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Negative parity bands of ^{115}Pd and band structures in ^{113,115,117}Pd

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Level structures of ^{113,115,117}Pd have been studied using the Gammasphere and a spontaneous fission source of ^{252}Cf. A new 85.1-keV transition was identified in ^{113}Pd. This indicates that the spin and parity of the isomeric state is $9/2^-$ rather than the previously assigned $11/2^-$. New low-energy transitions are confirmed in ^{115,117}Pd. In ^{115}Pd, the 39.0.- and 49.0-keV transitions are shown to be in prompt coincidence. This coincidence relationship indicates a spin and parity assignment of $1/2^+$ for the ground state rather than the previously assigned $3/2^+$.

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I. INTRODUCTION

Advances in experimental techniques to study the nuclei produced in spontaneous fission (SF) have led to new findings in neutron-rich nuclei [1]. Often, previously studied nuclei can be revisited to extend level structures and find new features. The region beyond the subshell closure at $N = 64$ is of interest in determining the behavior of the $h_{11/2}$ neutron shell in this neutron-rich region. A detailed study of the odd-mass Pd nuclei can shed light on the structure arising from this neutron shell.

The lighter odd-*A* nuclei, ^{109,111}Pd, have prolate ground state deformations [2]. As the mass number increases in these Pd nuclei, the deformation is expected to gradually change toward an oblate shape beyond ^{111}Pd [3]. However, past experiments have shown that the yrast structures in ^{113,115,117}Pd nuclei correspond to rotational bands arising from a prolate deformation [4–6]. The present experiment investigates these bands with very high statistics data to better determine the energy levels of odd-*A* Pd nuclei in this region.

Previous studies of odd-*A* $^{113-117}$Pd nuclei have identified several negative parity levels and transitions between them [4–6]. β decay studies [7–9] led to the identification of isomeric states in these nuclei leading to construction of decoupled rotational bands of negative parity built on these isomers. The isomeric states have been assigned spin and parity (J^π) of $11/2^-$. The past studies are in good agreement for the nuclei up to ^{111}Pd [2]. In ^{113}Pd, there is a discrepancy as to the J^π of the isomer, as one group [5] assigns a J^π of $9/2^-$ spin and places the rotational band on a $11/2^-$ level as a side band, while the other groups [4,6] assign a J^π of $11/2^-$ with the rotational band built on the isomer. The results in ^{115,117}Pd are in agreement regarding the rotational band placement. A diagram of the known negative parity level energies as previously assigned is shown in Fig. 1.

β-decay experiments have probed the ground state and low spin levels of these nuclei. The ground state of ^{113}Pd β-decays to a $7/2^+$ state in ^{113}Ag with a 75% branching ratio [10]. The log *ft* value of 5.4 indicates a Gamow-Teller type of transition, pointing to a $5/2^+$ ground state for ^{113}Pd. In ^{115}Pd, the isomer at 89.3 keV β decays to an excited state in ^{115}Ag that subsequently deexcites to the $1/2^-$ ground state [9]. This state has previously been assigned a J^π of $11/2^-$ because of the rotational band, but clearly this is questionable, as a $7/2^-$ assignment explains the β-decay results much better. The nucleus ^{117}Pd is populated in the β decay of ^{117}Rh [8]. Multipolarity measurements of γ transitions in the excited positive parity levels allows a ground state assignment of $3/2^+$ or $5/2^+$, and again $5/2^+$ was chosen to allow for the $11/2^-$ decoupled band.

The picture is somewhat unclear and unsatisfactory, and our new work resolves these discrepancies with the discovery of new transitions allowing a revision of spin and parity assignments to bring all experiments into agreement. Since our work was completed [11], a concurrent experiment examining ^{115,117}Pd has been published [12]. As with our experiment, they report the discovery of low-energy transitions below the rotational band cascade in both ^{115,117}Pd, ranging from 39 to 85 keV. But there is a disagreement in the analysis of the ^{115}Pd levels and spins. These new low-energy transitions shift the assignment of the isomeric state to explain both the decoupled rotational band structure and the ground state β-decay work.

