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Sub-microsecond isomer in $^{117}_{45}\mathrm{Rh}_{72}$ and the role of triaxiallity in its electromagnetic decay rate

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The neutron-rich nucleus ^{117}Rh was synthesized in the fission of relativistic ^{238}U beam produced at the GSI laboratory in Darmstadt, Germany. An isomeric state with $t_{1/2} = 138(17)$ ns decaying by a single γ-ray was observed, providing the first information on the excited states in this nucleus. The experimental data is discussed in terms of systematics and interpreted by using Woods-Saxon deformed shell model and Triaxial-Rotor-plus-Particle calculations. The origin of the isomer is explained as being due to a hindered $E2$ transition to the ground state.

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I. INTRODUCTION

The region of neutron-rich nuclei spanning the doubly magic $^{132}_{50}\mathrm{Sn}_{82}$ and the deformed $^{102}_{38}\mathrm{Sr}_{64}$ nucleus on the nuclear chart shows a rich variety of nuclear shapes and structure phenomena. There, spherical, prolate, rigid triaxial and γ-soft shapes are among the most commonly presented. A prolate-to-oblate shape transition is predicted to occur for the neutron-rich nuclei at approximately $A \approx 110$ [1], but this is still debated in the literature [2]. In some of the nuclei different shapes are observed to co-exist, leading to the occasional appearance of shape isomerism [3]. However, seniority [4, 5] and spin isomers [3] systematically appear in the neutron-rich nuclei close to the doubly magic ^{132}Sn. The existence of such metastable states has opened new possibilities [6] to study the most exotic neutron-rich nuclei and shed light on their structure, which has also provoked new theoretical searches [7].

In addition to the pure nuclear structure interest, some of these neutron-rich nuclei are on the r-process path and provide important experimental information for r-process path calculations. Others, being closest to the nuclei of astrophysical importance provide a crucial basis for extrapolation of different nuclear properties to-

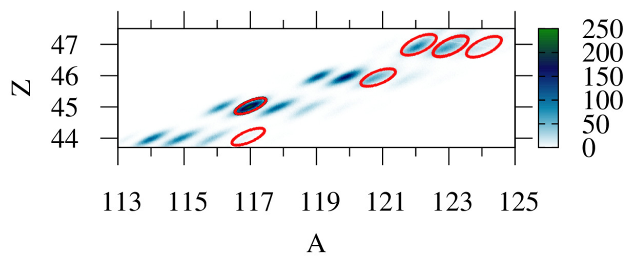

FIG. 1: (color online) The particle identification plot obtained from the FRS. The encircled peaks correspond to ${}^{122,123,124}_{47}$Ag, ${}^{121}_{46}$Pd, ${}^{117}_{45}$Rh and ${}^{117}_{44}$Ru.

wards the neutron drip-line and for tests of nuclear models further away from the line of β-stability. The focus of the present work is the neutron-rich nucleus ${}^{117}_{45}$Rh$_{72}$, where no experimental information on its excited states was available previously.

II. EXPERIMENTAL SET UP AND DATA ANALYSIS

Neutron-rich ${}^{117}_{45}$Rh nuclei were produced in fission of relativistic ^{238}U beam provided by the SIS accelerator at the GSI laboratory. The Uranium beam was accelerated up to 750 MeV per nucleon and impinged on a 1 g/cm^2 thick ^{9}Be target. The fission products were separated by the Fragment Recoil Separator (FRS), working in achromatic mode, and were implanted in a passive stopper. The isomeric delayed transitions were detected by the RISING multidetector array [8]. The full experimental details can be found in [9, 10].

