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Identification of the rare neutron-rich isotope ^{117}Rh

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In this paper we wish to report on the first observation of the beta decay of the very neutron-rich nucleus ^{117}Rh. It was produced via 23 MeV proton-induced fission of ^{238}U using the ion guide setup of the LISOL separator. A beta half-life to 0.44 ± 0.04 s was measured for this nucleus from the decay of the beta-coincident K x rays of Pd. The half-lives of neutron-rich Rh isotopes are compared with the newest model calculations. Three gamma rays of 34.6, 131.7, and 481.6 keV were found to be associated with the decay of ^{117}Rh. Its proposed beta-decay scheme and the decay of the recently discovered 19 ms isomer in ^{117}Pd imply spin and parity of $\frac{11}{2}^-$ for the isomer fed directly in fission.

Recent developments in experimental techniques have resulted in considerable progress in the studies of neutron-rich nuclei far from the valley of beta stability. Fragmentation has opened up a way to several new discoveries among the light elements, while fission and transfer reactions have remained thus far the only ways to produce medium-heavy and heavy neutron-rich nuclei. The discoveries of the r-process waiting point nuclei ^{80}Zn and ^{130}Cd [1,2] and the extension of the beta half-life systematics to new neutron-rich isotopes in the $A=80$ and $A=110$ [3,4] regions are recent achievements near the borderline of the unknown neutron-rich nuclei, which are all produced in fission.

In this work we wish to report on the first observation of an extremely neutron-rich isotope, ^{117}Rh, located 14 neutrons away from the nearest stable rhodium isotope. However, this isotope is still far from the β-equilibrium r-process path predicted to pass near the ^{125}Rh-^{128}Rh isotopes [5]. Earlier experiments at the IGISOL Facility of the University of Jyväskylä have produced detailed information on five neutron-rich rhodium isotopes from ^{112}Rh to ^{116}Rh [6–8]. The beta-decay properties, in general, and the half-lives and the decay energies, in particular, of the most neutron-rich nuclei are of significant value in testing the models used, for example, in the nucleosynthesis calculations.

The presence of a high j neutron orbital $h_{11/2}$ results in isomerism among Pd isotopes. These negative-parity isomers in odd-Pd isotopes were known from $A=103$ to 115 with the exception of $A=113$. A recently observed 19-ms isomeric state in ^{117}Pd [9], decaying via two $M2$ transitions, could also be a member of the $h_{11/2}$ isomer family. No firm assignment could, however, be made, and a search for ^{117}Rh was hoped to result in the spin and parity of this exotic isomeric state in ^{117}Pd.

Neutron-rich nuclides of highly refractory elements such as Rh have recently become available as on-line mass-separated sources by using the ion guide isotope separator on-line system, IGISOL, and charged-particle-induced fission as a production reaction [10]. The very short delay, i.e., 1 ms, between the production and implantation of the mass-separated activity should allow the detection of the shortest beta half-lives. The maximum production rates for the Rh isotopes were about 1000 atoms/s normalized to 1-μA proton beam intensity, reducing to about 50–100 atoms/s for the heaviest known isotope, ^{116}Rh. The extension of the experiments towards still heavier isotopes was hampered by the low production rate, mainly due to the limited beam intensity at the Jyväskylä cyclotron, which is of the order 1 μA at maximum with 20-MeV protons.

The experiment described in this paper was performed with the ion guide setup of the LISOL Facility located at the CYCLONE heavy-ion cyclotron laboratory in Louvain-la-Neuve. The nuclei studied were produced with an intense 23-MeV proton beam by inducing fission on ^{238}U. Four targets with a total thickness of 40 mg/cm^2 were used. The isobaric chain with $A=117$ was mass separated as singly charged ions as described in Ref. [10]. The mass-separated nuclei were implanted in a moveable collector tape. The radioactivity of the produced nuclei was detected at the point of implantation with a 70% n-type Ge detector, a 500 mm^2, 10-mm-thick planar low-energy Ge detector, and a 1-mm-thick Ne-102-type plastic operating as a ΔE detector for beta rays. Only double or triple coincidence events were recorded together with the cycle time information from a time to digit converter. The cyclotron beam was pulsed in order to create an implantation and decay period. One cycle consisted of a 1.5-s implantation period followed by a 3.0-s decay period. The shutdown of the cyclotron beam during the decay period considerably reduced the neutron-induced background. The background produced by the long-lived radioactive nuclei in the same isobaric chain was reduced by transporting the source away after each ten collection cycles.

