EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Total absorption beta decay studies around ^{186}Hg

September 28, 2021

A. Algora[1,2], S.E.A. Orrigo[1], L.M. Fraile[3], J. Agramunt[1], G. Alcala[1], G. de Angelis[4], G. Bartram[5], J. Benito[3], M.J.G. Borge[6], J.A. Briz[3], M. Fallot[7], E. Ganioğlu[8], W. Gelletly[5], L. Giot[7], V. Guadilla[9], A. Herzán[10], M. Karny[9], G. Kiss[2], S. Kovacs[2], R. Lică[11] , M. Llanos[3], F. Molina[12], A.I. Morales[1], O. Moreno[3], J.R. Murias[3], E. Nácher[1], N. Orce[13], B.F. Parra[1], A. Perea[6], Zs. Podolyak[5], D. Rodriguez[1], B. Rubio[1], P. Sarriguren[6], D. Sohler[2], J.L. Tain[1], O. Tengblad[6], J. Timar[2], A. Tolosa[14], J.M. Udías[3], M. Venhart[10], J.A. Victoria[1], J.L. Wood[15]

[1] Instituto de Física Corpuscular, CSIC - Universidad de Valencia, E-46071 Valencia, Spain
[2] Institute of Nuclear Research (ATOMKI), P.O. Box 51, H-4001 Debrecen, Hungary
[3] Grupo de Física Nuclear & IPARCOS, Universidad Complutense de Madrid, E-28040, Spain
[4] INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
[5] Department of Physics, University of Surrey, GU2 7XH, Guildford, UK
[6] Instituto de Estructura de la Materia, CSIC, E-28006, Madrid, Spain
[7] Subatech, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, F-44307 Nantes, France
[8] Department of Physics, Istanbul University, 34134 Istanbul, Turkey
[9] Faculty of Physics, University of Warsaw, 02-093 Warsaw, Poland
[10] Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia
[11] ISOLDE-EP, CERN, CH-1211 Geneva 23, Switzerland
[12] Comisión Chilena de Energía Nuclear, Casilla 188-D, Santiago, Chile
[13] Department of Physics and Astronomy, University of the Western Cape, P/BX17, ZA-7535, South Africa
[14] Department of Physics, University of Jyvaskyla FI-40014, Finland
[15] School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA

Spokespersons: Alejandro Algora (Alejandro.Algora@ific.uv.es)
Sonja E. A. Orrigo (Sonja.Orrigo@ific.uv.es) Luis Mario Fraile (lmfraile@ucm.es)
Local contact: Razvan Lică (Razvan.Lica@cern-ch)

CERN-INTC-2021-056 / INTC-P-617
28/09/2021

Abstract

We propose to study the β decay of the odd ^{183,185,187}Hg isotopes for the ground and isomeric states independently, profiting from the isomer selectivity of the ISOLDE VADLIS ion source. We will employ the total absorption spectroscopy technique. Our main goal is to determine the β-strength distributions for the decay of both ground and isomeric states, using the spectrometer *Lucrecia*. This new experimental information will be compared to QRPA calculations to infer the shape of the decaying states and to test further the validity of the model calculations in this region of drastic shape changes around ^{186}Hg. A recently developed method of analysis will be applied.

Requested shifts: 14 shifts (split into 1 run over 1 year)

1 Scientific Context and Motivation

Decay studies of exotic nuclei provide rich spectroscopic information of great relevance for the investigation of nuclear structure. In particular, the transitional region around A~186 is considered to be a benchmark for studies related to shape transitions and shape effects (see for example Refs. [Ulm86, Wal89, And00, Jul01, Hey11, Ven17, Mar18, Wrz19, Alg21a] and references therein). In this proposal we focus on the study of odd neutron-deficient Hg isotopes, namely ^{183,185,187}Hg, for which we intend to measure the β-strength distribution using the Total Absorption Spectrometer (TAS) *Lucrecia*. These isotopes are located in the region marked by the staggered changes in the mean-square charge radii, which are conventionally associated with shape changes. In these nuclei the ground and isomeric states are assumed to have different nuclear shapes.

