EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee
Following HIE-ISOLDE Proposal CERN-INTC-2012-051/INTC-P-352

Spectroscopy of ^{81}Zn populated via one-neutron transfer ^{80}Zn(d,p) using ACTAR TPC

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M. Babo[1], R. Raabe[1], H. Alvarez-Pol[2], B. Bastin[3], B. Blank[4], M. Caamaño[2], S. Ceruti[1], C. Delafosse[5], F. de Oliveira Santos[2], N. de Sereville[5], H. De Witte[1], B. Duclos[3], B. Fernandez-Dominguez[2], F. Flavigny[5], L. Gaffney[12], J. Giovinazzo[4], T. Goigoux[4], A. Gottardo[11], G.F. Grinyer[3], F. Hammache[5], F. Ibrahim[5], A. Illana[1], A.T. Laffoley[3], T. Marchi[1], B. Mauss[3], R. Orlandi[6], J. Pancin[3], J.L. Pedroza[4], J. Pibernat[4], O. Poleshchuk[1], E.C. Pollacco[7], F. Renzi[1], K. Rezynkina[1], T. Roger[3], A. M. Sánchez-Benítez[8], F. Saillant[3], P. Sizun[7], D. Suzuki[9], D. Verney[5], G. Wittwer[3], J. Yang[1, 10]

[1]KU Leuven, Instituut voor Kern en Stralingsfysica, Celestijnenlaan 200D, 3001 Leuven, Belgium
[2]Universidade de Santiago de Compostela, 15706 Santiago de Compostela, Spain
[3]Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3, Bvd Henri Becquerel, 14076 Caen, France
[4]Centre d'Études Nucléaires de Bordeaux Gradignan, Université Bordeaux 1, CNRS/IN2P3, Chemin de Solarium, 33175 Gradignan, France
[5]Institut de Physique Nucléaire Orsay, CNRS/IN2P3, Université Paris-Sud, Université Paris-Saclay, 91406 Orsay, France
[6]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki, 319-1195, Japan
[7]CEA, Centre de Saclay, IRFU/SPhN 91191 Gif-sur-Yvette, France
[8]Departamento de Física Aplicada, Universidad de Huelva, E-21071, Spain
[9]RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[10]Physique Nucleaire Théorique, Université Libre de Bruxelles, B-1050 Bruxelles, Belgium
[11]LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, F-38026 Grenoble Cedex, France
[12]ISOLDE, CERN, CH-1211 Geneva 23, Switzerland

Spokesperson: Mathieu Babo (mathieu.babo@kuleuven.be)
Contact person: Liam Gaffney (liam.gaffney@cern.ch)

Requested shifts: 17 shifts, (split into 1 run over 1 year)
Beamline: 2nd beamline

Abstract: We propose to perform an experiment to study the neutron effective single-particle energy (ESPE) in ^{81}Zn via the one-neutron transfer reaction (d,p) in inverse kinematic. This nucleus is only two protons and one neutron above the doubly-magic ^{78}Ni. Systematics of the neutron ESPE in N=51 isotones suggest a fall of the relative energy between the ν2d5/2 and the ν3s1/2 due to the tensor interaction, that could lead to a 1/2+ ground state instead of the 5/2+ usually observed due to the 0+⊗ν2d5/2 coupling. To identify the neutron configuration, we propose to measure the energy and the angular cross section using the novel active target and time projection chamber ACTAR-TPC developed at GANIL, where a gas of D2 will be used as a target. Full kinematics including angular distributions will be reconstructed in order to determine for the first time, the energy and the spin-parity of excited states in ^{81}Zn.

Physics case

The stability of nuclei is ensured by the nuclear interaction, which gives to the proton-and-neutron system enough energy to be bound. For certain numbers of protons and neutrons, referred as "magic numbers", a large increase in binding energy has been historically observed. These numbers of nucleons are described by correcting the standard well potential with a spin-orbit coupling, that splits the nucleon orbitals and create energy gaps. Nuclei around the shell gaps have been investigated in order to better understand the behaviour of the effective nucleon-nucleon interaction, and the evolution of the ESPE. Recent theoretical [Ots05,Ots10,Sie10,Shi12] and experimental [Hos05,Got16,Fla09] works aim to study the region of the doubly-magic ^{78}Ni which is at the crossing between two shell gaps, Z=28 and N=50.