In this measurement the lower limit of the production rate of ^{117}Rh was observed to be about 5 ions/s normalized to 1-μA proton beam intensity. Additional conversion electron measurements on the isomeric state of ^{117}Pd were performed at the IGISOL Facility in Jyväskylä using the magnetic conversion electron spectrometer ELLI [11].

In the measurements at the mass number $A=117$

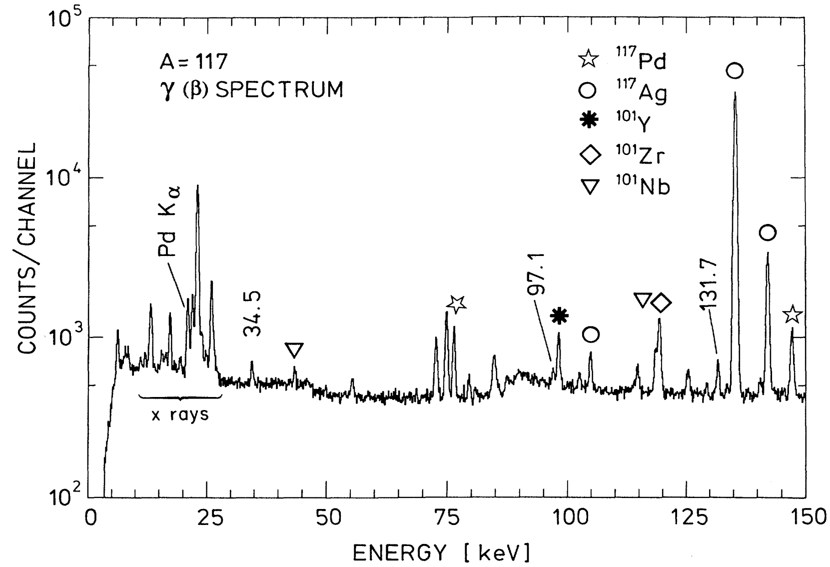

FIG. 1. The low-energy part of the gamma-ray spectrum at the mass $A=117$ observed in coincidence with beta particles. The gamma rays labeled with energy are assigned to the decay of ^{117}Rh. The nuclei with $A=101$ are mass separated as monoxide ions. Unlabeled peaks at 73 and 75 keV are Pb x rays.

several gamma rays were observed in coincidence with the Pd K x rays. The 34.6-, 71.5-, 97.1-, 131.7-, and 168.6-keV gamma rays were previously observed in connection with the decay of the 19.1(7)-ms isomeric state in ^{117}Pd [9,12]. The 34.6-, 97.1-, and 131.7-keV gamma rays, as well as the previously unknown weak 481.6-keV gamma ray, were also observed in coincidence with beta rays, as shown in Fig. 1. A half-life of 0.44(4) s was determined from the observed decay of the beta-gated Pd K x rays, produced mostly by the internal conversion of the 34.6-keV transition (Fig. 2). The decays of the beta-gated 34.6- and 131.7-keV transitions followed the same decay pattern. In the vicinity of the 481.6-keV gamma ray there is also a 482.1(4)-keV gamma ray that belongs to the beta decay of ^{117}Pd. For this doublet, the total intensity as a function of time was fitted assuming two components. The results obtained for the half-lives were ≈ 5 s [the half-life of ^{117}Pd is 4.3(3) s [12]] and ≈ 0.5 s.

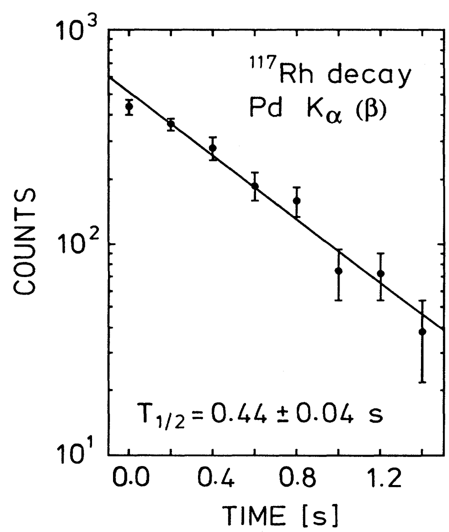

FIG. 2. The decay of Pd K x rays in coincidence with beta particles during the beam-off period.