The comparison of the deduced experimental β-strength to quasiparticle random-phase approximation (QRPA) calculations [Boi15] will allow us to infer the shape of the β-decaying states in ^{183,185,187}Hg in this unique region of the nuclear chart. Both the decays of ground and isomeric states will be studied independently profiting from the ISOLDE isomer separation capabilities. Measuring separately the decay patterns of these states in odd systems would improve significantly our understanding of deformation effects, from which our knowledge on deformation in even Hg nuclei will also profit. Moreover, the present study will also allow us to test further the QRPA calculations that led to the intriguing recent result in ^{186}Hg [Alg21a], characterized in our interpretation by mixing of prolate and oblate configurations.

The decay study of Hg isotopes was among the first measurements performed with the total absorption technique in the World [Hor75] at ISOLDE-CERN, where the technique was born [Duk70]. This proposal will also provide the opportunity to repeat the total absorption measurements of the Hg isotopes of interest using modern analysis techniques.

1.1 The β-strength distribution as a probe for nuclear shape

As a matter of fact, the β-decay strength distribution reflects the underlying nuclear structure and, in particular, it is sensitive to the nuclear shape. Hence a measurement of the β-strength distribution in the daughter nucleus can be a useful probe to investigate the shape of the progenitor state. The original theoretical idea about such a connection between β-strength and nuclear shape was presented in Refs. [Ham95a, Ham95b], then pursued by Ref. [Sar01] and successfully exploited in many experimental studies such as, e.g., the β-decay studies of the neutron-deficient ^{74}Kr, ^{76,78}Sr and ^{190,192}Pb nuclei performed with *Lucrecia* at ISOLDE [Nác04, Pér11, Est15]. The method is based on the comparison between the experimental β-strength distribution, measured with the Total Absorption γ-ray Spectroscopy (TAGS) technique (see Section 1.3), to theoretical QRPA calculations which assume different deformations (oblate, prolate or spherical). In favourable conditions, the calculated strength distribution shows different patterns depending on the shape of the parent nucleus. Hence this comparison makes it possible to deduce the shape of the ground state of the decaying nucleus. It is worth noting that the calculations assume the same shape for both parent and daughter nuclei.

Nuclei with shape mixing are, of course, more difficult and delicate to treat. A first example of such a case is ^{74}Kr [Poi04], where the comparison with QRPA calculations showed that the measured β-strength distribution lies in between the two curves calculated for pure oblate and pure prolate deformations, giving an indication of shape mixing and confirming previous findings for the ground state of this nucleus. Another interesting case of possible shape mixing is ^{72}Kr [Bri15] where, in addition to the QRPA calculations, shell-model calculations were also performed giving a first indication on the amount of shape mixing.

More recently, the β-strength distribution of ^{186}Hg was measured with *Lucrecia* at ISOLDE. The results were obtained using an improved TAGS analysis method [Alg21a]. ^{186}Hg was expected to be oblate in the ground state with a small mixing of the 0^+ prolate intruder state. But the comparison of the measurements with the calculations provided a very different outcome. In Ref. [Alg21a] the experimental β-strength was first compared with theoretical QRPA calculations using the SLy4 Skyrme force with pure parent and daughter shape configurations and assuming the same shape for both parent and daughter. The observed disagreement forced us to revisit the assumption of β-transitions between states of pure shape configurations for this decay. Our study showed that the measured Gamow-Teller strength distribution B(GT) (see Fig. 1) and the half-life of the decay are better described by mixing oblate and prolate configurations independently in the parent and daughter nuclei [Alg21a]. In this theoretical framework the best description of the experimental β-strength is obtained with dominantly prolate components for both the parent ^{186}Hg and daughter ^{186}Au nuclei, in contradiction to what was expected for the ground state of ^{186}Hg. This result shows that in some decays a more complex mixing scenario has to be considered. This new double-mixing approach allows us to treat cases in which the parent and daughter nuclei may both exhibit different degrees of mixing of the oblate and prolate components and open the way to the investigation of more complex cases in the framework of QRPA calculations. *The study of the odd Hg isotopes, proposed here, would be an additional verification and validation for this new method and the theoretical calculations presented in Refs. [Alg21a, Boi15].*