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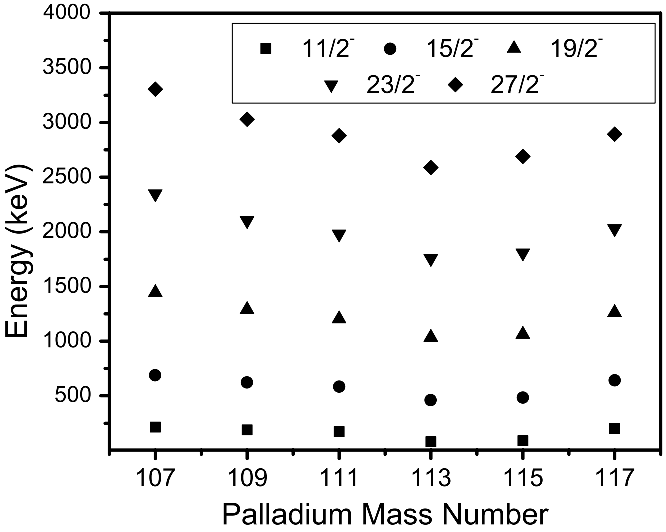

FIG. 1. Previous negative parity levels in ^{107,109,111,113,115,117}Pd.

II. EXPERIMENTAL DETAILS

The experiment was performed at the Lawrence Berkeley National Laboratory. A ^{252}Cf source with a strength of 62 μCi was placed in Gammasphere with 102 Compton suppressed Ge detectors. The source was sandwiched between Fe foils with thickness 10 mg/cm^2. Collecting 5.7×10^{11} triple coincidence or higher fold events, we constructed a γ-γ-γ coincidence cube. The cube is a three-dimensional histogram of γ-ray energies, constructed with the RADWARE software package [13]. The energy channels used minimal compression, allowing us to maximize the resolution and resolve peaks that are close in energy. The energy thresholds are set at 33 keV by adjusting the thresholds on the constant fraction discriminators. The master trigger event is derived from the coincidences between the Ge detector CFDs and a coincidence window of width 100 ns from the time spectrum. The photopeak efficiency was determined by using the standard sources such as ^{56}Co and ^{152}Eu and the transitions from ^{252}Cf. The efficiency curve is fitted to a function $\exp[(A + Bx + Cx^2)^{-G} + (D + Ey + Fy^2)^{-G}]^{-1/G}$ where $x = \log(E_\gamma/100)$ and $y = \log(E_\gamma/1000)$ with E_γ in keV. The seven parameters of the fit are determined with approximately 100 data points.

III. RESULTS AND DISCUSSION

We observed previously unknown low-energy transitions in each of the isotopes. Absorbers and energy thresholds had previously prevented the detection of these transitions. As seen in Fig. 2, by setting a double gate on 440.0- and 766.7-keV transitions in ^{117}Pd, we observed a low-energy transition of 63.7 keV. Figure 3 shows the discovery of an 85.1-keV transition in ^{113}Pd and 39.0- and 49.0-keV transitions in ^{115}Pd. Also labeled in the figure are x rays from W, Cf, and Cm. The complex around 72 keV is attributable to Pb x-rays and appear in all spectra.

The 63.7-keV transition is found to be depopulating the lowest previously known negative parity level. By gating on several pairs of transitions in ^{117}Pd, we place the transition directly below the previously known rotational band based on intensities. To maintain a J^π of $11/2^-$ for the band head of the decoupled rotational band, the low-energy transition

