EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Investigation of T=0 np pairing and quartetting in the *fp*-shell nuclei

31/05/2017

M.Assié [1], D. Beaumel [1], Y. Blumenfeld [1], F. Flavigny [1], J. Guillot [1], A. Georgiadou [1], I. Stefan [1], S. Franchoo [1], F. Hammache [1], N. de Séréville [1], L. Achouri [2], F. Delaunay [2], J. Gibelin [2], A. Matta [2], M. Parlog, N. Orr [2], D. Mengoni [3], W. Catford [4], M. Moukaddam [4], B. Dominguez-Fernandez [5], O. Sorlin [6], A.O Macchiavelli [7], N. Sandulescu [8], K. Hadynska-Klek [9], M. Sambatoro [10]

[1] IPN Orsay
[2] LPC Caen
[3] INFN Sezione di Padova
[4] University of Surrey
[5] University of Santiago
[6] GANIL
[7] University of Berkeley
[8] National Institute of Physics and Nuclear Engineering, Romania
[9] INFN Laboratori Nazionali di Legnaro, Italy
[10] INFN Catania, Italy

Spokesperson(s): Marlène Assié (assie@ipno.in2p3.fr)
Local contact: Liam Gaffney (liam.gaffney@cern.ch)

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Abstract

The aim of this letter of intent is to study isoscalar neutron-proton pairing and alpha quartetting in the *fp*-shell. Transfer reaction have shown to be a very powerful tool to infer information on the collectivity of the states populated. We will thus study:

- on the hand, the two-nucleon transfer reaction ^{44}Ti(^{6}Li,^{4}He)^{46}V that is selective of isoscalar state. In the *fp*-shell region, the spin-orbit is hindering the isoscalar channel. The investigation of the collectivity of the first J=1+,T=0 state of ^{46}V will give important information on the isoscalar pairing in the *fp*-shell.
- on the other hand, the alpha-transfer reaction ^{44}Ti(^{6}Li,d)^{46}V. No information is available for alpha transfer in the fp-shell. The aim of this measurement is to establish whether or not an enhancement of the cross-section to the ground state (and possibly to the first 0+ state) of ^{48}Cr is observed.

Both measurements will be performed at the same time and require particle-gamma coincidence measurement. For this purpose, the MUGAST Silicon array for light particle measurement will be coupled with the Miniball array.

Requested shifts: [22+2] shifts
Beamline: [MINIBALL]

1- Motivation

The aim of this experiment is two fold : (i) study the neutron-proton pairing in self-conjugate *fp*-shell nucleus ^{46}V through deuteron transfer reaction; (ii) study the quartetting in ^{48}Cr through alpha transfer reaction. Both quartetting and np pairing are important features to understand the N=Z nuclei.

a) Investigation of neutron-proton pairing through the reaction $^{44}Ti(^6Li,^4He)^{46}V$

The neutron-proton (np) pairing of fundamental interest for N=Z nuclei are associated to the isovector (J=0,T=1) and isoscalar (J=1,T=0) channels. Due to the isospin invariance of the nuclear forces, the isovector np pairing is expected to have similar properties as the neutron-neutron and proton-neutron pairing. A long standing open question is whether in nuclei there are isoscalar np correlations of BCS-type, as in the case of superconducting/superfluid systems (for a recent review on np pairing and new results see Ref. [1]).

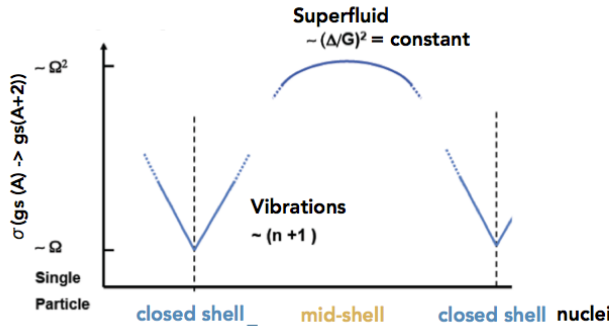

Figure 1 : Expected behaviour of 2n-transfer along a full shell (see text for details) and ref.[1].