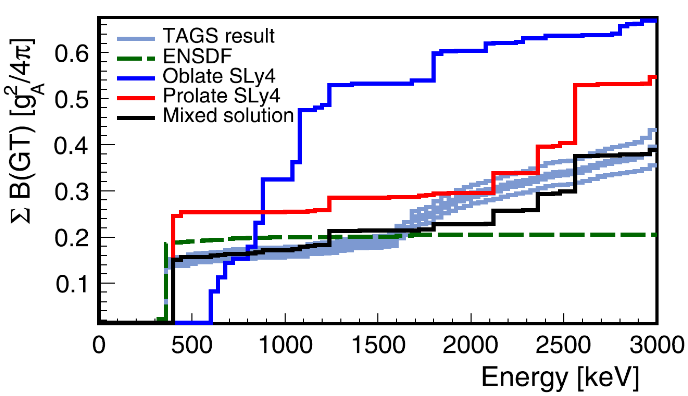

Fig. 1. Accumulated β-strength distribution measured for the decay of ^{186}Hg compared with QRPA calculations assuming different deformations and a mixed solution [Alg21a].

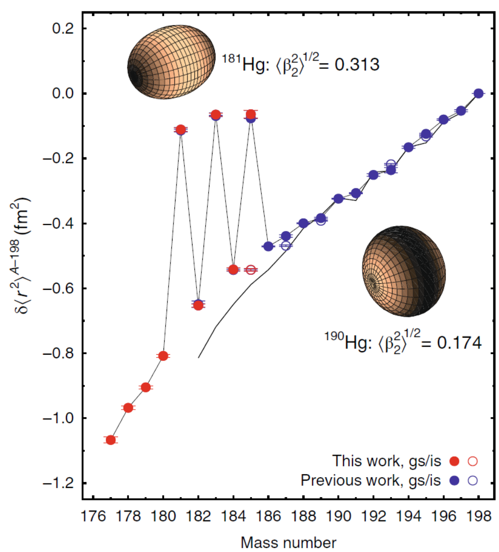

Fig. 2. Charge radius as a function of mass number [Mar18].

1.2 Physics case: ^{183,185,187}Hg ground states and shape isomers study

Neutron-deficient Hg isotopes in the region around A∼186 are of particular importance from the nuclear structure viewpoint. This region is characterized by competition between oblate and prolate configurations, leading to a complex scenario of shape evolution and coexistence that has become the focus of many experimental and theoretical efforts since the 1970s. Isotope shift measurements for the neutron-deficient Hg isotopes gave the first direct evidence for shape changes and coexistence near the Z=82 shell closure [Bon72, Bon76, Hub76]. Some even Hg isotopes showed the existence of coexisting shape structures at low excitation energies, while shape changes were found in the ground states of the odd Hg isotopes [Fra75]. A strong discontinuity in the mean square charge radii $\delta\langle r^2\rangle$ values was found first between ^{185}Hg and ^{187}Hg [Bon72], then confirmed also for other light odd isotopes with A<186, i.e., ^{181,183,185}Hg (see Fig. 2), with a large odd-even staggering in $\delta\langle r^2\rangle$ [Ulm86]. These findings were interpreted [Fra75, Ulm86] as shape transitions from a small oblate deformation (in light even Hg isotopes and for those with A>186) to strongly prolate deformation for light odd isotopes (^{181,183,185}Hg). A similar shape transition from slightly oblate to a strong prolate shape was also observed in the Au nuclei [Hil90]. Moreover, shape coexistence was observed in ^{185}Hg [Ulm86], where there exists a $1/2^-$ prolate ground state ($T_{1/2}$=49.1_{10} s) and a $13/2^+$ oblate isomer ($T_{1/2}$=21.6_{15} s). According to Ref. [Mar18], the shape staggering in the Hg isotopes, having ^{181}Hg as endpoint, is a unique and localized feature in the nuclear chart which is due to the interplay of single-particle and collective degrees of freedom. However, a complete comprehension of the underlying microscopic origin of the nuclear deformation phenomenon across the nuclear chart has still to be achieved.

The present proposal will allow us to further study shape evolution and shape coexistence phenomena in the Z=82 region using the TAGS technique. This well-proven method is an alternative and independent way to test such a phenomenon by using the information achievable from the β-decay data. It will complement the information available from in-beam measurements and will provide new experimental results to test further nuclear models in this region.

