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Two-quasiparticle and collective excitations in transitional ^{108,110}Pd nuclei

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Abstract. High-spin states in ^{108,110}Pd isotopes are studied by γ-ray spectroscopy of heavy-ion–induced fission. The Pd isotopes are produced in the fission channel of the ^{31}P + ^{176}Yb reaction at beam energy 152 MeV. The prompt γ-rays are detected with the EUROBALL4 multidetector array. The yrast states of ^{108,110}Pd have been observed above the region of the first backbend. The level scheme of ^{108}Pd was extended with a new negative-parity band. The yrast sequence in ^{110}Pd is observed up to spin $I = 14^+$ and negative-parity bands have also been identified. The backbending in these even-mass Pd isotopes is associated with the alignment of the neutron $(h_{11/2})^2$ pair. The negative-parity states arise from two neutron configurations $\nu h_{11/2} \otimes \nu g_{7/2}$ and $\nu h_{11/2} \otimes \nu d_{5/2}$ and they are interpreted in the frame of two-quasiparticle + rotor model as semidecoupled bands. The observed experimental staggering in the γ-bands of ^{108,110}Pd supports the theoretical predictions for γ-instability of their shapes.

PACS. 21.60.-n Nuclear structure models and methods – 23.20.Lv γ transitions and level energies – 25.70.Jj Fusion and fusion-fission reactions – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The low-lying excitation energies and transition probabilities in even-even Pd isotopes ($A = 102$–116) display a typical behaviour of transitional nuclei with weakly developed quadrupole deformation and a trend towards γ-unstable shapes with increasing neutron number. A prolate-to-oblate shape transition has been predicted around mass 110 in the framework of the Yukawa-plus-exponential microscopic model [1]. Recent calculations of the Potential Energy Surface (PES) obtained by HF + BCS + Lipkin-Nogami procedure [2] predict for ^{106,108,110}Pd a prolate shape with increasing softness in γ and β directions and a tendency to triaxiality. The shapes and shape changes in transitional nuclei have also been investigated within different modifications of the IBA approach. Recent IBM-2 calculations of a large set of parameters of even-mass Pd nuclei have confirmed the previously suggested qualitative shape transition from anharmonic vibrator to a γ-soft rotor, *i.e.* from $SU(5)$ to $O(6)$ symmetry with increasing neutron number [3]. The experimental study of high-spin states in ^{108,110}Pd nuclei is a good test for the predictions of the above-mentioned models.

The high-spin studies of the lighter Pd isotopes ($A \leq 106$) using fusion-evaporation reactions has contributed greatly to the understanding of the collective properties of these transitional nuclei. The observation of collective bands built on the two-quasiparticle states in the even-even Pd isotopes and of decoupled $\Delta I = 2$ bands involving unique-parity states in the odd-mass palladiums supported their interpretation as weakly deformed rotors. The underlying asymmetric rotor + particle model has reproduced successfully the main features of the structure of both odd- and even-mass light palladium nuclei [4,5].

High-spin states in the heavier Pd isotopes have been investigated only recently when the large multidetector arrays became available for experiments. The level scheme of ^{108}Pd has been obtained in a fusion-evaporation reaction [6] and using deep inelastic reactions [7]. Band structures in the most neutron-rich $^{112-116}$Pd nuclei have been

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populated via spontaneous fission of ^{252}Cf [8] and heavy-ion–induced fission [9] in experiments using the highly sensitive and efficient γ-ray multidetectors Gammasphere and EUROBALL3. A very complex level scheme with many new band structures has recently been established in ^{112}Pd produced in the fusion/fission reaction ^{18}O + ^{208}Pb using the Gammasphere array [10]. The energy levels of ^{110}Pd nucleus have been obtained only from β-decay studies of ^{110}Rh [11] and only recently the yrast band has been extended up to spin 14^+ [9].

In this work we present the results on neutron-rich isotopes ^{108,110}Pd produced by heavy-ion–induced fission and studied with the EUROBALL4 multidetector array.

2 Experiment

The prompt γ-rays in the Pd isotopes were observed following their formation as fission fragments (FF) in the fusion/fission reaction ^{31}P + ^{176}Yb at 152 MeV bombarding energy. The ^{31}P projectile nuclei were accelerated by the VIVITRON accelerator at IReS, Strasbourg. A 1.5 mg/cm^2 target of ^{176}Yb was used, onto which an Au layer of 15 mg/cm^2 had been evaporated in order to stop the recoiling nuclei. γ-rays were detected with the EUROBALL4 multidetector array [12]. The spectrometer consists of 30 HP Ge detectors, 26 Clover detectors and 15 Cluster composite detectors in anti-Compton shields. The data were recorded in an event-by-event mode with the requirement that a minimum of three unsuppressed Ge detectors triggered in prompt coincidence. A total of 2.2×10^9 coincidence events were collected: 1.2×10^9 are threefold, 6×10^8 fourfold, 2.4×10^8 fivefold.

Three techniques have been used in the data analysis: i) γ-γ-γ cubes constructed by the RADWARE code package [13] for level scheme extension; ii) two-dimensional (4K $\times$ 4K) γ-γ matrices (with and without energy condition) and multiple-gated spectra constructed by the code FANTASTIC [14]; iii) single-gated spectra constructed from these matrices by the code MAT + SPEC [15] with various options for background subtraction.

The cube provides a rapid access to the data which contain γ-ray cascades from more than eighty fission fragments as well as from the strong non-fission channels of the compound nucleus (CN) ^{207}At. The relative intensities had to be obtained from high-fold events due to overlapping of transition energies belonging to different reaction products. The γ-rays of complementary fission fragments are correlated in time. Double gating on one of the FF always gives yrast transitions of its complementary FF isotopes. In some cases intense lines from the Coulomb excitation in ^{176}Yb target and its Au backing overlap with yrast transitions in the FF nucleus being studied which make the background subtraction impossible. This is the case for the 547 keV yrast transition in ^{110}Pd.

