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Isomeric states observed in heavy neutron-rich nuclei populated in the fragmentation of a $^{208}$Pb beam

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Heavy neutron-rich nuclei were populated via the fragmentation of a $E/A = 1$ GeV $^{208}$Pb beam. Secondary fragments were separated and identified and subsequently implanted in a passive stopper. By the detection of delayed $\gamma$ rays, isomeric decays associated with these nuclei have been identified. A total of 49 isomers were detected, with the majority of them observed for the first time. The newly discovered isomers are in $^{201}$Ag, $^{197}$Au, $^{193}$Os, $^{190}$Re, $^{200}$W, and $^{193}$Ta. Possible level schemes are constructed and the structure of the nuclei discussed. To aid the interpretation, shell-model as well as BCS calculations were performed.

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I. INTRODUCTION

Low-lying yrast excited states of closed shell and near-closed shell nuclei provide excellent opportunities to study specific nuclear orbitals of the nucleus [1]. This is because the dominant contributions to their wave-functions come from only a few nuclear orbits. In the case of nuclei with a $^{208}$Pb closed core, there is relatively limited experimental information available on neutron-rich species. For example, prior to the present experiment with $N = 126$ isotones below $Z = 82$ have been limited to measurements of excited states in $^{207}$Sn and $^{205}$Tl [2] and $^{208}$Hg [3–5] and the ground state of $^{205}$Au [6].

Moving further from $^{208}$Pb, the neutron-rich W-Os-Pt nuclei are characterized by different shapes in their ground states, namely prolate, oblate, triaxial, and near $N = 126$, spherical shapes. The lighter isotopes are prolate deformed. By adding more and more neutrons, the shape becomes oblate [7–9]. The exact place where this change occurs is element dependent. Shape transitional nuclei are difficult to treat theoretically, consequently the properties of nuclei in this region are considered to provide a crucial testing ground for nuclear models.
Projectile fragmentation at intermediate and relativistic energies has proved to be an effective way of populating states in nuclei far from the valley of stability. The highest sensitivity is achieved with decay (both internal isomeric-decay and \(\beta\)-decay) spectroscopy. In this paper, experimental information obtained on a large number of heavy neutron-rich nuclei of the elements Ta
\(\rightarrow\)Tl \((Z = 73 \rightarrow 81)\) is presented. The experiment, performed in 2006, was part of the RISING stopped-beam campaign [10].

II. EXPERIMENTAL TECHNIQUE

An \(E/A = 1\) GeV \(^{206}\)Pb\(^{+67}\) beam was delivered by the GSI UNILAC and SIS-18 accelerator complex. The beam was fragmented on a Be target of thickness \(2.526\) g/cm\(^2\). The target was backed by a \(0.223\) g/cm\(^2\)-thick Nb foil, to optimize electron stripping of the outgoing fragments. The nuclei of interest, populated via fragmentation processes, were separated and identified using the fragment separator (FRS) [11]. The FRS was operated in standard achromatic mode. The matter at the midfocal plane of the FRS consisted of a \(4.9\) g/cm\(^2\) Al degrader, followed by a \(0.35\) g/cm\(^2\) scintillation detector used for time-of-flight (TOF) and position measurements, and another Nb foil \((0.108\) g/cm\(^2\) thick) to maximize electron stripping.

At the final focal plane of the FRS, a series of detectors characterized the beam. The nuclei passed through two multiwire detectors for position measurements; two multi sampling ionization chamber (MUSIC) detectors to measure the rate of energy loss of particles, \(\Delta E (\propto Z^2)\); and three scintillation detectors, for timing, position, and energy measurements. A variable thickness homogeneous Al degrader was used to slow down the beam particles, which were finally implanted into a passive plastic stopper. A schematic view of the experimental setup is shown in Fig. 1. The scintillation detectors placed in front of and behind the catcher allowed the offline suppression of the majority of fragments undergoing secondary reactions in the slowing-down process or those which were not stopped in the catcher.

The catcher was surrounded by the high-efficiency, high-granularity stopped RISING \(\gamma\)-ray spectrometer [10,12], which has a full-energy peak efficiency of \(15\%\) at 662 keV. Time-correlated \(\gamma\) decays from individually identified ions have been measured, allowing unambiguous identification of isomeric decays.

Multiple electronic branches recorded the time of emission of \(\gamma\) rays. XIA digital \(\gamma\)-ray finder (DFG) modules recorded \(\gamma\)-ray information with 25-ns resolution for up to 380 \(\mu\)s following implantation. Two other timing circuits were also used. These are termed the short-range (SR) timing circuit, operating with 0.293-ns resolution for an effective 850 ns and long-range (LR) circuit, operating with 0.7629-ns resolution for 100 \(\mu\)s following implantation. The use of the short-range timing is advantageous in the case of short-lived isomeric decays (<300 ns).

From synthesis of the fragmentation products at the target to implantation in the stopper approximately 300 ns elapsed. During this in-flight period, electron conversion branches of excited states were suppressed by the high degree of ionization of the nuclei. This had the effect of extending the half-life of the excited states for the in-flight period. Therefore, the experiment was sensitive to the decay of metastable states that are transmitted through the FRS and then decayed in the 380 \(\mu\)s following implantation. In general, this experimental setup can measure isomers with half-lives in the range 10 ns–1 ms.

During the experiment, nine different magnetic rigidity settings of the FRS were used. The results from six of these, dealing with heavy neutron-rich nuclei, are presented in this paper. In these cases, the magnetic rigidities were set to transmit fully stripped ions of \(^{206}\)Hg, \(^{203}\)Ir, \(^{202}\)Os, \(^{199}\)Os, \(^{192}\)W, and \(^{185}\)Lu. An average of 20 h of beam time was dedicated to each setting, with a primary beam intensity of \(\sim 10^9\) ions/22 s spill. Details summarizing which species and how many nuclei were implanted during the experiment are information given in Ref. [13], with a more detailed breakdown of this information is given in the PhD thesis [14]. The other three settings, centered at \(^{188}\)Pb, \(^{186}\)Pb, and \(^{147}\)Gd [15,16], aimed at the study of the fragmentation reaction mechanism, and in particular the angular momentum population probability [17].

As a first step in the identification of the nuclei, a charge state selection had to be performed. Charge state calculations with the GLOBAL code [18] show that when exiting the Be/Nb target approximately 94\% of the fragmentation products of interest were fully ionized (i.e., \(q = Z\), also referred to as “fully stripped”) and that the remaining 6\% had one electron bound to the nucleus \((q = Z - 1\), referred to as being in a “H-like” charge state). Following energy losses at the midfocal

![FIG. 1. Schematic of the fragment separator including the used detectors. For details see the text.](image-url)
FIG. 2. (Color online) Charge state selection for the $^{192}$W setting. The change in the magnetic rigidity at the mid-focal plane, $\Delta Br$, is plotted against $\Delta E (\propto Z^2)$ at the final focal plane measured by the MUSIC detectors. Changes in charge state are identified by the diagonally correlated data.

plane, 77% of the beam was fully stripped of electrons, 22% was in a H-like state, and 1% was in a He-like state ($q = Z - 2$). The matrix energy loss at the final focal plane versus change in magnetic rigidity, $\Delta Br (\propto q^2)$, at the intermediate focal plane can be used for charge state selection (see Fig. 2). This distinguishes nuclei that do not change charge state in the middle of the FRS (approximately all $\Delta q = 0$ correspond to $q = Z$ for the entire FRS flight time) from those which pick up one or two electrons ($\Delta q = -1$ and $\Delta q = -2$) or lose one electron ($\Delta q = +1$).

The identification plot corresponding to the $^{192}$W setting is shown in Fig. 3. The analogous pictures for the $^{203}$Ir and $^{199}$Os settings can be found in Refs. [19,20], respectively. All identification plots are available in Ref. [14]. Each identification plot has been confirmed by the observation of $\gamma$-ray transitions following the decay of previously reported isomers.

Following their identification, the nuclei were slowed down in the homogeneous Al degrader, before being implanted in a passive stopper. In the degrader, the ions were slowed down from an energy of $E/A \sim 400$ MeV to $E/A < 100$ MeV. In the slowing-down process, a number of the nuclei of interest were lost due to reactions in the degrader. A comparison of a $\Delta E$ measurement by a MUSIC chamber located upstream from the degrader and one made by the scintillation detector placed immediately following the degrader (Sci42) identifies nuclei that react inside it (see Fig. 4). The latter are removed from further analysis. It was found that $\approx 18\%$ of the nuclei react at this stage.

