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

Coulomb excitation of ^{185}Hg: Shape coexistence in the neutron-deficient lead region

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Abstract: In view of the most recent experimental and theoretical achievements related to Hg charge radii measurements, there is a renewed interest in shape coexistence in the neutron-deficient lead region, a phenomenon that results from an interplay between individual nucleon behaviour and collective degrees of freedom in the nucleus. The aim of this proposal is to investigate collective properties of low-lying states in the ground-state and isomeric bands in ^{185}Hg with a particular interest in determining their quadrupole moments. This detailed study builds on our extensive past experience and the results obtained from previous Coulomb-excitation measurements of neutron-deficient Hg nuclei performed with 2.85 MeV/u beams from REX-

ISOLDE. It would represent the first investigation of an odd-mass nucleus in this mass region using the powerful Coulomb-excitation technique.

Requested shifts: 10 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 between N = 82 and N = 126 using various experimental techniques. This resulted, amongst others, in the discovery of an unique odd-even mass staggering in the isotope shifts in the mercury isotopes around $^{181-185}$Hg [4], which has long been attributed to the intruder structure becoming the ground state in the odd-mass isotopes and the observation of shape coexistence at low excitation energy in ^{185}Hg [5]. Recent results obtained at CERN-ISOLDE from isotope-shift measurements extended the knowledge on the ground-state charge radii and indirectly the deformation systematics down to ^{177}Hg [6, 7, 8]. The endpoint of the famous, well localized odd-even mass staggering effect was established in ^{181}Hg (see Fig. 1, right side).

In the neutron-deficient even-even mercury isotopes with neutron number around mid-shell (N=104, ^{184}Hg) the intruding states, associated to the prolate deformation, come low in excitation energy and mix with the normal more spherical states (see Fig. 1, left side). Coulomb excitation of ^{182,184,186,188}Hg performed at REX-ISOLDE evidenced mixing of two distinct configurations, weakly deformed oblate and more deformed prolate, which coexist at low excitation energy [9]. Next to these findings a number of experiments have been carried out on the even-mass Hg isotopes involving lifetime measurements [10-14], and more recently β^+/EC decay spectroscopy with ISOLDE Decay Station [15]. The latter yielded important complementary data for the future IS563 Coulomb excitation experiment of ^{182,184}Hg with HIE-ISOLDE beams. The results obtained in these measurements support the interpretation that the ground states of exotic Hg isotopes from the mid-shell region N=104 are weakly deformed and of oblate nature, while those of heavier ones are dominated by the prolate configuration.

The experimental spectroscopic information on odd-mass Hg nuclei around N=104 is rather scarce. The lowest lying states in ^{185}Hg were investigated by means of the β^+/EC decay of ^{185}Tl at ISOLDE [16]. A number of new transitions have been identified, including very low-energy conversion electron lines observed for the first time. A partial low-spin level scheme of ^{185}Hg has been constructed. This resulted, amongst others, in a precise energy location of the $13/2^+$ isomeric state at 103.7(4) keV as well as the E2/M1 mixing ratio determination for the 26-keV $3/2^-_1 \rightarrow 1/2^-_{gs}$ transition. The properties of the higher-spin levels in ^{185}Hg were investigated through the ^{161}Dy(^{28}Si, 4nγ) reaction [17]. This study established four bands built on the prolate $1/2^-$[521], $7/2^-$[514] and $9/2^+$[624] Nilsson states and the $i13/2^+$ isomer (see Fig. 2).

Recent Monte-Carlo shell-model (MSCM) predictions obtained by the Tokyo group [6, 7] give a new insight into the connection between the shape coexistence in the N~104 Hg region and the evolution of single-particle orbits caused by nuclear forces. The MSCM calculations performed in the context of the Hg charge radii measurements provided information of the underlying mechanism and reproduced the localized nature of the observed shape staggering [6,7]. It was concluded that this phenomenon results from 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.