The complementary fragments of palladium isotopes in the ^{207}At fission channel are Y isotopes as proton evaporation is highly suppressed in the fission process and the fission fragments cool by neutron evaporation prior to their γ-ray de-excitation. Some Y isotopes had unknown level schemes before our previous γ-ray FF experiment where they were complementary fragments of the Rh isotopes [2]. In that experiment we used a ^{28}Si beam at an energy of 145 MeV on the same target and using the EUROGAM2 detector array. The CN in that reaction was ^{204}Po, thus the complementary FF of Pd isotopes were the Sr isotopes [16]. The non-fissioning channels of the CN mainly yielded well-known Po isotopes. This additional data set provided an important advantage for correct assignment of the new transitions in ^{108}Pd and ^{110}Pd.

The most populated nuclei in our experiment are the Mo-Tc pair of complementary FF corresponding to a symmetric fission of the odd-Z compound nucleus ^{207}At. In this experiment ^{108}Pd and ^{110}Pd are nearly equally populated which gives $\sim 10\%$ higher population for ^{108}Pd and $\sim 30\%$ for ^{110}Pd in comparison with the previous experiment [17].

The statistics in our FF γ-ray experiment were not high enough to perform angular-correlation analysis. The spin values have been tentatively assigned on the basis of already known spins of band head states, the usual assumption of increasing spin with the excitation energy for yrast population in the fission process and on the systematics.

3 Experimental results and level schemes

3.1 The nucleus ^{108}Pd

The high-spin states in ^{108}Pd have recently been studied via charged-particle γ coincidences [6] and using a deep inelastic reaction [7]. The yrast band was observed up to $I^\pi = 16^+$ and the even-parity sideband up to $I^\pi = (14^+)$. A negative-parity band starting at the 2324 keV level has been established to $I^\pi = (13^-)$. The low-spin members of the γ-band have been studied by heavy-ion Coulomb excitation [18].

The level scheme of ^{108}Pd obtained from our analysis is presented in fig. 1. The transition energies and their intensities relative to the intensity of the 723 keV transition are presented in table 1 and indicated in the level scheme by the thickness of the vertical arrows. Coincidence spectra supporting the new extension of the level scheme are shown in fig. 2.

The yrast sequence is confirmed up to $I^\pi = (16^+)$ as well as the positive- and negative-parity sidebands. We extended the negative-parity states with another sequence decaying to the 6^+ yrast state via a transition of 938 keV. This band was observed up to $I^\pi = (12^-)$. Two links $8^- \to 7^-$ and $6^- \to 5^-$ to the previously observed negative-parity band have been found. A linking transition $8^- \to 7^-$ of 258 keV from the 3100 keV level to a level decaying to the 6^+ yrast state via a 1071 keV transition has also been found. Our coincidences data allowed for a tentative placement of the $(14^+) \to (12^+)$ transition of 818 keV in the positive-parity sideband. The level at 2397 keV proposed in refs. [6,7] as the lowest 8^+ one is not confirmed by our data. The 627 keV transition which was placed to connect this level to the yrast 6^+ state at

Table 1. Transitions identified in ^{108}Pd.

Energy	$I_i \rightarrow I_f$	E_i	Intensity
257.5(5)	$(8^-) \rightarrow (7^-)$	3100.0	2(1)
286.9(4)	$(3^+) \rightarrow (4^+)$	1335.3	4(1)
327.7(5)	$(8^-) \rightarrow 7^-$	3089.0	3(1)
338.7(5)	$(8^-) \rightarrow 7^-$	3100.0	3(1)
385.2(5)	$(6^-) \rightarrow 5^-$	2709.5	< 1
390.5(3)	$(8^-) \rightarrow (6^-)$	3100.0	4(1)
404.1(3)	$(3^+) \rightarrow 2^+$	1335.3	18(2)
434.0	$2^+ \rightarrow 0^+$	434.0	
437.0(5)	$7^- \rightarrow 5^-$	2761.3	3(1)
497.2(3)	$2^+ \rightarrow 2^+$	931.2	23(1)
518.7(4)	$(9^-) \rightarrow 7^-$	3280.0	9(1)
541.1(3)	$12^+ \rightarrow 10^+$	3798.2	15(1)
576.1(5)	$(4^+) \rightarrow 4^+$	1624.5	7(1)
581.2(3)	$(5,6) \rightarrow (4,5)$	2863.9	26(2)
614.4(2)	$4^+ \rightarrow 2^+$	1048.4	135(5)
626.7(4)	$(10^-) \rightarrow (8^-)$	3726.7	3(1)
634.8(5)	$(6^+) \rightarrow (4^+)$	2259.3	2(1)
683.5(2)	$(11^-) \rightarrow (9^-)$	3963.5	4.5(10)
693.3(5)	$(4^+) \rightarrow 2^+$	1624.5	20(2)
694 (6)	$(8^+) \rightarrow (6^+)$	2953.3	~ 1
703.5(5)	$(10^-) \rightarrow (8^-)$	3792.5	2(1)
708.4(3)	$10^+ \rightarrow 8^+$	3257.1	21(1)
723.0(2)	$6^+ \rightarrow 4^+$	1771.5	100
748.0(3)	$(5^+) \rightarrow (3^+)$	2083.3	4(1)
765.0(3)	$(12^-) \rightarrow (10^-)$	4491.7	3(1)
777.2(2)	$8^+ \rightarrow 6^+$	2548.7	42(1)
802.2(3)	$10^+ \rightarrow 8^+$	3350.9	11(1)
807.8(3)	$(12^+) \rightarrow 10^+$	4158.7	5(1)
813.4(4)	$(13^-) \rightarrow (11^-)$	4777.9	< 1
818 (6)	$(14^+) \rightarrow (12^+)$	4971.7	< 1
843.3(3)	$14^+ \rightarrow 12^+$	4641.5	5(1)
901.3(3)	$(3^+) \rightarrow 2^+$	1335.3	23(1)
931.2	$2^+ \rightarrow 0^+$	931.2	10(2)
938.0(5)	$(6^-) \rightarrow 6^+$	2709.5	4(1)
947.4(3)	$(4,5) \rightarrow (3^+)$	2282.7	36(2)
989.8(4)	$7^- \rightarrow 6^+$	2761.3	24(1)
1048.0(5)	$(16^+) \rightarrow 14^+$	5689.5	2(1)
1071.0(4)	$(7^-) \rightarrow 6^+$	2842.5	7(1)
1092.4(5)	$(5,6) \rightarrow 6^+$	2863.9	3(1)
1234.3(4)	$(4,5) \rightarrow 4^+$	2282.7	7(2)
1275.9(3)	$5^- \rightarrow 4^+$	2324.3	14(1)

