Excited states in neutron-deficient iridium nuclei populated in radioactive decays of $^{177-181}$Pt

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The radioactivity of neutron-deficient platinum isotopes $^{177-181}$Pt was studied after the production in ^{146}Nd(^{36}Ar,xn) and ^{148}Nd(^{36}Ar,xn) reactions. The β-decay branches were identified by the detection of γ transitions in the iridium daughter nuclei. We report γ rays, $\gamma\gamma$ coincidences, and half-lives. Ground and excited states are discussed in terms of the single-particle structure in deformed nuclei and new results are presented for the systematics of the intruder $h_{9/2}$ band and $d_{3/2}$ states in iridium.

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Neutron-deficient isotopes below the magic $Z = 82$ nuclei are particularly interesting for nuclear structure studies. They are located in a transitional region where the nuclear shape changes from well deformed to the shell-model lead nuclei. Assignments of deformed single-particle Nilsson states had been derived from the identification of unhindered α decays [1, 2] or from the investigation of rotational bands observed in nuclear reactions in beam [3–6]. β-decay studies may also give structure information since the transition probabilities to states in the daughter nuclei are closely related to the intrinsic level structure.

In our systematic decay studies of hafnium-to-platinum isotopes, two interesting aspects are noted. First, the prolate-deformed $h_{9/2}$ $\frac{1}{2}^-[541]$ proton orbital intrudes from beyond the Z =82 shell gap. It has been well established in neutron-deficient lutetium (Z =71) to gold (Z =79) nuclei [7–10] and plays an important role in the rhenium (Z =75) and iridium (Z =77) isotopes [11–13], where the actual knowledge on level structure is very scarce. Second, the vicinity of deformed states originating from the major $d_{3/2}$ and $h_{11/2}$ shells and the $h_{9/2}$ $\frac{1}{2}^-[541]$ orbital gives rise to a new island of long-lived isomers which has recently been discovered in decay studies of rhenium and iridium nuclei [12, 13].

The earlier identification of these isotopes in the very neutron-deficient region was favored due to the strong α-decay branches and the appealing features of α spectroscopy such as low background, high detection efficiency, and good energy resolution. Today, using highly efficient detection and coincidence techniques, the β-decay branches are also experimentally accessible.

We report here on the β decays of neutron-deficient platinum isotopes $^{177-181}$Pt, which were identified by spectroscopy of γ rays depopulating levels in the iridium daughter nuclei. The platinum isotopes were produced in fusion-evaporation reactions of highly enriched, 2.3 mg/cm^2 thick ^{146}Nd and ^{148}Nd targets and a beam of ^{36}Ar ions, provided by the VICKSI accelerator facility of the Hahn-Meitner-Institut in Berlin. The initial beam energy of 240 MeV was reduced in the entrance window of the reaction chamber and could further be reduced stepwise by additional tantalum degraders in front of the target. The mean energy in the middle of the target was thereby varied in the range 173–201 MeV.

The recoiling evaporation residues were thermalized and swept out of the reaction chamber with a He/NaCl gas-jet flow. The samples were periodically collected on a fast transport tape and measured in a well-shielded array of α-, γ-, and x-ray detectors. The detectors were connected with standard coincidence circuits. Singles data were taken with all three counters and divided into eight subsequent time intervals for half-life analysis. Further, each coincidence event was tagged with the time elapsed since the last tape movement.

Since the desirable mass separation of platinum was not feasible, our isotopic assignments are based on the careful measurement of excitation functions. The decaying element was unequivocally identified on the basis of measured coincidences of α and γ rays with the respective daughter x rays.

In order to extract γ rays following the β decays of platinum isotopes, coincidences with Ir-K x rays were selected. The excitation functions were measured in detail using ten different combinations of ^{146,148}Nd targets and degrader foils. The proper assignments of the deexcitation channels were confirmed by comparison of the yields of new γ rays with the simultaneously measured α-ray data which included the prominent α-decay branches of the platinum isotopes [1]. Further, the similarity of the excitation functions of the ^{36}Ar induced xn and the $p(x-1)n$ deexcitation channels allowed us to compare the production yields of new γ radiation with those of the $^{177-180}$Ir neighbors [14, 15].