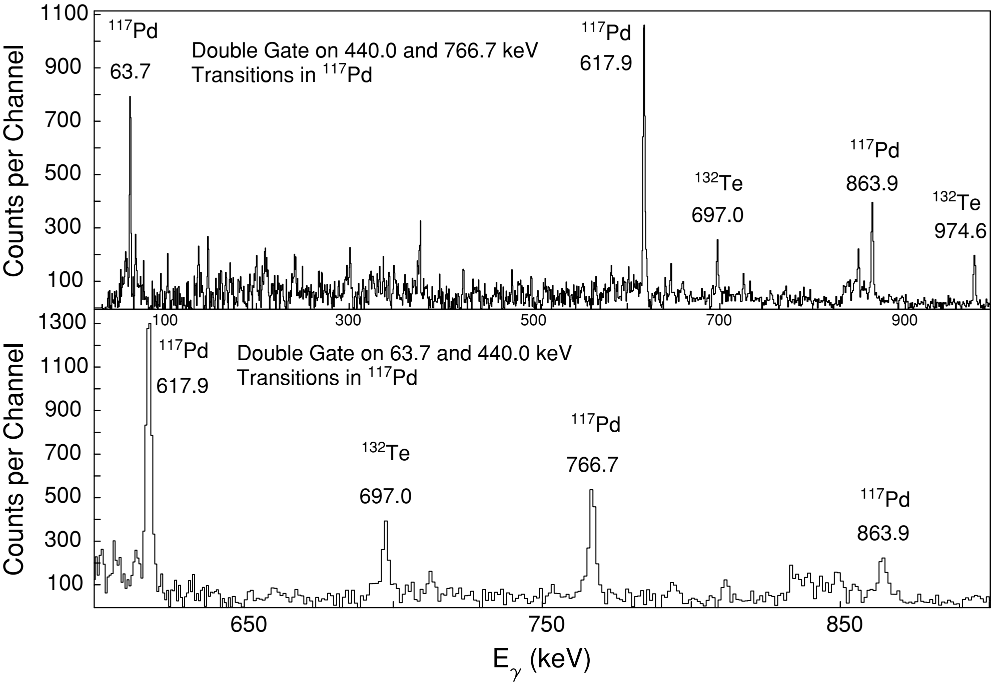

FIG. 2. Top spectrum shows double gate on 440.0- and 766.7-keV transitions in ^{117}Pd and new 63.7-keV transition. Bottom spectrum shows double gate on 440.0-keV and new 63.7-keV transitions and other transitions in the ^{117}Pd cascade.