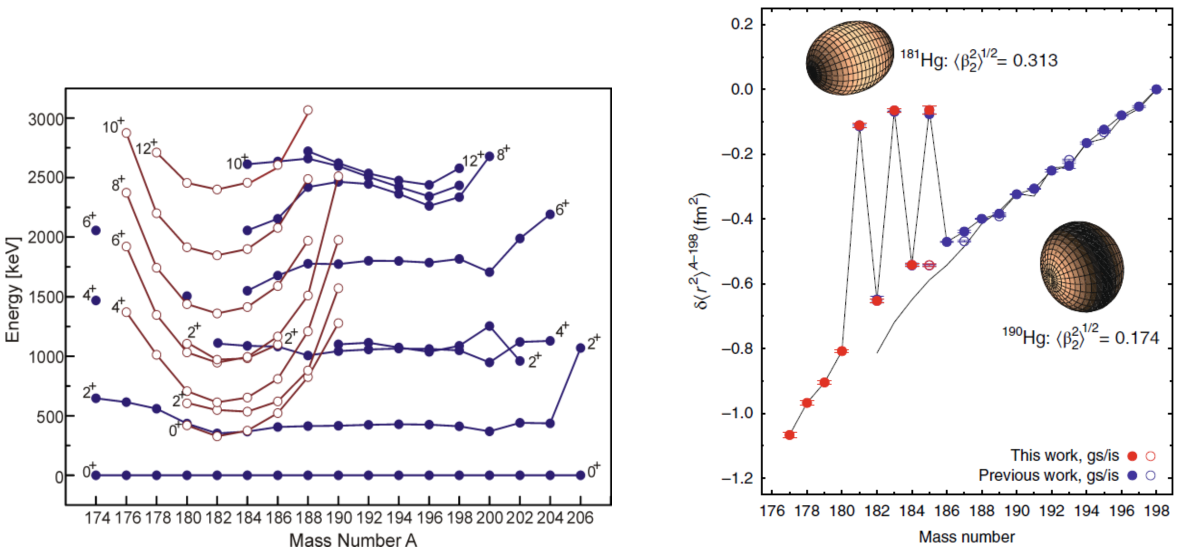

Figure 1: Left: energy level systematics of even-even Hg isotopes, taken from Reference [29]. The full circles denote weakly-deformed oblate states and the open circles the excited prolate structures in even – even Hg isotopes.; Right: Changes in the mean square charge radii for Hg isotopes, taken from Reference [6].

In order to verify this interpretation, we intend to perform a series of Coulomb-excitation studies of the light, N~104, odd-mass Hg isotopes as discussed in HIE-ISOLDE LOI110 [18]. Following our proposal on the even-even isotopes [31] we would like to propose to investigate the structure of ^{185m,g}Hg aiming in particular at the extraction of the quadrupole moments for states in the rotational bands built of the ground state and on the isomer.

2. Proposed experiment: Coulomb excitation of ^{185}Hg

The successful Coulomb-excitation experiments to study selected neutron-deficient, even-even mass isotopes of mercury, polonium, radon and radium have demonstrated the potential to perform such studies using post-accelerated REX-ISOLDE beams [e.g. 9, 19, 20-22].

The proposed measurement of ^{185m,g}Hg employs the same experimental technique. The ISOLDE facility is currently the only laboratory where Coulomb excitation of ^{185m,g}Hg can be carried out. As evidenced by recent laser spectroscopy measurements [6, 7, 8] it became possible to obtain pure and intense ground- and isomeric-state beams of ^{185}Hg, well suited for Coulomb-excitation studies. As in the afore-mentioned isotope shift experiment, the ^{185}Hg nuclei will be produced by impinging a proton beam on a molten lead primary target. The use of the VADLIS ion source [30] will be crucial to provide the isomeric state selection. Both ground and isomeric states can be well separated in ^{185}Hg, as shown in Fig. 7 of Ref. [7].

Proposed measurements will be performed using the MINIBALL array [23] composed of 8 triple clusters and equipped with an annular double-sided silicon strip detector (DSSSD) placed at forward angles with respect to the beam direction ($\sim 16^0 - 54^0$ in the laboratory frame). In order to measure directly the converted transitions, particularly those arising from the lowest lying states in ^{185}Hg, the electron spectrometer SPEDE [24] will be used and located inside the MINIBALL array upstream from the secondary target without hampering the γ-ray detection efficiency.

The accelerated ^{185m,g}Hg beams will be delivered to the MINIBALL target position were mercury ions will be Coulomb excited in inverse kinematics using two different secondary targets. Gamma rays and conversion electrons that de-excite the levels under investigation will be detected by MINIBALL and SPEDE, respectively. Measurements will be performed in a coincidence mode with scattered particles (Hg projectiles/ target recoils) registered by the DSSSD.

