Structure of ^{115}Ag studied by β^- decays of ^{115}Pd and ^{115}Pd^m

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The excited levels of ^{115}Ag have been studied via the beta decay of ^{115}Pd and ^{115}Pd^m. The beta-decay schemes for both states have been considerably extended, especially the scheme following the decay of ^{115}Pd^m which was practically unknown before this work. Transition intensities and $\log_{10} ft$ values are reported, which have been missing in the literature. A set of levels around 2 MeV has been found to be strongly populated by the beta decay of the ground state of ^{115}Pd and is suggested to have a three-quasiparticle nature. The properties of excited levels have been compared with the level systematics of lighter neutron-rich silver isotopes, and new spin assignments as well as identification of Nilsson states in ^{115}Ag have been made.

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I. INTRODUCTION

The Pd ($Z = 46$) and Ag ($Z = 47$) nuclei are located between the nearly spherical Sn nuclei ($Z = 50$) and strongly deformed Zr nuclei ($Z = 40$). In this region on the neutron-rich side of the nuclide chart, beta decay is expected to occur between the spin-orbit partner orbitals $g_{7/2}$ and $g_{9/2}$ of the spherical shell model. Since the Pd and Ag nuclei around $A = 115$ are predicted to be moderately deformed [1], the spherical shell model states are split into Nilsson states described by the asymptotic quantum numbers $\Omega^\pi[Nn_3\Lambda]$. In this case, the nuclear beta decay obeys the additional asymptotic quantum number selection rules. In addition, neutron-rich Ag nuclei may be in a region of shape coexistence, where the spherical shell model may be a more appropriate basis for some states, whereas the deformed shell model well describes other states [2,3].

For deformed odd-N parent nuclei, the "allowed-unhindered" (AU) beta decay proceeds via the interchange of an unpaired neutron to an unpaired proton in the states having the same asymptotic quantum numbers $[Nn_3\lambda]$ and $\Delta\Omega = \pm1$. These transitions are very fast, having low $\log_{10} ft$ values ($\log_{10} ft \leqslant 5$). If $\Delta\Omega = 1$ and $\Delta N = \Delta n_3 = \Delta\lambda = 0$ or 1, the beta decay is called "allowed-fast." All other allowed transitions are called "allowed-hindered." If there is no AU pair available for the unpaired neutron, the beta decay can proceed to a three-quasiparticle state. In this case, a neutron pair below the Fermi level needs to be broken. Instead of having a single unpaired neutron as a final state, two unpaired neutrons and one unpaired proton are found [4]. This situation is illustrated in Fig. 1.

^{115}Pd has two beta-decaying states, a negative-parity, high-spin isomeric state ($t_{1/2} = 50$ s [5]) and a positive-parity, low-spin ground state ($t_{1/2} = 25$ s [5]). The spins of both states have been under discussion; see for example Refs. [6,7]. A $(5/2^+)$ spin assignment for the ^{115}Pd ground state and $(11/2^-)$ for the isomeric state have been adopted in the Evaluated Nuclear Structure Data File [8,9] based on systematics. Later on, these assignments were changed to $(3/2^+)$ and $(9/2^-)$ [6], and further to $(1/2^+)$ and $(7/2^-)$, respectively [7]. These assignments are based on high-spin prompt γ-ray measurements. The latter values have been also supported by our previous work on the beta decay of ^{115}Rh [10,11] and are applied in this work.

The ^{115}Pd beta decay was studied at the OSIRIS [12] and SISAK [13] facilities over two decades ago. The lowest states populated by the beta decay of the ^{115}Pd ground state have been published in conference proceedings [14,15]. Also a partial beta-decay scheme concentrating on a band structure built on the $\pi 1/2^+[431]$ Nilsson configuration [16] and some additional levels fed by the beta decay of ^{115}Pd [5] have been reported. The beta-decay scheme of the isomeric state in ^{115}Pd is practically unknown; only one excited state fed by the beta decay has been observed [8]. In addition to beta-decay studies, the high-spin states in ^{115}Ag have been studied by prompt γ-ray spectroscopy [3]. There, a rotational band based on the $7/2^+[413]$ excitation together with three other bands were reported. However, these data sets are not complete. For example, the transition intensities, the beta feedings to different excited levels as well as the $\log_{10} ft$ values have not been published. In addition, only spins of the excited levels belonging to the rotational bands have been adopted in literature [8]. In this paper, a more complete picture of the beta decays of ^{115}Pd and ^{115}Pd^m will be reported.

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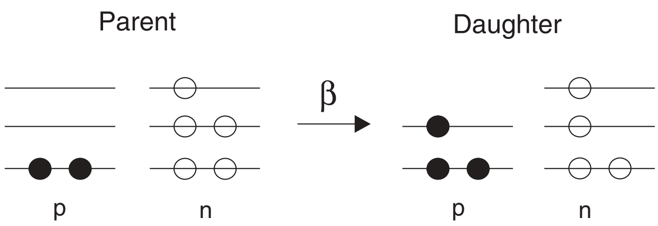

FIG. 1. Schematic presentation of the β^- decay to a three-quasiparticle state in the daughter nucleus. For allowed-unhindered (AU) transitions, the nucleons connected by the arrow have the same asymptotic quantum numbers $[Nn_3\lambda]$ and $\Delta\Omega = \pm 1$.

II. EXPERIMENT

The ions of interest were produced in proton-induced fission by bombarding a natural uranium target with a 25-MeV proton beam from the K-130 cyclotron at the ion guide isotope separator online (IGISOL) facility [17,18] at the University of Jyväskylä, Finland. Fission products were mass-separated with a 55° dipole magnet and cooled and bunched in a radiofrequency quadrupole cooler/buncher (RFQ) [19]. The JYFLTRAP double Penning trap setup [20] was used for isobaric purification of the ion samples. After the purification, the ion samples were implanted into a movable tape surrounded by the detector setup located after the Penning traps. The detector setup consisted of a 2-mm-thick plastic scintillation detector and three Ge detectors to measure the β and γ radiation, respectively. A planar Ge detector (LOAX) with a thin Be window was used for collecting x rays and low-energy γ rays, whereas two coaxial HPGe detectors were used to measure the γ radiation up to 4 MeV. The experimental setup and measurement procedures have been described in more detail in Ref. [21].

Decays of ^{115}Pd states were studied using the same data set as obtained for the main experiment focusing on the ^{115}Ru isotope [21]. JYFLTRAP was operated in bunched mode to transmit only ^{115}Ru ions every 111 ms. The transport tape was moved to remove accumulated daughter activities every 2700 cycles (≈300 s). Due to a relatively long accumulation time, a remarkable amount of statistics related to two subsequent beta decays (^{115}Rh and ^{115}Pd) was also collected; see Fig. 2. The results based on the same experimental data but related to the ^{115}Ru decay have been published in Refs. [21,23,24] and the results related to the ^{115}Rh decay in Refs. [10,11]. In this paper, the beta decays of ^{115}Pd and ^{115}Pd^m are presented.

