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Decay of ^{114}Rh to ^{114}Pd

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The decay of on-line mass-separated ^{114}Rh has been studied by γ spectroscopy. A definite odd parity and a probable $I=7$ are deduced for the high-spin β-decaying level. The 1116 keV and 1392 keV levels in the ^{114}Pd daughter nucleus are candidates for the bottom of the β band. There is no support for a previously reported very-low-lying 0^+ level at 871 keV. A $K=4$ band built on the new level at 1639 keV is proposed. The lowest-lying two-quasiparticle levels in ^{114}Pd are calculated in the framework of the quantum Monte Carlo pairing model using deformed shell model states. The lowest configurations are associated with an oblate minimum of the potential energy.

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I. INTRODUCTION

Neutron-rich palladium isotopes have an interesting structure representing a transition between the closed-shell Sn region and the Sr region of very large axial deformations. This transition occurs via triaxiality in Ru isotopes, the lower-Z even neighbors of Pd [1–6]. A systematic calculation of the properties of even-even palladium isotopes was made in the IBA-2 framework by Kim *et al.* in which their structure was reproduced by mixing the vibrational and gamma-soft symmetries [7]. In addition, a number of theoretical works were published recently, dealing with equilibrium deformation and yrast-band properties [2,8–12].

The first systematic experiments on even-even neutron-rich Pd isotopes were performed by Äystö *et al.* using β decay of their rhodium parents produced by proton-induced fission of uranium and on-line mass separated with the ion-guide technique [13]. The improvements in experimental conditions a few years ago made more detailed studies of these decays possible. Thus, new level schemes of ^{110}Pd, ^{112}Pd [14,15], and ^{116}Pd [16] are now available. Moreover, the decay of ^{118}Rh to ^{118}Pd was identified [17] and a comprehensive study of it is in progress [18]. In addition, prompt γ spectroscopy has been carried out by several groups using spontaneous or heavy-ion-induced fission to produce very-neutron-rich Pd isotopes [19–25], reaching as far from stability as ^{118}Pd.

In even-even Pd isotopes two pairs of low-lying 0^+ and 2^+ states are of special interest. These states have been firmly identified owing to extensive Coulomb excitation studies by Svensson *et al.* until ^{110}Pd [26,27] and γ-γ angular correlations following ^{112}Rh decay [28]. Candidates in heavier Pd isotopes have been proposed [13,16]. A pair of 0^+, 2^+ levels smoothly follows the trend of excitation energies of collective levels with neutron number, while another one moves rapidly in energy with a sharp minimum near the $N=66$ midshell. (Actually, the lowest 0^+ is observed in ^{110}Pd, i.e., at $N=64$.) The analogy with the even-even Cd neighbors suggests the presence of intruder states treated as proton-pair excitations across the $Z=50$ shell gap [29–31]. According to an extrapolation of the energy systematics, 0^+ states are expected in ^{114}Pd near 1.1 and 1.4 MeV, respectively. The candidates proposed in Ref. [13] are levels at 871 and 1116 keV. The lowest of them is thus in discrepancy with the new data.

In addition, it is well known that some of the two-quasiparticle states can be easily identified owing to their strong feeding in β decay. They provide a tool to study the pairing interaction as shown by Capote *et al.* for very-deformed neutron-rich $A\simeq 100$ nuclei [32]. Finally, from the feeding pattern some information on the higher-spin β-decaying level of ^{114}Rh postulated in Ref. [13] is expected to be gained.

These considerations formed the motivation to reinvestigate the ^{114}Rh decay. The β decay of the 1^+ state offers the opportunity to reach low-spin levels, like the 0^+ and 2^+ states mentioned above, whereas levels with spin values of about 6 are expected to be populated in the β decay of the other state. The identification is facilitated by the data recently obtained by prompt fission where spin and parity assignments are reported for numerous ^{114}Pd levels. Thus we make extensive use of the work by Butler-Moore *et al.* [22].

II. EXPERIMENT

The experiment was similar to the one performed one decade ago at the ion-guide-based isotope separator (IGISOL) in Jyväskylä [13]. However, it benefitted from production yields improved by two orders of magnitude after the upgrade of the facility [33–35] and the availability of larger-volume Ge detectors. In short, the fission products were obtained by bombarding a natural uranium target with 25 MeV protons with a typical beam intensity of 10 μA. The A

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TABLE I. Experimental β-decay half-lives obtained from the strongest transitions in ^{114}Rh decay deduced from a fit with a single component (including transitions known to be complex). The last column shows the average value using several transitions from the currently listed ^{114}Pd level.

Level Energy [keV]	I^{π}	Transition Energy [keV]	Half-life [s]	Average or comments
333	2^+	333	1.83 (4)	mixed
695	2^+	362	1.84 (9)	1.80 (8) mixed
		695	1.67(17)	
852	4^+	520	1.95 (5)	
1012	3^+	679	1.77 (8)	1.80 (7)
		317	1.85(11)	
1116	(0^+)	783	1.65(35)	pure 1^+ decay
1320	4^+	467	1.99(72)	1.90(28)
		625	1.89(30)	
1501	6^+	648	1.93(11)	
1631	5^+	619	1.87(13)	
1984	6^+	664	2.29(40)	
2065	4^-	1053	1.92(27)	
2184	5^-	1331	2.08(26)	
2520	6^-	336	1.67(38)	1.88(16)
		455	1.48(34)	
		890	2.02(17)	
2598	7^-	1098	2.17(51)	
2623	6^-	103	1.79(45)	1.75 (9)
		993	1.79(10)	
		1122	1.54(22)	

=114 isobars were collected in a cyclic mode, allowing half-life information to be extracted from the growth and decay curves of specific lines. Gamma-gamma coincidences were recorded with four 70%-efficiency Ge detectors. More details on the detector setup and the analysis can be found in Refs. [15,16].

III. RESULTS

A large number of transitions and levels are added to the previous decay data [13]. The former decay scheme is confirmed with misplacement of only two transitions. The 1508 keV line is now placed in agreement with the prompt-fission data [22]. The new placement of the 540 keV line from the 1392 keV level to the 4^+ level at 852 keV is of consequence and will be discussed in detail. Among the levels observed for the first time in the β decay of ^{114}Rh, some were already known from prompt fission. New transitions that deexcite these levels are dipoles or $E2$ according to assignments presented in Ref. [22]. There is therefore an excellent agreement between the different data sets. The new 1639 keV level is assumed to be the head of a collective band with the new levels at 2091 keV and 2350 keV being the next band members. A tentative interpretation will be proposed. Finally, the β-decay strength of the high-spin ^{114}Rh level turns out to be more fragmented than reported before, with most of it shared

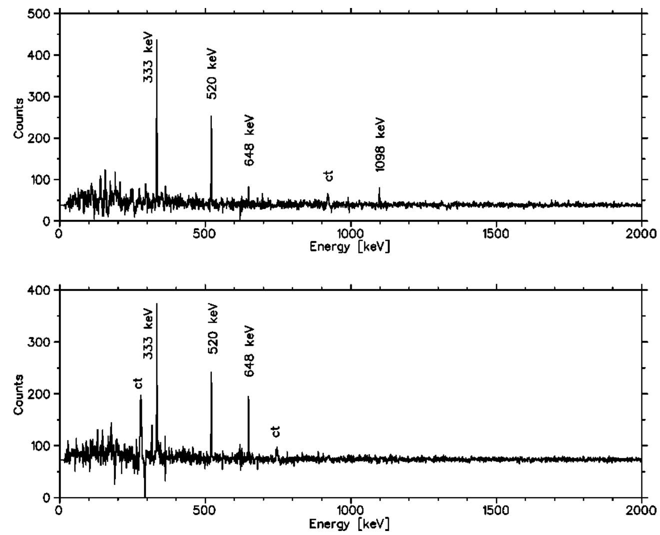

FIG. 1. Projections gated by the 539.6 keV (top) and 715 keV (bottom) transitions. The symbols ‘‘ct’’ denote the cross talk of a strong transition (993 keV and the background line of 1461 keV from ^{40}K) scattered from one detector to another. The upper spectrum implies the placement of the 539.6 keV line on top of the 4^+ level at 852 keV. The ratio of areas of the 333 ($2^+\rightarrow0^+$) and 520 keV ($4^+\rightarrow2^+$) peaks is the same as in the gate on the $8^+\rightarrow6^+$ transition at 715 keV shown below. The weak peaks at 648 and 1098 keV originate from another transition (540.2 keV) placed between the levels at 3139 and 2598 keV. The lower spectrum further shows that the presence of transitions strong enough to cancel the β feeding of the 8^+ state is rather unprobable.

among 6^- states. A probable $I^{\pi}=7^-$ is proposed for the higher-spin ^{114}Rh β-decaying level.