Figure 1 presents the particle identification plot for the ${}^{120}_{45}$Rh FRS settings, where ${}^{122,123,124}_{47}$Ag, ${}^{121}_{46}$Pd and ${}^{117}_{44}$Ru are marked from the known isomeric decays [10, 11] and the ${}^{117}_{45}$Rh peak is also indicated. The γ-ray energy spectrum, obtained in coincidence with the ${}^{117}_{45}$Rh$_{72}$ nuclei is presented in Fig. 2. A single γ-ray with an energy of 321.2(10) keV is observed for the first time in the present study. The inset to the figure presents the time distribution for the 321.2-keV γ-ray. The half-life, obtained from the exponential fit to the curve, is 138(17) ns. Table I lists the reduced transition probabilities for pure electric or magnetic transitions of energy 321.2 keV and shows that in the cases where the transition is of pure $M1$, $E1$ or $E2$ nature, the isomeric decay would be hindered. In all other cases the transition would be unprecedentedly enhanced and hence these multipolarities are considered as unlikely.

It was not possible to extract any other experimental information given that only one γ-ray was observed and the traditional methods such as angular correlation and γ-ray polarization measurements are inapplicable. Multipolarity assignments based on conversion electron measurements were also not possible, given the experiment was performed during the Passive stopper campaign [13]

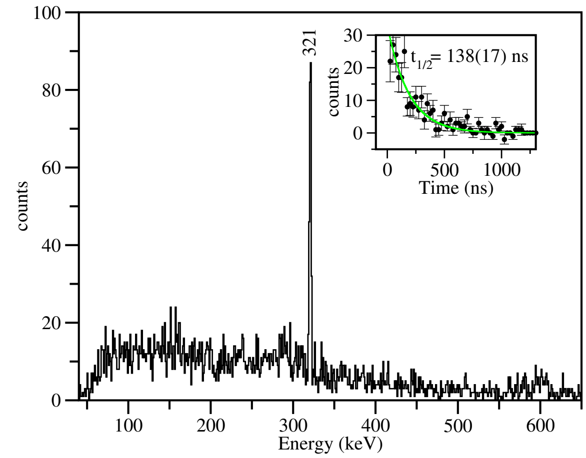

FIG. 2: (color online) Gamma-rays observed in coincidence with the ^{117}Rh ions; (inset) time spectrum, gated on the 321-keV transition.

TABLE I: Reduced transition probabilities for pure electric $B(E\lambda)$ and magnetic $B(M\lambda)$ transitions of energy 321 keV in ^{117}Rh. Here λ is the multipolarity and $\alpha_{E,M}$ are the calculated [12] internal conversion coefficients. The half-life of the level is 138(17) ns.

λ	α_E	$B(E\lambda)$, W.u.	α_M	$B(M\lambda)$, W.u.
1	0.0055	6.1×10^{-8}	0.0152	4.7×10^{-6}
2	0.0225	0.035	0.0641	2.6
3	0.0835	2.8×10^{4}	0.2463	1.9×10^{6}
4	0.3	3.0×10^{10}	0.9458	1.6×10^{12}

where thick secondary targets were used. As a result, the spin/parity assignments to the ^{117}Rh levels are based on systematics.

III. DISCUSSION

A. Systematics

The experimental level energies of the lowest-lying positive- and negative-parity states in the odd-mass rhodium isotopes are presented in Fig. 3(a) and 3(b), respectively. Figure 3(a) shows that the $7/2^+$ state is the ground state for all Rhodium nuclei with $58 < N \leq 70$. A $9/2^+$ is the first positive-parity excited state and indeed is the first excited state for $N \geq 60$. Depending on their evolution with neutron number, two different groups of positive parity states can be distinguished. The energies of one subset evolve smoothly with neutron number, while the remaining change abruptly and having a minimum energy at the neutron mid-shell. This late subset of levels is related to the appearance of the $1/2^+[431]$ intruder orbit.

