EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status report to the ISOLDE and Neutron Time-of-Flight Committee
(Following HIE-ISOLDE Letter of Intent I-110 and Proposal IS563)

# IS563: Coulomb excitation of $^{182,184}$Hg: Shape coexistence in the neutron-deficient lead region

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**Abstract:** We put forward a study of the interplay between individual nucleon behaviour and collective degrees of freedom in the nucleus, as manifested in shape coexistence in the neutron-deficient lead region. Based on our past experience and the results obtained from previous Coulomb-excitation measurements in this mass region performed with 2.85 MeV/u beams from REX-ISOLDE, we propose a detailed studies of $^{182,184}$Hg nuclei using higher beam energies from HIE-ISOLDE. Twelve shifts were approved for the IS563 proposal and the approved beam-time was not scheduled yet. In this report we present the current status of knowledge concerning the nuclei of interest, results obtained from previous Coulomb-excitation studies and recently performed complementary measurements at the ISOLDE Decay Station IS641. Finally, in view of the most recent experimental and theoretical achievements obtained in the scope of the Hg charge radii

measurements there is a renewed interest in performing for the first time the Coulomb-excitation measurements for the odd-mass Hg isotopes. This is planned to be addressed as an addendum to the IS563 proposal.

**Remaining shifts**: 12/12 shifts, (split into 1 run over 1 years)
**Beamline:** MINIBALL + DSSSD + SPEDE

## 1. Introduction and physics case

The neutron-deficient mercury isotopes (Z=80) serve as an illustrative example of shape coexistence [1,2], whereby at low excitation energies near-degenerate nuclear states are characterized by different shapes. The first observation of a dramatic change in the ground-state mean-square charge radii was observed through isotope shift measurements in $^{183}$Hg and $^{185}$Hg, when comparing to heavier mass mercury isotopes [3]. Since then a large amount of information has been collected for nuclei around the N =104 midshell using different experimental techniques. This resulted, amongst others, in the observation of a large odd-even staggering in the isotope shifts in the mercury isotopes around $^{181\text{-}185}$Hg [4,5]. Recent results obtained from isotope-shift measurements (see Fig. 1 right side) extended the knowledge on the ground-state charge radii and indirectly the deformation systematics down to $^{177}$Hg [6]. Further, lifetime measurements performed for $^{184}$Hg and $^{186}$Hg [7,8] suggested a sudden increase in deformation of the excited yrast states with the spin larger than two. Radioactive-decay studies identified coexisting bands in $^{184;186;188}$Hg, assumed to be characterized by different deformations [9,10,11]. This phenomenon was observed in $^{182}$Hg as well by means of in-beam spectroscopy studies [12]. In the neutron-deficient even-even mercury isotopes with neutron number around mid-shell (N=104, $^{184}$Hg) the intruding deformed states come low in excitation energy and mix with the normal more spherical states (see Fig. 1, left side). The mixing between the different states gives rise to strongly converted $2^+_2 \rightarrow 2^+_1$ transitions as recently deduced from beta-decay studies of $^{182,184}$Tl performed at ISOLDE [13]. Due to the proximity of Z=82 shell closure, the structure of the neutron-deficient mercury isotopes is highly sensitive to the interplay between the microscopic (single-particle degrees of freedom) and the macrosopic (collective degrees of freedom) effects. The experimental knowledge of the electromagnetic properties of these nuclei is important to test the predictions of various theoretical models, such as the beyond mean-field model (BMF) [14], the quadrupole collective model based on the General Bohr Hamiltonian (GBH) [15], the interacting boson-based model with configuration mixing (IBM) [16] as well as the very recent Monte-Carlo Shell Model calculations applied for the first time in the mercury region [6].

## 2. Results from previous Coulomb-excitation experiments performed at ISOLDE with neutron-deficient Hg beams at energy of 2.85 MeV/A

The successful Coulomb-excitation experiments to study some selected neutron-deficient, even-even mass isotopes of mercury, polonium, radon and radium have shown the potential to perform such experiments using post-accelerated REX-ISOLDE beams. The electromagnetic structure of even-mass $^{182\text{-}188}$Hg isotopes was studied using safe-energy (2.85 MeV/A) Coulomb excitation of neutron-deficient mercury beams delivered by the REX-ISOLDE facility at CERN. With the use of low-energy mercury beams the population of the excited states is mainly restricted to the $0^+_{1,2}$, $2^+_{1,2}$ and $4^+_1$ states. Moreover, intense X-ray peaks were present in the $^{182,184}$Hg $\gamma$ ray spectra.

