Coulomb excitation of $^{185}$Hg:

Shape coexistence in the neutron-deficient lead region

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for the P-603 collaboration
Shape coexistence around N=104 mid-shell
Shape coexistence around N=104 mid-shell

S. Sels PhD thesis KULeuven 2018
J. Bonn et al., PLB 38, 308 (1972)
Shape coexistence around $N=104$ mid-shell

S. Sels PhD thesis KULeuven 2018
J. Bonn et al., PLB 38, 308 (1972)
Shape coexistence around N=104 mid-shell

- **Coulomb excitation of even-even $^{182-188}$Hg at REX-ISOLDE:**

  Mixing of two different configurations which coexist at low excitation energy:
  
  less-deformed oblate and more-deformed prolate ones.
  
  Mixing is maximized at N=104.


- **IS563: Coulomb excitation of $^{182,184}$Hg with HIE-ISOLDE**
The experimental spectroscopic information on $^{185}\text{Hg}$

- **1988**: first in-beam spectroscopy experiment for $^{185}\text{Hg}$ was performed in the 80s
  
  *(F. Hannachi et al., ZP A330, 15 (1988))*
  
  - Excited states of $^{185}\text{Hg}$ investigated via $^{161}\text{Dy}(^{28}\text{Si}, 4\gamma)$ reaction at beam energy of 145 MeV
  
  - **Four bands established** built on the prolate $\frac{5}{2}^{-}[521]$, $7/2^{-}[514]$ and $9/2^{+}[624]$ Nilsson states and the $i13/2^{+}$ isomer.

- **2013**: the lowest lying states in $^{185}\text{Hg}$ were investigated by means of the $\beta^{+}/\text{EC}$ decay of $^{185}\text{Tl}$ at ISOLDE *(J. Sauvage et al. EPJ A 49: 109 (2013))*
  
  - A number of new transitions have been identified, including very low-energy conversion electron lines observed for the first time.
  
  - Precise energy location of the $13/2^{+}$ **isomeric state** at $103.7(4)$ keV

- **2021 (April)**: the in-beam $\gamma$-ray and conversion-electron spectroscopy experiment has been performed at Jyväskylä employing SAGE electron spectrometer in conjunction with MARA separator → high statistics data collected.
Monte Carlo Shell Model (MCSM) calculations

- performed in the context of the Hg charge radii measurements.

- Link between the shape coexistence in the N~104 Hg region and the evolution of single-particle orbits caused by nuclear forces.

- Reproduced the localized nature of the observed shape staggering.

- Underlying mechanism:

  an 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.

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Coulomb excitation of $^{185m,g}$Hg $\rightarrow$ quadrupole moments for states in the rotational bands built of the gs and on the isomer.

(a) Plot of $\delta \langle r^2 \rangle$ relative to that of the ground state of $^{186}$Hg. Red / blue points are experimental data. The shaded boxes indicate radii corresponding to the MCSM eigenstates. The grey areas show MCSM eigenstates for which the calculated magnetic moment differs from the measured value.

(c) The occupation numbers of the neutron $1i_{13/2}$ orbit and the proton $h_{9/2}$ orbit for the states indicated by the blue connected areas in (a) (these are the experimentally observed ground states).

Coulomb excitation of $^{185m,g}$Hg

- **Experimental set-up:**
  
  MB + CD ($\sim 16^0 - 54^0$ in the lab. frame) + SPEDE

- **Two secondary targets** used:
  - $^{120}$Sn $E(2^+_1) = 1171$ keV, 2 mg/cm$^2$
  - $^{48}$Ti $E(2^+_1) = 983$ keV, 1 mg/cm$^2$

Count rate estimate

- The **level scheme** of $^{185}$Hg taken from the in-beam spectroscopy measurements [1]

- Intra-band **matrix elements** calculated assuming the rotational coupling model scheme with the intrinsic quadrupole moment inferred from the known $<\beta_2^2>^{1/2}$ values, i.e.,:
  - 0.271(2) and 0.179(10) for the $\frac{3}{2}^-$ ground and $13/2^+$ isomeric states [2, 3];
  - 0.25 for $7/2^-[514]$ and $9/2^+[624]$ bands [1]

- Known **spectroscopic data**

- Assumed **beam intensity**: $10^5$ pps at Miniball

- Two secondary **targets**: $^{120}$Sn and $^{48}$Ti

Various beam-target combinations \( \rightarrow \) different population of states in \(^{185}\text{Hg}\).

\(^{120}\text{Sn} \rightarrow \) maximizes the probability of multi-step excitation

\(^{48}\text{Ti} \rightarrow \) limits the number of populated states; complementary measurements to provide constraints particularly for the ground-state-band transitions.

measured Coulomb-excitation cross sections in \(^{185}\text{Hg}\) normalized to the known excitation of the target nucleus.

