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Sudden change of intruder state decay pattern between ^{179}Au and ^{177}Au: population of low-spin positive-parity band from high-spin intruder states in ^{177}Au.

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Abstract

The extremely neutron-deficient isotopes ^{177,179}Au were studied by means of in-beam γ ray spectroscopy at the University of Jyväskylä. Specific tagging techniques, α-decay tagging in ^{177}Au and isomer tagging in ^{179}Au, were used for these studies. These were critical for elucidating subtle features of the low-energy details of the respective decay schemes, specifically a sudden change of intruder state decay pattern from a low-spin intruder isomer in ^{179}Au to a non-intruder ground-state band in ^{177}Au.

Keywords: in-beam spectroscopy, γ rays, ^{177}Au, ^{179}Au, two-state mixing

In this Letter we present results on in-beam γ-ray studies of ^{177,179}Au, with application of various tagging techniques [1, 2]. Previously, both isotopes were studied by means of in-beam γ-ray spectroscopy using the Gammasphere spectrometer coupled to the Fragment Mass Analyser (FMA) at Argonne National Laboratory. In ^{179}Au [3], four rotational bands associated with $1h_{9/2}$, $2f_{7/2}$, and $1i_{13/2}$ proton-intruder configurations were observed. Transitions connecting observed structures to the ground state were not observed. In ^{177}Au, only the yrast $1i_{13/2}$ band together with its decay pattern, was reported in the original publication [4]. Later, a data evaluation was published [5], which contained also a rotational band based on the $9/2^-$ state, probably associated with the $1h_{9/2}$ proton-intruder configuration. However, no relevant spectra documenting this band were ever reported in any refereed journal.

The Au isotopes play a unique role in our understanding of shape coexistence in that strongly deformed structures intrude to become the ground states at mid shell (^{183}Au) and to exhibit a classic "parabolic" trend in excitation energy. The isotopes ^{177,179}Au play a key role in that they establish the "left-hand side" of the intruder parabola. As we show in the present studies, a clear picture now emerges regarding which states are intruder structures. Further, there is the subtle feature of changing spins of intruder band heads, namely that

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decoupling effects result in changing spin order in each intruder band. This is established as occurring in a systematic manner in the positive-parity ("$1i_{13/2}$") band for the first time.

A major step in understanding the structure of ^{179}Au, and of odd-Au isotopes in general, was the discovery of a 326 ns isomer, with spin-parity $3/2^-$ [6]. This required a combined analysis of data acquired at the University of Jyväskylä and at the CERN-ISOLDE facility, with application of various techniques such as high-statistics γ-ray spectroscopy, α-decay spectroscopy, α-electron summing effects, including GEANT4 simulations of atomic relaxation processes, and mass measurements. The 326 ns isomer deexcites by either a strong 62.4-27.1 keV cascade or via a weak 89.5 keV cross-over transition to the ground state. The decay pattern suggested a positive-parity, proton-hole configuration to be the ground state. The in-source laser spectroscopy experiment, performed recently at ISOLDE has assigned ground state spin-parities for both ^{177,179}Au unambiguously as $1/2^+$ [7]. This confirms the previous conclusion. Measured magnetic moments suggest mixed $3s_{1/2} \oplus 2d_{3/2}$ proton-hole configurations for these ground states, which is in agreement with findings reported in [6]. The band head of structures reported in [3] was proposed to deexcite to the 326 ns isomer. Connecting transitions were not observed, due to their low energy and thus strong conversion. However, the data provided indirect evidence for them, see a detailed discussion in [6].

The data presented here prove that intruder configurations in ^{179}Au, identified in the study [3], decay exclusively via the 326 ns isomer. A new level scheme for ^{177}Au is constructed, which significantly differs from that reported in the study [4]. A major difference between the decay of the $1i_{13/2}$ band in ^{177}Au, and ^{179}Au is observed. The head of this band feeds also positive-parity structures, which is unprecedented in odd-Au isotopes. The ^{177}Au isotope is a unique case, with mixing of coexisting strongly and weakly deformed configurations, caused by their proximity. This mixing opens the decay path, which is otherwise suppressed.

