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Letter

New spins for ground states and isomers in ^{115}Pd and ^{117}Pd

W. Urban[1,a], A. Złomaniec[1], G. Simpson[2], J.A. Pinston[3], J. Kurpeta[1], T. Rząca-Urban[1], J.L. Durell[4], A.G. Smith[4], B.J. Varley[4], N. Schulz[5], and I. Ahmad[6]

[1] Faculty of Physics, Warsaw University, ul. Hoża 69, PL-00-681 Warsaw, Poland
[2] Institut Laue-Langevin, F-38042 Grenoble Cedex, France
[3] Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS/Université J. Fourier, F-38026 Grenoble Cedex, France
[4] Schuster Laboratory, Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK
[5] Institut de Recherches Subatomiques UMR7500, CNRS-IN2P3 et Université Louis Pasteur, F-67037 Strasbourg, France
[6] Argonne National Laboratory, Argonne, IL 60439, USA

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Abstract. Levels in ^{115}Pd and ^{117}Pd nuclei, populated in the spontaneous fission of ^{248}Cm were studied by means of prompt gamma spectroscopy using the EUROGAM2 array of Anti-Compton spectrometers. Negative-parity, $I = 9/2$ excitations were identified, which are associated with the long-lived isomers in these nuclei, reported previously as $11/2^-$ excitations. The new data indicate spin and parity $3/2^+$ for ground states in ^{115}Pd and ^{117}Pd instead of $5/2^+$ proposed in previous works. This result implicates changes of spin assignments to other levels in both nuclei.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.20.-g Electromagnetic transitions – 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$

The $\nu h_{11/2}$ neutron shell plays a crucial role in defining patterns of the near-yrast excitations in the neutron-rich nuclei of the $100 \leq A \leq 120$ region. It has been shown that population of the $1/2^-[550]$ and $3/2^-[541]$ orbitals originating from the $h_{11/2}$ neutron shell is responsible for the onset of deformation in the mass $A \sim 100$ nuclei at $N \sim 60$ [1–4]. At neutron numbers $N \geq 61$, deformed bands based on the $5/2^-[532]$ orbital are observed, corresponding to prolate shape [5–9]. An interesting question is how the $\nu h_{11/2}$ shell influences the nuclear structure at still higher neutron numbers.

In a recent theoretical study [10] of neutron-rich nuclei from the $A \sim 110$ region it has been suggested that in these nuclei, where the Fermi level of both protons and neutrons approaches high-energy subshells, one may expect oblate deformation in ground states. However, experimental studies of neutron-rich palladium isotopes report that the deformation is prolate up to the neutron number $N = 72$, [11,12]. There are also calculations, which do not reveal any oblate shape in this region. Instead, a weak prolate deformation, slowly decreasing to zero when approaching the $N = 82$ shell, is reported [12]. More data is needed to clear this discrepancy. One can see in the single-particle diagrams shown in ref. [10] that there is a clear difference between excitation patterns corresponding to prolate and oblate deformation. Therefore, a detailed knowledge of single-particle excitation patterns in odd-A nuclei from this region might be helpful. However, while the $\Omega \leq 5/2$ orbitals of the $\nu h_{11/2}$ parentage are well documented, the high-Ω $\nu h_{11/2}$ subshells are less known. The identification of high-Ω configurations in this region becomes, therefore, an important task.

A general picture of yrast excitations in the neutron-rich ^{115}Pd and ^{117}Pd nuclei, proposed in recent studies [11–13], is that of a decoupled rotational band on top of the $\nu h_{11/2}$ orbital, with weakly deformed, low-lying $11/2^-$ band head forming a long-lived isomer, due to a large spin difference between the band head and the $5/2^+$ ground state. This is quite different from the situation observed in neutron-rich ruthenium isotopes, just two protons below, where negative-parity bands are based on the $5/2^-$ and $7/2^-$ orbitals originating from the $\nu h_{11/2}$ shell and where long-lived isomers are not formed. One may try to attribute this difference to the proximity of the $Z = 50$ closed shell, where less deformed and spherical, high-Ω orbitals are expected. We note, however, that the 394.8 keV,

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[a] e-mail: `urban@fuw.edu.pl`

$15/2^- \rightarrow 11/2^-$ transition in ^{115}Pd has in fact lower energy than the corresponding 415.9 keV transition in ^{113}Ru. This suggests that ^{115}Pd is deformed and the $\nu h_{11/2}$ shell should split into subshells in this nucleus.