In the $^{206}$Hg, $^{203}$Ir, and $^{202}$Os settings, the selected beam nuclei were implanted in a 7-mm-thick perspex stopper. For the other three settings, a 9-mm-thick perspex stopper was used. One final scintillation detector (Sci43), placed after the stopper, acted as a veto on events where particles were detected after the stopper, this accounted for $\approx 0.2\%$ of the identified nuclei.

As each nucleus decelerates and comes to a halt in the stopper, bremsstrahlung is emitted, causing the so-called “prompt flash” [21,22]. The prompt flash is measured to have a FWHM $\sim 20$ ns when using the SR devices at $\gamma$-ray energies, $E_\gamma > 500$ keV; this width includes the uncertainty associated with synchronizing the independent time circuits of the 105 Ge crystals. Isomers with half-lives comparable to this width are subject to a large background contribution.

FIG. 3. (Color online) Identification plot for the FRS setting centered on $^{192}$W. The four figures correspond to different charge state combinations through the fragment separator.

III. RESULTS

The analysis of the data collected in this experiment has identified 49 isomers in 39 nuclear species between Ta ($Z = 73$) and Tl ($Z = 81$). The nuclei with isomeric states are indicated in Fig. 5 and the experimental observables are summarized in Table I. The experimental observables include the intensity of the $\gamma$ rays, the isomeric lifetime, and the.
isomeric ratio. Of the observed isomers, 20 have been already reported prior to performing the described experiment and 29 were observed for the first time.

An isomeric ratio is defined as the number of times a nuclide is populated in an excited state that decays through a given isomer, divided by the total number of times that the nuclide has been populated. A detailed explanation of how this is determined is given in Ref. [23]. Where more than one isomer has been observed in a nucleus, the isomeric ratio of the lower-lying isomer is inclusive of any feeding from the higher-lying isomer. If the same nucleus was transmitted in different settings and in different charge states, the isomeric ratios were determined for each charge-state combination separately. The final values are given in Table I. Isomeric states often decay via low-energy highly converted unobserved transitions. Without knowing the energy of the decaying transition, one cannot calculate how many of them decay while flying through the fragment separator. Therefore, only a lower isomeric ratio limit could be determined in these cases, assuming no decays (infinite conversion electron coefficient) during flight through the FRS.

A. Theoretical calculations

We performed shell-model calculations on the nuclei in the vicinity of 208Pb. The OXBASH code [24] was employed. The model space considered consisted of the proton orbitals 3s1/2, 2d5/2, 1h11/2, 2d5/2, and 1g7/2 below the Z = 82 closed shell and the neutron orbitals 3p1/2, 2f5/2, 3p3/2, 1i13/2, 2f7/2, and 1h9/2 below the closed N = 126 shell. Except for 202Au, where the πg7/2 and νh9/2 orbitals were kept filled, no further truncation was applied. Therefore, no core excitations across the 208Pb double-shell closure are allowed. The single proton-hole and neutron-particle energies are taken from the experimental spectra of 207Tl and 207Pb, respectively. The two-body interaction matrix elements (TBMEs) are from Ref. [25]. They are based on the Kuo-Herling interaction [26] including core polarization, with decisive elements adjusted to the experimental data available at the time. We shall refer to this as the standard parametrization.

In addition to the aforedescribed standard parametrization, a modified parametrization was also used. These modifications were introduced to get better agreement between theory and experiment for the new 204Pt and updated 206Hg data [5]. As explained in Ref. [19], the Rydström interaction [25] was modified in three points: (i) the (d3/2 h11/2)7− TBME was increased by +135 keV as needed for 206Hg; (ii) the (s1/2 d5/2) monopole was increased by +230 keV, which accounts for the 4+ level energy in 204Pt and the increased blocking of the h11/2 ⊗ 3− coupling lowering the effective d5/2 single hole energy; (iii) following a systematic search of the influence of nondiagonal TBME on the E2 strength evolution from 206Hg to 204Pt, the (s1/2 h11/2;d3/2 h11/2)6− TBME was changed to +160 keV, close to the value for the corresponding 5− TBME.

Here we examine whether these modifications needed by 204Pt and 206Hg improve the predictive power of the calculations for other nuclei in the region. This is especially important, since such shell-model calculations are used to predict the properties of the N = 126 r-process path nuclei [27].
### Table I. Summary of the observed isomeric states. Half-lives and isomeric ratios, as well as γ-ray energies and relative intensities are given. For details see the text.

<table>
<thead>
<tr>
<th>Nucleus, $I^\pi$, $T_{1/2}$, IR (%)</th>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{206}$Tl, $I^\pi = (5)^+$ [30], $T_{1/2} = 71(4)$ ns, IR = 14.2+$^{23}$−$^{32}$</td>
<td>265.4, 452.9, 685.8</td>
<td>89(6), 90(6), 100(7)</td>
</tr>
<tr>
<td>$^{206}$Hg, $I^\pi = (10^+)$ [30], $T_{1/2} = 112(4)$ ns, IR = 2.2+$^7$−$^8$</td>
<td>100.9, 363.4, 1156.3</td>
<td>3(3), 28(1), 8(1)</td>
</tr>
<tr>
<td>$^{206}$Hg, $I^\pi = 5^−$ [30], $T_{1/2} = 2.09(2)$ μs, IR = 21.9+$^{12}$−$^{20}$</td>
<td>1033.7, 1068.0</td>
<td>100(2), 99(2)</td>
</tr>
<tr>
<td>$^{203}$Hg, $I^\pi = (23/2^−)$, $T_{1/2} = 5.89(18)$ μs, IR = 3.5+$^2$−$^4$</td>
<td>227.6, 722.6, 810.0</td>
<td>8(1), 11(1), 100(3)</td>
</tr>
<tr>
<td>$^{205}$Hg, $I^\pi = 13/2^+$, $T_{1/2} = 1.09(4)$ ms [36], IR = 20.5+$^{25}$−$^{40}$</td>
<td>378.9, 967.0, 1014.7</td>
<td>37(2), 10(2), 33(2)</td>
</tr>
<tr>
<td>$^{204}$Hg, $I^\pi = (14^+)$, $T_{1/2} = 20(2)$ ns, IR &lt; 10</td>
<td>422.7, 597.2, 964.8</td>
<td>35(7), 100(14), 61(14)</td>
</tr>
<tr>
<td>$^{204}$Hg, $I^\pi = 7^−$ [38], $T_{1/2} = 6.7(5)$ ns [38]</td>
<td>436.6, 691.8, 1062.7</td>
<td>59(10), 36(9), 36(10)</td>
</tr>
<tr>
<td>$^{203}$Hg, $I^\pi = (13/2^+)$ [39], $T_{1/2} = 21.9(10)$ μs, IR = 11.8+$^{11}$−$^{20}$</td>
<td>341.0, 591.1</td>
<td>57(2), 100(3)</td>
</tr>
<tr>
<td>$^{205}$Au, $I^\pi = (19/2^+)$, $T_{1/2} = 163(5)$ ns, IR = 6.5+$^{10}$−$^{15}$</td>
<td>34.2, 243.4, 736.9</td>
<td>–, 4(2), 39(2)</td>
</tr>
<tr>
<td>$^{205}$Au, $I^\pi = (16^+)$, $T_{1/2} = 2.1(3)$ μs, IR = 0.6(2)</td>
<td>839.0, 976.6</td>
<td>100(15), 93(15)</td>
</tr>
<tr>
<td>$^{203}$Au, $I^\pi = 11/2^−$, $T_{1/2} = 140(44)$ μs, IR = 2.5+$^8$−$^{10}$</td>
<td>562.8</td>
<td>100(6)</td>
</tr>
<tr>
<td>$^{202}$Au, $I^\pi = unknown$, $T_{1/2} = 13.1(5)$ ns</td>
<td>137.8, 414.2</td>
<td>21(21), 100(5)</td>
</tr>
</tbody>
</table>