Two separate experiments were performed at the Accelerator Laboratory of the University of Jyv̈askylä. First, the ^{177}Au nuclei were produced via the ^{92}Mo(^{88}Sr,$p2n$)^{177}Au fusion-evaporation reaction. The bombarding energy of the ^{88}Sr^{10+} beam was 399 MeV with an average intensity of approximately 2 particle nA. For production of ^{179}Au, the ^{82}Kr(^{100}Ru,$p2n$)^{179}Au nuclear reaction was used. The energy of the ^{82}Kr^{15+} beam was 352 MeV with an average intensity of approximately 5 particle nA. In both experiments, self-supporting metallic targets of isotopically enriched materials were used. Heavy-ion beams were delivered to the target chamber by the K = 130 MeV cyclotron.

Prompt γ radiation following reactions in the target was detected by the JUROGAM-II array, which consists of 24 clover- and 15 EUROGAM-type Compton-suppressed germanium detectors. Products of reactions were separated from the primary beam by the RITU gas-filled separator [8] according to their magnetic rigidities. At the focal plane of the separator, nuclei were implanted into double-sided silicon strip detectors (DSSD) of the detection system GREAT [9]. Prior to the implantation, nuclei passed through the multiwired proportional counter (MWPC), which provides discrimination of recoiling evaporation residues from the scattered primary beam particles (using energy losses in the gas and time-of-flight measured between the MWPC and the DSSD) and radioactive decays. The data were analysed using GRAIN [10] and RADWARE [11] software. Isomeric transitions were detected at the focal plane of the separator with a planar double-sided germanium strip detector and three clover-germanium detectors.

Partial level schemes of both ^{177,179}Au, constructed in the present work are presented in Fig. 1 and are discussed in detail and explained in the following text.

The relatively long half life of ^{179}Au ($t_{1/2} = 7.1(3)$ s [12]) and high implantation rate into the DSSD prevented from the use of the recoil-decay tagging technique for this isotope, since randomly correlated events dominated the real events. Fortunately, the high production rate of the 326 ns isomer [6], which decays via low-energy, electric-dipole ($E1$) transitions that can be detected with high efficiency, offers an excellent option for application of the recoil-isomer tagging technique. In the data analysis process, the recoil implantations that were followed by detection of the above mentioned isomeric γ rays within the time window up to 1 μs, were selected. Prompt γ rays, observed in the target position array, that preceded such implantations, were sorted into a γ-γ matrix. Fig. 2a gives a projection of the matrix with the gate on the 353.8 keV transition, which is a known deexcitation of the $25/2^+$ member of the yrast $1i_{13/2}$ band [3]. Except

