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Lifetime measurements probing triple shape coexistence in ^{175}Au

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Lifetimes of the low-lying excited states in the very neutron-deficient nucleus ^{175}Au have been measured by the recoil-distance Doppler-shift method using γ-ray spectra obtained with the recoil-decay tagging technique. Transition quadrupole moments and reduced transition probabilities extracted for this odd-Z nucleus indicate the existence of three different shapes and the competition between collective and noncollective structures.

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A fundamental goal in the physics of atomic nuclei and other many-body mesoscopic systems is to understand how collective behavior arises from the fundamental interactions between the underlying constituents. In atomic nuclei, quantum coherence can manifest itself as two or more microscopic configurations of nucleons that are associated with different nuclear shapes at low excitation energies. The microscopic interpretation of this shape coexistence is based on different multiple particle-multiple hole (mp-nh) type excitations from orbitals below a given shell gap to orbitals above it [1,2].

Nuclei that have valence protons occupying orbitals below the $Z = 82$ shell closure have exhibited many examples of the coexistence of two shapes. For example, the even-even Hg isotopes have oblate ground states that coexist with prolate shapes based on 4p-6h proton excitations across this shell gap [3,4]. A striking example of shape coexistence with three different shapes was discovered in ^{186}Pb. In this nucleus, a triplet of 0^+ states was interpreted in terms of a coexisting spherical ground state (0p-0h) and excited states based on oblate (2p-2h) and prolate (4p-4h) shapes all within an excitation energy range of 800 keV [5]. However, triple shape coexistence is extremely rare, and most of the reported cases are observed in even-Z nuclei. The sparseness of such cases is due to the lack of specific configurations available at low energy to stabilize three shapes and the experimental challenges that must be overcome in order to observe excited states in nuclei that are usually very neutron deficient. Despite these limitations, evidence for the phenomenon has also been observed in several odd-A nuclei [6,7], including the odd-Z nucleus ^{175}Au [8], using very selective experimental techniques.

In ^{175}Au, different structures may be influenced by an unpaired proton occupying either the $s_{1/2}$, $d_{3/2}$, or $h_{11/2}$ orbitals below or the $h_{9/2}$, $f_{7/2}$, and $i_{13/2}$ orbitals above the $Z = 82$ shell closure. Figure 1 shows the low-spin excited states for ^{175}Au established by Kondev *et al.* [8], which are interpreted in terms of a spherical α-decaying $11/2^-$ isomer, an oblate $13/2^+$ state, and a positive-parity sequence assigned as a collective prolate band.

A major experimental challenge in studies of shape coexistence relates to obtaining information about the coexisting structures associated with different deformations. Although precision measurements of nuclear wave functions and deformations can be made through Coulomb excitation with radioactive ion beams [9,10], the production yields for such highly neutron-deficient species as ^{175}Au make experiments unfeasible at this time. However, it is possible to measure the lifetimes of weakly populated states using reactions of stable nuclei and utilizing the highly selective recoil-decay tagging (RDT) technique [11–13]. In this Rapid Communication, we report lifetime measurements of low-lying states in ^{175}Au using the recoil-distance Doppler shift (RDDS) method [14] and provide evidence for a coexisting triplet of shapes in a heavy odd-proton nucleus.

Excited states in ^{175}Au were populated in the ^{92}Mo(^{86}Sr,p2n) fusion-evaporation reaction in an experiment performed at the Accelerator Laboratory of the University of Jyväskylä. The ^{86}Sr^{16+} beam was accelerated to a bombarding energy of 401 MeV by the K130 cyclotron and impinged on a stretched 1 mg/cm^2 ^{92}Mo target. The reaction provided an initial recoil velocity $v/c = 4.4\%$ for the ^{175}Au ions.

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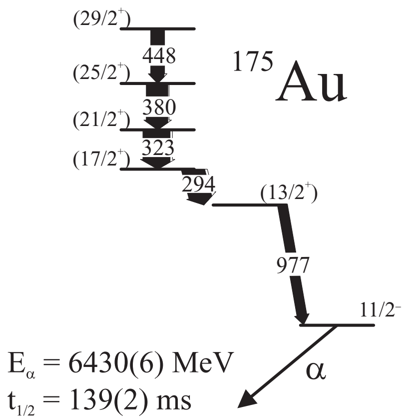

FIG. 1. Partial level scheme of ^{175}Au adapted from Ref [8]. The half-life was measured from decay curves generated from time differences between recoil implantations and $\alpha(^{175}\text{Au})$ decays detected in the GREAT spectrometer. The α-decay energy E_α was taken from Ref. [8].

