EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

**Addendum to the ISOLDE and Neutron Time-of-Flight Committee**

# Simultaneous spectroscopy of $\gamma$ 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 continue in studying of $^{183}$Hg$\rightarrow$$^{183}$Au decay with simultaneous detection of $\gamma$ rays and conversion electrons. $\gamma$ rays will be detected with Broad Energy Germanium detectors and large-volume coaxial detectors. This configuration will provide very good energy resolution for $\gamma$ rays with energy $< 1$ MeV and capability to detect also higher energies in coincidence mode. Conversion electrons will be detected with Si(Li) detector cooled with liquid nitrogen. The TATRA tape transportation system will be used to transport samples created by deposition of radioactive-ion beam.

**Requested shifts:** 30 shifts, (1 run over 1 year)

# 1 Motivation of the experiment

The motivation for the IS521 experiment is to study shape coexistence [1] in the odd-Au isotopes in great detail. The odd-Au isotopes offer a particularly suitable system for such studies, since multiple (four, possible five) coexisting configurations occur at low excitation energy. States due to the proton-intruder ($h_{9/2}$, $f_{7/2}$ and $i_{13/2}$) and proton-hole ($h_{11/2}$, $s_{1/2}$, $d_{3/2}$, and $d_{5/2}$) orbitals couple to different coexisting structures in corresponding Pt and Hg cores [2]. This leads to an enormous complexity for the level schemes of the neutron-deficient odd-Au isotopes [3]. However, it is essential since it has been found from many years of experience at the UNISOR Facility (Oak Ridge) [4] to be very effective way of establishing detailed complex structure far from stability.

Already, complementary to the proposed IS521 experiment, a series of in-beam studies of $^{173,175,177,179,187}$Au with unusually long running-times (between $7-14$ days) have been performed in $2011-2014$ by our collaboration at the University of Jyväskylä and at iThemba Labs. These studies produced data of excellent quality. However, in-beam studies cannot alone address critical issues of nuclear structure, since the population of non-yrast configurations in complete fusion reactions is limited. Therefore, Hg $\beta$-decay study is an excellent complementary technique, since it populates predominantly low-spin states in the Au daughter nuclei (due to presence of only low-spin $\beta$-decaying states in the Hg precursors of interest).

Such experiments must involve simultaneous measurements of both $\gamma$ rays and conversion electrons, since only in such a way can spins and parities be determined. Moreover, $E0$ transitions which are model-independent fingerprint of the shape coexistence can be identified.

# 2 IS521 experiment in August 2014

The IS521 experiment was performed in August 2014 at LA1 beam line. With 12 shifts of running time, datasets for $^{181,183,185}$Hg decays were collected. For the purpose of the IS521 experiment a new traveling setup, the TATRA tape transportation system, was developed at the Institute of Physics, Slovak Academy of Sciences in Bratislava. It uses a metallic tape, prepared by a rapid quenching ($10^6$ K/s) of an alloy, for transportation of the activity from irradiation point to detector position. The rapid quenching produces an amorphous metallic material, which has excellent mechanical properties needed for the tape transportation system. The tape cannot be stretched or broken by the small stepper motor. Its properties are very stable during operation and it is not corrosive. It keeps metallic properties and thus can be used in a high (possibly also an ultra-high) vacuum environment. The tape is welded to form an endless loop and is carried by a single reel. This concept was widely used at the UNISOR facility at Oak Ridge National Laboratory [6]. Such a design allowed only one stepper motor to be used, thus making control of the system simple and precise. The tape is completely insulated from the rest of the system allowing a direct beam current measurement. This, together with a segmented Faraday cup located at the entrance to the source collection chamber makes beam tuning very easy.

