EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Addendum to IS709: Exploring shape coexistence across N=60 using IDS

May 11, 2022

B. Olaizola[1], S. S. Bhattacharjee[2], R. Kanungo[3], A. Algora[4], A. Andreyev[5], Y. Ayyad[6], M.J. Borge[7], J.A. Briz[8], F. Browne[1], R. Caballero-Folch[3], C. Costache[9], J. Cubiss[5], S. J. Freeman[1], L.P. Gaffney[10], A. Illana[11], P. Jones[12] U. Koester[13], A. Korgul[18], M. Labiche[17], R. Lică[1,9], N. Marginean[9], C. Mihai[9], R. E. Mihai[9], J. Ojala[10], C. Page[5], J. Pakarinen[11], P. Papadakis[17], S. Pascu[9], V. Petousis[2], Z. Podolyak[14], W. Poklepa18, M. Stryjczyk[11], A. Turturica[9], M. Veselsky[2], N. Warr[15], K. Wimmer[16], Z. Yue[5]

[1]*ISOLDE-EP CERN*, [2]*Technical University in Prague*, [3]*TRIUMF*, [4]*IFIC Valencia*, [5]*University of York*, [6]*Universidad de Santiago*, [7]*CSIC Madrid*, [8] *Universidad Complutense de Madrid*, [9]*IFIN-HH Bucharest*, [10]*University of Liverpool*, [11]*University of Jyväskylä*, [12]*iThemba LABS*, [13]*ILL Grenoble*, [14]*University of Surrey*, [15]*Universität zu Köln*, [16]*GSI Darmstadt*, [17]*STFC Daresbury*, [18]*University of Warsaw*

Spokesperson: B. Olaizola [bruno.olaizola@cern.ch]
Spokesperson: S. S. Bhattacharjee [Soumendu.Bhatt@cvut.cz]
Contact person: Zoe Favier [zoe.favier@cern.ch]

Abstract: This is an addendum to experiment IS709, recently approved by the INTC. The collaboration wishes to expand the scope of the original proposal to search for excited 0^+ states and E0 transitions in ^{96,98}Sr, populated in the β decay of ^{96,98}Rb. IDS will be used to perform angular correlations and SPEDE to measure conversion electrons to systematically study shape coexistence and shape mixing in the $N = 60$ region.

Requested shifts: 4 shifts, (split into 1 runs over 1 years)

Installations: IDS and SPEDE

1 Introduction

At the 69th meeting of the INTC (February 2022) this collaboration presented a proposal to search for excited 0^+ states in ^{100}Sr ($N = 62$) using IDS [1]. The states would be populated in the β and βn decays of ^{100,101}Rb and the 0^+ states would be firmly identified by means of angular correlations and direct E0 observation. The proposal was approved and the committee encouraged the collaboration to expand the experiment to include lighter masses and perform a systematic study of the 0^+ states along the Sr isotopic chain. With this addendum, we ask for additional shifts to explore shape coexistence in Sr isotopes at and below $N = 60$. Considering that all the masses require the same setup and target/ion source combination and will employ the same experimental techniques, we believe running them all consecutively as a single beamtime would be the most efficient way to proceed.

Since the physics motivation remains the same as in the main proposal, the reader is referred to Ref. [1] for a detailed explanation of the scientific value of the experiment and the specific details of the experimental technique. Only a few details will be provided here to help guide the discussion.

2 Scientific value

As shown in Fig. 1, the region around $N = 60$ presents one of the most sudden ground-state shape transitions that has been observed in the nuclear chart. When crossing $N = 60$, the spherical (*normal*) and prolate (*intruder*) configurations invert, giving rise to a sudden increase of deformation for the ground state of Sr, Y and Zr isotopes [2, 3]. Although this interpretation is generally accepted, the full picture is far from clear. As can be seen in Fig. 1, no excited 0^+ state has been firmly established above $N = 60$ ($^{100}\mathrm{Sr}_{62}$ is the goal of the original proposal) and the oblate/triaxial one for $^{98}\mathrm{Sr}_{60}$ is only tentative. In the case of $^{96}\mathrm{Sr}_{58}$, no electron spectroscopy has been published, therefore key E0 transitions have not been measured.

