Observation of a new isomer in ^{185}Au*

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Abstract: Delayed γ-ray spectroscopy of ^{185}Au was studied at the Argonne Gas-Filled Analyzer. A new isomer at an excitation energy of 1504.2(4) keV with a half-life of 630(80) ns was identified via γ-γ coincidence analysis, decaying via a 294.8(3) keV transition. Based on Weisskopf estimates, the multipolarity of the 295 keV transition is assigned to be $E1$, $M1$, $E2$, or $M2$. Possible configurations for this new isomer are discussed based on configuration-constrained potential energy surface calculations.

Keywords: isomer, shape deformation, PES calculation, three-quasiparticle state, mid-shell

DOI: 10.1088/1674-1137/add70c **CSTR:** 32044.14.ChinesePhysicsC.49084004

I. INTRODUCTION

In the lead region ($Z = 82$) near the neutron mid-shell ($N = 104$), the shape coexistence of spherical, oblate, and prolate shapes is well established. A striking example of shape coexistence is ^{186}Pb, where a triplet of low-lying 0^+ states has been found [1, 2]. In odd-A ^{187}Pb, three bands with different shapes have also been reported [3, 4]. In addition, different shapes have been observed in ^{188,189}Po and ^{185,188,189,190}Pb [5−10].

Another interesting phenomenon in this region is the presence of high-K isomers. They are present in well-de-

Received 14 March 2025; Accepted 9 May 2025; Published online 10 May 2025

* Supported by the National Natural Science Foundation of China (12405140, 12135004, 11961141004, U2032138, 12275369) and the Natural Science Foundation of Gansu Province, China (24JRRA033). UK personnel are grateful for financial support from the STFC and A.N. Andreyev is funded by the Chinese Academy of Sciences President's International Fellowship Initiative (2020VMA0017). Supported by the U.S. Department of Energy, Office of Nuclear Physics, (DE-AC02-06CH11357, DE-FG02-94ER41041 (UNC), DE-FG02-97ER41033 (TUNL)). This work was also supported by the Slovak Research and Development Agency (APVV-22-0282) and Slovak Grant Agency VEGA (1/0019/25). This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility

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formed nuclei and even in transitional nuclei with mass near 190 [11, 12]. High-K isomers arise from the breaking of one or more nucleon pairs to form multi-quasiparticle (multi-qp) configurations. The K-hindrance and other properties of these states depend strongly on the proton and neutron states involved [13]. In ^{178}Hf, besides the remarkable 31-year K^{π} = 16^{+} four-quasineutron isomer [14], a two-quasineutron K^{π} = 8^{-} isomer arises from the coupling between nucleons in high-j orbitals ($\nu 9/2^{+}[624] \otimes \nu 7/2^{-}[514]$). Similar two-quasineutron isomers have been observed systematically in even-mass N = 106 isotones from ^{174}Er to ^{188}Pb [11, 15].

Furthermore, in the N = 106 odd-mass isotones from ^{175}Tm to ^{187}Tl (except the ^{183}Ir) [16−21], 3-qp high-K isomers, originating from the coupling between the odd proton and abovementioned K^{π} = 8^{-} isomer in even-mass cores, have been identified.

The N = 106 nucleus, ^{185}Au, was previously studied in decay and in-beam γ-ray spectroscopy [22, 23]. A ground-state quadrupole deformation of β_2 = 0.24 was determined in a laser spectroscopy experiment [24].

In this paper, we report on the discovery of a new isomeric state in ^{185}Au at an excitation energy of 1504.2(4) keV, with a half-life of $T_{1/2}$ = 630(80) ns, decaying to the (17/2^{-}) level previously assigned to the $\pi 1h_{11/2}$ band [22]. The possible spin-parities of this isomer are tentatively assigned based on Weisskopf estimates. The possible configuration of this isomer is discussed within the framework of configuration-constrained potential energy surface (cc-PES) calculations [25].