The velocity of the reaction products was reduced in a 1-mg/cm^2-thick Mg degrader foil downstream of the target to $v/c = 3.3\%$. The distance between the target and degrader was varied and actively stabilized using the Köln plunger device [15] mounted at the target position of the JUROGAM II γ-ray spectrometer. JUROGAM II comprised 15 EUROGAM Phase I type [16] and 12 Clover [17] escape-suppressed high-purity germanium (HPGe) detectors. In order to allow the application of the RDT technique to select γ rays associated with ^{175}Au ions, a degrader foil was used in place of a conventional stopper foil. This allowed evaporation residues to recoil into the recoil ion transport unit (RITU) gas-filled separator [18] where they were separated from the scattered beam and other products according to their magnetic rigidity.

The fusion residues were transported to the RITU focal plane within ~0.5 μs, where they were implanted into the double-sided silicon-strip detectors (DSSDs) of the Gamma Recoil Electron Alpha Tagging (GREAT) spectrometer [19]. Gamma-ray transitions originating from ^{175}Au were detected in JUROGAM II and identified through spatial and temporal correlations with implanted ^{175}Au ions and their subsequent radioactive decays. The data were collected using the triggerless Total Data Readout data acquisition system [20].

The energy of the γ rays emitted before reaching the degrader foil were fully Doppler shifted, whereas the energy of those emitted afterward were less shifted or "degraded" due to the lower velocity of the emitting nuclei. Lifetimes were extracted using the differential decay curve method (DDCM) [15]. Gamma-ray spectra tagged by the characteristic α decay of ^{175}Au [8] were collected at ten target to degrader distances ranging from 3 μm to 3000 μm. The EUROGAM Phase I detectors located at 158° (five detectors) and 134° (ten detectors), relative to the beam direction, provided sufficient separation between the fully shifted and degraded components of the γ-ray emission and were utilized in these measurements. Examples of γ-ray spectra, analyzed off-line with the GRAIN software package [21], are displayed in Fig. 2.

Lifetimes were extracted from fitted peak areas normalized to the summed intensities of degraded (I_d) and fully shifted

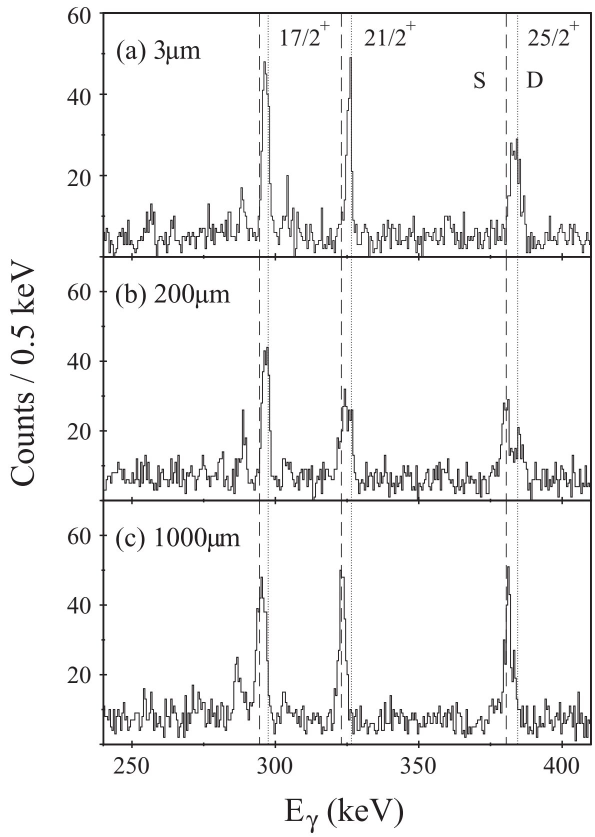

FIG. 2. Gamma-ray spectra measured with the ten Ge detectors positioned at 134° with respect to the beam axis at three target-to-degrader distances: (a) 3 μm, (b) 200 μm, and (c) 1000 μm. The γ rays are labeled with the spin and parity I^π of the state from which they are emitted. These spectra show γ rays correlated with fusion evaporation residues implanted in the GREAT spectrometer and followed by the characteristic α decay of ^{175}Au within the same DSSD pixel. The correlation time was limited to 470 ms. The lines labeled S (D) indicate the fully Doppler-shifted (degraded) components of the γ-ray transitions.