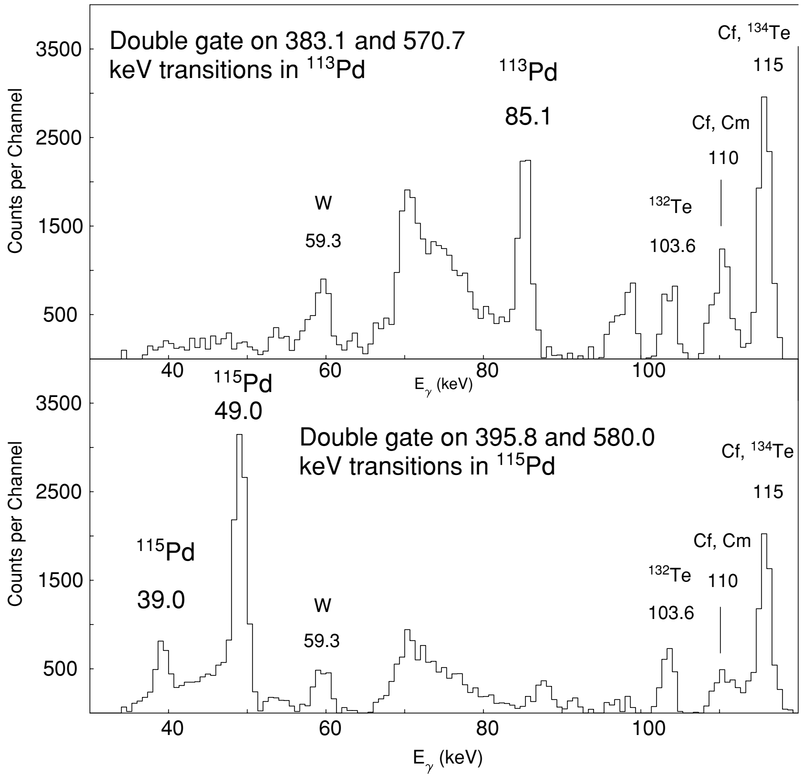

FIG. 3. Top spectrum shows double gate on 383.1- and 570.5-keV transitions in ^{113}Pd and new 85.1-keV transition. Bottom spectrum shows double gate on 395.8- and 580.0-keV transitions in ^{115}Pd and new 39.0- and 49.0-keV transitions.

is inserted in the cascade connecting the 11/2^{-} state to the previously known 203.1-keV level below. In ^{117}Pd, this shifts the J^{π} of the isomer down by one unit to 9/2^{-}, while the energy assignment remains at 203.1 keV, as shown in Fig. 4. The energy of the 11/2^{-} band head is changed to 266.8 keV.

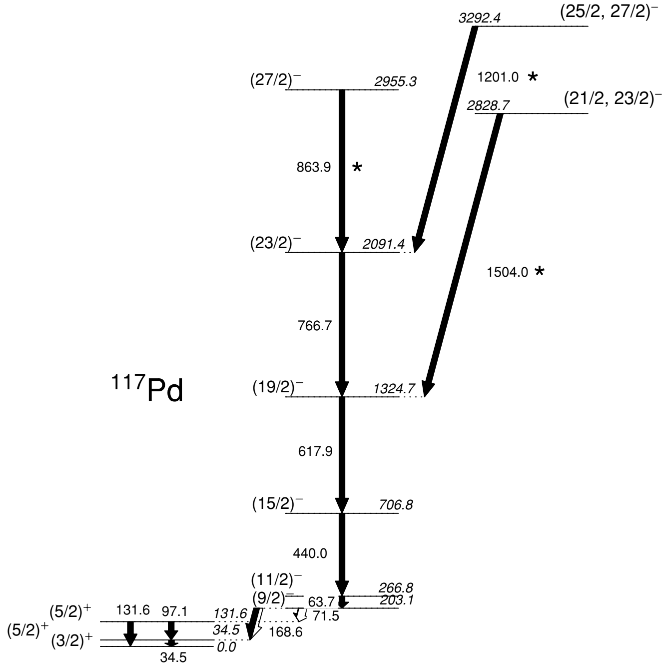

FIG. 4. New level scheme of ^{117}Pd. New transitions are marked with an asterisk.

For ^{115}Pd, two low-energy transitions of 39.0 and 49.0 keV are seen, shifting the J^{π} of the isomer at 89.3 keV down by two units of angular momentum to 7/2^{-} as shown in Fig. 5. Urban *et al.* [12] report these two transitions to be

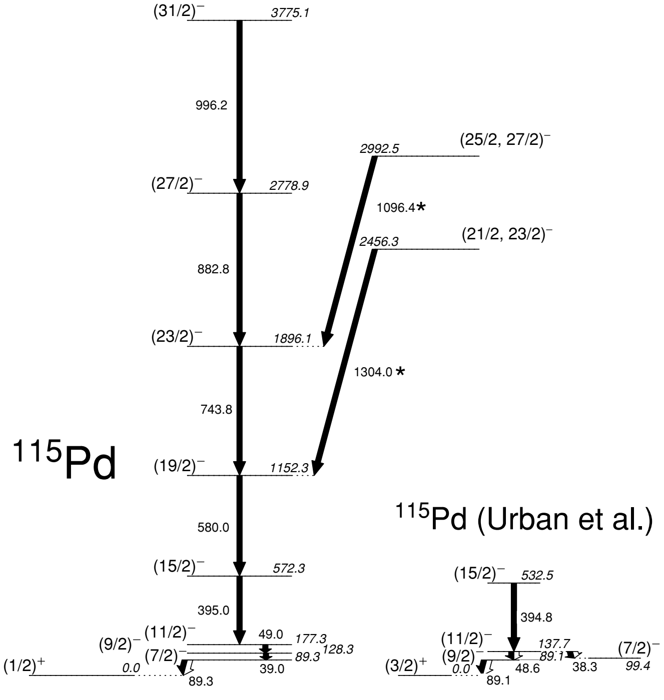

FIG. 5. New level scheme of ^{115}Pd. New transitions are marked with an asterisk. Also shown are the low spin levels from Urban *et al.* [12].