There are hints that $9/2^-$ (and possibly $7/2^-$) orbitals may be present in ^{115}Pd and ^{117}Pd isotopes at low excitations. Penttilä *et al.* [14,15] found that the $T_{1/2} = 0.3$ s isomer at 81 keV in ^{113}Pd has spin $9/2^-$. This result has been confirmed recently by Houry *et al.* [12], who reported rotational bands on top of both the $9/2^-$ and the $11/2^-$ levels in ^{113}Pd. The bands are connected by the 407 keV transition, which fixes the position of the $11/2^-$ level at 18 keV above the $9/2^-$ level. The $9/2^-$ is also known in ^{109}Pd where it is placed 98 keV above the $11/2^-$ isomer [16]. A simple extrapolation based on these two cases suggests that in ^{115}Pd and ^{117}Pd the $9/2^-$ level may be located below the $11/2^-$ level and, consequently, may correspond to isomeric levels in these nuclei. This, in turn, would imply changes of ground-state spins there.

In this work we report on the identification of $9/2^-$ excitations in the ^{115}Pd and ^{117}Pd nuclei. In our study we used multiple-gamma coincidence data from a measurement of prompt-gamma radiation following spontaneous fission of ^{248}Cm. High-fold coincidences between prompt-gamma rays were measured using the EUROGAM2 array [17] plus Low Energy Photon (LEP) detectors. The data were converted into triple coincidences (providing about 2×10^{10} events) and sorted into various three-dimensional histograms. More details on the experiment and the data analysis can be found in refs. [4,18–20].

We have searched for levels in the vicinity of the $11/2^-$ excitation in ^{115}Pd, reported as $T_{1/2} = 50$ s isomer at 89.3 keV [21]. To look for low-energy gamma lines we used triple coincidences where one of the energies was measured by the LEP detector and the other two by Ge detectors of the EUROGAM. In fig. 1a a low-energy part of the LEP spectrum, double gated on the 394.8 keV and 580.0 keV lines from the negative-parity band in ^{115}Pd, is shown. Clearly seen is a line at 48.6 keV and palladium K_α and K_β X-ray lines at 21.1 keV and 23.8 keV, respectively. In fig. 1b we show a spectrum doubly gated on the 48.6 keV and 580.0 keV lines. One can see the 394.8 keV and 743.5 keV lines of the negative-parity band in ^{115}Pd. Intensities seen in fig. 1 and other gated spectra indicate that the 48.6 keV transition is located in the negative-parity band below the 394.8 keV line rather than somewhere higher in the band.

In fig. 1a one can also see a line at 38.8 keV, which is in coincidence with the 394.8 keV, 580.0 keV and 743.5 keV lines, as illustrated in fig. 1c, showing a spectrum double gated on the 38.8 keV and 394.8 keV lines. The 38.8 keV line is most likely located at the the bottom of negative-parity cascade in ^{115}Pd, as suggested by the intensities in the coincidence spectra. We could not see any coincidences between the 48.6 keV and the 38.8 keV lines. Therefore, we could not establish, with certainty, the position of the 38.8 keV relative to the 48.6 keV transition. This negative result is probably due to an experimental limit and a better measurement may resolve the problem.