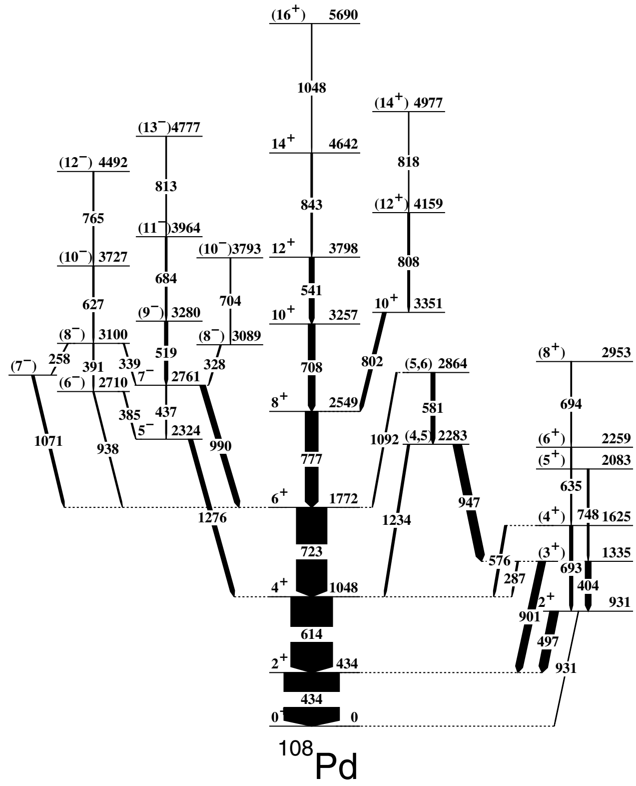

Fig. 1. Level scheme of ^{108}Pd.

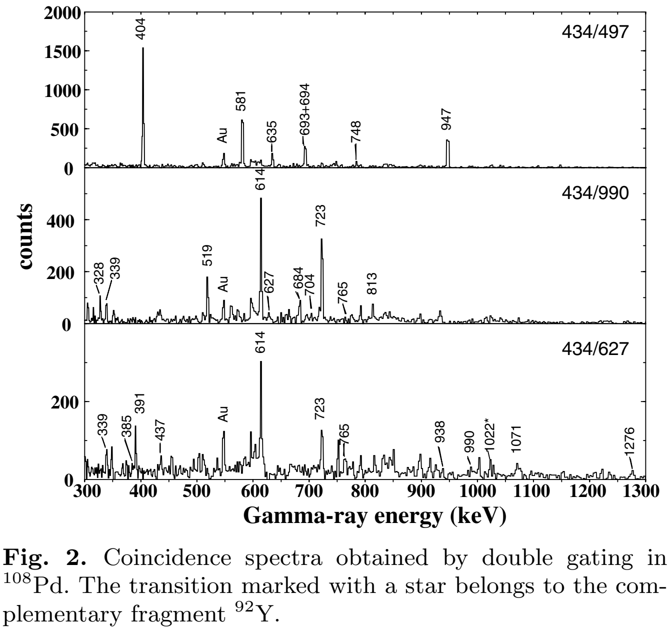

Fig. 2. Coincidence spectra obtained by double gating in ^{108}Pd. The transition marked with a star belongs to the complementary fragment ^{92}Y.

1772 keV is in fact a member of a new sequence based on the 2710 keV state. As can be seen from fig. 1, the band at 2710 keV level has a complex depopulation pattern which resolves the intensity disbalance reported in ref. [6].

We suggest this band to be the strong even-spin negative-parity sequence (see fig. 1) in analogy to a similar band in ^{106}Pd [19] . Another band fragment feeding into the 7^- level of the odd-spin negative-parity sideband is observed which also has its counterpart in ^{106}Pd as the second (weaker) even-spin negative-parity band.

The γ-band was extended above the known 2^+, 3^+ and 4^+ levels [20,21] up to the 5^+ and 8^+ states. The levels at 2864 and 2283 keV are known from the decay of the high-spin isomer in ^{108}Rh [20]. The former level is populated via a strong β^--branch with $\log ft = 4.7$. It decays by several transitions to the lower-lying levels. We observed the strongest one of 581 keV to the 2283 keV level and the weaker 1092 keV transition to the 6^+ ground-band state. The level at 2283 keV has no direct β-feeding. Analogous pairs of states are known also in heavier Pd nuclei ($A =$ 110–116) from β-decay studies [11]. We observe them in ^{108,110}Pd in the fission process (see also sect. 3.2).

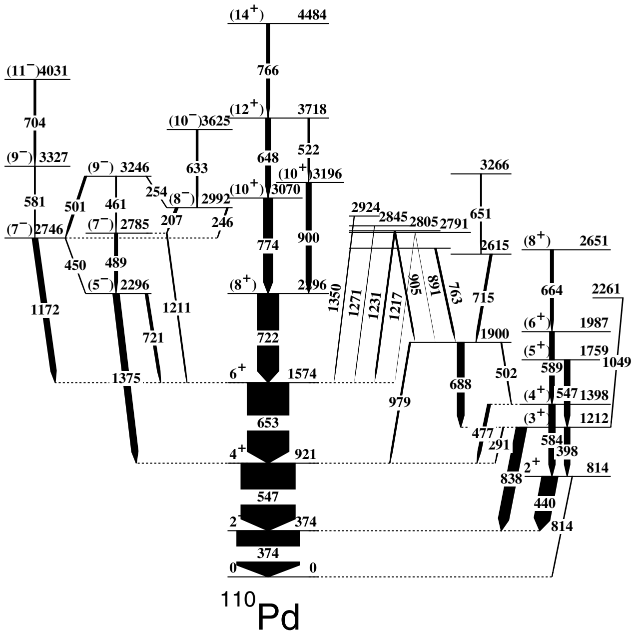

Fig. 3. Level scheme of ^{110}Pd.