The signature of the phase transition between single-particle like state and strongly correlated BCS-like phase is given by the occurrence of pair vibrations that are precursors of the strongly correlated phase.

A powerful tool for investigating the isoscalar np pairing is the two-nucleon transfer reaction. In these reactions the transfer amplitudes <A|a+a+|A-2> provide information on the collectivity of the states, as in the case of the B(E2) transitions. Thus, in the standard picture (see Fig. 1), near closed shells the system is characterized by an harmonic oscillation pattern and the cross-section is proportional to the number of pairs. As more pairs are added, the transition to the BCS-like state can occur and the cross-section becomes proportional to $(\Delta/G)^2$,where Δ is the pairing gap and G the strength of the pairing force. So the shape of the 2N-transfer along the shell is expected to be parabolic, as shown in Fig. 1., with a plateau at the mid-shell.

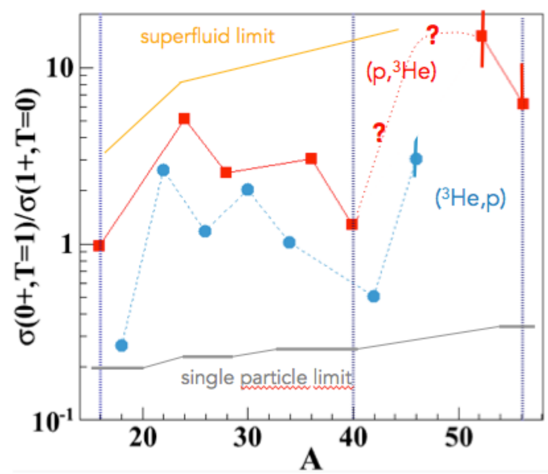

Figure 2 : Systematic for the ratio of cross-section σ(0+)/σ(1+) vs. mass for (^{3}He,p) and(p,^{3}He) transfer reactions. The isoscalar superfluid limit as well as the single particle estimate are also shown (see ref.[1]).

For np-pairing, the transfer reaction can either populate the J=0+, T=1 and/or J=1+,T=0. In order to study the competition between T=0 and T=1 channels the ratio of the cross-section for 2N-transfer to both state is used (see Fig.2). The parabolic shape is more or less found in the sd-shell with ^{16}O and ^{40}Ca being close to the single-particle estimate and the mid-shell nuclei almost reaching the isovector superfluid limit. The parabolic shape is attributed to the T=1 pairing.

Few measurements where performed in the fp-shell: $^{44}Ti(^3He,p)$, $^{56}Ni(p,^3He)$ and $^{52}Fe(p,^3He)$ [1].

What is clearly seen in these measurements is that the J=1+,T=0 state is sparsely populated in all cases. This is interpreted as the effect of the spin-orbit in the f-shell that hinders the isoscalar channel [2].

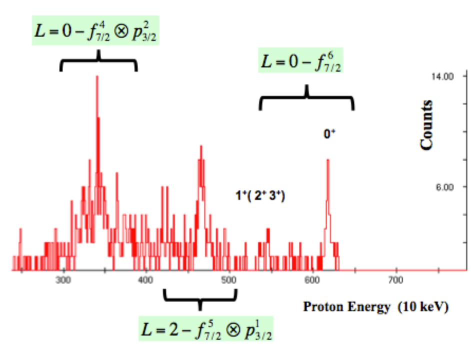

Figure 3 : Proton energy spectrum for $^{44}Ti(^3He,p)$ measurement.

Fig.3 shows the results obtained by A.O. Macchiavelli group at Argonne (from ref.[1]) for $^{44}Ti(^3He,p)$

measurement. In this measurement it was not possible to disentangle the contribution from the $3^+,2^+,1^+$ states.

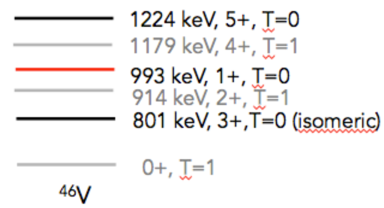

Figure 4 : Level scheme of ^{46}V. In grey the T=1 states not populated in ^{44}Ti(^{6}Li,^{4}He), in red the state of interest, in black the other T=0 states.