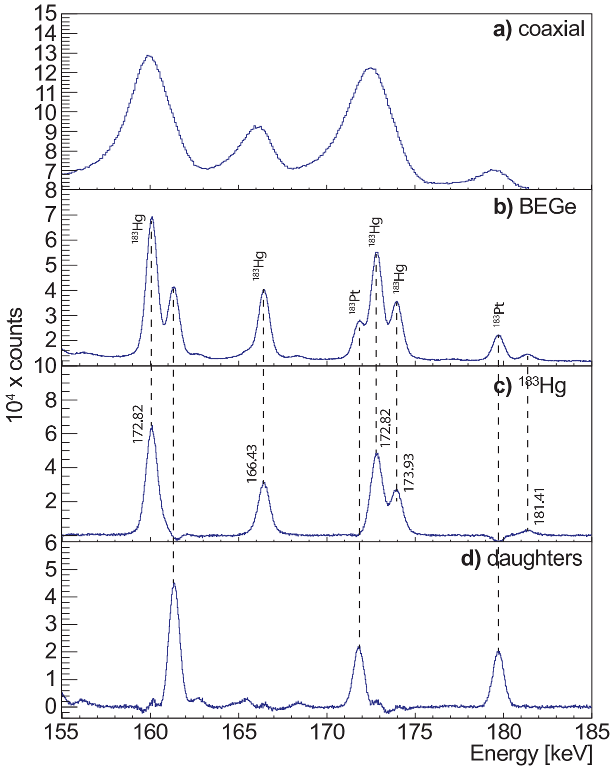

Figure 1: **a)** Spectrum of $^{183}$Hg $\gamma$ ray singles detected with coaxial detector. Measurement time of 15 s was used. **b)** Spectrum of $^{183}$Hg $\gamma$ ray singles detected with the BE2020 detector. Measurement time of 15 s was used. **c)** Deconvoluted spectrum of $^{183}$Hg $\gamma$-ray singles (without daughter decays and contaminants, see text for details). **d)** Deconvoluted spectrum of $\gamma$ ray singles of daughter activities.

Three germanium detectors were used to detect $\gamma$ rays: two conventional coaxial HPGe detectors together with one novel BE2020 type Broad Energy Germanium detector (BEGe) [5] designed by Canberra Industries, Inc. The detectors were instrumented with GO (Gain and Offset) amplifiers designed at the University of Liverpool. They were used to amplify the preamplifier signal without shaping. The signal was then analysed using a Pixie-16 digitiser produced by XIA, Inc. company. In such a way, the dynamical range of the digitiser covered energy $0-1$ MeV for the BEGe detector and $0-2.5$ MeV for the coaxial detectors. In this mode, the BEGe detector achieved excellent energy resolution. Doublet components differing by as little as 0.4 keV could be distinguished in the $\gamma$ ray singles spectrum. Thus, the $\gamma$ ray singles spectrum yields detailed information of the decay strength, which is usually not the case for studies of odd-mass decay with conventional detectors.

To detect conversion electrons, a Super Si(Li) detector with thickness of 5 mm was purchased from Canberra. The detector is cooled with liquid nitrogen in a retractable cryostat. This allows the retraction of the detector from the measurement chamber, and its isolation with a gate valve to keep it cold in the case of accidental opening of the system (with the breaking the vacuum) during the run. Measurement of conversion electrons failed. This was caused by a 5 months delay in delivery of the Super Si(Li) detector by Canberra. The detector was delivered only a few days before transportation of the system to CERN without a chance to have it tested at the Institute of Physics in Bratislava. The following problems were diagnosed during installation of the detector at the LA1 beam line:

1. There was a serious vacuum leak in the cryostat and proper vacuum could not be

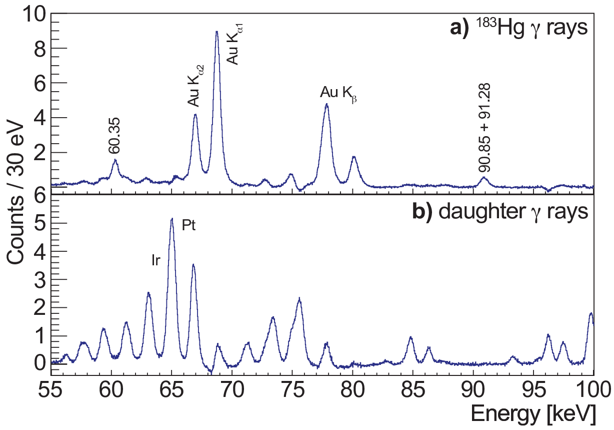

Figure 2: **a)** Deconvoluted spectrum of $^{183}$Hg $\gamma$-ray singles (without daughter decays and contaminants, see text for details). **b)** Deconvoluted spectrum of $\gamma$ ray singles of daughter activities.

reached.