Nuclei over the N=50 shell gap have been investigated in order to determine the evolution of the neutron effective single particle energy above the doubly magic ^{78}Ni core. In particular, the addition of one neutron to N=50 cores, via stripping reactions, have been performed on several stable nuclei or nuclei close to the valley of stability [Sha12,Tho05,Tho07]. Experimental studies of other exotic odd-A N=51 isotones, as presented on Fig. 1, enlighten the evolution of the neutron single-particle energy over this shell gap as a function of the number of proton in the *fp* shell. Based on beta-decay experiments [Kur12] and shell-model considerations [Sie09, Sie12], it has been well established that the ground states of these N=51 nuclei is 5/2+, due to the coupling of the 0+ core with the single neutron in the ν2d5/2. The first excited state in the nuclei from Z=34 to Z=40, however, is identified as 1/2+, and is dominated by the promotion of one neutron into the ν3s1/2 orbital.

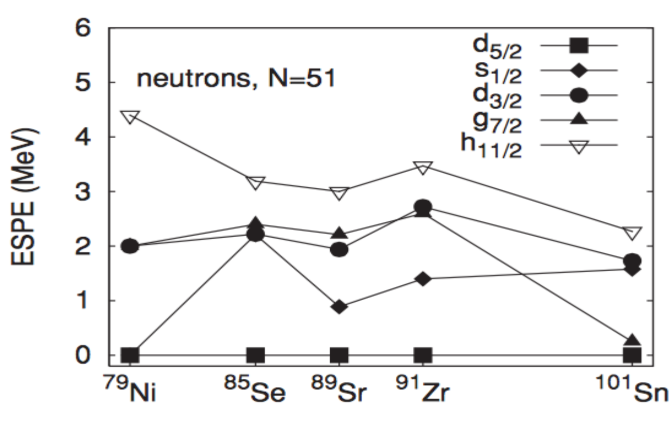

Fig. 1 Evolution of the neutron effective single particle energy
in the N=51 isotones above the ^{78}Ni core, from shell-model calculations (from [Sie09]).

As shown in Figure 1 from recent shell-model calculations [Sie09], the neutron effective single-particle energy (ESPE) of the ν3s1/2 is expected to decrease with respect to the ν2d5/2 for lower Z. This drift is explained by the tensor component of the monopole proton-neutron interaction [Ots05]: the emptying of the proton πf5/2 has a repulsive effect on the neutron ν2d5/2 orbital, while the ν3s1/2 is not affected because of its s-wave nature. If the ν2d5/2 is actually pushed above the ν3s1/2, one might expect a strong neutron skin effect to develop in that region. Experimentally, the decrease of the relative energy between these two shells was already observed in the odd-A N=51 isotones via the measurement of the energy of the first excited state from Z=40 to Z=32, as shown in Figure 2. The energy of the first excited state in the N=51 isotones is a particularly good probe to study the evolution of the neutron ESPE since only one-neutron occupies the (ν2d5/2, ν3s1/2, ν2d3/2) valence space.