The relevance of measuring E0 transitions has been discussed at length in different reviews, for example Refs. [4, 5], which contain specific sections about the Sr isotopes in the N=60 region. E0 transitions can only occur between states of equal J, and their monopole strength ρ is proportional to the mixing amplitudes α and β and their difference in mean-square charge radii $\Delta \langle r^2 \rangle$ (related to the quadrupolar deformation β_2). It is commonly expressed as:

$$\rho^2(E0, J \to J) \propto \alpha^2 \beta^2 (\Delta \langle r^2 \rangle)^2 \tag{1}$$

Therefore, the measurement of E0 transitions between different bands gives invaluable information about shape coexistence and shape mixing within a nucleus.

Indeed, the partial knowledge we have of shape coexistence in Sr isotopes suggests that there is nearly no mixing between spherical and prolate configurations, which is what allows for such a sudden increase of deformation [6]. It is argued that if the mixing was stronger, there would be a smoother evolution of deformation when crossing $N = 60$ [7]. On the other hand, an unpublished value for the $0_3^+ \to 0_2^+$ E0 transition presents the strongest ρ_0^2 of the entire nuclear chart [8], suggesting a very strong mixing between the two deformed structures of Sr isotopes. However, very little is known of this third oblate/triaxial band to understand what is the role it plays in the shape evolution of this isotopic chain.

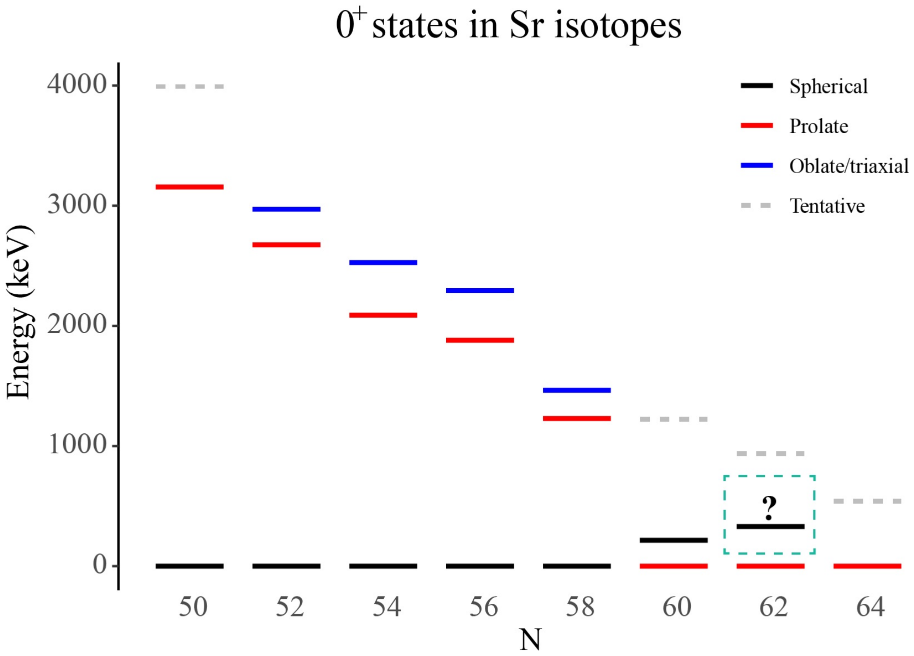

Figure 1: Level energy systematics of the 0^+ states in even-mass Sr isotopes. Levels in black are associated with spherical shape, while levels in red and blue have been associated with prolate and oblate/triaxial deformation, respectively. The dashed levels are tentative and it is unclear to which band they belong, although the energy trend seems to suggest they belong to the oblate/triaxial one. All data are from ENSDF [9].

3 Previous work

Figure 2 shows the known low-energy level schemes of ^{96,98}Sr, with the relevant levels and transitions for this experiment.

