EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Proposal for the ISOLDE and Neutron Time-of-Flight Committee

Shape effects in the vicinity of the Z=82 line: study of the beta decay of ^{182,184,186}Hg

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Abstract

This proposal is aimed at the study of the beta decay of the neutron-deficient ^{182,184,186}Hg nuclei using the total absorption technique. Recent theoretical results show that from measurements of the Gamow-Teller strength distribution the shapes of the ground states of the decaying Hg nuclei can be inferred. This study offers an independent way to study the phenomenon of shape co-existence in a region of particular interest.

Requested shifts: 13 shifts (to be divided in 9 shifts for the TAS setup and 4 shifts for a LA1/LA2 beta delayed particle detector setup)

1. General motivation

Neutron-deficient Hg nuclei have been the subject of intensive experimental and theoretical research since the 1970s. The main reason for this interest is the existence of coexisting shape structures at low excitation energies in some of the even isotopes and shape changes in the ground states of the odd ones. Actually, the first direct evidence for shape coexistence near the Z=82 shell closure was obtained for neutron-deficient mercury isotopes by means of isotope shift measurements [1]. Those measurements revealed drastic shape changes between the ground states of the odd-mass ^{185,187}Hg isotopes. These changes were interpreted as a transition from a weak oblate to a more deformed prolate shape in the odd nuclei [2]. Additional studies using the isotope shift measurement technique have revealed a weakly oblate-deformed character of the ground states of the even-mass Hg isotopes down to A=182 [3,4].

Shape effects have been also investigated in these nuclei from level energies using in-beam techniques. From these studies it was deduced that when moving to the neutron mid-shell at N=104 the weak oblate minimum remains constant until in ^{188}Hg intruding states based on the prolate minimum cross the yrast line (for a summary see [5]). The intruder 0^+ states have been observed down to ^{182}Hg in alpha decay studies and alpha decay hindrance factors i.e, the ratio between the alpha decay reduced widths of the ground-to-ground-state transitions and the reduced width of the decay to the excited 0+ states, have been used to deduce the structure and mixing of the 0^+ states [6]. The intruding excited 0^+ states are considered to have an structure similar to those observed in the Pb isotopes, and have been assigned to multiproton-multihole excitation across the Z=82 shell gap [6] and to the prolate minimum of the potential energy surface [7].

The co-existence of the low-lying excited 0^+ states in Hg has been studied in the framework of different models (Refs [2,7] were already mentioned). In a shell model picture, the excited 0^+ states have a two-particle-four-hole character (π(2p-4h)) and the 0^+ ground states are considered two-hole excitations (π(2h)) [6,8]. On the other hand, constrained Hartree-Fock-Bogoliubov [9] and Hartree-Bogoliubov model [10] calculations predict the existence of competing oblate and prolate minima in the deformation surface of these nuclei. This phenomenon has also been studied in the framework of the interacting boson model [11] and by means of Strutinski method calculations.

Shape effects can also be studied from the perspective of beta decay. It has been shown theoretically that the decay properties of unstable nuclei may depend on the shape of the decaying parent nucleus [12,13]. In particular cases the Gamow-Teller strength distribution shows different patterns depending on the shape of the parent nucleus [13]. This property can be used to determine the shape of the ground state of the decaying nucleus if a proper measurement of the Gamow-Teller strength distribution is available. Measurements performed at ISOLDE(CERN) of the beta decay of the neutron deficient ^{74}Kr and ^{76,78}Sr nuclei using the total absorption gamma spectrometer (TAGS) *Lucrecia* have shown the power of this method [14,15,16].

In the vicinity of the Z=82 region, theoretical calculations [17,18] predict that the Gamow-Teller strength distributions of the $^{184-194}$Pb and $^{180-192}$Hg isotopes show clearly differing patterns depending on the assumed deformation of the parent state (see Fig.1 for the $^{182-192}$Hg cases). This feature can be exploited to study the shape co-existence phenomenon if the theoretical results are combined with precise measurements of the B(GT) in the decay of these nuclei using the total absorption technique. In a broader context, precise measurements of the B(GT) are also important to test nuclear models further in the Z=82 region.