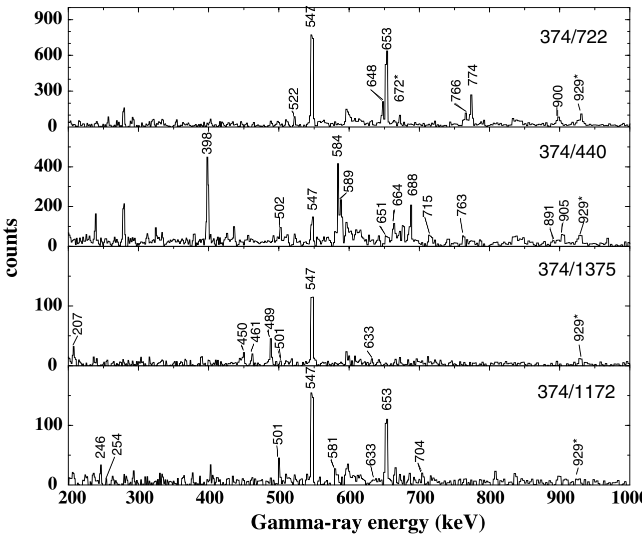

Fig. 4. Coincidence spectra obtained by double gating in ^{110}Pd. The transitions marked with a star belong to the complementary fragment ^{91}Y.

3.2 The nucleus ^{110}Pd

The low-spin states in ^{110}Pd have been populated by Coulomb excitation [21] and in the radioactive decay of ^{110}Rh [11]. The yrast band has been seen up to 6^+ and the γ-band to 4^+ levels. Negative-parity states have been excited in inelastic scattering [22] and the level 5^- at 2295 keV has been identified. A detailed level scheme was established recently in an extensive γ-ray study of the ^{110}Rh β-decay [23]. In a previous heavy-ion–induced fission experiment the yrast band was observed up to spin 14^+ [9].

The level scheme of ^{110}Pd obtained from our analysis is presented in fig. 3. Examples of coincidence spectra are shown in fig. 4 and the transition energies and their intensities relative to the 653 keV yrast transition are listed in table 2.

In the present work the yrast positive-parity band is observed up to $I^\pi = (14^+)$ beyond the first backbend in agreement with ref. [9] and a decay of the 12^+ state to the (10_2^+) state at 3196 keV has been identified. The quasi-γ–band is extended above the known 3^+ and 4^+ members up to the 5^+ and 8^+ levels.

Table 2. Transitions identified in ^{110}Pd.

Energy	$I_i \rightarrow I_f$	E_i	Intensity
207.2(4)	$(8^-) \rightarrow (7^-)$	2991.7	5(1)
246.1(5)	$(8^-) \rightarrow (7^-)$	2991.7	3(1)
254.5(6)	$(9^-) \rightarrow (8^-)$	3246.1	< 1
291.1(5)	$(3^+) \rightarrow 4^+$	1212.0	2(1)
373.8	$2^+ \rightarrow 0^+$	373.8	
398.4(3)	$(3^+) \rightarrow 2^+$	1212.0	16(1)
439.8(3)	$2^+ \rightarrow 2^+$	813.6	38(1)
450.0(6)	$(7^-) \rightarrow (5^-)$	2745.6	<1
461.6(5)	$(9^-) \rightarrow (7^-)$	3246.1	2(1)
477.1(5)	$(4^+) \rightarrow 4^+$	1398.0	7(1)
488.9(3)	$(7^-) \rightarrow (5^-)$	2784.5	7(1)
500.5(4)	$(9^-) \rightarrow (7^-)$	3246.1	5(1)
502.0(5)	$(?) \rightarrow (4^+)$	1900.0	2.5(10)
522.3(4)	$(12^+) \rightarrow (10^+)$	3718.2	4(1)
547.1(3)	$4^+ \rightarrow 2^+$	920.9	140(10)
547.2(3)	$(5^+) \rightarrow (3^+)$	1759.2	19(2)
581.4(5)	$(9^-) \rightarrow (7^-)$	3327.0	2(1)
584.4(3)	$(4^+) \rightarrow 2^+$	1398.0	19(1)
589.0(3)	$(6^+) \rightarrow (4^+)$	1987.0	11(1)
647.9(3)	$(12^+) \rightarrow (10^+)$	3718.2	11(1)
632.5(4)	$(10^-) \rightarrow (8^-)$	3624.2	4(1)
651.0(5)	$(?) \rightarrow (?)$	3265.8	2.5(10)
653.2(2)	$6^+ \rightarrow 4^+$	1574.1	100
663.5(3)	$(8^+) \rightarrow (6^+)$	2650.5	9(1)
688.0(3)	$(?) \rightarrow (3^+)$	1900.0	20(1)
704.2(3)	$(11^-) \rightarrow (9^-)$	4031.0	4(1)
714.8(3)	$(?) \rightarrow (?)$	2614.8	6(1)
721.5(5)	$(5^-) \rightarrow 6^+$	2295.6	5(1)
722.2(4)	$(8^+) \rightarrow 6^+$	2296.3	52(2)
762.6(4)	$(?) \rightarrow (?)$	2662.6	6(1)
766.0(4)	$(14^+) \rightarrow (12^+)$	4484.2	7(1)
774.0(3)	$(10^+) \rightarrow (8^+)$	3070.3	22(1)
813.6(4)	$2^+ \rightarrow 0^+$	813.6	8(2)
838.2(4)	$(3^+) \rightarrow 2^+$	1212.0	25(1)
890.6(5)	$(?) \rightarrow (?)$	2790.6	~ 1
899.6(3)	$(10^+) \rightarrow (8^+)$	3195.9	10(1)
905.0(5)	$(?) \rightarrow (?)$	2805.0	6(1)
979.1(4)	$(?) \rightarrow 4^+$	1900.0	3(1)
1049.0(5)	$(?) \rightarrow 3^+$	2261.0	< 1
1171.5(3)	$(7^-) \rightarrow 6^+$	2745.6	13(1)
1210.7(5)	$(7^-) \rightarrow 6^+$	2784.5	2(1)
1216.5(5)	$(?) \rightarrow 6^+$	2790.6	< 1
1230.9(5)	$(?) \rightarrow 6^+$	2805.0	5(1)
1271.3(6)	$(?) \rightarrow 6^+$	2845.4	2(1)
1349.8(6)	$(?) \rightarrow 6^+$	2923.9	3(1)
1374.7(5)	$(5^-) \rightarrow 4^+$	2295.6	15(1)