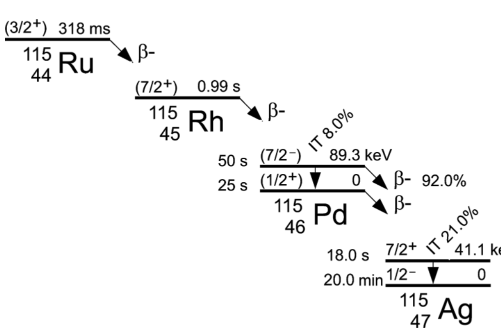

FIG. 2. Schematic illustration of the beta decay of ^{115}Ru and the subsequent beta decays. The data are from Refs. [10,21,22].

III. RESULTS

Altogether 65 gamma transitions assigned to the beta decays of either the ground state or isomeric state of ^{115}Pd have been identified. Of these transitions, 36 have been observed for the first time. All observed gamma transitions are presented in Table I with their intensities and coincidence relations.

The β-γ and β-γ-γ coincidences were used to build the beta-decay schemes of ^{115}Pd and ^{115}Pd^m. Two examples of coincidence spectra are shown in Fig. 3 and the resulting decay schemes in Figs. 4 and 5. The levels with spins $I \leqslant 3/2$ have been assigned to the ground-state decay and the levels with spins $I \geqslant 5/2$ to the isomer decay, assuming only allowed and first-forbidden beta transitions. In addition, the excited states in ^{115}Ag with unknown spins were assigned to the decay of the ground state of ^{115}Pd, since it is populated more strongly by the beta decay of ^{115}Rh compared to the isomeric state. The spin assignments will be discussed in more details in Sec. IV.

Altogether 14 excited levels related to the decay of ^{115}Pd and 12 excited levels related to the decay of ^{115}Pd^m have been found. Of these levels, 13 have been identified for the first time. The observed levels are presented in Tables II and III. The Q_β(g.s. → g.s.) = 4556(34) keV [26] and the $t_{1/2}$(g.s.) = 25(2) s and $t_{1/2}$(i.s.) = 50(3) s [5] have been applied in the $\log_{10} ft$ calculations. In addition, negligible direct beta feedings to the ground state and the isomeric

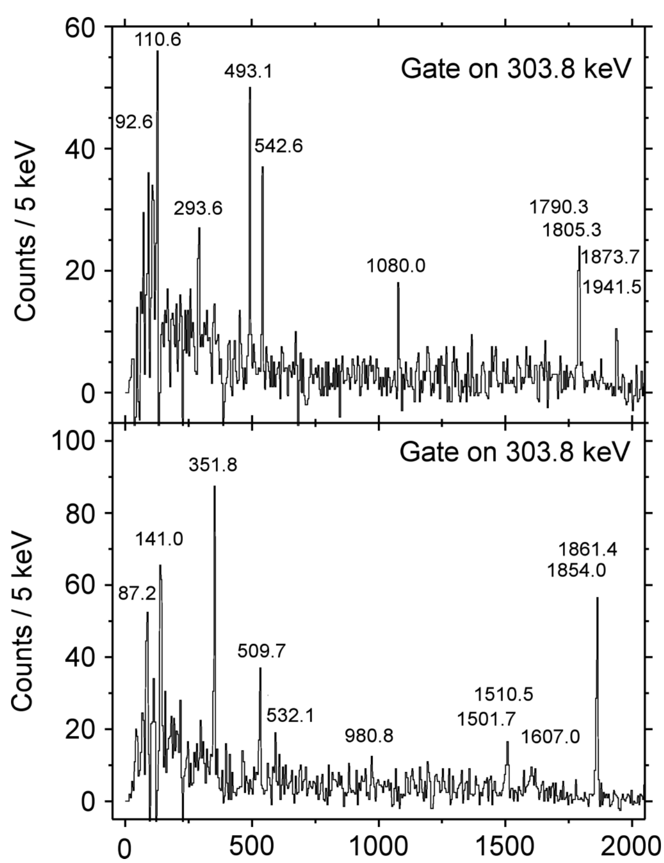

FIG. 3. Coincidence spectra gated by the two most intense gamma lines in ^{115}Ag. The peak energies are in keV.

TABLE I. Gamma rays following the beta decays of ^{115}Pd and ^{115}Pd^m. The transition intensities have been corrected with the internal conversion coefficient up to 400 keV. A notation [t] indicate that the multipolarity is the most probable based primarily on the spin differences between the levels, in which case the theoretical internal conversion coefficients [25] have been used. A notation [n] stands for a transition observed for the first time in this work. The coincident lines given in parentheses are tentative.

E_γ (keV)	Intensity	Multipolarity	Coincident lines
48.2(2)	0.7(5)	$(E1)$[t]	[a]
87.2(2)	9.8(12)	$M1$ [8]	255.5, 264.5, 422.8, 445.2
92.6(2)	7(3)	$E2$ [8]	303.8, (1719.8)
110.6(2)	3(2)	$(E2)$ [8]	303.8
125.5(2)	60(20)	$M1$ [8]	247.5, 398.8, 497.2, 623.3[b]
141.0(2)	10(2)	$(E1)$ [8]	200.8, 255.5
200.8(3)	2(2)	$(E2)$[t]	(92.6), 141.0, 396.3
247.5(2)	8(2)	$(M1)$[t]	125.5
255.5(2)	100(4)	$M1$ [8]	K_α(Ag), 87.2, 141.0, 351.8, 509.7, 532.1, 593.7, 980.8, 1501.7, 1510.5, 1607.0, 1854.0, 1861.4
264.5(2)[n]	2(2)	$(M1)$[t]	(87.2), 342.6
293.6(6)	0.8(8)	$(M1)$[t]	(303.8)[c]
303.8(2)	72(3)	$E1$ [8]	K_α(Ag), 92.6, 110.4, 293.6, 493.1, 542.6, 1080.0, 1790.3, 1805.3, (1873.7), 1941.5
342.6(2)	42(2)	$M1$,$E2$ [8]	(264.5), 422.8, 445.2, 593.7, 1519.7, 1750.6
351.8(2)	13(2)	$(E1)$[t]	255.5, 1501.7
373.1(2)	14(4)	$(M1)$[t]	1679.3, 1831.4[d]
396.3(2)	32(4)	$(E1)$[t]	200.7, 400.1, 450.6, 1712.7, 1719.8, 1781.3, 1848.0
398.8(5)	6(3)		125.5
400.1(10)[n]	3(3)		
422.8(3)	8(2)		87.2, 342.6
445.2(2)	7(2)		342.6
450.6(3)[n]	5(3)		396.3
468.9(2)	0.5(2)		(125.5)
493.1(2)[n]	6(2)		303.8
497.2(2)	1.4(4)		125.5
509.7(9)	2.2(5)		255.5
523.6(2)	19(2)		818.1, 1298.7
532.1(2)	1.2(3)		255.5,
542.6(2)[n]	6(1)		303.8
556.3(2)	18(2)		1496.3, 1512.2, 1579.9
593.7(2)	8(2)		255.5, 342.6
607.1(2)	33(2)		1255.0, 1485.5, 1501.7, 1510.5, 1571.2
623.3(10)[n]	1.2(8)		125.5
749.2(4)	2.5(5)		[e]
787.7(5)	1.9(12)		[f]
796.5(5)[n]	1.0(5)		[f]
818.1(2)[n]	8(2)		125.5, (398.8), 523.6
980.8(2)[n]	1.1(4)		255.5
1080.0(2)[n]	2.4(5)		303.8
1236.2(5)[n]	10(2)		[f]
1255.0(2)[n]	3.6(6)		607.1
1298.7(6)[n]	2(2)		125.5, 523.6
1341.6(6)[n]	5(2)		[e]
1485.5(5)[n]	1.8(8)		(607.1)
1496.3(5)[n]	3(2)		(255.5), (293.6), 556.3
1501.7(4)	13(2)		255.5, 351.8, 607.1
1510.5(4)[n]	26(2)		255.5, 607.1
1512.2(2)[n]	8(3)		(556.3)
1519.7(3)[n]	4(3)		
1571.2(2)[n]	3(2)		607.1
1579.8(4)[n]	3(2)		556.3
1607.0(5)[n]	1.3(4)		255.5
1679.3(4)[n]	3(3)		(373.1)