The $1/2^-$ state is the ground state in ^{101,103}Rh$_{56,58}$

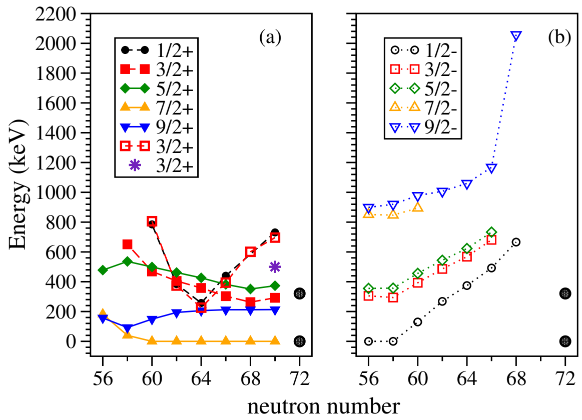

FIG. 3: (color online) Level energy systematics of (a) positive-parity and (b) negative-parity yrast states in the odd-mass Rh isotopes. Data retrieved from [14]. The data for $N = 72$ are from the present work (see text for details).

TABLE II: Low-lying isomeric states in the odd-mass rhodium isotopes [14]. The ground state (g.s.) is denoted for each nucleus.

nucleus	$1/2^+_1$	$3/2^+_1$	$3/2^+_2$	$5/2^+_1$	$7/2^+_1$	$9/2^+_1$	$1/2^-_1$
^{101}Rh$_{56}$					1.9 ns	4d	g.s.
^{103}Rh$_{58}$					56 min	1 ns	g.s.
^{105}Rh$_{60}$					g.s.		
^{107}Rh$_{62}$		15 ns			g.s.		> 10 μs
^{109}Rh$_{64}$	29 ns	1.7 μs			g.s.		33 ns
^{111}Rh$_{66}$	4.8 ns		87 ns	0.3 ns	g.s.		6.8 ns
^{113}Rh$_{68}$		0.4 ns	0.7 ns	0.3 ns	g.s.	0.2 ns	

and its energy increases smoothly with neutron number to 666 keV in ^{113}Rh$_{68}$ as shown in Fig. 3(b). All other negative-parity yrast states follow the same trend with neutron number.

For $N = 56, 58$, where $1/2^-$ is the ground state and $7/2^+$ or $9/2^+$ is the first excited state, low-lying long-lived spin isomers with half-lives from several nanoseconds to a few days appear. The systematics of these isomeric half-lives in the odd-mass Rhodium isotopes [14] is given in Table II.

In the heavier nuclei the ordering of the $1/2^-$ and the $7/2^+, 9/2^+$ levels swaps. The $1/2^-$ level energy increases towards the neutron mid-shell and a number of low-J positive parity states appear in the energy gap between the ground state and the $1/2^-$ excited state. As a result, the half-life of the $1/2^-$ state decreases from several microseconds in ^{107}Rh to 6.8 ns in ^{111}Rh. Moreover, based on analogy with the Silver isotopic chain [10], a decrease of the $1/2^-$ level energy and increase of its half-life can be expected in Rhodium nuclei as the $N = 82$ magic number is approached.

The extrapolation of the systematics in Fig. 3(a), to ^{117}Rh$_{72}$ suggests that the ground state has $J^\pi = 7/2^+$, while the $J^\pi = 3/2^+, 5/2^+$ and $9/2^+$ levels should lie

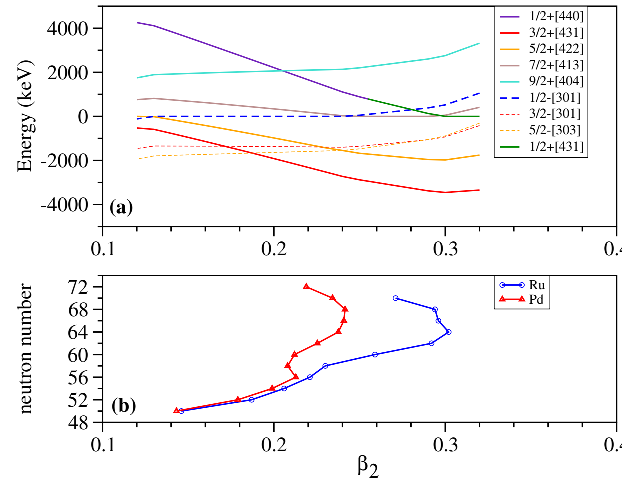

FIG. 4: (color online) (a) Deformed proton single particle states near the Fermi level calculated with a realistic Woods-Saxon potential and normalized with respect to the ground state of ^{117}Rh. (b) quadrupole deformation parameter β_2 as a function of the neutron number for neighboring even-even Ru and Pd nuclei.