A new structure, similar to the negative-parity bands observed in ^{112}Pd [10], has been identified. The feeding to the 4^+ and 6^+ ground band via strong 1375 keV and 1172 keV transitions, respectively, favours an assignment of 5^- for the 2296 keV level and 7^- for the 2746 keV level in analogy with ^{108}Pd. Two levels at energies 2296 keV and 2785 keV populated by 489 keV/461 keV sequential γ-rays feed the ground band via a high-intensity γ-ray of 1375 keV. The level of 2746 keV is fed by two consecutive transitions of energies 581 keV and 704 keV. We also observed a relatively strong 1211 keV transition linking the level at 2785 keV, tentatively 7^- with the yrast 6^+ level. The new level at 2992 keV seems to be the head of a new band beginning with a 633 keV transition. Two transitions of 207 keV and 254 keV connect this level with the negative-parity levels of 2785 keV and 3246 keV, respectively. The levels at 2992 keV and at 2746 keV are connected by a weak transition of 246 keV. Two linking transitions of 501 keV and 450 keV to another structure based on the level at 2746 keV have also been found.

The levels at 2791 and 2805 keV are known from the β-decay of ^{110}Rh [11]. These levels are populated by almost equally strong β-branches with log*ft* 4.8 and 5.1, respectively. Their γ-decay branch to the level at 1900 keV is observed in our data (the γ-rays 891 and 905 keV) as well as their linking transitions to the 6^+ yrast level (the 1217 and 1231 keV). We observed several new transitions: the γ-rays of 1271 keV and 1350 keV de-exciting the levels at 2845 keV and 2924 keV to the 6^+ yrast level are not observed in β-decay [23]. Two new transitions of 763 keV and 651 keV were also identified. The first one de-excites the level at 2663 keV to the 1900 keV level. The second one originates from a level above the 2615 keV level cascading via 651 keV and 715 keV transitions to the level at 1900 keV.

4 Discussion

4.1 Even-parity bands

4.1.1 Yrast band systematics

The nuclei in the region $42 \leq Z \leq 48$ exhibit a variety of shapes. Addition or subtraction of few nucleons may significantly change the nuclear deformation as in the case of $_{42}$Mo [24], whose energy level $E(2^+)$ decreases from 778 keV for the spherical ^{96}Mo nucleus to 172 keV for ^{106}Mo, a nucleus with a strong prolate deformation ($\beta_2 \sim 0.3$–0.4). This effect is less pronounced in the $_{44}$Ru isotope chain, where the $E(2^+)$ level decreases from 540 keV for ^{100}Ru to 237 keV for ^{112}Ru.

The neutron-deficient Pd isotopes are nearly good vibrators, while the neutron-rich Pd isotopes exhibit nearly $O(6)$ γ-soft behaviour. The experimental excitation ratio $E(4^+)/E(2^+)$ is 2.42 for ^{108}Pd and 2.46 for ^{110}Pd, which is very close to the predicted by IBM-2 value of 2.5 for an $O(6)$ nucleus. The $E(6^+)/E(2^+)$ ratio is 4.08 for ^{108}Pd and 4.21 for ^{110}Pd, which is again between the values for a harmonic vibrator and a rotor. In fact, these values are close to the IBM-2 value for an $O(6)$ nucleus (~ 4.5). The $O(6)$ limit of IBM-2 corresponds to Wilets-Jean's γ-soft rotor [25] which has exactly the same level structure. These models predict a level spacing intermediate between vibrational and rotational spectra.

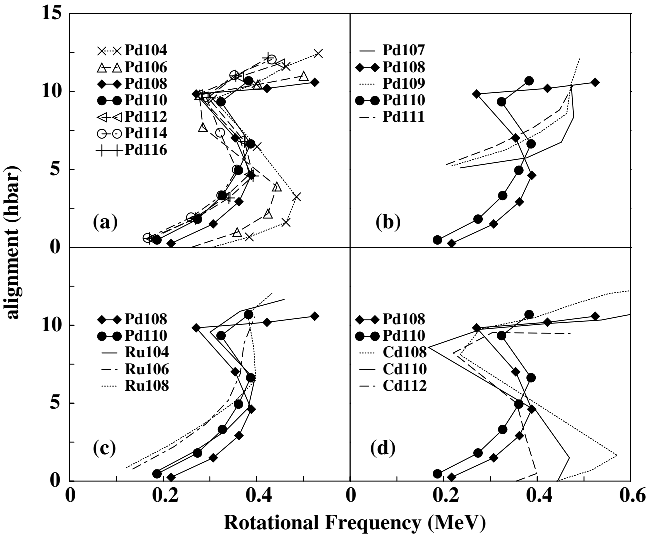

Fig. 5. The experimental alignments for positive-parity bands in ^{108}Pd and ^{110}Pd compared with even and odd Pd isotopes and with their Ru and Cd even-A isotones.