TABLE I. (*Continued.*)

E_γ (keV)	Intensity	Multipolarity	Coincident lines
1712.7(9)[n]	4(2)		396.3
1719.8(6)[n]	5(2)		141.0, 396.3
1750.6(8)[n]	7(3)		342.6
1781.3(8)[n]	1.7(8)		(255.5), 396.3
1790.3(5)[n]	9(2)		303.8
1805.3(5)[n]	1.5(4)		(303.8)
1831.4(10)[n]	1.1(7)		(247.5), (373.1)
1848.0(9)[n]	5(4)		(396.3)
1854.0(4)[n]	1.9(6)		255.5
1861.4(3)	26(2)		255.5
1873.7(4)[n]	1.7(5)		
1941.5(4)[n]	5(2)		303.8
2116(1)[n]	5(2)		[f]

[a]Seen only in the β-gated singles spectrum. The placement adopted from Ref. [8].
[b]A triplet with the 125.8-keV and 127.9-keV transitions in ^{115}Pd.
[c]A doublet with the 292.5-keV transition in ^{115}Rh. Multipolarity of $E2$ in Ref. [14].
[d]A doublet with the 372.5-keV transition in ^{115}Rh.
[e]Seen only in the β-gated singles spectrum. Assumed as a transition to the isomeric state owing to energy fitting.
[f]Seen only in the β-gated singles spectrum. Assumed as a transition to the ground state owing to energy fitting.

state of ^{115}Ag have been assumed, since no significant beta feedings to these states have been observed in Ref. [5]. This assumption introduces an additional source of uncertainty, and therefore, the $\log_{10} ft$ values are to be considered as lower limits.

IV. DISCUSSION

A wide range of excited levels in ^{115}Ag were populated by the beta decays of ^{115}Pd and ^{115}Pd^m. Different structures, including rotational bands and Nilsson states were identified among those states. The spin and parity assignments of the observed levels were made on the basis of the observed decay branchings and the level systematics of odd-A Ag isotopes, which are presented in Figs. 6 and 8. The spins of the lowest energy levels in the deformed bands based on the $1/2^+[431]$ and $7/2^+[413]$ Nilsson states have already been established by earlier works [3,16] and the spins of the lowest $(3/2^-)$ and $(5/2^-)$ levels have been suggested by Refs. [14,15,27]. In the following subsections arguments for the suggested spin assignments proposed in this work are given and the underlying structures are discussed.

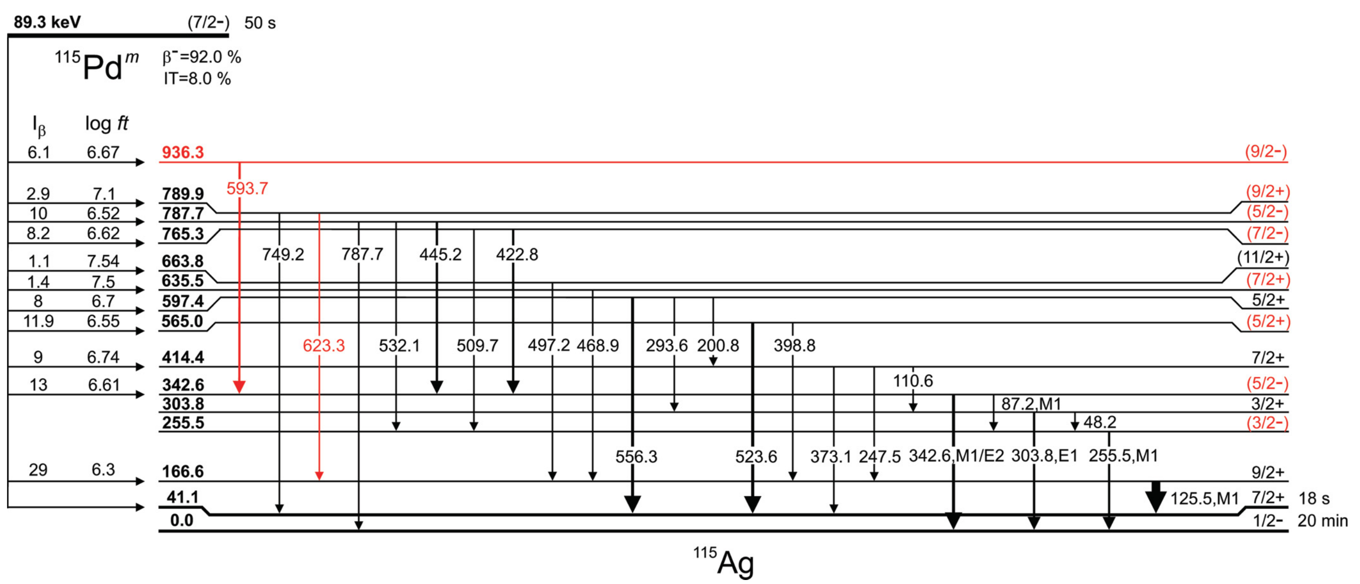

FIG. 4. (Color online) The beta-decay scheme of ^{115}Pd^m. The levels, transitions, and spin assignments drawn in red have been observed for the first time. The majority of the transitions in black have been assigned to the beta decay of the ^{115}Pd ground state in earlier beta-decay works [8]. Energies are in keV and the arrow widths correspond approximately to the transition intensities. Unfortunately, the direct beta feeding to the isomeric state could not be determined in this work.

