Single-particle isomeric states in ^{121}Pd and ^{117}Ru

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Abstract. Neutron-rich nuclei were populated in a relativistic fission of ^{238}U. Gamma-rays with energies of 135 keV and 184 keV were associated with two isomeric states in ^{121}Pd and ^{117}Ru. Half-lives of 0.63(5) μs and 2.0(3) μs were deduced and the isomeric states were interpreted in terms of prolate deformed single-particle states.

1. Introduction

Nuclear shell structure is one of the milestones in Nuclear Physics. It is related to enhanced robustness of nuclei with respect to excitations, when a particular number of nucleons is present [1]. A key element of the nuclear shell model is the spin-orbit force, which lifts the j-degeneracy and pushes down the orbits with higher-j towards orbits of opposite parity. One of the major successes of the model is the ability to reproduce the nuclear magic numbers and to explain the islands of isomerism emerging on the Segré chart when approaching the magic medium-mass and heavy nuclei.

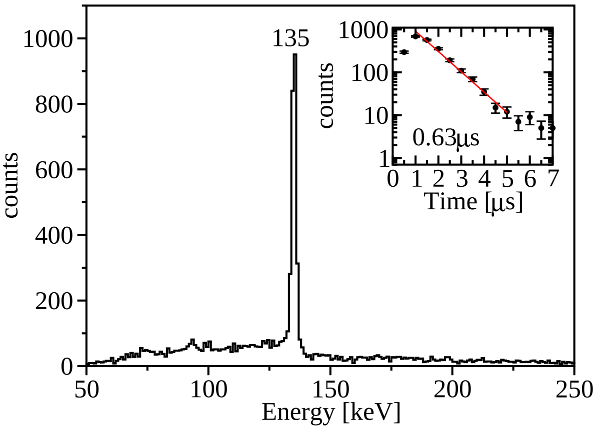

Figure 1. Isomeric transition in ^{121}Pd and time spectrum (inset) gated on it.

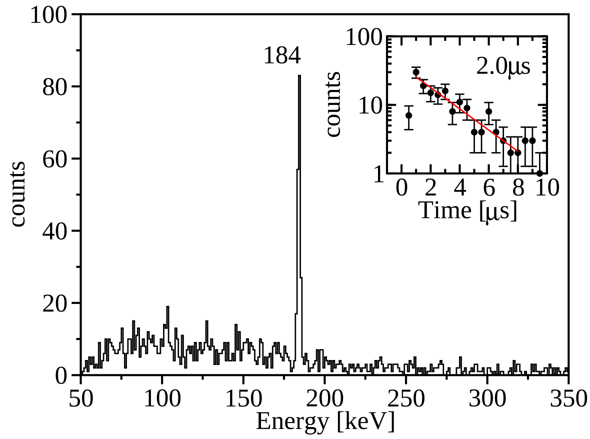

Figure 2. Isomeric transition in ^{117}Ru and time spectrum (inset) gated on it.

In addition to the spin-orbit force, it is the nuclear quadrupole deformation, which splits the high-j states into a number of orbits with a different third projection of the total angular momentum [2], causing new sub-shell closures to emerge [3] and high-K isomeric states to appear in the deformed regions on the Segré chart [4].

The present article addresses the structure of $^{121}_{46}$Pd$_{75}$ and $^{117}_{44}$Ru$_{73}$, which are the most neutron-rich nuclei in the palladium and ruthenium isotopic chains studied by means of γ-ray spectroscopy. They are placed in a region of the Segré chart where variety of shapes are expected, involving large degree of triaxiality and γ-softness [5, 6]. Also, because of the vicinity of the $N = 82$ magic number, a deformed-to-spherical shape transition [5, 6] is expected to take place. Due to the nature of the shell structure, isomeric states were observed in the two nuclei, which can be related to specific single-particle configurations, and hence can shed light on the nuclear shapes in the mass region.

2. Experimental set up and data analysis

Neutron-rich palladium and ruthenium isotopes were produced in a relativistic fission reaction. A ^{238}U beam was accelerated up to 750 MeV/n by the GSI SIS accelerator and impinged on 1g/cm^2 ^{9}Be target. The fission products were separated by the GSI Fragment Separator (FRS) and implanted in a passive stopper. Isomeric delayed transitions were detected by the RISING detector array [7], comprising 105 HPGe detectors. The data were processed by XIA DGF modules providing signals with an energy resolution of 3 keV at 1.3 MeV and a time resolution of 25 ns. The data acquisition was triggered by a particle detector, placed at the final focal plane of the FRS. The data were stored in event-by-event mode. Experimental details were previously published elsewhere [8].