Although the ratios of the cross-section give a nice insight into the relative strength of the isoscalar and isovector channel, it is highly desirable to be able to extract angular distributions. These latter not only give the L transferred but can also be compared with detailed DWBA calculations that take into account the reaction mechanism (in particular direct and sequential contributions).

In order to extract these angular distributions, we propose to measure ^{44}Ti(^{6}Li,^{4}He)^{46}V. This reaction is selective in ΔT=0 and will only populate the T=0 states in the residual nucleus ^{46}V. So that only the states in black and red in the level scheme of Fig. 4 will be populated.

Moreover, the experimental set-up that we are intending to use (see below) will enable to use particle/gamma coincidences to clearly identify the populated states and deduce their relative population. These relative populations will be used to constrait the fit of the excitation energy spectrum.

b) Study of alpha-like quartet correlations through the reaction ^{44}Ti(^{6}Li,d)^{48}Cr

In infinite matter calculations, there is some competition between deuteron condensates and alpha condensates. The deuteron condensate appears at high density than the alpha. In the nuclei, the shell-effects change completely this picture and favor the appearance of alpha condensate. In nuclei the connection between pair condensation and alpha-like condensation was analyzed recently in Refs [3,4]. It was thus shown that the np pairing interactions as well as more general pairing forces are in fact properly described by alpha-type quartets rather then by Cooper pairs.

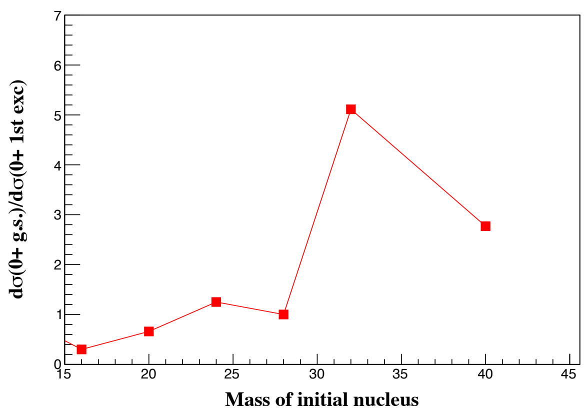

Figure 5: Systematic of the ratio of the cross-section to the 0+ ground state and to the first excited 0+ for (^{6}Li,d) transfer reactions measured in the *sd*-shell nuclei (red squares) [4].

In the same line as explained above for the pairing, the signature of a strongly correlated quartet state could be signed by the occurrence of the quartet vibrations. In this case, the alpha-transfer reactions can give the information on the collectivity of the state.

In the literature there are very few data available from which one can extract relevant information on the existence of alpha-like quarteting in N=Z nuclei. In the ENSDF database, the only data available concerns the sd-shell nuclei [5]. In order to avoid normalization issues, we show the ratio of the cross-section to ground state 0+ and to the first excited 0+ state in Fig. 5.

The case of ^{32}S(^{6}Li,d) looks suspicious and calls for a new measurement. Indeed the 0+ state was unresolved in ref.[4]. If we focus on the results up to ^{28}Si(^{6}Li,d)^{32}S, there seems to be a slight increase in the ratio at mid-shell. The only existing information for the fp-shell is ^{40}Ca(^{6}Li,d)^{44}Ti measurement that lies higher than the sd-shell measurements.

In this proposal, we would like to measure the ^{44}Ti(^{6}Li,d)^{48}Cr reaction in order to get some insight on the quartetting in the *fp*-nuclei. ^{48}Cr is the mid-shell nucleus of the $f_{7/2}$ and we would expect an increase of the cross-section here in the same line as shown in Fig.1. Although the alpha quarteting might be hindered by the fact that ^{48}Cr is deformed.
The measurement of the cross-section to the ground state and the angular distribution associated is the main aim. The measurement of the cross-section for the alpha transfer to the first excited 0+ will be more

difficult to establish. Indeed the level scheme is know but with some ambiguities, particularly for the first 0+ excited state. A 0+ state has been clearly observed by $^{50}Cr(p,t)^{48}Cr$ transfer reaction at 3.42 MeV but has not been observed in other experiments. There are 3 others candidates for 0+ state up to 4.28 MeV but no gammas are know for most of them.