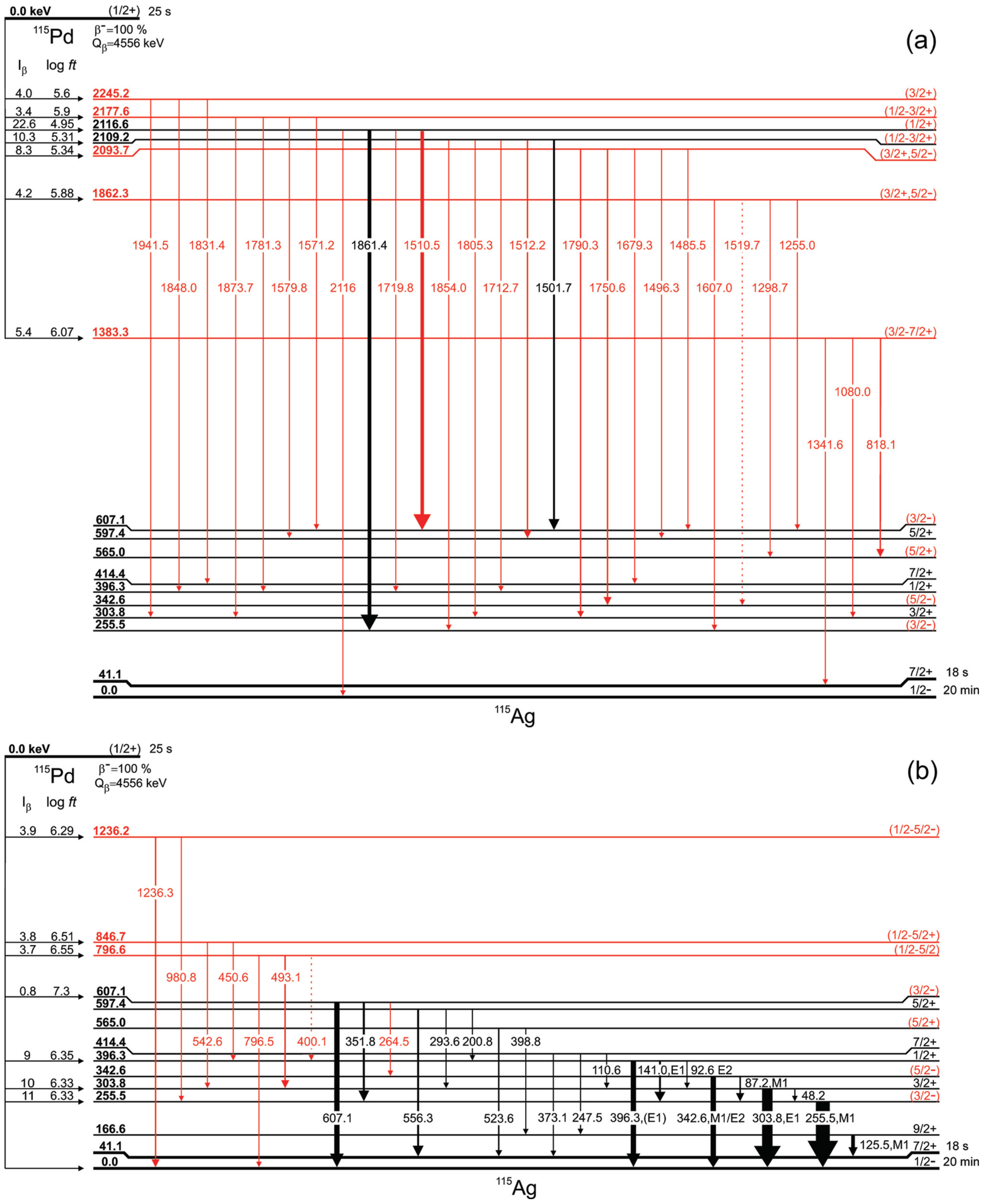

FIG. 5. (Color online) The high-energy part (a) and the low-energy part (b) of the ^{115}Pd beta-decay scheme. The levels, transitions, and spin assignments drawn in red have been observed for the first time. Energies are in keV and the arrow widths correspond approximately to the transition intensities. Unfortunately, the direct beta feeding to the ground state could not be determined in this work.

TABLE II. Levels in ^{115}Ag fed by beta decay of the $(7/2^-)$ isomeric state of ^{115}Pd. The notation ^{n} stands for a new level or a new spin assignment suggested in this work. The given intensities are upper estimates, and $\log_{10} ft$ values are lower limits only, as the direct beta feeding to the isomeric state could not be determined in this work.

E_{level} (keV)	β feeding (%)	$\log_{10} ft$	I^π	Nilsson configuration
41.1(5)			$(7/2^+)$	$7/2^+[413]$
166.6(5)	29(15)	6.3(3)	$(9/2^+)$	$7/2^+[413]$
342.6(2)	13(4)	6.61(14)	$(5/2^-)^n$	$1/2^-[301]$
414.4(2)	9(4)	6.7(2)	$(7/2^+)$	$1/2^+[431]$
565.0(5)	11.9(13)	6.55(6)	$(5/2^+)^n$	
597.4(6)	8(4)	6.7(3)	$(5/2^+)$	$1/2^+[431]$
635.5(6)	1.4(6)	7.5(2)	$(7/2^+)^n$	
663.8(6)	1.1(4)	7.54(13)	$(11/2^+)$	$7/2^+[413]$
765.3(5)	8.2(15)	6.62(8)	$(7/2^-)^n$	$1/2^-[301]$
787.7(2)	10(2)	6.52(8)	$(5/2^-)^n$	$5/2^-[303]$
789.9(5)	2.9(12)	7.1(2)	$(9/2^+)^n$	
936.3(3)^n	6.1(9)	6.67(8)	$(9/2^-)^n$	$1/2^-[301]$

A. Negative-parity structures in ^{115}Ag

The negative-parity structures located at low excitation energies in ^{111}Ag have been identified in Ref. [2] based on a very thorough experimental study using the ^{110}Pd(^{3}He,pnγ)^{111}Ag reaction and on particle-rotor model calculations. Three rotational bands based on the $1/2^-[301]$, $3/2^-[301]$, and $5/2^-[303]$ proton excitations have been identified in that study. The spins and parities of these band heads are supported also by transfer reaction studies [28–30]. The same Nilsson configurations can also be suggested for ^{115}Ag, see Fig. 7, assuming that the nuclear structure should not change by adding four more neutrons to an odd-proton nucleus. This is especially true for ^{111}Ag and ^{115}Ag, since both are located close to the neutron midshell ($N = 66$), ^{111}Ag being two neutrons below and ^{115}Ag two neutrons above it. In addition, both nuclei can be estimated to be almost equally deformed [1], which is supported by the locations of the $1/2^+[431]$ intruder bands at similar energies in both nuclei; see Fig. 8.

TABLE III. Levels in ^{115}Ag fed by the beta decay of the $(1/2^+)$ ground state of ^{115}Pd. The notation ^{n} stands for a new level or a new spin assignment suggested in this work. The given intensities are upper estimates, and $\log_{10} ft$ values are lower limits only, as the direct beta feeding to the ground state could not be determined in this work.

