	0.19(3)

[a] Data taken from Ref. [38].

[b] Using the equations based on the rotational model in Refs. [39,40] and the theoretical total internal conversion coefficient α_{tot} values.

TABLE VI. Comparison of some properties of ^{116}Pd and ^{124}Xe.

Quantity	^{116}Pd[a]	^{124}Xe[b]
E_{4_1}/E_{2_1}	2.58	2.48
E_{6_1}/E_{2_1}	4.58	4.37
E_{2_2}/E_{2_1}	2.17	2.39
$(E_{4_2}-E_{3_1})/E_{2_1}$	0.90	0.54
$(E_{4_2}-E_{3_1})/(E_{4_2}-E_{2_2})$	0.48	0.32
$(E_{3_1}-E_{0_2})/(E_{4_2}-E_{3_1})$	-0.14	-0.11
$B(E2;2_2^+\rightarrow0_1^+)/B(E2;2_2^+\rightarrow2_1^+)$	0.031	0.039
$B(E2;3_1^+\rightarrow2_1^+)/B(E2;3_1^+\rightarrow2_2^+)$	0.028	0.016
$B(E2;4_2^+\rightarrow4_1^+)/B(E2;4_2^+\rightarrow2_2^+)$	1.21	0.91

[a] From this work. $B(E2)$ ratios are extracted with assumption that all the transitions are pure $E2$.

[b] Data taken from Refs. [43–45].

Two β-decaying states are observed in the neutron-rich odd-odd Rh isotopes up to current ^{116}Rh. The 1^+ state decays to the low-spin states of even daughter Pd, including the 0^+ ground state and low-lying 0^+ states. The 0_2^+ level, according to Refs. [44,47], is also a signature for O(6). This level is predicted to lie at or slightly above the 3_1^+ energy at the limit. This is indeed observed from ^{110}Pd to present ^{116}Pd as displayed in Fig. 6. However, the predicted preferential decay of this level to the 2_2^+ state is observed only in some cases. From Ref. [25], a $B(E2;0_2^+\rightarrow2_2^+)/B(E2;0_2^+\rightarrow2_1^+)$ ratio of about 26 and 9 can be deduced for ^{110}Pd and ^{112}Pd, respectively. For ^{114}Pd and ^{116}Pd, this ratio can be estimated to be no more than 10 according to the experimental sensitivities. The disagreement shows again the deviation from a strict O(6) limit.

The intruder structure based on proton(hole)-pair excitation across the main shell is known to exist in $Z\approx50$ nuclei. The systematics of such intruder states has been presented for odd-A Rh, Ag [48,49], and even-even Ru, Cd [8,50]. Recently, Lhersonneau *et al.* [26] suggested such a systematics for even Pd nuclei from 106 up to 112. The minimum of energies was found to occur at ^{110}Pd, two neutrons fewer than the midshell. The excitation energies versus N exhibit a V shape and the 2^+ member is only about 300 keV higher.

