EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Simultaneous spectroscopy of γ rays and conversion electrons: Systematic study of $E0$ transitions and intruder states in close vicinity of mid-shell point in odd-Au isotopes

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Abstract:

This proposal focuses on detailed systematic studies of the beta/EC decays of ^{179,181,183,185}Hg leading to excited states in the neutron-deficient Au isotopes in the vicinity of the N=104 midshell. Gamma-ray, X-ray and conversion electron de-excitations of odd-A Au isotopes will be studied simultaneously. These studies will address important structural questions such as the excitation energies of coexisting states, properties of multiple intruder states (i.e. intruder particles coupled to intruder cores) and mixing of coexisting structures. The unique combination of Hg beam purity and yields make ISOLDE a unique facility for these experiments.

Requested shifts: 12 shifts

1 Physics motivation of proposed experiment

Neutron-deficient isotopes in the vicinity of Z = 82 and N = 104 have become the most extensively characterized region of low-energy shape coexistence [1, 2, 3]. In the past, odd-Au (Z = 79) isotopes in this region, in particular, have been the subject of many experiments of different types, including decay studies, in-beam γ-ray studies and laser spectroscopy, see e.g. [4, 5, 6] and references therein.

The structural feature behind the low-energy shape coexistence is the appearance of intruder states. These are states that intrude across closed shells because their energies are dictated not only by shell gaps but also by correlation energies resulting from changing shell occupancies. A very rich spectrum of coexisting intruder structures remains to be discovered in odd-Au isotopes and further systematic spectroscopic elucidation of these states is highly demanding. The quantification of the properties of intruder configurations, e.g. excitation energies and spectroscopic purities, particularly their nucleon number dependence, will demand that theory moves beyond mean-field descriptions to quantify the specific nucleon number dependence. Only in this way will we have a reliable framework within which structural questions like e.g. the appearance and disappearance of closed shells can be addressed.

Such experiments have to involve unambiguous identification of the electric monopole transitions (“$E0$”), which occur between states with the same spin and parity and are rare in odd-mass nuclei. Electric monopole transition strengths reflect the matrix elements of the $E0$ operator, $\hat{T}(E0)$ [8]. The diagonal matrix elements of $\hat{T}(E0)$ are directly related to the change in mean-square charge radii, $\delta\langle r^2\rangle$ of the initial and final state. The mean-square charge radii are well known to reveal shape changes in nuclei and thus the presence of $E0$ transition can be associated with shape coexistence phenomenon [9, 10].

In the case of $E0$ transition, only two-photon emission, internal-pair formation or internal conversion is possible. Two-photon emission is extremely improbable and internal-pair formation is possible above the 1.022 MeV threshold only. Therefore the dominant $E0$ process is emission of conversion electrons (since the the single γ-ray emission is strictly forbidden). In odd-mass nuclei,.where all the possible spins are half integers (J¿=1/2), the concurrence with M1 and/or E2 admixture take place. In odd-mass nuclei, pure $E0$ transtions, i.e. without corresponding $M1$ component, are extremely rare [11]. Therefore to reveal the presence and study the properties of $E0$ transitions, *both γ rays and conversion electrons from depopulation of excited states need to be measured simultaneously.*

In the past, β^+/EC decay of odd-Hg precursors appear to be very powerful method to study the structure of odd-Au isotopes, see the discussion and references below. Systematic studies revealed both proton-hole and proton-particle excitations in odd-Au isotopes. Proton particles and proton holes couple to different cores; the proton particles couple to Pt cores and the proton holes couple to the Hg cores, resulting in distinct groups of states. The idea behind this fundamental point was demonstrated on illustrative example of ^{189}Au, where both types of excitations were unambiguously identified [14]. Previously, studies of odd-Au isotopes revealed:

- The presence of proton-hole $\pi s^{-1}_{1/2}$, $\pi d^{-1}_{3/2}$, $\pi d^{-1}_{5/2}$ and $\pi h^{-1}_{11/2}$ configurations and asso-