A. Decay half-lives of ^{114}Rh

The decay of two ^{114}Rh levels is suggested by the β feeding of palladium levels with very different spins, but there is no evidence for two different half-lives [13]. As a matter of fact, most of the transitions intense enough to extract a half-life belong to the decay of high-spin Rh only or are superpositions of both decay modes. The weighted average for the high-spin decay using transitions from levels with $I>4$ is 1.86(6) s. This matches well the value reported in Ref. [13], which was obtained by including transitions from low-spin levels. The low-spin Rh level is assigned $I^{\pi}=1^+$ based on the large ground-state (g.s.) feeding both in the decays of ^{114}Ru to ^{114}Rh [36] and of ^{114}Rh to ^{114}Pd [13]. The half-life deduced from the 783 keV transition depopulating a very probable 0^+ state, as well as that deduced from the transitions from 2^+ states, is consistent with the 1^+ half-life being shorter than 1.86 s. Unfortunately, a reliable decomposition of the decay curves of the intense lines from the 2_1^+ (333 keV) and 2_2^+ (695 keV) states has not been possible. Table I shows the half-lives extracted from a single-component analysis for the most intense transitions.

B. Decay of the 1^+ level

The first and second 2^+ states are fed in the β decay of the 1^+ level of ^{114}Rh. Under the assumption that they are not directly fed in the high-spin decay, their β feeding is calculated by a balance of the γ-intensity flow. The deduced values are indeed sizable but have large errors. This is due to the dominance of the high-spin contributions. The 1^+ decay only accounts for about 13% and 20% of the observed feeding of the 333 and 695 keV levels, respectively.

The levels at 1116 and 1392 keV were known from β decay [13] but have not been observed in the recent prompt-fission works. No γ rays which could have fed these levels from any identified high-spin level are observed. Consequently, the 1116 and 1392 keV levels are directly fed in the β decay of the 1^+ state in Rh. The new placement of the 540 keV transition to the 4^+ state of the g.s. band assigns 2^+ to the 1392 keV level. It results from the presence of the 333 keV ($2^+ \rightarrow 0^+$) and 520 keV ($4^+ \rightarrow 2^+$) lines in the gate on the 540 keV transition; see Fig. 1. Comparison of peak areas with those in the gate on the 715 keV ($8^+ \rightarrow 6^+$) transition implies a 540-520-333 cascade. It is logical to assume $I^\pi = 0^+$ for the 1116 keV level that is linked only to the 2^+ levels at 333 and 1392 keV. These results confirm the 1116 keV level as a candidate for a low-lying excited 0^+ state, as postulated in Ref. [13]. However, the new placement of the 540 keV transition removes the only existing support for another low-lying 0^+ state at 871 keV.

Another pair of 0^+ and 2^+ states is expected near 1.4 and 1.7 MeV, respectively. Unfortunately, there is not sufficient evidence for these levels. If the 0_3^+ state would be degenerated with the 2^+ level at 1392 keV, there could exist two transitions of very close energies feeding the 2_2^+ state at 695 keV. However, this possibility could not be tested due to the absence of γ rays on top of the 1392 keV level, which could be used to set gates. A tentative coincidence of a 1452 keV line with the 333 keV transition could indicate a level at 1775 keV, making this a suitable candidate for the 2_4^+ state.

A 30% g.s. β feeding has been measured [13]. A value can also be obtained from experimental γ-ray intensities in

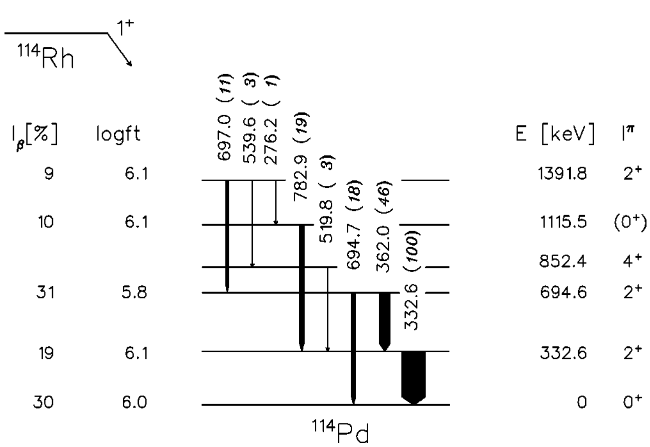

FIG. 2. Decay scheme of the 1^+ level of ^{114}Rh. The g.s. β feeding is from Ref. [13]. It must be noted that β-decay intensities and log*ft* values have large uncertainties due to corrections for the contribution of the high-spin β decay of ^{114}Rh, populating the 333 (2_1^+) and 695 keV (2_2^+) levels via γ-ray cascades, as well as the possibility of a higher ground-state β branching. See text for details.

TABLE II. Transitions in the β decay of the 1^+ state of ^{114}Rh. The large errors in intensities of transitions from 2^+ states are due to the subtraction of the contribution of the high-spin decay of Rh. The intensity of the 520 keV ($4^+ \rightarrow 2^+$) transition is set equal to the experimental intensity of the 540 keV transition since direct β feeding of the 4^+ state is assumed to be negligible. One hundred intensity units correspond to a branching of 60% in the decay of Rh when adopting 30% g.s. direct feeding [13].

Energy [keV]	Intensity	Placed from	to	Coincidences
276.2 (4)	1.3 (5)	1392	1116	(783)
332.6 (1)	100 (28)	333	0	362, 520, 540, 783
362.0 (2)	46 (21)	695	333	333, 697
519.8 (2)	3.1(12)	852	333	333, 540
539.6 (2)	3.1(10)	1392	852	333, 520
694.7 (3)	18 (7)	695	0	697
697.0 (2)	11 (2)	1392	695	333, 362, 695
782.9 (2)	19 (2)	1116	333	333

the decay of the 1^+ level of ^{114}Rh if the number of decays is known by an independent method. As a matter of fact, the relative direct populations (i.e., in fission) of the 1^+ and higher-spin β-decaying levels of ^{114}Rh ought to be comparable with those of their corresponding levels in other odd-odd rhodium isotopes. Comparison with ^{112}Rh [15] suggests that the direct populations of the g.s. and isomer of ^{114}Rh should be roughly equal. The extra feeding of the 1^+ state in ^{114}Rh by β decay of ^{114}Ru [36] during the collection cycle is estimated to be small according to a parametrization of cross sections presented in Ref. [37]. As an example, a 80% g.s. β branching is required to reproduce equal populations, i.e., a ratio of yield(1^+)/yield(high spin)$=1$. In contrast, the experimental g.s. branching of 30% leads to a yield ratio of only 0.22. This low value can be regarded as a significant deviation from the systematics of relative populations of ground states and isomers [38]. It seems therefore probable that the g.s. branching in the ^{114}Rh 1^+ β decay was underestimated. Nevertheless, since these considerations are model

TABLE III. Levels in ^{114}Pd fed in the 1^+ decay of ^{114}Rh. The adopted g.s. branching is from Ref. [13] but is possibly larger as discussed in the text. The direct β feeding of the 4^+ state is assumed to be negligible. Other large uncertainties are caused by the corrections for extra population of the 333 and 695 keV levels in the high-spin decay of ^{114}Rh. The log*ft* values are calculated with $T_{1/2}$=1.85 s and Q_β=7.9 MeV [39].

Energy [keV]	Beta feeding [%]	log*ft*	I^π
0.0	30(15)	6.0	0^+
332.6 (1)	19(16)	6.1	2^+
694.6 (2)	31(12)	5.8	2^+
852.4 (2)			4^+
1115.5 (3)	10 (4)	6.1	(0^+)
1391.8 (2)	9 (3)	6.1	2^+

TABLE IV. Transitions in the β decay of the high-spin level of ^{114}Rh. The intensities of the 333, 362, and 695 keV transitions have been calculated by balancing the feeding and depopulation of the 333 and 695 keV 2^+ levels without direct β feeding. Coincidences with a significance poorer than the 2σ limit are only listed if fitting between well-established levels or if the transitions occur several times and consistently. In order to keep the table compact only new coincidences, extending the former decay work of Ref. [13], are listed. One hundred relative intensity units correspond to a branching of 80% in the decay of Rh.