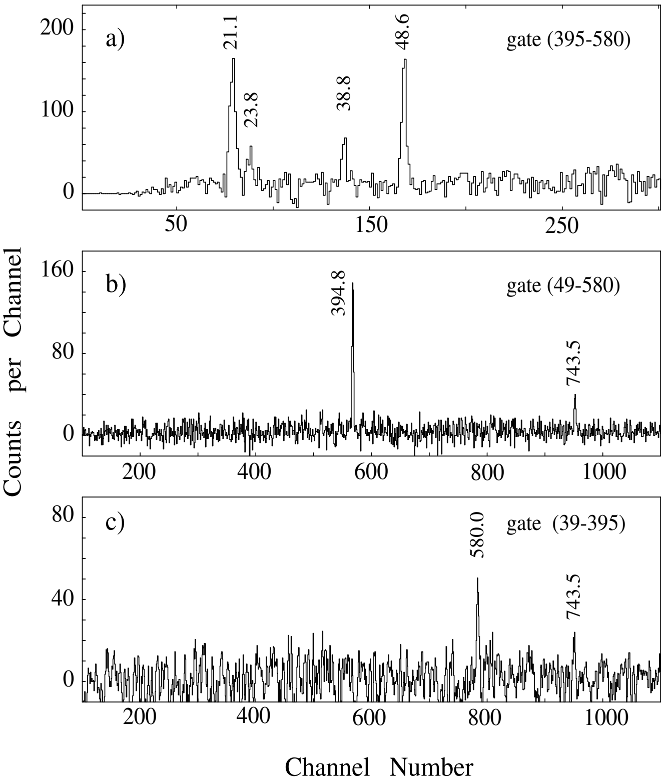

Fig. 1. γ-γ coincidence spectra double gated on lines in ^{115}Pd. Transition energies and gates are given in keV.

From fig. 1a one can estimate conversion coefficients for the 38.8 keV and 48.6 keV transitions assuming that the X-ray intensity, seen in fig. 1a, is due to the conversion of the two lines. The theoretical values are 1.0 for $E1$, 2.6 for $M1$ and 10.3 for an $E2$ transition at 49 keV and 1.9 for $E1$, 5.0 for $M1$ and 18.5 for an $E2$ transition at 39 keV (we did not consider $M2$ multipolarity due to the prompt character of both transitions). Taking the efficiency-corrected relative intensities of the palladium K_α line at 21.2 keV, the 38.8 keV line and 48.6 keV line, we conclude that it is not possible that both lines have an $E1$ multipolarity. If one of the lines is an $E1$ then the other is $M1+E2$ with the resulting conversion coefficient of 8(2) for the 48.6 keV line or 16(4) for the 38.8 keV line (both values being close to a limit expected for an $E2$ multipolarity). The other possibility is that both transitions are of a $M1 + E2$ character. If, for instance, they have the same intensity (are in a cascade) their conversion coefficients are 9(2) and 5(1) for the 38.8 keV and 48.6 keV lines, respectively, both consistent with a $M1 + E2$ multipolarity. The above results leave several solutions. Fortunately, there are other constraints:

i) there is only one long-lived isomer observed in ^{115}Pd and the isomeric transition is an $E3$, as deduced from its conversion coefficient [21]. The $T_{1/2} = 50$ s half-life of the isomer implies a high hindrance of 497 for this $E3$ transition [21]. Because of this long half-life one might consider a $\Delta I = 4$ character of the isomeric transition. We note, however, that the decay of the 253.7 keV level to the 89.1 keV isomer by the 164.6 keV transition [22], on