^{96}Sr

The ^{96}Rb→^{96}Sr decay level scheme in ENSDF [9] is actually a PhD thesis [8], of which only a small fraction of the results pertaining some angular correlations seems to have been published [10]. Of note is the mixing ratio $\delta(E2/M1)$ obtained for the $2_2^+ \rightarrow 2_1^+$, with a large error bar of over 50%. Also, lifetimes have been measured for all states up to 0_3^+ and an upper limit for 2_2^+ [11]. However, the E0 transitions, key ingredients to complement the picture of the different shapes in this nucleus and their mixing, are missing, since no electron spectroscopy has been published.

^{98}Sr

Reference [12] is the most complete β decay experiment on ^{98}Sr. It presented a level

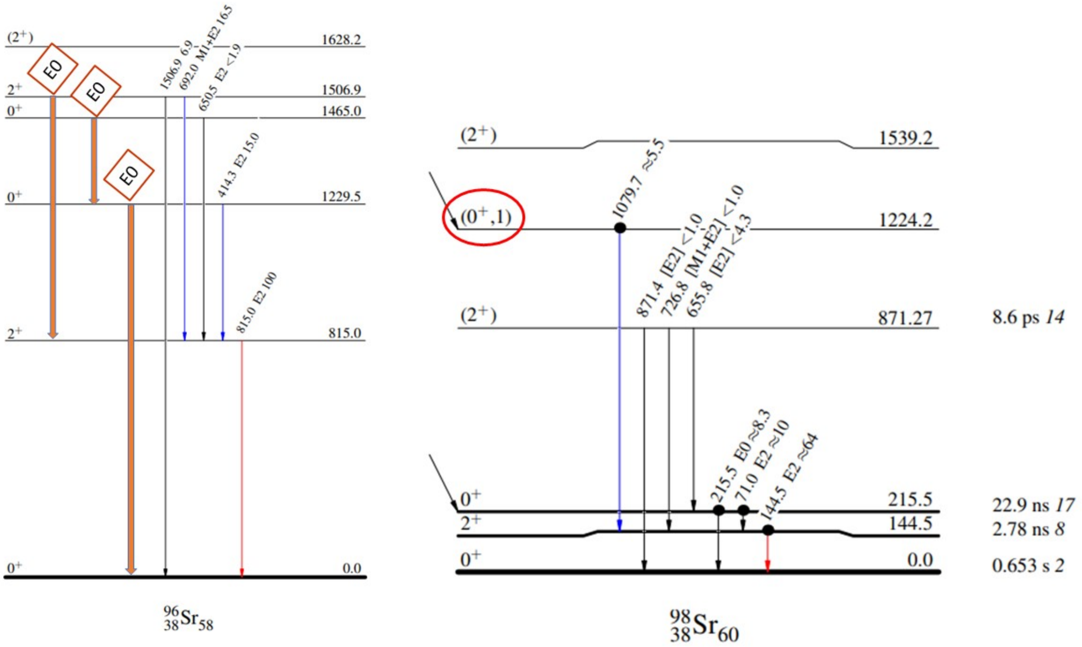

Figure 2: *(Left)* Low-energy level scheme of ^{96}Sr. The orange arrows are the unobserved E0 transitions that this experiment aims to measure using SPEDE. *(Right)* Low-energy level scheme of ^{98}Sr. The spin-parity circled in red will be firmly established using angular correlations with IDS. All data are from ENSDF [9].

scheme with levels up to $\sim$ 3.6 MeV (out of a Q_β of 12 MeV) with an admixture of the g.s. and isomeric decay from ^{98}Rb, from two experiments at ISOLDE and ILL-Grenoble. Only the $0^+_2 \rightarrow 0^+_1$ E0 transition has been observed [13, 6]. The state at 1224 keV is usually treated as the tentative bandhead of the oblate/triaxial band. However, nor is its spin only tentative, the possibility of it having $J = 1$ with either parity could not be ruled out.

