EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Beta-decay spectroscopy of neutron-rich Cd isotopes

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L.M. Fraile[1], J. Benito[1], M. Llanos[1] J.R. Murias[1], V. Sánchez-Tembleque[1], J.M. Udías[1],
A. Korgul[2], A. Fijalkowska[2], Z. Janas[2], M. Karny[2], L. Koszuk[2], C. Mazzocchi[2] ,
K. Miernik[2], M. Piersa[2], A. Jungclaus[3], M.J.G. Borge[3], J.A. Briz[3], A. Gargano[4],
M. Stryjczyk[5], T.E. Cocolios[5], P. Van Duppen[5], H. De Witte[5], R. Lică[6], B. Olaizola[6],
N. Mărginean[7], C. Mihai[7], A. Negret[7], S. Pascu[7], C. Sotty[7], A. Illana[8], N. Bernier[9],
T.D. Bucher[9], N. Orce[9], T. Kurtukian[10], P. Jones[11], E. Nácher[12], A.I. Morales[12],
U. Köster[13], G. Georgiev[14], J. Jolie[15], J.-M. Régis[15], A. Blazhev[15], A. Esmaylzadeh[15],
G. Haefner[15], F. Dunkel[15], Th. Kröll[16], N. Pietralla[16], V. Werner[16], U. Datta[17]
(IDS Collaboration)

[1] *Grupo de Física Nuclear & IPARCOS, Universidad Complutense, Madrid, Spain*
[2] *Faculty of Physics, University of Warsaw, Warsaw, Poland*
[3] *Instituto de Estructura de la Materia, CSIC, Madrid, Spain*
[4] *Instituto Nazionale di Fisica Nucleare, Napoli, Italy*
[5] *Instituut voor Kern- en Stralingsfysica, KU Leuven, Leuven, Belgium*
[6] *CERN, Geneva, Switzerland*
[7] *IFIN-HH, Bucharest, Romania*
[8] *Department of Physics, University of Jyväskylä, Jyväskylä, Finland*
[9] *University of the Western Cape, South Africa*
[10] *CNBG, Bordeaux*
[11] *iThemba Labs, South Africa*
[12] *Instituto de Física Corpuscular, CSIC-Universitat de Valencia, Valencia, Spain*
[13] *ILL Grenoble, France*
[14] *IJC Lab/IN2P3/CNRS, Orsay, France*
[15] *Institut für Kernphysik, Köln, Germany*
[16] *Institut für Kernphysik, Technische Universität Darmstadt, Germany*
[17] *Saha Institute Of Nuclear Physics, Kolkata, India*

Spokespersons: L.M. Fraile (lmfraile@ucm.es)
A. Korgul (Agnieszka.Korgul@fuw.edu.pl)
Contact person: Razvan Lică (Razvan.Lica@cern.ch)

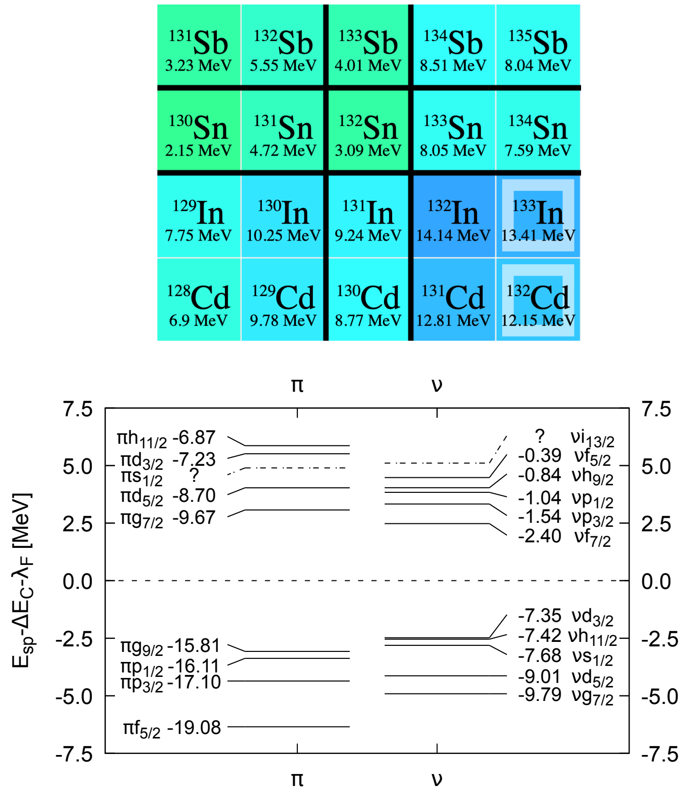
Abstract: We propose to use β-decay and β-n decay of neutron-rich Cd isotopes to populate excited states in neutron-rich In (Z=49) isotopes at and around N=82. High-resolution γ-spectroscopy will be performed. The measurements will be complemented by excited-state lifetime measurements using the fast-timing technique. The beam intensities and purities at ISOLDE will allow to investigate the decays of ^{130}Cd, ^{131}Cd, ^{132}Cd and ^{133}Cd, shedding light on the structure of ^{130,131,132}In. We will use the high-efficiency ISOLDE Decay Station (IDS) setup.