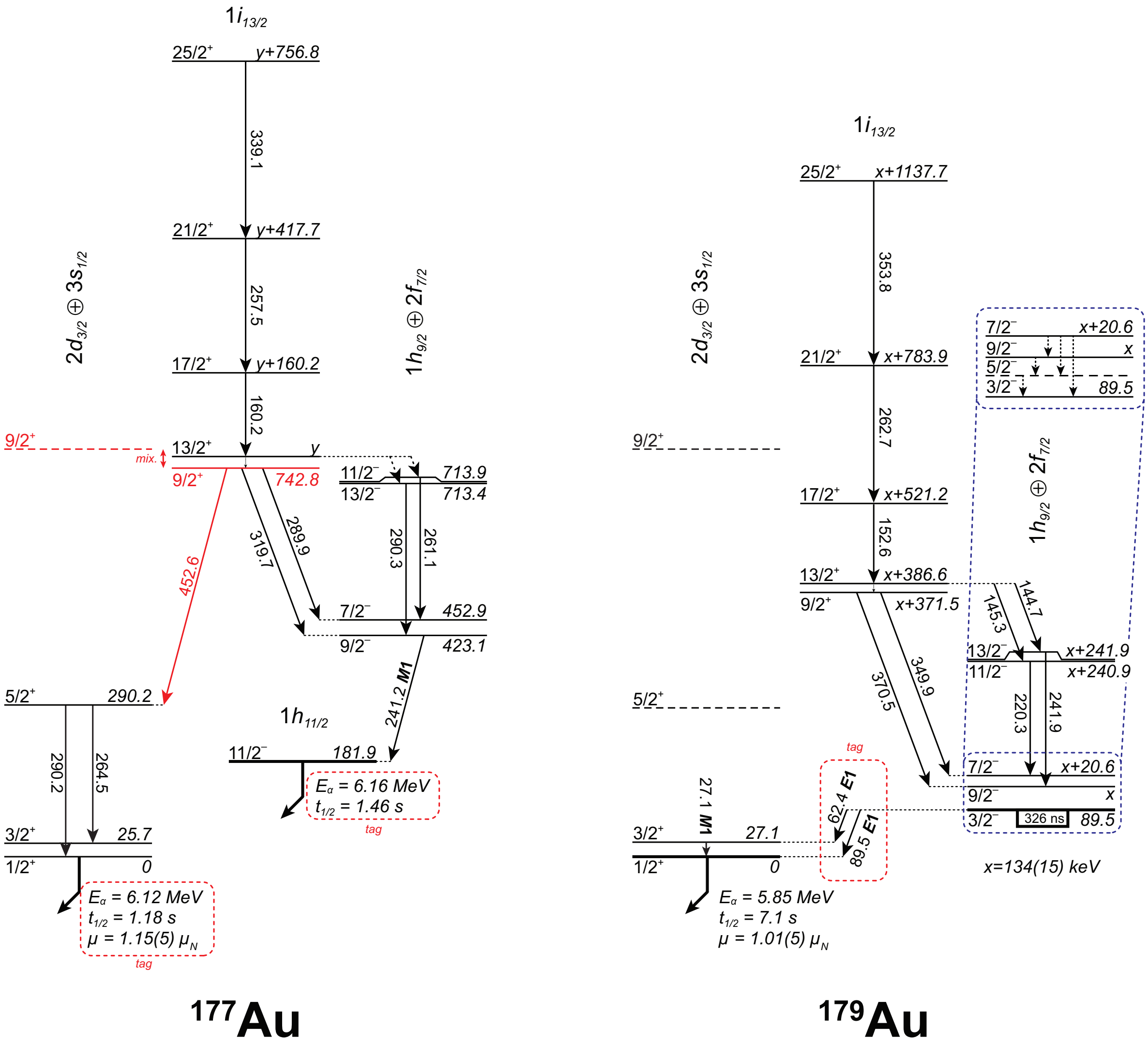

Figure 1: Partial level schemes of the ^{177,179}Au isotopes deduced in the present work. Note that transitions between $3/2^+$ and $1/2^+$ states, and between $7/2^-$ and $9/2^-$ states were not observed due to large internally converted decay and low detection efficiency. Rotational bands associated with $1i_{13/2}$ proton-intruder configuration are known up to spin $57/2\hbar$ in ^{177}Au, and $53/2\hbar$ in ^{179}Au. So-far unobserved positive-parity states that are expected according to known systematics of odd-Au isotopes, associated with $3s_{1/2} \oplus 2d_{3/2}$ proton-hole configuration (ground state), are indicated with dashed lines. The blue insert gives possible decays of $9/2^-$, $7/2^-$ and $5/2^-$ states of the $1h_{9/2}$ and $2f_{7/2}$ proton-intruder configurations in ^{179}Au. These transitions are not known, however there is indirect evidence for them from the present data and from the α decay of ^{183}Tl [6].

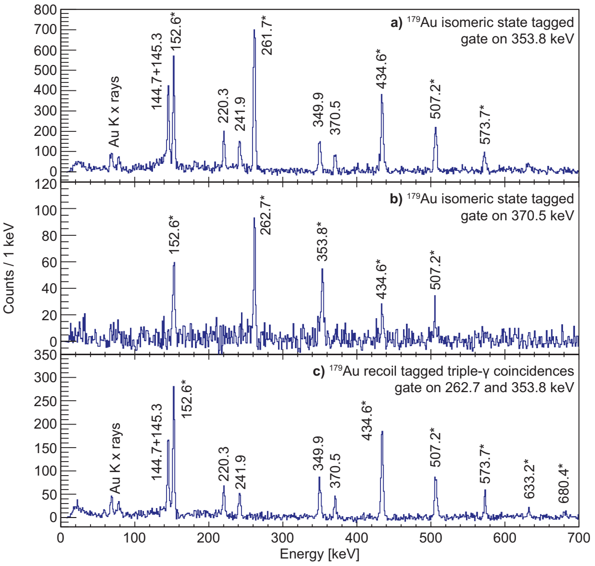

Figure 2: Spectra of γ rays of ^{179}Au **a)** tagged with decay of the 326 ns isomer and in prompt coincidence with the 353.8 keV transition, **b)** tagged with decay of the 326 ns isomer and in prompt coincidence with the 370.5 keV transition, and **c)** in prompt coincidence with the 353.8 keV (without tagging). Transitions of the yrast $1i_{13/2}$ band are denoted with an asterisk.

