EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Addendum 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: We propose to perform the study of β decay of mass-separated samples of the ^{185}Hg isotope. Samples will be collected by the deposition of low-energy radioactive-ion beam on the rapidly quenched metallic tape of the TATRA system. Conversion electrons will be detected with windowless Si(Li) detector cooled with liquid nitrogen. Gamma rays will be detected with the BE2020 Broad Energy Germanium detector. Level scheme of the ^{185}Au isotope will be constructed and electric monopole transitions will be identified.

Requested shifts: 7 shifts, (in 1 run together with remaining 5 shifts)

1 Motivation for study of ^{185}Hg

The Au isotopes play a unique role in our understanding of shape coexistence in that strongly-deformed structures intrude to become the ground state at mid shell (^{183}Au) and to exhibit a classic "parabolic" trend in excitation energy [1]. Present addendum is a part of our focused experimental programme on the study of nuclear structure of odd-Au isotopes. The programme involves in-beam γ-ray and conversion electron studies (performed at University of Jyvaskyla and iThemba Labs) [2, 3], β-decay experiments (ISOLDE) [4, 5] and isomer spectroscopy [6].
Our previous achievements at ISOLDE were reported to the INTC in 2019 and we refer the committee to the INTC-SR-061 status report. In this report, we suggested a construction of the new detection system based on rapidly-quenched metals with longer and wider tape. This would allow to extend studies to isotopes with half lives of few seconds. However in 2019, Ministry of Education, Science, Research and Sport of Slovak Republic stopped completely the funding of our activities at ISOLDE. This decision, which had purely political nature, included also the payments of CERN and ISOLDE member fees. After massive campaign in the Slovak media, which was closely followed also by CERN management and created public pressure to authorities, the funding was returned at very end of 2019 and in early 2020. Due to these reasons, the group at the Institute of Physics, Slovak Academy of Sciences, could not construct the prototype of the system. The only system that is available in the moment is the original TATRA. However, the development of new system is still planned and it will be discussed with representatives of the new Slovak government.
Therefore, as a continuation of the program we propose to carry out dedicated study of the β decay of ^{185}Hg. It can be performed with existing setup and there are further reasons for this choice (it was our plan to study this decay anyway).
An interest in systematic study of the Au isotopes can be traced back to before the emergence of shape coexistence as a feature of heavy nuclei. Experiments at the UNISOR [7] and the ISOCELE facilities [8, 9] revealed a remarkable constancy in excitation energies for many low-lying excited states in the odd-Au isotopes. However, "intruder" states, i.e., "unexpected" states that appeared at low energy, were established in the most neutron-deficient Au isotopes accessible at the time [8, 9]. This led to the first review of shape coexistence in nuclei [10]. The structure of the neutron-deficient Au isotopes became clearer with the summary provided in a paper by Kortelahti *et al.* in 1988 [11]. It revealed a complex situation of four coexisting structures in ^{185,187}Au. Some details of the ^{185}Hg^{m,g} decay to ^{185}Au are summarized in an unpublished thesis [12]. It pointed to serious errors in an earlier study of the ^{185}Hg decay. Most critical was a failure to identify parity-changing $E1$ transitions, which led to wrong parity assignments for a series of excited states and thus to misinterpretation of the underlying nuclear structure. These errors occurred due to missing of doublets (or even higher multiplets) in measured spectra. Analysis of γ-gated electron spectra and application of a running gates technique solved this problem.
A very detailed investigation of the decays of ^{187}Hg^{m,g} to ^{187}Au followed [13]. These studies involved measurements of conversion electrons using γ-e$^-$ coincidences and identification of electric monopole transitions ($E0$), which provide a model independent fingerprint of