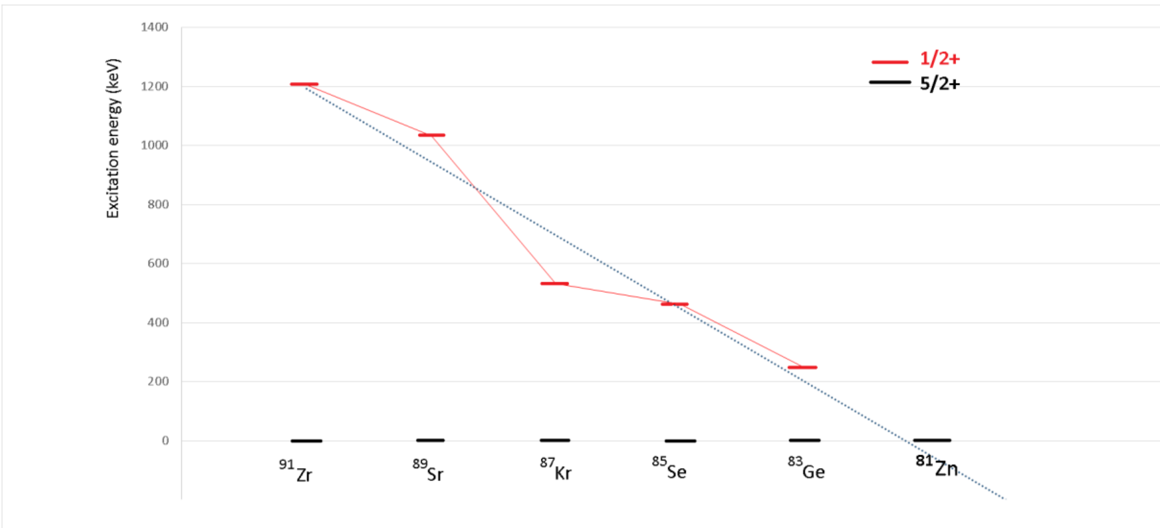

Fig. 2 Evolution of the difference in energy between the first excited state (1/2+) and the ground state (5/2+)in the even-Z N=51 isotones (adapted from [Per06])

Extrapolating the energy systematics of the first excited state from ^{91}Zr to ^{83}Ge suggests an inversion of the 5/2+ and 1/2+, with the latter becoming the ground state of ^{81}Zn. As described in recent calculations for ^{79}Ni (only 2 protons less than ^{81}Zn), the decrease of their relative energies could even lead to a near degeneracy of these two states [Hag16]. Up to now, only beta-decay experiments focused on the decay of ^{81}Zn ground state to ^{81}Ga have been performed [Ver07, Pad10,Paz13], and lead to contradictory spin-orbit assignments of the ground-state. Therefore, it is clear that the measurements of the ground state and the first excited state in ^{81}Zn are essential to predict if and where the inversion of the neutron ν2d5/2 and ν3s1/2 orbitals occurs.

The 1/2+ state at low energy can originate from the coupling of the excited 2+ core with the neutron in ν2d5/2, as it has already been observed in [Per06], or from a single particle state. Because the core-coupling states carry a weak single-particle strength, the best way to disentangle these two cases is to perform the ^{80}Zn(d,p)^{81}Zn reaction in order to populate single-particle states. The beam energy available at ISOLDE is ideal for matching low-momentum transfer (l=0, l=2). Therefore, we propose to populate the excited states of ^{81}Zn via the one-neutron transfer reaction ^{80}Zn(d,p)^{81}Zn in inverse kinematics at ISOLDE, that will transfer one neutron in the *sd* shells above the ^{80}Zn core. In these type of transfer reactions, the states arising from the coupling between the neutron and the 2+ core of ^{80}Zn [Van07] will weakly populated.

Such (d,p) one-neutron transfer reaction experiments have already been performed on several N=51 isotones and were used to populate and identify low-lying states, such as in ^{85}Se and ^{83}Ge [Tho05,Tho07].

The excitation energies of their first 1/2+ excited states were measured, at 0.46 MeV and 0.28 MeV, respectively. The identification of the transfer momentum was performed by measuring the angular distributions of the emitted protons and followed by comparison with DWBA calculations.

An experiment based on this reaction has already been approved by the INTC (INTC-2012-051/IS556): a beam of ^{80}Zn produced at ISOLDE would impinge a thick (1 mg/cm^2) CD_2 target. Protons from the (d,p) reaction would be detected by the TREX silicon array in order to obtain the angular distributions and the transferred angular momentum. However, the resolution would not be sufficient to identify the populated states. This experiments relies on the detection of coincident gamma-rays in the MINIBALL set-up which will allow to gate on the protons and possibly extract the angular distributions, as it has already been performed in the ^{78}Zn(d,p) [Orl15].Based on the systematics of the first excited states in the odd N=51 isotones, one can expect that the energy of the first excited state to be very low, between 100 and 300 keV. Thus, the de-excitation through an E2 transition would therefore imply a nanosecond lifetime, that might not be too long to be observed in MINIBALL.

