CERN-INTC-2021-004 / INTC-P-590
05/01/2021

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Beta-decay spectroscopy of ^{27}Na and ^{22}O for isospin asymmetry studies in the *sd* shell

January 5, 2021

V. Guadilla[1], M. Pfützner[1], J. Agramunt[2], A. Algora[2], A. Andreyev[3], G. de Angelis[4], A. Beloeuvre[5], J. Benito[6], M.J.G. Borge[7], J.A. Briz[7], T.D. Bucher[8,9], M. Estienne[5], M. Fallot[5], A. Fijałkowska[1], L.M. Fraile[6], E. Ganioğlu[10], W. Gelletly[11], L. Giot[5], A. Illana[12,13], Z. Janas[1], M. Karny[1], A. Korgul[1], R. Lică[14], C. Mazzocchi[1], F. Molina[15], A. I. Morales[2], E. Nácher[2], B. Olaizola[14], N. Orce[8], S.E.A. Orrigo[2], J. Pakarinen[12,13], A. Perea[7], M. Piersa[1], Z. Podolyak[11], A. Porta[5], B. Rubio[2], J.L. Tain[2], M. Stryjczyk[16], O. Tengblad[7]

[1] *Faculty of Physics, University of Warsaw, 02-093 Warsaw, Poland*
[2] *Instituto de Física Corpuscular, CSIC-Universidad de Valencia, E-46071 Valencia, Spain*
[3] *Department of Physics, University of York, York, YO10 5DD, United Kingdom*
[4] *INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[5] *Subatech, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, F-44307 Nantes, France*
[6] *Grupo de Física Nuclear & IPARCOS, Universidad Complutense de Madrid, E-28040, Spain*
[7] *Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[8] *University of Zululand, Department of Physics, P/B X1001, KwaDlangezwa, South Africa*
[9] *University of the Western Cape, P/BX17, ZA-7535, South Africa*
[10] *Department of Physics, Istanbul University, 34134 Istanbul, Turkey*
[11] *Department of Physics, University of Surrey, GU2 7XH, Guildford, UK*
[12] *University of Jyväskylä, Department of Physics, FI-40014, Jyväskylä, Finland*
[13] *Helsinki Institute of Physics, University of Helsinki, FIN-00014, Helsinki, Finland*
[14] *ISOLDE-EP, CERN, CH-1211 Geneva 23, Switzerland*
[15] *Comisión Chilena de Energía Nuclear, Casilla 188-D, Santiago, Chile*
[16] *KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium*

Spokesperson: Víctor Guadilla [vguadilla@fuw.edu.pl]
Contact person: R. Lică [Razvan.Lica@cern.ch]

Abstract: This proposal is aimed at the precise measurement of the β decays of ^{27}Na and ^{22}O. Improved information on the β-intensity probabilities of these decays will shed light on the large isospin mirror asymmetry recently observed when compared with the decays of the corresponding mirror nuclei ^{27}S and ^{22}Si. If confirmed, such a large isospin asymmetry could be interpreted as evidence of proton halo structures in ^{27}S and ^{22}Al.

We plan to exploit the potential and variety of the ISOLDE set-ups for decay spectroscopy. On the one hand, a total absorption γ-ray spectroscopy measurement of the β decay of ^{27}Na is proposed, taking advantage of the sensitivity of this technique to determine the β intensity above the neutron separation energy. On the other hand, for the study of ^{22}O we propose a measurement at the ISOLDE Decay Station intended to determine precisely the β intensities populating the 1^+_1 and 1^+_2 states in ^{22}F and to look for evidence of β feeding to a 1^+_3 state.

Requested shifts: 7 shifts, (split into 2 runs over 1 year)

1 Motivation

The most promising region to observe nuclei with proton halo structure is the *sd* shell, where proton rich nuclei can have one or two loosely bound protons in the $2s_{1/2}$ orbital (see Figure 1 for a schematic picture of the single-particle levels in sulfur). In such a configuration the centrifugal barrier that tends to suppress the formation of the halo is absent and it is expected that protons will have small binding energies and nuclei will exhibit abnormally extended radial density distributions.