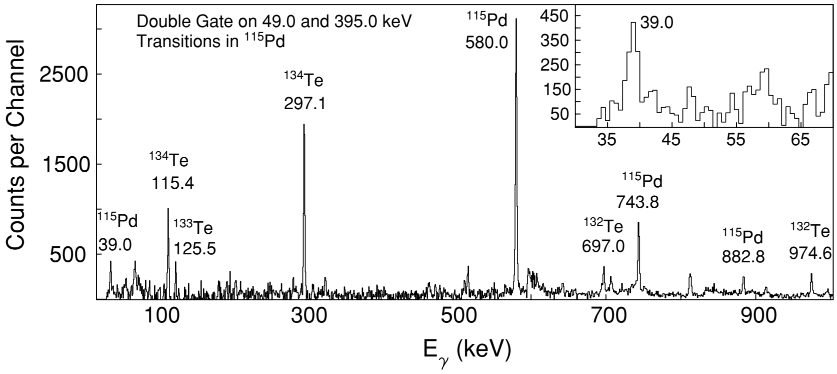

FIG. 6. Double gate on 49.0- and 395.0-keV transitions in ^{115}Pd showing coincidence relation between the 39.0- and 49.0-keV transitions. Observed full widths at half maximum of the peaks are 1.8(3) keV for the 39.0-keV peak, 2.3(1) for the 115.4-keV peak, and 2.5(1) for the 580.0-keV peak. The energy dispersion is 0.333333 keV per channel.

not in coincidence and place them in parallel, but our higher statistics data clearly show them to be in coincidence, as shown in Fig. 6. The ordering of these two transitions is difficult to determine, as we are near the limits of our detection efficiency at this energy. In Fig. 7, the coincidence gate on 39.0- and 49.0-keV is shown. The rotational band transitions are clearly visible, and they disappear if we shift the gate into the background.

The new transition in ^{113}Pd has an energy of 85.1-keV, placing the $11/2^-$ band head at 166.1 keV and the $9/2^-$ isomer at 81.0 keV, as shown in Fig. 8. Our new negative parity level systematics are shown in Fig. 9. Of special interest are the new low-energy transitions and the corresponding modification of the spin-parity assignments.

The structures of these nuclei are now more self-consistent. The decoupled rotational bands are all built on an $11/2^-$ band head as before. But now the isomeric transitions and the ground state assignments correspond with other experimental results. Each nucleus is discussed in more detail below.

A. ^{117}Pd

The identification of the 63.7-keV transition is confirmed, as well as the reassignment of the ground state spin and parity to $3/2^+$ [12]. We have also identified two new transitions of 1201.0 and 1504 keV. Levels at 2828.7 and 3292.4 keV are assigned a J^π of $(21/2, 23/2)^-$ and $(25/2, 27/2)^-$. These populate high-spin $23/2^-$and $19/2^-$ levels (Fig. 3). The exact spin assignment is unknown, tentative assignments assume $M1$ and $E2$ transitions, respectively.