2- Experiment

We propose to measure $^{44}Ti(^{6}Li,d)$ and $^{44}Ti(^{6}Li,^{4}He)$ at 10 MeV/u with a target of ^{6}Li of $0.5 mg/cm^2$ with a set-up coupling the Miniball array with the MUGAST Silicon array.

a) Beam

The beam of ^{44}Ti will be produced in the same way as for experiment IS543 (spokesperson : A. Murphy) but at a different energy. Here we ask for 10 MeV/u to be in the best conditions for the stripping reaction measurement.
The beam of ^{44}Ti will be produced by radiochemical separation of highly irradiated components at the PSI, inserted in to a FEBIAD ion source, and accelerated on the REX-ISOLDE beam line. The beam intensity in this experiment was of 10^6 pps at the beginning and then dropped at 5.10^5 pps. With the slow extraction of the beam, we expect an instantaneous counting rate hundred times higher than the averaged counting rate.

b) Set-up

The experimental set-up will be composed of a ring of four two-layer telescopes, called MUGAST,

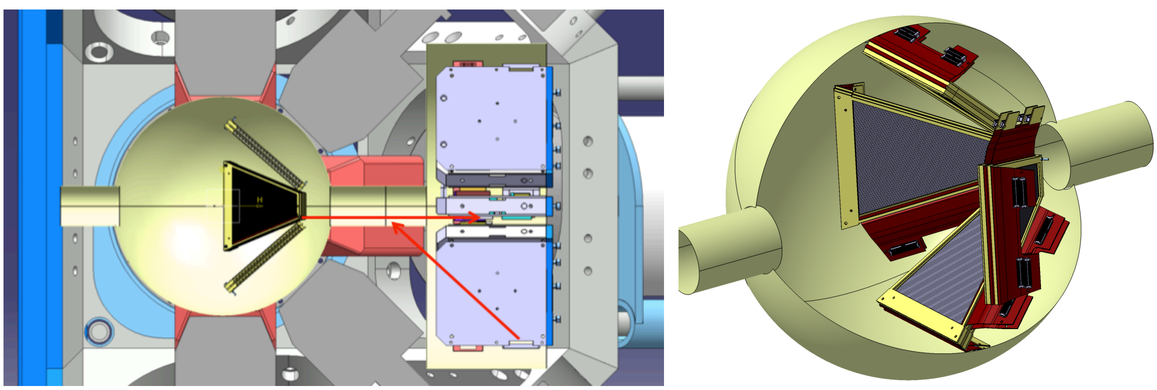

Figure 6 : Conceptual design of the MUGAST set-up that is intended to be coupled with MINIBALL.

placed in the backward direction. Each telescope is composed of double-sided stripped Silicon detectors (DSSSD) with 128 strips on each side and a 1.5 mm thick Silicon detector as a second layer. The spherical chamber shown on Fig. 6 is currently being designed at LPC Caen. It will have a radius of 135mm in order to keep the gamma detectors as close as possible to the target. The DSSSDs channels will be read by the MUST2 electronics (MUFEE) [6] placed upstream at about 40cm from the detectors. The MUFEE boards can read 128+16 channels and give the time and energy information.
The MUGAST detectors will be coupled with the MINIBALL array. The efficiency of MINIBALL at 135 mm is of about 5% at 1.3 MeV.

We have contacted the MINIBALL collaboration to discuss the technical issues of the coupling. This experiment would not be an isolated experiment. The MUGAST collaboration intends to propose new experiments with the HIE-ISOLDE beams.

c) Kinematics

The kinematical lines of the two stripping reactions $(^{6}Li,d)$ and $(^{6}Li,^{4}He)$ are shown in Fig. 7. Both of them have highest cross-section in the backward direction (180 deg.).

