EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

The (d,p) reaction on ^{206}Hg

June 1, 2016

B. P. Kay[1], C. R. Hoffman[1], M. Avila[1], B. B. Back[1], S. Bottoni[1], P. A. Butler[2],
S. J. Freeman[4], L. P. Gaffney[3], R. V. F. Janssens[1], M. Labiche[5], R. D. Page[2],
Zs. Podolyák[6] R. Raabe[7], P. H. Regan[6], M. Rudigier[6], D. Santiago-Gonzalez[8,1]
G. Savard[1] J. P. Schiffer[1], D. K. Sharp[4], J. F. Smith[3], R. Talwar[1], and S. Zhu[1]
[1]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK*
[3]*Nuclear Physics Group, The University of the West of Scotland, Paisley PA1 2BE, UK*
[4]*Schuster Laboratory, University of Manchester, Manchester M13 9PL, UK*
[5]*STFC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK*
[6]*Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, UK*
[7]*Instituut voor Kern- en Stralingsfysica, KU Leuven, Belgium*
[8]*Dept. of Physics & Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA*

Spokesperson: B. P. Kay (kay@anl.gov)
Co-spokesperson C. R. Hoffman (crhoffman@anl.gov)
Contact person: Karl Johnston (karl.johnston@cern.ch)

Abstract: We propose to study the (d,p) reaction on ^{206}Hg at an energy of 10 MeV/u to probe the structure of ^{207}Hg. Adding a neutron to the closed shell of 126, this measurement will initiate exploration of single-particle configurations in one of the most inaccessible regions of the nuclear chart; only the ^{207}Hg ground-state decay has been previously observed. With the HIE-ISOLDE upgrade and a new instrument, the ISOL solenoidal spectrometer, this measurement becomes feasible. The principal goal of the experiment is to explore the structure of ^{207}Hg and the relation of its low-lying states, that are expected to be single-neutron excitations, to ^{209}Pb. Special attention will be given to determining the location and strength of the $3s$ and $2d$ excitations, to predict how they will evolve in lighter $N = 126$ systems. This region is of particular interest in explosive nucleosynthesis.

Requested shifts: 18 shifts
Installation: ISOL solenoidal spectrometer (see Appendix 1).

1 Physics case

Motivation—The $N = 126$ isotones, with the exception of ^{208}Pb and (for practical purposes) ^{209}Bi, are unstable. Knowledge of single-nucleon overlaps are confined to transfer studies on stable doubly-magic ^{208}Pb, ^{209}Bi, and on the long-lived ^{210}Po. The study of isotones below $Z = 82$ remains particularly challenging as pure and intense beams of these nuclei are difficult to produce. Next to nothing is known about their structures, yet these nuclei could serve as a cornerstone to our understanding of heavier systems. This

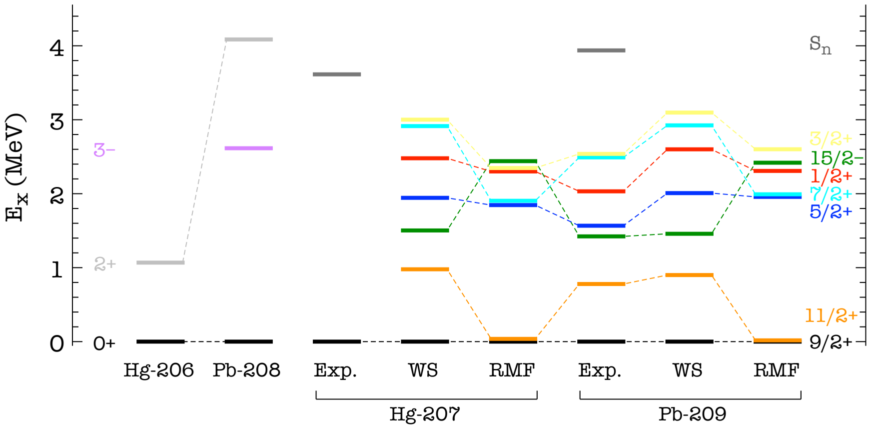

Figure 1: Core excitations for the even $N = 126$ isotones, ^{206}Hg and ^{208}Pb, and single-neutron excitations for corresponding $N = 127$ isotones. The experimental data (Exp.) are taken from Ref. [1]. Excited states in ^{207}Hg and ^{209}Pb were estimated using Woods-Saxon calculations [2] (WS), and a spherical relativistic mean-field calculation [3] (RMF).

region also plays an important role in explosive nucleosynthesis, where questions remain as to the path of the r-process, and how much it is delayed at $N = 126$.