### Table I. (Continued)

<table>
<thead>
<tr>
<th>Nucleus, $I^\pi$, $T_{1/2}$, IR (%)</th>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{201}$Au, $I^\pi = 11/2^−$, $T_{1/2} = 340+$900−260μs, IR = 13+$^{16}$−$^{21}$</td>
<td>553</td>
<td>100(11)</td>
</tr>
<tr>
<td>$^{201}$Au, $I^\pi = unknown$, $T_{1/2} = 5.6(24)$ μs, IR = 5(3)</td>
<td>378.2, 638.0</td>
<td>58(17), 100(34)</td>
</tr>
<tr>
<td>$^{204}$Pt, $I^\pi = (10^+)$, $T_{1/2} = 146(14)$ ns, IR = 9.2+$^{25}$−$^{32}$</td>
<td>96.1, 1060.8, 1157.5</td>
<td>2(2), 20.7(11), 3.7(5)</td>
</tr>
<tr>
<td>$^{204}$Pt, $I^\pi = (7^−)$, $T_{1/2} = 55(3)$ μs, IR = 27+$^7$−$^9$</td>
<td>872.4, 1122.7</td>
<td>100(2), 97(2)</td>
</tr>
<tr>
<td>$^{203}$Pt, $I^\pi = (33/2^+)$, $T_{1/2} = 641(55)$ ns, IR = 1.3(2)</td>
<td>1104.0</td>
<td>100(8)</td>
</tr>
<tr>
<td>$^{202}$Pt, $I^\pi = 7^−$ [67], $T_{1/2} = 141(7)$ μs, IR = 12+$^1$−$^2$</td>
<td>534.3, 718.8</td>
<td>95(2), 100(3)</td>
</tr>
<tr>
<td>$^{201}$Pt, $I^\pi = (25/2^−, 27/2^−)$, $T_{1/2} = 18.4(13)$ ns, IR ≥ 4(2)</td>
<td>353.6, 373.9, 726.9</td>
<td>76(6), 80(5), 100(6)</td>
</tr>
<tr>
<td>$^{200}$Pt, $I^\pi = (12^+)$ [68], $T_{1/2} = 13.9(10)$ ns, IR ≥ 2(1)</td>
<td>318.4, 542.5, 708.6</td>
<td>16(2), 17(2), 22(3)</td>
</tr>
<tr>
<td>$^{200}$Pt, $I^\pi = 7^−$ [68], $T_{1/2} = 17.0(5)$ ns, IR ≥ 7(4)</td>
<td>298.9, 397.5, 463.6, 470.1</td>
<td>8(2), 8(2), 72(3), 87(3)</td>
</tr>
<tr>
<td>$^{199}$Pt, $I^\pi = (25/2^−, 27/2^−)$, $T_{1/2} = 18.6(34)$ ns, IR ≥ 5(3)</td>
<td>633.0</td>
<td>84(19), 86(15), 100(15)</td>
</tr>
<tr>
<td>$^{198}$Pt, $I^\pi = 7^−, T_{1/2} = 3.4(2)$ ns [47]</td>
<td>382.0, 407.2, 577.8</td>
<td>54(16), 100(29), 65(25)</td>
</tr>
<tr>
<td>$^{197}$Pt, $I^\pi = (25/2^−, 27/2^−)$, $T_{1/2} = 10.2(13)$ ns, IR ≥ S(2)</td>
<td>374.5, 432.2, 546.9</td>
<td>100(12), 72(14), 66(12)</td>
</tr>
<tr>
<td>$^{203}$Ir, $I^\pi = (23/2^+)$, $T_{1/2} = 798(350)$ ns, IR = 5+$^3$−$^4$</td>
<td>207.0, 841.3, 894.7</td>
<td>18(8), 73(21), 100(25)</td>
</tr>
<tr>
<td>$^{202}$Ir, $I^\pi = unknown$, $T_{1/2} = 3.4(6)$ μs, IR = 0.7+$^2$−$^3$</td>
<td>311.5</td>
<td>41(13)</td>
</tr>
</tbody>
</table>
Shell model calculations with both the standard and the modified parametrization have been performed for all cases. As the changes involve only proton orbitals, the energy spectra of both calculations are presented only for the $N = 126$ nuclei. In $N < 126$ nuclei, the differences in the energy spectra are generally small and only the energy spectra of the modified parametrization are given. Transition rates were calculated using effective operators as listed in Table II. The effective charges and $g$ factors were adjusted to transitions in the one- and two-hole neighbors of $^{208}\text{Pb}$. The measured transition strengths are compared with both shell model calculations for all nuclei for which such calculations could be performed (see Table II).
In the case of deformed nuclei, multi-quasi-particle calculations were performed with a BCS blocking code [28]. The deformation parameters were taken from Ref. [29].

B. N = 126 nuclei

Isomeric decays were observed in four N = 126 nuclei: \(^{206}\)Hg, \(^{205}\)Au, \(^{204}\)Pt, and \(^{203}\)Ir. The associated delayed \(\gamma\)-ray spectra are shown in Fig. 6.

Previously, experimental information existed only on the excited states of \(^{206}\)Hg, where two isomeric states were identified. These are an \(I^\pi = 5^-\), \(T_{1/2} = 2.15(21)\) \(\mu s\) state \([3-5,30]\) and an \(I^\pi = (10^-)\), \(T_{1/2} = 92(8)\) \(\text{ns}\) state \([5,30]\), which has 100% feeding to the lower-lying isomer. Our measured half-lives of \(T_{1/2} = 2.09(2)\) \(\mu s\) and \(T_{1/2} = 112(4)\) \(\text{ns}\) agree with the previously published values. The determined isomeric ratios, given in Table I, are in fair agreement with the predictions of two nucleon removal reaction theory, as discussed in Ref. [31]. In addition, the dependence of the isomeric ratio of the \(5^-\) state on the transferred longitudinal momentum was compared with the theoretical calculations [32].

In \(^{205}\)Au, an isomeric state with \(T_{1/2} = 163(5)\) \(\text{ns}\) was observed. In \(^{204}\)Pt three isomeric states with half-lives of 146(14) \(\text{ns}\), 55(3) \(\mu s\), and 5.5(7) \(\mu s\) were identified. The data on these nuclei have already been discussed in detail in Refs. [19,20], respectively.

In the case of \(^{203}\)Ir two \(\gamma\)-ray transitions were observed, with energies of 841 and 895 keV. The half-life of the isomer is measured to be \(T_{1/2} = 0.84(4)\) \(\mu s\). It has a candidate for a third \(\gamma\)-ray transition with 207 keV energy.

The shell-model predictions and interpretation of experimental data are presented in Fig. 7. In the case of \(^{204}\)Pt [19], based on similarities with \(^{206}\)Hg as well as shell model predictions, the three isomeric states were interpreted as \(I^\pi = (5^-), (7^-),\) and \((10^-)\) with \(\pi h_{11/2}^1s_{1/2}^1, \pi h_{11/2}d_{5/2}^1,\) and \(\pi h_{11/2}\) predominant configurations, respectively.

In \(^{205}\)Au, the yrast structure has been established up to spin-parity \((19/2^+)\) via the observation of the decay of an isomeric state with configuration \(\pi(h_{11/2}^2)s_{1/2}^{1/2}(s_{1/2}^1)\) (for details see Ref. [20]). This isomer feeds into the long-lived \(11/2^-\) state.

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### Table II. Experimental and calculated transition strengths