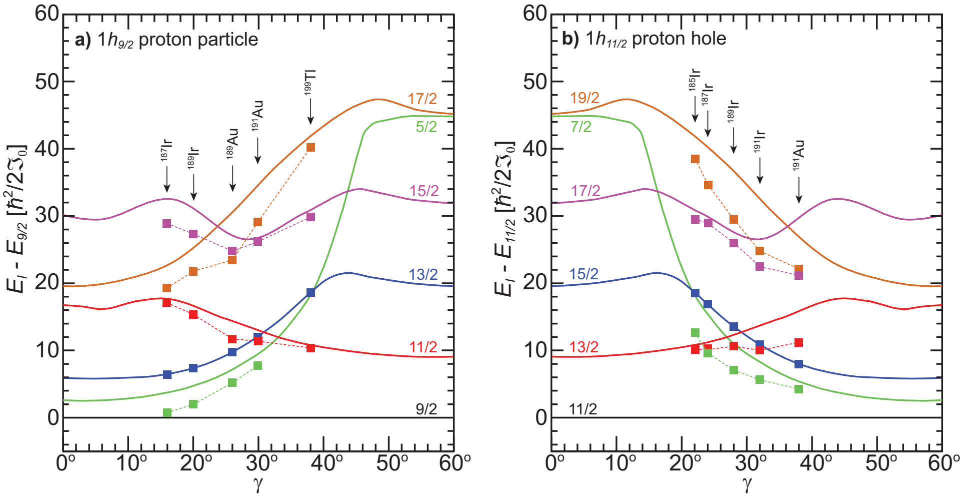

Figure 1: Comparison of calculations based on the PTRM approach, see the text for details, with experimental data. Energy of excited states is given as a function of the γ deformation parameter for **a)** $1h_{11/2}$ proton-hole and **b)** $1h_{9/2}$ proton-particle configurations.

shape coexistence. Decay schemes have been constructed incorporating 99 % of the decay intensities assigned to the high-spin and low-spin decays. The detection limit was pushed down nearly to 0.1 % if the intensity of the strongest γ ray. The γ-ray gated conversion-electron spectra permitted determination of 367 conversion coefficients. In total 9 $E0$ transitions were identified between both negative- and positive-parity states. Compared to that, the existing information on ^{185}Au is incomplete. Counterparts of only few $E0$ transitions that are known in ^{187}Au were observed. Knowledge of systematic evolutions of these coexisting structures will provide major constraints for nuclear models. Known $E0$ transitions were observed in the ^{185}Hg decay with intensities of 5 - 10 % of the strongest γ ray (which is not assigned into the level scheme!). *Therefore, the spectroscopy at least at the level of 1 % of the strongest γ ray is demanding.*

Other motivation for study of excited states ^{185}Au is the evolution of deformation as mid-shell point is approached. In general, deformation parameters, both axial and triaxial can be deduced from the spectra of excited states of the odd-mass nuclei. The odd particle or hole acts as a probe of the even-even core. The particle-core coupling models [14] suggest a very strong dependence of excitation energies of states with various spins. Fig. 2 gives a spectra of excited states associated with the $1h_{11/2}$ odd particle and $1h_{9/2}$ odd hole as a function of the triaxial deformation parameter (with fixed axial parameter). It is evident that the spectrum changes gradually from decoupled at $\gamma = 0°$ to strongly-coupled structure at $\gamma = 0°$, when passing through the triaxial plane. Comparison with the experimental data for several isotopes is also given. Different regions of the triaxial deformation have a typical signature. This allows to deduce the γ parameter from measured spectra of the odd-mass isotopes. This approach was successfully used in the study of ^{187}Au - see a comparison of the calculation with various deformation parameters given in Fig. 2. Present proposal aims to extension of this towards the lighter isotope.