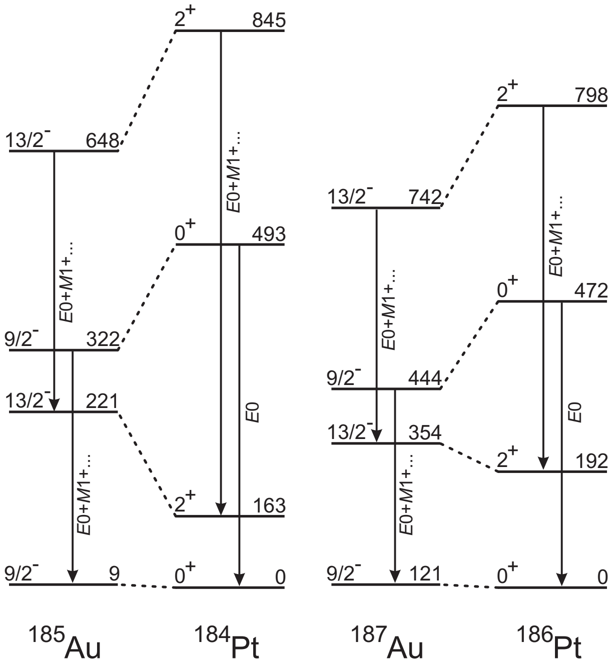

Figure 1: Part of the $\pi h_{9/2}^{+1}$ intruder bands in ^{185,187}Au compared with corresponding 0^+ and 2^+ levels in ^{184,186}Pt core nuclei. The core-particle couplings are denoted with dashed lines. Only transitions with $E0$ components are shown here. The data were taken from [17]. Similar $E0$ transitions were observed between coexisting $\pi h_{11/2}^{-}$ structures.

ciated bands which appear through whole Au isotopic chain [6, 12].

- The presence of proton-particle $\pi h_{9/2}^{+1}$, $\pi f_{7/2}^{+1}$ and $\pi i_{13/2}^{+1}$ intruder structures and associated bands in the N = 104 mid-shell region. However, quantifying the energy trends of these states closed to and beyond the neutron mid-shell has proved to be very challenging. Previously, the most relevant data for odd-Au isotopes with A $\leq$ 183 came from in-beam γ-ray spectroscopy. There is a further difficulty since the states of interest are often isomeric and therefore their decay cannot be detected by in-beam spectrometers. In consequence, most available data are for "floating" bands of states, see e.g. [4, 15, 16], which give no quantitative information on intruder state energies. AAnother problem is that in-beam studies using fusion-evaporation reactions preferentially populate yrast states and the coexisting states of interest in this proposal are non-yrast, which are weakly populated.

The existence of differently shaped 0^+ states at low energy in both even-Hg and even-Pt isotopes, see [1] and references therein, which act the role of core of odd-Au isotopes, naturally suggests need for search of four different types of excitations in Au isotopes in close vicinity of mid-shell point N = 104:

- $j^{+1} \otimes {}^{A-1}$Pt, 0_1^+ (strongly-deformed band)
- $j^{+1} \otimes {}^{A-1}$Pt, 0_2^+ (weakly-deformed band)
- $j^{-1} \otimes {}^{A+1}$Hg, 0_1^+ (weakly-deformed band)
- $j^{-1} \otimes {}^{A+1}$Hg, 0_2^+ (strongly-deformed band)

Previously, such a states were studied in ^{185,187}Au together with interconnecting $E0$ transitions [17, 18]. The evolution of properties of these structures and $E0$ transitions in lighter nuclei is unknown. The power of complete spectroscopy following radioactive decay is represented by extensive study of ^{187}Au. The states of ^{187}Au have been populated via β^+/EC decay of mass-separated samples of ^{187}Hg^{g} and ^{187}Hg^{m} produced by the UNISOR facility at the Holifield Heavy Ion Research Facility at the Oak Ridge National Laboratory. Decay schemes have been constructed incorporating 99 % of the decay intensities assigned to the decays of Hg sample. The γ-ray gated conversion-electron spectra permitted determination of 367 conversion coefficients. A variety of coexisting band structures were established in ^{187}Au, which revealed new degrees of freedom at low excitation energy. Two diabatic bands with identical spins and nearly identical relative energies and $E0$ connecting the favored signature partners. These bands are interpreted as intruder proton configuration $\pi h_{9/2}$ and $\pi f_{7/2}$ coupled to coexisting prolate or near-prolate cores. Besides that, hole states and associated bands have been unambiguously identified.

In our recent studies [7, 13], which comprise isomer and α decay spectroscopy with direct mass measurements, we quantified the excitation energy of lowest-intruder states in ^{177,179}Au. This fixes the left-hand side of the intruder parabola, which reaches the minimum exactly at the mid-shell point, i.e. at N =104.