for other known in-band transitions of the yrast band, the unresolved 144.7-145.3 keV doublet together with the 220.3, 241.9, 349.9, and 370.5 keV transitions are evident. Energies of components of the doublet were determined using the "running" gate technique [13]. In the analysis of the γ-γ matrix, a single channel gate is run through the peak of interest to generate coincidence spectra. The area of the response lines of interest is plotted as a function of the γ-ray energy of the gates, which allows determination of the energies of the doublet components. The 220.3 and 241.9 keV transitions are known deexcitations of the $11/2^-$ and $13/2^-$ members of the $2f_{7/2}$ and $1h_{9/2}$ proton-intruder configurations. The 144.7, and 145.3 keV transitions, as correctly assigned in the previous in-beam study [3], are deexcitations of the $13/2^+$ state of the yrast band feeding nearly degenerate $11/2^-$ and $13/2^-$ states, see the level scheme in Fig. 1. In the study [3], the 349.9 and 370.5 keV transitions were assigned as deexcitations of $13/2^+$ and $9/2^+$ members of the $1i_{13/2}$ proton-intruder configuration feeding a floating state without spin assignment. Although the authors of the study [3] discuss in the text the option that these γ rays arise from a single initial state.

Since the 349.9 and 370.5 keV transitions are observed in the spectrum tagged with the decay of the 326 ns isomer, they feed states associated with intruder structures above the isomer. In the previous study, no γ ray detectors were employed at the focal plane of the FMA and thus this conclusion could not be made. The energy difference of the 349.9 and 370.5 keV transitions exactly matches the energy difference of known $9/2^-$, and $7/2^-$ band heads of $1h_{9/2}$, and $2f_{7/2}$ intruder configurations. This suggests that both transitions have a common initial state and feed these band heads, see the level scheme in Fig. 1.

Fig. 2b depicts a projection of the γ-γ matrix tagged with the decay of the 326 ns isomer, with the gate on the 370.5 keV transition. The spectrum shows only known in-band transitions of the $1i_{13/2}$ yrast band. Therefore, the initial state of the 370.5 keV transition is a member of this configuration. An alternative assignment with, e.g., $1h_{9/2}$, or the $2f_{7/2}$ intruders, would require an observation of corresponding rotational bands in coincidence with the 370.5 keV transition. This is not observed in the data and therefore the initial state is interpreted as the $9/2^+$ member of the $1i_{13/2}$ proton-intruder configuration. The $9/2^+$ state is produced by the anti-aligned coupling of the $1i_{13/2}$ proton with the first-excited 2^+ state in the ^{178}Pt core. Several such anti-aligned states are known in odd-Au isotopes, see [13–15] and references therein, although all of them are associated with the $1h_{9/2}$, or the $2f_{7/2}$ intruder configuration. The 15.1 keV transition with presumably electric-quadrupole ($E2$) character, connecting the $13/2^+$ with the $9/2^+$ state was not observed due to strong internal conversion.

States associated with the $3s_{1/2} \oplus 2d_{3/2}$ proton-hole configuration were studied in heavier odd-Au isotopes and well developed systematics were established [14–16]. The first-excited state above the $1/2^+$ ground state is the $3/2^+$ state, which was observed in ^{179}Au at 27.1 keV [6]. According to known systematics, a spin-parity of the next excited state is $5/2^+$. This state, which is expected at approximately 270 keV in ^{179}Au, could be fed by the $E2$ deexcitation of the $9/2^+$ state of the $1i_{13/2}$ configuration. Such a decay branch would not proceed through the 326 ns isomeric state and therefore cannot be observed in the spectrum presented in Fig. 2a. To identify this decay path, prompt γ rays preceding all recoil implantations, i. e., without requiring the isomeric decay to be detected, were analysed. To suppress contaminations from isotopes produced via different evaporation channels of the reaction, the data were sorted into a triple-γ coincidence cube. This provides significantly reduced statistics, compared with double coincidences, but the influence of contaminations in a double gate is negligible and thus cleaner spectra can be projected. Fig. 2c gives a projection of the cube with gates on the 262.1, and 353.8 keV transitions. A signature of the direct decay path into the ground state would be observation of two parallel transitions that differ by 27.1 keV, and of the $E2$ deexcitation of the $9/2^+$ state. Parallel transitions would be decays of the $5/2^+$ to the $1/2^+$ ground state, and to the $3/2^+$ 27.1 keV first-excited state. No such transitions appear in the spectrum depicted in Fig. 2c. Therefore, the direct feeding of the $3s_{1/2} \oplus 2d_{3/2}$ proton-hole configuration from the $1i_{13/2}$ proton-intruder configuration is excluded.