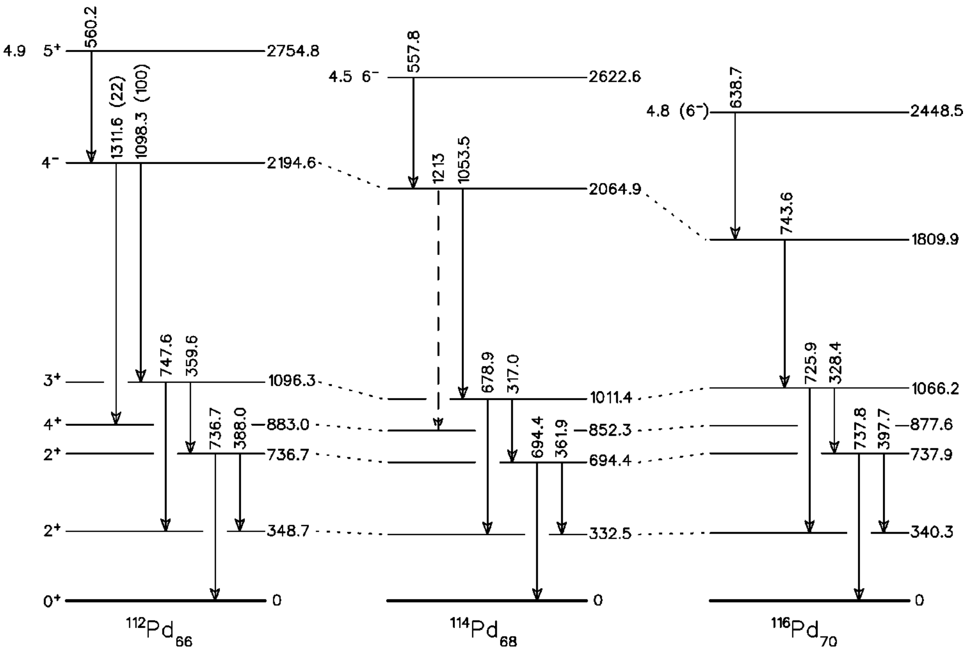

FIG. 7. Systematics of two-quasiparticle levels in even $^{112-116}$Pd strongly fed in the decay of high-spin state of Rh. Only selected transitions are shown for clarity. For less neutron-rich Pd nuclei, such a systematics can be found in Ref. [25]. See text.

In addition, the 2_3^+ levels favor the strongest transitions to 2_2^+ and 0^+ ground state, rather than to the 0_3^+ bandhead or 2_1^+. According to that, we proposed spin and parity assignments of 0_3^+, 2_3^+ to 1732.9 and 2074.1 keV levels, respectively. The very weak β feedings to these two levels hindered any detailed examination, but still one can find that our assignments of 0_3^+ and 2_3^+ follow the systematic trend very well.

Since the $\nu 1g_{7/2} \rightarrow \pi 1g_{9/2}$ GT transition is primarily responsible for the allowed β decays of neutron-rich Rh, the 1^+ Rh state could originate from the configuration of $[\pi g_{9/2} \otimes \nu g_{7/2}]_{1^+}$, which is lowered in energy with respect to other multiplet members [51]. The Rh high-spin isomer could arise from the configuration of a $g_{9/2}$ proton or $(g_{9/2})^3_{7/2}$ cluster, which is the ground state of odd Rh, coupled to a $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, or $h_{11/2}$ neutron. As the $h_{11/2}$ is the only orbital of odd parity in $N=50-82$ shell, our proposed negative parity for ^{116}Rh high-spin state can be understood as the 71st neutron fills the $h_{11/2}$ orbital in forming an isomer. The β decay of this isomer via the $\nu 1g_{7/2} \rightarrow \pi 1g_{9/2}$ GT transition would leave an odd $g_{7/2}$ neutron, which couples to the spectator neutron in the final state, resulting in the two-quasineutron states in even Pd nuclei. However, since both Rh and Pd have some deformation, this is surely an oversimplified picture. The systematics of two-quasineutron levels in even $^{112-116}$Pd is shown in Fig. 7 with $\log ft$ values. In principle, the excitation energy of a two-quasiparticle band is determined by the strength of the pairing interaction and the energies of the contributing single-particle states relative to the Fermi level. Therefore, if the nuclear deformation and the potential parameters are known, it is possible within a model description of pairing to determine the strength of the pairing interaction from the bandhead energies. Currently, an intensive investigation is being carried out to attempt the calculation for neutron-rich even Pd nuclei, by using a Monte Carlo method [52].

In conclusion, low-energy level structure of even ^{116}Pd has been explored in detail through the β decays of intense ^{116}Rh sources. The behavior of the quasi-γ band in ^{116}Pd shows some deviation from a strict O(6) limit. Unique two-quasineutron levels in even Pd disclosed in Rh high-spin isomer decays offer the probability to obtain the strength of neutron pairing interaction for these transitional nuclei. However, the lack of experimental data on excitation energies, deformation and more definite spin and parity of these Rh isomers make this work extremely challenging. Therefore, further experiments to locate these β-decaying isomers turn out to be very essential.

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