II. EXPERIMENT

The experiment was conducted at Argonne National Laboratory (ANL), and this study extends prior results reported in earlier experiments from the same experimental program, which included ^{187}Pb, ^{188}Bi, ^{188}Po, ^{183}Hg, and ^{187}Tl [3, 6, 21, 26]. In the present study, the ^{185}Au nucleus was produced in the ^{50}Cr + ^{142}Nd → ^{192}Po* → ^{185}Au + 3$p\alpha$ fusion-evaporation reaction. The ^{50}Cr ions were accelerated to an energy of 255 MeV with a typical intensity of 7 pnA by the superconducting linear accelerator at ANL. The target material, enriched to 99.8% in ^{142}NdF$_3$, had a thickness of 700 μg/cm^2. To minimize target heating, four target sectors were mounted on a rotating wheel, and the beam was wobbled horizontally by ±2.5 mm across the target using a magnetic steerer.

Evaporation residues (EVRs) were separated from the primary beam by the Argonne Gas-Filled Analyzer (AGFA) [27], which was filled with 0.65 mbar of helium gas. The flight time of EVRs in the AGFA separator was estimated to be several hundred nanoseconds (approximately 500 ns flight time for v = 0.02c EVRs). The energy loss and arrival time of the EVRs were measured by a parallel grid avalanche counter (PGAC). The EVRs were then implanted into a double-sided silicon strip detector (DSSD) located at the focal plane, which recorded the deposition energy of the recoil and subsequent charged particle decay.

The present study was conducted with the delayed γ correlation method, using the DSSD and X-array detector in the focal plane. The X-array detector setup consisted of four Clover HPGe detectors and was used to detect X rays and γ rays emitted from the EVRs [28]. The typical energy resolution for the X-array was approximately 4 keV (FWHM) for γ rays of approximately 300 keV.

III. EXPERIMENTAL RESULTS

The delayed γ-ray spectrum recorded by the X-array detectors within 2 μs after implantation in the DSSD, with the background in the time window of 2−4 μs subtracted, is shown in Fig. 1. Most of the prominent γ-ray peaks are from known isomers produced in other reaction channels, including the strong γ ray from microsecond isomers in ^{187}Tl and ^{187,188}Pb.

The 212-, 462-, and 527-keV γ rays shown in Fig. 1 were initially reported in the in-beam experiment by Larabee *et al.* [22] as a prompt 527-462-212 keV transition cascade. Considering that the transport time through AGFA is more than hundreds of nanoseconds, these transitions are considerably delayed, indicating the existence of an isomer de-exciting via this prompt cascade.

A previously unobserved 294.8(3)-keV transition was identified in the γ-gated spectra of 527-, 462-, and 212-keV γ transitions, as shown in Fig. 2(a)−(c). The spectrum gated on the 295-keV transition and summed spec-

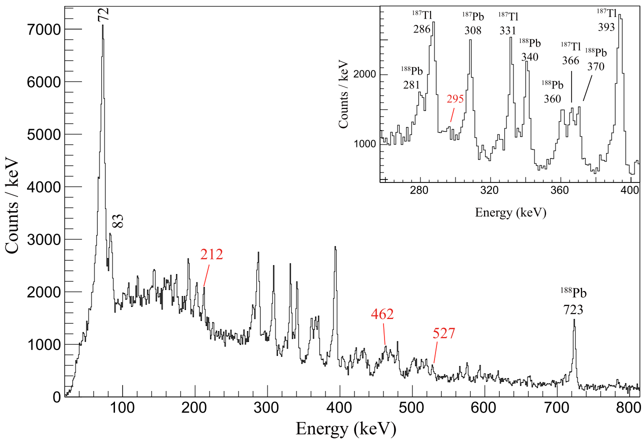

Fig. 1. (color online) Main panel: γ-ray energy spectrum recorded by the X-array within a 2 μs window after EVR implantation in the DSSD. A background spectrum taken from the 2−4 μs after EVR implantation is subtracted. The three γ-rays highlighted in red were experimentally established as a cascade in ^{185}Au [22]. Inset: Expanded view of prominent γ-ray peaks from 260 to 400 keV.