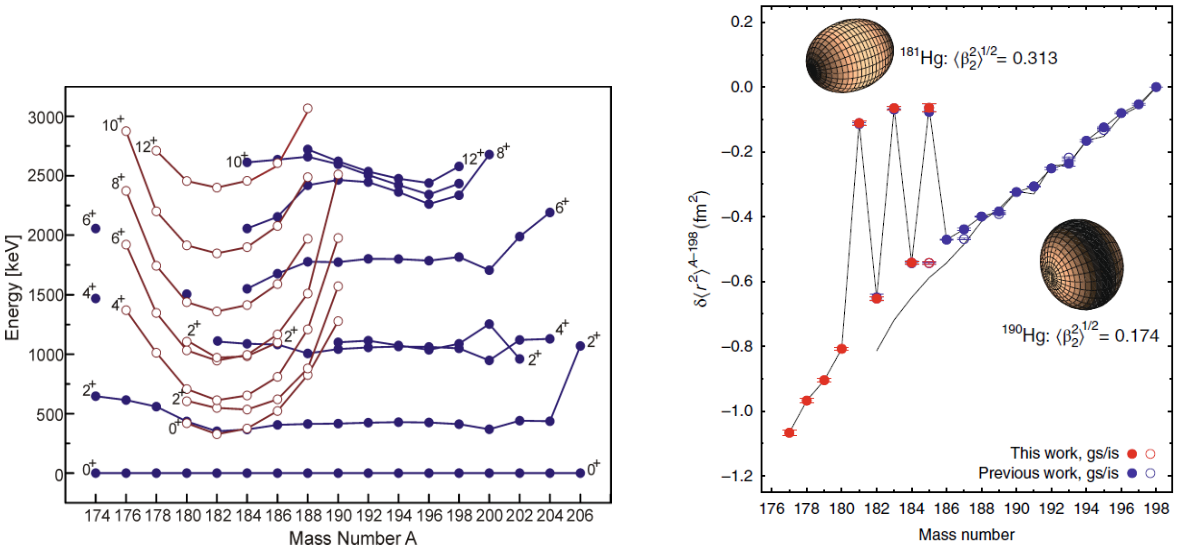


*Figure 1: Left: energy level systematics of even-even Hg isotopes, taken from Reference [26]. The full circles are associated with the weakly oblate band and the open circles are those related to the excited prolate band in even – even Hg isotopes.; Right: The changes in the mean square charge radii for Hg isotopes, taken from Reference [6].*

These X rays originate from: (i) atomic processes taking place when the mercury beam passes through the target [17], (ii) the conversion of the observed γ-ray transitions and (iii) the *E*0 de-excitation after Coulomb excitation. From the intensity of observed X-rays the population of the $0^+_2$ intruder states in $^{182}$Hg and $^{184}$Hg could be deduced albeit with limited accuracy. Finally, the main achievement of that project was the extraction of the transitional reduced E2 matrix elements coupling lowest-lying yrast and non-yrast states, including their relative signs [18,19]. Moreover, the Coulomb-excitation data for $^{182;184}$Hg have been recently re-evaluated [20] since new, revised spectroscopic information, i.e., gamma ray branching ratios and total conversion coefficients, $\alpha_{tot}(2^+_2 \rightarrow 2^+_1)$, have become available, equal to 7.2 +/- 1.3 in $^{182}$Hg and 14.2 +/- 3.6 in $^{184}$Hg [13]. The knowledge on the latter was crucial for the Coulomb-excitation analysis.