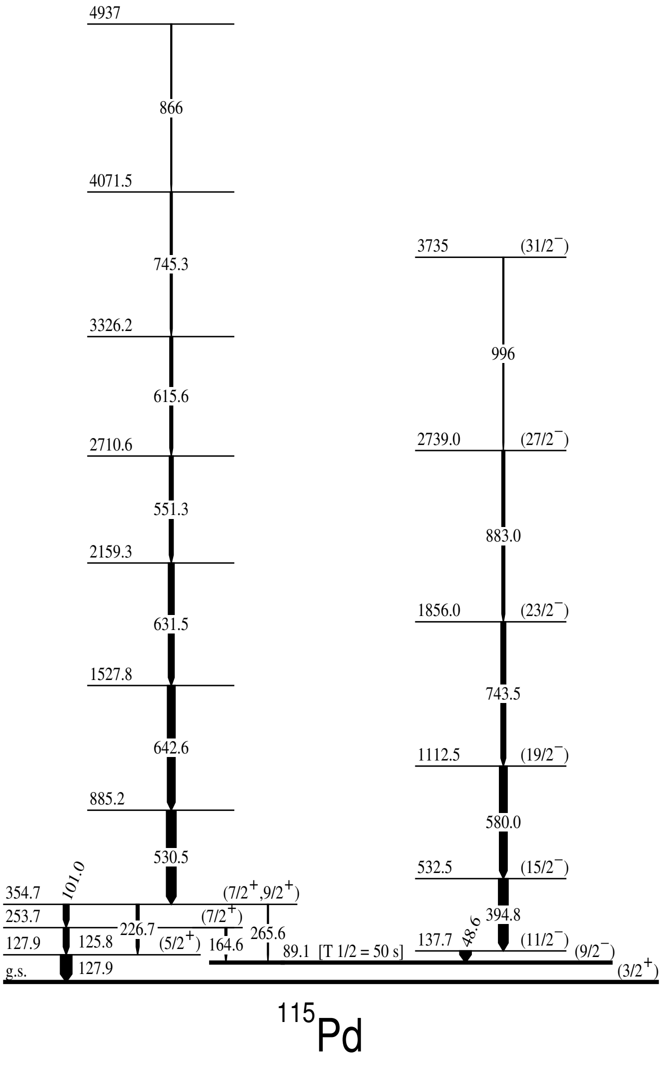

Fig. 2. Partial decay scheme of ^{115}Pd, as obtained in this work.

the one hand, and to the ground-state level by a cascade of the 125.8 keV and 127.9 keV transitions, both of $M1+E2$, $\Delta I \leq 1$ character [14,22], on the other hand, excludes the $\Delta I = 4$ character of the 89.3 keV isomeric transition;

ii) while the $9/2^-$ excitation in ^{115}Pd may be easily explained, as due to $h_{11/2}$ neutrons, the only explanation for a low-lying $9/2^+$ isomer would be the $9/2^+[404]$ neutron configuration. Such an excitation has been observed recently in ^{97}Sr, ^{99}Zr, and ^{101}Sr [23–25] but it is not expected at the Fermi surface in ^{115}Pd. Moreover, its properties (strongly deformed bands on top of it) are different from what one sees in ^{115}Pd;

iii) there is no crossover (38.8 + 48.6) keV transition in the spectra.

Considering all these arguments we conclude that both, the 38.8 keV and the 48.6 keV transitions are of a $M1+E2$ multipolarity and it is likely that they depopulate the $11/2^-$ level in parallel cascades. Consequently, two new levels are defined below the $11/2^-$ band head, which does not correspond anymore to the 50 s isomer reported in ^{115}Pd [21]. It is also unlikely that the higher of the two new levels corresponds to the 50 s isomer because it could decay to the lower level by a $M1 + E2$ transition. We propose that the lower level, located 48.6 keV below the $11/2^-$ band head, as shown in fig. 2 in the partial decay scheme of ^{115}Pd obtained in this work, corresponds to the isomer with half-life of 50 seconds reported at 89.3 keV [21].

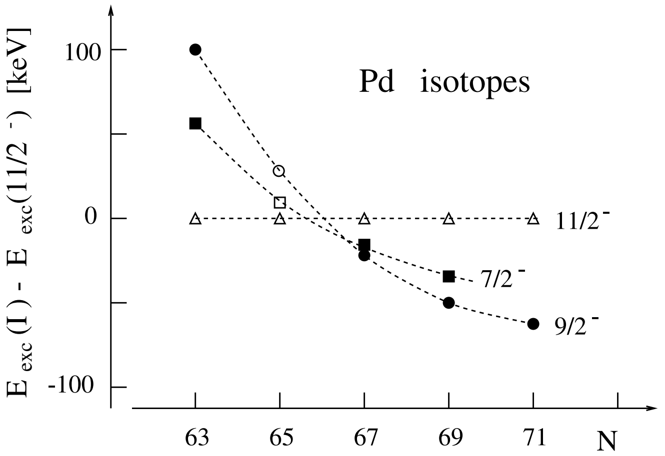

Fig. 3. The position of the $7/2^-$ and $9/2^-$ excitations relative to the $11/2^-$ level in odd-N palladium isotopes. The data at $N = 69$ and 71 are from this work and at other N values from refs. [14–16,26]. Open square and open circle mark values expected for the $7/2^-$ and $9/2^-$ levels in ^{111}Pd, respectively. Dashed lines are drawn to guide the eye.