The principal goal of the proposed measurement is to identify and determine the strength of low-lying $3s_{1/2}$, $2d_{5/2}$, and other single-neutron excitations outside of the $N = 126$ neutron shell closure at $Z = 80$. Such data will help better predict the evolution of these excitations in $N = 127$ nuclei with lower proton numbers. The proposed measurement will determine the excitation energy and spin-parity assignments of all major components of the single-neutron strength outside ^{206}Hg—that is the $1g_{9/2}$ (the ground state), $0i_{11/2}$, $0j_{15/2}$, $2d_{5/2}$, $3s_{1/2}$, $1g_{7/2}$, and $2d_{3/2}$ levels. No information on *any* excited state of ^{207}Hg is available in the literature, to the best of our knowledge [1, 4].

The binding energy of the 127th neutron in ^{209}Pb is 3.93 MeV. The $3s_{1/2}$ state is at 2.03 MeV in excitation energy, 1.9 MeV below threshold. In ^{207}Hg, the last neutron is bound by 3.61(4) MeV and, thus, the neutron $3s_{1/2}$ state may be at ~1.7 MeV below threshold. As the neutron threshold is approached the behavior of s-states has been found to differ from that of other states [5, 6], yet the influence of this state is likely to be critical in the capture of neutrons in nucleosynthesis [7, 8].

The level structure of ^{206}Hg yields some clues: the first-excited 2^+ state at 1.07 MeV is likely to be the excitation of the proton core. This state then could couple to the $5/2^+$ and $3/2^+$ neutron states, seen in ^{209}Pb, at 1.57 and 2.54 MeV, to form $1/2^+$ states near the neutron threshold. These weak-coupling states then could admix with the single-neutron state at lower excitation. Such admixtures are known in the Pb region, in ^{207}Pb and ^{209}Bi. The observation of such fragments would be valuable input to estimations of neutron-capture cross sections.

Figure 1 shows the known core excitations for the $N = 126$ isotones ^{208}Pb and ^{206}Hg and single-neutron excitations for the respective $N = 127$ isotones as reported in Ref. [1]. We have estimated the location of single-neutron excitations in ^{207}Hg using Woods-Saxon [2] and spherical relativistic mean-field calculations [3]. The results are disparate and at odds with known excitations in ^{209}Pb.

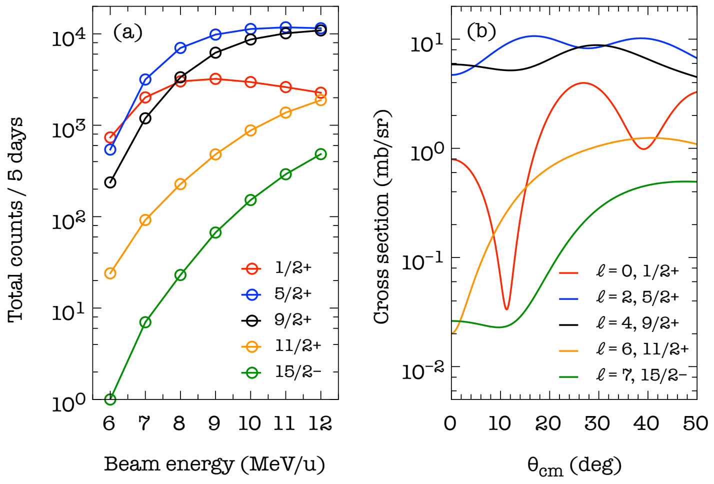

Figure 2: (a) Total counts in 5 days (15 shifts) versus beam energy for single-neutron excitations in ^{207}Hg following the (d,p) reaction on ^{206}Hg in inverse kinematics, assuming 1×10^6 ions per second in the beam and a deuterated polyethylene target of 75 μg/cm^2. (b) Proton angular distributions for the same reaction at 10 MeV/u.