(I_s) components of the γ-ray transitions under investigation resulting in decay curves of $I_s/(I_d + I_s)$; see Fig. 3. The resulting mean lifetime τ values presented in Table I are weighted averages of the two values extracted independently from the data recorded with the detectors at 134° and 158°.

The effect of unobserved feeding transitions must be taken into account in a γ-ray singles RDDS measurement. The time behavior of the unobserved side feeding transitions is assumed to be similar to that of the observed direct feeding intensity. This is found to be a valid assumption when the side-feeding intensity is low and the observed feeding times are similar to the deexcitation of the state (see Ref. [22] and references therein). This assumption is valid for all the transitions measured in this work. The mean lifetime measurements of excited states in ^{175}Au and the values of transition quadrupole moments $|Q_t|$ and reduced transition probabilities are listed in Table I.

The γ-ray transitions originating from the $25/2^+$ and $21/2^+$ states have high quadrupole moments relative to the low spin

TABLE I. Electromagnetic properties of the low-lying excited states in ^{175}Au. The resulting mean lifetimes are weighted averages of the two values extracted independently from the data recorded with the JUROGAM detectors located at 134° and 158° relative to the beam direction.

E_γ (keV)	I_i^π	τ (ps)	$B(E1)$ (W.u.)	$B(E2)$ (e^2 b^2)	$B(E2)$ (W.u.)	$\|Q_t\|$ (e b)
997	$13/2^+$	300–11000	$<0.114 \times 10^{-5}$			
294	$17/2^+$	44(4)		0.76(7)	130(10)	4.8(2)
323	$21/2^+$	11(2)		1.96(40)	340(60)	7.6(7)
380	$25/2^+$	7(2)		1.40(40)	240(70)	6.4(9)

states and indicate a collective structure. Figure 4 compares the transition quadrupole moments (extracted from RDDS lifetime measurements) as a function of Z for excited states in several neutron-deficient nuclei near the neutron midshell. The $|Q_t|$ values and their corresponding reduced transition probabilities $B(E2)$ indicate that the high-spin states in ^{175}Au are similar to collective prolate structures observed in nearby nuclei. These data are consistent with the assignment of a prolate band based on an odd proton occupying a high-j $i_{13/2}$ orbital as proposed by Kondev *et al.* [8].

The longer lifetime of the $17/2^+$ state in ^{175}Au, measured from the Doppler-shifted $17/2^+ \rightarrow 13/2^+$ γ-ray transition, results in a lower $|Q_t|$ value relative to those measured for transitions between the higher-spin prolate states. Figure 4 reveals that similar $|Q_t|$ values are observed for the $2^+ \rightarrow 0^+$ transition in ^{180,182}Hg [22,24] and the $17/2^+ \rightarrow 13/2^+$ transition in ^{187}Tl [25]. In ^{180,182}Hg the relatively low quadrupole moments are interpreted as arising from a change in intrinsic structure from prolate shapes at high spin to the oblate-deformed ground state [26]. Indeed, the $|Q_t|$ for the $17/2^+ \rightarrow 13/2^+$ transition extracted in the present work is interpreted in terms of the unpaired proton deexciting from a prolate configuration to occupy an oblate state based on a high-Ω $i_{13/2}$ orbital. The drop in the $|Q_t|$ value for this transition compared with those of the higher-lying transitions can be interpreted in terms of the two-state mixing, in which mixing between the oblate and prolate structures is expected at low spin. The $|Q_t|$ values for the transitions deexciting the $25/2^+$ and $21/2^+$ states are constant within error bars. Assuming these values represent pure prolate states, the contribution of the oblate structure to the $13/2^+$ state can be estimated from the