Energy [keV]	Intensity	Placed from	Placed to	Remarks	New coincidences
103.2 (2)	1.8 (5)	2623	2520	a,b	1020
159.4 (3)	0.4 (2)	1012	852	c	333, 520, (619)
166.4 (3)	0.5 (2)	2789	2623		(619), (993)
273.4 (3)	1.1 (3)	2623	2350		333, (520), (619), 627, (648) (711), (944),[d] 1030
310.7 (2)	1.2 (3)	1631	1320	a	
317.0 (2)	28.8(22)	1012	695	a,b	627
332.6 (1)	100	333	0	a,b	
336.0 (3)	2.6 (5)	2520	2184	a,b	
362.0 (2)	27.9(26)	695	333	a,b	627, 944,[d] (1079)
372.1 (3)	0.9 (3)	2892	2520		333, (455), (619), (679), (890)
400.2 (3)	0.6 (3)	3139	2739		333, (520), (648), (1238)
407.3 (3)	0.7 (3)	2927	2520		(333), (455), (619), (679), (890)
414.2 (3)	0.4 (2)	2598	2184	b	(333), (520), (1331)
426.5 (5)	0.3 (2)	2065	1639		(558), (627), (679), (944)
439.5 (3)	1.2 (3)	2623	2184	a,b	
441.0 (3)	1.9 (4)	3064	2623		(333), (520), (558), 619, 679, 993, (1053), (1122)
451.7 (3)	1.0 (3)	2091	1639		(333), (362), 627, (679), (944),[d] (1048)
455.0 (3)	2.1 (4)	2520	2065	a,b	
459.8 (4)	0.4 (2)	2091	1631		(619), (1048)
467.4 (2)	1.8 (3)	1320	852	a,b	
483.0 (4)	0.4 (2)	1984	1501		(520), (648)
503.7 (4)	0.4 (2)	2688	2184		(1331)
504.9 (4)	0.5 (2)	3128	2623		(993)
519.8 (2)	57.7(31)	852	333	a,b	
540.1 (4)	0.2 (1)	3139	2598		(648), (1098)
544.0 (3)	2.5 (5)	3064	2520		333, (362), (455), 619, (679), 890, (1020), 1053, (1331)
550.5 (4)	0.5 (2)	2997	2447		(333), (520), (1594)
557.8 (4)	0.5 (2)	3078	2520		(890)
558.2 (2)	5.7 (5)	2623	2065	a,b	
568.0 (3)	0.8 (3)	2752	2184		(333), (520), (1331)
605.0 (3)	0.4 (2)	2789	2184		(520), (1331)
608.0 (3)	0.9 (3)	3128	2520		(317), (333), (455), (520), (619), (679), (890), (1331)
618.2 (5)	0.5 (2)	3064	2447		(520), (1594)
619.0 (2)	39.7(22)	1631	1012	a,b	(520)[e]
625.3 (2)	9.5 (7)	1320	695	a,b	
627.1 (3)	1.5 (3)	1639	1012		317, (452), 679, (711), (1048)
639.5 (3)	0.9 (2)	2623	1984		333, (362), (625), (664)
648.1 (2)	35.7(19)	1501	852	a,b	
659.3 (2)	1.4 (3)	2290	1631	b	(317), 333, (362), 619, (679), (849)[f]
663.8 (2)	3.7 (4)	1984	1320	a,b	
679.0 (2)	26.2(13)	1012	333	a,b	
681.2 (5)	0.3 (2)	3128	2447		(520), (1594)

TABLE IV. (*Continued*).

Energy [keV]	Intensity	Placed from	Placed to	Remarks	New coincidences
694.7 (3)	12.0(10)	695	0	a,b	
705.7 (4)	0.9 (4)	(3056	2350)		(711), (1030)
711.0 (4)	0.7 (2)	2350	1639		(333), (362), (627), (789), (944)[d]
715.3 (4)	1.0 (3)	2216	1501	b	333, 520, 648
718.9 (4)	0.3 (2)	(2350	1631)		(619)
770.7 (4)	0.9 (2)	2091	1320		(333), (362), (467), (625), (1048)
778.4 (3)	1.1 (3)	1631	852	c	333, 520, (890), (993)
789.2 (3)	1.1 (3)	3139	2350		(333), (520), (625), (1030)
812.3 (3)	0.6 (3)	3128	2316		(520), (1464)
848.9 (4)	0.5 (3)	2350	1501		(273), (520), (648)
863.7 (4)	0.8 (3)	2184	1320		(333), (362), (467), (625)
888.2 (4)	0.8 (3)	2953	2065		(1053)[g]
889.4 (2)	9.4 (8)	2520	1631	a,b	
898.0 (4)	0.6 (2)	2399	1501		(333), (520), (648)
907.7 (4)	0.8 (4)	2997	2091		(333), (362), (467), (625), (771), (1079)
944.2 (3)	1.6 (3)	1639	695		(333), (362), (452), (711), (1048)
944.4 (2)	1.5 (3)	3128	2184	a,b	
992.6 (2)	23.2(18)	2623	1631	a,b	
1012.9 (5)	0.3 (1)	2997	1984		(362), (625), (664)
1019.7 (3)	1.9 (4)	2520	1501		(103), 333, (520), (648)
1029.9 (4)	1.4 (3)	2350	1320		(273), (333), (362), (467), 625, (789)
1048.4 (4)	1.6 (5)	3139	2091		333, (362), (452), (625), (679), (771), (1079)
1053.5 (2)	9.3 (9)	2065	1012	a,b	
1056.9 (4)	1.0 (3)	2688	1631		(317), (333), (362), 619, (679), (695)
1078.7 (4)	1.4 (3)	2091	1012		(317), (333), (362), (679), (1048)
1080.9 (3)	0.6 (3)	3064	1984		(362), (625), (664)
1097.9 (2)	2.9 (4)	2598	1501	b	333, 520, (540)
1122.6 (2)	6.3 (8)	2623	1501	a,b	
1144.6 (5)	0.5 (3)	3128	1984		(362), (625), (664)
1187.3 (3)	1.0 (4)	2688	1501		(333), (520), (648)
1213.1 (4)	1.1 (3)	2065	852	a	
1238.0 (3)	2.1 (4)	2739	1501		333, (400), 520, 648
1242.9 (5)	0.8 (3)	2563	1320		(333), (362), (625)
1288.8 (3)	3.1 (6)	2789	1501	a,b	(520), 648
1292.3 (3)	2.1 (5)	2793	1501		(333), 520, (648)
1321.1 (3)	0.6 (3)	(2822	1501)		(333), (520), (648)
1331.6 (2)	11.0(13)	2184	852	a,b	
1352.7 (3)	1.1 (4)	2853	1501	b	333, 520, 648
1463.8 (3)	1.2 (4)	2316	852		(333), 520
1468.6 (4)	1.4 (4)	3099	1631		(317), (333), (362), 619, (679)
1497.8 (4)	1.6 (4)	3128	1631	b	(317), 333, (362), 619, (679)
1508.0 (4)	2.3 (5)	3139	1631	a,b	317, 333, (362), 619, (679)
1563.8 (4)	0.6 (3)	3064	1501		(333), (520), (648)
1577.9 (3)	2.2 (5)	3078	1501		333, 520, 648
1594.3 (4)	2.9 (5)	2447	852		333, 520
1598.6 (5)	0.7 (3)	3099	1501		(520), (648)
1628.0 (3)	3.3 (7)	3128	1501	a,b	
1638.5 (4)	1.0 (3)	3139	1501		(333), (520), (648)

TABLE IV. (*Continued*).