2. The detector was equipped with a beryllium window, even though it was ordered windowless.

3. A transistor reset preamplifier was erroneously fitted, which is not compatible with our data acquisition system.

Therefore the Si(Li) detector could not be used and only $\gamma$-ray data, albeit of high quality, were collected. These data are now under analysis. From this analysis several new approaches and algorithms for the data handling were developed. The methodology of this work is expected to lead to several publications in Nuclear Instruments and Methods. However for the physics focus of this proposal the measurement of conversion electrons is critical. Also the statistical quality of the data, especially of the $\gamma$-$\gamma$ coincidences must be improved.

## 3 Preliminary results

The most important finding of the run in August 2014 is fact that a BEGe type detector is the best option for detailed studies of $\beta$ decay of odd-mass isotopes, since odd-mass decay schemes have a large density of excited states at low energy. This density is reflected in the enormous complexity of corresponding $\gamma$ ray and conversion electron spectra. This complexity is furthermore exacerbated due to interferences, e.g., from decay of radioactive-ion beam contaminants, decays of daughter and granddaughter isotopes, from additional decay modes of the parent isotope ($\alpha$ decay or $\beta$-delayed processes) or from processes induced by neutrons that are typically present in experimental areas.
The spectrum in Fig. 1a) shows a $\gamma$-ray singles of the $^{183}$Hg decay ($T_{1/2} = 8.8\,\mathrm{s}$) detected with a coaxial p-type HPGe detector with a relative efficiency of 80 % and FWHM of 2.2 keV at an energy of 1.332 MeV. A data collection time of 15 s was used for each sample of $^{183}$Hg. Fig 1b) shows the spectrum of $\gamma$ ray singles of the $^{183}$Hg decay detected with the BE2020 detector and acquired with the same timing conditions as the previous one. A significant difference of energy resolution between detectors is evident.

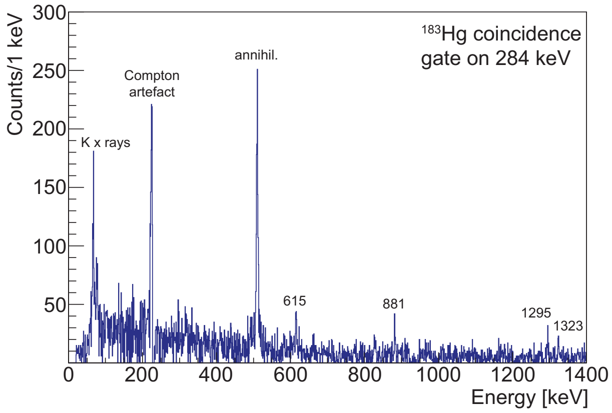

Figure 3: Spectrum of $\gamma$ rays coincident with the 264 keV transition. Spectrum was produced by gating on the BE2020 detector. Coincident $\gamma$ rays were detected with coaxial detectors.

Using the timestamped stream of the data, acquired with the Pixie-16 cards, it is possible to distinguish between peaks occurring due to $^{183}$Hg (decay of interest) and daughter decays. For this analysis, modern algorithms incorporated in the ROOT package for background continuum estimation were used. The power of this technique is clearly demonstrated in Fig. 1c) and d). Panel c) gives the $\gamma$-ray spectrum of $^{183}\mathrm{Hg}\rightarrow^{183}\mathrm{Au}$ decay, while panel d) gives the $\gamma$-ray spectrum of daughter decays. The method clearly can de-convolute both components and thus allows for unambiguous identification of particular peaks in the spectrum. Separate analyses of $\gamma$-gated decay curves and $\gamma$-$\gamma$ coincidences confirmed the validity of this technique. Daughter decays can be analysed separately, providing additional information on other isotopes, which are usually only poorly studied.

The resolving power of the BEGe detector at energies below 100 keV is demonstrated in Figure 2. The same de-convolution technique as described above, was used. Spectrum in Fig. 2a) is dominated by Au K X rays. The 60.35 keV line, which is a proposed $1/2^+$ to $3/2^-$ $E1$ transition in $^{183}$Au [7], is also evident. In Fig. 2b), X rays of Pt, Ir and Os are dominant, while Au is suppressed.

Very good energy resolution of the BEGe detector in the region up to 1 MeV, together with the proposed deconvolution technique, allow to employ the Rydberg–Ritz combination principle [8] as an important element of the level scheme construction. This will be combined with $\gamma$-$\gamma$ and $\gamma$-electron coincidences from the proposed experiment. Also, the coincidence gating greatly benefits from the improved resolution; application of the running gate technique, employed, e.g., in [3], will not be needed. This will reduce the time for the data analysis significantly.