Requested shifts: 21 shifts (split into 1 run over 1 year)

1 Motivation

The properties of exotic nuclei located at and around shell closures are of importance for the understanding of nuclear structure far off stability. Their investigation makes it possible to address the evolution of shell structure and how collective effects develop in the vicinity of magic nuclei. Nuclei with a valence particle or hole with respect to fully occupied nuclear shells provide single-particle energies, which are key parameters for the microscopic description of nuclear structure. Nuclei with two particles or holes outside a double shell closure give information on the two-body effective interaction for correlated pairs close to the Fermi surface. These inputs, together with the effective electromagnetic operators, are then used in model calculations that extend well beyond the nuclei presently at reach.

The region around ^{132}Sn (see Figure 1) is one of the most thoroughly studied and within reach of current experimental facilities. Apart from the interest from the nuclear structure point of view, nuclei in this area are known to play a role regarding the abundances of elements produced in the astrophysical rapid neutron-capture process. Shell model calculations have been developed to provide a good description of the nuclear structure around ^{132}Sn, for instance [1, 26]. But in spite of the huge experimental pogress in the last years some spectroscopic information is still lacking.



^{131}Sb 3.23 MeV	^{132}Sb 5.55 MeV	^{133}Sb 4.01 MeV	^{134}Sb 8.51 MeV	^{135}Sb 8.04 MeV
^{130}Sn 2.15 MeV	^{131}Sn 4.72 MeV	^{132}Sn 3.09 MeV	^{133}Sn 8.05 MeV	^{134}Sn 7.59 MeV
^{129}In 7.75 MeV	^{130}In 10.25 MeV	^{131}In 9.24 MeV	^{132}In 14.14 MeV	^{133}In 13.41 MeV
^{128}Cd 6.9 MeV	^{129}Cd 9.78 MeV	^{130}Cd 8.77 MeV	^{131}Cd 12.81 MeV	^{132}Cd 12.15 MeV

Figure 1: (Top) The region of the nuclear chart under investigation in this proposal. Q_{β^-} values are shown. (Bottom) Relevant single-particle energies, adopted from [3].

The single particle and hole states around ^{132}Sn are available in their vast majority. They are collected in Figure 1. Information on neutron single particle and hole states around ^{132}Sn are taken from ^{133}Sn [4, 5, 6] and ^{131}In [7, 8, 9, 10, 11], with the exception of the missing $\nu i_{13/2}$ state, proposed at 2669(70) keV [12], still subject of investigation. Recently, the β decay of $^{131-134}$In to excited states in $^{131-134}$Sn has been measured at the IDS both with high-resolution γ-ray detectors and fast-timing techniques [3, 13, 14]. Neutron emission has been also addressed via neutron time-of-flight measurements [15].

Experimental energies are also available for the proton states above $Z = 50$ from ^{133}Sb [16], with the exception of the $\pi s_{1/2}$ state, which remains experimentally unkown [17]. Relevant for this proposal, the single-hole proton states can be obtained from the structure of ^{131}In. Relative to the $\pi g_{9/2}$ ground state the single-proton hole states have been established, the $\pi p_{1/2}$ state at 365(8) keV [18, 19], the $p_{3/2}$ at 1353 keV [20] and recently the $\pi f_{5/2}$ state at 2910(50) keV [21]. These states are populated in the decay of ^{131,132}Cd, although the feeding of the $\pi f_{5/2}$ level may be suppressed [21].