The study of the beta decays of Pb isotopes was the main motivation of the IS440 proposal [19]. The experiment related to this proposal was performed in November 2008. In the run, the beta decays of the ^{188,190,192}Pb isotopes were studied using the total absorption spectroscopy (TAS) technique. The analysis of the ^{188,190,192}Pb decays is part of the thesis of M. E. Estevez, which should be defended in 2012 [20]. In all these cases the electron capture component of the decays was analyzed, which was obtained by requiring coincidences of the measured TAS spectra with the characteristic K X-rays of the Tl daughter nuclei. The X-rays were measured using a planar detector positioned inside the total absorption gamma spectrometer.

In the original IS440 proposal 15 shifts were requested, of which 7 were approved to show the feasibility of the study. From the seven shifts six were used in the 2008 experiment and one shift still remains to be used. We have also an approved addendum (5 shifts) [21] to continue with the study of the ^{188}Pb decay by means of two complementary measurements to the IS440 proposal (high resolution and beta delayed particle emission measurement, which are required to improve the reliability of the ^{188}Pb study).

The analysis of the beta decay of ^{192}Pb from our TAS experiment is presented in Figure 2 [20]. The strength distribution deduced from our analysis is compared with the theoretical predictions of [18] in Figure 3. Looking at the values of the total strength our preliminary results are consistent with the assumption of a spherical ground state shape for the ^{192}Pb decaying nucleus in consistency with other experimental results (see for example [22]). The agreement of the detailed distributions (theory vs. experiment) is not so satisfactory if we compare this result with previous studies [14,15,16] in the A~80 region. This issue is currently under study, and may be related to the spherical character of the present cases compared to the deformed nature of the previously studied nuclei in the A~80 region (the model used is supposed to work better for deformed nuclei). It is worth mentioning that the theoretical calculations presented in Figure 3 have not been further refined and were taken from the published results in [18]. Similar results were obtained for the decay of ^{190}Pb [20].

The present proposal will allow us to further study the shape coexistence phenomena in the Z=82 region using the TAS technique, but in this case for more deformed nuclei. From this point of view ^{182,184,186}Hg are very interesting nuclei. They are expected to be oblate in their ground states with small mixing of the 0^+ prolate intruder states. This feature (small mixing) combined with the results of [18] makes the study of these decays by means of the total absorption technique very attractive. The oblate character of the ground state can be confirmed independently by means of a TAS measurement from the comparison of the deduced B(GT) distribution with theory.

Most of the information available on the shape co-existence phenomenon in neutron-deficient Hg nuclei has been obtained from measurements of the α-decay of Pb isotopes (see for example [6]) and from in-beam measurements of high-spin states populated in fusion-evaporation reactions [23,24,25] and references therein. The method proposed in IS440 and in this proposal is an alternative way to study this phenomenon using β-decay as the source of information. Our studies can be considered an independent way to test the results of [3,6], and can provide new experimental results to test nuclear models in the region.

Compared with the Pb decays, the study of the Hg decays has an additional appealing. In general oblate shapes are less common than prolate shapes in the nuclide chart. The study of the beta decay of Hg nuclei can make possible the independent confirmation of the oblate nature of the ground state of these nuclei and they can be the first oblate cases studied by means of the total absorption technique. In addition due to the moderate deformation of these nuclei we can expect that the theoretical description of the B(GT) will work better for the Hg than for the Pb cases due to their moderate deformed character [18].

Furthermore, the study of even Hg nuclides paves the way for the investigation of odd Hg, where selection of the decaying isomer, with a particular deformation, can be achieved via narrow band ionization with RILIS.