Energy [keV]	Intensity	Placed from	Placed to	Remarks	New coincidences
1661.4 (4)	1.0 (4)	3162	1501		(333), (520), (648)
1758.9 (3)	1.2 (5)	2611	852		333, 520
1923.4 (4)	0.8 (4)	(3424	1501)		(333), (520), (648)

[a]Reported in β decay [13].
[b]Reported in prompt fission [22].
[c]Not reported in Ref. [22] although it was shown in a former report by the same group [21].
[d]Coincidence with new transition of 944.2 keV.
[e]Coincidence due to transition of 618.2 keV.
[f]Coincidence could indicate a second 848 keV transition from level 3128 to 2290 keV.
[g]Expected coincidences with 317 and 679 keV cannot be evaluated due to interference of 890 keV transition.

dependent, we have adopted the experimental value of 30% for the calculation of β feeding and log*ft* values. A decay scheme of the 1^+ level of ^{114}Rh is constructed based on these data; see Fig. 2 and Tables II and III.

C. High-spin decay

Several of the levels newly observed in β decay of ^{114}Rh were discovered in prompt fission. The g.s. and γ bands are populated up to their 8^+ and 7^+ levels, respectively. In addition, levels belonging to two-quasiparticle bands with $K=4^-$ and 5^- and several bandheads, mostly 6^- states, happen to be quite strongly populated. Since the new transitions are consistent with the spin and parity assignments of Ref. [22], we limit the presentation of decay results to a new band structure and comment on some changes in the distribution of β feeding with respect to Ref. [13]. The complete list of transitions observed in this work is shown in Table IV.

1. Possible K=4 band structure on the 1639 keV level

The new level at 1639 keV is based on two new transitions at 627.1 and 944.2 keV that were not identified in the former decay work or in prompt fission, presumably due to interference with the strong transitions at 625.3 and 944.4 keV. Thus, the 1639 keV level decays to the 2^+ and 3^+ states of the γ band. The other new level at 2091 keV has transitions to the 1639 keV level and to the 3^+, 4^+, and 5^+ members of the γ band. A somewhat similar pattern is observed for the 2350 keV level with branches to the 1639 keV level, the 4^+ level of the γ band, and, tentatively, the 5^+ level of the γ band. While the 1639 keV level is only populated by transitions from the 2091 and 2350 keV levels, the latter ones are fed from $I^\pi=6^-$ levels. Finally, we assign the 2997 keV level, with a transition to the 2091 keV level and the 6^+ level of the γ band among others, as tentatively belonging to this set. These transitions suggest a spin sequence of $I(1639)$, $I+1$ (2091), and $I+2$ (2350), in which case the only possibilities are $I^\pi=3^-$ or 4^+. The lowest-lying 3^- states in Pd isotopes are slightly above 2 MeV and clearly prefer to decay to the two first 2^+ states with a strong branch to the 2_1^+ state [39]. These features do not make the 1639 keV level a probable 3^- state. Therefore, in the following the 1639, 2091, and 2350 keV levels will be assumed to be a $K^\pi=4^+$ band. A partial decay scheme of the high-spin ^{114}Rh level with the above mentioned Pd levels and their depopulation is shown in Fig. 3.

2. Higher-spin ^{114}Rh level

The large number of high-energy γ transitions modifies the feeding pattern, making it more fragmented than originally reported in Ref. [13], where the decay strength was shared among the 2520 keV and 2623 keV levels. The feeding of the 2520 keV level (log*ft*=5.9) has decreased. This level is not a two-quasiparticle level but the 6^- member of the $K=4$ band built on the 2065 keV level [22]. The 2623 keV level is still strongly populated (log*ft*=5.2) and several new levels are also likely to be fed by allowed β decays, e.g., the 3064 keV (5.8), the 3128 keV (5.7), and the 3139 keV (5.8) levels. The clearly allowed character of the β transition to the 2623 keV level, a 6^- bandhead [22], assigns odd parity to the high-spin level of ^{114}Rh and restricts I to 5, 6, or 7. The early tentative assumption of even parity based

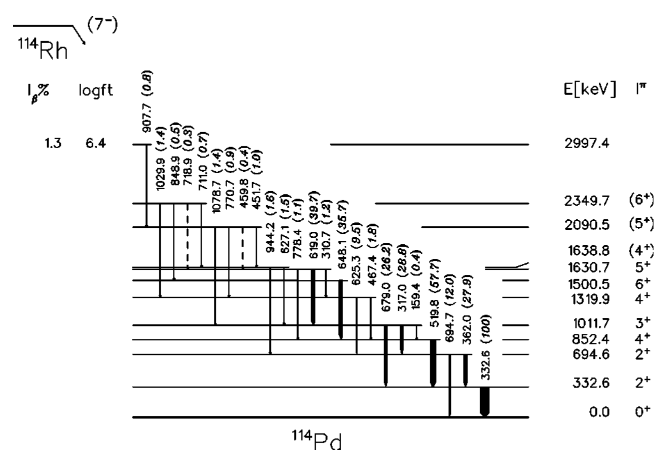

FIG. 3. Partial decay scheme of the higher-spin level of ^{114}Rh. The scheme is complete up to the 1639 keV level (see continuation in Figs. 4 and 5). Above this level only the $K+1$ and $K+2$ members and the tentative $K+3$ level of the postulated $K=4$ band are shown.

on a sizable feeding of the 6^+ state of the g.s. band at 1501 keV was a consequence of the partial nature of the decay scheme. This feeding is considerably decreased after placement of numerous new transitions populating the 6^+ state. A spin lower than 7 for the higher-spin level of ^{114}Rh appears to be rather improbable since there is hardly any direct β decay to levels with spin lower than 6. There are very few exceptions, e.g., the weak branches to the 1320 keV (4^+) and 2184 keV (5^-) levels that vanish at 2.5 standard deviations. A spin value of 7 is consistent with the weak branch to the 8^+ level of the Pd g.s. band. Thus, $I^\pi = 7^-$ is used in the determination of spins and parities of new levels shown in Table V. The upper part of the decay scheme is shown in Figs. 4 and 5.

D. Theoretical description of the two-quasiparticle levels in ^{114}Pd

Equilibrium deformations and potential-energy surfaces for neutron-rich Pd isotopes have been calculated by several authors; for instance, see Refs. [2,8,11,12]. It turns out that neutron-rich palladium nuclei exhibit rather flat potential-energy surfaces versus the triaxial degree of freedom.

Recently, the deformed shell model combined with the quantum Monte Carlo (QMC) [32,40] and Monte Carlo projection (MCP) [41] methods for pairing calculations were employed to study the two-quasineutron level structure in the $A \simeq 100$ region [32,42]. The same theoretical formalism is used in the present work. The only difference is that we use the universal Woods-Saxon (WS) parameters recently updated [43] to improve the description of the experimental data far from the stability valley. The ^{114}Pd isotope is predicted to have an oblate deformed ground state with quadrupole deformation $\varepsilon = -0.22$, i.e., a β_2 value of about -0.24. A prolate minimum occurs at $\varepsilon = 0.18$ ($\beta_2 = 0.19$). The minima are separated by a barrier of about 1 MeV at zero deformation.

The experimentally observed $5/2^+$ ground state and $9/2^-$ state at 81 keV in ^{113}Pd [44,45] indicate shape coexistence following Ref. [46]. They can be associated with orbitals near the Fermi surface only for prolate (the [402]5/2 orbital) and oblate (the [514]9/2 orbital) deformations, respectively. Shape coexistence is indeed supported by Hartree-Fock-Bogoliubov (HFB) calculations for odd-mass Pd isotopes. A description of the method can be found in a paper by Gautherin *et al.* [47]. The results are shown in Fig. 10 of Ref. [23]. They predict prolate ground states for Pd isotopes with $A = 109$ and heavier. Deformation decreases smoothly with A so that ^{121}Pd and ^{123}Pd are quasi spherical. In addition, a low-lying oblate deformed state is predicted for the most deformed isotopes ^{111,113,115}Pd near neutron midshell.

In our calculation the best agreement with the experimental single-particle levels for odd-mass Pd isotopes is obtained at slightly different deformations. The ε values of -0.15 and 0.16 have accordingly been used in the following to calculate the single-particle levels needed for the pairing calculation for ^{114}Pd.

Experimentally the lowest two-quasiparticle states in ^{114}Pd are the levels at 2065 (4^-), 2184 (5^-), and 2623 keV (6^-) [22]. It is interesting to remark that for the proton system no such levels are expected. In the prolate minimum the single-particle energy difference between two proton states close to the Fermi surface is about 1 MeV as shown in Table VI. Moreover, in the oblate minimum the generated lowest-lying two-quasiproton states have $K \leqslant 3$. Therefore, the above-mentioned levels must be due to neutrons. This conclusion is in agreement with cranked-HFB calculations performed by Houry *et al.* [23]. Neutron two-quasiparticle levels are shown in Table VII for oblate and prolate deformations.