In this proposal we would like to complete the experimental information available on neutron rich In isotopes populated in the β-decay of Cd including the measurement of level lifetimes. We focus on the structure of ^{131}In, which is relevant for single-hole proton energies and excitations of the doubly-magic ^{132}Sn core, and investigate proton-neutron couplings in simple two-nucleon systems such as ^{130}In and ^{132}In.

2 Proposed physics cases

2.1 Structure of ^{130}In

Since ^{130}Cd is a N=82 wating point r-proceess nucleus, it has been extensively studied, specially regarding its half-life and beta-delayed neutron emission probability. In [22] the β decay of ^{130}Cd was investigated, and a revision of the previous level scheme of ^{130}In [23] was proposed, see Figure 2. The previosuly proposed energy levels in [23] have been replaced by states at lower energy in [22], except for the 1^+ state in ^{130}In at an excitation energy of 2120 keV that takes most of the strength via a Gamow-Teller transition from the even-even ^{130}Cd. Even in the completely revised decay scheme open questions still remain, including the missing branch from the 388-keV (3^+) state to the known β-decaying (5^+) state, whose energy is still not known, and the placement of several transitions in the MeV range.

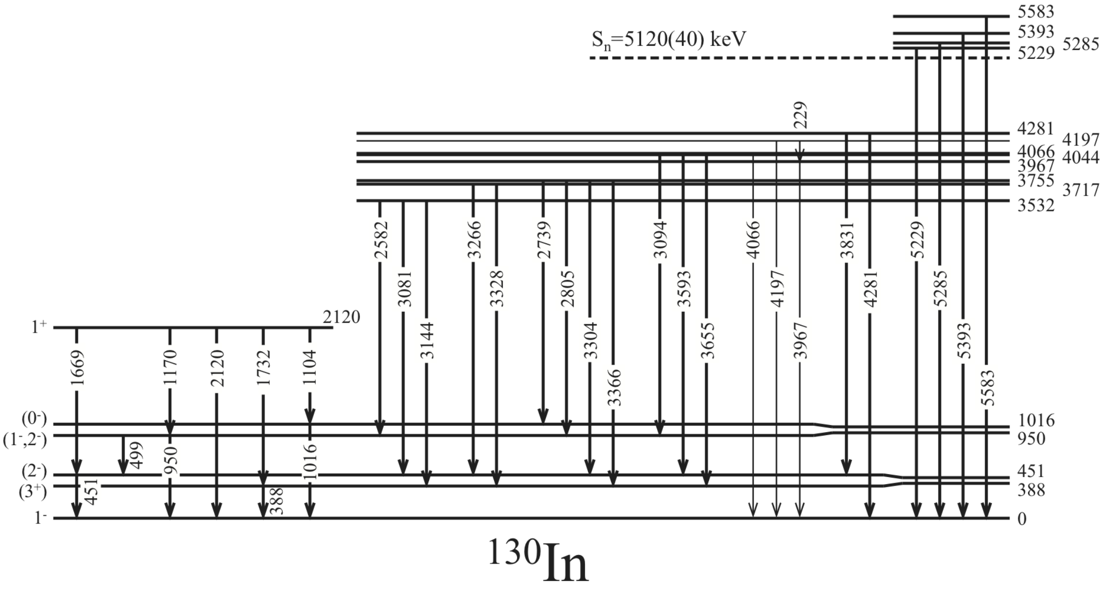


Figure 2: The level scheme of ^{130}In populated from the β-decay of ^{130}Cd, taken from [22].

The investigation of core-excited states in this proton and neutron hole nucleus is also of relevance, and they have been observed above 3.5 MeV in [22]. They are also observed in neighbouring nuclei, including the ^{132}Sn core [3]. In ^{130}In they correspond to one-particle three-hole states. A high-sensistivity measurement, as proposed here, will contribute to expanding the knowledge about core excitations. In addition to the known 3^+ 3 μs state, the measurement of level lifetimes will help to assess the nature of the transitions interconnnecting the expected negative-parity states at low excitation.

