Excited states in ^{115}Pd populated in the β^- decay of ^{115}Rh

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Excited states in ^{115}Pd, populated following the β^- decay of ^{115}Rh have been studied by means of γ spectroscopy after the Penning-trap station at the IGISOL facility, University of Jyväskylä. The $1/2^+$ spin and parity assignment of the ground state of ^{115}Pd, confirmed in this work, may indicate a transition to an oblate shape in Pd isotopes at high neutron number.

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In a recent reinvestigation of odd-A, neutron-rich Pd isotopes [1] we proposed new spins for isomers in ^{115}Pd and ^{117}Pd, that are lower than the $11/2^-$ values suggested previously [2–5]. Our finding shows that the $h_{11/2}$ neutron shell splits in Pd isotopes, thus indicating the presence of nuclear deformation in these nuclei.

Another consequence of the proposed lower spins in ^{115,117}Pd are correspondingly lower spins of ground states in these nuclei. Correct identification of ground-state spins is crucial for a proper description using nuclear models. The $9/2^-$ spin for the 203.2-keV isomer and spin $3/2^+$ for the ground state in ^{117}Pd proposed in our work [1], were confirmed in another study [6]. However, for the isomer in ^{115}Pd a $(7/2^-)$ spin was reported in Ref. [6] instead of the $(9/2^-)$ value [1]. Consequently, the spin of the ground state in ^{115}Pd was lowered to $(1/2^+)$ [6].

In Ref. [1] we discussed the possible spin assignment of $1/2^+$ for the ground state in ^{115}Pd, following an earlier suggestion [7]. The $(3/2^+)$ value was adopted based, among others, on the systematics of the $11/2^-$, $9/2^-$, and $7/2^-$ excitation energies in odd-A Pd isotopes, as shown in Fig. 3 of Ref. [1]. However, the data on ^{113}Pd [3] used in these systematics, were recently questioned [6]. We therefore decided to reinvestigate low-spin excitations in ^{115}Pd to verify the results of Refs. [1,6] and to explain the structure of ^{115}Pd.

To understand the systematic behavior of negative-parity excitations in this region we used the data for odd-A Ru nuclei, which are better known than the odd-A Pd isotopes. In Fig. 1 we show excitation energies in $^{105-113}$Ru nuclei, relative to their $11/2^-$ excitations. A characteristic "parabolic" variation of the $E_{\mathrm{exc}}(I^-) - E_{\mathrm{exc}}(11/2^-)$ energy difference as a function of neutron number is observed for an excitation with a given spin I^-. This can be understood in terms of the Fermi level approaching to and departing from the subshell with spin I^-, when neutrons are added. The shape of these "parabolas" is consistent with notions that only two neutrons can be added to an individual subshell, and that the population of a given subshell is a smooth rather than "steplike" function of neutron number.

In ^{107}Ru$_{63}$ and ^{109}Ru$_{65}$ isotopes, the $5/2^-[532]$ orbital forms the head of the negative-parity band, whereas the $7/2^-$ and $9/2^-$ levels are collective excitations based on this band head. In ^{111}Ru$_{67}$ and ^{113}Ru$_{69}$ isotopes, the Fermi level approaches the $7/2^-[523]$ orbital, which becomes the band head. The $9/2^-$ level in these two nuclei corresponds to a collective excitation on top of the $7/2^-$ band head. This picture coincides with the variation of the 2^+ excitation energies in the respective core nuclei, shown in Fig. 1 as open squares. Interestingly, the minimum of the 2^+ excitation energy, expected at $N = 66$, the middle of the $50 < N < 82$ shell, consists of two minima. One correlates with the minimum for the $5/2^-[532]$ excitation and the other with the minimum for the $7/2^-[523]$ excitation. This supports the leading role of the $h_{11/2}$ intruder orbital in generating nuclear deformation in this region, as discussed in Ref. [8].

For neutron-rich Pd isotopes one may expect, in general, a behavior similar to that shown in Fig. 1, with possible disturbances due to a lower deformation and, consequently, a larger decoupling in the negative-parity bands.

In this work we report on the study of low-spin states in ^{115}Pd, populated as a granddaughter in the β^- decay chain of ^{115}Ru. The β decay of ^{115}Ru will be published elsewhere [9]. The production of isotopically pure beam of ^{115}Ru grandmother nuclei as well as the experimental setup are described in [10]. The monoisotopic ion samples of ^{115}Ru were implanted into a plastic tape which was moved at regular intervals of about 300 s, thus the 0.99 s [7] daughter activity of ^{115}Rh (populating the excited states of interest in ^{115}Pd) was not much suppressed.