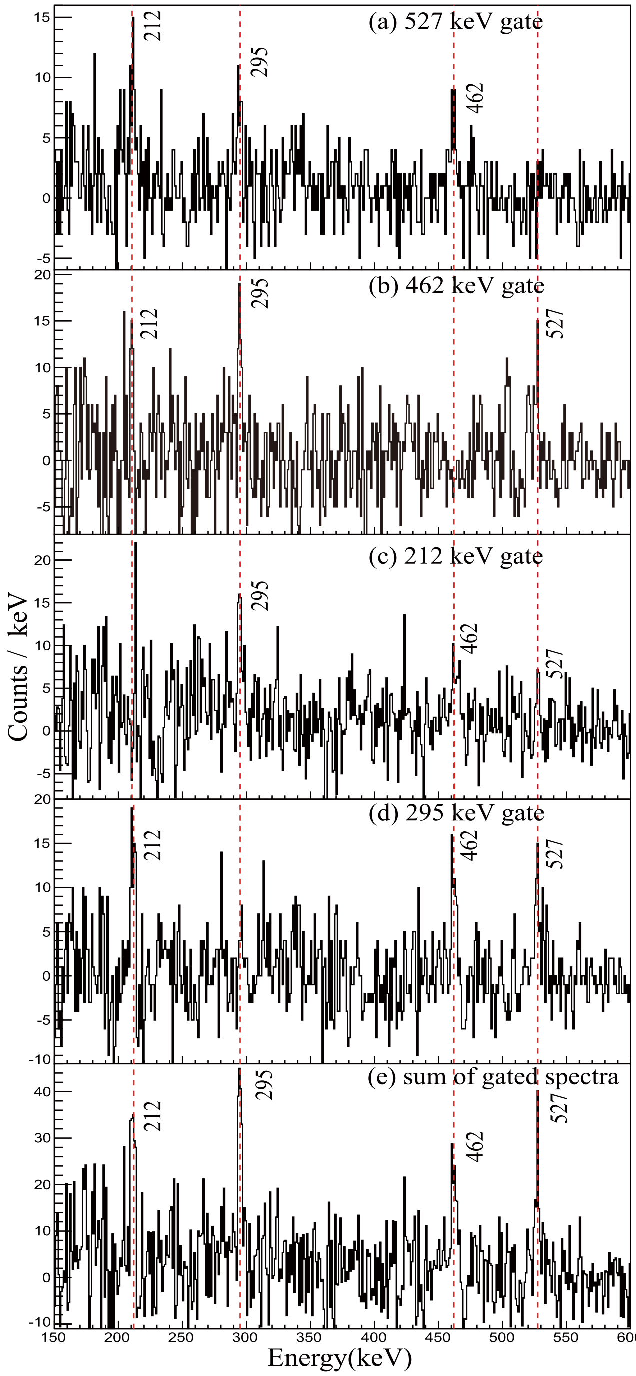

Fig. 2. (color online) γ-ray energy spectrum gated on the 527-, 462-, 212-, and 295-keV transitions (a)−(d) and the sum of these spectra (e).

trum gated on the four transitions are shown in Fig. 2(d) and (e), respectively. This 295-keV γ ray is attributed to the deexcitation of the new isomer in ^{185}Au.

The time distribution of ΔT(EVR-γ (212 keV and 527 keV)) is shown in Fig. 3. Based on a least-squares fit of this time distribution, with an exponential function plus a constant background, the half-life of the isomer was determined to be 630(80) ns.