In the case of (^{6}Li,d) reaction, the deuterons will have energies higher than 12 MeV and will punch through the first Silicon layer (500 um) so that their identification can be obtained by ΔE-E technique.
For a target of ^{6}Li of 0.5mg/cm^2, the energy resolution will be of 320 keV (FWHM) according to the simulations (see Fig. 8 right)

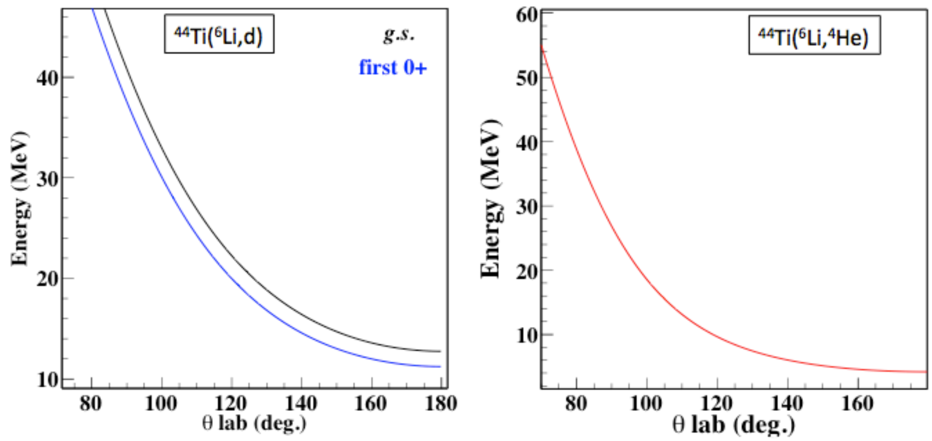

Figure 7 : Kinematical line for ^{44}Ti(^{6}Li,d)^{48}Cr (for the two first 0+ states) (left) and ^{44}Ti(^{6}Li,^{4}He) ^{46}V* (T=0;J=1+) (right).

On the other hand, for the (^{6}Li,^{4}He), the ^{4}He will get out of the target with quite low energy (down to 4 MeV) and will be very sensitive to straggling in the target. That is why we will use a thin target of 0.5 mg/cm^2. The simulation gives a resolution of 840 keV (FWHM) for the excitation energy. The straggling is the main contribution.

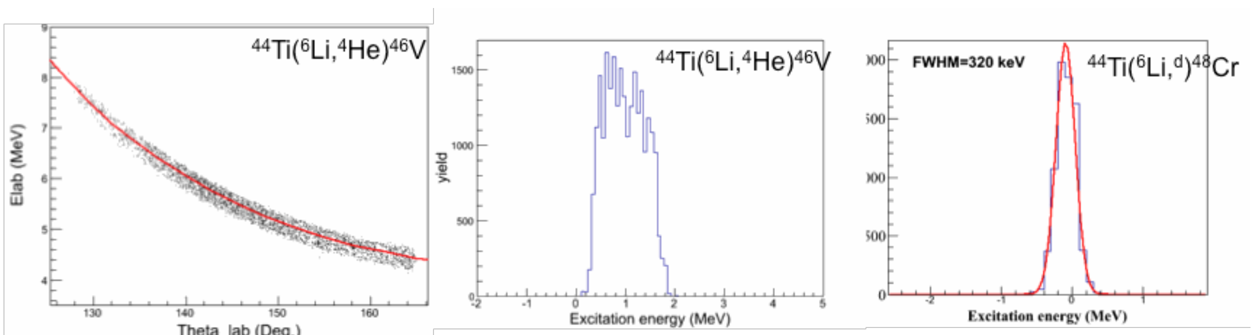

Figure 8 : (Left) Kinematical line for the ^{44}Ti(^{6}Li,^{4}He)^{46}V reaction compared with the theoretical line. (Middle) Excitation energy spectra for ^{44}Ti(^{6}Li,^{4}He)^{46}V (Right) Excitation energy spectra for ^{44}Ti(^{6}Li,d)^{48}Cr(g.s.) .