The ^{177}Au isotope has two α-decaying isomers with well separated energies of emitted α particles ($E_\alpha = 6.12$ MeV and $t_{1/2} = 1.18$ s for the ground state and $E_\alpha = 6.16$ MeV and $t_{1/2} = 1.46$ s for the isomeric state [4]). In contrast to the ^{179}Au data, influence of randomly correlated events was found to be negligible. Therefore the recoil-decay tagging technique could be applied. The prompt γ-ray data were sorted into two separate γ-γ matrices, tagged with the two different α decays.

The α-decaying isomer is assigned as the $11/2^-$ state of the $1h_{11/2}$ proton-hole configuration. This assignment is supported by the recent observation of a pattern of transitions feeding this state [17] and comparison with well established systematics [13–15]. The excitation energy of 189(16) keV was determined by the α-γ decay spectroscopy of the ^{181}Tl isotope performed at the velocity filter SHIP at GSI Darmstadt [18]. The large experimental uncertainty arises from the uncertainties of the measured energies of α particles with a silicon detector at the focal plane of the separator. Note that the $1h_{11/2}$ proton-hole configuration is not involved in the decay of intruder configurations in ^{179}Au, because known systematics [14] suggests that the intruder band-head is located below the $1h_{11/2}$.

Fig. 3a gives the spectrum of γ rays tagged with the $11/2^-$ isomeric state α decay and in coincidence with the 257.5 keV transition of the known yrast band, which is associated with the $1i_{13/2}$ proton-intruder coinfiguration, see previous in-beam γ-ray study [4]. In addition to the yrast band transitions the 241.2, 289.9, and 319.7 keV transitions are observed. The 241.2 keV transition is the known magnetic-dipole ($M1$) deexcitation of the $9/2^-$ band head of the $1h_{9/2}$ intruder configuration to the $11/2^-$ of the $1h_{11/2}$ proton-hole configuration [18].

Fig. 3b gives a spectrum of γ rays tagged with the $11/2^-$ isomeric state α decay and in coincidence with the 319.7 keV transition, which shows only the 241.2 keV transition together with the yrast band members. Therefore, the initial state of the 319.7 keV transition is interpreted as the $9/2^+$ member of the $1i_{13/2}$ proton-intruder configuration, on the basis of the same arguments as were used for the 370.5 keV transition in ^{179}Au, see the above discussion.

In the data evaluation for ^{177}Au [5], the 290.3 keV transition was reported. It was interpreted as the first in-band transition of the $1h_{9/2}$ band. The observed coincidence between the 290.3 keV and transitions of the $1i_{13/2}$ band, which was reported already in the original publication [4], was explained by an unobserved $E1$ feeding from the $13/2^+$ state of the yrast band. Presently, the 289.9 keV transition is interpreted as a feeding of the $7/2^-$ band head of the so-far unknown $2f_{7/2}$ band from the $9/2^+$ state. This interpretation is based on the analogy with the decay pattern of the $9/2^+$ state in ^{179}Au, see the level scheme in Fig. 1. However, $E1$ decays of the $13/2^+$, analogous to 144.7, and 145.3 keV transitions in ^{179}Au, can exist. There is a weak peak at 261.2 keV observed in coincidence with the 257.5 keV transition, see Fig. 3a. The rotational band associated with the $2f_{7/2}$ configuration is not known, but according to known systematics of $1h_{9/2}$ and $2f_{7/2}$ bands [3, 19, 20], $11/2^-$ and $13/2^-$ members are expected to be nearly degenerate. Therefore, the 261.2 keV is interpreted as the $11/2^-$ to $7/2^-$ transition of the $2f_{7/2}$ band. The 289.9 keV peak is probably an unresolved doublet. In this case it is not possible to apply the "running" gate technique, since there are no characteristic coincidences for both transitions. However, this does not affect the understanding of the nuclear structure of ^{177}Au. The $E1$ transitions feeding the $11/2^-$ and the $13/2^-$ state were not observed because of their low energy and thus low detection efficiency of the Jurogam2 array.