2. Experimental techniques

For the study of the ^{182,184,186}Hg decays we plan to use the TAGS *Lucrecia*, installed at ISOLDE (CERN). It consists of a large NaI(Tl) crystal of cylindrical shape (l=Ø=38 cm) with a cylindrical hole perpendicular to the symmetry axis. The transverse hole allows us to take the activity to the centre of the crystal and it also makes possible the placement of ancillary detectors in close geometry to the sources. The total efficiency of the TAGS has been estimated, using Monte Carlo methods, to be ~ 90 % for mono-energetic gamma rays of 300-3000 keV energy, which gives an approximate 99 % total efficiency for gamma cascades of more than one gamma ray.

The analysis of the TAGS data requires solving the **d=R(B)f** inverse problem. In this equation **d** represents the measured spectrum (free of contaminants), **R(B)** is the response matrix of the TAGS detector, which depends on the branching ratios of the levels in the daughter nucleus **(B)** and **f** is the feeding distribution. To construct the branching ratio matrix **B** the standard procedure is to use high-resolution results for the low-lying levels and to use a statistical model to construct the "unknown" or high-lying part. For the proposed study the decays of interest are relatively well known from high-resolution measurements [26,27,28]. These studies also included internal conversion coefficients measurements.

The analysis of the TAGS data will be carried out using the methods developed by the Valencia group [29]. The application of these methods will allow one to determine the B(GT) in a reliable way up to the limit of the Q_{EC} as in the earlier cases studied [15,16].

The calculation of the response function of *Lucrecia* (**R(B)**) requires a separate treatment of the EC and the β^+ processes. In the Pb studies we have relied on the analysis of the EC component of the decay, which was obtained using a Ge planar detector for the detection of the X-rays produced in the EC process in coincidence with *Lucrecia* [20]. In the present proposal we cannot rely on the analysis based on the EC component, because of the large conversion coefficient for some of the electromagnetic transitions in the daughter nuclei [26-28]. The conversion process is also a source of X-rays in the daughter, but these transitions can also be produced when a β^+ process occurred. For that reason the EC spectrum obtained by coincidences with the planar detector may be contaminated with the β^+ component. To avoid this systematic error, we plan to study these nuclei in singles mode, in a similar fashion as it was done in [15]. For that reason separate measurements of daughter activity as well as background measurements are required.

The standard TAS measurement should be complemented with a high-efficiency beta delayed charge particle spectroscopy measurement. The setup will be based on large area ΔE-E Si telescopes to determine the beta-delayed proton and alpha emission probability in ^{182,184,186}Hg. The lack of space inside the TAGS, along with the inconvenience of adding dead material around the radioactive sources, makes this setup more efficient in a different beam-line, namely one of the LA1 or LA2 spectroscopy beam-lines. The ΔE-E charged particle telescopes will be combined with gamma detectors for proper normalization.

We propose to use the ISOLDE RILIS resonance ionization laser ion source [30] for the production of the sources in the same way as in IS440. The separated parent activity will be carried to the centre of the total absorption gamma spectrometer *Lucrecia* by a tape transport system.

Parent isotope	Half-life	EC branch (%)	S_p [keV] (daughter)	Q_{EC} [keV]	Reference
^{182}Hg	10.83(6) s	84.9(9)	1215(25)	4725(22)	B. Singh, J. C. Roediger NDS 111 (2010) 2081
^{184}Hg	30.87(26) s	98.89(6)	1835(27)	3970(24)	C. M. Baglin, NDS 111 (2010) 275
^{186}Hg	1.38(6) min	100	2320(50)	3176(24)	C. M. Baglin, NDS 99 (2003)1

Table 1. Relevant experimental data for the present proposal: the half-life values and the EC branches are taken from the last ENSDF database compilations. S_p is the proton separation energy in the corresponding daughter nuclei. S_p and Q_{EC} are taken from Audi et al, Nucl. Phys. A729 (2003) 337.