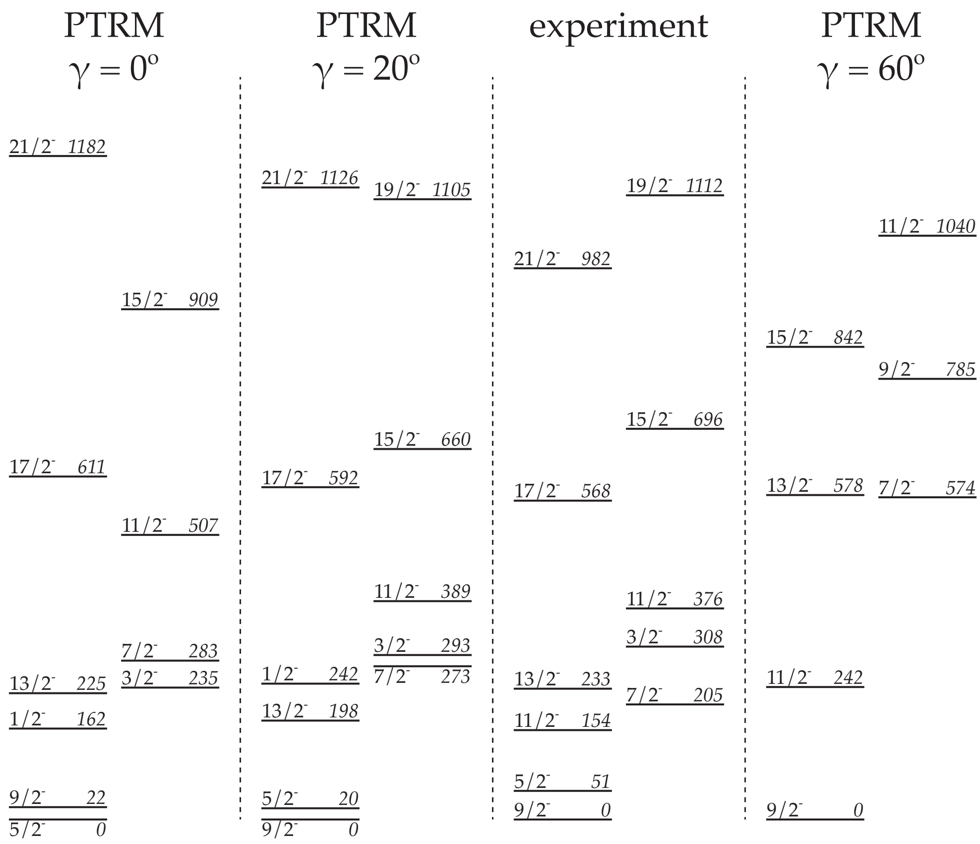

Figure 2: Excited states of the $1h_{9/2}$ proton-intruder configuration in ^{187}Au calculated for axially symmetric, prolate, oblate and triaxial ($\gamma = 20°$) shape. For a comparison, experimental data is shown. Figure is adapted from [13].

Therefore, multipolarities of transitions need to be determined.

2 Detection system

The TATRA tape system [16] will be used for collection and transportation of samples of the ^{185}Hg isotope. The operation principle of the system is given in Fig. 3. The tape is made of rapidly quenched metal and it is designed at the Institute of Physics. To solve the problems with welding of the quenched material that complicated runs in 2014 and 2016, new tape with two layers was prepared and tested.
Conversion electrons will be detected with the 5 mm thick Si(Li) detector with 80 mm^2 surface. The detector is windowless, cooled with liquid nitrogen and it is housed in the retractable cryostat. It detects conversion electrons approximately up to 2.5 MeV with full width at half maximum of 1.6 keV. The TATRA system reaches vacuum below 10^{-7} mbar, which allows operation of such detector. The system is equipped with cryogenic module to ensure safe cooling and warming of the detector. Conversion electrons are detected both in singles and coincidence modes. It is important to note, that due to large density