E_{level} (keV)	β feeding (%)	$\log_{10} ft$	I^π	Nilsson configuration
0.0			$(1/2^-)$	$1/2^-[301]$
255.5(2)	11(2)	6.33(9)	$(3/2^-)^n$	$1/2^-[301]$
303.8(2)	10(3)	6.33(10)	$(3/2^+)$	$1/2^+[431]$
396.3(2)	9(3)	6.35(15)	$(1/2^+)$	$1/2^+[431]$
607.1(2)	0.8(8)	7.3(5)	$(3/2^-)^n$	$3/2^-[301]$
796.6(4)^n	3.7(11)	6.55(14)	$(1/2–5/2^+)^n$	
846.7(4)^n	3.8(9)	6.51(11)	$(1/2–5/2^+)^n$	
1236.2(4)^n	3.9(6)	6.29(8)	$(1/2–5/2^-)^n$	
1383.3(3)^n	5.4(10)	6.07(9)	$(3/2–7/2^+)^n$	
1862.3(4)^n	4.2(13)	5.88(14)	$(3/2^+, 5/2^-)^n$	
2093.7(3)^n	8.3(13)	5.34(8)	$(3/2^+, 5/2^-)^n$	
2109.2(4)^n	10.3(12)	5.31(7)	$(1/2–3/2^+)^n$	
2116.6(6)^n	22.6(12)	4.95(5)	$(1/2^+)^n$	
2177.6(8)^n	3.4(8)	5.9(2)	$(1/2–3/2^+)^n$	
2245.2(4)^n	4.0(15)	5.6(2)	$(3/2^+)^n$	

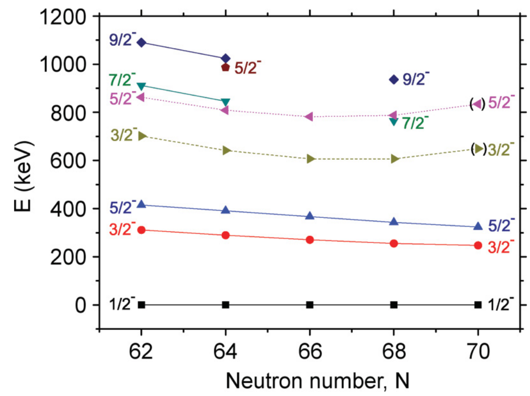

FIG. 6. (Color online) Level systematics of odd-mass, neutron-rich silver isotopes. The levels based on the $1/2^-[301]$ excitation are connected with solid lines, the levels based on the $3/2^-[301]$ excitation are connected with dashed lines, and the levels based on the $5/2^-[303]$ excitation are connected with dotted lines. The different excitations have slightly different behavior, the energies of the levels based on the $1/2^-[301]$ excitation are decreasing as a function of increasing neutron number, whereas the other states have shallow minima at $N = 66$ at the neutron midshell. The data are from Refs. [8,27]. The spin assignments for the levels in ^{117}Ag (at $N = 70$) shown in brackets have been suggested in this work based on systematics.

1. The $\pi 1/2^-[301]$ excitation

^{115}Ag as well as the majority of neutron-rich Ag isotopes has a ground-state spin of $1/2^-$ [8]. This may correspond to the $\pi 1/2^-[301]$ Nilsson state originating from the $2p_{1/2}$ spherical shell, being the only suitable state near the Fermi surface for $Z = 47$. A ground-state band based on this configuration has been observed in ^{111}Ag [2], which supports this interpretation. A set of levels with similar properties can be found in ^{115}Ag, the levels at 255.5 and 342.7 keV being the next members of this band. A spin of $(3/2^-)$ for the level at 255.5 keV and a spin of $(5/2^-)$ for the level at 342.7 keV have been suggested in a conference proceedings [15], although not adopted in Ref. [8]. A multipolarity of $M1$ for the 255.5-keV transition and $M1/E2$ for the 342.7-keV transition support these spin assignments.

According to systematics, the next member in the ground-state band should have an energy of around 800 keV. The level at 765.3 keV has connections to the levels at 255.5 keV $(3/2^-)$ and 342.6 keV $(5/2^-)$ but not to the ground state $(1/2^-)$. The intensity ratio of the transitions depopulating this level $I_\gamma(509.7, E2/422.8, M1)$ is close to the ratio based on the Weisskopf estimates assuming an enhanced $E2$ transition and some $E2/M1$ mixing of the $M1$ transition. In addition, a 599.3-keV transition deexciting this level to the $(9/2^-)$ level at 166.6 keV has been reported in Ref. [8]. These arguments support an assignment of $(7/2^-)$ to the 765.3-keV level in

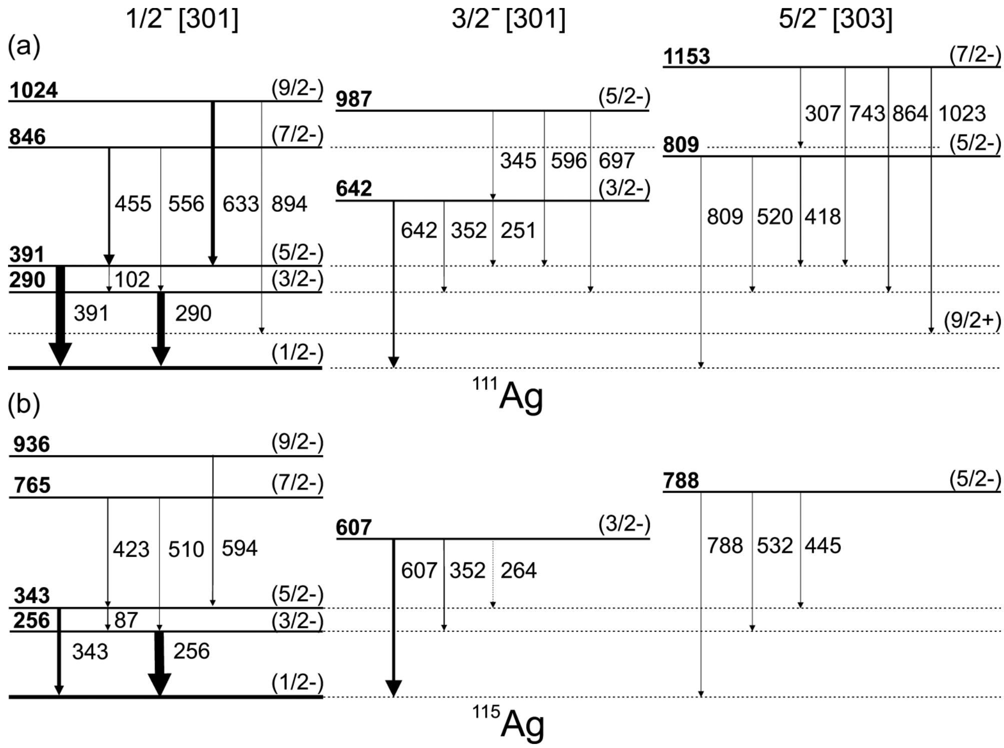

FIG. 7. States identified as members of negative-parity rotational bands in ^{111}Ag (a) [2]. Similar structures have been adopted for ^{115}Ag (b). The line widths correspond approximately to the transition intensities.

the ground-state band. No transition to the $(3/2^-)$ state based possibly on the $3/2^-[301]$ excitation has been observed, which suggests different structures for these states.

