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Observation of an isomeric state in ^{197}Au

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A medium-spin isomer in ^{197}Au is identified with $t_{1/2} = 150(5)$ ns following a multinucleon transfer reaction between an 850-MeV ^{136}Xe beam and a ^{198}Pt target. The transitions identified here are considered and possible configurations for the associated levels discussed. In addition, a newly observed out-of-beam transition in ^{195}Au is briefly reported.

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The odd-A gold isotopes are characterized by decoupled rotational bands based on proton-hole states at low spins and three-hole configurations at medium spins, many of which are isomeric [1,2]. However, while the data for $A \leqslant 193$ are relatively complete, for heavier masses few medium- or high-spin levels have been reported. The reasons are twofold. By ^{197}Au, the only stable gold nuclide, the isotopes are beyond the reach of conventional heavy-ion fusion–evaporation reactions. Second, deep-inelastic reactions (see, e.g., Ref. [3]) have the drawback that often it is not possible to uniquely identify the isotope or element to which populated de-excitations belong. Therefore, while a decay scheme may be relatively straightforward to construct, for it to be assigned correctly, other, complementary data are frequently required. Such is the case here in which we observe a newly placed three-hole isomer decay in $^{197}_{79}$Au. This was made possible following the recent comprehensive publication by Fotiades *et al.* [4] of the low-spin states in ^{197}Au using $(n, n'\gamma)$ reactions.

A thin, 420-μg cm^{-2}, self-supporting target of $^{198}_{78}$Pt was bombarded with an 850-MeV $^{136}_{54}$Xe beam provided by the 88" cyclotron at Lawrence Berkeley National Laboratory. Gamma rays were detected using the GAMMASPHERE array consisting of 102 Compton-suppressed germanium detectors for this experiment and heavy-ion recoils were stopped in the CHICO gas-filled PPAC ancillary detector [5]. The event trigger condition required two co-planar CHICO elements and at least three germanium detectors to fire within 670 ns. Further software time conditions demanded that the first three γ rays be in prompt coincidence, within ± 45 ns of the CHICO detection of the two recoils. However, subsequent γ-rays could be delayed by up to 670 ns, allowing both prompt (Doppler corrected) and out-of-beam (uncorrected) events to be recorded. (Note that the beam had a natural pulsing period of 178 ns.) A detailed description of the analysis can be found in Ref. [6].

The SORT-SHELL software [7] was used to construct a variety of multidimensional histograms. Those relevant to the current work are

(i) γ-γ-delayed, out-of-beam γ rays arriving between 45 and 670 ns after the first three prompt γ-ray signals;
(ii) prompt-delayed-γ-γ for which the x axis is incremented with out-of-beam γ rays and the y axis with prompt γ rays, Doppler corrected for platinum-like recoils;
(iii) the corresponding matrix with Doppler corrected γ rays from xenon-like products on the y axis;
(iv) prompt-γ-γ with prompt γ rays, Doppler corrected for platinum-like products on both axes; and
(v) γ-time for extracting isomeric decay half-lives.

The RADWARE analysis package [8] was used to project and view background subtracted, gated spectra.

One of the most intensely populated out-of-beam cascades observed in this experiment consists (in order of increasing excitation energy) of the transitions 357.7, 639.7, 429.2, 261.1, and 435.6 keV shown in Fig. 1 (top), all in mutual coincidence. The first three of these transition energies match