The identification of the ^{4}He will be more difficult. As it is a backward reaction, there are very few contaminants. The deuterons and ^{4}He will be the mainly produced particles. The ^{4}He will stop into the first layer of DSSSD whereas most of the deuteron will punch through.
The best option would be to use ToF information in order to identify unambiguously the ^{4}He. However, even if the beam intensity is on average 10^6 pps, the instantaneous rate can reach 10^8pps. Very few detectors can handle such high rate. We are currently investigating the possibility to use a stripped diamond detector placed downstream the target and do some tests of electronics associated to it.

If we do not succeed in having a STOP detector signal, we will assume that all particles that stop in the first layer DSSSD are alpha. The background produced from fusion-evaporation reaction could be removed by using a trifoil plastic similar as the one used with 3. 10^7pps in ref.[8]. The background produced from stripping reactions would then be the main contribution and could be removed by simulation.

3-Couting rates

For the ^{44}Ti (^{6}Li,d) reaction cross-section estimation, we use the (^{6}Li,d) measurement in the same region (fp shell) but on stable isotopes from ref.[7]. The cross-section is of the order of 10 µb/sr per level. Although we expect some enhancement of the cross-section at the mid-shell, we will keep this value for the count rate estimate.

For the ^{44}Ti (^{6}Li, α) reaction, we cannot use the previous measurement ^{44}Ti(^{3}He,p) because no absolute cross-sections have been measured. We extrapolate the cross-section from the ^{56}Ni(p,^{3}He) measurement that we have performed at GANIL [1]. The cross-section of the J=1+,T=0 state was of about 15 µb/sr. We will keep the conservative value of 10 µb/sr in the counting rate estimate because the reaction and the Q-value is very different.

Both measurements will be performed at the same time with the same beam and target conditions.

reaction	**Beam intensity(pps)**	**Target thickness (mg/cm^2)**	**Counts/hour 1 level**	**UT requested**	**Total counts for 1 level**
^{44}Ti (^{6}Li,d)	10^6	0.5	2	22	**320 particles**
^{44}Ti (^{6}Li,α)	10^6	0.5	2	22	**320 part. /20 γ photopeak**

Summary of requested shifts:

We ask for 22 shifts of ^{44}Ti beam + 2 shifts for commissioning the coupling of the MUGAST and Miniball array.

References:

[1] S. Frauendorf, A. O. Macchiavelli, Prog. in Part. and Nucl. Phys. 78 (2014) 24; B. Le Crom, PhD thesis of Paris-Saclay University (2016).

[2] H. Sagawa, Y. Tanimura, K. Hagino, PRC 87 (2013) 034310.

[3] N. Sandulescu, D. Negrea, D. Gambacurta, Phys. Lett. B 751,348 (2015)

[4] M. Sambatoro, N. Sandulescu, Phys. Rev. Lett. 115, 112501 (2015), EPJA 53 (2017) 47.

[5] J.P. Draayer et al, Phys. Lett 53B (1974) 250; Lindgren et al Phys. Lett 49B (1974) 263; U. Strohbusch et al, Phys Rev. Lett 29 (1972) 735 and ENDSF database.

[6] E. Pollacco et al.; Eur. Jour. Phys. A25 (2005) 287.

[7] U. Strobusch et al, Phys Rev. Lett 34 (1975) 968.

[8] G.T. Wilson et al, Journal of Physics: Conference Series 381 (2012) 012097.

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 Choose an item.	Availability	Design and manufacturing
MINIBALL	☒ Existing	☒ To be used without any modification
MUGAST + ToF beam detector (existing detectors + electronics, chamber to be designed)	x☐ Existing	☐ To be used without any modification x☐ To be modified
	x☐ New	☐ Standard equipment supplied by a manufacturer x☐ 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	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum		under vaccum	
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	6Li		
Beam particle type (e, p, ions, etc)	44Ti ions		
Beam intensity	10^5-10^6 pps		
Beam energy	10 MeV/u		
Cooling liquids	N		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	x☐	x	
• Isotope	152Eu, 60Co, 137Cs	tri-alpha source	
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact	[dose][mSV]		

and in 10 cm distance			
• 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	[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	pumps		
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