New γ-rays following the decays of $^{177-181}$Pt were identified and are given in Table I. Half-lives were measured for the strongest transitions. The quality of the decay data is demonstrated in Fig. 1. We report new half-life values of 9.8(4) s, 22(2) s, 21.2(4) s, 60(3) s, and 56(5) s for the isotopes $^{177-181}$Pt, respectively. Our value of 21.2 s for ^{179}Pt is in striking disagreement with the values 54(4) s and 33(4) s adopted in literature [16], but is supported by the observation of a 22 s activity in the ^{183}Hg decay chain by Romanski *et al.* [17], probably of ^{179}Pt.

The decay schemes were constructed from the measured coincidence and intensity data. Low-lying states were assigned in the odd-mass iridium daughters and are displayed in Fig. 2.

Some levels in ^{177}Ir have been reported by Sauvage *et al.* [2] using the feeding in fine-structure α decay

TABLE I. Energies E_γ, relative intensities $I_\gamma^{\rm rel}$, and measured coincidences of γ rays following the β decays of $^{177-181}$Pt.

Isotope	E_γ (keV)	$I_\gamma^{\rm rel}$	Coincident γ rays[a]
^{177}Pt	65.0	weak[b]	
	71.8	weak[b]	
	85.4	62(8)[c]	65,72
	148.0	100(13)[d]	75,90,183
	157.2	24(4)	
	183.4	9(3)	
	223.1	52(8)	
^{178}Pt	36.9	43(2)	55
	55.0	39(2)	37,127,137
	84.6	100	90,101
	90.4	80(6)	85,(88),101,148
	91.7	54(4)	
	101.3	76(4)	85,(90),101
^{179}Pt	93.3	16(1)	
	99.8	81(14)[e]	93,95,106,172,203,243,300 309,393,402,915,1565
	106.3	15(1)	
	171.7	100	100,106,1565
	193.1	87(5)	203,300,309,(915)
	203.3	15(1)	
	243.2	41(5)[f]	100
	300.0	32(3)	
	309.0	20(3)	
	393.3	41(3)	100,915
	402.4	32(3)	
	915.3	48(7)	(100),(193),300,393
	1565.4	68(6)	100,172
^{180}Pt	80.6	45(3)	95
	95.2	100	81
	113.9	16(3)	
	123.3	<20	
^{181}Pt	111.9	100	131,230,(533)
	131.1	25(5)[f]	112
	230.1	85(7)	112
	289.2	94(6)	
	335.3	44(6)	

[a]Observed with gate on radiation in the second column.
[b]Transition identified in coincidence spectra.
[c]Not corrected for a contribution of Pb-K x rays.
[d]Corrected for a contribution of ^{177}Ir.
[e]Corrected for a contribution of ^{179}Ir.
[f]Intensity evaluated from coincidence spectra.

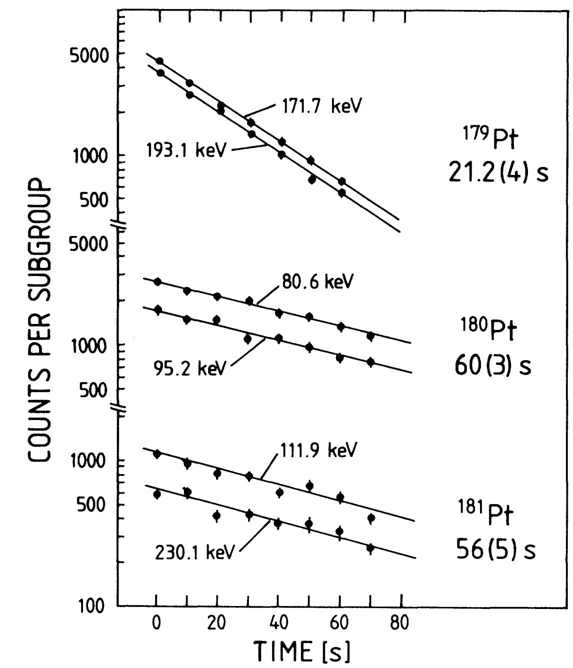

FIG. 1. Decay curves measured for γ rays of ^{179,180,181}Pt.