3. Beam time request

Due to the superior selectivity, the proposed target/ion+ source combination for the experiment is UC_x/graphite target with RILIS. Although Pb molten metal target with Mk6 plasma source gives higher yields, there is a second drawback apart from the purity, namely the fact that the splashes due to proton impact may cause deterioration of the extraction electrode. For the proposed UC_x/graphite target with RILIS we have calculated the yields by scaling the available SC yields in the ISOLDE database by the energy dependence of the cross section, the target thickness (50 g/cm^2 versus 9.7 g/cm^2) and the ionization efficiency, where the value of 0.1 % given in [30] for RILIS has been used. The beam time request is based on these yields, on the limitation of a maximum counting rate acceptable for the TAS measurements of 5 kHz, on the average current of 1.5 μA available nowadays at ISOLDE and on the beam-line transmission from the separator to the TAGS setup of 70 %. A summary of the information used for the calculation of the number of shifts is presented in Table 2.

Parent	Estimated ISOLDE Yield (ions/μC)	Hg ions/s at TAGS station	Number of Hg ions in 1 Shift
^{182}Hg	1.0E+02	1.1E+02	3.1E+06
^{184}Hg	3.1E+03	3.2E+03	9.4E+07
^{186}Hg	1.5E+04	1.6E+04	4.7E+08

Table 2. Used information for the calculation of the requested shifts. Note that for ^{186}Hg we will have a limitation of 5kHz imposed by the maximum acceptable counting rate in the TAGS.

For the TAGS measurement of the ^{182,184,186}Hg decays we request 3 shifts (1 shift/isotope). Three additional shifts are requested to measure the daughter activity of these decays with the TAGS. Background measurements are also needed at regular intervals for the single analysis, for that two additional shifts are required.

For the on-line calibration of the TAGS we need one additional shift. This shift is requested for the calibration of the TAGS using a ^{24}Na source that should be produced at ISOLDE during our experiment.

For the measurement of the beta delayed particle emission in ^{182,184,186}Hg we request 4 shifts. We are planning to use a compact setup with 40 % efficiency for charged particles and an estimated 1 % efficiency for gammas. For an estimated beta-delayed proton branch limit of 10^{-3} we estimate that a measurement with the above counting rates can be achieved in 2 shifts for ^{182}Hg and 1 shift each for ^{184}Hg and ^{186}Hg.

Accordingly:

- 2 shifts are required for the TAGS measurement of the ^{186}Hg decay with its daughter activity (2 separate measurements of 1 shift each)
- 2 shifts are required for the TAGS measurement of the ^{184}Hg decay with its daughter activity (2 separate measurements of 1 shift each)
- 2 shifts are required for the TAGS measurement of the ^{182}Hg decay with its daughter activity (2 separate measurements of 1 shifts each)
- 2 shifts are required for the background TAGS measurements (background measurements at regular intervals during the decay measurements)
- 1 shift is required for the on-line calibration using the ^{24}Na (TAS)
- 4 shifts are required for the beta delayed particle emission in ^{182,184,186}Hg at LA1 or LA2