An exploration of neutron s states in light nuclei and their behavior near threshold was recently summarized in Ref. [5], emphasizing the connection between the tendency of s states to "linger" below threshold, in a manner different from higher angular momentum states, and the link between this behavior and neutron halos. The extent to which neutron halos are important in heavier nuclei and how they manifest themselves is an open question. For instance, recent theoretical studies suggest that ^{62}Ca could perhaps be a large halo nucleus [9]. Without knowledge of the s state excitations below Pb, it is difficult to estimate whether or not the s state will cross the low-lying $5/2^+$ (and $9/2^+$) excitation as seen in lighter systems.

We propose a first study of the (d,p) reaction on ^{206}Hg to determine the ordering, locations, and possible fragmentation of the single-neutron states past $N = 126$. Exploration of the fragmentation of the s-wave strength has interesting astrophysical implications. High-j states will be populated, though with this reaction only limited information, such as their spin assignment and excitation, can be determined.

2 Experimental details

We will use the ISOL solenoidal spectrometer to analyze protons from the (d,p) reaction on ^{206}Hg at 10 MeV/u. The specific details for the proposed measurement are discussed in the following sections.

Beam energy—A beam energy of 10 MeV/u has been chosen to optimize the yield to both low- and high-j states, which for this measurement covers angular-momentum transfers of 0 to 7 $\hbar$. Around 10 MeV/u the (d,p) reaction is well matched for low-ℓ transfer. The higher-ℓ (particularly $\ell = 6$ and 7) transfers are expected to be populated more weakly—it will be possible to identify them, but the spectroscopic information will be less robust. Figure 2(a) shows the estimated yields for a typical set up (assumptions discussed below) for a five-day (15-shift) period as a function of beam energy on the assumption of 1×10^6 pps of ^{206}Hg. A beam energy of 10 MeV/u is expected to match well with the capabilities of the accelerator.

Figure 2(b) shows proton angular distributions as a function of center-of-mass angle for $\ell = 0$, 2, 4, 6, and 7 transfer at an incident beam energy of 10 MeV/u. The calculations were carried out using the distorted wave Born approximation with the Ptolemy code [10]. Typical bound-state form factors were used along with global optical-model parameters (Ref. [11] for deuterons and Ref. [12] for protons) to describe the distorting potentials. The set up described below will allow proton yields to be measured over $10^\circ \lesssim \theta_{\rm cm} \lesssim 30^\circ$ for all states below the neutron threshold. In this regime, the calculations show the distributions to be distinct. Comparisons can be made to previous works by Kovar *et al.* studying ^{208}Pb(d,p) at 20 MeV, where the angular distributions are very similar [13].

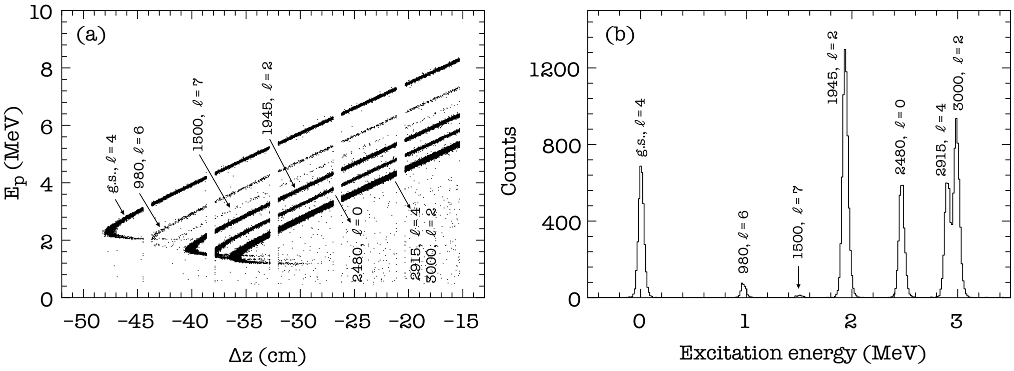

Figure 3: (a) A simulated spectrum of proton energy, E_p, versus distance between the target ($\Delta z = 0$ mm) and the point at which the proton hits the Si array [14], using energies from Woods-Saxon calculations [2]. Assumptions are discussed in the text. (b) The excitation energy spectrum projected for $-260 < \Delta z < -210$ mm. States are labeled by excitation energy in keV and by ℓ transfer required to populate them.