Compared to the previous experiment [22], we expect to accumulate more than 2 orders of magnitude higher statistics and will thus be able to confirm the recent decay scheme. The experiment should help to detect more states based of proton-neutron excitations, the placement of the high-energy transitions and the location of the β-decaying (5^+) level. Level lifetimes will be accessed via the fast-timing method.

2.2 Investigation of ^{131}In

The single-hole proton states are populated from the $Z = 48$, $N = 51$ nucleus ^{131}Cd, where the expected allowed Gamow-Teller transition is the $\nu g_{7/2} \rightarrow \pi g_{9/2}$ one. The $\nu g_{7/2}$ is bound in the $N = 50 - 82$ shell, and the transition is relevant for lighter Cd and In isotopes. The previous β-decay experiment is discussed in [19] and illustrated in Figure 3. Here, the first-forbidden transitions between single-particle states play a significant role, in particular the $\nu f_{7/2} \rightarrow \pi g_{9/2}$ one transforming the valence neutron above $N = 82$ in a proton below $Z = 50$. The role of the $\nu h_{11/2} \rightarrow \pi g_{9/2}$ is also relevant as discussed in [?] and mirrors the decay of ^{132}In to ^{132}Sn [3, 24].

The elusive $\pi f_{5/2}$ state has been recently located at 2910(50) keV in knock-out reaction studies [21]. In principle it should be fed by a GT transition from the $\nu f_{7/2}$ orbit, but the radial wave-functions are not matched and the transition is strongly suppressed. Still a weak transition may be present if there is mixing with other configurations and it is worth searching for the direct or inderect population of this state and measuring its precise energy if possible. In the proposed high-resolution γ spectroscopy experiment the state can be identified by its main decay branch to the ($1/2^-$) state and weaker branches to the ($3/2^-$) and ground states (see discussion in [19]). The expected high statistics at ISOLDE, about 50 times larger than in the previous decay experiment [19], will make it possible to address this important point.

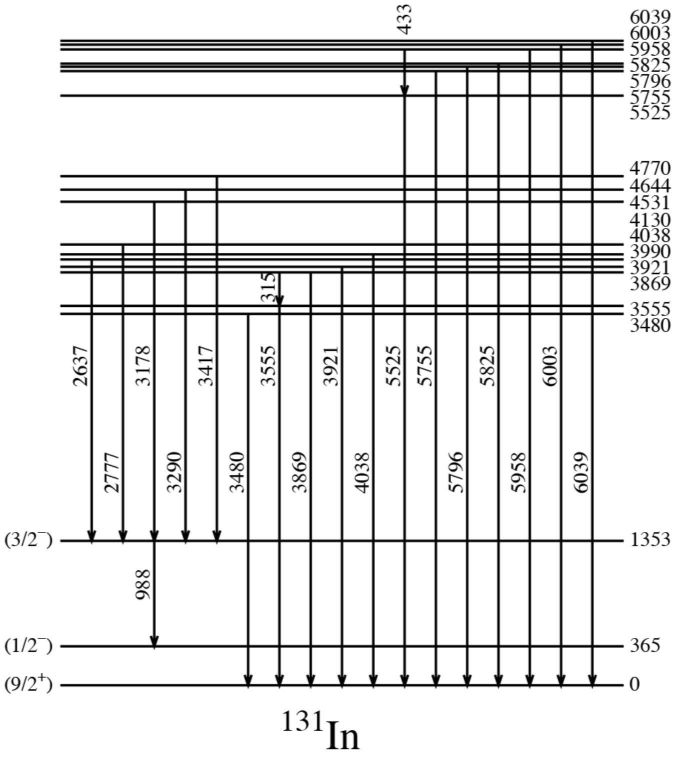


Figure 3: Level scheme of ^{131}In taken from [19]