B. ^{115}Pd

In the case of ^{115}Pd, rotational band interpretations [4–6] are in conflict with β^--decay results [7,9,14]. An assignment

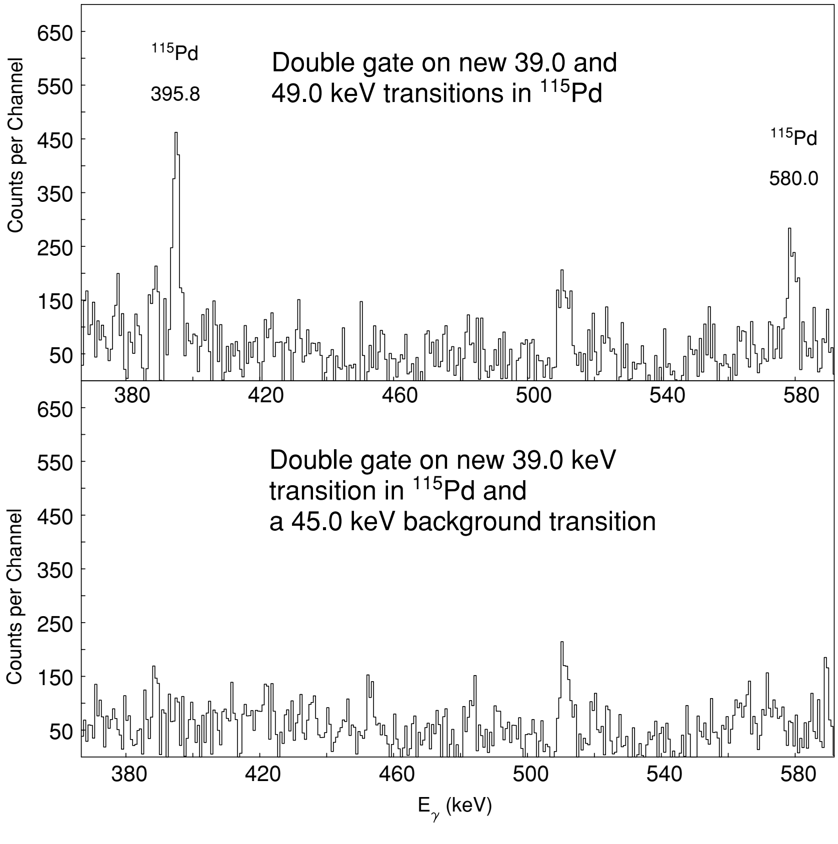

FIG. 7. Top spectrum shows double gate on 49.0- and 39.0-keV transitions in ^{115}Pd and coincidence relation. Bottom spectrum shows a background gate on 39.0- and 45.0-keV transitions and no coincidence with the rotational band.

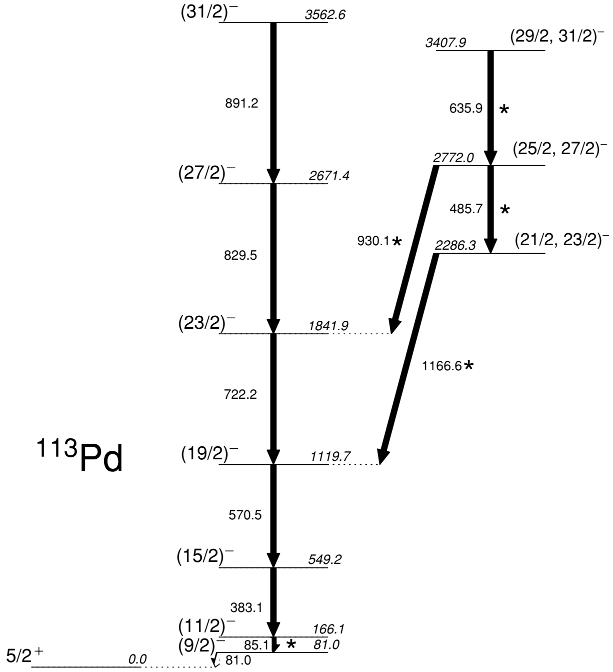

FIG. 8. New level scheme of ^{113}Pd. New transitions are marked with an asterisk.