Fig. 1 presents the γ-ray energy spectrum in singles, obtained in coincidence with the ^{121}Pd nuclei. A γ transition with an energy of 135 keV is observed. The inset of the figure presents the time distribution, gated on the 135-keV γ-ray. The half-life, obtained with a single exponential curve, is 0.63(5) μs.

Fig. 2 shows the energy spectrum, gated on ^{117}Ru ions, where a single transition with an energy of 184 keV was observed. The inset of the figure presents the time distribution of the 184-keV transition and a half-life of 2.0(3) μs was obtained from the slope of the curve. The two γ rays in ^{121}Pd and ^{117}Ru were previously observed [9], but no half-life information was published.

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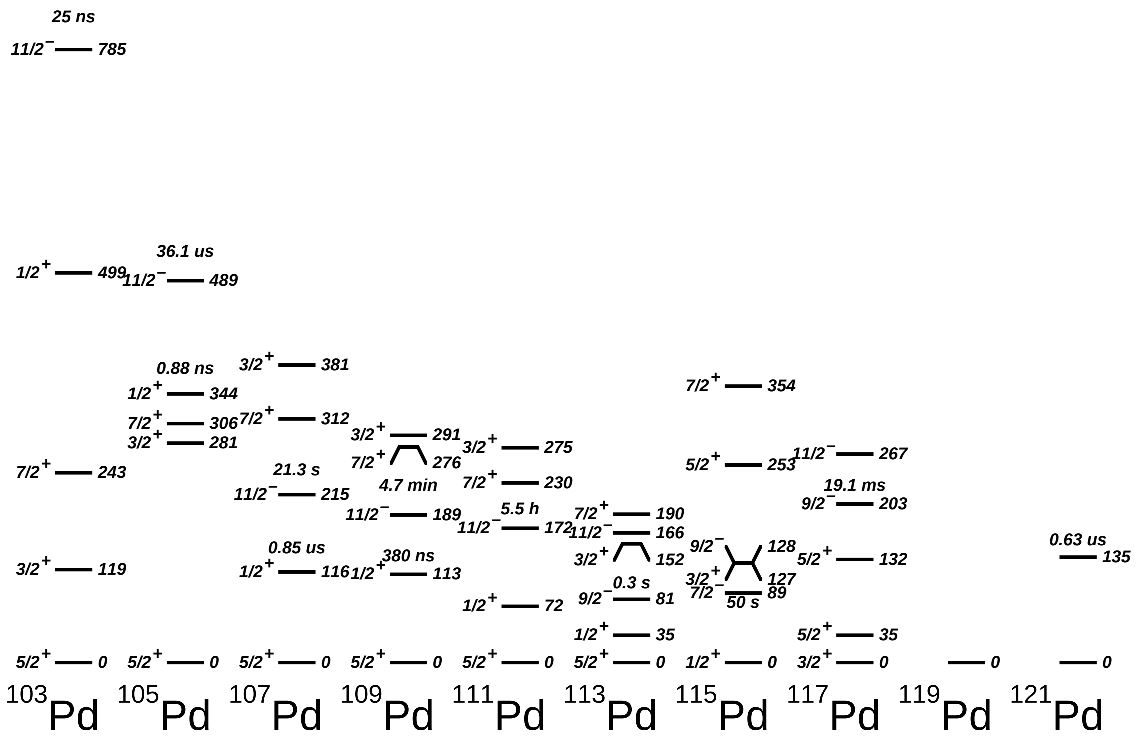

Figure 3. Systematics of the low-lying excited states in the neutron-rich palladium isotopes: $^{103-113}$Pd [10], ^{115}Pd [11], ^{117}Pd [12] and ^{121}Pd (present work).

3. Discussion

Fig. 3 presents the systematics of the low-lying excited states in the neutron-rich odd-A palladium isotopes. The ground state in ^{103}Pd to ^{113}Pd is a $J^{\pi}(g.s.) = 5/2^{+}$ state [10], while the J^{π} value for the ground state in ^{115}Pd and ^{117}Pd are subject of discussion in the literature [10, 11, 12]. Here, we adopt the J^{π} assignments for ^{115}Pd and ^{117}Pd as given in [11] and [12], respectively. The extrapolation of the systematics towards the extremely neutron-rich odd-A palladium nuclei suggests that $J^{\pi} = 1/2^{+}$ to $7/2^{+}$ and $J^{\pi} = 7/2^{-}$ to $11/2^{-}$ states will be present close to the ^{121}Pd ground state, but not all candidates give rise to a sub-microsecond isomer. The low-lying isomeric states, observed in the odd-A palladium isotopes are related to the decay of the negative-parity states as well as to the decay of the $J^{\pi} = 1/2^{+}$ excited state via stretched $E2$ low-energy transitions. Hindrance factors (HF), defined as $F_W = T_{1/2,\gamma}/T_{1/2,W.e.}$ where $T_{1/2,\gamma}$ is the partial half-life and $T_{1/2,W.e.}$ is the single-particle estimate, were calculated for the isomeric $E1$, $E2$, $E3$ and $M2$ transitions and plotted on figure 4 as a function of the neutron number.