Only one transition depopulating the 936.3-keV level has been observed in this work. It goes to the $(5/2^-)$ level at 342.6 keV. Based on the level systematics and the similar structure in ^{111}Ag, a $(9/2^-)$ spin assignment for the 936.3-keV level can be suggested. This level can be tentatively assigned as a member of the ground-state band. Another possibility is that this level is the $5/2^-$ member of the band based on the $3/2^-[301]$ excitation. However, that level in ^{111}Ag deexcites via three weaker transitions; see Fig. 7. Since only one transition was observed in this work, it most probably corresponds to an intense transition from the $(9/2^-)$ level.

2. *The $\pi 3/2^-[301]$ excitation*

The level at 607.1 keV deexcites via a strong transition to the ground state and two weaker transitions to the $(3/2^-)$ and $(5/2^-)$ states at 255.5 keV and 342.6 keV, respectively. A $(3/2^-)$ spin assignment can be suggested based on systematics, as already proposed in Ref. [15]. The level at 641.92 keV in ^{111}Ag has been interpreted as a band head of the rotational band based on the $3/2^-[301]$ Nilsson configuration originating from the $1f_{5/2}$ spherical shell. A smooth behavior of the level systematics suggests the 607.1-keV level in ^{115}Ag to have the same structure.

3. *The $\pi 5/2^-[303]$ excitation*

The level at 787.7 keV has connections to the $1/2^-$ ground state as well as to the excited states with spins of $(3/2^-)$ at 255.5 keV and $(5/2^-)$ at 342.6 keV. Therefore, the most probable spin for this level is $3/2^-$ or $5/2^-$. No good candidate for the $3/2^-$ spin assignment can be found in systematics. Instead, candidates for the $5/2^-$ and $7/2^-$ spin assignments are found for either this level or for the level at 765.3 keV. These levels can be distinguished by different intensity ratios of the deexciting transitions as well as the 787.7-keV transition to the ground state, and a spin of $(5/2^-)$ for the 787.7-keV level has been suggested. The same spin assignment was also proposed in a conference proceedings [15]. No transition to the $(3/2^-)$ state based possibly on the $3/2^-[301]$ excitation has been observed, which supports different structures for these states. Therefore, a possible $5/2^-[303]$ configuration split from the $1f_{5/2}$ spherical shell can be suggested, which is identical with the Nilsson configuration of the 809.3-keV level in ^{111}Ag [2].

The authors of Ref. [15] have studied the $^{105-109}$Rh and $^{113-115}$Ag nuclei by fission and single-particle transfer reactions. They observe that, in all studied cases, the largest $2p_{3/2}$ and $1f_{5/2}$ single-particle strengths are not carried by the first but by the second excited $(3/2^-)$ and $(5/2^-)$ levels. This argument supports also the $3/2^-[301]$ and $5/2^-[303]$ assignments for the second $(3/2^-)$ and $(5/2^-)$ levels at 607.1 and 787.7 keV, respectively.

B. Low-energy positive-parity structures in ^{115}Ag

The positive-parity level systematics of neutron-rich Ag isotopes are presented in Fig. 8. Three different structures can be identified, two rotational bands based on the $7/2^+[413]$ and $1/2^+[431]$ excitations (upper panel of Fig. 8), and a bandlike structure above the 565.0-keV level (lower panel of Fig. 8). A

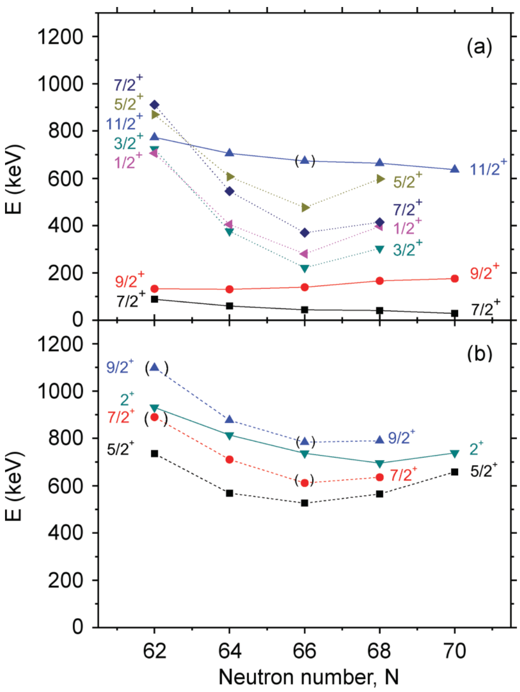

FIG. 8. (Color online) Systematics of positive-parity levels in odd-mass silver isotopes. The rotational band structures are shown in the upper panel (a) and the nonrotational structures in the lower panel (b) together with the 2_2^+ states in even-even Pd isotopes. The $7/2^+[413]$ band members are connected with solid lines and the members of the intruder band based on the $1/2^+[431]$ excitation are connected with dotted lines in the upper panel. The 2_2^+ states in even-even Pd isotopes are connected with solid lines and a set of levels built on the 565.0 keV level are connected with dashed lines in the lower panel. The data are from Refs. [8,15,27]. The spin assignments for the levels shown in brackets have been suggested in this work based on systematics.

rotational band with a $(11/2^+)$ band head at 285.5 keV was reported in Ref. [3] but not observed in this work.

1. The $\pi 7/2^+[413]$ excitation

A rotational band in ^{115}Ag based on the $7/2^+[413]$ excitation has already been observed in Ref. [3]. In this work, three lowest-spin members of this band, located at 41.1 keV $(7/2^+)$, 166.6 keV $(9/2^+)$, and 663.8 keV $(11/2^+)$ were confirmed. The level at 663.8 keV $(11/2^+)$ was seen also in the earlier beta decay work of Ref. [14] but no spin assignment was given. This level cannot be directly fed by beta decay of the $(7/2^-)$ isomeric state due to a $\Delta I = 2$ character of a possible beta transition. Therefore, it is probably fed by γ transitions from high-lying states, which are too weak to be detected.

Similar bands have also been observed in other odd-A Ag isotopes [31,32] supported by the transfer reaction data [28]. A spin of the 673.4-keV level in ^{113}Ag in Fig. 8 is tentative, since it has been reported to deexcite via transitions to the $9/2^+$ state and to the $1/2^+$ ground state in Ref. [14] and no spin assignment has been adopted in Ref. [8]. Since it is not very probable that this level deexcites only to two states with such a large spin difference, the ground-state transition has been omitted and a $(11/2^+)$ assignment has been suggested. The members of this band exhibit almost linear behavior with decreasing energies of the $7/2^+$ and $11/2^+$ states and increasing energies of the $9/2^+$ states as a function of neutron number.