The energies of core-excited configurations and the interpretation via the shell model provides information on two-body matrix elements of the effective interaction. The situation for ^{131}In [19] is equivalent to other nuclei in the region, including ^{132}Sn and ^{133}Sn, for which a recent experiment at ISOLDE [3, 14] has provided core-excited states at high excitation energies, arising from many of the allowed multiplets. The proposed experiment offers the opportunity of completing the existing information for ^{131}In. It should be noted that there is no data available on the lifetimes of the high-lying core excited states in ^{131}In, which provide direct information on electromagnetic transition rates and help to identify the configurations involved. The recent experiment on ^{132}Sn [3] provides detailed information on the lifetimes of neutron and proton multiplets, and serves as illustration of the potential of the measurements for ^{131}In with the fast-timing method. Specifically, lifetime measurements will shed light on members of the $\nu f_{7/2}h^{-1}_{11/2}$ and $\nu f_{7/2}d^{-1}_{3/2}$ multiplets coupled to $\pi g^{-1}_{9/2}$ configurations [25].

2.3 Structure of ^{132}In

The nucleus ^{132}In arises from the coupling of a proton hole and a neutron to the doubly-magic ^{132}Sn. The first observation of γ de-excitations in ^{132}In is quite recent, reported in [26]. It was populated in the β-delayed neutron emisison from ^{133}Cd. The comparison to shell-model calculations [25, 26] suggests that the observed γ-rays connect transitions between members of the $\pi g^{-1}_{9/2}\nu f_{7/2}$ multiplet, which is the lowest in energy, and is rather special in the whole nuclear chart.

Not much extra information on this nucleus exists. The proposed experiment at ISOLDE will profit from β and β-n decays of ^{132}Cd and ^{133}Cd, respectively, and will be uniquely suited to investigate the structure of ^{132}In. The $^{132}\text{Cd} \rightarrow {}^{132}\text{In}$ decay will be of particular interest, since the β-decay of the 0^+ g.s. will strongly populate the (1^-) level, leading to a cascade of γ transitions of equal intensity. Information on the structure can be also obtained via γ-γ coincidences from the β-n decay of ^{133}Cd, provided sufficient statistics are gathered.

In the proposed experiment more that 2 orders of magnitude higher statistics than the previous one are expected. It will provide the first information on the ^{132}In excited states, which will help to constrain shell-model calculations in the region including $Z < 50$ and $N > 82$ orbits [26]. This should provide a better prediction capability in this area of the nuclide chart that is not easy to access experimentally, but which has impact in stellar nucleosynthesis processes.

3 Experimental Details

The In isotopes of interest will be populated in the β-decay of the $^{130-133}$Cd isotopes. Apart from direct feeding, large beta-delayed neutron branches are reported for the heaviest Cd isotopes, see Table 4, leading to selective population of states in ^{131}In and ^{132}In from the beta-delayed one-neutron decay. In particular the quoted β-delayed neutron branch for ^{133}Cd is 100% [27]. The decay of the daugther In isotopes is alreay known and will help to identify the decay patterns.

The measurement will be performed at the ISOLDE Decay Station (IDS), which will include two LaBr$_3$(Ce) and four HPGe clover detectors, together with a fast β plastic detector close to the deposition point. The activity will be implanted in the center of the setup and removed with the help of a tape drive. The tape cycles can be adjusted as a function of the decay lifetimes of parent and daughter activities. The experimental full-energy peak efficiencies for the HPGe clovers after addback have been measured in several experiments, they are of the order of 7%

at 400 keV, 4% at 1 MeV and 1.5% at 4 MeV. For the two LaBr$_3$(Ce) detectors in compact geometry the FEP efficiency is about 4% at 400 keV, and drops below 2% at 1000 keV. For the beam time estimates a conservative β efficiency of the fast detector of 20% has been used. A similar setup has yielded results on the structure of Sn isotopes populated in the β decay of In [3, 14].

4 Yields and beam time request

We request the use of a UC$_2$/graphite target equipped with a neutron converter to produce Cd isotopes via neutron-induced fission. The ISOLDE Resonance Ionization Laser Ion Source (RILIS) [28] with a Ta ionizer is needed for ionization. In addition, we request a temperature-controlled quartz glass transfer line to suppress surface-ionized contaminants, including In, Cs and Ba. This production method has recently been used at ISOLDE [29]. The in-target production and expected Cd yields are plotted in Figure 4. The yields up to A=130 have been extracted from the ISOLDE database but scaled down to match the observed yields in 2017 at ISOLDE, when the quartz glass line was employed. The yields above are estimates based on extrapolations using the production cross sections and the experimental lifetimes.