Total number of requested shifts: 13

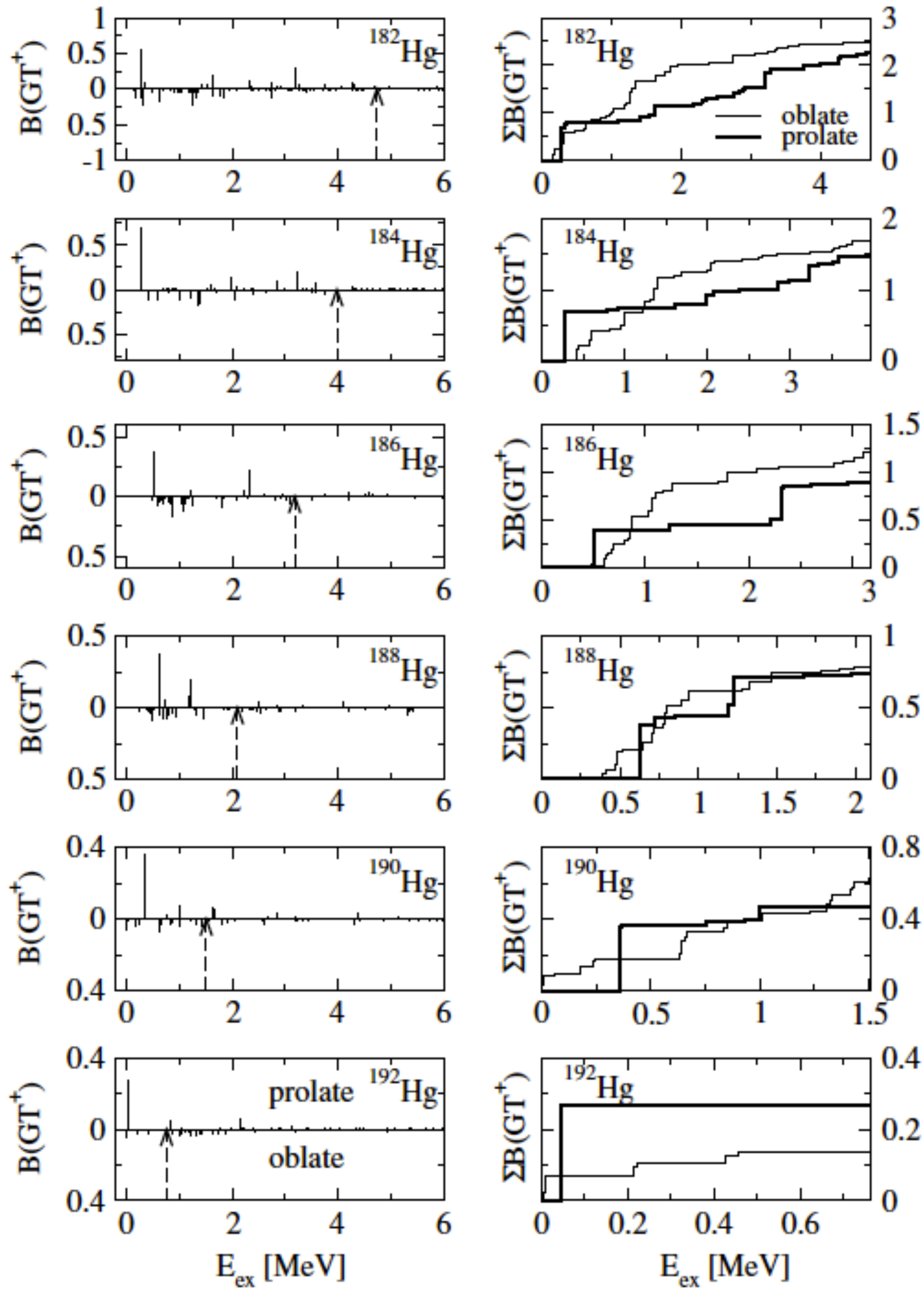

Fig. 1 (Left) Gamow-Teller strength distributions in $[g^2_A/(4\pi)]$ for the Hg isotopes for oblate (downward) and prolate (upward) shapes. The experimental Q_{EC} values are showed by dashed arrows. (Right) Accumulated Gamow-Teller strength for prolate (thick lines) and oblate (thin lines) shapes plotted up to the Q_{EC} energies. Results are obtained from SLy4 force with fixed gap parameters [18].