The excitation energy of a two-quasiparticle band is determined as described in Refs. [32,42]. We have calculated ground-state $\Delta E_{GS}(G)$ and two-quasiparticle $\Delta E_{2QP}(G)$ pairing energies for ^{114}Pd. The pairing energies for the ground states differ by less than 0.1 MeV for the QMC, MCP, and Lipkin-Nogami pairing calculations [48] while BCS pairing [49] yields a value smaller by about 0.6 MeV. The two-quasiparticle energies calculated with QMC and MCP differ by less than 0.15 MeV. This difference is of the order of the uncertainties associated with the calculations — which are less than 0.1 MeV in each case — and is not regarded as being significant. MCP results have been selected for bandhead calculations, considering their somewhat smaller uncertainties.

IV. DISCUSSION

The collective properties of neutron-rich Pd isotopes show a smooth evolution with neutron number. The transition from the vibrational to the γ-soft limit near ^{114}Pd has been reproduced in the interacting boson approximation (IBA) framework by Kim *et al.* [7]. The band structure for $^{112-116}$Pd was extensively discussed recently following prompt-fission experiments by various groups, especially in Refs. [19,22,24]. We therefore concentrate on the low-spin levels, the new level at 1639 keV and a possible band structure on it, the lowest two-quasiparticle levels, and a qualitative discussion of ^{114}Rh and its decay.

A. Low-spin levels

The energies of the 1116 keV (0_2^+) and 1392 keV (2_3^+) levels compare well with those of other 0^+ and 2^+ states in ^{110}Pd and ^{112}Pd [15,26–28]. A remarkably smooth energy systematics of $0^{+\prime}$ states can be formed with the level at 1171 keV (0_3^+) in ^{110}Pd, one of the 1126 (0_2^+) or 1140 keV (0_3^+) levels in ^{112}Pd, and the 1116 keV (0_2^+) level in ^{114}Pd. It probably continues with the 1110 keV level in ^{116}Pd [16]. The ^{110}Pd level at 1171 keV decays by two branches to 2^+ states while the levels in $A > 112$ palladium nuclei have a single branch to the first excited state. Thus, it remains unclear which of the 1126 of 1140 keV 0^+ states in ^{112}Pd belongs to this set of levels. The energy trend of 2_3^+ states is also smooth, starting at 1470 keV in ^{110}Pd, 1423 or 1403 keV in ^{112}Pd, and 1392 keV in ^{114}Pd. The 2_3^+–$0^{+\prime}$ energy differences are only slightly lower than the 2_1^+ level energies and show the same decreasing trend with N. We also note the evolution of the branching ratios of the 2_3^+ states, the transi-

TABLE V. Levels in ^{114}Pd populated in the β decay of the high-spin state (assumed $I^{\pi}=7^{-}$) of ^{114}Rh. The feedings to the g.s. and the 2^{+} states are assumed negligible. Arguments for spins and parities, from this work and from previous reports, are given as footnotes. Spins and parities are not listed when not limited to a few alternatives. The logft values are calculated with $T_{1/2}=1.85$ s and $Q_{\beta}=7.9$ MeV [39].

Energy [keV]	β feeding [%]	logft	I$^{\pi}$	Remarks
0			0^{+}	
332.6 (1)			2^{+}	g.s. band[a,b]
694.6 (2)			2^{+}	γ band[a,b]
852.4 (2)	1.0(32)		4^{+}	g.s. band[a,b]
1011.7 (2)	2.8(28)		3^{+}	γ band[a,b]
1319.9 (2)	2.0 (9)	6.8	4^{+}	γ band[a,b]
1500.5 (3)	2.0(22)		6^{+}	g.s. band[a,b]
1630.7 (2)	1.0(25)		5^{+}	γ band[b,c]
1638.8 (3)	0.9 (5)		$(3^{-}, 4^{+})$	assumed 4^{+}; see text
1983.6 (3)	1.5 (5)	6.7	6^{+}	γ band[b,c]
2065.2 (2)	1.7(11)	6.6	(4^{-})	bandhead[b,c]
2090.5 (3)	1.0 (8)		$(4^{-}, 5^{+})$	assumed 5^{+}; see text
2183.9 (3)	3.6(14)	6.3	(5^{-})	band head[b,c]
2215.8 (5)	0.8 (3)	6.9	8^{+}	g.s. band [b]
2290.0 (3)	1.1 (3)	6.7	7^{+}	γ-band [b]
2316.2 (4)	0.5 (4)			d
2349.7 (3)	−0.4 (6)		$(5^{-}, 6^{+})$	assumed 6^{+}; see text
2398.5 (5)	0.5 (3)			
2446.7 (5)	1.5 (5)	6.5	(6^{+})	e
2520.1 (2)	7.0(13)	5.9	(6^{-})	member of $K^{\pi}=4^{-}$ band[b,c]
2562.8 (6)	0.6 (3)	6.9	(6^{+})	e
2598.3 (3)	2.7 (5)	6.2	(7^{-})	member of $K^{\pi}=5^{-}$ band [b]
2611.3 (4)	1.0 (4)	6.7	(6^{+})	e
2623.3 (2)	30.0(30)	5.2	(6^{-})	b,c,f
2687.7 (3)	1.9 (5)	6.4	(6)	g,h
2738.5 (4)	1.2 (4)	6.5		
2751.9 (4)	0.6 (3)	6.8	$(6, 7^{-})$	i
2789.3 (3)	3.2 (6)	6.1	$(6, 7^{-})$	c,h,i
2792.8 (4)	1.7 (4)	6.4		
2853.2 (4)	0.9 (4)	6.6		h
2892.2 (4)	0.7 (3)	6.7		
2927.4 (4)	0.6 (3)	6.8		
2953.4 (5)	0.6 (3)	6.7	(6^{-})	j
2997.4 (5)	1.3 (4)	6.4		k
3064.3 (2)	4.9 (8)	5.8	$(6, 7)^{-}$	l
3078.2 (3)	2.2 (5)	6.1	(6, 7)	l
3099.2 (4)	1.7 (5)	6.2	$(6, 7^{+})$	m
3128.3 (2)	7.2(10)	5.6	(6^{-})	a,b,m
3138.8 (2)	5.3 (8)	5.7	(6^{-})	b,m
3161.9 (5)	0.8 (3)	6.5		
3423.9 (5)	0.6 (3)	6.5		

[a]Reported in β decay [13] with spin and parity.
[b]Reported in prompt fission [22] with spin and parity.
[c]Reported in β decay [13].
[d]Fed from a 6^{-} state and decays to a 4^{+} state, possible 4^{-}, 5, 6^{+}.
[e]Decays to a 4^{+} state.
[f]Decays to 4^{-} and 5^{+} states.
[g]Decays to 5^{-} and 5^{+} states.
[h]Reported in prompt fission [22].
[i]Decays to a 5^{-} state.
[j]Decays to a 4^{-} state.
[k]Possibly two closely lying levels. A tentative 7^{+} level is discussed; see text.
[l]Decays to 6^{-} and 6^{+} states.
[m]Decays to a 5^{+} state.