\(^{185\text{m,g}Hg} \, @ \, 4 \, \text{MeV}/A \, + \, ^{120}\text{Sn}\)

\(^{185\text{m,g}Hg} \, @ \, 3.5 \, \text{MeV}/A \, + \, ^{48}\text{Ti}\)
Sensitivity to quadrupole moments

- Data collected in $^{185m,6}\text{Hg} + ^{120}\text{Sn}$ experiment will be sensitive to quadrupole moments ($Q$) of excited states (angular data subdivision)

An example: the intensities of $\gamma$ rays depopulating the $9/2^-_{gsb}$ and $17/2^+_i$ states determined with uncertainties $\sim 5\% \rightarrow \sim 5$ and $3.5$ sigma difference, respectively, between solutions corresponding to positive or negative quadrupole moments of these states (assuming rotational limits).
**185m,\textit{g} Hg beam request**

- isotope: $^{185}\text{Hg}$ **in a ground and isomeric states** (half-life of the $\frac{1}{2}$- ground state is 49.1 s and of the $13/2^+$ isomeric state is 21.6 s);
- resonant laser technique needed to produce isomeric beam ($13/2^+$ isomer in $^{185}\text{Hg}$);
- ion source: VADLIS
- intensity: $10^5$ pps for $^{185}\text{Hg}$ in isomeric and ground states;
- beam energy: 3.5 MeV/A and 4 MeV/A;
- target material: molten lead target
- spatial properties of the beam: 3 mm diameter beam spot size at the target position;

**$^{185m,\textit{g}}\text{Hg}$ yield estimation:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury production yield: $^{185}\text{Hg(m+g)}$ yield</td>
<td>$1.7 \times 10^7$ ions/µC (S. Sels PRC 99, 044306 (2019))</td>
</tr>
<tr>
<td>Proton current</td>
<td>0.5 µA</td>
</tr>
<tr>
<td>Primary yield</td>
<td>$8.5 \times 10^6$ ions/s</td>
</tr>
<tr>
<td>Transmission through EBIS+REX+HIE</td>
<td>5%</td>
</tr>
<tr>
<td>Isomeric ratio (g:m)</td>
<td>50:50</td>
</tr>
<tr>
<td>Yield at Miniball</td>
<td>$2.1 \times 10^5$ ions/s</td>
</tr>
<tr>
<td>Beam intensity at Miniball in the proposal</td>
<td>$1.0 \times 10^5$ ions/s (assuming narrow-band mode for ground or is state)</td>
</tr>
<tr>
<td>RILIS narrow-band efficiency</td>
<td>~50% (a factor of 2 less yield already considered in the proposal)</td>
</tr>
</tbody>
</table>
Number of shifts

Requested number of shifts was chosen to obtain a sufficient level of statistics of 2700 counts in total for the $2^+_1 \rightarrow 0^+_1$ transition in $^{120}$Sn and 995 (1990) counts for the $2^+_1 \rightarrow 0^+_1$ transitions in $^{48}$Ti with $^{185m,g}$Hg ($^{185m}$Hg) beams.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Secondary target</th>
<th>Number of shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{185}$Hg (ground state) @ 4 MeV/A</td>
<td>$^{120}$Sn @ 2 mg/cm²</td>
<td>3</td>
</tr>
<tr>
<td>$^{185}$Hg (isomeric state) @ 4 MeV/A</td>
<td>$^{120}$Sn @ 2 mg/cm²</td>
<td>3</td>
</tr>
<tr>
<td>$^{185}$Hg (ground state) @ 3.5 MeV/A</td>
<td>$^{48}$Ti @ 1 mg/cm²</td>
<td>1</td>
</tr>
<tr>
<td>$^{185}$Hg (isomeric state) @ 3.5 MeV/A</td>
<td>$^{48}$Ti @ 1 mg/cm²</td>
<td>2</td>
</tr>
</tbody>
</table>

9 shifts of beam time are required for the measurement of $^{185m,g}$Hg + 1 shift for energy change of HIE-ISOLDE $\rightarrow$ 10 shifts in total

Further notes

- The same experimental setup as for the approved IS563 experiment will be used.
- Beneficial to perform $^{185m,g}$Hg measurements in conjunction 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.
Thank you for your attention!

P-603 collaboration


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<table>
<thead>
<tr>
<th>CDS#</th>
<th>Proposal #</th>
<th>IS #</th>
<th>Setup</th>
<th>Shifts</th>
<th>Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN-INTC-2021-032</td>
<td>INTC-P-603</td>
<td></td>
<td>Miniball + DSSSD + SPEDE</td>
<td>10</td>
<td>185Hg (gs + IS)</td>
</tr>
</tbody>
</table>

**Beam intensity/purity, targets-ion sources**

The discussion of the beam request is largely feasible. The request for VADLIS is fine; the biased version of this needs to be tested. An alternative to the molten Pb unit could be UCx with RILIS.

RILIS in narrow band mode will result in a factor of 2-5 less yield.

Isomer selection by RILIS, using liquid lead with VADLIS.

**HIE-ISOLDE**

The neighbouring beams of Hg have already been delivered. The energy of 4 and 3.5 MeV/u is not an issue.

The daughter isotopes can present a problem for maintenance of the machine: 185Os t1/2=94 days and 181W t1/2=121 days.

The proposal requests a 3mm beam spot. This can be difficult to guarantee. A collimator to allow this may need to be installed in the setup.