With our setup, a much higher luminosity coupled to very good resolution (better than 200 keV) allows to detect the emitted protons and to identify the excited states with no need for coincident gamma-ray detection.

Experimental method

The ^{80}Zn beam will be produced using the UC_X target within the RILIS facility. The expected intensity in the primary target is about 2×10^5 pps. The typical transmission for this beam is approximately 5%, which leads to a beam intensity of 1×10^4 pps at the entrance of the active-target volume. Beam energy is 7 MeV/u for now but could reach 10 MeV/u in the near future.

We propose to use the active-target ACTAR-TPC [Act] that has been recently developed at GANIL (see Fig. 3). In this device, (i) the reaction between the beam and the gas takes place in the active volume, and (ii) the same gas volume is used as a detector: the reaction products ionize the gas, releasing electrons that drift to a highly pixelated pad plane. The charge collected on the pads provides the 2D projection of the tracks while the third dimension can be reconstructed using the drift time of the electrons in the chamber. This allows a full 3D reconstruction to be performed, on an event by event basis, that provides a complete measurement of the kinematics, including angular distributions over a wide range of angles.

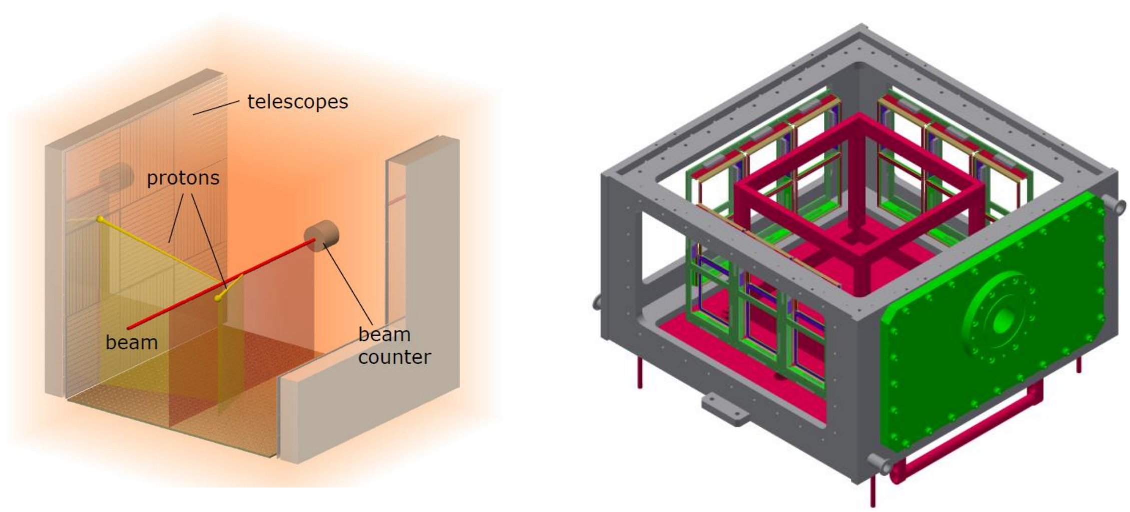

Fig. 3 The ACTAR TPC detector consists of a gas volume that is used as a reaction target and as a detector. 3D tracks are reconstructed using the projection on the pad plane and the drift time of the electrons. Si detectors are added to the sides to record the energy of the particles that escape the gas volume.

Based on previous inelastic-scattering experiments with the ACTAR TPC demonstrator, the angular resolution is approximately 1 degree (FWHM)[Pan14], and excitation energies have been measured with resolutions better than 200 keV (FWHM). This resolution, that is achievable with ACTAR TPC, is nearly two times better than the one expected (between 400 and 1000 keV) in the solid target experiment of the previous proposal and similar experiments performed in this region [Tho07]. The length of the chamber acts like a very thick target, and allows for an increased reaction yield (by a factor of 8 compared to the TREX/MINIBALL proposal). These two characteristics make the active target ideally suited for transfer reaction in inverse kinematics with beam intensities below 10^4 ions/s.

The gas used as a target in this experiment will be a mixture of D2 (95%) and iC4H10 (5%) or CF4(5%), in order to have sufficient gain to observe the protons on the pad. The mixture with CF4 would be preferable in order to reduce the background of proton scattering from the gas. The pressure in the chamber will be between 500 mbar and 1 bar, depending on the gas mixture used.