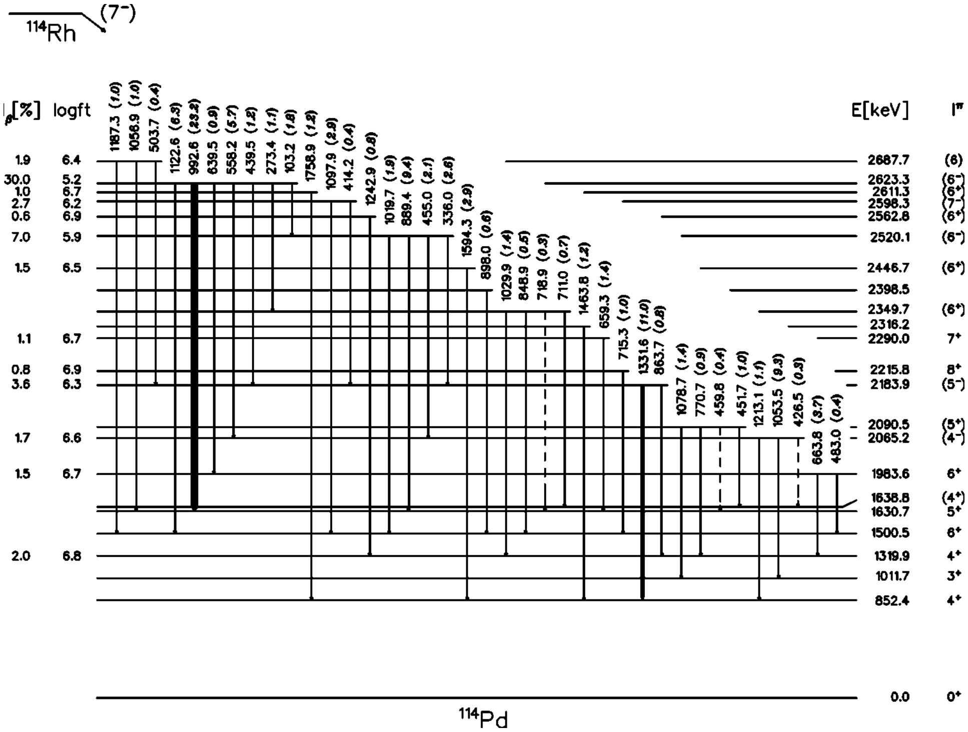

FIG. 4. Decay scheme of the higher-spin level of ^{114}Rh (continued). Levels and transitions belonging to the band on the 1639 keV level are also shown in Fig. 3.

tions to the g.s. and 2_1^+ state becoming weaker with increasing N and remaining unobserved in ^{114}Pd and beyond. As a result of the evolution of energies and γ branchings these levels can probably be associated with a β-band-like structure at least for $A \geqslant 112$. In ^{118}Pd a level at 1020 keV with a single decay to the 2_1^+ state is so far the best candidate for the corresponding 0_2^+ level [18]. It is an open question whether the somewhat lower energy indicates a structural change. The $E(4^+)/E(2^+)$ ratio indeed decreases, in contrast with the trend at lower N [17,23].

Other pairs of 0^+, 2^+ excited levels have been identified in even-even Pd isotopes. They are interpreted as intruder states, based on their excitation energies forming a V shape versus neutron number [14]. The energy of the 0^+ level is

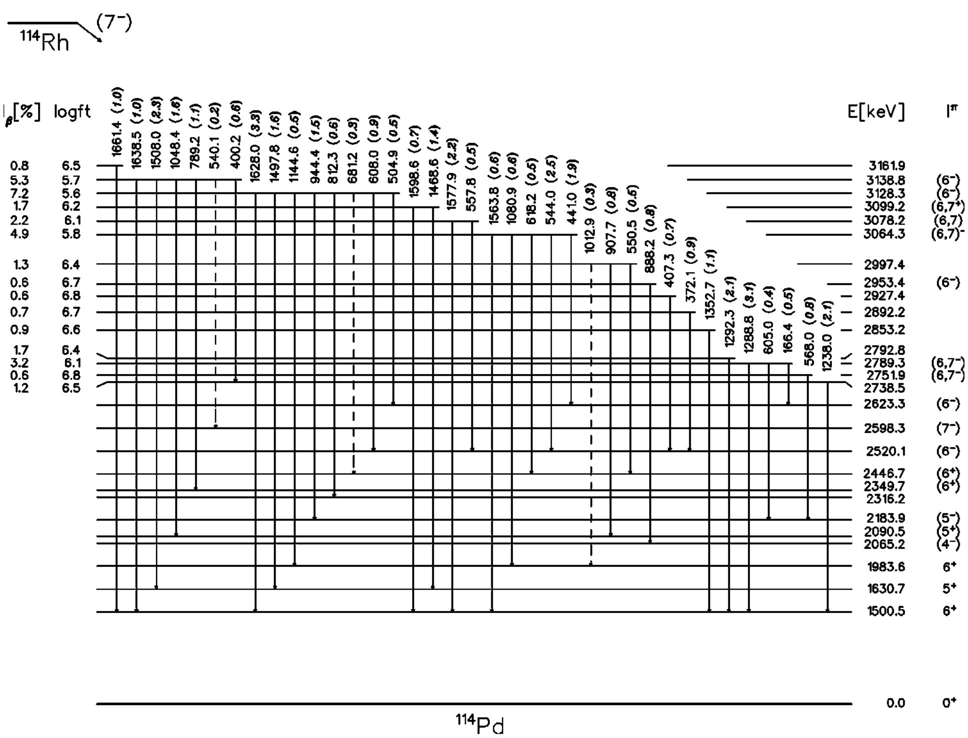

FIG. 5. Decay scheme of the higher-spin level of ^{114}Rh (continued).

TABLE VI. Proton single-particle levels close to the Fermi level for ^{114}Pd calculated using the Woods-Saxon potential at the oblate deformation of $\varepsilon=-0.15$, $\alpha_4=-0.01$, and prolate deformation of 0.16. The proton Fermi levels are at the $\pi[431]3/2$ (oblate) and $\pi[301]1/2$ (prolate) orbitals, respectively.

Oblate minimum		Prolate minimum	
Orbital	Energy [MeV]	Orbital	Energy [MeV]
$\pi[413]7/2$	−11.82	$\pi[301]3/2$	−12.32
$\pi[422]5/2$	−10.98	$\pi[422]5/2$	−11.57
$\pi[431]3/2$	−10.39	$\pi[301]1/2$	−11.35
$\pi[301]1/2$	−10.37	$\pi[413]7/2$	−10.31
$\pi[440]1/2$	−10.10	$\pi[404]9/2$	−8.71

the lowest in ^{110}Pd (947 keV), and rises in ^{112}Pd (1126 or 1140 keV). These states should further move upwards with larger N, i.e., farther from the neutron midshell. A reasonable candidate for the 0_3^+ state in ^{116}Pd is the 1733 keV level, based on its energy and its decays to both lower 2^+ states [16]. The 2_4^+ partner level is tentatively proposed at 2074 keV. We have not been able to find the corresponding levels in ^{114}Pd. It is interesting to compare the energies of these 0^+ and 2^+ states with the energies of the levels of the $K=1/2$ band in the odd-proton Rh isotopes [50–55]. The bandhead has been interpreted as the strongly downsloping [431]1/2 proton orbital at prolate deformation. For this reason we now favor the interpretation of the intruder states in Pd as prolate states, in contrast to our former statement about spherical two-particle–two-hole excitations [14]. A systematics of the lowest-spin collective states in neutron-rich palladium isotopes is shown in Fig. 6.

B. Band on the 1639 keV level

The energy of the 1639 keV level is quite lower than those of quasiparticle states in this region (the lowest-lying two-quasiparticle state in ^{114}Pd is the $K^\pi=4^-$ bandhead at 2065 keV). It therefore indicates a collective excitation. The depopulation of the 1639 keV bandhead and of the postulated other members strongly favors levels in the γ band. In particular, the 1639 keV level decays to the 2^+ and 3^+ states of the γ band but a transition to the other 2^+ states is not

TABLE VII. Neutron single-particle levels close to the Fermi level for ^{114}Pd calculated using the Woods-Saxon potential at the oblate deformation of $\varepsilon=-0.15$, $\alpha_4=-0.01$, and prolate deformation of 0.16. The neutron Fermi levels are at the $\nu[514]9/2$ (oblate) and $\nu[402]5/2$ (prolate) orbitals, respectively.