Transition probabilities for possible decays of $13/2^+$ states of the yrast bands were investigated for both isotopes. In the present work, fast collective $E2$ decays into the $9/2^+$ band head are proposed, see the discussion above. The transition rate for the $E2$ multipolarity is given as

$$T(E2) = 1.225 \times 10^9 E_\gamma^5 (1+\alpha_T) B(E2), \qquad (1)$$

where the transition rate $T(E2)$ is in s^{-1}, E_γ is the γ-ray energy in MeV, $B(E2)$ is the reduced-transition probability in $e^2\mathrm{fm}^4$ units, and α_T is the dimensionless total internal conversion coefficient. Competing with these transitions are $E1$ decays feeding the $11/2^-$ and the $13/2^-$ states of the $1h_{9/2}$, and the $2f_{7/2}$ intruder structures. The transition rate for the $E1$ multipolarity is given as

$$T(E1) = 1.590 \times 10^{15} E_\gamma^3 (1+\alpha_T) B(E1), \qquad (2)$$

where the transition rate $T(E1)$ is in s^{-1}, E_γ is the γ-ray energy in MeV, $B(E1)$ is the reduced-transition probability in $e^2\mathrm{fm}^2$ units, and α_T is dimensionless total internal conversion coefficient. Reduced transition probabilities are directly related to matrix elements and therefore they carry important information on the nuclear structure. A useful scale of the $B(E1)$ and $B(E2)$ values is provided by Weisskopf single-particle units [21] (denoted as W.u. in the following text) calculated assuming a uniform charge density, which gives

$$B(E1)_W = 0.06446 A^{2/3}\, e^2\mathrm{fm}^2, \qquad (3)$$
$$B(E2)_W = 0.05940 A^{4/3}\, e^2\mathrm{fm}^4, \qquad (4)$$

where A is the mass number of the nucleus.

A reduced transition probability of 200 W.u. is assumed for the $13/2^+$ to $9/2^+$ transition. This assumption is based on the known reduced transition rate $B(E2) = 200(120)$ W.u. [22] for the $9/2^-$ to $5/2^-$ transition in ^{185}Au. The $B(E1) = 10^{-4}$ W.u. was obtained for both $E1$ transitions feeding the $11/2^-$, and $13/2^-$ states in ^{179}Au. This is a typical value for such transitions and thus corroborates the above interpretation.

Adopting these values of reduced transition probabilities for the ^{177}Au isotope suggests that 5 - 10 % of deexcitation of $13/2^+$ state should proceed via unobserved $E1$ decays. This is in agreement with the observation of the weak 261.2 keV transition in coincidence with the 257.5 keV transition, see Fig. 3a.

Fig. 4a gives the spectrum of γ rays tagged with the ground-state α decay and in prompt coincidence with the 257.5 keV transition which, as already noted, is a member of the $1i_{13/2}$ band. In addition to the yrast band members, 264.5, 290.2, and 452.6 keV transitions are observed. Fig. 4b,c give spectra of γ rays tagged with the ground-state α decay and in prompt coincidence with the 452.6, and 290.2 keV transitions. The 264.5, and 290.2 keV transitions are not in coincidence but both are in coincidence with the 452.6 keV transition. Therefore they are interpreted as members of the ground-state band, see level scheme in Fig. 1. The energy difference of parallel 264.5, and 290.2 keV transitions identifies the first excited state of the ^{177}Au isotope at 25.7 keV.

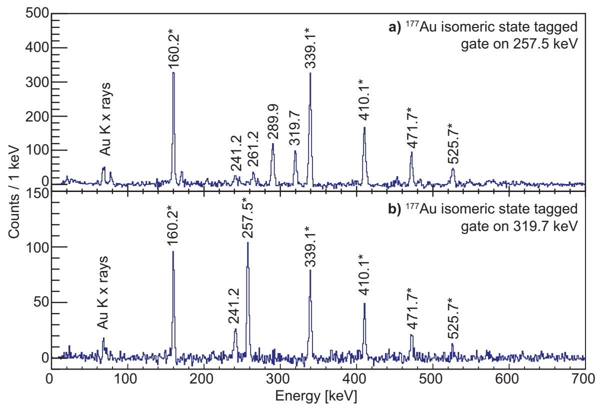

Figure 3: Spectra of γ rays tagged with the isomeric state α decay of ^{177}Au and in prompt coincidence with **a)** the 257.5 keV, and **b)** the 319.7 keV transitions. Transitions of the yrast $1i_{13/2}$ band are denoted with an asterisk.