To summarize, the obtained results clearly show that the low-energy electromagnetic structure of $^{182,184,186,188}$Hg isotopes can be described in terms of mixing of two distinct configurations which coexist at low excitation energy. Mixing between a weakly deformed oblate and more deformed prolate structures gains importance when going towards neutron midshell N = 104. Moreover, combined information from Coulomb excitation and spectroscopic data [13] enable to extract, for the first time, the *E*0 monopole strengths, which is a critical indicator of shape coexistence. The resulting $\rho^2(E0)*10^3$ values for the $2^+_2 \rightarrow 2^+_1$ transitions are 141(51) and 90(30) for $^{182}$Hg and $^{184}$Hg, respectively. Complementary to our previous work [19], a systematic and detailed comparison of experimental results , i.e., level energies, quadrupole and monopole transition probabilities, with theoretical predictions was performed. A summarizing publication presenting a comprehensive Coulomb-excitation studies of shape coexistence phenomena in the even-even neutron-deficient mercury isotopes has been submitted to European Physics Journal and is now under the refereeing process [20].

## 3. IS563 HIE-ISOLDE experiment and complementary measurement

Coulomb excitation of exotic neutron-deficient mercury beams at REX-ISOLDE has spawned a large array of data on lowest-lying excited states evidencing shape coexistence in this region. However, because of the low-beam energy from REX-ISOLDE only information on the lowest lying states was obtained in $^{182,184,186,188}$Hg. Moreover, there is a lack of information on mixing coefficient values of $\Delta I=0, I\neq 0$ transitions, as well as lack of precision on some of the critical spectroscopic data, i.e. γ-ray branching ratios and conversion coefficients [13]. The latter influences the extracted uncertainties of some of the deduced E2 matrix elements considerably (especially on the quadrupole moments of the $2^+$ states), preventing, in certain cases, to draw firm conclusions on the structure of the two bands observed.

The goals of the IS563 experiment are multi-fold. Firstly, we will explore the higher lying non-yrast states in $^{182}$Hg and $^{184}$Hg where currently very little is known or no experimental information is available concerning their electromagnetic properties. Secondly, we will provide information on the quadrupole moments for the excited states, particularly $2^+$'s as well as other transitional matrix elements between higher-lying yrast and non-yrast states populated in the experiment. Thirdly, through the use of the quadrupole sum rules the shape invariants can be extracted for a given state, provided the relative signs and magnitudes of the connecting $E2$ matrix elements are measured. In this way the magnitude and type of deformation of the intruding states in mercury isotopes can be extracted independently on the nuclear-structure models. The Coulomb-excitation technique has the potential to provide such rich information with higher beam energies utilizing the larger multi-step excitation cross-section. ISOLDE is the only place to provide intense and pure neutron-deficient mercury beams ideally suited for Coulomb-excitation studies. While HIE-ISOLDE will bring about the required beam energies, i.e., 4 MeV/A, higher beam intensity as well as improved purity, this will allow to extract the set of reduced matrix elements that couple several excited yrast and non-yrast states [21].

In order to draw firm conclusions from IS563 Coulomb-excitation experiment precisely known complementary spectroscopic data are crucial [2]. This concerns e.g. the unknown mixing ratio values which recently have been proposed to be measured through angular correlations using the GRIFFIN array at ISAC-TRIUMF facility [29]. The lifetime values of the yrast states in $^{182}$Hg and $^{184}$Hg were measured at JYFL in Jyväskylä and at ANL Laboratory, respectively, and published in Refs. [31-33]. Further, the previous beta-decay studies [13] allowed to measure some of the γ-ray branching ratios of the transitions from many of the low-lying states as well as $\alpha_{tot}(2^+_2 \rightarrow 2^+_1)$ in $^{182,184}$Hg. However, the uncertainties of some of these values were relatively high (over 30%). The precise knowledge of these values is particularly important for the analysis of the data from the multi-step Coulomb-excitation experiments providing important constraints and gaining in this way sensitivity to subtle second orders effects such as quadrupole moments of excited states or relative signs of matrix elements.