**General implantation and setup**

**General Comments**

**Safety**

Safety clearance of MINIBALL experiment can be found at 1806701. The ISIEC form needs to be updated and an electrical inspection to be performed before start of the experiment. No additional hazards brought by this experiment.

**TAC recommendation**

The TAC does not foresee serious issues with this proposal. The long-lived daughters may complicate maintenance. A beam spot of 3mm may require installation of collimation in the setup. It should be noted that the yields with RILIS in narrow band mode will be a factor of 2-5 less than in broad band mode.
Backup slides
TAC comment for the INTC-P-603 proposal

„The proposal requests a 3mm beam spot. This can be difficult to guarantee. A collimator to allow this may need to be installed in the setup. ”

➢ it is possible to install the collimator in the setup

➢ SPEDE chamber compatible with MB target chamber, i.e. stacked MB target chamber collimators can be fitted to SPEDE chamber

➢ Balance between good transmission and small beam spot size:

5 mm collimator upstream of the target position
3 mm collimator for beam tuning at the target position

→ tails beyond 5mm are cut out
→ beam spot optimised to maximise transmission at the target position.
FIG. 2. Mercury production yield data for different target-ion source configurations: VADLIS or RILIS with lead or uranium-carbide target material for different proton-beam currents.
Level scheme of $^{185}$Hg

The bands are labeled with their Nilsson configuration (except for the $i13/2$)

Large odd-even staggering in the isotope shifts in the mercury isotopes around $^{181-185}\text{Hg}$ has long been attributed to the intruder structure becoming the ground state in the odd-mass isotopes.

Shape coexistence at low excitation energy in $^{185}\text{Hg}$

\[ \beta^+ / \text{EC decay of } ^{185}\text{TI} \]

Laser spectroscopy:
- B. A. Marsh et al., NP 14 (2018) 1163
- S. Sels PRC 99, 044306 (2019)
- S. Sels PhD thesis KULeuven 2018
- J. Bonn et al., PLB 38, (1972) 308
- T. Kuhl et al., PRL 39, (1977) 180

\[ ^{185}\text{Hg} \]

\[ <\beta_2^2>^{1/2}_{g.s.} = 0.271(2) \]

\[ \delta(E2/M1) = 0.18(3) \]

\[ T_{1/2} = 21.6(15) \text{ s} \]

\[ Q_s = -0.15(41) \]

\[ Q_s = 0.19(32) \text{ G. Ulm Z.Phys A325 1986} \]
Previous Coulex campaigns with post-accelerated REX-ISOLDE beams

<table>
<thead>
<tr>
<th>Atomic Number</th>
<th>Isotope</th>
<th>Neutron Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>82</td>
<td>$^{182}$Hg</td>
<td>94</td>
</tr>
<tr>
<td>186</td>
<td>$^{186}$Po</td>
<td>99</td>
</tr>
<tr>
<td>184</td>
<td>$^{184}$Po</td>
<td>98</td>
</tr>
<tr>
<td>192</td>
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<tr>
<td>202</td>
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</tr>
<tr>
<td>206</td>
<td>$^{206}$Po</td>
<td>98</td>
</tr>
<tr>
<td>222</td>
<td>$^{222}$Rn</td>
<td>132</td>
</tr>
</tbody>
</table>

$I_{^{182,184}$Hg} = 4 \cdot 10^3 - 2 \cdot 10^4$ pps

$I_{^{186,188}$Hg} = 3 \cdot 10^4 - 2 \cdot 10^5$ pps
Experimental setup: MINIBALL + DSSSD

- Array of HPGe of 8 triple clusters
- 6-fold electronic segmentation
- $\epsilon = 6.8\%$ @ 1.3 MeV

Particle ID in the Double-Sided Si Strip Detector DSSSD
(LAB: $15^\circ$-52$^\circ$)

Interpretation with two-level mixing model

Mixing of two different configurations which coexist at low excitation energy: less-deformed oblate and more-deformed prolate ones. Mixing is maximized at N=104.

Un-mixed BE2 and Qs in Hg:

- **Regular**
  - $2^+_1$: 1.36 eb
  - $0^+_1$: 0.3 $e^2 b^2$

- **Intruder**
  - $2^+_\parallel$: -3.03 eb
  - 2.2 $e^2 b^2$

$\left\langle 0^+_1 \| E2 \| 2^+_1 \right\rangle$ and $\left\langle 0^+_2 \| E2 \| 2^+_2 \right\rangle$

$\left\langle 2^+_1 \| E2 \| 4^+_1 \right\rangle$ and $\left\langle 2^+_2 \| E2 \| 4^+_1 \right\rangle$

```
\begin{array}{|c|c|c|c|}
\hline
Channel & $\alpha_{0+}^2$ & $\alpha_{2+}^2$ & $\alpha_{4+}^2$ \\
\hline
\text{182 Hg} & 92\% & 29\% & 3\% \\
\text{184 Hg} & 95\% & 51\% & 4\% \\
\text{186 Hg} & 98\% & 90\% & 7\% \\
\text{188 Hg} & 99\% & 98\% & 20\% \\
\hline
\end{array}
```


L.P. Gaffney et al, PRC 89, 024307 (2014)