The multipolarities of the observed transitions were determined by conversion electron measurements using the copiously produced 19-ms isomeric state in ^{117}Pd. The low production rate of ^{117}Rh excluded these measurements in the β decay. The results are given in Table I.

The β-decay scheme of ^{117}Rh is shown in Fig. 3 together with the earlier established decay scheme of ^{117}Pd^m. These schemes are based on the coincidence relations and the intensities of the observed transitions. The 481.6-keV transition could not be placed in the decay scheme.

To determine the spin and parity of the ^{117}Pd levels from the beta decay of ^{117}Rh we assumed a $\frac{7}{2}^+$ ground state for ^{117}Rh. This assumption is derived from the level systematics of the other odd Rh nuclei, where the ground state has been uniquely assigned with $\frac{7}{2}^+$. The first excited state has been observed to be $\frac{9}{2}^+$ with an excitation energy of about 200 keV with a very smooth systematic behavior starting from $A=107$. The strongest observed beta-decay feeding goes to the 35-keV level in ^{117}Pd. We thus conclude positive parity ($\frac{5}{2}^+$-$\frac{9}{2}^+$) for this level. A similar assignment can also be made for the 132-keV level.

Since the ground state and the 35-keV state must have the same parity as can be seen in Table I, the beta branching to the ground state may be large. A recent systematic study of the cumulative fission yields of neutron-rich nuclei indicates substantial ground-state feeding [14]. An average drop in yield of a factor of 5 between neighboring isotopes with increasing neutron number was observed for the neutron-rich rhodium isotopes. On the basis of the beta-gated gamma-ray intensity the fission yield of ^{117}Rh

TABLE I. Conversion coefficients and proposed multipolarities of transitions in ^{117}Pd. The conversion coefficients are deduced from a simultaneous electron and gamma-ray measurement, except α_K for 34.5 keV, which is derived from Pd x-ray fluorescence yield. The 71.5-keV gamma-ray intensity was deduced by subtracting the contribution of 71.1-keV photon from ^{117}In decay, which was deduced from the intensity of the 89.7-keV photon belonging to the same decay [13]. Otherwise, the gamma and electron intensities are deduced from single peaks. Multipolarity assignments are based on theoretical values from Ref. [19].

Transition	Experiment				Theory		
(keV)	α_K	α_L	K/L	Multipolarity	α_K	α_L	K/L
34.5	7.1 ± 0.9	0.62 ± 0.18		$M1$	$M1$: 7.34	$M1$: 0.83	
71.5	7^{+15}_{-4}		≈ 4	$M2$	$E2$: 3.15 $M2$: 11.3		$E2$: 3.2 $M2$: 5.1
97.1	0.42 ± 0.16			$M1$	$M1$: 0.369		
131.7	0.38 ± 0.09			$E2/M1$	$M1$: 0.158 $E2$: 0.412		
168.6	0.55 ± 0.07		≈ 6.5	$M2$	$M2$: 0.518		$E2$: 6.1 $M2$: 6.8

seems to drop a factor of 20 in comparison to ^{116}Rh. This suggests that about 70% of the beta decays could go to the ground state of ^{117}Pd, implying a spin and parity in the range of $\frac{5}{2}^+$ to $\frac{9}{2}^+$ for the ground state of ^{117}Pd.

The above information, the observed branching ratios and the decay of the isomeric state via the cascade of the 168.6-keV $M2$ and the 34.6-keV $M1$ transitions, results finally in the $\frac{11}{2}^-$, $\frac{7}{2}^+$, and $\frac{5}{2}^+$ assignments for the isomeric 203-keV, 35-keV, and the ground states, respectively. The $M2$ assignment for the 71.5-keV transition fixes the spin of $\frac{7}{2}^+$ for the 132-keV level.