Isomer-selective ionization using the ISOLDE resonant ion source opens up a unique opportunity to investigate the β decay of two different shape configurations in neutron-deficient odd Hg isotopes. From this point of view the odd ^{183,185,187}Hg isotopes are of great interest. The expected strong prolate deformation in their ground state and the assumed different shape

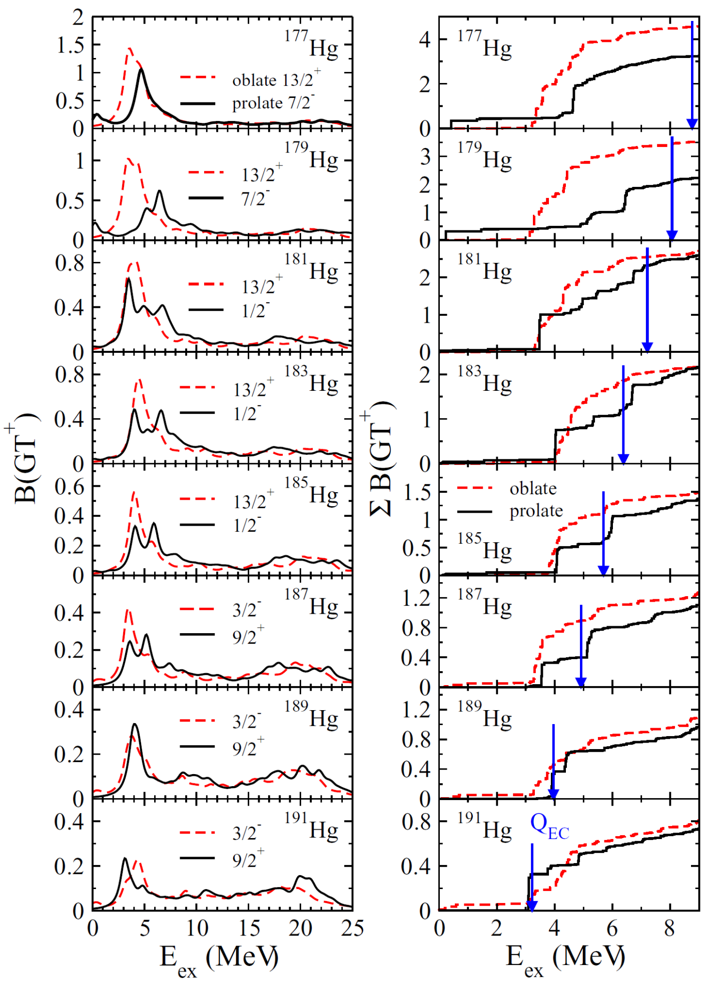

Fig. 3. β-strength (left) and accumulated β-strength (right) distributions for the odd $^{177-191}$Hg isotopes from QRPA calculations [Boi15].

of the $13/2^+$ isomers make the study of their decay by means of the TAGS technique very appealing. The isomer and ground states are characterized by both a different spin-parity and deformation, and this should influence the B(GT). From the experimental point of view the study will allow to assess the impact on the B(GT) distribution of the odd particle in comparison to neighbouring even-even nuclei, and the sensitivity of the decay patterns to different odd-A nuclei.

The ground state prolate character can be confirmed independently by comparing the measured β-strength to the calculated distribution [Boi15]. Fig. 3 displays the theoretical accumulated β-strength distribution of the odd $^{177-191}$Hg isotopes from Ref. [Boi15], obtained by QRPA calculations using the SLy4 Skyrme force and assuming different deformations for the parent state. We propose also to measure the β-strength distributions in the odd Hg nuclei corresponding to both the ground and isomeric states independently. For the nuclei of interest, ^{183,185,187}Hg, Fig. 3 shows differing patterns depending on the assumed deformation. Hence the comparison with the TAS measurements should allow us to extract new information on the nuclear shape and validate further the calculations. *In addition, this study, to the best of our knowledge, will be the first case where it is possible to study shape effects from different shape isomers in the same nucleus from the perspective of β decay.*

1.3 β-decay strength with the TAGS technique

In order to determine the β-decay strength distribution, one needs to measure the γ radiation following the β decay of the nucleus under study. Conventional measurements are based on the use of high-purity germanium (HPGe) detectors to measure the individual γ rays emitted after the decay. However, this kind of measurement is affected by the so-called Pandemonium effect [Har77], i.e., many weak and/or high-energy γ rays can remain undetected. In this way a significant part of the β-strength can be missed, which leads to large systematic uncertainties in the determination of its distribution.