4 Experiment goals

^{96}Sr

The main goal for the ^{96}Rb→^{96}Sr decay is to perform the first electron spectroscopy for this nucleus. Although the $0^+_2 \rightarrow 0^+_1$ would certainly be the most interesting one to be measured, its large energy makes it challenging to observe, even more so if we consider that the internal pair creation would be open. At least, an upper limit will be set. The $0^+_3 \rightarrow 0^+_2$ E0 appears in some works as observed in the PhD thesis of G. Jung [8]. However, said work is not publicly available, so its method of determination or reliability cannot be assessed and a re-measurement is warranted. This experiment will perform a direct observation of this E0 electron using SPEDE.

In the case of the 2^+_2 level, we will use SPEDE to measure the total conversion coefficient of the $E0 + M1 + E2$ $2^+_2 \rightarrow 2^+_1$ transition. For this γ ray, a significant mixing ratio of $\delta(E2/M1) = 2.0(11)$ has been measured, but its error bar is larger than 50% [10]. This experiment will use angular correlations with the IDS HPGe clovers to remeasure this value. By increasing the amount of statistics manifold, the error bar will be reduced enough to allow the precise extraction of the M1 and E2 conversion coefficient, and from there the E0 component.

For all these levels mentioned before, the lifetimes or stringent limits are known. If we are able to measure the E0 transitions, ρ_0^2 can be extracted which will yield the first picture of mixing between the different shapes of this nucleus.

^{98}Sr

The main goal for this mass is the firm assignment of the spin-parity for the 1224.4-keV level. Currently, it is a tentative $(0^+, 1)$, and therefore is the best candidate for the bandhead of the oblate/triaxal band. The $1079.8 \rightarrow 144.6 \rightarrow 0$ γ cascade should allow to perform angular correlations. Such a potential $0 \rightarrow 2 \rightarrow 0$ cascade presents one of the most anisotropic angular distribution, and easily allows for an unambiguous determination of 0^+ states.

The level at 871 keV is the tentative (2_2^+). A high statistics experiment as this one may be able to observe the $(2_2^+) \rightarrow 4_1^+$, which would make the assignment firm. A complementary approach is to perform angular correlations with the $(2_2^+) \rightarrow 2_1^+ \rightarrow 0_1^+$ cascade. In that case, J=2 for the first state would always yield $a_4 > 0$, while J=1 (the only other viable option) would yield $a_4 < 0$ (a_i being the coefficients of the Legendre polynomials describing the angular correlation). In addition, this would yield $\delta(E2/M1)$. If the $\alpha(E0 + M1 + E2)$ is observed in SPEDE, it would allow to establish shape mixing between these two bands.

5 Proposed experiment at IDS

As already discussed in the original proposal [1], the experiment will be conducted at IDS. Five IDS clovers will be arranged in order to maximize the number of different angles, as was successfully done in Ref. [14]. The neutron-rich Rb beams will be implanted in the tape, placed at the centre of the IDS array, and the activity will be removed with the help of a tape drive system. Plastic scintillators will be used downstream, around the implantation point, to detect the β particles. On the upstream side, the SPEDE spectrometer will be installed to detect conversion electrons [15].

6 Beam time estimation

Neutron-rich Rb $A = 95,\ 100 - 102$ beams were measured in ISOLTRAP using an UC$_\mathrm{X}$ target [16]. An interpolation of the yields suggests $2 \cdot 10^5$ pps for ^{96}Rb and 6750 pps for ^{98}Rb. The only contaminants were isobaric Sr, with a factor ~ 2 higher yield. In all cases, the lifetimes of the Rb nuclei are 4-5 times shorter than those of the Sr isobars. This ensures that by using the proton-on-target time signal we can separate both decays and subtract the Sr activity in the offline analysis.