Coulomb-excitation cross sections depend on beam energy, scattering angle as well as atomic (Z) and mass (A) numbers of beam and target nuclei. In order to exploit this dependence we propose to use two targets with significantly different Z numbers, i.e., ^{120}Sn (Z=50) and ^{48}Ti (Z=22). The use of such beam-target combinations will result in different population of states in ^{185}Hg. Scattering on a high-Z reaction partner maximizes the probability of multi-step excitation. In such cases, a number of matrix elements will affect the Coulomb-excitation cross section in a complex way, with the contribution from various excitation paths varying with the scattering angle. It is possible to disentangle them from differential measurements of Coulomb-excitation cross sections, gaining sensitivity to subtle higher-order effects, such as quadrupole moments. Complementary measurements with a reaction partner of a lower Z will limit the number of populated states which is required to elucidate various excitation paths and to determine the transition probabilites in low-energy part of the level scheme in ^{185}Hg.

The ^{185m,g}Hg beam energy of 4 MeV/A and 3.5 MeV/A (depending on the secondary target used, i.e., ^{120}Sn and ^{48}Ti, respectively) has been chosen such that the distance between the collision partners is greater than $1.25\ (A_{projectile}{}^{1/3} + A_{target}{}^{1/3}) + 5$ [fm] over the angular range covered by the DSSSD. This ensures the purely electromagnetic interaction between collision partners.

It should be noted that additional in-beam γ-ray and conversion-electron spectroscopy experiment has just been performed at Jyväskylä to probe low-lying states in ^{185}Hg and to clarify the level scheme, particularly with respect to the $9/2^+$[624] band and a missing $13/2^+_2$ state. For these measurements the SAGE electron spectrometer in conjunction with the MARA separator was employed. Such combination allowed an investigation of the inter-band transitions (particularly the *E*0 components of the $I^+ \rightarrow I^+$ transitions) and the properties of both yrast and non-yrast excited states in ^{185}Hg. These measurements will provide important complementary spectroscopic data for future Coulomb-excitation analysis.

3. Count rate estimate

The gamma-ray yields estimated for the proposed Coulomb-excitation experiment were calculated using the GOSIA code [25, 26] and are shown in Figure 2 .

The information on the level scheme of low-lying states in ^{185}Hg was taken from Ref. [17]. The intra-band matrix elements used for these estimations were calculated assuming the rotational coupling model scheme [27] with the intrinsic quadrupole moment inferred either from the measured $<\beta_2^2>^{1/2}$ values for the ½- ground and $13/2^+$ isomeric states in

^{185}Hg [6, 7] (equal to 0.271(2) and 0.179(10), respectively) or from the proposed one ($\beta_2 =$ 0.25) in Ref. [17] used to interpret bands built on the 7/2$^-$[514] and 9/2$^+$[624] Nilsson orbitals. Additionally, known spectroscopic data were used in the calculations, whenever available [16, 17].

The Miniball gamma-ray detection efficiency at energies of interest was taken from [28]. The calculations were performed assuming ^{185m,g}Hg beam intensity of 10^5 pps at the secondary target. It should be noted that numbers given in Fig. 2 are for the whole DSSSD detector. In the final analysis it is foreseen that the data will be divided into few angular ranges to enhance sensitivity to quadrupole moments of excited states in bands built on the ground state and the isomer as shown in Figure 3.

Next to the ground- and isomeric-band excitation, a possible population of the 7/2$^-$[514] and 9/2$^+$[624] side-bands was considered as well. Due to low excitation energy of the 7/2$^-$[514] level, this state and the band built on it may influence the excitation of the ground-state band. In such case the number of states and transitions involved in the excitation process will increase. However, the complementary measurements performed with the lower beam energy (3.5 MeV/A) and the lower-Z (^{48}Ti) secondary target will provide necessary constraints, particularly for the ground-state-band transitions, making it possible to disentangle various excitation paths and enabling extraction matrix elements from measured gamma-ray yields.