at approximately 350 keV. For the Rhodium nuclei with $N \geq 62$, the $5/2^+$ and $9/2^+$ states have sub-nanosecond half-lives and hence unlikely to generate the isomer observed in ^{117}Rh. The $3/2^+$ states, however, have a more tantalizing behaviour. In the light Rhodium isotopes only one low-lying $3/2^+$ level is present. This level appears throughout the entire isotopic chain shown in Fig. 3(a) and its energy has only a slight dependence on the number of valence neutrons. A second $3/2^+$ level appears in the $N \geq 50$ Rhodium isotopes. Its energy depends strongly on the neutron number and is correlated to the $1/2^+$ level energy. This level has a minimum energy at $N = 64$, generating a long-lived $3/2^+$ isomer close to the ground state. Recently, a third low-lying $3/2^+$ state was found in ^{115}Rh [15], but its nature is still not well understood.

Thus, based on the systematics, three states with $J^\pi = 7/2^+$, $3/2^+$ and $1/2^-$ can be expected to play a role in the observed isomerism in ^{117}Rh$_{72}$. Also, given that the 321-keV γ-ray is of $E1$, $E2$ or $M1$ nature, and assuming $^{117}_{45}$Rh$_{72}$ is deformed, a $\Delta K \leq 3$ transition can be expected from the Löbner systematics [16].

B. Deformed shell model calculations

To study the single-particle levels involved in the observed isomer in $^{117}_{45}$Rh, Deformed Shell model calculations were performed by using a Woods-Saxon potential with "universal" parameters [17]. Figure 4(a) presents the proton single-particle level energies, relative to the Fermi energy, as a function of the quadrupole deformation parameter β_2. For $0.13 < \beta_2 < 0.25$ the ground state has $1/2^-[301]$ as leading Nilsson configuration. In

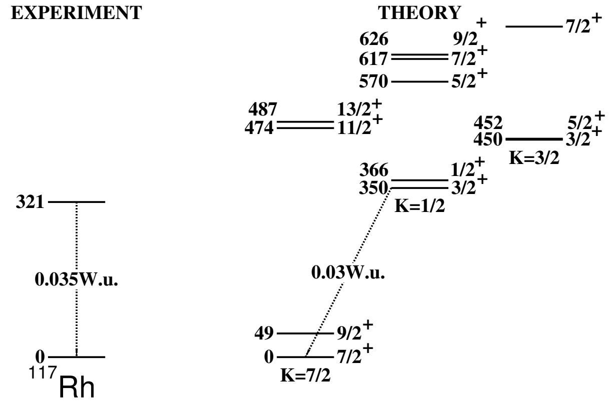

FIG. 5: Isomeric decay observed in ^{117}Rh and compared to the theoretical level scheme from RTRPM calculations for the positive parity states in ^{117}Rh obtained with $\epsilon_2 = 0.26$ and $\gamma = 27.02°$.