ISOL solenoidal spectrometer—The experiment will use the ISOL solenoidal spectrometer to momentum analyze the outgoing protons from the ^{206}Hg(d,p) reaction. We will use the spectrometer in a manner that is conceptually and operationally similar to that used in experiments carried out with the Argonne National Laboratory (ANL) solenoidal spectrometer, HELIOS [15, 16]. For this experiment, the same Argonne position-sensitive silicon-detector array will be used. We have extensive experience with these detectors.

The advantages of this solenoidal-spectrometer technique are many. The detector efficiency is large, demanding only known geometrical-efficiency corrections, which are about 40% for the proposed setup. This allows for the use of thin targets with weak beams, and provides good Q-value resolution without the deleterious effects of kinematic compression. Given the nuclear structure of the region, isomers are prevalent. For example, the $15/2^-$ state in ^{211}Po has a half life of 14 ns. Using other approaches, such as a particle–γ-ray coincidences, can result in such states being 'missed' as they may decay after the recoiling nucleus has left the γ-ray detector.

Reaction kinematics and experimental setup—Protons emitted at forward center-of-mass angles in the (d,p) reaction in inverse kinematics are emitted at backwards angles in the laboratory at energies of $\sim$2–8 MeV. The Si array, placed around the beam and parallel to the field axis of the solenoidal spectrometer, is upstream of the target inside the solenoid. Simulations, shown in Fig. 3, suggest that an optimal set up will use a field of 2.5 T, with the Si array covering a distance of $-500 < \Delta z < -150$ mm from the target. The characteristic kinematic lines are shown in Fig. 3(a) in terms of proton energy versus Δz, the distance between the target and the point at which the emitted proton intercepts the array. These simulations include the target thickness and allow us to place some limits on the anticipated Q value resolution. We estimate about 75 keV resolution (FWHM) on the assumptions of a deuterated polyethylene target of thickness 75 μg/cm^2. The spectrum shown in Fig 3(b) illustrates this. The location of the excited states was estimated using the assumptions discussed above. The spectrum assumes that a background subtraction was applied. Without recoil detection, a smooth background of protons, and to a lesser extent alpha particles, will be present at these backwards angles [17]. We do not require recoil detection for this measurement.

Targets—We will use deuterated polyethylene targets of thickness $\sim$75 μg/cm^2. These targets will be provided by Argonne National Laboratory. We now have extensive experience in the use of such targets for deuteron-induced transfer reactions with light to medium mass beams (e.g., with Xe beams) in the energy regime of 5-10 MeV/u and intensities of 10^6 ions per second and greater. They are known to degrade under beam bombardment—experience with xenon suggests that they tolerate a dose of $\sim 10^{11}$ particles in a beam spot of a few mm in diameter. A monitor detector will be used to provide information on the target degradation (see Ref. [18] for a discussion of this method). The target mechanism for the solenoidal spectrometer can accommodate multiple targets. Once a target is damaged a new one can be moved into the beam path without breaking the vacuum.

Previous ISOLDE runs with Hg beams—Mercury beams have been used several times at ISOLDE. The yield database cites $\sim 1\times10^8$ ions per μC using the PbVD5 approach [19]. An efficiency of about 2-4% in the acceleration process can be expected. We assume 1×10^6 ions per second on target for this measurement. A purity of >99% can be anticipated if the VADLIS mode is used [20], with comparable intensity.