The neutron-rich odd-A palladium ($Z = 46$) isotopes show structure close to that of the odd-A ruthenium ($Z = 44$) nuclei (figure 5). The HF, calculated for the low-lying isomeric transitions in the neutron-rich odd-A ruthenium nuclei are also plotted on fig. 4. To increase the statistics on the systematics in figure 4, HF were calculated for a number of low-lying isomeric transitions in the odd-A Cd nuclei [10, 13]. Inside the encircled regions on figure 4 HF for the 184-keV and 135-keV isomeric transitions in ^{117}Ru and ^{121}Pd are presented.

On figure 4, the $E1$ HF are in the $10^4 < F_W < 10^8$ range. If the 135-keV and the 184-keV isomeric transitions, observed in ^{121}Pd and ^{117}Ru nuclei, are of $E1$ nature the respective HF will follow the systematics presented in figure 4. The $E2$ HF shows a steady behaviour with the neutron number having $F_w \approx 1$. The ^{121}Pd and ^{117}Ru data points would follow the systematics

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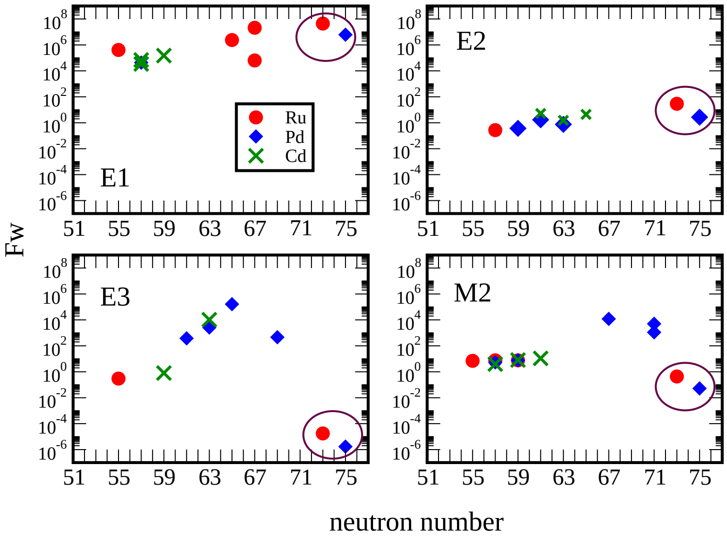

Figure 4. Hindrance-factor systematics for the low-lying isomeric states in the neutron-rich odd-A ruthenium, palladium and cadmium nuclei. The encircled regions present the hindrance factors for the 135-keV and 184-keV transitions studied here.