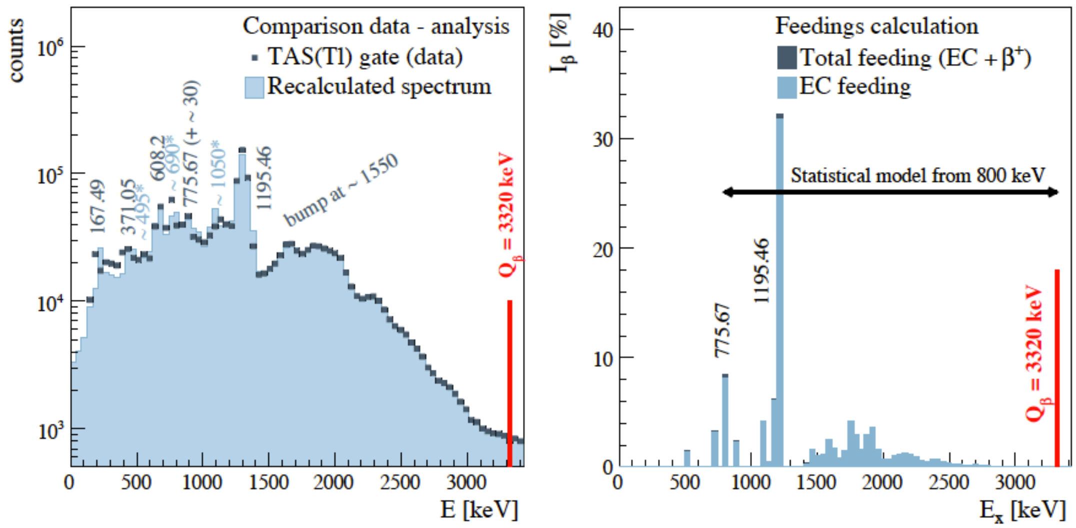

Fig. 2 Results from the preliminary analysis of the 192Pb case [20]: the left panel shows the comparison of the analyzed spectrum with that obtained after the analysis. The right panel shows the deduced feeding distribution.

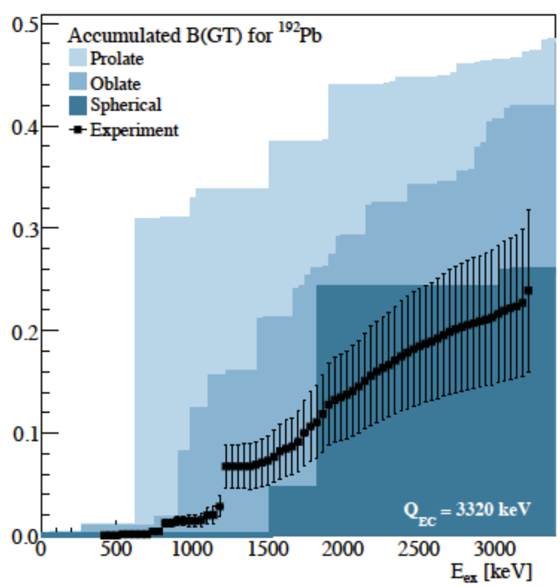

Fig. 3 Comparison of the accumulated experimental strength distribution in the decay of ^{192}Pb [20] with the theoretical calculations of [18] assuming different ground state deformations in the ^{192}Pb parent nucleus.