^{96}Sr

Ref. [10] does not show a complete level scheme for ^{96}Sr nor the amount of statistics collected. However, it seems that their angular correlation plots are not normalized and the Y-axis shows the number of coincidences per angular bin. In that case, the $2_2^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ cascade would contain $\sim 1.1 \cdot 10^4$ counts. We will limit the beam rate to 10^5 pps (or lower if the contaminants add much activity, since the DAQ cannot handle higher rates). Using a branching ratio of 8% for the 692-keV $2_2^+ \rightarrow 2_1^+$ transition with a 4% efficiency and 5% for the 815-keV $2_1^+ \rightarrow 0_1^+$, and with 30% for the β-particle detector, we can observe near $3.5 \cdot 10^5$ coincidences in a single shift. This 30-fold increase in statistics should greatly reduce the uncertainty of the $\delta(E2/M1)$ mixing ratio extracted from angular correlations.

In that same shift, we can set constrains in the E0 transitions we would be able to observe. Assuming a total intensity for the $0_3^+ \rightarrow 0_2^+$ transition of 0.6%, a 10% efficiency for SPEDE and a gate on the $0_2^+ \rightarrow 2_1^+$ γ-transition (5% efficiency) and a β-particle tag to suppress background (30%), we should detect over $2.6 \cdot 10^4$ coincidences, more than enough for a precise measurement of the E0 branching ratio. On the other hand, an observation of the $0_2^+ \rightarrow 0_1^+$ E0 is difficult due to the large energy separation between the two 0^+ states. Assuming that the minimum peak we can observe in SPEDE above the β background is $\sim$ 100 counts (the background is expected to be very low at this energy), we can estimate what is the minimum branching ratio we would be sensitive to. We would require a gate on several γ rays that populate the 0_2^+ from above, adding up to a total intensity of $\sim$ 1% (not shown in Fig. 2), with an average efficiency of 5% and, again, a tag in the β-particle detector (30%). Under these conditions, we should be able to set an upper limit of 1% partial branching ratio. This is a stringent limit that can help quantify the amount of mixing between the *normal* and *intruder* shapes for this nucleus.

^{98}Sr

For this mass, the $(0_2^+) \rightarrow 2_1^+ \rightarrow 0_1^+$ cascade has an absolute intensity of $\sim$ 5% and efficiency of 4% for the 1079-keV $0_2^+ \rightarrow 2_1^+$ transition and 10% for the 144-keV $2_1^+ \rightarrow 0_1^+$ one, with 30% for the β plastic, so $1.1 \cdot 10^4$ counts will be detected per shift. As established in the original proposal, a $0 \rightarrow 2 \rightarrow 0$ cascade requires $1.6 \cdot 10^4$ coincidences (100 per detector pair, see Ref. [1]). However, the absolute intensity of the 1079-keV transition was measured from an unknown admixture of ^{98}Rb g.s. [$J^\pi = 0^{(-)}$] and isomeric [$J^\pi = (3^+)$] decay [12] and these two decays could not be disentangled. Although that experiment was performed at ISOLDE, it used 600 MeV protons, not the current 1.4 GeV and therefore the ratio ^{98m}Rb/^{98g}Rb could be significantly different. Due to their very different spin-parity, this would, in turn, induce very different apparent intensities of γ transitions. For this reason, we request 3 shifts instead of 1.5, in case the population of (0_2^+) is significantly lower.

In these 3 shifts, we would obtain also over 100 times more statistics than the previous experiment [12]. This will allow to greatly expand the level scheme beyond the current 3.6 MeV (out of a Q_β=12 MeV). Lastly, Park *et al.* [6] obtained $\sim$ 4000 counts in the $(2_2^+) \rightarrow 0_2^+ \rightarrow 0_1^+$ cascade in $\gamma - e^-$ coincidences. We expect to obtain at least 4 times more statistics (doubling the sensitivity) plus an additional gate on the β plastic detectors, thus reducing our background compared to theirs. This improvements should allow us to observe many more E0 transitions than that previous work.

Summary of requested shifts: 4 shifts with an UC$_x$ target

References

[1] B. Olaizola, S. S. Bhattacharjee, and *et al.* Exploring shape coexistence across $N = 60$ in $^{100}\mathrm{Sr}_{62}$ using IDS. *INTC-P-622*, 2022.