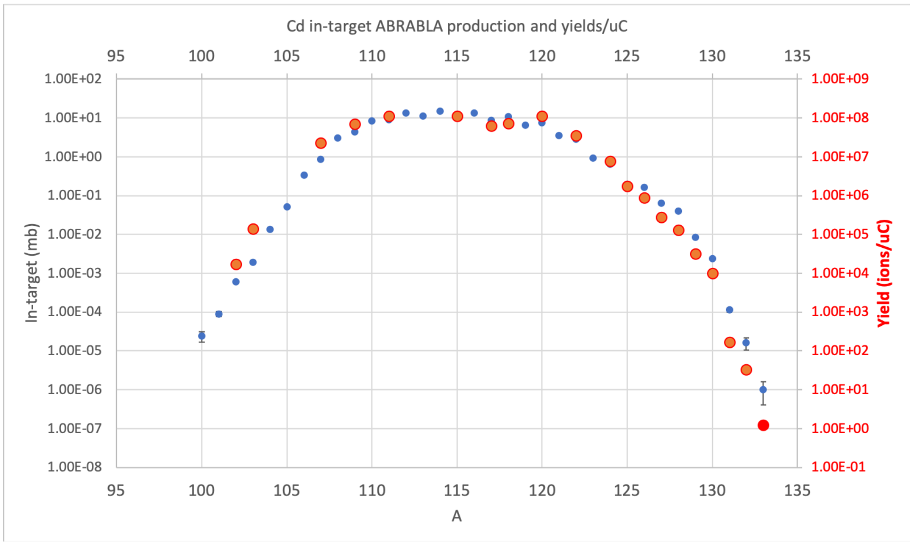


Figure 4: ISOLDE Cd yields and in-target production.

Table 1: Half-lives and P$_n$ values of $^{130-133}$Cd [30], production yields and intensities at IDS.

Isotope	T$_{1/2}$ (ms)	P$_n$ (%)	Yield (μC^{-1})	Intensity at IDS (pps)	Requested shifts
^{130}Cd	162(7)	3.5	5.0E+03	8500	1
^{131}Cd	68(3)	3.5	8.3E+01	140	2
^{132}Cd	97(10)	60	1.7E+01	28	6
^{133}Cd	57(10)	∼100	6.1E-01	1	10

Table 4 compiles the basic information on the requested ion species, with the estimated yields and number of shifts. A proton current of 2 μA and transmission of ∼80% to the IDS station were considered. It is expected that In isobars will be completely suppressed, while Cs and Ba contamination can be minimised by the use of the neutron converter and the reduction of surface ionization. In addition the very long half lives of the relevant Cs and Ba isotopes would give rise to very low activities. Isobaric contamination on the same masses has not posed a problem to perform In decay spectroscopy up to $A = 133$ [14, 3]. For the yield estimates, we consider to collect of the order of 5 million decays. Using the γ FEP and β efficiencies discussed above this translates in ∼1000 $\beta\gamma\gamma$ coincidences for 400 and 4000 keV energies. For the ^{133}Cd decay a total of 250000 ions can be collected in the requested beamtime, assuming a yield of 1 ion/μC^{-1}.

Summary of requested shifts: we request 21 shifts: 1 shift for tuning of the quartz transfer line, 1 shift for ^{130}Cd decay, 2 for ^{131}Cd, 6 for ^{132}Cd and 10 shifts for ^{133}Cd, plus 1 shift for online time calibrations from the same target/ion-source.

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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	Availability	Design and manufacturing
IDS	☒ Existing	☒ To be used without any modification ☐ 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 [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 experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum	high vacuum 10^{-6} mbar		
Temperature	LN_2 77 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)	Cd		
Beam intensity	10000 s^{-1}		
Beam energy			

Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	^{152}Eu, ^{60}Co		
• 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 (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
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]		

Hazard identification:

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]