The best method to measure the β-intensity distribution free from Pandemonium is the TAGS technique [Rub05, Alg21b], which we will exploit to obtain a precise determination of the β-strength distribution in ^{183,185,187}Hg. The TAGS technique is based on the detection of the full energy of the γ cascades that follow the decay, exploiting the large γ-efficiency which characterizes the TAS spectrometers. It allows us to obtain a precise measurement (free from Pandemonium) of the strength distribution as a function of the excitation energy in the daughter nucleus. The β-intensity will be obtained by performing the deconvolution of the TAS total energy spectrum with the response of the spectrometer to the decay [Tai07a, Tai07b, Val17, Alg21a]. The response depends on the knowledge of the branching ratios of the energy levels in the daughter nucleus, for which the TAGS analyses use the results from high-resolution measurements for the low-lying levels and a statistical model for the unknown high-lying states. For the proposed study the decays of interest are relatively well known from high-resolution studies [Ven17, Rup98, Bou82, ENSDF], which also include internal conversion coefficients measurements.

The TAGS technique has been developed further by the IFIC-Valencia Group and successfully employed in several experiments with different TAS spectrometers [Nác04, Alg10, Tai15, Val17, Gua19a, Gua19b, Gua19c, Alg21a]. It will allow us to obtain high-quality data on the β-strength distribution from the decay of these odd Hg isotopes, very useful to investigate their nuclear shape and thus the prolate-oblate shape transition around A∼186.

2 Experimental setup

We propose to use the TAS *Lucrecia*, which is installed at ISOLDE (CERN), to study the β decays of the odd Hg isotopes of interest. *Lucrecia* is a large NaI(Tl) scintillator crystal of cylindrical shape with 38 cm height and diameter. A cylindrical hole perpendicular to the symmetry axis allows us to bring the activity to the centre of the crystal. It also makes possible to place ancillary detectors very close to the sources. Monte Carlo simulations estimated the TAS total efficiency as 90% for mono-energetic γ rays in the energy range of 300-3000 keV, which corresponds to 99% total efficiency for the γ cascades of at least two γ rays. This detector has been widely and successfully used during the last 20 years [Rub17].

As in the ^{186}Hg case, the TAS spectrum generated in coincidence with the X rays will be used in the analysis. This procedure allows us to select the electron capture (EC) component of the decay. Since there are transitions with large internal conversion coefficients in the daughter, some β^+ contamination might appear in this spectrum. To solve this problem and to tackle the possible penetration and summing of X rays in the total absorption spectrometer we plan to apply the new method of analysis developed in [Alg21a], which allows one to handle such situations. To test further the integrity of the data, separate measurements of the daughter activity as well as background measurements are also required.

3 Beam time request

We propose to use a molten-metal Pb target coupled to a VADLIS ion source [God16], with isomeric separation of ground state and $13/2^+$ isomer capabilities. This target ion-source combination has been successfully used for in-source laser spectroscopy of Hg isotopes [God17, Sel19]. An illustration of the laser scans from the latter works is shown in Fig. 4.