of ^{181}Au. From the interpretation of the hindrance factors, they concluded that the states at 0, 43(20), 84(16), 148.4(2), and 220(16) keV are the $\frac{5}{2}^-$, $\frac{9}{2}^-$, $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{7}{2}^-$ members of the $h_{9/2}$ $\frac{1}{2}^-[541]$ band. The same ground-state assignment for ^{177}Ir, namely, $h_{9/2}$ $\frac{5}{2}^-$, $\frac{1}{2}^-[541]$, was achieved in our earlier study of its β decay to states in ^{177}Os [14]. In the present decay work on ^{177}Pt, levels in ^{177}Ir at 85.4, 148.0 and 223.1 keV were established. These three levels decay through γ emission to the ground state. We identify these states with the $\frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{7}{2}^-$ members of the ground-state band, see Fig. 2. The results of Sauvage *et al.* [2] are fully supported and improved with our accurate determination of the excitation energies in ^{177}Ir. New results from the α decay of ^{181}Au were recently reported by Bingham *et al.* [18].

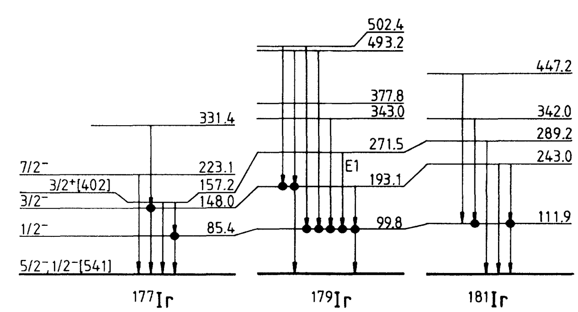

FIG. 2. Systematics of low-lying states in the odd-mass iridium nuclei ^{177,179,181}Ir studied in the β decays of platinum isotopes. The strongest transitions are shown to connect the $h_{9/2}$ band members and the proposed $d_{3/2}$ $\frac{3}{2}^+[402]$ state. For details, see text. Observed coincidences are marked with a dot.

They include the measurement of $\alpha\gamma$ coincidences and confirm the 85, 148, and 223 keV transitions observed in our ^{177}Pt decay study. Our new 157 keV state in ^{177}Ir decays to the $\frac{1}{2}^-$ and $\frac{5}{2}^-$ states and is tentatively assigned to the $\frac{3}{2}^+$[402] Nilsson orbital.

The ground state of ^{177}Pt has the $\frac{5}{2}^-$[512] configuration [5]. This was already proposed by Hagberg *et al.* [1] who studied the decay of the α precursor ^{181}Hg. While $N = 99$ isotones below tungsten have a $\frac{7}{2}^+$[633] ground state, Hagberg *et al.* [1] excluded this structure for ^{177}Pt. The change from the ground-state configuration $\frac{7}{2}^+$[633] to $\frac{5}{2}^-$[512] of the $N = 99$ isotones takes place in ^{173}W [9]. The β decay of ^{177}Pt feeds mainly the ^{177}Ir levels at 148 and 223 keV. This observation is in accord with the $\frac{5}{2}^-$ spin of ^{177}Pt and the $\frac{3}{2}^-$ and $\frac{7}{2}^-$ assignments for the states in the iridium daughter.

In the neighboring isotope ^{179}Ir we found a very similar level sequence, which is again interpreted as the $h_{9/2}$ $\frac{1}{2}^-$[541] band, see Fig. 2. Earlier decay studies of ^{179}Ir led to the identification of the $\frac{5}{2}^-$ member for the ground state [15]. The β decay of ^{179}Pt populates states at 99.8 and 193.1 keV, which are the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members. These assignments are confirmed by a recent measurement of $\alpha\gamma$ coincidences in the decay of ^{183}Au [18]. The β decay to the higher-lying $\frac{7}{2}^-$ state is unlikely due to the low spin, $\frac{1}{2}^-$[521], of the ^{179}Pt ground state [16]. The 172 keV transition deexciting the 272 keV state in ^{179}Ir, see Fig. 2, has $E1$ character. This was concluded from the estimate $\alpha_K \sim 0.1$ of its K-conversion coefficient and suggests that the 272 keV state has positive parity. Since it decays to $\frac{1}{2}^-$ and $\frac{5}{2}^-$ states, we propose the $d_{3/2}$ $\frac{3}{2}^+$[402] configuration for this low-lying level. Some higher-lying states included in Fig. 2 are populated in the β decay. They proceed also to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states and are probably connected with the $\frac{1}{2}^+$[411] and $\frac{1}{2}^+$[400] Nilsson orbitals.