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Transition</th>
<th>exp.</th>
<th>B(E1) (W.u.)</th>
<th>SM(_\text{standard})</th>
<th>SM(_\text{mod})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{206})Hg</td>
<td>(B(E3 : 10^+ \rightarrow 7^-))</td>
<td>0.25(3) ([5])</td>
<td>0.17</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>(^{206})Hg</td>
<td>(B(E2 : 10^+ \rightarrow 8^+))</td>
<td>0.94(15) ([5])</td>
<td>0.87</td>
<td>0.87</td>
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<tr>
<td>(^{206})Hg</td>
<td>(B(E3 : 5^- \rightarrow 2^+))</td>
<td>0.18(2) ([5])</td>
<td>1.17</td>
<td>0.90</td>
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<tr>
<td>(^{205})Au</td>
<td>(B(E3 : 19/2^+ \rightarrow 13/2^-))</td>
<td>0.3(1)</td>
<td>0.004</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>(^{205})Au</td>
<td>(B(E3 : 19/2^+ \rightarrow 15/2^-))</td>
<td>0.3(1)</td>
<td>1.0</td>
<td>1.10</td>
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<tr>
<td>(^{205})Au</td>
<td>(B(E2 : 19/2^+ \rightarrow 15/2^-))</td>
<td>1.2(2)</td>
<td>2.99</td>
<td>1.70</td>
<td></td>
</tr>
<tr>
<td>(^{204})Pt</td>
<td>(B(E4 : 11/2^- \rightarrow 3/2^+))</td>
<td>(\leq 1.7(7)) ([34])</td>
<td>1.92</td>
<td>2.46</td>
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<tr>
<td>(^{204})Pt</td>
<td>(B(E3 : 10^- \rightarrow 7^-))</td>
<td>0.19(3)</td>
<td>0.21</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>(^{204})Pt</td>
<td>(B(E2 : 10^- \rightarrow 8^+))</td>
<td>0.80(8)</td>
<td>2.64</td>
<td>1.22</td>
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<tr>
<td>(^{204})Pt</td>
<td>(B(E2 : 7^- \rightarrow 5^-))</td>
<td>0.0174 (\pm 0.0034^4)</td>
<td>1.21</td>
<td>0.0037</td>
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<tr>
<td>(^{203})Ir</td>
<td>(B(E3 : 5^- \rightarrow 2^+))</td>
<td>0.039(5)</td>
<td>0.713</td>
<td>0.612</td>
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<tr>
<td>(^{203})Ir</td>
<td>(B(E2 : 23/2^+ \rightarrow 19/2^+))</td>
<td>0.020(9)</td>
<td>3.58</td>
<td>0.013</td>
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<tr>
<td>(^{205})Hg</td>
<td>(B(E3 : 19/2^+ \rightarrow 15/2^-))</td>
<td>1.3(6)</td>
<td>0.39</td>
<td>0.44</td>
<td></td>
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<tr>
<td>(^{205})Hg</td>
<td>(B(E3 : 23/2^+ \rightarrow 17/2^-))</td>
<td>1.3(6)</td>
<td>0.144</td>
<td>0.50</td>
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<tr>
<td>(^{205})Hg</td>
<td>(B(E2 : 23/2^- \rightarrow 19/2^+))</td>
<td>0.10(1)</td>
<td>1.80</td>
<td>1.34</td>
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<tr>
<td>(^{205})Hg</td>
<td>(B(E2 : 13/2^+ \rightarrow 7/2^-))</td>
<td>(8(1) \times 10^{-5})</td>
<td>0.008</td>
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<tr>
<td>(^{205})Hg</td>
<td>(B(E2 : 13/2^+ \rightarrow 9/2^-))</td>
<td>1.14(7) ([36])</td>
<td>3.50</td>
<td>3.38</td>
<td></td>
</tr>
<tr>
<td>(^{204})Au</td>
<td>(B(E2 : 16^+ \rightarrow 14^-))</td>
<td>(4.7(3) \times 10^{-4}) ([36])</td>
<td>0.03</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>(^{203})Pt</td>
<td>(B(E3 : 16^+ \rightarrow 14^-))</td>
<td>(4.7(8) \times 10^{-4})</td>
<td>(3.5 \times 10^{-4})</td>
<td>(21 \times 10^{-4})</td>
<td></td>
</tr>
<tr>
<td>(^{203})Pt</td>
<td>(B(E3 : 33/2^+ \rightarrow 27/2^-))</td>
<td>0.28(5)</td>
<td>0.80</td>
<td>0.83</td>
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<td>(^{203})Hg</td>
<td>(B(E2 : 11/2^- \rightarrow 7/2^-))</td>
<td>0.38(4)</td>
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<tr>
<td>(^{203})Au</td>
<td>(B(E2 : 11/2^+ \rightarrow 9/2^-))</td>
<td>0.0457(21)</td>
<td>0.05</td>
<td>0.045</td>
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<tr>
<td>(^{202})Pt</td>
<td>(B(E3 : 7^- \rightarrow 4^+))</td>
<td>0.268(13)</td>
<td>0.09</td>
<td>0.058</td>
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</table>

\(^{4}f\)Assuming a transition energy between 10 \(\rightarrow\) 78 keV.
FIG. 6. Delayed $\gamma$-ray energy spectra for $N = 126$ nuclei. Background peaks are indicated by ☆. The peaks indicated by ○ belong to the nucleus of interest, but originate from a different isomeric state than that for which the time limits of the $\gamma$ spectrum are optimised. Inset spectra are time curves associated with the decay of the observed isomers. The transitions used to measure half-lives are indicated in the time spectra. For $^{203}$Ir, the inset presents an expanded $\gamma$-ray energy spectrum to highlight the observed energy peaks.

with $\pi h_{11/2}$ configuration. This latter state has been identified and its lifetime measured in a later RISING experiment using an active Si stopper [33], by observing the conversion electron associated with the $\pi h_{11/2} \rightarrow \pi d_{3/2}$ transition [34]. The higher-lying, $19/2^+$, isomer decays into the yrast $15/2^+$ state by a low-energy E2 transition. In addition, it decays by a 963 keV transition into a state that can have spin-parity of either $13/2^-$ or $15/2^-$. The shell-model calculations predict that even if it is $15/2^-$, the transition will have predominantly E3 character with only a very small, $\sim 10^{-5}$ W.u., M2 admixture. The $15/2^+$ state decays by three high-energy transitions to states with $I^\pi = (13/2^-, 15/2^-)$.

In $^{203}$Ir, similarly to $^{205}$Au, the observed isomeric state is expected to decay into the $11/2^-$ long-lived level. The isomer is likely to have a spin in the $19/2^-$-$23/2$ range. There are two possible scenarios. One is that the isomer is similar to that in $^{205}$Au, so has $I^\pi = 19/2^+$ and it decays to the $15/2^+$ state by a low energy E2 transition. Alternatively, the isomer
has $I^+ = 23/2^+$ and it decays to the $19/2^+$ state, possibly via the 207 keV tentative $\gamma$-ray transition. In this case, the $19/2^+$ state is most likely isomeric as well, decaying by a strong E3 into either a $13/2^-$ or $15/2^-$ state. Based on the shell-model calculations, we are inclined toward this second scenario. The existence of two isomeric states would explain the lower intensity of the tentative 207 keV transition. The transition strength was determined assuming the same half-life for both metastable states (Table II).

We compare the standard and the modified shell model calculations with the experimental data, with the energy spectra presented in Fig. 7, and with the reduced transition strengths in Table II. The main differences are: (i) the modified shell model gives a better description of the decay of the long-lived $11/2^+$ isomer in $^{205}$Au. According to the calculations, the isomer should decay via an E3 transition into the yrast $5/2^+$ state with a partial half-life of the order of $\sim 0.1$ s. This is contradicted by the experiment as the measured half-life is much longer [34]. The $5/2^+$ state cannot be as low as predicted by the standard shell model, it is likely that it lies above the $11/2^-$ state; (ii) the B(E2 : $19/2^+ \rightarrow 15/2^+$) transition strength in $^{205}$Au is described much better by the modified shell model; (iii) in $^{203}$Ir the modified shell-model gives a low B(E2) transition strength for the transition depopulating the isomer, in agreement with the experiment. (iv) the modified shell model calculation predicts a much longer half-life (when compared with the standard calculations) for the $11/2^-$ state in $^{203}$Ir. However, in this case we do not have experimental information. Based on the above evidence, (i), (ii), and (iii) we conclude that the modifications of the shell-model TBMEs improve the description of the odd-A $^{205}$Au and $^{203}$Ir nuclei.

Two of the observed isomers and their decay have been reported previously. These are the $I^+ = 5/2^+, T_{1/2} = 78(1)$ ns [30,35] isomeric state in $^{206}$Tl, and the $I^+ = 13/2^+, T_{1/2} = 1.09(4)$ ms [36] isomer in $^{205}$Hg. The lifetime of $T_{1/2} = 71(4)$ ns for $^{206}$Tl measured in the present experiment agrees with the published value. We could not determine the half-life of the above mentioned isomeric state in $^{205}$Hg since our correlation time, 85 $\mu$s in this case, was much shorter than the lifetime.

In $^{205}$Hg a previously unreported isomer has also been detected. Transitions with energies of 228, 723, 810, and 950 keV have been observed. The isomer has a lifetime of $T_{1/2} = 5.89(18)$ $\mu$s. Time differentiated $\gamma$-$\gamma$ coincidence analysis proves that this newly discovered isomer feeds the previously observed $I^+ = 13/2^+$ isomer. Within experimental uncertainties the sum of the energies of the 228 and 723 keV transitions is equal to the 950 keV transition, indicating that these are parallel decay pathways, which was confirmed by $\gamma$-$\gamma$ coincidence analysis. All these three transitions are in coincidence with the 810 keV line.