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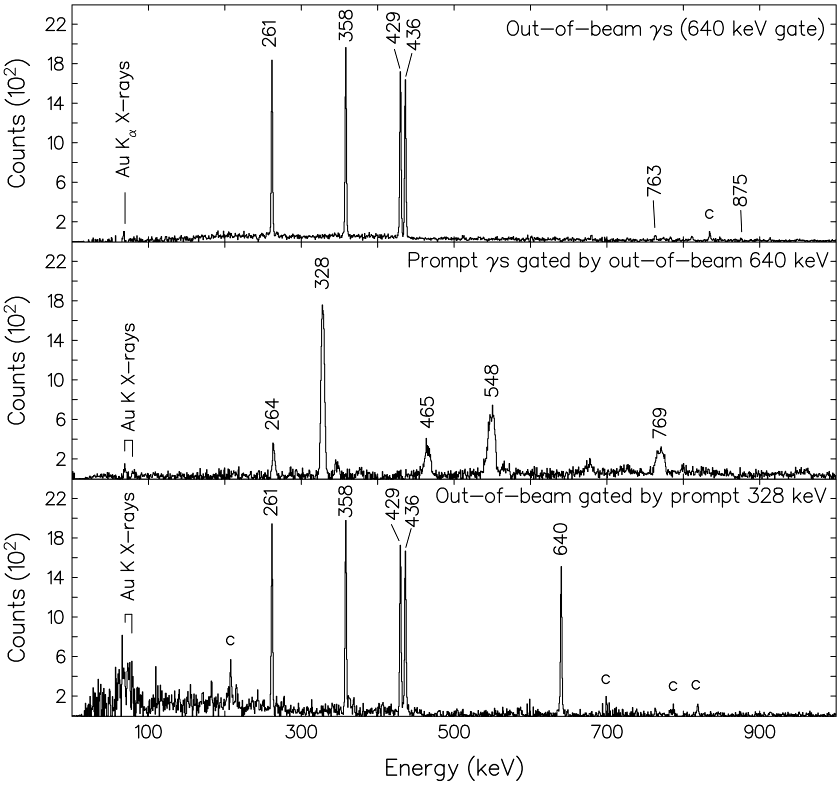

FIG. 1. (Top) Out-of-beam γ-ray spectrum gated by the 640-keV $(\frac{19}{2}^-) \rightarrow (\frac{15}{2}^-)$ transition in ^{197}Au. A contaminant, labeled c, at 834 keV from ^{72}Ge$(n, n'\gamma)$ is also present. (Middle) Prompt γ-rays gated by the out-of-beam 640-keV transition. (Bottom) Out-of-beam transitions in coincidence with prompt 328-keV decays. Contaminants, predominantly from ^{136}Ba because of a near energy degeneracy, are labeled c. The x-ray peaks in this spectrum are contaminated by contributions from lower Z nuclei.

those built on the 409-keV, $I^\pi = \frac{11}{2}^-$, $t_{1/2} = 7.7$ s, bandhead in ^{197}Au, recently published by Fotiades *et al.* [4], enabling the transitions observed here to be firmly placed in this nucleus. In Ref. [4], the transitions are assigned as 358.0 keV, $(\frac{15}{2}^-) \rightarrow (\frac{11}{2}^-)$; 639.7 keV, $(\frac{19}{2}^-) \rightarrow (\frac{15}{2}^-)$; and 429.2 keV, $(\frac{21}{2}^+) \rightarrow (\frac{19}{2}^-)$. The latter being the transition depopulating the highest reported spin state in this nucleus. A half-life of $t_{1/2} = 150(5)$ ns is obtained for the newly observed isomeric state by fitting the time spectrum shown in Fig. 2.

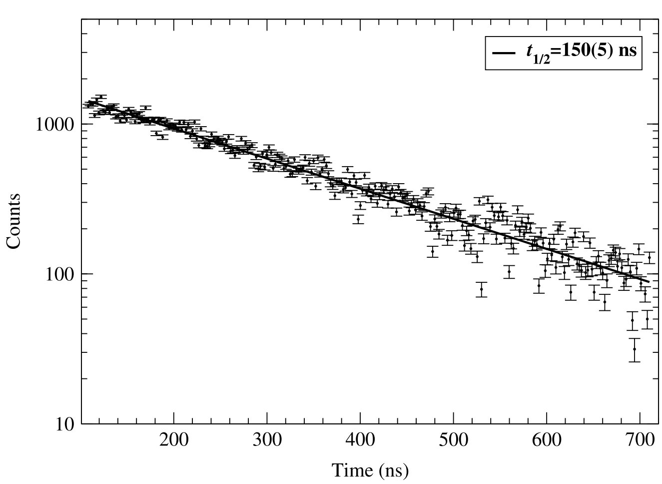

FIG. 2. Time spectrum gated by the 261-, 358-, 436-, and 640-keV transitions in ^{197}Au (data points) from which the half-life (solid line), $t_{1/2} = 150(5)$ ns, is obtained.

The ordering of the two higher-lying, 261- and 436-keV transitions could not be established solely from the out-of-beam GAMMASPHERE data. However, data from an earlier experiment obtained using the same reaction at 780 MeV with the 8π detector array at Berkeley was used to tie down the ordering to that given above. Transitions up to and including the 261-keV transition were observed, but not the 436-keV decay, which was beyond the sensitivity of the 8π setup. These data were obtained using a thick, 7-mg cm^{-2} ^{198}Pt target backed by 50-mg cm^{-2} $^{\rm nat}$Pb. Details of the experiment and analysis technique can be found in Ref. [9].