The isotope ^{181}Ir was populated in the β decay of ^{181}Pt which has a Nilsson $\frac{1}{2}^-$[521] ground-state configuration [1, 6]. Six γ rays were arranged in a level scheme of ^{181}Ir with $h_{9/2}$ states $\frac{1}{2}^-$ and $\frac{3}{2}^-$ at 111.9 and 243.0 keV, see Fig. 2. This structure confirms the detailed discussion of the ^{181}Pt decay which has recently been published by Sauvage *et al.* [2]. They established 26 excited states in ^{181}Ir and proposed members of the $h_{9/2}$ $\frac{1}{2}^-$[541] band for the low-lying negative-parity states. The fine-structure α decay of ^{185}Au to the ^{181}Ir states at 243 keV ($\frac{3}{2}^-$) and the ground state ($\frac{5}{2}^-$) has been observed by Bingham *et al.* [19], in agreement with the results from the ^{181}Pt β-decay studies.

Some γ rays were assigned to the β decays of ^{178}Pt and ^{180}Pt, see Table I, which proceed to odd-odd daughter nuclei. Their level structure remains a puzzle although in the case of ^{178}Pt decay the coincidence of 37 and 55 keV γ rays and the probable crossover transition 92 keV suggest a partial level scheme of ^{178}Ir. We assume that the 55 keV transition is the same one which had been observed in coincidence with the α decay of ^{182}Au [1]. The main feature of the ^{180}Pt decay is a cascade of 81 and 95 keV transitions. Two further γ rays with energies of 114 and 123 keV were also assigned to ^{180}Pt, but they were too weak to obtain any reliable coincidence information.

We may therefore concentrate a brief discussion on the odd-mass cases. The investigated region lies below the midshell line $N = 104$. The strongest transitions in the decays of ^{177,179,181}Pt belong to the $h_{9/2}$ sequence $\frac{1}{2}^-$[541] which originates from beyond the Z =82 shell gap. This strongly prolate-driving orbital plays an intruder role in very neutron-deficient isotopes between the rare-earth and the sublead elements. One feature of this $h_{9/2}$, $K = 1/2$ band is a large decoupling parameter. As a consequence, the level order is disturbed and its $\frac{5}{2}^-$ member becomes the ground state of several isotopes of tantalum, rhenium, and iridium [9, 12, 14, 15]. Further, the low-lying band structures accessible by in-beam reactions are limited to the $(+\frac{1}{2})$ signature rotational states starting with the $\frac{5}{2}^-$, $\frac{9}{2}^-$, and $\frac{13}{2}^-$ members. We have shown that the study of the β decay of the platinum isotopes is a suited tool for the identification of the low-spin members of the $h_{9/2}$ band. They dominate the level structure in ^{177,179,181}Ir, Fig. 2, and suggest that these nuclei are of prolate shape. This information is supported by the comparison with the single-particle states in the neighboring iridium isotopes. The occurrence of positive-parity states was concluded from the 157 keV transition in ^{177}Ir and the 172 keV $E1$ transition in ^{179}Ir (see above) and from the work of Sauvage *et al.* [2] in ^{181}Ir. These states are likely connected with the $d_{3/2}$ orbitals $\frac{3}{2}^+$[402] and $\frac{1}{2}^+$[400] which are well known in heavier iridium isotopes [7] and correspond to prolate Nilsson states. The downsloping excitation energy of the $\frac{3}{2}^+$ state below the N <104 region seems to be established by our new results. This information is important for the understanding of the isomers in lighter iridium nuclei [13] which were interpreted as neighboring $d_{3/2}$ and $h_{11/2}$ configurations.

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