[2] Tomoaki Togashi, Yusuke Tsunoda, Takaharu Otsuka, and Noritak Shimizu. *Phys. Rev. Lett.*, 117:172502, 2016.

[3] J. Dudouet, A. Lemasson, et al. *Phys. Rev. Lett.*, 118:162501, 2017.

[4] T. Kibédi, A.B. Garnsworthy, and J.L. Wood. Electric monopole transitions in nuclei. *Progress in Particle and Nuclear Physics*, 123:103930, 2022.

[5] Paul E. Garrett, Magda Zielińska, and Emmanuel Clément. An experimental view on shape coexistence in nuclei. *Progress in Particle and Nuclear Physics*, 124:103931, 2022.

[6] J. Park et al. *Phys. Rev. C*, 93:014315, 2016.

[7] S. Cruz, P.C. Bender, R. Krücken, K. Wimmer, F. Ames, C. Andreoiu, R.A.E. Austin, C.S. Bancroft, R. Braid, T. Bruhn, W.N. Catford, A. Cheeseman, A. Chester, D.S. Cross, C.Aa. Diget, T. Drake, A.B. Garnsworthy, G. Hackman, R. Kanungo, A. Knapton, W. Korten, K. Kuhn, J. Lassen, R. Laxdal, M. Marchetto, A. Matta, D. Miller, M. Moukaddam, N.A. Orr, N. Sachmpazidi, A. Sanetullaev, C.E. Svensson, N. Terpstra, C. Unsworth, and P.J. Voss. Shape coexistence and mixing of low-lying 0+ states in 96sr. *Physics Letters B*, 786:94–99, 2018.

[8] G. Jung. *Kernspektroskopie an netronenreichen Rubidium-Spaltprodukten mit gerader Massenzahl.* PhD thesis, Justus Liebig-Universitat, Giessen, 1980.

[9] Evaluated nuclear structure data file, https://www.nndc.bnl.gov/ensdf/.

[10] G. Jung, B. Pfeiffer, L. J. Alquist, H. Wollnik, P. Hungerford, S. M. Scott, and W. D. Hamilton. Gamma-gamma angular correlations of transitions in $^{94}\mathrm{Sr}$ and $^{96}\mathrm{Sr}$. *Phys. Rev. C*, 22:252–263, Jul 1980.

[11] H. Mach, F.K. Wohn, G. Molnar, K. Sistemich, John C. Hill, et al. Retardation of b(e2; 01+ → 21+) rates in 90–96sr and strong subshell closure effects in the a   100 region. *Nuclear Physics A*, 523:197 – 227, 1991.

[12] G. Lhersonneau, B. Pfeiffer, R. Capote, J. M. Quesada, H. Gabelmann, and K.-L. Kratz. A $k = 3$ two-quasiparticle isomer in $^{98}\mathrm{Sr}$. *Phys. Rev. C*, 65:024318, Jan 2002.

[13] E. Monnand F. Schussler, J.A. Pinston et al. Discovery of a very low-lying 0^+ state in $^{98}\mathrm{sr}$ and shape coexistence implication in $^{98}\mathrm{sr}$. *Nuclear Physics A*, 339(3):415–428, 1980.

[14] T. A. Berry and Zs. *et al.* Podolyák. Octupole states in $^{207}\mathrm{Tl}$ studied through β decay. *Phys. Rev. C*, 101:054311, May 2020.

[15] P Papadakis, DM Cox, GG O'Neill, MJG Borge, PA Butler, LP Gaffney, PT Greenlees, R-D Herzberg, A Illana, DT Joss, et al. The spede spectrometer. *The European Physical Journal A*, 54(3):1–8, 2018.

[16] S. Stegemann for the TISD group. Rb yields. *Private communication*, 2021.

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
(if relevant, name fixed ISOLDE installation: COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH)	☒ Existing	☒ To be used without any modification
[Part 1 of 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
[Part 2 of 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 experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of 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)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• 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 (1-300 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]