The $Q$ value of the $^{183}\mathrm{Hg}\rightarrow^{183}\mathrm{Au}$ decay is approximately 6 MeV. Therefore the decay pattern is controlled by the Pandemonium effect. It is the nature of level schemes dominated by the Pandemonium effect that the coincidence information is mainly between low- and high-energy $\gamma$ rays. Thus the coincidence efficiency is reduced by a factor of 10 compared with schemes dominated by low-low energy coincidences.

A typical coincidence spectrum gated with the 284 keV $\gamma$-ray is given in Fig. 3. Poor statistical quality of the coincidence spectra, acquired in August 2014 run, does not allow construction of an extensive level scheme and the unambiguous placement of many transitions. The partial level scheme of states associated with the $h_{9/2} \oplus f_{7/2}$ mixed intruder configuration, extracted from present data, is shown in Fig. 4. Note that the proposed

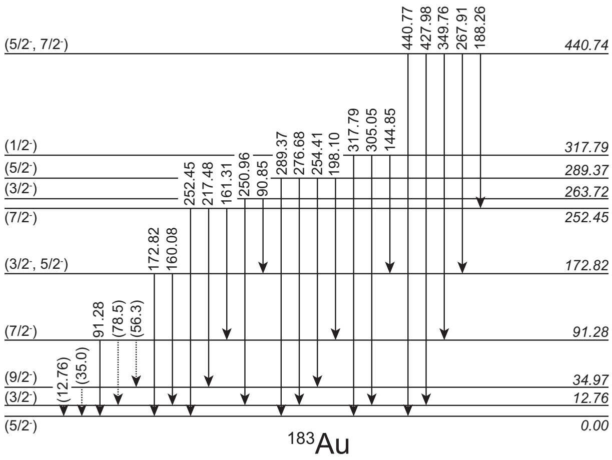

Figure 4: Partial level scheme of $^{183}$Au: negative-parity states associated with the $h_{9/2} \oplus f_{7/2}$ mixed intruder configuration

spins and parities are based entirely on the systematics of the heavier isotopes [4].

# 4 Proposed second run

We propose to carry out a second run of the IS521 experiment, which will aim to elucidate the level scheme of $^{183}$Au. The proposed ultra-high statistics experiment will tie down a pure low-spin $^{183}$Hg decay scheme (the high spin isomer in $^{183}$Hg is too short lived to $\beta$ decay). Significant improvement of $\gamma$-$\gamma$ coincidence information is needed. With such an improvement, together with state-of-art BEGe detectors, conversion electron and low-energy $\gamma$ ray measurement (with a Si(Li) detector inside of the chamber) the anticipated very complex level scheme will be constructed.

Due to only low spin $\beta$ decay, Tthe analysis of the $^{183}$Hg decay is less complicated than that for $^{185}$Hg (which has also $13/2^+$ $\beta$-decaying isomer). Preliminary analysis of the systematics and the IS521 data suggest a similarity between the $^{183}$Au and the $^{185}$Au isotopes. Therefore, as an optimal strategy of the Au program we propose to get the best possible data for the $^{183}$Hg. Later we will continue with a dedicated $^{185}$Hg decay study with the assistance of the laser ion source to separate the low- and high-spin isomers. Only then can we effectively study lightest isotopes reachable at ISOLDE by the decays of $^{177,179,181}$Hg.

In a new version, the TATRA system is equipped with turbo molecular pump with pumping speed of 300 l/s. The pump is connected directly to the chamber of the system. This system allows to pump the station quickly to a vacuum below $10^{-7}$ mbar. The measurement position has been redesigned completely. Now it is based on an aluminium cube with 50 µm thick titanium windows. These windows are sealed with standard copper gaskets of the ConFlat standard. This allows to reach very good vacuum at the measurement position. Thin titanium windows and aluminium based construction material will improve the transmission of $\gamma$ rays, especially at low energies, into the BEGe detectors.

The $\gamma$ rays will be detected with two BEGe detectors: BE2020 (relative efficiency 9 %) and BE6530 (relative efficiency 60 %). The BE2020 was successfully used in the first run and therefore it is well characterised and therefore we prefer to use it together with the new large BE6530 (largest BEGe detector available). This will increase the total BEGe efficiency of the system by a factor of 6 − 7. For $\gamma$ rays with energies above 1 MeV, two large volume germanium detectors will be used. The same electronics instrumentation of detectors as in the previous run will be used.