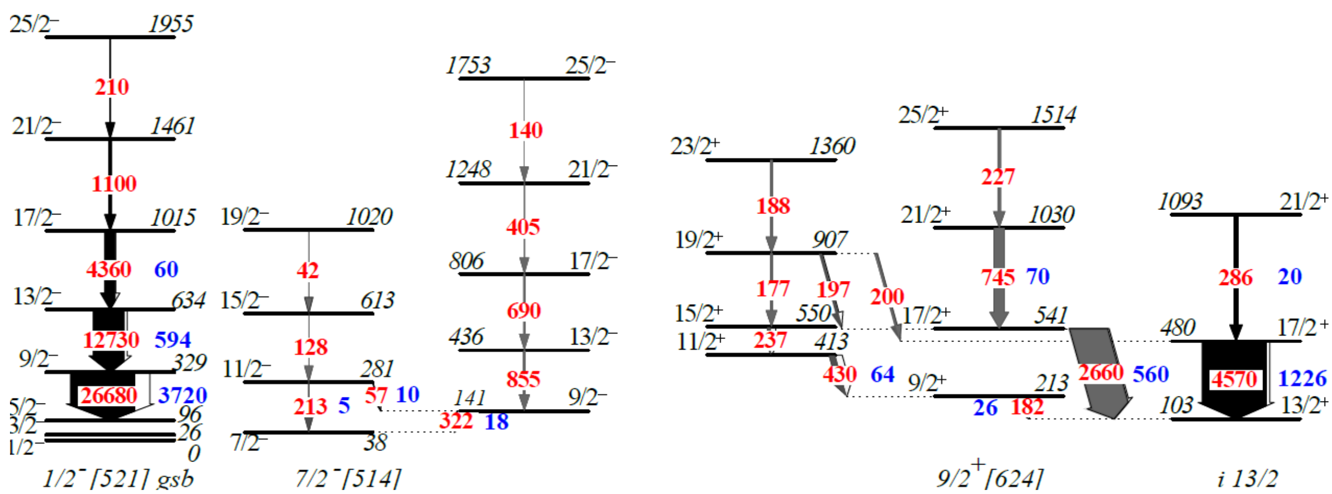

***Figure 2**: Low-lying levels in ^{185}Hg, taken from Ref. [17] and expected to be populated in the Coulomb excitation with a ^{120}Sn (red) and ^{48}Ti (blue) secondary targets at beam energies of 4 MeV/A and 3.5 MeV/A, respectively. The labels represent total numbers of estimated photopeak counts assuming the requested number of shifts indicated in Table 1. The widths of the arrows are proportional to the simulated γ-ray yields. The excitation patterns for the two proposed secondary targets exhibit a clear difference. Calculations were performed assuming negative signs of quadrupole moments of excited states in bands built on the ½$^-$ gs and i13/2 isomeric states. For positive signs of quadrupole moments the intra-band yields increase by ~25 – 36 % and by ~ 19% for lowest gs- and isomeric band transitions, respectively. This demonstrates a significant sensitivity to the quadrupole moments expected in ^{185m,g}Hg+^{120}Sn measurements. The strongly converted lowest-energy transitions in the ½- ground-state-band will be detected with SPEDE electron spectrometer.*

The data collected in ^{185m,g}Hg + ^{120}Sn experiment will be sensitive to quadrupole moments of states in the ground-state band and that built on the isomer. As an example, the intensities of γ rays depopulating the $9/2^-_{gsb}$ and $17/2^+_{is}$ states will be determined with uncertainties at a level of 5% (this includes both statistical and systematic contributions), which will correspond to a ~ 5 and 3.5 sigma difference, respectively, between the solutions corresponding to negative or positive quadrupole moments of these states (assuming rotational limits).

As the measured Coulomb-excitation cross sections in ^{185}Hg will be normalized to the known excitation of the target nucleus, the requested number of shifts, summarized in Table 1 in Section 4, was chosen to obtain a sufficient level of statistics of 2700 counts/shift and 995 counts/shift for the $2^+_1 \rightarrow 0^+_1$ transitions in ^{120}Sn and ^{48}Ti, respectively.