Due to spin $7/2^+$ of the β^- decaying ground state of ^{115}Rh, spins up to $9/2^+$ could be populated (directly or via γ cascades). The partial level scheme of ^{115}Pd, obtained in this work is shown in Fig. 2. The ^{115}Pd nucleus has been studied before in β^- decay [7,17]. We confirm all transitions and levels reported in Refs. [7,17]. We also confirm the levels

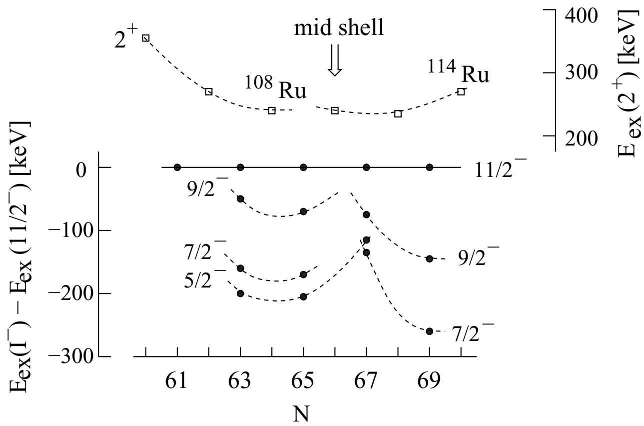

FIG. 1. Excitation energies in Ru isotopes versus neutron number, relative to the $11/2^-$ level. The data are taken from Refs. [11–13] for odd-A Ru and from Refs. [14–16] for even-even Ru isotopes. Dashed lines are drawn to guide the eye.

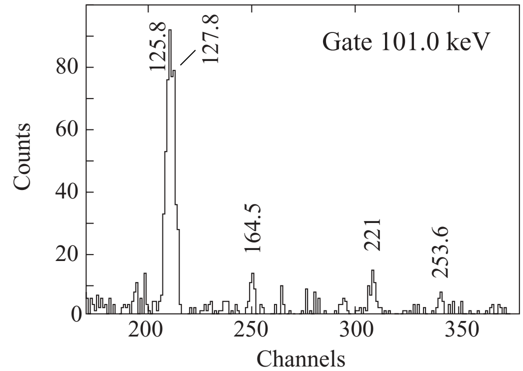

FIG. 3. A coincidence spectrum of γ rays following the beta decay of ^{115}Rh, gated on the 101.0-keV line.

at 127.8, 253.6, and 354.7 keV with their decays, as reported in Ref. [1]. To this band we add a new level at 575.5 keV, for which we propose spin $(9/2^+)$, because of the observed branchings.

In Fig. 3 we show a γ spectrum gated on the 101.0-keV line, where a line at 164.5 keV is seen, in accord with Ref. [1]. The 164.5-keV transition populates the 50-s isomer at 89.1 keV in ^{115}Pd [18]. The intensity ratio of the 164.5- and 127-keV lines is consistent with their E1 and M1 character, respectively, which is imposed by the E3 multipolarity of the 89.1-keV IT transition [18]. We also observe the coincidence between the 265.6- and 221-keV lines, confirming the 265.6-keV decay branch from the 354.7-keV level to the 89.1-keV isomer.

An important result of this work is the observation of the 38.8-keV line, reported in prompt-γ measurements [1,6] (a 38.5-keV line was reported in ^{115}Pd in Ref. [17], but not placed in the level scheme [17,19]). The 38.8-keV line is seen in a single-γ spectrum shown in Fig. 4. No lines in coincidence with the 38.8-keV line have been observed. Therefore, we propose that this line feeds the 50-s isomer at 89.1 keV, defining a level at 127.9 keV. We note that in Fig. 4 there is no line at 48.6 keV, reported in the negative-parity band in prompt-γ works [1,6] as depopulating the level with spin $11/2^-$. We conclude, therefore, that the β^- decay of the $7/2^+$ ground state of ^{115}Rh populates the 127.9-keV level with spin $9/2^-$ in ^{115}Pd (possibly via γ cascades), but cannot populate the $11/2^-$ level at 176.7 keV in ^{115}Pd. The observation of the 38.8-keV transition in the present work allows the order of the 38.8- and 48.8-keV transitions in the negative-parity band of ^{115}Pd to be established. The present work supports the $1/2^+$ spin and parity assignment to the ground state of ^{115}Pd and, consequently, the $7/2^-$ spin and parity assignment to the 50-s isomer in ^{115}Pd.