The decay of ^{117}Pd to the levels of ^{117}Ag further supports the $\frac{5}{2}^+$ assignment for the ground state via the

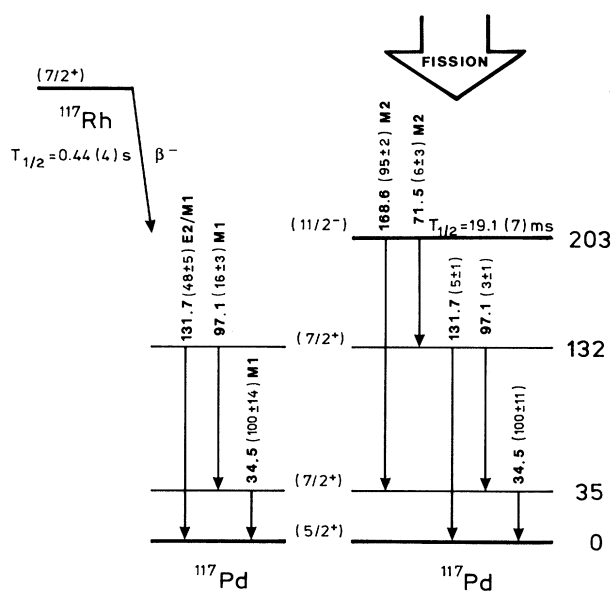

FIG. 3. The decay scheme of ^{117}Rh. The given intensities are total intensities in which conversion is included. In the 132-keV transition 85% $E2$ is assumed in the basis of observed K conversion. The right-hand part of the figure shows the levels in ^{117}Pd known from the decay of isomeric state which is fed directly in fission.

nonobservation of the $\frac{9}{2}^+$ state in beta decay, observed in the neighboring odd Ag isotopes. Instead, the 28.6-keV, $\frac{7}{2}^+$ isomeric state in ^{117}Ag could now be strongly fed in the beta decay of ^{117}Pd. In this case, the log*ft* values for β decays to the negative-parity states of ^{117}Ag would increase, and our previous speculation [12] about the possibility of a negative-parity ground state for ^{117}Pd could be omitted.

Based on the observed half-life and the Q_β value of 7.8 MeV deduced from the current mass formulas given in Ref. [15] we obtain a total log*ft* value of about 4.5 for the beta decay of ^{117}Rh. This is a typical value found for the spin-flip transitions, expected in this case to be mediated via the $\nu g_{7/2} \rightarrow \pi g_{9/2}$ transformation. This necessarily involves the decay of the "core" neutrons, and consequently complex core-coupled wave functions are required to give an adequate description of the process. A recently advanced field of the *np* quasiparticle-random-phase-approximation calculations for the beta-decay properties, in general, and beta half-lives, in particular, can thus be tested for their performance on predictions far from stability. Such calculation for the beta-decay half-lives has been presented by Staudt *et al.* for neutron-rich nuclei [16]. The predictions of this model for the beta half-life of ^{117}Rh are 0.21, 0.41, and 0.23 s, when using the Q_β values from the mass formulas of Groote *et al.*, Hilf *et al.*, and Möller and Nix, respectively (see Ref. [16] for references). The critical dependence of the predictions on the decay energies is explained by a very high sensitivity on the beta-decay phase-space factor on the decay energy ($f \propto E_\beta$ [5]). Similar predictions based on the Q_β values from the compilation of Wapstra and Audi [17] for ^{112}Rh to ^{116}Rh gives an average ratio of 1.46 between the experimental and theoretical values. This agreement is an excellent improvement as compared with the earlier predictions and it is obvious that the beta-decay transition strengths can be fairly reliably calculated with the random-phase-approximation approach. However, it should be noted here that further extrapolations to more *n*-rich nuclei will be even more sensitive to the prediction of the beta-decay energies.

The $\frac{11}{2}^-$ isomeric state in ^{117}Pd could be a quasiparticle state associated with the $h_{11/2}$ neutron orbit. Its $M2$ decay is hindered by a factor of 4000, which should be compared with similar, large hindrance factors observed for the other nearby odd Pd isotopes [18]. This phenomenon has been explained to be the consequence of pairing, which causes the cancellation of the transition rate between the states above and below the Fermi level. The fact that the $N=71$ nucleus ^{117}Pd has an $\frac{11}{2}^-$ state as an excited state suggests that the pairing strength for the $h_{11/2}$ neutrons is considerably larger than that for the nearby s and d orbital neutrons. This effect becomes obviously very important in the structures of the neutron-rich nuclei in this region as was already pointed out in connection with the observation of the onset of the γ-soft deformation in neutron-rich Ru nuclei [4].

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