The Super Si(Li) detector was repaired and modified in Canberra factory and will be ready for the next run. Extensive testing at the Institute of Physics will be possible, which was not the case of previous run. All the detectors will be instrumented in the same way as in previous run. Conversion electron measurements will be critical, since they will establish multipolarities of transitions and they will also identify transitions with $E0$ components, that are expected in $^{183}$Au.

In previous experiment, roughly 4 shifts were spent to study the $^{183}$Hg decay. Therefore, with the requested 10 days of beam time, i.e., 30 shifts, and the above-described BEGe efficiency increase, we will collect approximately factor of 70 more data, which will be sufficient to elucidate the nuclear structure of $^{183}$Au isotope.

Another important issue is that an extensive dataset of hitherto poorly studied $^{183}$Au→$^{183}$Pt decay will be collected. Further, the $^{183}$Hg has a 12 % $\alpha$ branch producing $^{179}$Pt isotope. The recoiling effect of $\alpha$-decay causes escape of $^{179}$Pt species from the tape that accumulate at the measurement position. As demonstrated above, these peaks do not disturb the main study. However, thanks to this effect, long lived decays within the A = 179 mass chain can be studied. Note that these are refractory elements and thus are not so easily accessible for dedicated $\beta$-decay studies.

**Summary of requested shifts:** We request 30 shifts (10 days) of $^{183}$Hg beam (molten Pb target, plasma ion source)

# References

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# 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 spectrometer (Bratislava tape system) | ☒ Existing | ☒ To be used without any modification |
| [Part 1 of experiment/ equipment] | ☐ Existing | ☐ To be used without any modification<br>☐ To be modified |
|  | ☐ New | ☐ Standard equipment supplied by a manufacturer<br>☐ CERN/collaboration responsible for the design and/or manufacturing |
| [Part 2 of experiment/ equipment] | ☐ Existing | ☐ To be used without any modification<br>☐ To be modified |
|  | ☐ New | ☐ Standard equipment supplied by a manufacturer<br>☐ CERN/collaboration responsible for the design and/or manufacturing |
| [insert lines if needed] |  |  |

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 | [pressure][Bar], [volume][l] |  |  |
| Vacuum | Standard ISOLDE vacuum |  |  |
| Temperature | [temperature] [K] |  |  |
| Heat transfer |  |  |  |
| Thermal properties of materials |  |  |  |
| Cryogenic fluid | $LN_2$ |  |  |
| **Electrical and electromagnetic** |  |  |  |
| Electricity | 4.5 kV (bias of HPGe detectors) |  |  |
| Static electricity |  |  |  |

| | | | |
|---|---|---|---|
| Magnetic field | [magnetic field] [T] | | |
| Batteries | ☐ | | |
| Capacitors | ☐ | | |
| **Ionizing radiation** | | | |
| Target material [material] | | | |
| Beam particle type (e, p, ions, etc) | $^{183}$Hg | | |
| Beam intensity | $10^8$ particles/s | | |
| Beam energy | 30 keV | | |
| Cooling liquids | $LN_2$ | | |
| Gases | [gas] | | |
| Calibration sources: | ☒ | | |
| • Open source | ☐ | | |
| • Sealed source | ☒ [ISO standard] | | |
| • Isotope | $^{152}$Eu, $^{133}$Ba, $^{137}$Cs, $^{60}$Co and $^{241}$Am | | |
| • Activity | all sources $< 40$ 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 shielding of HPGe detectors | | |
| Harmful | [chem. agent], [quant.] | | |
| CMR (carcinogens, mutagens and substances toxic to reproduction) | [chem. agent], [quant.] | | |
| Corrosive | [chem. agent], [quant.] | | |
| Irritant | [chem. agent], [quant.] | | |
| Flammable | Isopropylalcohol for cleaning of the inner installations | | |
| 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) | Stepper motor located outside of the vacuum chamber | | |
| Mechanical properties (Sharp, rough, slippery) | Detector chamber is heavy | | |
| 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 | [location] | | |
| Poor ergonomics | [location] | | |

Hazard identification: Negligible.

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): 3 kW (dominantly electrical cooling of HPGe detectors).