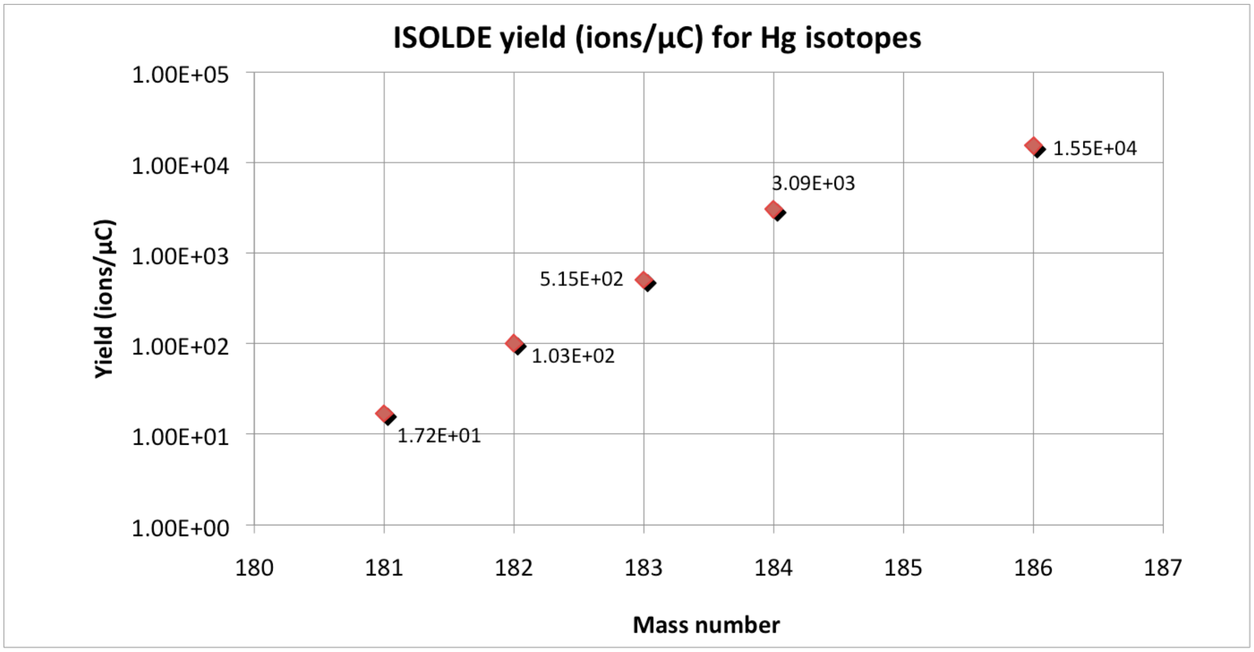

Fig. 4 Estimated PSB yields for Hg from UC_x/graphite target with RILIS ionization.

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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
TAS station	☒ Existing	☐ To be used without any modification
High resolution setup at LA1/LA2	☐ 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 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 the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	Air [2-3 Bar]	Air [2-3 Bar]	
Vacuum	High vacuum	High vacuum	
Temperature	LN2 (77K)	LN2 (77K)	
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LN2	LN2	
Electrical and electromagnetic			
Electricity	4.0 kV (Ge HV supply)	4.0 kV (Ge HV supply)	
Static electricity			
Magnetic field			
Batteries			
Capacitors			
Ionizing radiation			
Target material	UCx/grafite ion source with W surface ionisation source with RILIS	UCx/grafite ion source with W surface ionisation source with RILIS	
Beam particle type (e, p, ions, etc)	^{182}Hg, ^{184}Hg, ^{186}Hg, ^{24}Na	^{182}Hg, ^{184}Hg, ^{186}Hg	
Beam intensity	^{182}Hg (1.1x10^{2}), ^{184}Hg(3x10^{3}), ^{186}Hg(5x10^{3}), ^{24}Na(4x10^{3})	^{182}Hg (1.1x10^{2}), ^{184}Hg(3x10^{3}), ^{186}Hg(5x10^{3})	
Beam energy	60 keV	60 keV	
Cooling liquids			

Gases			
Calibration sources:	☒	☒	
• Open source	☐	☐	
• Sealed source	☒ [ISO standard]	☒ [ISO standard]	
• Isotope	152Eu, 133Ba, 22Na, 241Am	152Eu, 133Ba, 22Na, 241Am	
• Activity	10 kBq	10 kBq	
Use of activated material:			
• Description	☐	☐	
• Dose rate on contact and in 10 cm distance	[dose][mSV]	[dose][mSV]	
• Isotope			
• Activity			
Non-ionizing radiation			
Laser	RILIS	RILIS	
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic			
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)			
Mechanical properties (Sharp, rough, slippery)			
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			

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)*

2.5 kW