The quasirotational behaviour of ^{108}Pd continues up to spin $I = 8^+$ where the yrast band is crossed by a sequence of transitions having purely vibrational character. The same structure was observed in ^{112}Pd (band 8 [10]) and ^{110}Cd (band 18 [26]) where a two-quasiparticle configuration ($(\nu h_{11/2})^2$ or $(\pi g_{9/2})^2$) is expected. The existence of these vibrational bands in the neighbours of ^{110}Pd (^{108}Pd, ^{112}Pd and ^{110}Cd) probably indicates that the observed splitting of the level 10^+ in ^{110}Pd is due to the coupling of vibrational motion to the two-quasiparticle configuration $(\nu h_{11/2})^2$.

The rotational properties of ^{108,110}Pd can be understood by exploring their experimental alignments of the yrast band as a function of the rotational frequency. The experimental alignments are calculated following the procedure prescribed by Bengtsson and Frauendorf [27]. The Harris parameters $J_0 = 5\hbar^2$/MeV and $J_1 = 16\hbar^4$/MeV^3 have been chosen in such a way that the yrast sequence has constant alignment after the first crossing.

The experimental alignments of many Pd isotopes as well as for some even-A Ru and Cd isotopes are presented in fig. 5. The comparison between even Pd isotopes ($A =$ 104–116) (fig. 5(a)) shows that they all gain alignment of $10\hbar$ which indicates that the $\nu h_{11/2}$ pair is broken and both neutrons align their spins along the rotational axis, which is consistent with the Cranked-HFB calculations performed in ref. [9].

The comparison of alignments in odd [28] and even palladium nuclei (fig. 5(b)) shows that the backbending in the odd Pd is delayed with respect to that of the even ones. The band-crossing of ^{108}Pd and ^{110}Pd is observed at frequency ~ 0.35 MeV and that of the odd palladium isotopes is at ~ 0.5 MeV. The unpaired neutron blocks its orbital, so this delay is a good indication that the backbending is due to a neutron pair breaking.

The value of the alignment for Pd isotopes before the band-crossing increases with neutron number (see fig. 5(a)). Such behaviour in Ru isotopes was also observed and was explained with the increase of the nuclear deformation from $N = 58$ to $N = 64$ [17]. The alignment before the first backbend decreases with Z approaching the $Z = 50$ shell. One can see in fig. 5(c, d) that before the backbending the highest alignment value is in the Ru ($Z = 44$) isotones. The alignments of Pd and Cd isotopes have similar behaviour after the first band-crossing which might be explained by similar shapes for these nuclei at high energies.

4.1.2 γ-band systematics

Both ^{108}Pd and ^{110}Pd have a strongly populated quasi-γ–band like the heavier Pd isotopes. The γ-band is not as well developed in lighter palladium isotopes ^{102,104,106}Pd as it is in the heavier.

The systematics of the γ-band level energies in several even Pd and Ru isotopes is presented in fig. 6. One can deduce from these systematics the following:

i) the energy of the γ-band 2^+ level decreases with neutron number (N) from 1128 keV for ^{106}Pd to 695 keV for ^{114}Pd$_{68}$, after $N = 68$ it increases. In the case of Ru isotopes it decreases from 893 keV for ^{104}Ru to 524 keV for ^{112}Ru$_{68}$. Again after $N = 68$ it increases;

ii) the 2^+ level energy of the γ-band in Ru isotopes is below the energy of the 2^+ level in their respective Pd isotones. The higher-spin levels have the same behaviour;

iii) the even-spin levels in the γ-band are depressed with respect to the odd-spin levels (staggering effect) for all Ru and Pd nuclei;

iv) the energy of transitions between states with even spin increases with the angular momentum (with exception of ^{104}Ru, ^{108}Pd and ^{112}Pd);

v) the energy of transitions between states with odd spin in the Ru isotopic chain increases with the angular momentum. ^{112}Pd, ^{114}Pd and ^{116}Pd show irregular behaviour above the 7^+ level in the odd-spin sequence of the γ-band.

The decrease in energy of the γ-band levels in the Pd isotopic chain might be explained by increasing the degree of collectivity. The systematics show that it increases from ^{102}Pd to ^{114}Pd. The heaviest known Pd nuclei are 116 and 118 [30]. Their 2^+_2 levels have energies of 738 keV and 813 keV, respectively. So, the γ-band level energy starts to increase again. The Ru isotopes, for which the proton filling is deeper below the $Z = 50$ closed shell than Pd isotopes, have γ-band levels lower in energy than their respective Pd isotones.

Two geometrical models accounting for deviation from axial symmetry show spectra with $2^+, 3^+, 4^+$ etc. level sequence: the static model of Davidov [31], and the dynamic model of Wilets and Jean. The first one reproduces

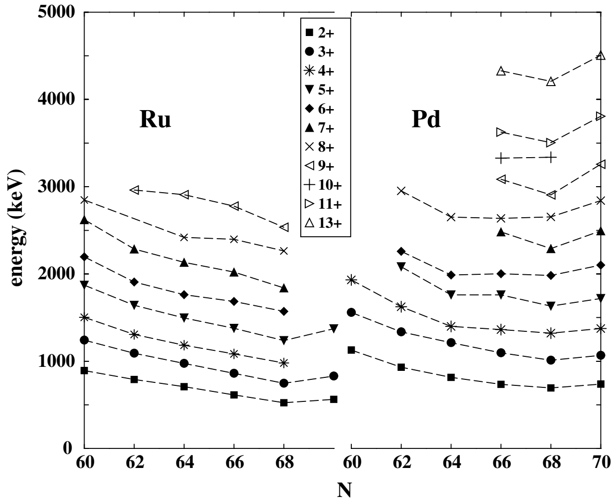

Fig. 6. Gamma-bands systematics in several Ru and Pd isotopes. The data for ^{108,110,112}Ru isotopes is taken from [29].