Rate estimates and shifts required—Rate estimates are based on the assumption of an angular coverage of $10^\circ \lesssim \theta_{\mathrm{c.m.}} \lesssim 30^\circ$, with a 50% efficiency in the azimuthal angle and 85% efficiency in the theta angle. These are typical values for experiments using the ANL Si array. Cross sections for $\ell = 0$, 2, 4, 6, and 7 transfer to states of $1/2^+$, $5/2^+$, $9/2^+$, $11/2^+$, and $15/2^-$, respectively, were calculated using DWBA with the code Ptolemy as discussed above. The total measured yield of protons over five-days [Fig. 2(a)] of beam on target at 1×10^6 pps, and target thickness of 75 μg/cm^2, are about 3000, 11300, 8700, 900, and 150 counts for these states, assuming a spectroscopic factor of 1. This should allow for robust ℓ-value assignments, and spectroscopic factors, for the low-ℓ states, while significantly constraining those for high-ℓ states. Further, even small fragments of the *s*-wave strength will still be measured with statistically significant yields. We request 15 shifts of beam on target. Three additional shifts are requested, one for likely target changes, one for the optimization and calibration of the set up, and one to record the background from fusion-evaporation of the beam on a C foil. This totals 18 shifts.

3 Summary

We request 18 shifts of beam time to carry out the (d,p) reaction on ^{206}Hg at 10 MeV/u in inverse kinematics. We will use the ISOL solenoidal spectrometer to analyze the outgoing protons. The number of shifts is based on a beam of 1×10^6 pps of ^{206}Hg on target. We will use a deuterated polyethylene target of thickness $\sim$75 μg/cm^2. It is expected that a Q-value resolution of 75 keV will be achieved. The results will inform us, for the first time, on the trends of single-neutron excitations below lead and beyond $N = 126$—to date, terra incognita. These are of considerable interest for nuclear structure studies, as well as for the synthesis of heavy elements.

References

[1] ENSDF and XUNDL databases, May 2016.
[2] A. Volya, http://www.volya.net.
[3] P. Zhao, private communication 2016.
[4] O. Sorlin and M.-G. Porquet, Prog. Part. Nucl. Phys. **61**, 602 (2008).
[5] C. R. Hoffman, B. P. Kay, and J. P. Schiffer, Phys. Rev. C. **89**, 061305(R) (2014).
[6] C. R. Hoffman and B. P. Kay, Nuclear Physics News International, Volume 24, Issue 4, page 16-21, October-December 2014.
[7] T. Rauscher *et al.*, Phys. Rev. C **57**, 2031 (1998).
[8] M. R. Mumpower *et al.*, Prog. Part. Nucl. Phys. **86**, 86 (2016).
[9] G. Hagen *et al.*, Phys. Rev. Lett. bf 111, 132501 (2013).
[10] M. H. Macfarlane and S. C. Pieper, ANL-76-11 Rev. 1, ANL Report (1978).
[11] H. An and C. Cai, Phys. Rev. C **73**, 054605 (2006).
[12] A. J. Koning and J. P. Delaroche, Nucl. Phys. A **713**, 231 (2003).
[13] D. G. Kovar, Nelson Stein, and C. K. Bockelman, Nucl. Phys. **A231**, 266 (1974).
[14] M. Labiche, private communication 2016.
[15] A. H. Wuosmaa *et al.*, Nucl. Instrum. Methods Phys. Res. A **580**, 1290 (2007).
[16] J. C. Lighthall *et al.*, Nucl. Instrum. Methods Phys. Res. A **622**, 97 (2010).
[17] Calculations with PACE suggest fusion-evaporation cross sections for ^{206}Hg on ^{12}C comparable with the those in previous measurements with Xe, which amounted to background counts which increased linearly across the array from about 10-100 counts per channel per side of the array. However, a factor 5 fewer protons are emitted for the ^{206}Hg case.
[18] B. P. Kay *et al.*, Phys. Rev. C **84**, 024325 (2011).
[19] F. J. C. Wenander and T. Stora, private communication 2016.
[20] F. Wienholtz, private communication 2016. Data from the IS598 experiment at MR-TOF and T. Day Goodacre *et al.*, Nucl. Instrum. Methods Phys. Res. B **376**, 39 (2016).