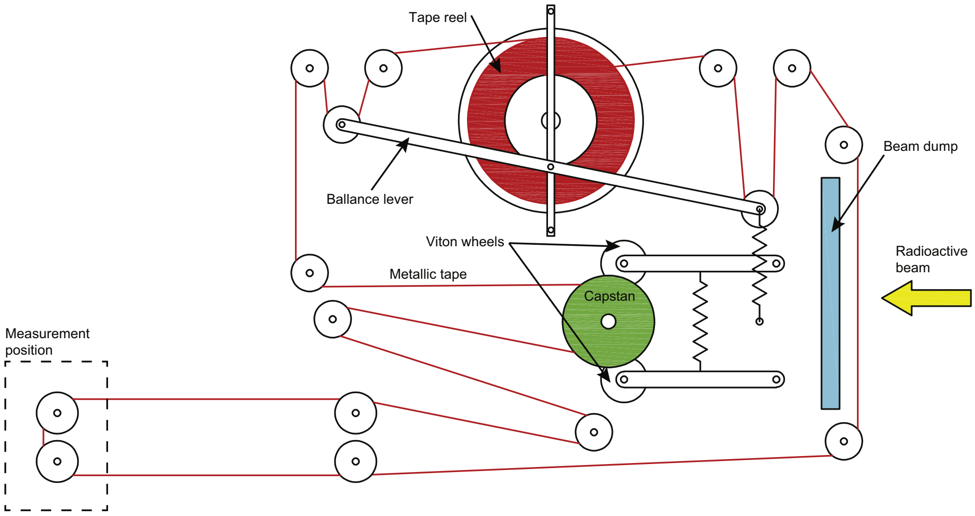

Figure 3: Operation principle of the TATRA tape transportation system. Figure is adopted from [?].

of excited states, the cryogenic Si(Li) detector is the only option for this study. Silicon detector cooled with, e.g., alcohol does not have sufficient resolution - see details in ??.
A general complication related to studies of odd-Au isotopes is a large density of excited states at low energies, see e.g. [13]. This leads to the complexity of odd-mass decay schemes (several hundreds of γ rays), that renders the Rydberg-Ritz technique too ambiguous to be useful, unless γ-ray energies are measured to a precision better than 50 eV. Therefore, advanced coincidence analysis has to be performed, which includes, e.g, running gates technique. This makes the analysis procedure very complicated a leaves a risk of serious mistakes to be made, see [11]. Further, the use of coincidence spectroscopy to reliably sequence decay paths can be difficult or impossible because of isomerism (coincidence delay) occurring for some of the low-lying excited states. In the face of such challenges, we have developed and applied a dedicated experimental technique [15], which is based on novel Broad Energy Germanium (BEGe) detector, for these studies.
A BE2020 BEGe detector operated at ultra-high gain was successfully used to construct the level scheme of ^{181,183}Au [4, 5], which are nuclei with large densities of excited states at low energies. The advantage of the BEGe detector is not only excellent resolution, and nearly ideal gaussian peak shape, but also the ability to detect high-energy γ rays. Using this detector, γ-ray energies with a precision below 50 eV (in most cases even down to 10 eV) could be determined. To reach such precision, it is critical to operate the detector at ultra-high gains and also to ensure the stability of the electronics. With precisely determined γ-ray energies, the Rydberg-Ritz combination principle at the level of 30 eV precision could be used, which makes the process of complex level scheme construction much more simple. Properties of the BEGe detector, particularly the smooth background continuum (which helps normalisation and deconvolution), allowed the peaks of interest to be distinguished from other processes such as from the decay of daughter activities. This is very important since it simplifies the analysis and reduces the risk of misinterpreting

observed transitions. It also provides additional information on the daughter isotopes, which can be analysed separately. Even with the precision of the BEGe detector, the γ-γ coincidence analysis cannot be omitted. Therefore the BE2020 BEGe detector will be used in a combination with coaxial germanium detectors.