Coincidence relations presented in fig. 2 are consistent with the existence of an isomer at 89.1 keV. The 89.1 keV level, shown in fig. 2 is fed by the 164.6 keV line (observed already in refs. [14,15]) and a new 265.6 keV line seen in our data. Since no decay of the 89.1 keV level is observed in our data, this level must have a long half-life. The excitation energy of this level is very close to the 89.3 keV excitation energy of the isomer measured in [21]. We propose that the 89.1 keV level corresponds to the 50 seconds isomer while the $11/2^-$ band head is now located at 137.7 keV.

To propose spins for the two new levels we inspect excitation energies of negative-parity levels in the neighbouring, odd-N Pd isotopes. Energies of the $7/2^-$ and $9/2^-$ levels in ^{109}Pd [16] and ^{113}Pd [14,15,26] are shown in fig. 3, relative to the energy of the $11/2^-$ band head in these nuclei. In fig. 3 we also show relative energies of the two new levels in ^{115}Pd$_{69}$, seen in this work. The 89.1 keV level follows the trend of $9/2^-$ excitations and the 99.4 keV level (proposed 38.3 keV below the $11/2^-$ level but not displayed in fig. 2) fits the trend of $7/2^-$ excitations.

The above result has implications for the spin of the ground state in ^{115}Pd. With the $9/2^-$ spin of the 89.1 keV isomer and the isomeric transition of a stretched $E3$ multipolarity, the spin and parity of the ground state of ^{115}Pd is $I^\pi = 3/2^+$, instead of $5/2^+$ reported in [11–15]. Let us mention that the $3/2^+$ spin assignment to the ground state in ^{115}Pd was considered already in refs. [14,15,22]. As

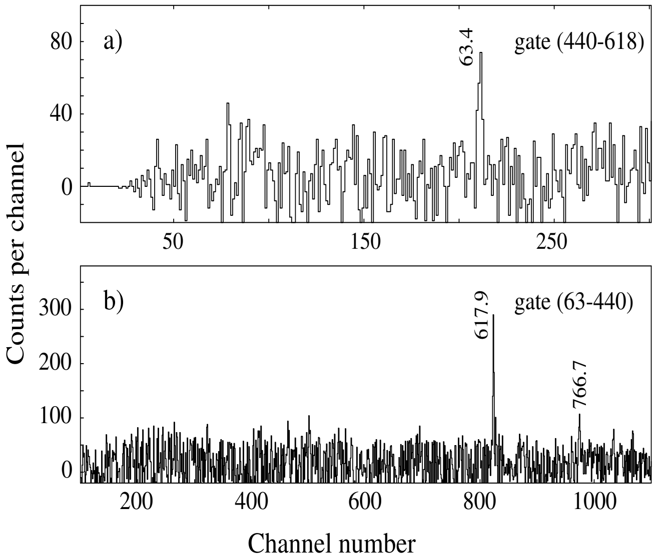

Fig. 4. Coincidence spectra double gated on lines in ^{117}Pd. Transition energies and gates are given in keV.

reported there, the $11/2^-$ spin assignment to the isomer (and, consequently, spin $5/2^+$ for the ground state) was chosen due to the systematics of the $11/2^-$ levels, thought to be isomers in all odd-A Pd isotopes, whereas β^--decay properties of ^{115}Pd indicated spin $3/2^+$ for the ground state (and, consequently, spin $9/2^-$ for the isomer).

The assignment of $3/2^+$ spin to the ground state and the $9/2^-$ to the 89.1 keV isomer fixes spins of the 127.9 keV and 253.7 keV levels at $5/2^+$ and $7/2^+$, respectively, since the 127.9 keV and 125.8 keV transitions are of $M1+E2$, $\Delta I \leq 1$ character [15,27] and, consequently, the 164.6 keV transition must be a stretched $E1$ ($M2$ multipolarity is unlikely, considering prompt character of this transition). One can also limit the spin of the 354.7 keV level to $7/2^+$ or $9/2^+$ due to the presence of the 265.6 keV transition of prompt character. The $9/2^+$ spin value is preferred since otherwise, the band on top of the 354.7 keV level becomes rather non-yrast, while it is commonly observed that spontaneous fission populates preferably yrast states.