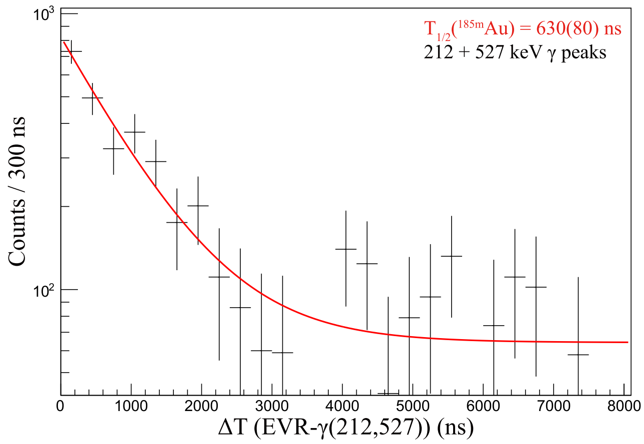

Fig. 3. (color online) Time distribution of the summed 212 and 527 keV γ rays after EVR implantation, with a background subtraction made by gating on nearby Compton background. The data are fitted with an exponential function with a constant background.

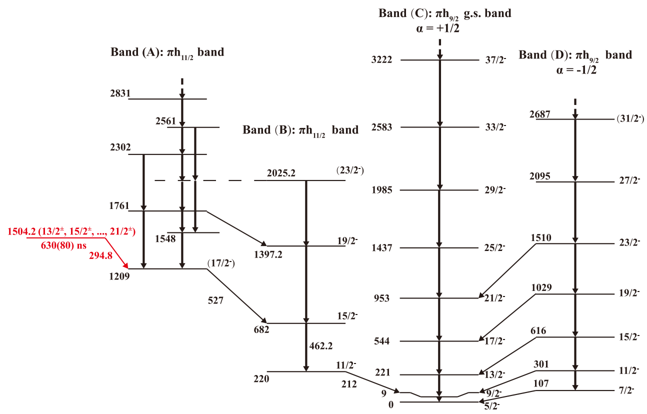

Fig. 4. (color online) Partial level scheme of ^{185}Au: spin and parity are taken from Refs. [22, 23]. For the new isomer, possible spin-parities are given based on Weisskopf estimates, and states are labeled with their energies in keV.

Figure 4 illustrates the proposed decay scheme of the isomer along with a partial level scheme of ^{185}Au, and it shows that the new 1504.2(4)-keV isomer decays to the 1209.4(3)-keV ($17/2^-$) level. The spin and parity assignments for established levels were adopted from previous studies [22, 23], while the corresponding energy values were derived from the latest ENDF Library evaluations of ^{185}Au [29].

No decay to other low-lying levels from this isomer was observed after a thorough analysis of the singles and coincidence spectra. We attempted to perform an intensity balance analysis of the 295-527-462-212 keV γ-ray cascade in the recoil-delayed γ-ray spectrum Fig. 1. However, as shown in the inset of Fig. 1, there is only a slight indication of a peak at 295 keV; hence, no definitive conclusions can be drawn on its multipolarity.

IV. DISCUSSION AND CALCULATIONS

The Weisskopf single-particle transition probabilities for possible multipolarities ($E1$, $M1$, $E2$, $M2$, and $E3$) of the 295-keV γ-ray, corrected for internal conversion, are presented in Table 1. The $E3$ and higher multipolarities can be excluded based on the recommended upper limits [32]. The possible multipolarities constrain the spin of the 1504 keV isomer, decaying to ($17/2^-$), to a range from 13/2 to 21/2. The Weisskopf hindrance factors (Fw, which is the reciprocal of transition probability) of the $E1$, $M1$, and $E2$ multipolarities are large, indicating significant hindrance.