Oblate minimum		Prolate minimum	
Orbital	Energy [MeV]	Orbital	Energy [MeV]
$\nu[420]1/2$	−7.48	$\nu[411]1/2$	−7.06
$\nu[505]11/2$	−7.42	$\nu[541]3/2$	−7.05
$\nu[514]9/2$	−6.44	$\nu[402]5/2$	−6.58
$\nu[411]1/2$	−5.82	$\nu[532]5/2$	−6.38
$\nu[402]3/2$	−5.81	$\nu[404]7/2$	−5.77

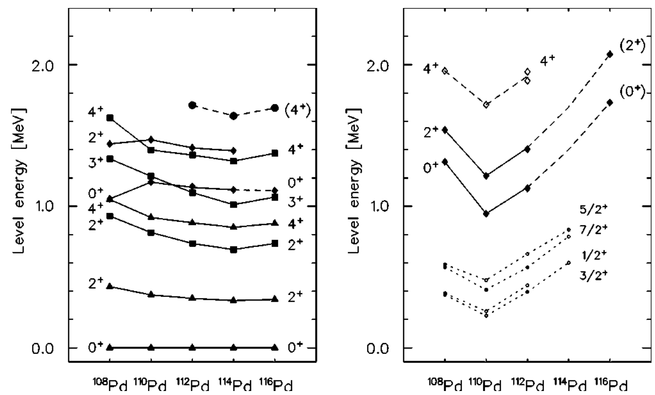

FIG. 6. Systematics of levels with $I\leqslant 4$ in neutron-rich Pd isotopes. In the left panel the evolution of structure, departing from the vibrational limit in ^{108}Pd with increasing N and reaching the maximum of collectivity in ^{116}Pd, is clearly visible. Solid diamonds indicate the 0^+ and 2^+ states of a probable β band. The energy of the highest 4^+ shown in ^{112,114,116}Pd (tentative assignment in ^{114}Pd) follows the trend of the 2_2^+ state versus N, in agreement with its proposed interpretation as a double-γ vibration. In the right panel are shown the well-established 0^+ and 2^+ intruder states and tentative ones. The $K=1/2$ band due to the [431]1/2 prolate orbital in the odd-mass odd-Z Rh isotones of Pd is shown for comparison.

seen. A similar pattern was observed in ^{106}Mo for a $K^\pi=4^+$ band built on a double-γ vibration [56]. The energy of the $K=4$ bandhead is slightly larger than twice the energy of the γ bandhead (695 keV), i.e., $E(4_{2\gamma}^+)/E(2_\gamma^+)=2.36$. The assumed 5^+ and 6^+ states are, respectively, too high and too low, with respect to an average energy computed from the g.s. and γ bands. This could be due to a large staggering. We note that including the 2997 keV level as a tentative 7^+ band member indeed creates a staggering pattern; see Fig. 7. It has

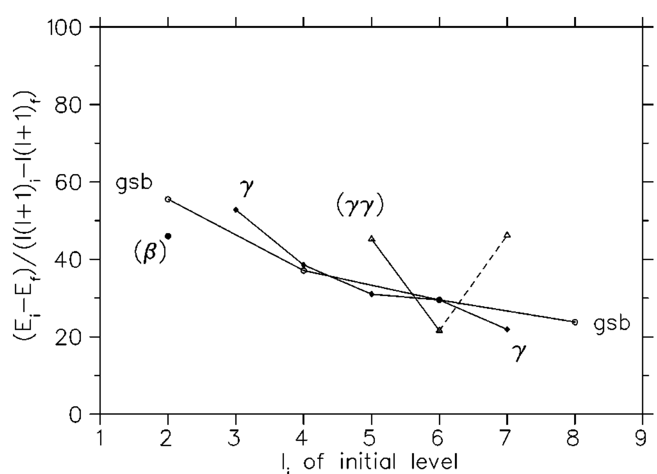

FIG. 7. Inertia parameters versus spin of initial level for several bands in ^{114}Pd. Only the levels seen in decay of ^{114}Rh are shown. The 5^+ and 6^+ states of the proposed $K=4$ band on the 1639 keV level imply a large staggering in order to keep reasonable values of the moment of inertia. Assuming the 2997 keV level (connected with dashed line) to be the 7^+ state of this band indeed creates a staggering pattern.

TABLE VIII. Monte Carlo–projected results for the pairing energies and two-quasineutron bandhead energies (MeV) for a neutron pairing strength $G_N=22/A$ in the oblate minimum. The statistical uncertainty of the MCP calculation is 0.1 MeV. The two-quasiparticle energies are given by $U_{2QP}=U_{2P}+\Delta E_{\mathrm{g.s.}}(G)-\Delta E_{2QP}(G)$, where U_{2P} is the Fermi gas excitation energy, and $\Delta E_{\mathrm{g.s.}}(G)$ and $\Delta E_{2QP}(G)$ are pairing energies of ground state and of the two quasiparticle configurations. The $\Delta E_{\mathrm{g.s.}}(G)$ values are 6.60, 6.52, 6.65, and 5.56 for QMC, MCP, LN, and BCS, respectively.

Configuration	U_{2P}	$\Delta E_{2QP}(G)$	U_{2QP}
$\nu[514]9/2\otimes\nu[411]1/2$ [a]	0.62	4.85	2.29
$\nu[514]9/2\otimes\nu[402]3/2$ [b]	0.63	4.80	2.35
$\nu[505]11/2\otimes\nu[411]1/2$	1.60	5.05	3.07
$\nu[505]11/2\otimes\nu[402]3/2$	1.61	5.27	2.86
$\nu[420]1/2\otimes\nu[411]1/2$	1.66	5.23	2.95
$\nu[420]1/2\otimes\nu[402]3/2$	1.67	5.20	2.99

[a]Configuration proposed for the 2065 keV 4^- level.
[b]Configuration proposed for the 2623 keV 6^- level.

been mentioned that staggering of the γ bands is related to the flatness of the potential energy surfaces versus the γ parameter [22,24].

A similar level structure has not yet been noticed in the neighbors ^{112}Pd and ^{116}Pd but there exist levels with a reasonable analogy with the 1639 keV bandhead. The levels with suitable branching ratios and energy are the 1715 keV $[E(4^+_{2\gamma})/E(2^+_{\gamma})=2.33]$ in ^{112}Pd and 1695 keV (2.30) in ^{116}Pd. The former has an additional weak branch to the 4^+ state of the g.s. band. The levels of the γ band and of the proposed double-γ $K=4$ band are the lowest in ^{114}Pd (see Fig. 6), i.e., two neutrons past midshell. This contrasts with the systematics of (prolate) intruders which have their minimum two neutrons before midshell.

C. Quasiparticle levels

The systematics of quasiparticle levels observed in neutron-rich Pd isotopes by decay spectroscopy have been shown in Refs. [15,16]. The lowest-lying levels are 4^- levels. Their energies and decay branchings vary smoothly. The energies decrease faster after $A=112$, i.e., 2282, 2261, 2195 keV from ^{108}Pd to ^{112}Pd, while 2065 keV in ^{114}Pd (Ref. [22] and this work) and 1810 keV in ^{116}Pd [16,22]. The strongly fed levels in $^{108-110-112}$Pd have a spin definitely not larger than 5. The 2623 keV (6^-) level in ^{114}Pd is therefore a different one. It could be instead similar to the strongly fed 2449 keV level in ^{116}Pd. There is no level obviously corresponding to the 2184 keV (5^-) level in the decay data for Pd isotopes lighter than ^{114}Pd but the 1982 keV level in ^{116}Pd is very similar.

As we already pointed out, the lowest-lying high-spin quasiparticles states in ^{114}Pd are due to neutron excitations. They are shown in Tables VIII and IX. The lowest bandheads arise from two-quasineutron states in the oblate minimum (it is estimated to be around 100 keV above the prolate minimum). These are the $[514]9/2\otimes[411]1/2$ configuration calculated at 2.29 MeV and the $[514]9/2\otimes[402]3/2$ configuration at 2.35 MeV. The next states originate from the coupling of the $[402]5/2$ orbital to the $[532]5/2$ and $[404]7/2$ levels coming from the prolate minimum. They are calculated near 2.6 MeV. It is therefore reasonable to interpret the 2065 keV (4^-) and 2623 keV (6^-) levels as due to quasiparticles in the oblate minimum. Nevertheless, the nature of the 2184 keV (5^-) level remains unclear as it can be the partner state of the 4^- level with the other K value or one of the lowest states in the prolate potential well.

TABLE IX. Monte Carlo–projected results for the pairing energies and two-quasineutron bandhead energies (MeV) in the prolate minimum. See caption of Table VIII for details. The $\Delta E_{\mathrm{g.s.}}(G)$ values are 7.30, 7.28, 7.32, and 6.20 for QMC, MCP, LN, and BCS, respectively.