In $^{204}$Au excited states have been observed for the first time. Transitions are detected at the energies 839 and 977 keV. The half-life of the isomer is $T_{1/2} = 2.1(3)$ $\mu$s. There are other, tentatively identified $\gamma$-ray transitions at energies of 97, 277, 427, and 704 keV [14]. We note that recently the $\beta$ decay of $^{204}$Pt was studied and $\gamma$ rays belonging to $^{204}$Au, with energies of 165 and 305 keV, in mutual coincidence, were reported [37].

In $^{203}$Pt, one transition has been identified, with an energy of 1104 keV and associated half-life of $T_{1/2} = 641(55)$ ns. In $^{202}$Ir, no experimental observation was available prior to this work. $\gamma$ rays with energies of 312, 656, 737, 889, and 968 keV and Ir K x rays were detected. A parallel decay branch is likely as the sum of the energy of the 312 and 656 keV transitions is equal to 968 keV, within experimental uncertainties. The half-life of the isomer is determined to be $T_{1/2} = 3.4(6)$ $\mu$s.

The experimental and calculated level schemes of the $N = 125$ nuclei are shown in Fig. 9. In $^{205}$Hg, the low

C. $N = 125$ nuclei

Isomeric decays were observed in five $N = 125$ nuclei: $^{206}$Tl, $^{205}$Hg, $^{204}$Au, $^{203}$Pt, and $^{202}$Ir. The corresponding delayed $\gamma$-ray spectra are shown in Fig. 8.
energy part is dominated by single-neutron orbitals. The $p_{1/2}$, $f_{3/2}$, $p_{3/2}$, and $i_{13/2}$ neutron holes are associated with the 0, 379, 468, and 1556 keV states. The latter one is isomeric. All the yrast states above 2 MeV must involve at least three unpaired holes. The calculations suggest that the 23/2$^-$ state should be isomeric and decaying into the yrast 17/2$^+$ and 19/2$^+$ states. The 23/2$^-$ and 19/2$^+$ states have predominant $\pi(s_{1/2}^{-1}h_{11/2}^{-1})5^{-}vi_{13/2}^{-1}$ and $\pi(d_{3/2}^{-1}h_{11/2}^{-1})7^{-}vf_{5/2}^{-1}$ configurations, respectively, while the 17/2$^+$ state has a leading $\pi(s_{1/2}, d_{3/2})^{-2}2^+vi_{13/2}^{-1}$ configuration. Therefore, the parity changing M2 and E3 transitions will be hindered as they proceed via minority components in the wave functions. We associate these decay out transitions with the observed 950 and 723 keV $\gamma$ rays. Assuming that both transitions are stretched, the deduced transition strengths are $B(E3; 950 \text{ keV}) = 0.10(1)$ W.u. and $B(M2; 723 \text{ keV}) = 8(1) \times 10^{-5}$ W.u. The E3 transition is mediated by the $\pi h_{11/2} \to \pi d_{5/2}$ conversion; i.e., the weak $d_{5/2}$ content in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8.png}
\caption{Delayed $\gamma$-ray spectra for $N = 125$ nuclei. Background peaks are indicated by $\ast$, transitions arising due to contaminant nuclei are indicated by $\blacksquare$. The peaks indicated by $\circ$ belong to the nucleus of interest, but originate from a different isomeric state than that for which the time limits of the $\gamma$ spectrum are optimised. Inset spectra are time curves associated with the decay of the observed isomers. The transitions used to measure half-lives are indicated in the time spectra.}
\end{figure}
the wave function of the final state is crucial. Analogue E3 transitions with similar transition strengths have been observed in the $N = 126$ nuclei $^{204}$Pt, $^{205}$Au, $^{206}$Hg (see Table II), supporting our interpretation. The level schemes of $^{203}$Pt and $^{205}$Hg are expected to be very similar, as shown by the calculated level schemes of Fig. 9. The obvious difference is that the negative parity three-hole configurations should have a much longer lifetime than the observed $\mu$s isomers, because it has to decay by E3/M4 transitions (in $^{206}$Tl it has $T_{1/2} = 3.74$ min). Consequently, it is likely that the observed transitions feed the long-lived $12^+$ isomer, again a spin trap. The observation of $\gamma$ rays with similar intensity at 600–1000 keV supports this interpretation, as the $12^-$ and $5^+$ isomers should have very different decay patterns. In $^{204}$Au, it is most likely that the two observed transitions correspond to the decay of the $16^+$ isomer into the $14^−$ state via an $M2 + E3$ and a consequent $E2$ into the long-lived $12^+$ state. The ordering of the two transitions cannot be determined from the experiment and is guided by the shell model calculations. Assuming a stretched M2 decay from the $16^+$ isomer, the transition strength is $B(M2; 977$ keV)$ = 5(1) \times 10^{-4}$ W.u.; assuming a stretched E3, the transition strength is $B(E3; 977$ keV)$ = 0.28(5)$ W.u. We note that the very low isomeric ratio, below 1%, supports the idea of the high-spin isomer.

In $^{203}$Ir, the shell model predicts the same isomeric states and decay patterns as in its $^{204}$Au isotone. Due to the larger number of observed transitions, we cannot suggest an experimental level scheme. The isomeric ratio is below 1% in this case as well, suggesting that the isomer has a high spin.
We note that the transition strengths calculated with the two shell model parametrizations are close to each other for the $N=125$ nuclei (Table II).

D. $^{204,203}$Hg and $^{203,202,201}$Au

Delayed $\gamma$-ray spectra associated with $^{204,203}$Hg and $^{203,202,201}$Au are shown in Fig. 10.

In $^{204}$Hg, in addition to the transitions depopulating a very short lived $I^\pi = 7^-$, $T_{1/2} = 6.7(5)$ ns [38] isomeric state, new $\gamma$ lines were identified at 597, 965, and tentatively at 423 and 1014 keV (note that a 423 keV line is known to decay into the $7^-$ isomeric state [38]). These have equal half-lives within experimental uncertainties, $T_{1/2} = 20(2)$ ns. The effective half-life of the transitions depopulating the $7^-$ isomer (437, 692, and 1063 keV) is 38(8) ns (see Fig. 10), longer than the real half-life of this metastable state. This suggests that the newly identified transitions decay into the previously known isomer. The proposed level scheme is shown in Fig. 11. Shell model calculations predict a $14^+$ isomeric state decaying via a low-energy E2 transition. Due to the low statistics, we cannot establish the decay sequence from this higher-lying isomeric state.

In $^{203}$Hg, the previously reported $I^\pi = (13/2^+)\nu_{13/2}$ isomer [39] has been observed in the present work (see Fig. 11). The half-life is measured to be $T_{1/2} = 1.9(10)$ μs, which is consistent with and more accurate than the accepted value of...
FIG. 11. Level schemes of $^{204}\text{Hg}$, $^{205}\text{Hg}$ [39], $^{203}\text{Au}$, $^{201}\text{Au}$ and $^{202}\text{Au}$. The low-lying levels up to the $7^-$ isomer in $^{205}\text{Hg}$ [36] and the energies of the 11/2$^-$ isomeric states in $^{203,204}\text{Au}$ [39,42] are taken from the literature.

$T_{1/2} = 24(4)$ µs. The isomer decays by an M2 transition with $B(M2) = 0.0457(21)$ W.u. strength, which is reproduced by the shell model (see Table II).

In $^{203,204}\text{Au}$, Caamaño et al. [40] identified a single transition (563 keV) with a half-life of 40$^{+7000}_{-20}$ µs. Our half-life, $T_{1/2} = 140(44)$ µs, is consistent with and more precise than the published value. The error bars are large because in this case the $\gamma$-ray correlations following implantation were limited to a maximum time of 85 µs. Nevertheless, the improved lifetime measurement is the key to the interpretation of this decay (Fig. 11). It is expected that the $\pi h_{11/2}$ state is isomeric. A charged particle reaction experiment pinned down this state as being at 641(3) keV [38,41]. The half-life of the isomer suggests a low-energy M2 transition and rules out a low-energy E3. (Note, that while the standard shell model calculation does predict an inverse ordering of the 11/2$^-$ and 7/2$^+$ states, the modified one agrees with the experiment.) The observed 563 keV transition connects the 7/2$^+$ state with the 3/2$^+$ $\pi d_{3/2}$ ground state. The B(M2) transition strength of the unobserved 78(3) keV $\gamma$ ray is 0.03(2) W.u., in excellent agreement with the shell model prediction. The lack of strong K x rays indicates that the energy of the M2 transition is below the K-electron binding energy of 80.725 keV. The rather low isomeric ratio, 2.5$^{+10}_{-10}$ % here and >1% in Ref. [40], suggests the existence of a higher lying long-lived isomer in this nucleus.