This last argument helps to discriminate against another possibility, namely that the 38.8 keV and the 48.6 keV transitions are in a cascade. Although in such a version the observed properties of both transitions are easier to explain, it implies spin $7/2^-$ for the isomer and, consequently, spin $1/2^+$ for the ground state of ^{115}Pd. This in turn fixes spins and parities of the 127.9 keV and the 253.7 keV levels to $3/2^+$ and $5/2^+$, respectively. Consequently, the spin of the 354.7 keV level should be $5/2^+$ or $7/2^+$, making the band on top of the 354.7 keV level rather non-yrast, while it is populated stronger that the yrast, negative-parity band. Therefore, the population argument supports spin $3/2^+$ for the ground state and spin $9/2^-$ for the isomer.

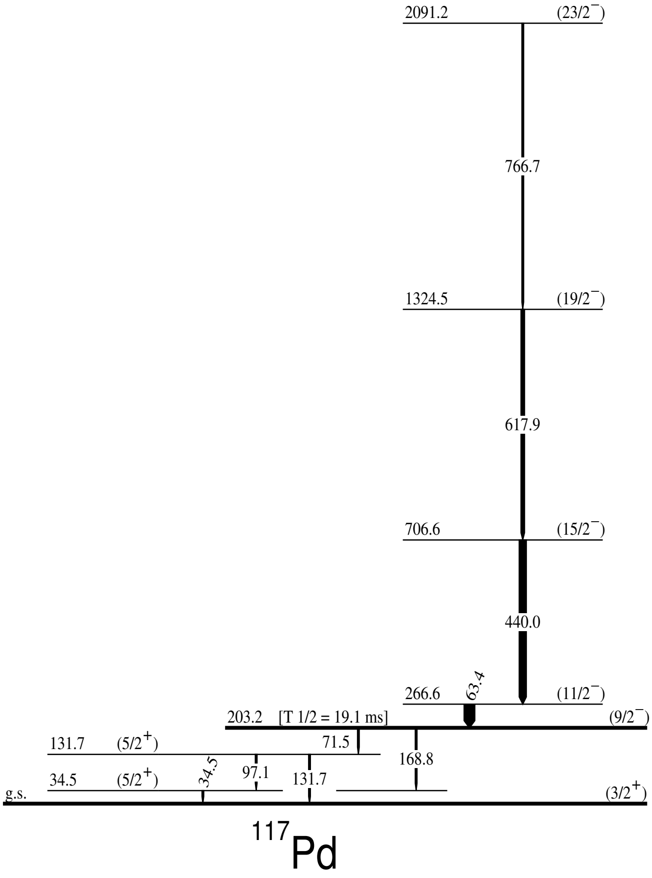

Fig. 5. Partial decay scheme of ^{117}Pd as proposed in this work.

It has to be remarked, however, that the $1/2^+$ possibility will need further studies. The $1/2^+$ orbital of the $d_{3/2}$ parentage is positioned close to the Fermi surface at $N = 69$, as has been shown in our recent study of ^{113}Ru [26], the isotone of ^{115}Pd, where the $T_{1/2} = 0.5$ s isomer [28] has been assigned spin $7/2^-$ and the ground state spin $1/2^+$ [26]. Moreover, spin $1/2^+$ was considered for the ground state in ^{115}Pd already in ref. [22], based on the observed feeding of the ground state of ^{115}Pd in β^--decay of the $7/2^+$ ground state of ^{115}Rh. Finally, the $1/2^+$ level is reported at low energies in the neighbouring odd-N Pd isotopes [14,15]. Considering all this, the $1/2^+$ ground state in ^{115}Pd would not be unusual.