To prepare for future Coulomb-excitation measurements, profiting from the higher beam energy at HIE-ISOLDE, a dedicated measurements of $\beta^+$/EC deay of $^{182;184;186}$Tl with the ISOLDE Decay Station (IDS) was proposed for the ISOLDE Neutron Time of Flight Committee (CERN) and approved [22]. For the preparation of this campaign (IS641) a new conversion electron detector system (SPEDE) was developed and installed at IDS. This work was performed in collaboration with the Universities of Jyvaskyla (Finland) and York (UK). After the preparatory work (testing different detector configurations, adapting the ancillary detector chamber and data system) a successful campaign took place in November 2018. The on-line data analysis shows that the statistics is improved by one order of magnitude compared to the previous campaign were only two germanium detectors were used [13]. The multi-germanium detector arrangement of IDS used for

IS641 will substantially improve the decay data. The achieved on-line energy resolution of the electron spectra collected with the SPEDE detector was 6 keV at 250 keV. Full data analysis is currently being performed by a KU Leuven PhD student. The results from this experiment represent essential input for a planned IS563 experiment for Coulomb excitation of $^{182,184}$Hg after CERN's Long Shutdown 2.

As it was stated in the IS563 proposal we intend to perform measurements for neutron-deficient $^{182}$Hg (N=102) and $^{184}$Hg (N=104). For these measurements we propose to use the MINIBALL array coupled with the DSSSD CD detector, which subtends an angular range around 15°- 50° in the laboratory frame. In order to measure directly the converted transitions arising from $0^+_2$, $2^+_2$ states, and also maybe other higher-spin states populated in the experiment, the electron spectrometer SPEDE [27] will be used and located in the MINIBALL target chamber at backward angles without hampering the γ-ray detection efficiency. The $^{182,184}$Hg beam energy is chosen to be 4 MeV/A. In the original IS563 proposal we have requested 24 shifts for $^{182}$Hg and 4 shifts for $^{184}$Hg assuming beam intensity of $10^4$ pps for $^{182}$Hg and $10^5$ pps for $^{184}$Hg [21]. However, as the mercury yields are expected to be an order of magnitude higher with the use of the VADIS ion source the number of approved shifts was reduced to 12 in total providing that the expected beam intensities (i.e. $10^5$ pps for $^{182}$Hg and $10^6$ pps for $^{184}$Hg at MINIBALL) and purities will be reached. More recent experiments using Hg beams at ISOLDE have benefited from the new VADLIS ion source [30], which has the same efficiency as VADIS but with a much improved purity due to the use of the RILIS lasers. No shifts allocated for the IS563 experiment were scheduled before LS2. To summarize, a total number of **12 shifts** of Hg beam time is approved to perform IS563 experiment: **8 shifts** for $^{182}$Hg and **2 shifts** for $^{184}$Hg, as well as **2 shifts** for setting–up HIE ISOLDE.

There is an intensified interest in the light, N~104, mercury isotopes which was sparked by the recent laser spectroscopy measurements performed at ISOLDE [6,28]. As introduced in Section 1 of this report, it became possible at CERN-ISOLDE to probe, with this technique, the extremely neutron-deficient mercury isotopes, down to $^{177}$Hg. The endpoint of the famous, well localized odd-even mass staggering effect was determined in $^{181}$Hg (see Fig.1, right side). Moreover, new theoretical Monte Carlo shell model calculations performed by the Tokyo group in the scope of the Hg charge radii measurements, provided information of the underlying mechanism and reproduced the localized nature of the observed shape staggering [6,28]. It was concluded that this phenomenon results from the interplay between monopole and quadrupole nucleon-nucleon interactions with a major role of the neutron $1i_{13/2}$ orbital in driving the large quadrupole deformation. In order to validate this observation, we intend to submit for the next year ISOLDE INTC an addendum to the IS563 proposal aiming Coulomb-excitation study of $^{185m,g}$Hg (following HIE-ISOLDE LOI110 [23]). Yield estimates indicate that 3 shifts for $^{185m}$Hg in the isomeric $13/2^+$ state and 3 shifts for $^{185}$Hg in the 1/2 - ground state are needed for this experiment and the use of VADLIS ion source will be crucial for these measurements to provide the isomeric state selection. The same experimental setup as for the IS563 experiment will be used. In order to reduce systematic uncertainties and to have the same experimental conditions it will be beneficial to perform $^{185m,g}$Hg measurements with the $^{182,184}$Hg experiment (IS563). By doing both measurements for even and odd masses together we reduce the setup time, minimise efforts to calibrate and stabilise the SPEDE spectrometer and reduce systematic uncertainties introduced by the experimental conditions.