In $^{202}\text{Au}$, no excited states were reported before. Two transitions are identified at 138 and 414 keV. The half-life is $T_{1/2} = 13.1(5)$ ns. $\gamma$-\gamma coincidences confirmed that the two transitions are in coincidence [14]. The intensity balance supports an M1 or possible E2 assignment for the 138 keV transition. Based on the shell model calculations we propose the tentative level scheme shown in Fig. 11. Either the 7$^+$ or the 5$^+$ state could be isomeric. The isomer decays by the 138 keV E2 transition, followed by a fast 414 keV E1. The measured transition strength, $B(E2) = 5.0(2)$ W.u., is consistent with the ~11 W.u. value predicted by the shell model.

In $^{201}\text{Au}$, three new delayed transitions are identified at 378, 553, and 638 keV. The half-life of the 553 keV transition is $T_{1/2} = 340^{+900}_{-290}$ µs, while the other two transitions originate from a shorter lived isomeric state with $T_{1/2} = 5.6(24)$ µs. Previously, excited states of $^{201}\text{Au}$ were studied experimentally in the $^{202}\text{Hg}(t,a)$ reaction [41,42]. The yrast 11/2$^-$ state with $\pi h_{11/2}$ configuration was identified at 594(5) keV [42]. Below this state only low-spin states (3/2 and 1/2) and a tentative level with no spin-parity assignment at 549(5) keV were observed. Based on the lifetime, and the similarity between the observed $\gamma$-ray energy of 553 keV and the 549(5) keV excitation energy, we propose the level scheme shown in Fig. 11. The 11/2$^-$ isomer at 594(5) keV decays by an unobserved low-energy 41(6) keV M2 transition into the 7/2$^+$ state, which decays into the 3/2$^+$ ground state by the 553 keV $\gamma$ ray. This decay pattern, as well as the M2 transition strength of $B(M2) \sim 0.02$ W.u., is similar to that observed in the neighboring $^{199}\text{Au}$ [43] and $^{202}\text{Au}$ (this paper) odd-mass isotopes. This interpretation fits with the conclusions of a recent ISOLDE experiment [44]. There it was concluded [45] that the 11/2$^-$ state cannot have a half-life of the order of seconds; i.e., it does not decay directly into the 3/2$^-$ ground-state by an M4 transition (the case in $^{203}\text{Au}$). The 368 and 378 keV transitions are associated with a higher lying isomeric state which decays into the 11/2$^-$ one. The intensity balance and lifetime are compatible with the 378 keV
transition being an M2 transition decaying from the isomer with a strength of $B(M2) = 0.014(7)$ W.u. Note that due to the large number of holes outside the $^{208}$Pb core, no shell model calculations were performed for $^{201}$Au.

E. Platinum isotopes\textsuperscript{202,201,200,199,198,197}Pt

In $^{202}$Pt\textsubscript{124}, an $I^\pi = (7^-)$ isomer was previously observed by Caamaño\textit{et al.}\textsuperscript{[40]}. Our half-life of $T_{1/2} = 141(7)$ $\mu$s is consistent with and more accurate than the previous value of $T_{1/2} = 280^{+420}_{-190} \mu$s. $\gamma$-$\gamma$ coincidence analysis has confirmed the doublet nature of the 535 keV peak\textsuperscript{[14]}. This is consistent with the interpretation made by Caamaño\textit{et al.}\textsuperscript{[40]}.

In $^{201}$Pt\textsubscript{123}, the previously reported isomer\textsuperscript{[40]} has been observed in the current work. In addition to the three known transitions, we searched for a possible low-energy one, without success. The isomeric half-life is measured to be $T_{1/2} = 18.4(13)$ ns, which is consistent with the previous measurement of $T_{1/2} = 21(3)$ ns\textsuperscript{[40]}.

![FIG. 12. Gamma-ray spectra for Pt nuclei with $N < 125$ measured in the described experiment. Background peaks are indicated by $\star$. Inset spectra are time curves associated with the decay of the observed isomers. The transitions used to measure half-lives are indicated in the spectra.](image-url)
The 13/2<sup>−</sup> decay of the previously reported measurements [40,46]. This work reports a half-life of $g_{\pi}$

$\pi g_{\pi}$

The lower-lying $I^\pi = (7^−)$ isomer has a half-life of $T_{1/2} = 14.3(6) \text{ ns}$, which is the weighted average of the previous measurements [40,46]. This work reports a half-life of $T_{1/2} = 17.0(5) \text{ ns}$. The other isomer has only been reported by Caamaño et al. [40], it has a spin-parity $I^\pi = (12^+)$ and it feeds the $I^\pi = (7^−)$ isomer. The current work agrees with the previous findings and reports a half-life of $T_{1/2} = 13.9(10) \text{ ns}$; it was previously reported to be $T_{1/2} = 10.3(24) \text{ ns}$.

In $^{200}_{78}\text{Pt}_{122}$, two previously reported isomers were observed. The lower-lying $I^\pi = (7^−)$ isomer has a half-life of $T_{1/2} = 4(2) \text{ ns}$, which is the weighted average of the previous measurements [40,46]. This work reports a half-life of $T_{1/2} = 3.4(2) \text{ ns}$ isomer [47]. A higher-lying isomer with $T_{1/2} = 36(2) \text{ ns}$ was also reported [48,49], feeding the lower-lying $I^\pi = (7^−)$ isomer. The data evaluators of Ref. [47] suggested $I^\pi = (12^−)$ for this isomer. There is weak evidence in the $\gamma$-ray energy spectrum (see Fig. 12) for the presence of the 135-, 752-, and 823-keV transitions that feed the $I^\pi = (7^−)$ state; therefore, the half-life determined from the present experiment has a large uncertainty due to the poor statistics, and it is consistent with previous measurements.

In $^{197}_{78}\text{Pt}_{120}$, three transitions emitted following the decay of a previously unreported isomer have been detected with energies of 319, 420, and 597 keV. All three transitions exhibit the same decay lifetime, within experimental uncertainties. The half-life of the isomer is $T_{1/2} = 18.6(34) \text{ ns}$.

In $^{198}_{78}\text{Pt}_{121}$, we observe an unreported isomeric state. $\gamma$-ray transitions have been detected at the energies 319, 420, and 597 keV. All three transitions exhibit the same decay lifetime, within experimental uncertainties. The half-life of the isomer is $T_{1/2} = 18.6(34) \text{ ns}$.

No experimental information on the excited states of $^{195}_{77}\text{Ir}_{124}$, $^{197}_{77}\text{Ir}_{124}$, and $^{199}_{77}\text{Ir}_{124}$ are shown in Fig. 14. In $^{200}_{77}\text{Ir}_{124}$, no experimental information on the excited states was previously available. Presently, an isomer has been observed, emitting three transitions: 440, 452, and 681 keV. The half-life is $T_{1/2} = 10.5(17) \text{ ns}$.

No experimental information on the excited states of $^{200}_{77}\text{Ir}_{124}$ was previously available. Two transition were
observed, at energies of 120 and 127 keV. The transitions are not in coincidence with each other [14]. The half-lives associated with the decay of these two transitions are $T_{1/2} = 17.1(12)$ and $28.5(15)$ ns, respectively.

In $^{199}$Ir$_{122}$, a new isomeric state has been observed decaying by 449-, 500-, 547-, and possibly 597-keV transitions. The intensity of the tentative 597-keV transition (its energy is similar to that from the $^{76}$Ge(n,n') reaction) is distinctly less than the intensity of the other three. $\gamma$-$\gamma$ coincidence analysis shows that the three stronger transitions are in mutual coincidence. In addition, the 500 keV is a doublet, since it is in coincidence with itself. The 597-keV transition is tentatively observed to be in coincidence with the other three transitions. Based on the presently available experimental data, it is interpreted that all of the transitions are emitted following the decay of a single isomer with a half-life of $T_{1/2} = 8.9(5)$ ns. Caamaño et al. [40] have previously tentatively reported the existence of an isomer in $^{199}$Ir$_{122}$. Candidate transitions were suggested at the energies 104, 112, 122, and 162 keV. Our spectrum, with the same time range $\Delta t = 80 \rightarrow 390$ ns is shown in Fig. 14. No indication of the tentatively observed isomer has been detected in this work.
An isomer has previously been identified in $^{198}$Ir with a half-life of $T_{1/2} = 77(9)$ ns [40]. Our measured half-life of $T_{1/2} = 73.0(11)$ ns is in agreement with the previous value. A previously unreported isomer has been identified in $^{195}$Os. The transitions are observed to have energies 268, 404, 477, 538, and 567 keV. None of these transitions were known before [57]. The half-life of the isomer measured from the combined statistics of all of the transitions is found to be $T_{1/2} = 4.4(6)$ μs.