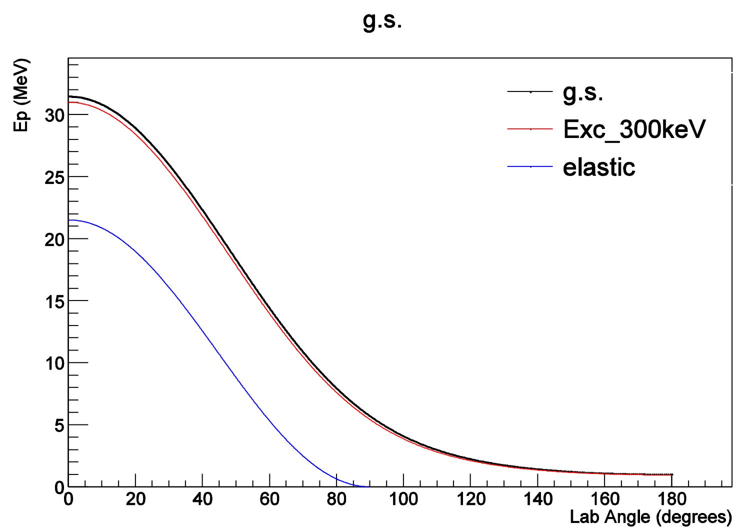

Fig. 4 Kinematic lines of the protons in the (d,p) reaction in inverse kinematics.
The first excited state is taken with an hypothetical excitation energy of 300 keV.

From kinematic calculations, protons above 7 MeV are expected at forward angles (see Fig.4). As a result, we intend to use of Si (or DSSD) detectors positioned around the chamber, to identify the protons going through the gas volume and to measure their total kinetic energy. These auxiliary detectors have already been successfully tested and used in previous experiments. In the final design of the ACTAR TPC, the expected efficiency with the two Si walls parallel to the beam, and the Si positioned at forward angles, is approximately 37%. This experiment aims to detect protons following (d,p) reactions in inverse kinematics. Most of the protons will be emitted at forward angles in the centre of mass, which corresponds to backward angle in the laboratory frame. Detection of these protons would require a Si wall to be designed that would cover the backward angles, and that will increase overall efficiency.

The Si detectors that will be added to ACTAR TPC have an energy resolution of approximately 75 keV. This is sufficient to resolve both kinematic lines (presented in Fig. 5) of the ground state and the first excited state, which are separated by 100 keV at very backward angles.

Beam request

Because the beam goes through the gas volume, the beam energy at the interaction point varies, and is experimentally deduced from the reconstruction of the vertex. In the following section, an average energy of 5.5 MeV is taken to estimate the reaction rates. A gas pressure of 1 bar is used as the most probable setting, with the ideal gas mixture of D_2(95%) with CF_4(5%).

The average total reaction cross section obtained from DWBA calculation (see Fig. 5) gives approximately 64.7 mb for the d-wave and 37.6 mb for the s-wave in the angular coverage of the detector. Applying a spectroscopic factor of 0.6, this leads to 1645 and 956 particles per hour respectively.

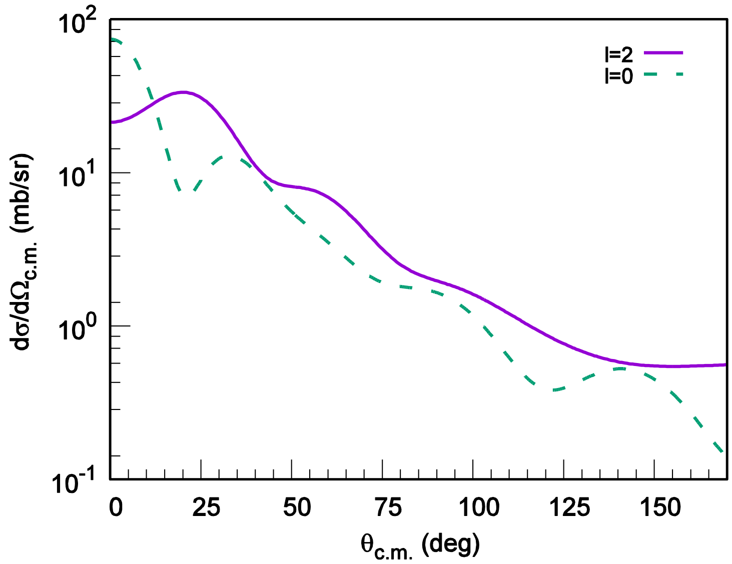

Fig. 5 Differential cross section from DWBA calculations for a first excited state at 300 keV, and with a beam energy of 5.5 MeV/U.