Configuration	U_{2P}	$\Delta E_{2QP}(G)$	U_{2QP}
$\nu[402]5/2\otimes\nu[532]5/2$	0.20	4.93	2.55
$\nu[402]5/2\otimes\nu[404]7/2$	0.81	5.36	2.73
$\nu[541]3/2\otimes\nu[532]5/2$	0.67	5.02	2.93
$\nu[541]3/2\otimes\nu[404]7/2$	1.28	5.51	3.05
$\nu[411]1/2\otimes\nu[532]5/2$	0.68	5.03	2.93
$\nu[411]1/2\otimes\nu[404]7/2$	1.29	5.52	3.05

One should keep in mind that the accuracy of this theoretical prediction is affected by the single-particle level scheme and by spin-spin shifts which have been neglected, as well as by the monopole pairing approximation. However, the relative positions of the bandhead levels are much less influenced by these approximations than their absolute energies.

D. Decay of the high-spin ^{114}Rh level

The shape of ^{114}Rh is not established experimentally. A systematic feature of odd-mass rhodium isotopes is their $7/2^+$ ground states and low-lying $9/2^+$ excited states. Spherical shape was assumed based on the smooth evolution with N of level properties observed in decay studies of odd-mass rutheniums [50–54]. The level order was explained in the frame of the $I=j-1$ anomaly with j being the $g_{9/2}$ single particle. In contrast, deformation was invoked for ^{107}Rh and ^{109}Rh, based on band structure observed in prompt fission [55]. In the latter case the level sequence is the straightforward result of prolate deformation.

An attempt to use a spherical microscopic description of the high-lying two-quasiparticle levels and their β feeding was made. The excitation spectrum of ^{114}Pd was calculated by using the spherical quasiparticle random-phase approximation (QRPA) model within the $1p$-$0f$-$2s$-$1d$-$0g$-$0h$ valence space both for protons and neutrons. The single-particle energies were obtained by using a Woods-Saxon well with a global empirical parametrization. A realistic nuclear Hamiltonian, derived from the Bonn G matrix, was used. Indeed, several two-quasiparticle states with $I^\pi=6^-$, 7^-, and 8^- were predicted by the model between 2.4 and 3.5 MeV of excitation in ^{114}Pd. The 7^- state in ^{114}Rh was produced by using the proton-neutron QRPA model. The β-decay matrix elements between this state and the two-quasiparticle excitations in ^{114}Pd were calculated by adopting the multiple-commutator model (MCM) approach of Ref. [57]. This model reproduced succesfully the decay properties of spherical neutron-rich nuclei in the $A=100$ region [58]. It turned out that for ^{114}Rh decay the qualitative pattern of the predicted feeding did not match the experimentally observed one even if some changes in the single-particle energies near the proton and neutron Fermi surfaces were done. The β feeding is shared among two final states, a 6^- state at 3.75 MeV (log*ft*=4.0) and a 7^- state at 3.50 MeV (4.4). The initial 7^- state is the pure proton-neutron $\pi g_{9/2}\otimes \nu h_{11/2}$ configuration. The final states are dominated by the $g_{7/2}\otimes h_{11/2}$ two-quasineutron configuration that represents more than 90% of their wave functions. These states are thus reached by fast Gamow-Teller $\nu g_{7/2}\rightarrow \pi g_{9/2}$ transitions. The failure to describe the fragmentation of the feeding pattern confirms that deformation plays an important role in either one or both of the studied nuclei.

A low-lying 1^+ state in ^{114}Rh can be created by coupling the configurations of the ground states of the odd nuclei ^{113}Rh ($7/2^+$) [54] and ^{113}Pd ($5/2^+$) [44]. States with these spins and parities exist at low energy for both spherical shape and prolate deformations, but not for oblate deformation (see Table VII), for which a $5/2^+$ neutron level is missing. It is not experimentally established if the 1^+ state is the g.s. of ^{114}Rh. This nevertheless looks probable since the involved quasiparticles are the lowest-lying ones.

The fairly high spin and odd parity of 7^- require a high-*K* orbital of odd parity. It is indeed available among the low-lying neutrons orbitals. Low-lying odd-parity states have been identified by conversion-electron spectroscopy in odd-*N* Pd where they create isomers [44,45] and odd-parity bands were later reported [23,59]. In this work, the $9/2^-$ isomeric state at 81 keV in ^{113}Pd has been associated with the [514]9/2 orbital at oblate deformation. A suitable proton orbital with $K^\pi=5/2^+$ close to the Fermi surface at oblate deformation is [422]5/2. According to the Gallagher-Moszkowski rule [60] the lowest state of the coupling of these states both with $\langle s_z\rangle>0$ is their parallel coupling, i.e., $K=7$. An alternative is to invoke orbitals in the prolate potential well. The [413]7/2 proton g.s. of odd-*A* rhodium isotopes or the low-lying [404]9/2 first excited state could be coupled with the [523]7/2 or [532]5/2 neutrons. The energy-favored coupling is also the one with $K=7$. With these configurations the allowed β decay of a neutron bound in a spectator 0^+ pair can create final 6^- states. This corresponds to the possible spins and parities of the mostly fed levels. The alternative with oblate deformation leads to the configuration proposed for the 2623 keV 6^- level. The log*ft* value of 5.2 indicates that the mechanism is more complex than a pure Gamow-Teller transition between spin-orbit partner orbitals, which indeed cannot be achieved within the postulated configurations.

The spin and parity of ^{116}Rh has been assumed to be 6^- based on the rather large feeding of the 5^- level at 1982 keV (log*ft*=5.6) [16]. In the alternative of oblate deformation discussed above, the next odd-parity neutron orbital to be filled is [523]7/2, which has a spin unit less than [514]9/2. In the other alternative, for prolate deformation the next orbital has a unit of spin more. Therefore, $I^\pi=7^-$ for ^{114}Rh and $I^\pi=6^-$ for ^{116}Rh, respectively, are logical in case of oblate deformation.

It is interesting to note that the contributions of transitions of allowed character add up to about the same strength in the decays of the highest-spin levels of ^{112}Rh, ^{114}Rh, and ^{116}Rh but the strength is less spread in the former. The 2755 keV level in ^{112}Pd has a log*ft* value of 4.9 and collects 74% of the β-decay feeding. It has been proposed to be a 5^+ state [15] or a $K=4$ bandhead [22], and definitely is not a 6^- level. As a matter of fact, the 5^- and 6^- states observed by β decay in ^{114}Pd and ^{116}Pd are missing in the lighter Pd isotopes. These results indicate a spin and very probably a parity change of Rh occuring in ^{114}Rh, the decay of which selects different palladium quasiparticle states.

V. CONCLUSION

A large number of new levels have been observed in the β decay of ^{114}Rh to ^{114}Pd. There is confirmation for decay of a 1^+ and a higher-spin level with probable $I^\pi=7^-$ of ^{114}Rh. The fragmented decay pattern of the latter cannot be reproduced in the spherical framework. The levels at 1116 and 1392 keV in ^{114}Pd are a probable 0^+ and a firmly established 2^+ state, respectively. This pair of states is a candidate for being the β band. A tentative band structure built on a new level at 1639 keV shows transitions consistent with those of a $K=4$ band due to a two-phonon γ vibration. Based on their energies the g.s. and γ bands are the most collective in ^{114}Pd. This trend is also followed by the states tentatively assigned to the $K=4$ bandheads. This contrasts with the energy systematics of the $K=0$ intruder band which has the characteristic feature of a minimum at $N=64$ (^{110}Pd) in the same way as the [431]1/2 proton intruder band in odd-mass Rh isotopes. However, the intruder states expected in ^{114}Pd could not be found. The extra 0^+ level at 871 keV previousy reported was indeed not confirmed. The lowest-lying two-quasiparticle levels have been calculated with the quantum Monte Carlo pairing model using deformed shell model states. Two of the experimental levels—namely, the 2065 keV (4^-) and the 2623 keV (6^-) levels—are associated with oblate shape. The various observations presented above indeed indicate a rich structure of neutron-rich Pd isotopes.

The new data confirm the potential of decay studies to investigate low-spin and low-lying states of medium spin and of the ion-guide technique for on-line mass separation of refractory elements. This particular case is also one of the best demonstrations of mutual benefit of combining decay and prompt methods. Still, the presently available data call for dedicated high-precision experiments of angular correlations and measurements of $E0$ transitions and of transition rates in order to definitely establish the nature of the discussed levels. This program is certainly within reach in the not too far future, considering steady improvements in production rates and instrumentation.

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