To assign the possible configuration to this new isomer in ^{185}Au, we performed cc-PES calculations [25] based on the non-axial deformed Woods-Saxon (WS) potential [33] with universal parameters [34]. The total energy is composed of a macroscopic part with the standard liquid-drop energy [35]. To avoid possible pairing collapse in multi-qp states, the approximate particle-number conservation uses the Lipkin-Nogami (LN) method [36]. For a multi-qp state, the microscopic energy incorporates the contribution from the unpaired particles that occupy the single-particle orbits associated with the given configuration. The blocking effects from the unpaired nucleons are considered by removing the singly occupied orbitals from the LN calculation. The cc-PES calculations were performed in the lattice of deformation space (β_2,β_4,γ). The resultant PESs can self-consistently provide information on the deformation, excitation energy, and pairing interaction properties of multi-qp states. The calculations successfully reproduced the experimental results for the 3-qp configurations in N = 106 odd-A isotones, with excitation energy deviations ranging between 1 and 174 keV (^{181}Re $21/2^-$ isomeric state [19] and ^{175}Tm $23/2^+$ isomeric state [16]). Details of the calculations will be presented in a forthcoming paper [37].

In previous experimental studies, the ground-state band (C) was proposed to originate from the strongly mixed $\pi 3/2^-[532]$ and $\pi 1/2^-[541]$ configuration [38, 39], while Band (B) was assigned to an $h_{11/2}$ single-quasiproton configuration [22]. PES calculations for all possible low-lying proton configurations near the Fermi surface were also performed, and the results for the $3/2^-[532]$ and $1/2^-[550]$ configurations are shown in Fig. 5. The results for the $3/2^-[532]$ configuration reproduce the $\beta_2 = 0.24$ ground-state deformation from the laser spectroscopy measurements [40]. Band (B) corresponds to the $1/2^-[550]$ orbital, as shown in Fig. 5 (right). Notably, the PES calculations show remarkable triaxial deformations for the two low-lying configurations, similar to those observed in calculations for neighboring ^{183,187}Au [41, 42].

The calculated excitation energies and deformations for possible 3-qp configurations in ^{185m}Au are presented in Table 2. These high-K states are all predicted to lie close to the measured excitation energy of 1504 keV. However, it should be mentioned that the residual interactions between unpaired nucleons are not accounted for in the present calculations. These residual interactions can lead to energy shifts of up to a few hundred keV, depending on the relative orientation of intrinsic spins of the nucleons involved [43−45]. Therefore, in the context of the excitation energy and decay patterns, we are unable to make a firm assignment for the configuration of the observed isomer from the calculated 3-qp configurations. The calculated results incorporating the neutron configuration $\nu 9/2^+[624] \otimes \nu 7/2^-[514]$ are consistent with systematics of 3-qp configurations in odd-mass nuclei with $N =$ 106. However, further experimental data are required to unambiguously assign the spin-parity and configuration of the 1504 keV isomer.

Table 1. Weisskopf estimates of single-particle transition probabilities for different multipolarities of the 295-keV γ ray.

Multipolarity assumed	Weisskopf half-life estimates (s)	Transition probability (W.u)
$E1$	$8.13(3)\times10^{-15}$	$1.3(2)\times10^{-4}$ [a]
$M1$	$8.59(3)\times10^{-13}$	$1.4(2)\times10^{-6}$
$E2$	$4.06(2)\times10^{-9}$	$6.5(8)\times10^{-3}$
$M2$	$4.29(2)\times10^{-7}$	$6.9(9)\times10^{-1}$
$E3$	$3.08(2)\times10^{-3}$	$4.9(7)\times10^{3}$

[a] The transition probability of K-allowed $E1$ transitions is multiplied by 10^4, as suggested in Refs. [30, 31].