With spins and parities of the negative-parity band in ^{115}Pd reliably established one may explain the systematic behavior of these excitations in odd-A Pd nuclei. In Fig. 5 we show excitation energies in odd-A $^{109-117}$Pd isotopes, relative to their $11/2^-$ levels. We have used the present data and the data of Refs. [1,6] to fix energies of the $7/2^-$, $9/2^-$, and $11/2^-$

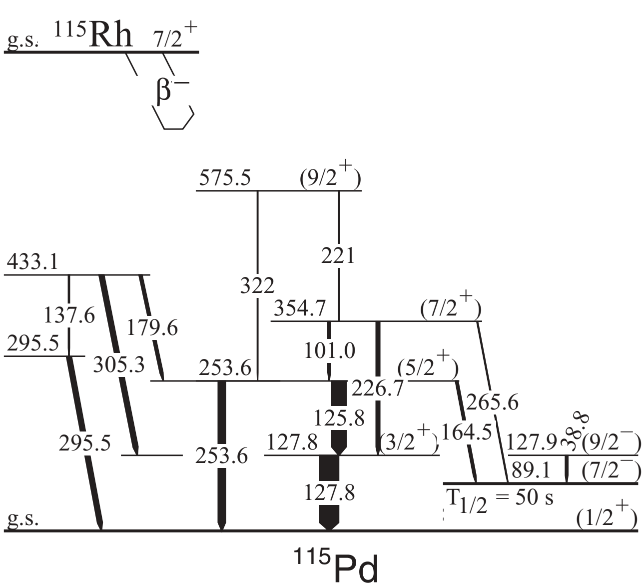

FIG. 2. Partial level scheme of ^{115}Pd as observed in the present work.

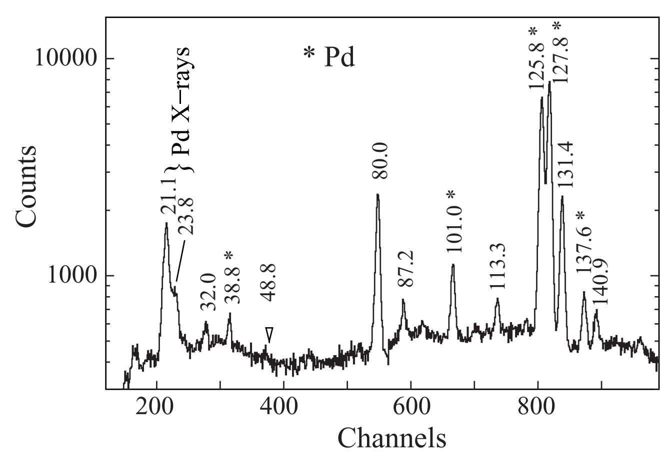

FIG. 4. Single spectrum of γ rays in the beta decay chain of ^{115}Ru. Transitions in ^{115}Pd (see Fig. 2) are marked with an asterisk.

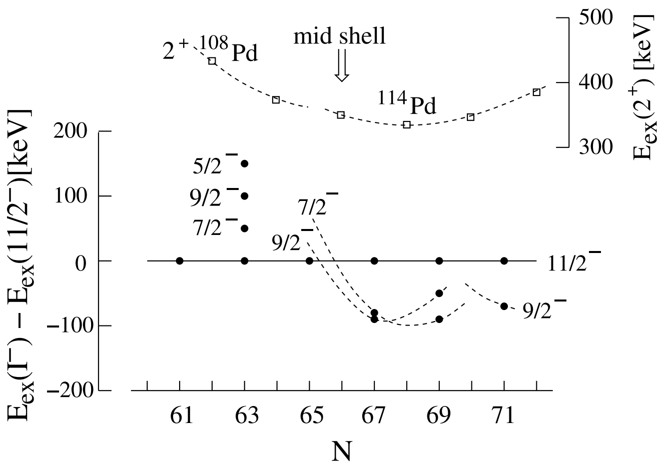

FIG. 5. Excitation energies of negative-parity states in Pd isotopes, relative to the $11/2^-$ level. The data for odd-A Pd are taken from Refs. [1,6,17,19,21–23] and for even-even Pd from Refs. [14,24]. Dashed lines are drawn to guide the eye.