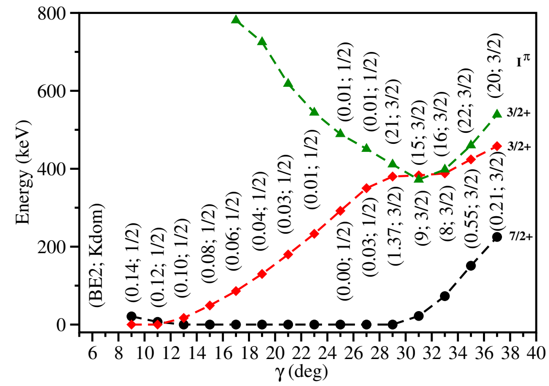

FIG. 6: (color online) Level energies of the positive parity states in ^{117}Rh calculated with the RTRPM as a function of the triaxial parameter γ. The $B(E2)$ values for the $3/2^+ \rightarrow 7/2^+$ transition in W.u. and the dominant K_{dom}-value are denoted as a function of triaxial parameter γ from 9° to 37°.

the range $0.25 \leq \beta_2 < 0.30$ the main component of the ground state wave function is $7/2^+[413]$ and for $0.30 \leq \beta_2 \leq 0.32$ the ground state is based on the $1/2^+[431]$ Nilsson configuration. As β_2 increases from 0.25 to 0.30 the $1/2^+$ state decreases in energy with respect to the $7/2^+$ ground state, while the energy of the $1/2^-$ state shows the opposite trend. This effect is consistent with the systematics of the experimental data in Fig. 3 for $0.24 \leq \beta_2 \leq 0.30$, where the evolution of the intruder band has the same trend.

Fig. 4(b) presents the evolution of the quadrupole deformation parameter β_2 with the neutron number, calculated from the 2_1^+ level energy in the even-even Palladium and Ruthenium nuclei and using the Grodzins' relation [18]. This shows, that the maximum value of $\beta_2 \approx 0.24 - 0.30$ is achieved at $N \approx 66$ for both the Palladium and Ruthenium nuclei, which is consistent with the $7/2^+$ being the ground state in the medium mass Rhodium isotopes. The extrapolation of the β_2 curves for the Palladium and Ruthenium isotopes suggests that for ^{117}Rh ($N = 72$) β_2 would be ≈ 0.22 to 0.26. In this range, the $1/2^-$ and $7/2^+$ single particle orbits lie close in energy and swap their relative positions at $\beta_2 \approx 0.24$. It should be noted also that for $0.22 \leq \beta \leq 0.26$ on Fig. 4(a) an $\Omega^\pi = 1/2^+$ single-particle level can be expected close to the $7/2^+$ level. The $\Omega^\pi = 1/2^+$ level has a leading $1/2^+[440]$ Nilsson configuration for small deformation, while for $\beta_2 \geq 0.255$ the leading configuration of the wave function is $1/2^+[431]$. This configuration is responsible for the appearance of the positive-parity intruder band, observed in the odd-mass Rhodium isotopes, where due to the negative Coriolis decoupling parameter the $3/2^+$ band member lies lower in energy than the $1/2^+$ band member [15].

C. Particle-rotor model calculations

Given that $^{117}_{45}\mathrm{Rh}_{72}$ is in a region where a significant degree of triaxiallity can be expected [19] Rigid Triaxial Rotor plus Particle model (RTRPM) calculations were also performed. The model deformation parameters $\epsilon_2 \approx 0.944\beta_2 - 0.122\beta_2^2 = 0.21$ to 0.24 were determined from the systematics of the 2^+ level energies in the neighboring Palladium and Ruthenium isotopes and the triaxiallity parameter $\gamma = 1/3 \arcsin\sqrt{9/8(1-(X-1)^2/(X+1)^2)} = 27°$ was deduced from the 2_1^+ and 2_2^+ level energies in $^{118}\mathrm{Pd}_{72}$, where X is defined by the ratio $E(2_2^+)/E(2_1^+)$. The single-particle levels were calculated with the GAMPN code [20] and a Modified Oscillator potential. The model parameters κ and μ, used in the present work, are the parameters obtained in [21] which have been found to be more appropriate for $A \approx 120 - 140$, than the standard Nilsson parameters [22].