The unambiguous $1/2^+$ ground-state spin-parity assignment [7] provides another supporting argument for an unobserved transition in the decay path of the $13/2^+$ state of the yrast band. This path contains only two transitions in a cascade, since the 290.2, and 264.5 keV transitions are parallel, see the level scheme in Fig. 1. The $13/2^+$ state cannot decay into the $1/2^+$ ground state via only two transitions, since it would require a large multipolarity, and thus a slow transition rate, for at least one of them. This is clearly not the case with the present data, since all transitions were observed at the target position, and in prompt coincidences.

The ^{177}Au isotope is a unique case where the proton-intruder $1i_{13/2}$ yrast cascade splits at the bottom, feeding both the ground and the isomeric state (via the $1h_{9/2}$ intruder state). This is not the case with the ^{179}Au isotope, see the discussion above and the level scheme in Fig. 1. The extensive systematics for intruder structures in odd-Au isotopes was established by means of the in-beam γ-ray spectroscopy [3, 19, 20, 23–26], and β decay spectroscopy [13, 14]. The states asso-

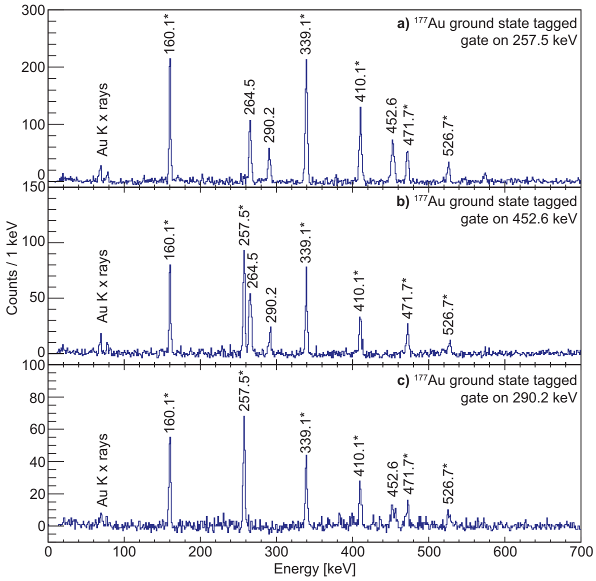

Figure 4: Spectra of γ rays tagged with the ground state α decay of ^{177}Au and in prompt coincidence with **a)** the 257.5 keV, **b)** the 452.6 keV, and **c)** the 290.2 keV transitions. Transitions of the yrast $1i_{13/2}$ band are denoted with an asterisk.

ciated with the $1i_{13/2}$ band decay *exclusively* to states of the same configuration or into the $1h_{9/2}$ configuration via parity-changing $E1$ transitions. Decay into positive-parity states associated with the proton-hole configurations is strongly hindered due to the intruder-state-to-hole-state character of such transitions. The different decay pattern observed in ^{177}Au is explained by a configuration mixing. According to the systematics of the positive-parity bands in odd-Au isotopes, the $9/2^+$ state of the ground state band can be expected at a similar energy as in ^{187,189}Au, i.e., between 700 and 760 keV [13–15]. Therefore, there are two $9/2^+$ states expected to be located close to each other in ^{177}Au. One is the anti-aligned state of the $1i_{13/2}$ configuration, see the discussion above and one is the $9/2^+$ member of the ground-state band. Because these configurations are probably located close to each other, a strong mixing is expected. It is an intruder component in the wave function of both states that opens a decay path of the $13/2^+$ member of the $1i_{13/2}$ configuration towards the ground state. Such a situation does not occur in any other odd-Au isotope, and therefore decays into proton-hole states were not observed.

The present work provides a key advance in understanding spin order associated with intruder bands. Thus, the $1i_{13/2}$ band exhibits the appearance of a spin-(j-2) state below the spin-j state, similar to the $1h_{9/2}$ and $2f_{7/2}$ bands. Establishing this is critical for the organization of the decays of high-spin states. In this mass region, high-spin in-beam studies play a major role because it is very difficult to populate low-spin states: the standard approach via β decay is limited by competing α-decay channels. At the next level of study, the present work paves the road to adding the high level of detail expected in ^{181,183}Au by comparison with ^{185,187}Au. We note in particular that the strongly coupled band observed in ^{177}Au, reported earlier [17], indicates that there are structural changes occurring in the Au isotopes which point to multiple shape coexistence, even lying beyond such structures established in ^{187}Au.

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