## 4. Beam requirements for IS563 experiment

- isotopes: $^{182,184}$**Hg** (half-life times: 10.8 s and 30.9 s respectively);
- intensity**: 10$^5$** pps for $^{182}$**Hg** and **10$^6$** pps for $^{184}$**Hg**;
- beam energy: **4 MeV/A**;
- ion source: VADIS or VADLIS (to perform simultaneous measurements for both even and odd masses of Hg isotopes - see addendum that will be submitted for the next INTC meeting)
- target material: molten lead target
- spatial properties of the beam: 3 mm diameter beam spot size at the target position;
- purity: >90% purity was reached in the previous experiments;
- time profile: the beam pulse from the EBIS should be as long and as homogeneous as possible (a flat profile >400 microsecond long would be ideal).

HIE-ISOLDE should be fully operational for heavy mass beams for slow extraction from the EBIS. For the IS563 experiment we need SPEDE spectrometer to be fully operational. An additional stable-isotope beam time is required for the SPEDE test (as it is planned to be requested along with the status report for IS566).

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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 Choose an item. | Availability | Design and manufacturing |
|---|---|---|
| [if relevant, name fixed ISOLDE installation: MINIBALL + only CD MINIBALL + TREX] | ☐ Existing | ☐ To be used without any modification |
| | | |
| [Part 1 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 |
| MINIBALL + DSSSD + SPEDE | ☐ Existing | ☐ To be used without any modification<br>☐ To be modified |
| | X New | ☐ Standard equipment supplied by a manufacturer<br>X CERN/collaboration responsible for the design and/or manufacturing<br>modifications to target chamber |
| [insert lines if needed] | | |

## HAZARDS GENERATED BY THE EXPERIMENT

*(if using fixed installation)* Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

| ***Hazards*** | *[Part 1 of the experiment/equipment]* | *[Part 2 of the experiment/equipment]* | *[Part 3 of the experiment/equipment]* |
|---|---|---|---|
| **Thermodynamic and fluidic** | | | |
| Pressure | [pressure][Bar], [volume][l] | | |
| Vacuum | | | |
| Temperature | [temperature] [K] | | |
| Heat transfer | | | |
| Thermal properties of materials | | | |
| Cryogenic fluid | [fluid], [pressure][Bar], [volume][l] | | |
| **Electrical and electromagnetic** | | | |
| Electricity | [voltage] [V], [current][A] | | |
| Static electricity | | | |
| Magnetic field | [magnetic field] [T] | | |
| Batteries | ☐ | | |
| Capacitors | ☐ | | |
| **Ionizing radiation** | | | |
| Target material | [material] | | |
| Beam particle type (e, p, ions, etc) | 182Hg ions, 184Hg ions | | |

| | | | |
|---|---|---|---|
| Beam intensity | $10^5$ pps for $^{182}$Hg<br>$10^6$ pps for $^{184}$Hg | | |
| Beam energy | 4 MeV A for $^{182}$Hg and $^{184}$Hg | | |
| Cooling liquids | [liquid] | | |
| Gases | [gas] | | |
| Calibration sources: | ☐ | | |
| • Open source | ☐ | | |
| • Sealed source | X<br>Standard $\gamma$ -ray sources for MINIBALL [ISO standard] | | |
| • Isotope | | | |
| • Activity | | | |
| 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 (1-300MHz) | | | |
| **Chemical** | | | |
| Toxic | [chemical agent], [quantity] | | |
| Harmful | [chemical agent], [quantity] | | |
| CMR (carcinogens, mutagens and substances toxic to reproduction) | [chemical agent], [quantity] | | |
| Corrosive | [chemical agent], [quantity] | | |
| Irritant | [chemical agent], [quantity] | | |
| Flammable | [chemical agent], [quantity] | | |
| Oxidizing | [chemical agent], [quantity] | | |
| Explosiveness | [chemical agent], [quantity] | | |
| Asphyxiant | [chemical agent], [quantity] | | |
| Dangerous for the environment | [chemical agent], [quantity] | | |
| **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 | [location] | | |
| Poor ergonomics | [location] | | |

## 0.1 Hazard identification

3.2 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)*

*… kW*