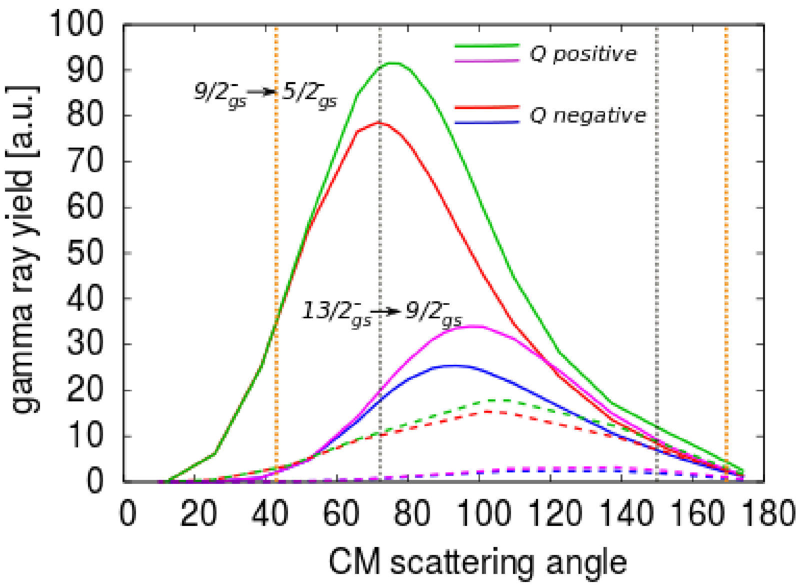

***Figure 3**: Gamma ray yields of the intra-band $9/2^-_{gs} \rightarrow 5/2^-_{gs}$ (red and green lines) and $13/2^-_{gs} \rightarrow 9/2^-_{gs}$ (magenta and blue lines) transitions as a function of center-of-mass (CM) scattering angle shown for the two secondary targets proposed in the present experiment, i.e., ^{120}Sn (solid lines) and ^{48}Ti (dashed lines). Different beam-target combinations allows to probe different CM angular ranges marked with orange (^{185}Hg+^{120}Sn) and grey (^{185}Hg+^{48}Ti) dotted lines. The sensitivity to the quadrupole moments (varied within rotational limits) of relevant excited states is clearly visible. Combining the data from the measurements involving two different targets will enable determination of both the transitional and diagonal matrix elements.*

To summarize, the increased beam energies available at HIE-ISOLDE, i.e., ~4 MeV/A, allow performing multistep Coulomb excitation and probe, for the first time, the collective properties of excited states in both ground and isomeric bands. Moreover we aim to determine the quadrupole moments, including signs, of states in the ground-state and isomeric bands to provide, amongst other, a decisive direct evidence for a long-standing hypothesis of a prolate deformation of the ground-state band of ^{185}Hg.

4. ^{185m,g}Hg beam request

- isotope: **^{185}Hg in a ground and isomeric states** (half-life of the ½- 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}Hg)
- ion source: **VADLIS**
- intensity: **10^5** pps for ^{185}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;
- time profile: the beam pulse from the EBIS should be as long and as homogeneous as possible.

HIE-ISOLDE should be fully operational for heavy mass beams for slow extraction from the EBIS. For the this experiment we need SPEDE spectrometer to be fully operational

***Table 1**. Summary of the requested number of shifts and beam parameters, i.e. energy and intensity at the Miniball target station.*

Beam	Secondary target	Number of shifts
^{185}Hg (ground state) @ 4 MeV/A	^{120}Sn 2 mg/cm^2	3
^{185}Hg (isomeric state) @ 4 MeV/A	^{120}Sn 2 mg/cm^2	3
^{185}Hg (ground state) @ 3.5 MeV/A	^{48}Ti 1 mg/cm^2	1
^{185}Hg (isomeric state) @ 3.5 MeV/A	^{48}Ti 1 mg/cm^2	2

4. Further notes

The same experimental setup as for the approved 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.

To summarize, 9 shifts of beam time are required for the measurement of ^{185m,g}Hg. As it will be beneficial to perform these measurements in conjunction with IS563, additional 1 shift is required for energy change of HIE-ISOLDE. Thus**, in total we request 10 shifts for Coulomb excitation of ^{185m,g}Hg.**

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: MINIBALL+CD+SPEDE

Part of the Choose an item.	Availability	Design and manufacturing
MINIBALL + only CD	X Existing	X To be used without any modification
MINIBALL	X Existing	X To be used without any modification ☐ To be modified
SPEDE	X New	☐ Standard equipment supplied by a manufacturer X CERN/collaboration responsible for the design and/or manufacturing
CD	X Existing	☐ To be used without any modification X To be modified
[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 installation.

Additional hazards:

Hazards	*MINIBALL+CD+SPEDE*	*[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)	185Hg ions in ground and isomeric states		
Beam intensity	10^5 pps for $^{185\ m,g}Hg$		
Beam energy	4 MeV/A and 3.5 MeV/A for $^{185\ m,g}Hg$		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	X [ISO standard] Standard γ -ray sources for MINIBALL		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser	VADLIS, scheme for Hg		
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