The ^{117}Pd nucleus was studied before in spontaneous fission [11]. In fig. 4a we show a low-energy part of the spectrum, double gated on the 440 keV and 618 keV lines from the negative-parity band in ^{117}Pd, reported in ref. [11]. In the spectrum one can see a new line at 63.4 keV. In a spectrum double gated on the 63.4 keV and the 440.0 keV lines, shown in fig. 4b, there are 617.9 keV and 766.7 keV lines of the negative-parity band in ^{117}Pd. Intensities seen in gated spectra suggest that the 63.4 keV transition is located in the negative-parity band below the 440.0 keV line. The 63.4 keV transition defines thus a new level below the $11/2^-$ band head, as shown in fig. 5 in the partial level scheme of ^{117}Pd obtained in this work. We propose that the new level corresponds to the 203.2 keV isomer with the half-life of 19.1 ms, reported in ref. [27]. Consequently, the $11/2^-$ band head is now located at 266.6 keV.

In fig. 3 we show the position of the new $9/2^-$ level in ^{117}Pd, relative to the $11/2^-$ band head. The level fits well the trend of $9/2^-$ excitations in odd-N Pd isotopes. We note that the regularity of this picture allows the estimate of the, yet unknown, positions of the $7/2^-$ and $9/2^-$ levels in ^{111}Pd expected about 10 keV and 30 keV above the $11/2^-$, 172 keV isomer [15,16], respectively. Experimental identification of these two levels would add credibility to the proposed picture.

The $9/2^-$ spin assignment to the isomer in ^{117}Pd has implications for the spin of the ground state and the 34.5 keV and 131.7 keV levels [27] in this nucleus. In ref. [27] it was found that the 71.5 keV and 168.8 keV isomeric transitions are of a stretched $M2$ character. Consequently, considering that the spin of the 203.2 keV isomeric level is $9/2^-$, we propose that the spin and parity of both the 34.5 keV and the 131.7 keV levels are $I^\pi = 5/2^+$, instead of $7/2^+$ reported previously [27]. The multipolarity of the 34.5 keV ground-state transition in ^{117}Pd was reported as $M1$, $\Delta I = 1$ [27], because of the non-observation of a $M2$ decay of the 203.2 keV isomer to the ground state. Considering this and the new $I^\pi = 5/2^+$ spin of the 34.5 keV level, we propose that the ground-state spin of ^{117}Pd is $I^\pi = 3/2^+$, instead of $I^\pi = 5/2^+$ [27].

The new spin and parity assignments in ^{115}Pd and ^{117}Pd, proposed in this work, are consistent with the available Nilsson excitations at neutron number $N \geq 69$. The change of palladium ground-state spin from $5/2^+$ at $N \leq 67$ to $3/2^+$ at $N > 67$ is what one expects. Inspecting the scheme of single-neutron levels calculated for this region (see, *e.g.*, [10]), one finds that at moderate prolate deformation of $\beta_2 \approx 0.2$, the Fermi level approaches both the $9/2^-[514]$ orbital of the $\nu h_{11/2}$ shell as well as the $3/2^+[402]$ orbital of the $\nu d_{3/2}$ shell. The latter configuration has been recently observed in the ^{111}Ru nucleus [29, 30], which supports its presence at the Fermi level around $N = 69$. The new results improve the overall agreement between the experimental data and the calculated pattern of single-neutron levels in odd-N Pd. In this picture both, positive- and negative-parity excitations in odd-N Pd are due to valence-neutron levels in a moderately-deformed, prolate-shaped potential.

Summarizing, we conclude that the available data indicate spins of the 89.1 keV and 203.2 keV isomers in ^{115}Pd and ^{117}Pd, respectively, lower than $11/2^-$, reported previously. Consequently, ground-state spins in both nuclei are lower than $5/2^+$. The new data indicate, as a likely solution, spin $9/2^-$ for isomers and $3/2^+$ for ground states in both nuclei. In case of ^{115}Pd both spins may be lowered by one unit, if the future studies would show that the 38.8 keV transition is in cascade with the 48.6 keV transition in this nucleus. Further detailed studies of neutron-rich odd-N palladium isotopes are of high interest in order to verify the new spin assignments proposed in this work.

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