3 Clarification of amount of requested beam time

We aim on the spectroscopy at the level 1 % of the intensity of the strongest observed γ ray. Such sensitivity guarantees that expected $E0$ transitions between both negative- and positive-parity states will be identified and assigned to the level scheme. Our previous study of the ^{183}Hg decay, presented [4], was based on the data collected during approximately 2 days of measurement. Weakest assigned γ rays have intensity 6 % of the strongest transition. Compared with study reported in [4], the γ-ray detection efficiency of the TATRA system was increased by installation of third large (90 % relative efficiency) coaxial germanium detector. This increased γ-γ coincidence efficiency by a factor of approximately 3 and γ-electron coincidence efficiency by a factor of approximately 1.5. Another increase of the statistical quality of the data will come from increased activity of samples of ^{185}Hg. The data acquisition system of the TATRA has been optimised and presently it can accept count rates of approximately factor of 2 larger, then previously. The yield for the ^{185}Hg is not a limitation, since it is so high that the beam gate needs to be manipulated carefully, to keep the activity of the each sample and thus counting rate of detectors sufficiently low to not overload the electronics.
Therefore, within 4 days of beam time (i.e., twice more than it was used for the study of ^{183}Hg) a factor of 12 more γ-γ coincidences and a factor of 6 more γ-electron coincidences will be detected. This will allow to fulfil the above goal.
Since the TATRA system is transportable and needs to be delivered to CERN by ground means, the economy aspect of the experiment needs to carefully planned. We consider 4 days of measurements as acceptably long time that pays off the costs of transportation, installation with the final tuning of the system and uninstallation after the experiment. Study of ^{189}Hg could be proposed, within present document. However, we still have data from previous measurements and we prefer to finish their analysis. After this will completed, if needed, we will apply for dedicated experiment on the ^{189}Hg decay. Proposals to study ^{179,181}Hg decays will come as soon as the new high-vacuum tape system is ready, see the discussion above. Therefore we propose to add 7 shifts to already approved 5 and use 12 shifts to study ^{185}Hg decay.

Summary of requested shifts: 7

References

[1] M. Venhart *et al.*, Phys. Lett. B **695**, 82 (2011).

[2] M. Venhart *et al.*, Phys. Rev. C **95**, 061302(R) (2017).

[3] M. Venhart *et al.*, accepted for publication in Phys. Lett. B

[4] M. Venhart *et al.*, J. Phys. G **44**, 074003 (2017).

[5] M. Sedlák *et al.*, submitted to Eur. Phys. J. A

[6] M. Balogh *et al.*, to be published

[7] E. F. Zganjar *et al.*, Phys. Lett. B **58**, 159 (1975).

[8] V. Berg *et al.*, Nucl. Phys. A **244**, 462 (1975).

[9] C. Bourgeois *et al.*, Nucl. Phys. A **295**, 424 (1978).

[10] K. Heyde, P. Van Isacker, M. Waroquier, J. L. Wood and R. A. Meyer, Phys. Rep. [**?**], 291 (1983).

[11] M. O. Kortelahti *et al.*, J. Phys. G: Nucl. Phys. **14**, 1361 (1988).

[12] M. O. Kortelahti, PhD. Thesis Georgia Institute of Technology, Atlanta, GA, USA, (1987).

[13] D. Rupnik *et al.*, Phys. Rev. C **58**, 771 (1998).

[14] J. Meyer-ter-Vehn, Phys. Rev. Lett. **32**, 24 (1974).

[15] M. Venhart *et al.*, Nucl. Instrum. and Methods in Phys. Res., Sect. A **849**, 112 (2017).

[16] V. Matousek *et al.*, Nucl. Instrum. and Methods in Phys. Res., Sect. A **812**,118 (2016).

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
TATRA tape transportation system (needs to be transported from Bratislava)	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure			
Vacuum	10^{-7} mbar		
Temperature	100 K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	4 kV, 1 μA - bias of germanium detectors		
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]	molten Pb target		
Beam particle type (e, p, ions, etc)	^{185}Hg		
Beam intensity	10^{7} particles/s		
Beam energy	30 keV		

Cooling liquids	liquid nitrogen		
Gases	venting gas - nitrogen		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope	^{60}Co, ^{152}Eu, ^{241}Am - γ calibration sources		
• Activity	100 kBq		
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	Pb bricks will be used for shielding of γ radiation		
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable	alcohol for cleaning of vacuum chambers		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		

Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	Vacuum chamber is heavy and needs to be manipulated carefully		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]