of 11/2$^-$ for the J^π of the isomeric state is in conflict with β^- decay of ^{115}Pd to the states in the daughter nucleus ^{115}Ag. Specifically, the isomeric state is found to populate a state in ^{115}Ag that subsequently decays to the 1/2$^-$ ground state [9]. The intermediate state most likely has a J^π of 5/2$^-$, indicating the isomer should have a J^π of 7/2$^-$ rather than 11/2$^-$. With our two new low-energy transitions, we can construct a scheme that removes the conflict. By assigning the 89.3-keV isomeric state a J^π of 7/2$^-$ and placing the two new transitions above it, we preserve the rotational band structure from the 11/2$^-$ neutron shell (Fig. 4). If this change is made, the half-life of 50 s for the isomeric state requires a reexamination of the ground state $J^\pi = 5/2^+$. An $E1$ transition between a 7/2$^-$ state and a 5/2$^+$ state will not lead to such a long half-life for the 7/2$^-$ state.

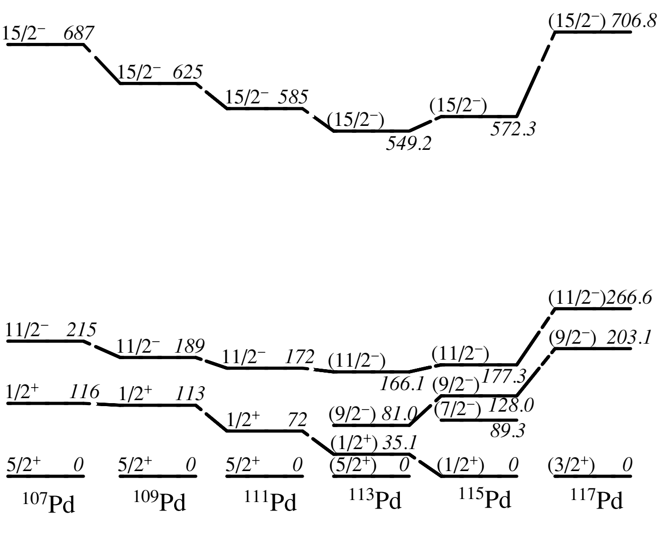

FIG. 9. New negative parity level systematics in ^{107,109,111,113,115,117}Pd.

By examining the systematics of the Pd isotopes, we can assign a different J^π to the ground state in this nucleus. In ^{107}Pd, the 1/2$^+$ state is more than 100 keV higher in energy than the 5/2$^+$ state; but as the mass number increases, the 1/2$^+$ state descends steadily in energy. In ^{113}Pd, the 1/2$^+$ state is only 35 keV above the 5/2$^+$ ground state [7]. Systematics suggest that the 1/2$^+$ state crosses over in ^{115}Pd to become the ground state. In addition, a similar structure is observed in ^{123}Xe [15], a nucleus with the same neutron number ($N = 69$). The ground state has a J^π of 1/2$^+$, and the lowest negative parity states, 7/2$^-$, 9/2$^-$, and 11/2$^-$, are closely spaced in energy. Two new transitions of energies 1096.4 and 1304.0 keV are also found in ^{115}Pd and are placed populating the 23/2$^-$ and 19/2$^-$ levels in the 11/2$^-$ rotational band. These new transitions lead to the identification of two new levels, with J^π of 21/2$^-$ and 25/2$^-$. This is the same pattern as in ^{117}Pd, reinforcing the similarity in the rotational band structure.

Turning to the positive parity structure, a 1/2$^+$ ground state changes the spin assignments of these levels as well. The 128-keV level becomes a 3/2$^+$ state, the 254-keV level becomes a 5/2$^+$ state, and the 354-keV band head becomes a 7/2$^+$ state. A 9/2$^+$ band head as proposed in [12] is harder to explain, because of the a lack of available 9/2$^+$ single-particle levels. A ground state of 1/2$^+$ fits all the data, and with our two low-energy transitions found to be in prompt coincidence, this provides the most complete explanation of the structure.