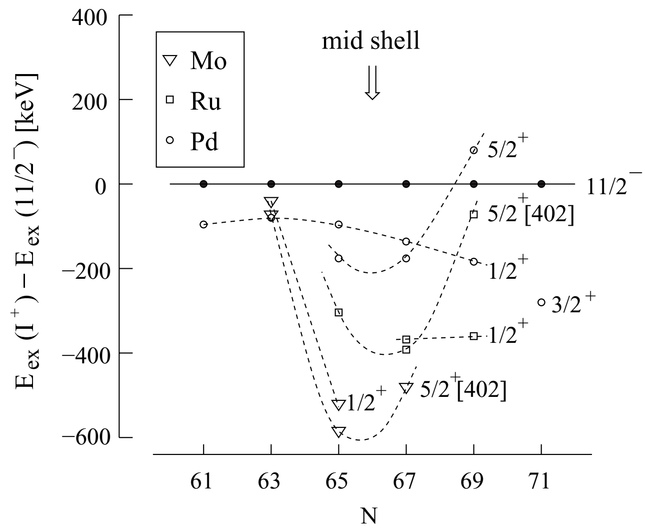

FIG. 6. Excitation energies of positive-parity states in Mo, Ru, and Pd isotopes, relative to the $11/2^-$ level. The data are taken from Refs. [1,6,13,17,19,21–23,28,29]. Dashed lines are drawn to guide the eye.

levels in ^{115}Pd at 89.1, 127.9, and 176.5 keV, respectively. In ^{113}Pd we used the data of Ref. [6] to fix positions of the $9/2^-$ and $11/2^-$ levels at 81.0 and 166.1 keV, respectively. The change of the $11/2^-$ excitation energy from 99 keV proposed in Ref. [3] to 166.1 keV reported by Fong *et al.* [6] is of prime importance for the discussed systematics. The unique $5/2^+$ spin and parity assignment to the ground state [20] and the M2 multipolarity of the 81.3-keV isomeric transition in ^{113}Pd [19] define a spin and parity of $9/2^-$ for the 81.3-keV, 0.3-s isomer in this nucleus [19]. Therefore, the $7/2^-$ level in ^{113}Pd should be located above the $9/2^-$ level. The $X + 84.9$-keV level in ^{113}Pd, proposed in Ref. [17], which decays by an E1 transition of 84.9 keV, is a good candidate, assuming that $X = 0$. Considering firm $11/2^-$ spin and parity assignment to the 5.5-h isomer at 172.2 keV in ^{111}Pd [21] we conclude negative-parity levels with spins lower than $11/2^-$ in ^{111}Pd should be located above the isomer, as observed in ^{109}Pd [22,23]. We note that, unlike in the $^{107}Ru_{63}$ isotone (see Fig. 1), in $^{109}Pd_{63}$ the $5/2^-$ level is located above the $7/2^-$ level, most likely due to lower deformation and higher decoupling.

The inspection of the Nilsson scheme for neutrons in the $A\sim110$ region (see, e.g., Fig. 13 in Ref. [25] or Fig. 5 in Ref. [26]) shows that the 69th neutron is expected to populate either the $7/2^-$[523] or the $5/2^+$[402] orbital. The former may be associated with the 89.1-keV isomer in ^{115}Pd, which has now been assigned a spin and parity $7/2^-$. In a number of previous works [3–5], the ground state of ^{115}Pd was reported with a tentative $(5/2^+)$ spin and parity assignment, which would naturally correspond to the $5/2^+$[402] configuration. The presence of this orbital near the Fermi level in the middle of the $50 < N < 82$ shell is well documented, as illustrated in Fig. 6, which shows positive-parity excitations relative to the $11/2^-$ level in odd-N, Mo, Ru, and Pd nuclei of the region. The Fermi level approaches the $5/2^+$[402] orbital around $N = 66$ but then it quickly departs. At $N = 69$ the $5/2^+$ level has already high excitation energy and, instead, a $1/2^+$ state appears close to the Fermi level.

The $1/2^+$[411] orbital is expected close to the Fermi level at $N = 67$. Its presence in this region is also well established. It is observed at low excitation energies in the odd-N, $^{107-113}$Pd isotopes (see, e.g., systematics of Pd excitations in Fig. 9 of Ref. [6]). The proposed $1/2^+$ spin and parity for the ground state in ^{115}Pd fits well the trend for $1/2^+$ excitations seen for Pd isotopes in Fig. 6. The $1/2^+$ excitation was also found in odd-N, ^{111,113}Ru [13,27,28], and ^{105,107}Mo isotopes [29].