Therefore we have two sets of the data, one from well studied A $\geq$ 187 region and second from moderately understood A $\leq$ 179 region. The proposed experiment is aimed on studies of poorly understood odd-mass nuclei $^{179-185}$Au, which lie between these two regions. Note that $^{179-185}$Au are located near the minimum of “intruder parabola” (N = 104 [7]) and are expected to manifest shape coexistence more vivdly than other Au isotopes. We emphasize that β decays of odd-Hg precursors, which can be produced with sufficient yield only at ISOLDE, is the most suitable method for studies of totally converted $E0$ transitions in odd-Au nuclei. These data, together with planned collinear laser spectroscopy of Au isotopes [19] , will give us complex systematic picture of the shape coexistence in odd-Au isotopes down to ^{179}Au, i.e. 18 neutrons away from the stability.

2 Proposed experiment

We propose to study γ rays and conversion electrons emitted after β^+/EC decay of odd-Hg precursors. Present proposal heralds continuation of work, that started at UNISOR almost 20 years ago and which reached down to mass 187. Due to insufficient yields of lighter Hg isotopes, this program could not continue. Only a small fraction of ^{185}Hg decay data from UNISOR were ever published, and a very strong γ ray was never assigned to the scheme and thus derailing the systematics. Parallel to UNISOR studies, odd-Au isotopes have been studied at ISOCELLE facility, but with production of only very incomplete level schemes with several critical mistakes - see the discussion in [6]. Further justifications of our choice are:

- Excellent yields of mass-separated Hg isotopes, which is a necessary condition for a high statistical quality spectra, critical for this type of study.

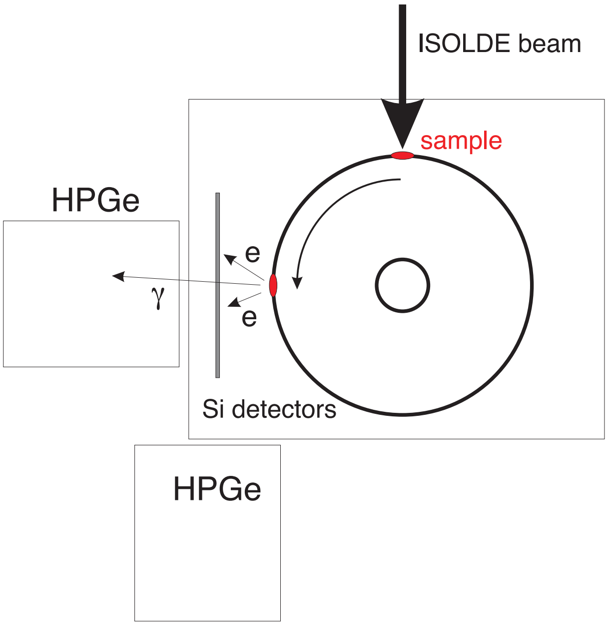

Figure 2: Proposed setup.

- The availability of the information from the systematics based of the well studied heavier, i.e. A $\geq$ 187, odd-Au isotopes and on very recent discovery of the 328 ns isomer in ^{179}Au.
- Presence of totally converted $E0$ transitions in ^{185,187}Au. Several $E0$ transitions are expected in nuclei, which are proposed to be studied. Extension of systematic studies of $E0$ transitions is crucial for understanding of underlying mechanisms of the shape coexistence and intruder states, see the discussion in previous section.
- $E0$ transitions arise from non-yrast, which are poorly populated in-beam and thus it is very difficult to study the facilities like new SAGE spectrometer at University of Jyväskylä. This makes β decay of Hg's much more suitable method.

The mass separated samples of odd-Hg nuclei will be produced by deposition of low-energy ISOLDE beam at rotating aluminum tube. Collection time, i.e. the time with opened beam gate, needs to be optimized with respect to the yields and half-lives of Hg precursors. This is needed to keep the activity of the sample reasonably low to avoid the dead-time problems. After the collection, the sample will be transported to the measurement station (by rotation of the tube). At the measurement station, a small array of silicon detectors for conversion electrons will be positioned (inside of the vacuum chamber). Outside of the chamber, segmented HPGe detectors will be used for K x rays and γ rays. See Fig. 2 for schematic drawing of the proposed measurement setup. After the measurement period, the daughter activities will be removed by rotation of the tube. Summary of yields and proposed deposition and measurement periods together with expected activities of samples is given in Tab. 1.