In addition to the intense transitions discussed above, other weaker out-of-beam coincidences have been observed. A 1069.2-keV transition is found to be in coincidence with all but the 429- and 640-keV de-excitations. This leads to its placement as the $(\frac{21}{2}^+) \rightarrow (\frac{15}{2}^-)$, $(E3)$ transition. It is noteworthy that this 1069-keV decay, observed here with a partial γ-ray intensity of 0.02(1), is not reported in Ref. [4]. Further, much weaker coincidences between the intense cascade and a 763.0-keV γ ray have been identified, implying a second isomer, either more weakly populated or with a half-life $\gg$1 μs. (A second, even weaker transition at 875 keV, showing coincidences similar to those of the 763-keV decay remains unplaced.) Both the 763- and 875-keV energies are coincident with all of the intense transitions, distinguishing them from stronger contaminant decays (Figs. 1 and 3).

Following the projection of the prompt transitions in coincidence with the 640-keV out-of-beam decay, the cascade energies (relative γ-ray intensities) 328 (54), 548 (51), and 465 (19) keV were observed to lie above the isomer, together with two additional prompt transitions at 264 (7) and 769 (27) keV

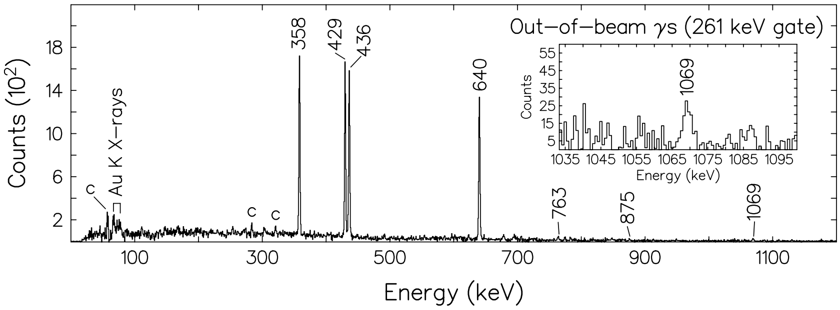

FIG. 3. Out-of-beam γ-ray spectrum gated by the 261-keV transition in ^{197}Au showing the 1069-keV ($E3$) transition (inset). Contaminants, labeled c, are from ^{182}W.

[Fig. 1 (middle)]. This relationship was confirmed by projecting the delayed transitions from a prompt gate at 328 keV, as shown in Fig. 1 (bottom). Gold K x-rays have been identified in all of the spectra in Figs. 1 and 3. The level scheme resulting from this analysis is shown in Fig. 4.

Comparison with lighter odd-A gold nuclei suggests the possibility of an unidentified low-energy transition directly depopulating the isomeric state. Low-energy transitions are known to directly depopulate the $I^\pi = \frac{31}{2}^+$ isomers in ^{191}Au (67 keV) and ^{189}Au (39 keV) [1]. In the current work the limits for such a decay to be unobserved are $E_\gamma < 85$ keV ($E2$), <69 keV ($M1$), and <45 keV ($E1$) [10] and would lead to an isomer with a spin of $\approx \frac{31}{2}\hbar$. In the absence of such a low-energy transition the 436-keV decay would directly depopulate the isomer. In such a scenario, based on the Weisskopf single-particle estimate, multipolarities higher than $\lambda = 2$ would lead to Weisskopf hindrance factors, $F_W = (t_{1/2}^{\rm expt.}/t_{1/2}^{\rm Weiss.}) < 1$, and would therefore not be allowed. Considering an intermediate state of either $I^\pi = \frac{23}{2}$ or $\frac{25}{2}$ suggests possible spins of $I^\pi = \frac{25}{2} \rightarrow \frac{29}{2}$ for the newly observed isomer, in the absence of any additional (unobserved) low-energy decay.