2. The $\pi 1/2^+[431]$ excitation

Another positive-parity rotational band in odd-A Ag isotopes is based on the intruder $1/2^+[431]$ Nilsson configuration, which originates from the down-sloping proton orbital. This orbital crosses the $Z = 50$ shell gap and intruders among the $g_{9/2}$ and $p_{1/2}$ subshells. The existence of this band at low energies is a clear indication of a prolate deformation, which reaches its maximum at $N = 66$, in the middle of the $N = 50$ and 82 shell closures. This configuration has been suggested for ^{115}Ag already in earlier beta-decay works [16] and has been observed also in odd-A Rh isotopes; see for example Refs. [16,21]. The band members at energies of 303.8 keV $(3/2^+)$, 342.6 keV $(1/2^+)$, 414.4 keV $(7/2^+)$, and 597.4 keV $(5/2^+)$, respectively, were confirmed in this work. No candidates for the higher spin levels with the same configuration have been observed.

3. Bandlike structure built on the 565.0-keV level

The level at 565.0 keV deexcites to the $(7/2^+)$ and $(9/2^+)$ states at 41.1 keV and 166.6 keV, respectively, which limits the possible spins for this level to $(5/2$–$11/2^+)$. In the level systematics shown in Ref. [15] it has already been assigned as $(5/2^+)$, which has been adopted also in this work.

The level at 635.3 keV has been observed in Ref. [14] to deexcite via a 468.8-keV transition to the $(9/2^+)$ state at 166.6 keV. The 468.9-keV transition can be seen in this work in the β-gated singles spectrum and weakly in coincidence with the 125.5-keV transition. The coincidence spectrum gated by the 125.5-keV transition suffers from background generated by the strong 125.8-keV transition in ^{115}Pd, which may prevent observation of a clear coincidence relation. A possible 635-keV transition to the $(7/2^+)$ state could not be observed in this work due to an intense peak at 638 keV in ^{115}Rh.

The level at 789.9 keV (790 keV in Ref. [8]) has been assigned to be fed by the beta decay of the $(7/2^-)$ isomeric state [8]. It has been reported to deexcite via two transitions, to the $1/2^-$ ground state and to the $7/2^+$ isomeric state. In this work another transition to the $(9/2^+)$ state at 166.6 keV was found. Due to a large spin difference, a transition to the ground state is not very probable and a high and positive spin $(5/2$–$11/2^+)$ for this level can be suggested.

Assigning the levels at 635.3 keV and 789.9 keV to spins of $(7/2^+)$ and $(9/2^+)$, respectively, a set of levels with similar spacings as in ^{111}Ag can be found. This set of levels in ^{111}Ag, decaying mainly to the first $7/2^+$ and $9/2^+$ states having a possible $7/2^+[413]$ Nilsson configuration, has been interpreted as a part of a nonrotational multiplet in Ref. [2]. A similar set of levels with spins of $(5/2$–$9/2^+)$ can be tentatively identified in other Ag isotopes as well, see the lower panel of Fig. 8. The behavior of these levels as a function of increasing neutron number is rather similar to the behavior of the second 2^+ states in the even-even Pd core, reaching its minimum

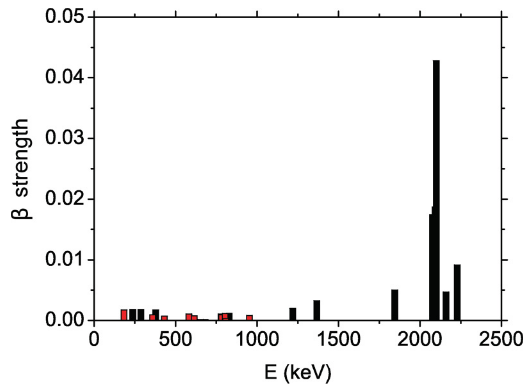

FIG. 9. (Color online) The beta-strength distribution of the decays of the ground state (black) and the isomeric state (red) of ^{115}Pd. A considerable part of the feeding goes to states around 2 MeV, which has not been seen in earlier beta-decay studies [8].

near the neutron mid-shell at $A = 114$. Therefore, they may originate from the coupling of an odd proton to the 2_2^+ state of the core.

Some interpretation of the literature data was needed to identify these states in lighter Ag isotopes. The spins of the lowest members ($5/2^+$) of this multiplet were already well established in literature except for the level at 526.2 keV in ^{113}Ag, which has been assigned to ($5/2^+$) in this work based on the similarities in decay patterns as well as on the level systematics. The energies of the ($7/2^+$) and ($9/2^+$) states in ^{109,113}Ag are not well established, but a behavior similar to that of the ($5/2^+$) states can be found among the states with unknown spins.

The level at 890 keV in ^{109}Ag has been assigned as ($9/2^+$) in Ref. [28] and assignments of ($7/2,9/2^+$) have been adopted in Ref. [8]. The 611.3-keV level in ^{113}Ag deexcites to the $7/2^+$ and $9/2^+$ states, and no spin assignment has been adopted in Ref. [8]. Both states fit in the level systematics if assigned as ($7/2^+$).

The 1098.5-keV level in ^{109}Ag deexcites to the $7/2^+$ and $9/2^+$ states and a state with a similar decay pattern can be found at 783.2 keV in ^{113}Ag. A ($9/2^+$) spin assignment for both states fits well in systematics. Both states are populated by the beta decays of ^{109,113}Pd ($5/2^+$) with $\log_{10} ft$ values of 6.1 [8,14], and therefore these states have been assigned to have a spin lower than $9/2^+$ [8]. However, due to the well known Pandemonium effect, the $\log_{10} ft$ values in the studied region need to be considered as lower limits. It is possible that in those studies performed with smaller Ge detectors the high-energy transitions have not been observed due to limited detector efficiency. It would be of great interest to remeasure those cases with modern experimental techniques to see whether the similar beta-strength patterns can be observed as in Fig. 9 for ^{115}Ag.

4. *Nonband levels at intermediate energies*

The level at 796.6 keV has weak connections to the $1/2^-$ ground state and to the ($1/2^+$) excited state at 396.3 keV, as well as somewhat stronger connection to the ($3/2^+$) level at 303.8 keV. The level at 846.7 keV de-excites via transitions to the ($1/2^+$) state at 303.8 keV and the ($3/2^+$) state at 396.3 keV. Both levels are fed by the beta decay of ^{115}Pd with a $\log_{10} ft$ value of around 6.5. A low and positive spin ($1/2$–$5/2^+$) can be proposed for both states.

The level at 1236.2 keV deexcites via a strong transition to the ($1/2^-$) ground state and a weaker transition to the ($3/2^-$) level at 255.5 keV. Therefore, a low and negative spin ($1/2$–$5/2^-$) can be suggested.

The level at 1383.2 keV deexcites via transitions to the $7/2^+$ isomeric state as well as to the excited states at 303.8 keV ($3/2^+$) and 565.0 keV ($5/2^+$). Therefore a positive spin ($3/2$–$7/2^+$) can be suggested. This level has been assigned to the beta decay of the ^{115}Pd ground state although it may belong also to the decay of the isomeric state.

The level at 1862.3 keV is fed by an allowed beta transition and deexcites via transitions to the levels with spins of ($3/2^-$), ($5/2^-$), and ($5/2^+$). It has been assigned to the beta decay of the ground state of ^{115}Pd, in which case the only possible spin for this state is ($3/2^+$). However, assigning this state to be fed by the beta decay of the isomeric state of ^{115}Pd leaves also the ($5/2^-$) option open.