In addition, two new transitions are found with energies of 1096.4 and 1304.0 keV. Two new levels are placed in a side band, with the new transitions populating 19/2$^-$ and 23/2$^-$ levels in the rotational band. The energy of these levels are 2456.3 and 2992.5 keV, respectively. These are lower in energy than the corresponding levels in ^{117}Pd, following the trend of the other levels.

C. ^{113}Pd

The addition of a low-energy transition below the rotational band does not require changing the assignment of the ground state spin for this nucleus (Fig. 8). The β-decay work is quite clear on the assignment of 5/2$^+$ for the ground state [10]. The J^π of the isomer at 81.0 keV is firmly established as 9/2$^-$. The original β-decay work had assigned 9/2$^-$, but subsequent fission work [4,6] assigned 11/2$^-$. The isomeric transition to the ground state has a half-life of 0.3 s. The previous assignment of 11/2$^-$ would make the transition an $E3$. The Weisskopf estimate of the half-life for such a transition is greater than 1 s. Assigning a J^π of 9/2$^-$ allows this transition to be an $M2/E3$, with a corresponding half-life estimate of less than 1 s. The structure of ^{113}Pd now appears consistent with the discovery of the new 81.0-keV transition.

We have also identified four new transitions of energies 485.7, 635.9, 930.1, and 1166.6 keV in ^{113}Pd. Three levels are placed in a side band with energies 2286.3, 2772.0, and 3407.9 keV, with J^π of (21/2, 23/2)$^-$, (25/2, 27/2)$^-$, and (29/2, 31/2)$^-$. The transitions connecting the levels in cascade are observed as well as the transitions that connect this side band

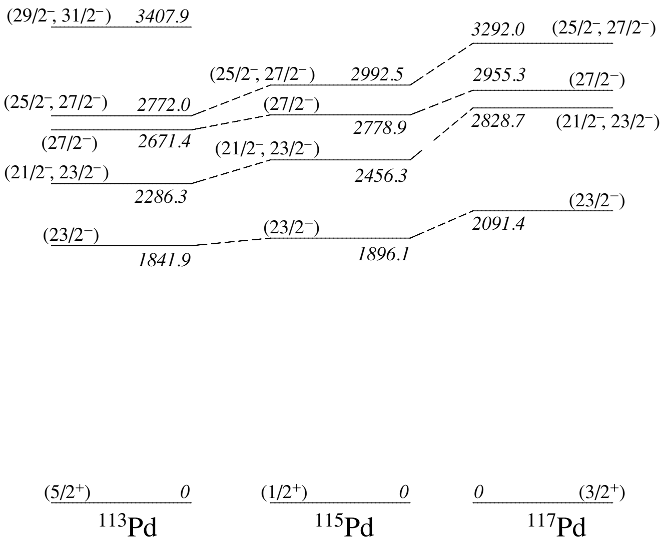

FIG. 10. New high-spin side band level systematics in ^{113,115,117}Pd (bold). Selected levels in the rotational bands are shown as well.

with the $23/2^-$ and $19/2^-$ levels in the $11/2^-$ rotational band. The energies of these high-spin levels are lower than in ^{115}Pd, continuing the trend toward a minimum at ^{113}Pd. This trend can be observed in Fig. 10, showing the energies of the levels in the high spin side band in ^{113,115,117}Pd.

In summary, examining the series of Pd nuclei, the new picture appears greatly improved. The isomeric transitions make it difficult for prompt coincidence studies to probe both positive parity and negative parity structures. However, by examining different complementary experiments, a comprehensive understanding can be achieved. These Pd nuclei exhibit very similar behaviors in their negative parity structures, with common $11/2^-$ decoupled rotational bands. The ground state J^{π} changes from $5/2^+$ in the lower mass Pd nuclei to $1/2^+$ in ^{115}Pd and to $3/2^+$ in ^{117}Pd. New high-spin levels beginning at $21/2^-$ in ^{113,115,117}Pd show the same energy systematic trend as the other negative parity levels, with the lowest energy occurring in ^{113}Pd.

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