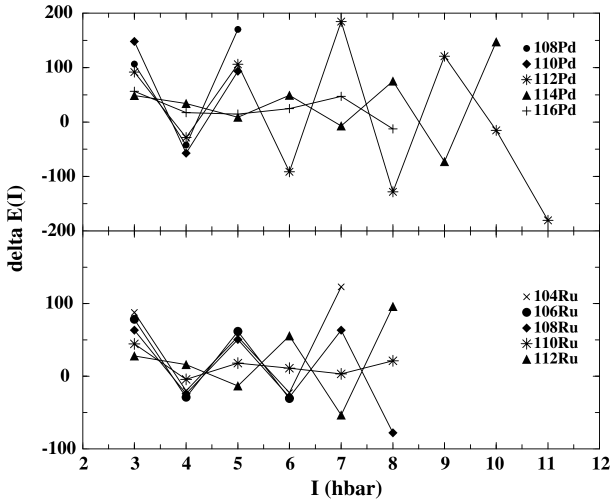

Fig. 7. Odd-even staggering in some Pd and Ru isotopes as a function of spin.

the low-lying states 2^+_1, 2^+_2 and 3^+_1 well but it cannot reproduce the higher-energy levels. The levels of the γ-band in Davidov's model are grouped in doublets $(2^+, 3^+)$, $(4^+, 5^+)$. In contrast to this model, the γ-soft model of Wilets and Jean shows a different behaviour —the levels are grouped in doublets: $(3^+, 4^+)$, $(5^+, 6^+)$. Consequently, one could distinguish these models by the staggering effect. The third point of the above-mentioned systematics perhaps indicates that Pd nuclei are γ-soft rather than rigid triaxial rotors.

The odd-even staggering can be expressed quantitatively by the formula

$$\delta E(I) = E(I) - \frac{\{(I+1)E(I-1) + IE(I+1)\}}{2I+1} \quad (1)$$

given by Bonatsos [32] and shown in fig. 7 for some Pd and Ru isotopes. The IBM model predicts a strong odd-even

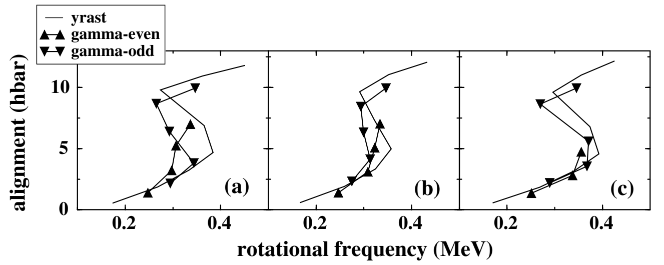

Fig. 8. Experimental alignment in yrast and γ bands in ^{112}Pd (a), ^{114}Pd (b) and ^{116}Pd (c) nuclei (the odd and even sequences of the γ-bands are shown separately). The same Harris parameters were used as for the yrast bands.

staggering in $U(5)$ vibrational and $O(6)$ (γ-unstable) limits and no staggering in the $SU(3)$ limit.

^{108,110,112}Pd show a large displacement of the odd-spin levels with respect to their even-spin neighbours (see fig. 7). The staggering effect decreases with neutron number and ^{114,116}Pd isotopes do not show staggering at low spins but it appears at higher spins $I > 5\hbar$. The staggering amplitude in Ru isotopes is lower than that in Pd isotopic chain. If we follow the IBM predictions this comparison means that ^{114,116}Pd are not so soft as ^{108,110,112}Pd nuclei and that Pd isotopes are softer than Ru isotopes.

As can be seen in fig. 8, the irregular behaviour of odd-spin levels of the γ-bands in ^{112,114,116}Pd can be explained by the backbending effect. The band-crossing in a γ-band occurs earlier than the band-crossing between the ground-state band (g.s.b.) and the s-band, due to the fact that g.s.b. is below the γ-band. The alignment plots of yrast and γ bands have similar behaviour after the band-crossing. Therefore, we could propose that both g.s.b. and γ-bands are crossed by the same s-band, associated with the γ-vibrational motion imposed on the $(\nu h_{11/2})^2$ configuration.

In spite of the fact that we have not enough statistics to extend the γ-bands in ^{108,110}Pd nuclei up to the region of the band-crossing, we could expect by analogy with the heavier Pd isotopes that they show a backbending at the same frequency as the backbending in the yrast bands.

4.2 Negative-parity bands systematics

At least two strong negative-parity bands with odd and even spins are known in a number of Ru, Pd and Cd isotopes. The interpretation of such a structure in ^{104}Pd as a semidecoupled band was given by Flaum and Cline [4] in the framework of the two-quasiparticle + rotor model.

This description was successfully applied in several Ru, Pd and Cd isotopes [17,6,9].

Recent HFB calculations for $^{100-108}$Ru [17] indicate that the lowest two-quasineutron states are expected at an excitation energy around 2 MeV. The neutron Fermi level is predicted to lie between the positive-parity orbitals $d_{5/2}$ and $g_{7/2}$ and between the $\Omega = 3/2^-$ and $5/2^-$ levels of the $\nu h_{11/2}$ shell.

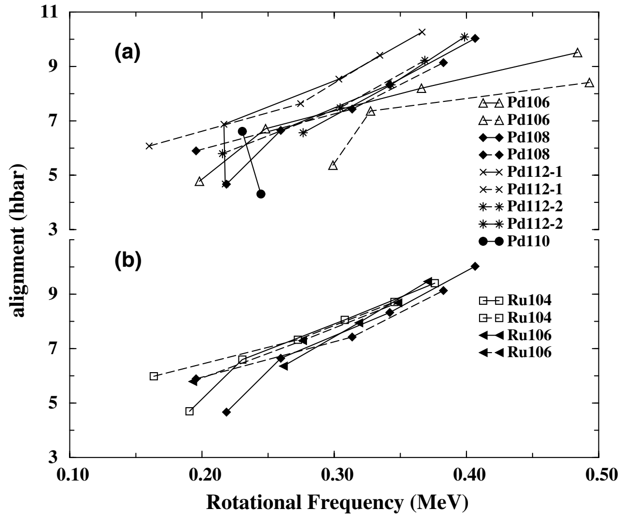

Fig. 9. The experimental alignments for negative-parity bands in several Pd and Ru isotopes. The long-dashed lines correspond to odd-spin states and the solid lines to even-spin states. Pd112-1 corresponds to band 3 and 4 and Pd112-2 corresponds to bands 5 and 6 from ref. [10].