The systematic behavior of the $1/2^+$ excitations in odd-N Pd is rather unusual because the $1/2^+$ level stays close to the Fermi level over a very wide range of neutrons. Moreover, trends seen in Fig. 6 suggest that the $1/2^+$ level may be close to the ground state also at $N = 71$. Indeed, our recent measurement indicates that the spin of the ground state in ^{115}Ru should be $1/2^+$ [30] and Fig. 6 suggests that the $1/2^+$ level should be close to the ground state also in ^{117}Pd.

Such a behavior can be understood assuming a change of both the value and the sign of deformation as a function of an increasing neutron number. The transition from prolate to oblate deformation has been predicted in this region of nuclei to occur at neutron number $N > 70$ [31]. Single-particle energies calculated in Ref. [31] (cf. Fig. 1), show that the $1/2^+$[411] orbital, originating from the $3s_{1/2}$ shell is close to the Fermi level for $62 < N < 68$ on the prolate side and for $66 < N < 78$ on the oblate side of the deformation axis.

The correlation shown in Fig. 1, between the energy of the 2^+ excitation in even-even and the negative-parity excitations in the odd-A Ru nuclei, both of which show two minima suggest a possible transition to oblate deformation at large neutron number, due to the population of high-Ω subshells of the intruder shell. In this picture, the low-N minimum of 2^+ excitations corresponds to a prolate deformation, due to population of the $3/2^-$[541] and $5/2^-$[532] orbitals while the high-N minimum may correspond to an oblate shape, due to the population of the $7/2^-$[523] and $9/2^-$[514] orbitals.

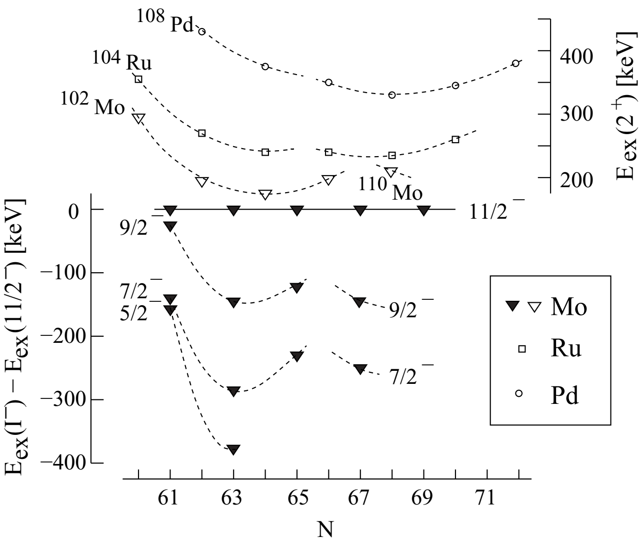

FIG. 7. Excitation energies of negative-parity states in Mo isotopes, relative to the $11/2^-$ level. The data for odd-A Mo are taken from Refs. [29,32–34] and for even-even nuclei from Refs. [14–16,24,35]. Dashed lines are drawn to guide the eye.

This correlation is a systematic feature in the region. It is also seen for Mo isotopes, as shown in Fig. 7. Because of larger deformation of Mo nuclei the prolate minimum is more pronounced and clearly correlates with the population of the $5/2^-[532]$ orbital. It was proposed in Ref. [35] that the value of the 2^+ excitation energy in ^{110}Mo indicates a transition to another region of deformation. This data point, shown as ^{110}Mo in Fig. 7, most likely belongs to the second minimum of 2^+ excitation energies in Mo. This minimum, still to be established, should correlate with the population of the $7/2^-[523]$ orbital and might correspond to an oblate shape.

The 2^+ excitation energy in Pd nuclei is correlated with the population of the $7/2^-[523]$ and $9/2^-[514]$ neutron orbitals (see Fig. 5). It is likely that in heavy Pd isotopes one may expect effects due to an oblate shape, as discussed already in Ref. [36]. One such possible effect may be the $3/2^+$ spin and parity of the ground state in ^{117}Pd [1], also shown in Fig. 6. In the Nilsson diagram, the only level with spin $3/2^+$ available at $N = 71$ is due to the $3/2^+$ *oblate* orbital, originating from the $2d_{3/2}$ spherical shell. We note that an oblate $1/2^+[411]$ level is also close in energy at $N = 71$, which is consistent with the expectation from Fig. 6.

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