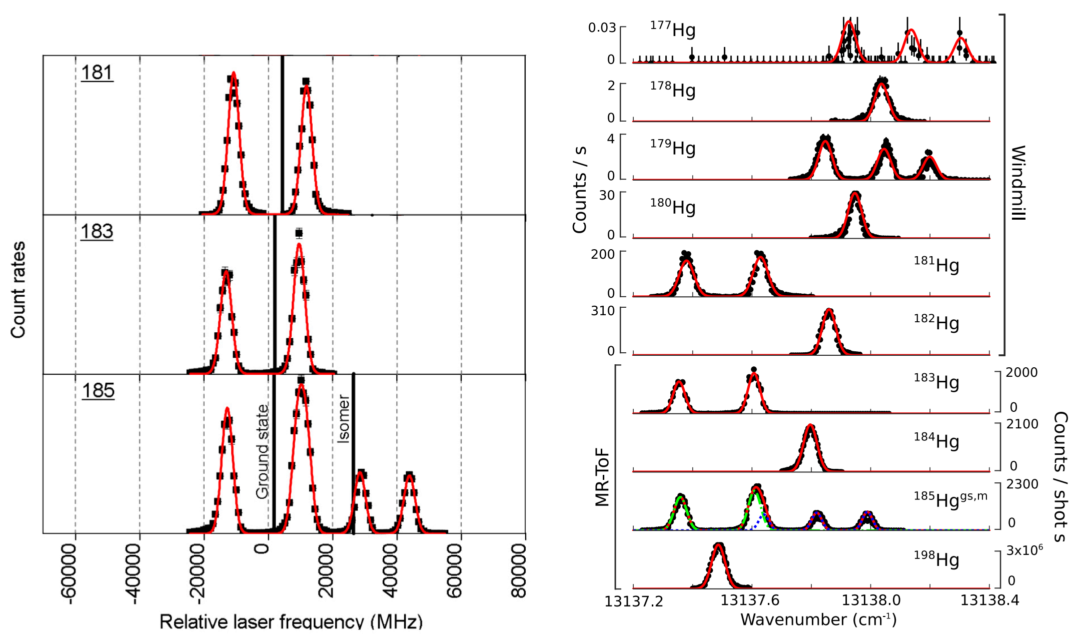

Fig. 4. (Left) Laser scans for mercury isotopes taken from Ref. [God17]. (Right) Hyperfine structure scans taken from Ref. [Sel19].

The yields (shown in Table 1) have been extrapolated from the measurements reported in [Sel19] for a molten Pb and VADLIS combination, and cross checked with the available information on the ISOLDE yield database for molten metal targets with plasma ion sources. The values are consistent with measured yields in the previous experiment [IS539] dealing with the ^{182,184,186}Hg decays. A minimum yield of 10^5 ions/μC is estimated for ^{183}Hg, and higher for heavier isotopes, see Table 1. To calculate the number of ions per second transported to the TAS setup we recall that the proton intensity limit is 10^{13} protons per pulse for molten targets, yielding a maximum average proton current of 0.7 μA assuming only 40% of the PSB pulses reach ISOLDE. The quoted Hg ionization efficiency in Refs. [God17, Sel19] is 6%. In order to take care of the ionization and the operation in narrow-band mode for nuclear state selection the yields have been scaled down by an extra factor of 5. This mode of operation is not required for ^{185}Hg, but should be tested for the other two isotopes. We note that the isomer half-life in ^{183}Hg and decay branches are not known to date. In addition a transmission of 80% from the separator to the setup is assumed. For the less favourable case the number of implanted ions per second into the TAS setup is in excess of 10000. Thus the main experimental limitation does not come from the available yields, rather from the maximum counting rate acceptable for the TAS measurements of 5 kHz, which is common for all three isotopes.

The data analysis will be performed following the procedure presented in Ref. [Alg21a] relaying on coincidences with X rays detected in a planar ancillary detector. This will provide isotopically clean spectra and will avoid the α contamination for the cases where α emission from the β-decaying states is possible. In the estimation of the number of shifts we have employed an efficiency of 0.1 for the planar detector, a lower bound for the EC branch of 30% and a probability of X-ray emission after a vacancy in the K-alpha1 shell in Au of 0.46. We calculate that 1 shift for each decay will be sufficient to accumulate of the order of 2 million coincidences taking into account decay losses and the tape duty cycle. For the measurement of the ground state decays **3** shifts will be required, and **3** additional ones for the isomeric states. We require **3** more shifts to measure the daughter activities. Background measurements are also needed at regular intervals for the singles analysis. For that purpose, **2** additional shifts are required. Furthermore, **2** additional shifts are requested to fine-tune the VADLIS. Finally, an on-line calibration of the TAS using a ^{24}Na source is required for **1** shift. It is requested that this calibration source is produced at ISOLDE during our experimental beamtime.

Table 1. Information used for the calculation of the requested shifts.

Parent	Estimated yield (ions/μC)	p current (μA)	Ionization factor	Transm.	Hg ions/s at TAS station
^{183}Hg	1E+05	0.64	>20%	80%	1.0E+04
^{185}Hg	1E+06	0.64	>20%	80%	1.0E+05
^{187}Hg	1E+07	0.64	>20%	80%	1.0E+06

Summary of requested shifts:

We request a total of **14 shifts**, as detailed above.

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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 ☒ To be modified by upgrade of tape drive system
[Part 2 experiment/ equipment]	☐ 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]		
Vacuum	High vacuum		
Temperature	LN2 [77 K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LN2		
Electrical and electromagnetic			
Electricity	4.0 [kV] (Ge HV supply)		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)	^{183}Hg, ^{185}Hg, ^{187}Hg, ^{24}Na		
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	^{152}Eu, ^{133}Ba, ^{22}Na, ^{241}Am		
• Activity	10 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 (1-300MHz)			
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)*