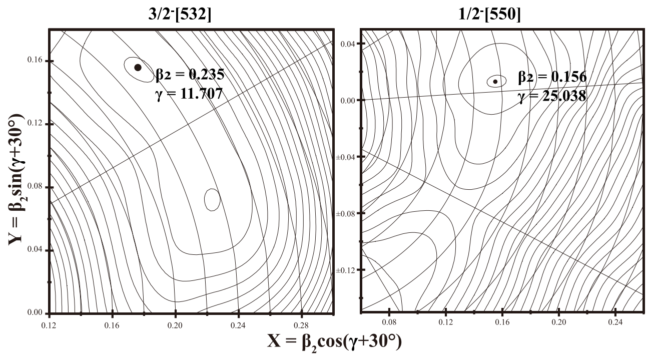

Fig. 5. PES of low-lying proton states in ^{185}Au: (left) $h_{9/2}$ ground-state band and (right) $h_{11/2}$ band. In calculations using cc-PES calculations, the minima are indicated by black circles and labeled with their deformation parameters.

V. SUMMARY

A new isomer at 1504 keV in ^{185}Au was identified through its deexcitation to a previously known level, by a 295-keV transition coinciding with the known 212-462-527 keV cascade. Possible multipolarities of $E1$, $M1$, $E2$, and $M2$ have been proposed for this transition in comparison with predictions from Weisskopf estimates. By us-

Table 2. Possible 3-qp configurations for the isomeric states in ^{185}Au. Excitation energies and deformation parameters were calculated using cc-PES calculations.

K^π	Configuration	Energy/keV	β_2	β_4	γ
$17/2^-$	$\pi1/2^-[541]\otimes\nu9/2^-[505]\otimes\nu7/2^-[503]$	1041	0.153	-0.010	22.907
$21/2^+$	$\pi11/2^-[505]\otimes\nu9/2^-[624]\otimes\nu1/2^-[521]$	1289	0.168	-0.041	-25.477
$17/2^+$	$\pi1/2^-[541]\otimes\nu9/2^+[624]\otimes\nu7/2^-[514]$	1444	0.230	-0.033	1.036
$19/2^+$	$\pi3/2^-[532]\otimes\nu9/2^+[624]\otimes\nu7/2^-[514]$	1458	0.246	-0.031	1.144
$17/2^+$	$\pi1/2^-[541]\otimes\nu9/2^+[624]\otimes\nu7/2^-[503]$	1582	0.165	-0.037	25.680
$17/2^+$	$\pi1/2^-[541]\otimes\nu9/2^-[505]\otimes\nu7/2^+[633]$	1632	0.159	-0.024	24.605
$17/2^+$	$\pi1/2^-[530]\otimes\nu9/2^+[624]\otimes\nu7/2^-[514]$	1633	0.252	-0.030	0.210
$13/2^+$	$\pi3/2^-[532]\otimes\nu9/2^+[624]\otimes\nu1/2^-[521]$	1652	0.223	-0.038	20.593
$15/2^+$	$\pi1/2^-[541]\otimes\nu7/2^+[633]\otimes\nu7/2^-[503]$	1667	0.169	-0.032	25.437
$19/2^-$	$\pi3/2^-[532]\otimes\nu9/2^+[624]\otimes\nu7/2^+[633]$	1733	0.227	-0.037	-14.634
$21/2^-$	$\pi5/2^+[402]\otimes\nu9/2^+[624]\otimes\nu7/2^-[514]$	1757	0.266	-0.028	0.299
$17/2^-$	$\pi1/2^-[550]\otimes\nu9/2^+[624]\otimes\nu7/2^+[633]$	1778	0.153	-0.026	-26.763
$19/2^+$	$\pi3/2^-[532]\otimes\nu9/2^+[624]\otimes\nu7/2^-[503]$	1875	0.200	-0.044	-26.624
$15/2^-$	$\pi1/2^-[541]\otimes\nu7/2^-[503]\otimes\nu7/2^-[514]$	1969	0.214	-0.031	21.749

ing the cc-PES calculations, which describe the systematics of known three-quasiparticle isomers in odd-mass $N = 106$ isotones well [37], possible spin-parity and configuration candidates for the new isomer at 1504 keV in ^{185}Au were provided.

ACKNOWLEDGMENTS

We thank the Target Labor team of GSI for preparing the targets for the experiment.

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