Since the reaction occurs in the gas volume of ACTAR-TPC, this active-target offers an angular coverage of 4π, with a detection efficiency close to 100% [Van15]. However, the beam is highly ionizing the gas volume and the tracks close to the trajectory of the beam will be difficult to reconstruct. With a safe estimation of 90% to account for is effect, we expect a total count rate of 1480 and 860 charged particles per hour.

As described above, the use of Si detectors surrounding the active volume would reduce the angular coverage and the charged-particle detection efficiency to at least 37%, leading to a minimum of 548 and 318 detected protons per hour. Based on these estimations, we require 10 shifts to run with Lasers ON to perform the identification of the first single-particle excited states with sufficient statistics to distinguish between the l=0 and l=2 components.

Despite the advanced techniques developed by the TISD team (neutron converter, quartz transfer line) other nuclei such as ^{80}Ga will also be produced, either directly or as decay product along the beam preparation, and will contaminate the ^{80}Zn beam. Therefore, several runs with Lasers ON/OFF are required to discriminate the ^{81}Zn events from this contamination. Based on previous (d,p) reactions Coulomb excitation on neutron rich Zn isotopes at MiniBall [Van09] and more recent experiments [Orl15], ^{80}Ga would represent about 20% of the laser-ionized beam. As a result, we require 5 shifts with Lasers OFF. 2 additional shifts will be dedicated to the beam and detector tuning, leading to a total of 17 shifts.

Remarks

As mentioned in the previously approved experiment (INTC-2012-051), if the energy of the first excited state is very low, the two states may be unresolved, and the detection of the gamma rays would not be feasible due to its long lifetime. The total angular distribution of detected protons would thus be a weighted sum of both l=0 and l=2 components which are presented in Fig. 3. It has been shown that the two contributions can be distinguished if their relative spectroscopic factors differ by a factor of 1.5 to 2 [Orl15] in the case of a solid target. In any case, the upper energy limit for the first excited state will be deduced.

The full ACTAR TPC detection system will be constructed and prepared to perform first physics experiment starting in the Summer of 2017. This detector was funded through an ERC starting grant that included an experiment at ISOLDE as one of its three milestone experiments. This experiment is therefore proposed within the framework of the ERC grant, as the first transfer reaction using this novel apparatus.

Summary of requested shifts:

Beam	Intensity	Target	Energy, MeV/u	Laser	Shifts
*			-	-	2*
^{80}Zn	1. 10^4 pps	UCx	7	ON	10
^{80}Zn	1 10^4 pps	UCx	7	OFF	5

***2 shifts for setting up and tuning the beam and the detector.**

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises ACTAR TPC, DSSD or Si detectors

Part of the Choose an item.	Availability	Design and manufacturing
[if relevant, name fixed ISOLDE installation: MINIBALL + only CD, MINIBALL + T-REX]	☐ Existing	☐ To be used without any modification
ACTAR TPC	☐ 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

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	ACTAR-TPC	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	1 bar; 80 L		
Vacuum			
Temperature	295 K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity	[V], [current][A]		
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	D2 (95%) + iC4H10 (5%) or D2 (95%) + CF4 (5%)		
Beam particle type (e, p, ions, etc)	Ions		
Beam intensity	4.5 10^3 pps		
Beam energy	Up to 10 MeV/U		
Cooling liquids			

Gases	D2 (95%) + iC4H10 (5%) or D2 (95%) + CF4 (5%)		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	^{228}Th, or standard 3α source		
• Activity			
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	D2, 80 L		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	D2, 80 L		
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*