C. High-energy levels around 2 MeV

A set of levels at around 2 MeV populated strongly by the beta decay of the ^{115}Pd ground state has been observed in this work. All five levels have a $\log_{10} ft$ value smaller than 6, indicating allowed beta transitions. Therefore, the spins of these states have been assigned as ($1/2^+$) or ($3/2^+$). Similar states have not been observed in lighter Pd decays. Only two states at 2259 keV and 2351 keV in ^{117}Ag populated strongly by the beta decay of ^{117}Pd have been observed in Ref. [27].

The level at 2093.7 keV deexcites via transitions to low-energy levels having spins and parities of ($3/2^+$), ($3/2^-$), ($5/2^+$), ($5/2^-$), and ($7/2^+$). Assuming this level to belong to the beta decay of the ground state of ^{115}Pd with a $\log_{10} ft$ value of 5.34 limits the possible candidates for the spin and parity to ($1/2$–$3/2^+$). Since it deexcites also to a ($7/2^+$) level, the ($1/2^+$) assignment can be discarded and the ($3/2^+$) is the most probable spin assignment for this level. As for the 1862.3-keV level, assigning to be fed by the beta decay of the isomeric state leaves also the ($5/2^-$) assignment possible.

The level at 2109.2 keV has connections to low-energy levels with spins of ($1/2^+$), ($3/2^+$), ($3/2^-$), and ($5/2^-$). Due to an allowed beta transition, the possible candidates for the spin and parity are ($1/2$–$3/2^+$). This level has been reported already in Ref. [5], deexciting via the 1503-keV transition (1501.7 keV in this work).

The level at 2116.6 keV deexcites via transitions to levels having spins and parities of ($1/2^+$), ($1/2^-$), and ($3/2^-$). Since it is fed by an allowed beta transition and since it does not deexcite to the levels having spins larger than 3/2, a ($1/2^+$) spin assignment can be suggested. This level has already been reported to deexcite via a 1862-keV transition in Ref. [5]. A level at 2351 keV fed strongly ($\log_{10} ft = 5.1$) by the beta decay of ^{117}Pd has been observed in Ref. [27]. This level deexcites via transitions to the first $3/2^-$ state at 247 keV and to the state at 649 keV, which should have a spin of

($3/2^-$) and a possible $3/2^-[301]$ Nilsson configuration based on systematics. This deexciting pattern is analogous with the deexciting pattern of the 2116.6 keV level in ^{115}Ag.

The level at 2177.6 keV has connections to the low-energy levels with spins of ($1/2^+$), ($3/2^+$), ($3/2^-$), and ($5/2^-$). The decay properties and the relatively low $\log_{10} ft$ value of 5.9 suggest the spin and parity of ($1/2^+$) or ($3/2^+$).

The level at 2245.2 keV deexcites to the levels at 303.8, 396.3, and 414.4 keV with spins of $3/2^+$, $1/2^+$, and $7/2^+$, respectively. These levels have been proposed to be members of a rotational band based on the $1/2^+[431]$ intruder state. Due to an allowed beta transition, a ($3/2^+$) spin assignment can be suggested.

1. Beta-strength distribution

Strong beta feedings to the excited states at around 2 MeV are demonstrated in Fig. 9, where the beta-strength values are presented. These values have been calculated in a manner similar to that in Ref. [21]. The beta-strength distribution can be compared to Fig. 7 in Ref. [21], in which the beta-strength values have been plotted for odd-*A* Ru decays in the same region of the nuclide chart.

The level at 2116.6 keV in ^{115}Ag is fed by a beta transition with a $\log_{10} ft$ value of 4.95, which corresponds to an allowed-unhindered beta transition. The only AU pair available near the Fermi level for $N \approx 69$ and $Z \approx 47$ at $\beta \sim 0.2$–0.3 is $\nu 5/2^+[413]$ and $\pi 7/2^+[413]$; see for example Fig. 1 in Ref. [33] or Fig. 1 in Ref. [34]. Assuming the $\nu 1/2^+[411]$ Nilsson state to be the ground-state configuration for ^{115}Pd, the $\nu 5/2^+[413]$ Nilsson state is located near but below that and the corresponding AU transition would populate a three-quasiparticle state above the pairing gap. The same Nilsson states may be active also in odd-*A* Ru beta decays.

D. Spins and parities of ^{115}Pd and ^{115}Pd^m

In this work, the ground-state spin of ($1/2^+$) and the isomeric-state spin ($7/2^-$) of ^{115}Pd suggested by Refs. [7,10] have been applied to the interpretation of the experimental data. This work partially supports the above mentioned spins and parities, but also leaves a ($3/2^+$) ground-state spin possible, which would further change the spin of the isomeric state. This statement is due to the observation of the total transition intensities populating the ground state and isomeric state of ^{115}Pd being somewhat different compared to the intensities of beta transitions depopulating these states. However, it is worth commenting that there are uncertainties in those intensity values; for example, the direct feedings to the ground and isomeric states in ^{115}Pd and ^{115}Ag are not known. According to the Alaga rules for deformed nuclei [35], since the next states in the rotational bands are populated by beta decay, the beta feedings to the ground and isomeric states should also be nonzero. In beta decays of the odd-mass Ag isotopes close to ^{115}Pd, similar first-forbidden beta transitions have been observed with relatively large branching rations [36–38]. Therefore, unambiguous definitions of the spins of the beta-decaying states in ^{115}Pd cannot be made based on this beta-decay data.

V. CONCLUSIONS

To summarize, the excited levels in ^{115}Ag have been studied via beta decays of ^{115}Pd and ^{115}Pd^m. The beta-decay schemes of both states were considerably extended. The observed levels have been compared to the level systematics of odd-*A* Ag isotopes and several different structures have been identified.

The existence of two positive-parity rotational bands based on the $\pi 7/2^+[413]$ and $\pi 1/2^+[431]$ Nilsson states in ^{115}Ag has been confirmed. A new rotational band structure based on the $\pi 1/2^-[301]$ Nilsson state as well as possible candidates for the $\pi 3/2^-[301]$ and $\pi 5/2^-[303]$ excitations have been proposed. All the observed deformed states are located at $\beta \approx$ 0.2–0.4 on the prolate side of the Nilsson diagram [33,34]. In addition, a set of nonrotational levels deexciting to the lowest ($7/2^+$) and ($9/2^+$) states, which are based on the $\pi 7/2^+[413]$ configuration, has been proposed. Similar states have been observed in ^{111}Ag [2] and can also be tentatively proposed for ^{109,113}Ag isotopes.

A set of levels strongly populated by the beta decay of the ^{115}Pd ground state has been observed. These states may have a three-quasiparticle nature. Similar strong beta feedings have not been found in lighter Pd decays. The level at 2116.6 keV has been observed to be populated by an allowed-unhindered beta transition, which could occur between the prolate $\nu 5/2^+[413]$ and $\pi 1/2^+[413]$ Nilsson states.

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