The level energies of $^{117}_{45}$Rh were determined by using the ASYRMO code [20]. The Coriolis attenuation parameter ξ was set to 0.8. The transition probabilities were calculated with PROBAMO [20]. The value of ϵ_2 was varied to study the evolution of the low-lying states as a function of the deformation parameters. A good description of the experimental data was achieved for $\epsilon_2 = 0.26$. The low-lying levels calculated with the RTRP model are presented in Fig. 5 where they are compared to the experimental data obtained in the present work. The theoretical level scheme has an excited level at 350 keV with $J^\pi = 3/2^+$ and dominant $K = 1/2$, which decays to the $7/2^+$, $K_{dom} = 7/2$ ground state via an $E2$ transition. The transition strength, calculated with the RTRP model, $B(E2; 3/2^+ \rightarrow 7/2^+) = 0.03$ W.u., is close to the experimental value of $B(E2; 3/2^+ \rightarrow 7/2^+) = 0.035$ W.u.

To study how the triaxiallity affects the electromagnetic decay rates, RTRPM calculations were performed for $\epsilon = 0.26$, while the degree of triaxiallity γ was varied. Results from these calculations are presented in Fig. 6. The $I^\pi = 7/2^+$ level with a dominant $K_{dom} = 7/2$ contribution is the ground state for $13^\circ < \gamma < 31^\circ$. Outside this range it is an excited state. For $8^\circ < \gamma < 28^\circ$, the first $3/2^+$ level has $K_{dom} = 1/2$. As a result it decays to the $I^\pi = 7/2^+$ state via a retarded $\Delta K_{dom} = 3$ $E2$ transition, which is consistent with the experimental data.

For $\gamma \geq 28^\circ$, however, the first $3/2^+$ level would mix with the second and the dominant K-quantum number becomes $K_{dom} = 3/2^+$. In this region the $B(E2; 3/2^+ \rightarrow 7/2^+)$ value would be enhanced from 1 W.u. to 22 W.u., which is inconsistent with our data.

For oblate deformations, an abrupt re-arrangement of the levels takes place. The $7/2^+$ level becomes an excited state with its energy strongly dependent on γ. The first $I^\pi = 3/2^+_1$ state decays via a hindered $E2$ transition to the $7/2^+$ excited state, while the transition $3/2^+_2 \rightarrow 7/2^+$ is enhanced. Again, this scenario is inconsistent with the new experimental data for ^{117}Rh, where only one γ-ray was observed.

Concluding remarks

Further to the present discussion, it worth noting that the calculated $1/2^-$ level appears close in energy to $7/2^+$ and their mutual position depends on the deformation parameters. The average distance between the two states is of the order of 400 keV which leads to the Weisskopf estimate of 8×10^{-4}s for an $E3$ transition. A careful inspection of the experimental data, however, shows that except for the background lines at 1462 and 511 keV and the 198-keV transition from the ^{71m}Ge $T_{1/2}$=20.4 ms IT decay [14], there is no other delayed transition in the 25 ns to 50 μs time range. It should be noted, however, that the negative-parity and the positive-parity states in ^{117}Rh may have different deformations, which would lead to an additional hindrance of the $E3$ transition and would make it unlikely to be seen with the RISING multidetector array operating in the microsecond and sub-microsecond time range.

IV. CONCLUSIONS

Isomeric decay has been observed for the first time in ^{117}Rh. Model calculations were performed showing that for moderate quadrupole deformations $\epsilon_2 \approx 0.26$ and at significant triaxiallity a low-energy $I^\pi = 3/2^+$ level emerges in ^{117}Rh decaying to the $7/2^+_1$ state via a hindered $\Delta K_{dom} = 3$ $E2$ transition. The calculated $B(E2)$ value is in good agreement with the experimental observation for $13^\circ < \gamma < 28^\circ$. As a result, the RTRPM calculations give a consistent description of the available experimental data only for $\epsilon_2 = 0.26$ and $\gamma \approx 27^\circ$.

Acknowledgments

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