The odd-mass $^{193,195,197}$Ir nuclei have a remarkably similar single quasiparticle level structure [53,54,57]. The ground-state is $\pi 3/2^+$ [402], followed by the $\pi 1/2^-$ [400] at ~60-keV excitation energy and by $\pi 1/2^- [505]$ at ~100 keV. The $11/2^-$ is isomeric with very long half-life (e.g., 10.5 days in $^{195}$Ir). The similarity indicates that these isotopes must have very similar deformation. This, and the further similarity to less neutron-rich $^{189,191}$Ir nuclei suggests that they all exhibit prolate deformation (note that the calculations of Möller et al. [29] suggest that Ir isotopes up to $^{196}$Ir are prolate, and become oblate from $^{197}$Ir onwards). The proposed level scheme for $^{195}$Ir is shown in Fig. 15. Based on BCS calculations, we suggest for $^{195}$Ir that a three-quasiparticle $27/2^+$ isomer with configuration $\pi 11/2^-[505]e 3/2^-[512]13/2^-[606]$ decays into the rotational band built on $\pi 11/2^- [505]$. The transition energies within the band fit into the systematics of the lighter odd-mass Ir isotopes. The transition strength of the 268-keV E1 transition is $B(E1) = 2.3(3) \times 10^{-9}$ W.u.

In $^{198}$Ir and $^{200}$Ir, the lack of x rays in the spectra suggests that the observed low-energy transitions are of E1 character. In the case of $^{199}$Ir, following the previous suggestion [40] that the observed transition is E1 in nature and it depopulates the isomer directly, a transition strength of $B(E1) = 1.4(3) \times 10^{-6}$ W.u. and an isomeric ratio of $IR = 5(4)$% is measured. This is lower than the previous IR $= 19(3)$ value [40]. With the same assumptions for $^{200}$Ir, we get $B(E1) = 2.8(2) \times 10^{-6}$ W.u and $B(E1) = 5.4(4) \times 10^{-6}$ W.u., $\text{Ir} = 3.5(14)$% and $\text{IR} = 22(12)$%, for the 127- and the 121-keV transitions, respectively.

The lifetimes, of order of tens of nanoseconds, in $^{201}$Ir and $^{199}$Ir are compatible with decays via low-energy E2 transitions. Both nuclei are predicted to be almost spherical, with small, $\beta_2 < 0.1$, oblate deformation [29]. The observed γ-ray spectra do not resemble rotational bands, in agreement with the above prediction. No level schemes are proposed for these nuclei.

**G. Osmium isotopes $^{199,198,197,195,193}$Os**

The delayed γ-ray and time spectra for $^{199,198,197,195,193}$Os nuclei are shown in Fig. 16.

A previously unreported isomer has been observed in $^{199}$Os. Five transitions have been detected with energies 379, 402, 425, 737, and 971 keV. The half-life of the isomer is measured to be $T_{1/2} = 25.2(20)$ ns.

Two new isomers were found in $^{197,198}$Os. These results have been discussed in detail by Podolyák et al. [58]. In supplement to the previous publication, we present here limits on the isomeric ratios of the observed $I^z = (12^+)$ and $I^z = (7^-)$ metastable states (see Table I). No states have previously been reported in $^{197,198}$Os. Presently, four transitions have been observed, these are at energies 204, 416, 487, and 629 keV. The half-life is found to be $T_{1/2} = 78.2(66)$ ns. All four transitions are in mutual coincidence [14].

In $^{197}$Os, we confirm the isomeric state previously observed both in fragmentation [40] and deep-inelastic [48] experiments. Our half-life is $T_{1/2} = 34.0(23)$ ns, similar to the previously determined values of $T_{1/2} = 26(4)$ ns [40] and $T_{1/2} = 26(9)$ ns [48].
An isomer is reported for the first time in $^{193}$Os. One transition with 242 keV is associated with the decay of the isomer that has a half-life of $T_{1/2} = 132(29)$ ns. This energy does not fit into the known low-spin-level scheme [53] and we are unable to propose a level scheme.

The observed isomer in $^{195}$Os was interpreted [48] to have $I^\pi = (27/2^-)$ with $\nu_{13}^1/2^+[606]3/2^-[501]1/2^+[615]$ character. Here we suggest an alternative interpretation, as shown in Fig. 15. The $I^\pi = (29/2^-)$ with $\nu_{13}^1/2^+[606]11/2^-[505]5/2^+[402]$ (or, alternatively, the $I^\pi = (25/2^+)$ with $\nu_{13}^1/2^+[606]3/2^-[501]9/2^-[505]$) isomer decays via a low-energy E2 (or E1) transition into the $25/2^-$, $\nu_{13}^1/2^+[606]11/2^-[505]1/2^+[411]$ band-head, which decays via the 714-keV transition into the $\nu_{13}^1/2^+[606]$ band. We note that the $\nu_{13}^1/2^+[606]$ and $\nu_{3}^1/2^-[501]$ states are expected to be close in energy, one of them being the ground state and the other a long-lived isomer.

Theoretical calculations predict a weakly deformed oblate shape for $^{197-199}$Os [29,59], similar to the platinum isotopes. From the experimental side, the similarity between the excitation spectra of $^{198}$Os and $^{200}$Pt [58] suggests that the neighboring odd-mass nuclei are also similar. Consequently, a low-energy $13/2^+$ state, with a long half-life, is expected in the odd-mass Os isotopes. Most likely, the isomers observed in $^{197,199}$Os decay into this yrast $13/2^+$ state. Possible isomeric states should have the $i_{13/2}$ neutron coupled with $\pi h_{11/2}^1d_{5/2}^1$ and/or $\pi h_{11/2}^2$. For $^{197}$Os, we suggest a level scheme similar to that of its $^{199}$Pt isotope, with the isomer having $\nu_{i_{13/2}}^1\pi h_{11/2}^1d_{5/2}^1$ configuration (see Figs. 15 and 13). In $^{199}$Os, the number of observed $\gamma$ rays suggests a higher spin isomer, possibly with $\nu_{i_{13/2}}^2\pi h_{11/2}^2$ character; however, we are unable to propose a level scheme.

We note that no isomeric state was observed in $^{196}$Os [58]. This suggests that $^{196}$Os has a different shape from the slightly

![Gamma-ray spectra for Os nuclei measured in the described experiment. Inset spectra are time curves associated with the decay of the observed isomers. The transitions used to measure half-lives are indicated in the spectra.](image)
oblate $^{198}$Os \cite{58} and the platinum isotopes. Here we propose that the shape transition to oblate happens after $^{196}$Os.

**H. Rhenium isotopes** $^{196,194,193,192,187}$Re

The delayed $\gamma$-ray and time spectra of $^{196,194,193,192,187}$Re nuclei are shown in Fig. 17.

For the first time an excited state is reported to be observed to decay in $^{196}$Re. Characteristic rhenium $K_\alpha$ and $K_\beta$ x rays are observed following the decay through an unobserved highly converted transition. The half-life associated with the $K_\alpha$ x rays is measured to be $T_{1/2} = 3.6(6)$ $\mu$s.

In $^{193}$Re \cite{119}, Caamaño et al. \cite{40} tentatively reported an isomeric state by observing possible transitions at 128, 148, and 464 keV and rhenium $K_\alpha$ and $K_\beta$ x rays. The current report confirms the existence of an isomer with a measured half-life of $T_{1/2} = 45(18)$ $\mu$s. We observe the x rays and the 86-keV $\gamma$ ray. The 128-, 148-, and 464-keV transitions have not been observed.

In $^{193}$Re previous work by Caamaño et al. \cite{40} identified the emission of a 145-keV $\gamma$-ray transition and characteristic rhenium $K_\alpha$ and $K_\beta$ x rays following the decay of an isomer with a half-life of $T_{1/2} = 75(300)$ $\mu$s. We confirm the existence of this isomer. The determined half-life, $T_{1/2} = 65(9)$ $\mu$s, is consistent with and more precise than the previous value. A more recent experiment also detected this isomer and gave $T_{1/2} = 72(8)$ $\mu$s \cite{60}.