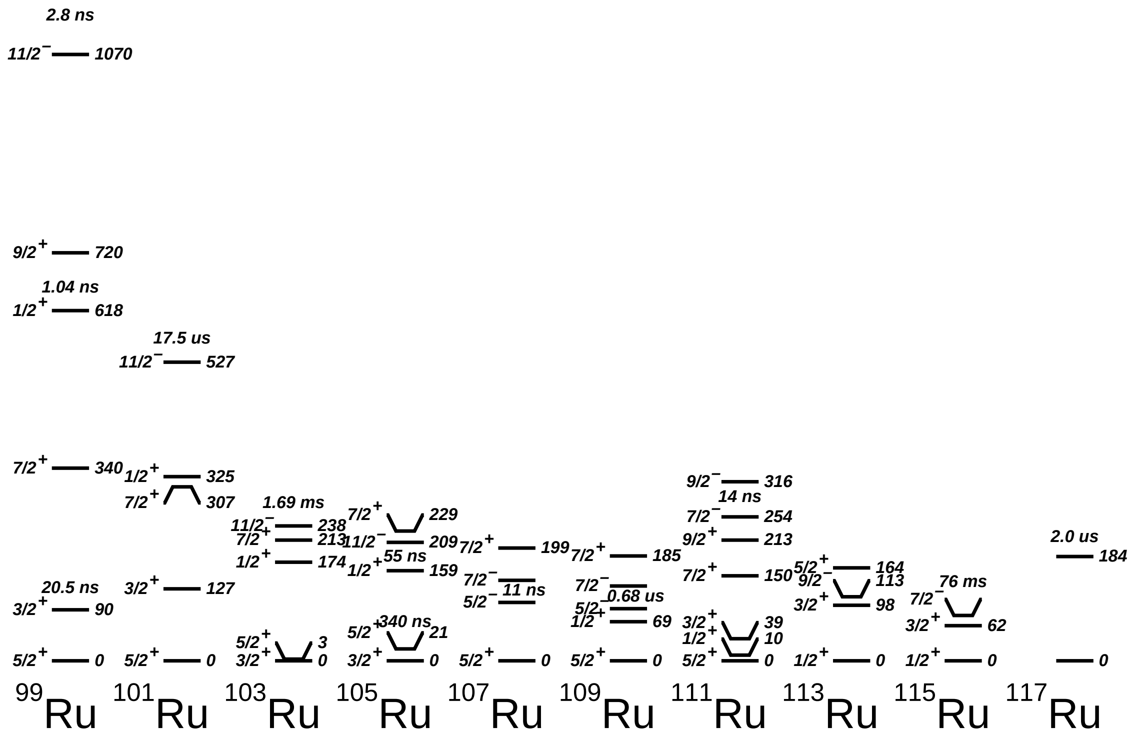

Figure 5. Systematics of the low-lying excited states in the neutron-rich ruthenium isotopes. Data from [10] for $^{99-115}$Ru and from the present work for ^{117}Ru.

in figure 4 if the two transitions are of $E2$ nature. In contrast to the $E2$ HF, the $E3$ F_W data points show an abrupt change varying six orders of magnitude. If the 135-keV and 184-keV transitions are of $E3$ nature, then they will be six orders of magnitude more enhanced than the other $E3$ transitions. Hence, the $E3$ nature for the two isomeric transitions in ^{117}Ru and

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^{121}Pd can be ruled out. The $M2$ transitions in the region have $F_w \geq 1$. If 135-keV and 184-keV transitions are of $M2$ nature, than they would be enhanced and would not follow the systematics of the $M2$ transitions. Therefore, $M2$ nature is unlikely.

The single-particle levels, calculated with a Woods-Saxon potential for the nuclei in the $A \approx 110$ mass region region [3], show that the ^{121}Pd Fermi surface involves $7/2^+[404]$, $1/2^+[400]$, $3/2^+[402]$, and $9/2^-[514]$ Nilsson orbits, where $\beta_2 = 0.19$ was calculated from the energy of the first excited state in ^{120}Pd. Given the HF systematics (fig. 4), $9/2^- \to 7/2^+$ $E1$ and $3/2^+ \to 7/2^+$ $E2$ transitions would cause isomeric states in the sub-microsecond time range. However, $J^\pi = 9/2^-$ assignment for the isomeric state can be ruled out because of the direct β^- feeding observed to the $9/2^+$ state in ^{121}Ag [14] suggesting the $J^\pi = 9/2^-$ isomeric state in ^{121}Pd has a half-life longer than the half-life of the observed in the present study nanosecond isomer. Therefore, we tentatively interpret the 135-keV transition as a prolate $3/2^+[402] \to 7/2^+[404]$ $E2$ transition.

The 73^{th} neutron of ^{117}Ru, which has β_2 =0.25 estimated from the first excited state in ^{116}Ru, is placed on $1/2^+[400]$ Nilsson orbit [3]. At this deformation, the $1/2^-[541]$ down-sloping orbit is also present close to the ground state, therefore we tentatively interpret the isomeric transition as a $1/2^- \to 1/2^+$ $E1$ transition. It should be noted, however, that at this deformation the $3/2^+[402]$, $7/2^+[404]$ and $9/2^-[514]$ Nilsson orbits are also present close to Fermi level, which can give rise to a situation similar to the ^{121}Pd scenario. The analysis of ^{121}Pd and ^{117}Ru is further complicated by the fact that the two nuclei are in a region where triaxiality, shape transitions and shape co-existence [6] are expected to occur, which may result in unexpected deviations from the hindrance factors systematics presented here. Therefore, in order to draw firm conclusions on the structure of these neutron-rich nuclei more experimental information and deeper theoretical analysis are needed.

4. Conclusions

Neutron-rich nuclei were populated in a relativistic fission of ^{238}U. Gamma rays with energies of 135 keV and 184 keV were associated with isomeric states in ^{121}Pd and ^{117}Ru, respectively. Half-lives of $0.63(5)\mu$s and $2.0(3)\mu$s were deduced and the isomeric states are interpreted in terms of prolate deformed single-particle states.

Acknowledgments

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