The configurations measured or suggested (based on the available orbitals) for the higher-spin states are given in Table I, including the newly observed levels in ^{197}Au. Considering the available neutron orbitals in this region a change in structure may naïvely be expected around ^{197}Au, beyond which the $[\nu i_{13/2} \otimes \nu h_{9/2}]_{10^-}$ coupling will move to relatively higher excitation energies due to the increasing Fermi level as the neutron closed shell is approached. A second manifestation of this effect will be the favoring, at higher spins, of the $\nu i_{13/2}^{-2}$ couplings to the $h_{11/2}$ proton hole, leading to configurations with $I^\pi = \frac{33}{2}^-$ and $\frac{35}{2}^-$, one of which may de-excite via the weak 763-keV out-of-band decay observed here. Whether this point has been reached will become clear following characterization of the states observed here and further study of ^{195}Au (see also below).

The provisional $E3$, $(\frac{21}{2}^+) \rightarrow (\frac{15}{2}^-)$ transition at 1069 keV is consistent with a nanosecond (or shorter) half-life based on the relative branching intensity (0.02(1)) and the Weisskopf single-particle estimate, though no intermediate lifetime was observed. This and the $E3$ systematics for the lighter odd-A isotopes are shown in Table II. In addition to ^{197}Au, previously

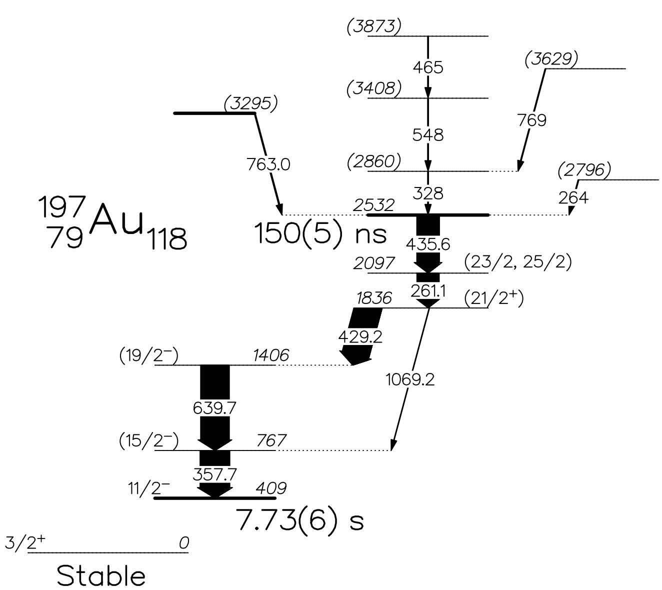

FIG. 4. Partial level scheme for ^{197}Au as obtained in the current work. Half-lives are shown for some states. Tentative level energies (in parentheses) indicate the possibility of an unobserved low-energy transition feeding the 2532-keV state. The widths of the arrows below the isomeric levels (thick lines) are proportional to the intensities. Level information for the known levels (up to 1836 keV) is taken from Refs. [2,4]. The 150-ns half-life may belong to the 2532-keV level or to another, higher-lying state (not shown) de-exciting by a low-energy, unobserved transition.

TABLE I. Configurations for isomeric states in odd-A gold isotopes observed in the current work.

Nuclide	I^π [$\hbar$]	$E_{\rm level}$ [keV]	Suggested/measured configuration	Ref.
^{189}Au	$\frac{31}{2}^+$	2555	$\{\pi h_{\frac{11}{2}} \otimes [\nu i_{\frac{13}{2}} \otimes \nu f_{\frac{7}{2}}]_{10^-}\}^{\rm a}$	[1]
^{191}Au	$\frac{31}{2}^+$	2490	$\{\pi h_{\frac{11}{2}} \otimes [\nu i_{\frac{13}{2}} \otimes \nu h_{\frac{9}{2}}]_{10^-}\}^{\rm a}$	[1]
^{193}Au	$\frac{31}{2}^+$	2487	$\{\pi h_{\frac{11}{2}} \otimes [\nu i_{\frac{13}{2}} \otimes \nu h_{\frac{9}{2}}]_{10^-}\}^{\rm b}$	[13]
	$\frac{31}{2}^+$	2487	$\{\pi h_{\frac{11}{2}} \otimes [\nu i_{\frac{13}{2}} \otimes \nu f_{\frac{7}{2}}]_{10^-}\}^{\rm b}$	[13]
^{197}Au	$(\frac{27}{2}^+)$	2532[c]	$\{\pi h_{\frac{11}{2}} \otimes [\nu i_{\frac{13}{2}} \otimes \nu p_{\frac{3}{2}}]_{8^-}\}^{\rm b}$	—
	$(\frac{27}{2}^+)$	2532[c]	$\{\pi h_{\frac{11}{2}} \otimes [\nu i_{\frac{13}{2}} \otimes \nu f_{\frac{5}{2}}]_{8^-}\}^{\rm b}$	—
	$(\frac{31}{2}^+)$	2532 + x[c,d]	$\{\pi h_{\frac{11}{2}} \otimes [\nu i_{\frac{13}{2}} \otimes \nu f_{\frac{9}{2}}]_{10^-}\}^{\rm b}$	—
	$(\frac{33}{2}^+)$	2532 + x[c,d]	$\{\pi h_{\frac{11}{2}} \otimes [\nu i_{\frac{13}{2}} \otimes \nu h_{\frac{9}{2}}]_{11^-}\}^{\rm b}$	—