In $^{192}$Re \cite{117} Caamaño et al. \cite{40} have previously identified the decay of an isomer. We confirm the existence of this isomer by detecting a 159 keV, $\gamma$ ray, as well as characteristic rhenium $K_\alpha$ and $K_\beta$ x rays. The determined half-life, $T_{1/2} = 85(10)$ $\mu$s, is consistent with and more precise than the previous value of $T_{1/2} = 120(210)$ $\mu$s. A more recent experiment also detected this isomer and reported $T_{1/2} = 93(15)$ $\mu$s \cite{60}.

FIG. 17. Gamma-ray spectra for Re nuclei measured in the described experiment. Background peaks are indicated by $\star$. Inset spectra are time curves associated with the decay of the observed isomers. The transitions used to measure half-lives are indicated in the spectra.
In $^{191}\text{Re}_{116}$, an isomer has tentatively been identified by Caamaño et al. [40] with possible transitions at 53, 139, 225, 308, 360, 419, and 444 keV with Re x rays as well. We confirm the existence of this isomer. There are differences between the transitions observed in this and the previous work. The suggested transitions at 53, 308, and 360 keV have not been observed in this work, although the others have. In addition, in this work a transition of 135 keV is tentatively identified, which was not previously observed. The intensity of the 225-keV line is double compared to the others, suggesting a doublet nature. The half-life of the isomer is $T_{1/2} = 77(33)$ μs.

Odd-mass $^{187}\text{Re}$ [61] and $^{189}\text{Re}$ [61] are characterized by an $\pi 5/2^+ [402]$ ground state with a low-lying $\pi 9/2^- [514]$ excited state. Our BCS calculations predict the same situation for $^{193}\text{Re}$. We propose that the observed 145-keV transition connects these states and has an $M2$ transition strength of $B(M2) = 0.0175(25)$ W.u. The intensity of the observed x rays is in agreement with this scenario.

In $^{191}\text{Re}$, we are unable to suggest a level scheme. Most likely the isomer feeds the $\pi 9/2^- [514]$ band head as the energy of the 140-keV transition is in agreement with the $(11/2^- \rightarrow 9/2^-)$ energy difference [52]. The strong x rays as well as the lifetime suggest an $M2$ decay from the isomer, possibly arising from the same proton configuration change (with a broken neutron pair) as in $^{193}\text{Re}$. We note that the $9/2^-$ band head at 145(3) keV [52] is likely to be isomeric with a similar lifetime, decaying into the $5/2^+$ band head at 97(3) keV (but the observed x rays are not from this decay and the 97(3)-keV transition is not observed).

The odd-odd $^{192,194,196}\text{Re}$ nuclei all exhibit strong x rays and similar microseconds lifetimes. These would suggest a low-energy $M2$ decay, similarly to the odd-mass nuclei. However, the x rays in $^{192}\text{Re}$ and $^{194}\text{Re}$ are too weak for the 159- and 86-keV transitions to be of $M2$ character, respectively. Consequently, no level schemes are suggested for the odd-odd rhenium nuclei. The isomeric ratios were determined assuming $M1$ character for the 159- and 86-keV transitions.

FIG. 18. Gamma-ray spectra for W and Ta nuclei measured in the described experiment. Inset spectra are time curves associated with the decay of the observed isomers. The transitions used to measure half-lives are indicated in the spectra.
I. The $^{191,193}$W and $^{189,191}$Ta nuclei

The delayed $\gamma$-ray and time spectra of $^{191,193}$W and $^{189,191}$Ta nuclei are shown in Fig. 18.

The first observation of excited states in $^{191}$W have been made in the present work [13,14]. $\gamma$-ray transitions at 68 and 167 keV and characteristic tungsten x-rays are observed. The half-life is $T_{1/2} = 0.36(2) \mu$s. This isomer is confirmed by Alkhomashi et al., who in a subsequent experiment performed one year later measured $T_{1/2} = 0.32(2) \mu$s [60]. We are unable to propose a level scheme.

In $^{193}$W$_{114}$, an isomeric state has been previously reported [40,62]. The results from the present experiment and possible interpretations were discussed in detail in Ref. [63]. The half-life of the isomer has been measured to be $T_{1/2} = 108(9) \mu$s. We note that a subsequent experiment confirmed this isomer and reported a half-life of $T_{1/2} = 106(18) \mu$s [60]. In addition, there are indications for a previously unreported isomer with a much shorter life-time. Characteristic tungsten x-rays have been observed, but no $\gamma$-ray transitions, with an associated half-life of $T_{1/2} = 0.35(4) \mu$s. There are insufficient statistics available for $\gamma$-$\gamma$ analysis to identify whether there is any feeding between this newly discovered isomer and the previously observed one. Very recently, results from an experiment employing deep-inelastic collisions were published by Lane et al. [64]. They deduce that a $10^{-2}$ $T_{1/2} = 166(6) \mu$s isomer decays by a low-energy M2 transition into the $8^+$ 110(17) isomer. The lower-lying isomer decays via the $\gamma$-ray transitions observed in the present experiment. Our experimental data supports the level scheme suggested by Lane et al. (see Fig. 1 of Ref. [64]). However, our short-lived x-ray spectrum cannot be explained by that level scheme. It was previously noted that a possible cause of the low E($4^+$/E($2^+$)) ratio in $^{195}$W is shape coexistence [9]. Consequently, it might be that the observed x rays are from the $0^+ \rightarrow 0^+$ shape-changing transition. This has to be isomeric also because its decay has to proceed via conversion electron as the $\gamma$-ray transition is forbidden.

Excited states have been measured in $^{193}$Ta$_{116}$ for the first time. $\gamma$-ray transitions have been observed at energies of 154, 284, 343, 389, and 482 keV. The half-life is $T_{1/2} = 0.58(22) \mu$s. $\gamma$-$\gamma$ coincidence analysis shows that all of the $\gamma$ rays are in mutual coincidence [14]. A more recent experiment has also detected this isomer, $\gamma$ rays with energies 57 (x ray), 83, 134, 154, 199, 264, 284, 389, and 481 keV were reported with a half-life of $T_{1/2} = 1.6(2) \mu$s [60]. The additional, lower intensity $\gamma$ rays show up in our spectrum as tentative lines (also 99 keV). It seems that two isomers are involved, and we are unable to propose a level scheme.

In $^{191}$Ta$_{115}$, we confirm the previous observation of an isomeric state by Caamaño et al. [40]. A single 292-keV transition is observed with half-life of $T_{1/2} = 3.5(4) \mu$s, which is in agreement with the previous value of $T_{1/2} = 5(2) \mu$s. A subsequent fragmentation experiment has also seen this isomer and reported a $T_{1/2} = 4.4(10) \mu$s half-life [60]. No level scheme is proposed.

J. Lighter nuclei

The experiment covered a number of nuclei in the region of $^{191}$Ta and $^{193}$W, as shown in Fig. 1. The yields of these nuclei were rather low [13]. Therefore, no conclusion can be drawn from the nonobservation of isomeric states in the region. To some extent, the above is valid for tantalum isotopes as well. Actually, we know that this region is characterized by K isomerism, and some K isomers have been identified. For example, fragmentation experiments populate isomeric states in $^{190}$Ta [60] and $^{183,184,186}$Hf [65], while deep-inelastic reactions made them in $^{182}$Hf [66].

IV. SUMMARY

Isomeric states were observed in a large number of heavy neutron-rich nuclei in the Ta-Hg region. In the case of nuclei close to the doubly magic $^{208}$Pb, the results were interpreted with the aid of the shell-model. It was found that the modifications introduced in order to obtain a better description of $^{204}$Pt and $^{206}$Hg improved the agreement with experiment for the whole region.

Information on the prolate-oblate shape transition was obtained. It is suggested that osmium isotopes with mass $A \geq 197$ are slightly oblate and have isomeric states similar to those in the platinum nuclei. The lighter osmium isotopes such as $^{193,195}$Os exhibit isomeric states characteristic of prolate shapes. The lack of isomeric transitions in $^{196}$Os are interpreted as an indication that this nucleus is still prolate deformed. The spectra obtained from iridium isotopes indicate that up to $^{197}$Ir they are prolate while the $^{199,201}$Ir isotopes are oblate.

Several isomeric states with half-lives beyond the sensitivity of the technique used here are predicted. It may be possible to identify them using other methods, such as the GSI storage ring.

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