The predicted deformation of $\beta_2 \sim 0.2$ for both Pd isotopes indicates that the neutron Fermi surface is inside the same orbitals as in $^{100-108}$Ru, which is consistent with the interpretation of the low-lying states in ^{107}Pd given by Pohl *et al.* [6] as based on Nilsson $3/2^+[411]$ and $5/2^+[413]$ orbitals. In the framework of the model of Flaum and Cline the negative-parity band in ^{108}Pd could be explained as based on two neutron configurations $\nu h_{11/2} \otimes \nu g_{7/2}$ and $\nu h_{11/2} \otimes \nu d_{5/2}$, where the low-$\Omega$ quasineutron from $h_{11/2}$ is rotation aligned and the $\{g_{7/2}$ or $d_{5/2}\}$ neutron is deformation aligned. If both neutrons were completely aligned, then the $\nu h_{11/2} \otimes \nu g_{7/2}$ and $\nu h_{11/2} \otimes \nu d_{5/2}$ configurations would give bands with band head spin values 8^- and 9^-, respectively. The band members below these states at 6^-, 7^- and 5^- indicate that these states are built on non-completely aligned neutron quasiparticles, which is consistent with the change of the slope of the negative-parity band alignments in ^{108}Pd (fig. 9).

Figure 9 illustrates the negative-parity alignments for ^{108,110}Pd and their neighbouring nuclei: all Pd isotopes (a) and comparison of ^{108}Pd with ^{104}Ru and ^{106}Ru (b). The alignment plots for ^{108}Pd and ^{112}Pd (bands 5 and 6) coincide with the alignments for the negative-parity bands in ^{104}Ru and ^{106}Ru.

All these alignments start at a value of $5\hbar$ and no crossing is observed at $\hbar\omega \sim 0.35$, as was for the yrast band, due to the blocking effect of one of the neutrons. This indicates that the negative-parity bands in ^{108}Pd are based on $\nu h_{11/2} \otimes \nu g_{7/2}$ and $\nu h_{11/2} \otimes \nu d_{5/2}$ configurations, as is in ^{104}Ru and ^{106}Ru.

Four negative-parity bands in ^{112}Pd [10] are known —two strongly coupled bands with no signature splitting (bands 3 and 4) and other two bands (5 and 6) with an increasing signature splitting at higher rotational frequencies. The total Routhian surface calculations based on

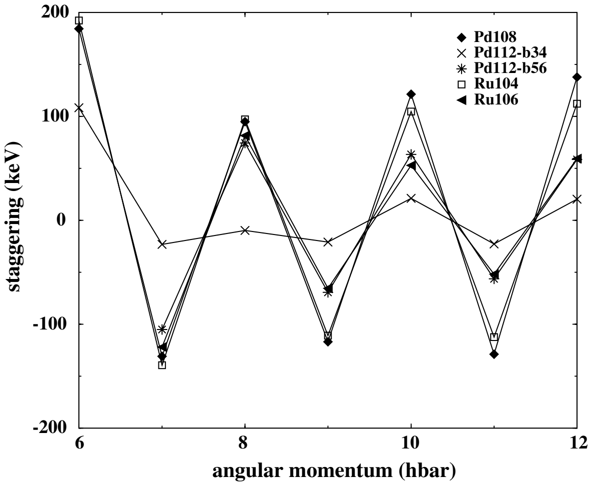

Fig. 10. $\Delta I = 1$ staggering in the negative-parity bands in some Pd and Ru isotopes.

Woods-Saxon potential performed in ref. [10] suggest a $\nu h_{11/2} \otimes g_{7/2}$ or $\nu h_{11/2} \otimes d_{5/2}$ configuration for the first structure and a $\nu h_{11/2} \otimes s_{1/2}$ or $\nu h_{11/2} \otimes d_{3/2}$ for the second, which is in contradiction with the observed alignment plots shown in fig. 9. The curves for ^{108}Pd and ^{112}Pd (bands 5 and 6) show a similar behaviour after the alignment of both quasiparticles which would not be the case if both bands (in ^{108}Pd and ^{112}Pd) arose from different quasiparticle configurations. We can propose that these bands are based on a $\nu h_{11/2} \otimes g_{7/2}$ or $\nu h_{11/2} \otimes d_{5/2}$ configuration as the $s_{1/2}$ orbit lies too high to be involved.

The splitting can be measured quantitatively by using the Bonatsos formula for the staggering effect (see fig. 10). It seems that the splitting in bands $(5, 6)$ in ^{112}Pd is the same as in ^{106}Ru and it is very near to the behaviour of ^{108}Pd and ^{104}Ru nuclei. This large signature splitting indicates large Coriolis interaction which means that the negative-parity bands in ^{104,106}Ru and of the ^{108}Pd are built on a high-j low-Ω configuration, which is consistent with the interpretation in the framework of $\nu h_{11/2} \otimes g_{7/2}$ or $\nu h_{11/2} \otimes d_{5/2}$ based configuration.

5 Summary

Twelve new transitions in ^{108}Pd and more than 15 new transitions in ^{110}Pd have been identified from the γ-ray data analysis of fission fragments obtained in heavy-ion–induced fission. A new negative-parity band was found in ^{108}Pd with two linking transitions to the previously known negative-parity band. A new cascade of two transitions parallel to the yrast band in ^{110}Pd has been placed in the level scheme, a similar structure to that in ^{104}Ru [17]. It was possible to put the majority of the new transitions in new negative-parity bands interpreted as semidecoupled two-quasineutron bands similar to those in Ru isotopes. The general trend of the γ-bands in Ru and Pd nuclei indicates a large deviation from axial symmetry of their shapes. The observed band-crossing in the γ-bands of heavier Pd isotopes may indicate that after the back-bending the γ-instability of their shapes remains.

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