Table 1: Summary of properties of ground-states of isotopes of interest, yields, proposed deposition and measurement time and activity of each sample.

Isotope	**Half-life**	b_β	**Yield [ions/s]**	**Deposition time**	**Activity of the sample**	**Measurement time**
^{185}Hg^g	49.1 s	94 %	2.5×10^8	50 ms	176 kBq	60 s
^{183}Hg	9.4 s	88 %	4.5×10^7	50 ms	166 kBq	12 s
^{181}Hg	3.6 s	73 %	7.1×10^5	1 s	137 kBq	6 s
^{179}Hg	1.0 s	45 %	1.6×10^3	1 s	1 kBq	2 s

Table 2: Requested shifts and expected statistics.

Isotope	**Number of decays per 1 shift**	**Requested shifts**	**Total collected decays**
^{185}Hg	0.84×10^8	3	2.54×10^8
^{183}Hg	3.98×10^8	1	3.98×10^8
^{181}Hg	6.56×10^8	1	6.56×10^8
^{179}Hg	1.47×10^7	7	1.03×10^8

Tab. 2 gives expected statistics according to the yields of odd-Hg isotopes given in the ISOLDE web page. In total for each studied isotope, the statistics on the level of 10^8 of β^+/EC decays will be collected. In the case of ^{185}Hg, this heralds more than 100 times more than it was observed previously. We recall that for the rest of the isotopes, reliable β^+/EC studies were never performed before.

Summary of requested shifts:

In total we request 12 shifts, i.e. 4 days of Hg beam to fulfill the proposed program.
We request molten Pb target and plasma ion source.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

Part of the	Availability	Design and manufacturing
Setup for γ and e^- spectroscopy	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☐ Standard equipment supplied by a manufacturer ☒ ~~CERN~~/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

Hazards	Setup for γ and e^- spectroscopy	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	-	-	-
Vacuum	Standard ISOLDE vacuum	-	-
Temperature	-	-	-
Heat transfer	-	-	-
Thermal properties of materials	-	-	-
Cryogenic fluid	LN$_2$ cooling of HPGe detectors	-	-
Electrical and electromagnetic			
Electricity	3 kV (HPGe detectors)	-	-
Static electricity	-	-	-
Magnetic field	-	-	-
Batteries	-	-	-
Capacitors	-	-	-
Ionizing radiation			
Target material	-	-	-
Beam particle type (e, p, ions, etc)	^{179,181,183,185}Hg	-	-
Beam intensity	10^8 ions/s	-	-
Beam energy	60 keV	-	-
Cooling liquids	LN$_2$	-	-
Gases	-	-	-
Calibration sources:	☒		

• Open source	☐		
• Sealed source	☒ [ISO standard]	-	-
• Isotope	^{152}Eu, ^{133}Ba, ^{241}Am and ^{60}Co	-	-
• Activity	all the sources $< 40\,\mathrm{kBq}$	-	-
Use of activated material:			
• Description	☐	-	-
• Dose rate on contact and in 10 cm distance	-	-	-
• Isotope	-	-	-
• Activity	-	-	-
Non-ionizing radiation			
Laser	-	-	-
UV light	-	-	-
Microwaves (300MHz-30 GHz)	-	-	-
Radiofrequency (1-300 MHz)	-	-	-
Chemical			
Toxic	Pb shielding of HPGe detectors	-	-
Harmful	-	-	-
CMR (carcinogens, mutagens and substances toxic to reproduction)	-	-	-
Corrosive	-	-	-
Irritant	-	-	-
Flammable	-	-	-
Oxidizing	-	-	-
Explosiveness	-	-	-
Asphyxiant	-	-	-
Dangerous for the environment	-	-	-
Mechanical			
Physical impact or mechanical energy (moving parts)	small step motor inside detector chamber	-	-
Mechanical properties (Sharp, rough, slippery)	Detector chamber is expected to be heavy	-	-
Vibration	-	-	-
Vehicles and Means of Transport	-	-	-
Noise			

Frequency	-	-	-
Intensity	-	-	-
Physical			
Confined spaces	-	-	-
High workplaces	-	-	-
Access to high workplaces	-	-	-
Obstructions in passageways	-	-	-
Manual handling	-	-	-
Poor ergonomics	-	-	-

Hazard identification:

Negligible.