[a] Measured.
[b] A suggested assignment based on the available orbitals.
[c] Present work.
[d] Implies an unobserved, low-energy transition, denoted by "x." See text for details.

TABLE II. Systematics of $E3$, $I^\pi = \frac{21}{2}^+ \rightarrow \frac{15}{2}^-$ decays in odd-A gold isotopes. The quantities given are level energies for the $I^\pi = \frac{21}{2}^+$ states, E_{level}; $E3$ γ-ray energies, E_γ; $E3$ relative branching ratios, $I_\gamma/I_{\mathrm{level}}$; level half-lives, $t_{1/2}^{\mathrm{level}}$; partial γ-ray half-lives, $t_{1/2}^{\gamma}$; and Weisskopf hindrance factors, F_W.

Nuclide	E_{level} (keV)	E_γ (keV)	$I_\gamma/I_{\mathrm{level}}$	$t_{1/2}^{\mathrm{level}}$ (ns)	$t_{1/2}^{\gamma}$ (ns)	F_W
^{189}Au	2062	(1380)[a]	<0.1[b]	—	—	—
^{191}Au	1991	1304[b]	≈0.1[b]	<0.3[c]	<3	<0.04
^{193}Au	1947	1249	0.21	10[d]	48	0.43
^{195}Au	1813	(1107)[a]	<0.15[b]	8[e]	<53	<0.2
^{197}Au	1836	1069	0.02	<10[b]	<500	<1.6

[a]Not yet identified.
[b]Current work.
[c]Reference [2].
[d]Reference [11].
[e]Reference [12].

reported isomers in the odd-A gold isotopes from $A = 195$ to 189 [1,2,11,12] were all observed in the current work. For ^{191}Au a 1304-keV, ($E3$) transition was newly identified here with a branching ratio of approximately 10%. Furthermore, while the corresponding 1380-keV transition in ^{189}Au was not observed, it was possible to obtain an upper limit on the relative intensity of <10% in the current work. The 10-ns upper limit for the half-life of the $I^\pi = \frac{21}{2}$ state in ^{197}Au is consistent with the corresponding lifetimes in the lighter odd-A isotopes.

The bandheads of the decoupled $\pi h_{11/2}^{-1}$ prolate structures form isomeric states in the odd-A isotopes because of the large difference in spin compared to the $\pi d_{3/2}$ ground states. The series of $I^\pi = \frac{21}{2}^+$ states are explained as couplings between the $[\nu i_{13/2} \otimes \nu p_{3/2}]_{5^-}$ configurations and the $h_{11/2}$ proton hole [12].

In addition to ^{197}Au, there is evidence of a previously unreported 481.5-keV transition in ^{195}Au in the out-of-beam γ-γ matrix. This transition feeds the known $I^\pi = (\frac{21}{2}^+)$, 8-ns, 1813-keV level [12]. A half-life, other than that in agreement with the 8-ns intermediate lifetime, could not be obtained in the current work and the 482-keV transition itself is too heavily contaminated to allow a direct measurement, free from the 8-ns feeding.

In summary, the de-excitation of an isomer in ^{197}Au was newly observed and a half-life of 150(5) ns measured following deep-inelastic reactions between an 850-MeV ^{136}Xe beam and a ^{198}Pt target. Prompt, higher lying transitions have also been identified. The assignment of this isomer to ^{197}Au was possible due to the availability of recent results from $(n, n'\gamma)$ work. In addition, a new out-of-beam transition is reported in ^{195}Au.

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