Appendix 1: Status of the solenoidal spectrometer

The £5M UK STFC project, ISOL-SRS, will build two spectrometers, one external and one internal to the Test Storage Ring (TSR), over the period 2015-2019. The external solenoidal spectrometer, ISS (the ISOL Solenoidal Spectrometer), will eventually accept cooled beams from the TSR, enabling the energies of final states in two-body reactions to be measured with Q-value energy resolutions of around 20 keV FWHM. In order to achieve this, a 50 cm six-fold hexagonal DSSD array with 1 mm position resolution in the axial direction and 2 mm in the transverse direction, with individual read-outs, will be constructed. This array will measure the position and energy of light ions emitted from the target as they are deflected through a homogeneous magnetic field on a trajectory that intercepts the detector near the beam axis. This is the "HELIOS" technique first developed at ANL (A. H. Wuosmaa *et al.* 2007, NIM A**580**, 1290). Initial exploitation of HELIOS at Argonne (20+ experiments) has led to 10+ publications, four or which are in Physical Review Letters or Rapid Communications. The studies have been primarily focused on nucleon-transfer reactions with weak radioactive ion beams (RIB).

In the light of delays in the approval for the CERN TSR project, CERN management has provided funding to construct a third beam-line dedicated to the external spectrometer that will enable direct HIE-ISOLDE beams be exploited. The expected energy resolution will be around 45 keV FWHM which is adequate for many experiments that can make use of the large range of accelerated RIB from HIE-ISOLDE. The magnetic field is provided by an ex-MRI magnet purchased by the UK collaboration, which was delivered to CERN in April 2016. While the maximum field in the 1m diameter bore of the magnet is 4 T, it is expected that most experiments will use fields in the range 1.5-2.5 T. The magnet has field-cancelling coils, and additional Fe shielding will reduce the stray field to levels that satisfy the requirements for both health & safety and for beam acceleration and transport.

Satisfactory readings of the transportation shock-log, coil impedance at room-temperature, etc. suggest that the magnet will cool to liquid helium and be energized without difficulty. It is planned to cool the magnet before the end of 2016 and position it on the end of XT02 (2nd beam line in the ISOLDE hall) at the beginning of 2017. The early-implementation Si array (see below) will be installed and optimized with alpha sources or stable beams during 2017, allowing experiments on ISS to be scheduled in 2018.

While the full DSSD Si array will not be available for experiments until after the second long shutdown at CERN (LS2), the US HELIOS collaboration has offered the use of the position-sensitive Si array currently installed in HELIOS at Argonne (Lighthall *et al.* 2010, NIM A**622**, 97), together with a heavy-ion recoil detector, for experiments at HIE-ISOLDE. This provides the ISS collaboration with an opportunity to perform (d,p) measurements, before LS2, in particular cases where Q-value energy resolution of around 85 keV is sufficient to resolve the states of interest.

The MRI magnet of ISS will be shared with a second detection setup, the SpecMAT active target of the KU Leuven group. For this project, supported by a 2M€ ERC grant, the Si array of ISS will be replaced by a gaseous detector surrounded by an array of scintillators. Experiments with this device are also foreseen for 2018, after realization and commissioning of the setup. The UK and Leuven groups are closely collaborating for the technical and logistical aspects of the use of the magnet.

Note that this major project will strongly benefit from timely entry into CERN's Grey Book, as this would facilitate release of resources to the project, remove obstacles from external collaborators participating in the setting-up phase, and strengthen our applications for further grant funding.

Appendix 2

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: ISOLDE solenoidal spectrometer

Part of the	Availability	Design and manufacturing
(if relevant, name fixed ISOLDE installation: MINIBALL + only CD, MINIBALL + T-REX)	☐ Existing	☐ To be used without any modification
ISOLDE solenoidal spectrometer	☐ 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 [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards			
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature	4 K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LHe, ~1650 l, LN_2, ~200 l, 1.0 Bar		
Electrical and electromagnetic			
Electricity	0 V, 300 A		
Static electricity			
Magnetic field	2.5 T		
Batteries			
Capacitors			
Ionizing radiation			
Target material	Deuterated polyethylene		
Beam particle type	^{206}Hg		
Beam intensity	1×10^{6} pps		
Beam energy	10 MeV/u		

Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☒ (α calibration sources)		
• Sealed source			
• Isotope			
• Activity			
Use of activated material:			
• Description			
• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant	Helium		
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			

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): 5 kW