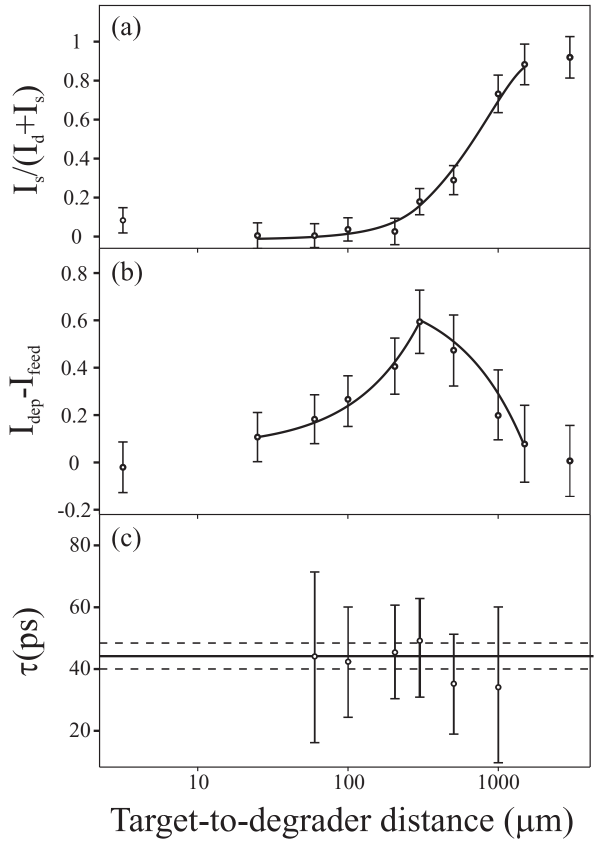

FIG. 3. Lifetime determination using a differential decay curve analysis of the Ge detectors positioned at 134° for the $17/2^+$ state in ^{175}Au. (a) The decay curve of the depopulating transition. (b) The difference in intensity between the degraded components of the feeding and depopulating transitions. The solid line represents the derivative of the decay curve shown in (a). (c) The individual lifetimes at the target-to-degrader distances in the region of sensitivity and the final average lifetime from all the measurements.

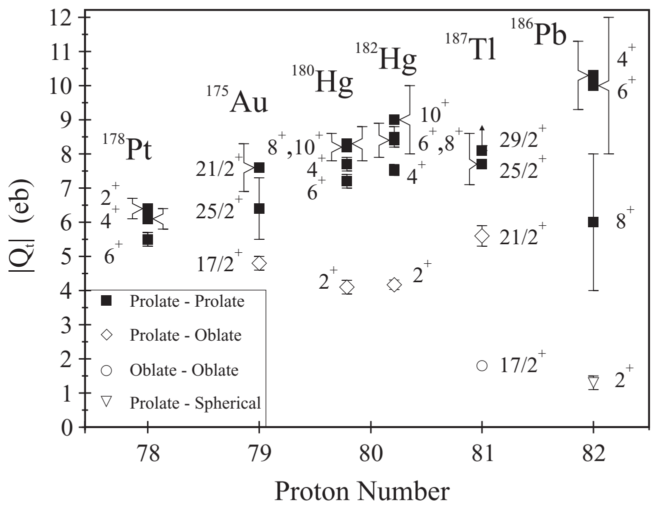

FIG. 4. Experimental $|Q_t|$ values as a function of proton number for ^{175}Au and neighboring neutron-deficient nuclei near the neutron midshell. The states are labeled with the spin and parity I^π of the state from which the depopulating transitions are emitted. Data are taken from Refs. [22–25,28]. Note that the Hg isotopes are offset from $Z = 80$ for clarity.

experimental $|Q_t|$ values, as in Refs [27,28]. Using the $|Q_t|$ values extracted from our lifetime measurements, a 55(3)% oblate admixture may be derived for the $13/2^+$ state in ^{175}Au.

A range for the lifetime of the $13/2^+$ state was obtained. The 977-keV γ ray is observed to be in prompt coincidence with the γ-ray transitions between high-spin states, suggesting that the $13/2^+$ state deexcites within sight of JUROGAM II at the target position. However, no fully shifted component was observed for the 977-keV depopulating transition at the maximum target-degrader distance (3000 μm). This implies a lifetime in the range of 0.3–11 ns for the $13/2^+$ state. The $13/2^+$ state is predominantly depopulated by an $E1$ transition to the $11/2^-$ α-decaying state. From the upper limit on the lifetime, an experimental $B(E1)$ reduced transition probability has been determined at the 10^{-5} W.u. level, which is consistent with that of a noncollective single-proton transition from the $13/2^+$ mixed oblate-prolate state to the $11/2^-$ near-spherical state.

In summary, the lifetimes of the low-lying yrast states in ^{175}Au have been measured using the RDDS method aided by highly selective radioactive tagging techniques. The extracted transition quadrupole moments and reduced transition probabilities provide evidence for a triad of coexisting shapes at low spin. These measurements indicate that a collective prolate shape, based on an $i_{13/2}$ odd-proton configuration, is stabilized at high spin. The lower $|Q_t|$ and $B(E2)$ values extracted for the transition depopulating the $17/2^+$ state suggests a mixed oblate-prolate configuration for the $13/2^+$ state. The constraints on the experimental $B(E1)$ reduced transition probability for the decay from the $13/2^+$ state indicates a noncollective single-particle transition as the unpaired proton deexcites the $13/2^+$ state to an α-decaying near-spherical $11/2^-$ state.

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