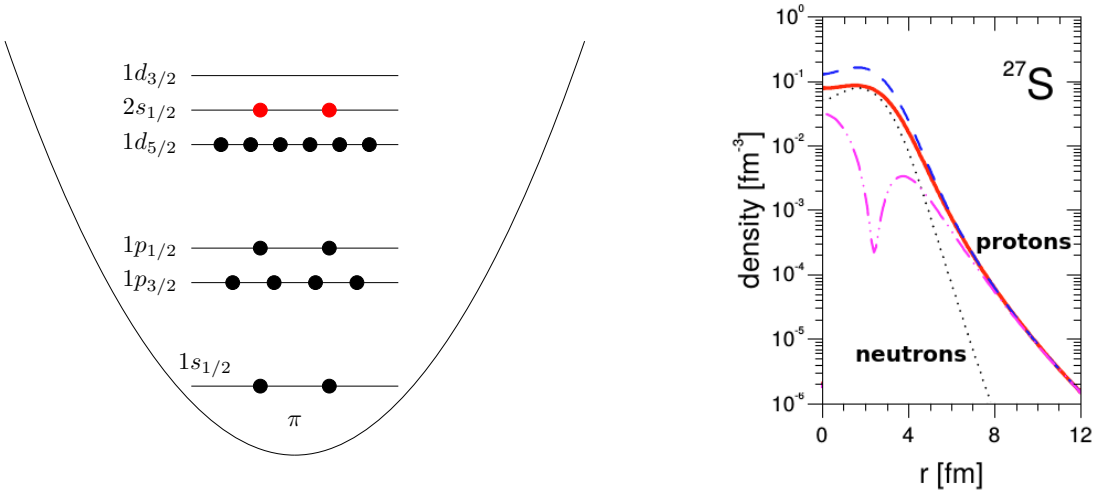

Figure 1: Left: schematic single particle levels for protons in sulfur. The two protons in the $2s_{1/2}$ orbital are highlighted in red. Right: density distributions for ^{27}S from Ref. [1]: neutron distribution (dotted line), proton distributions (solid line), mass distribution (dashed line) and contribution from the $2s_{1/2}$ orbital (dashed-dotted line).

One of the main candidates for a proton halo is ^{27}S, which is expected to have two weakly-bound s-orbital protons [2]. According to the latest mass evaluation [3], the one- and two-proton separation energies of this nucleus were known to be low: S_{1p}=1229(447) keV and S_{2p}=1375(400) keV. However, a new mass excess was recently determined for ^{27}Si [4], reducing considerably the proton separation energies to S_{1p}=581(214) keV and

S_{2p}=727(78) keV. Theoretical calculations also predict low proton separation energies and point to a long tail in the proton radial distribution [1,2,5], as shown in Figure 1. Cluster-core model calculations show a minimum in the potential energy surfaces for a two-proton cluster, although it is very close to the one-proton cluster [6,7]. Experimentally, β-delayed one- and two-proton emission has been observed for this nucleus [8, 9].

Another candidate for a proton halo is ^{22}Al, because of its very low proton separation energy S_{1p}=-7(400) keV [3]. It is known to be a β-delayed one- and two-proton emission precursor [10]. As in the neighboring ^{23}Al nucleus, the spin-parity assignment of the ground state (4^+ for ^{22}Al and $5/2^+$ for ^{23}Al, in agreement with their mirror pairs ^{22}F and ^{23}Ne) does not support the occupation of the $2s_{1/2}$ level by the last proton. A scenario with deformation, such as that suggested by the strong quadrupole deformation of ^{22}Al (β_2=0.56(10) [11]) could open the possibility for inversion or mixing between the $1d_{5/2}$ and $2s_{1/2}$ orbitals. This would be in agreement with the enhanced reaction cross section observed for ^{23}Al, pointing to an s-wave valence proton and to a halo structure [12].

An additional and promising way to find evidence of a proton halo may come from the study of the β decays of mirror nuclei in the isospin symmetry framework. Assuming that isospin is conserved in the nuclear interaction, the *ft* values corresponding to analogue β^+ and β^- transitions should be identical. Possible deviations from such a situation are quantified by means of the asymmetry parameter $\delta = ft^+/ft^- - 1$ and they may be attributed to isospin non-conserving ingredients in the interaction in β decay. While the mean isospin asymmetry in the *sd* shell has been estimated to be about 5% [13], large mirror asymmetries have been reported in transitions involving halo states. Some classical examples are the pairs ^{17}Ne-^{17}N and ^{9}Li-^{9}C. Recently, a ^{26}P-^{26}Na mirror asymmetry of δ=51(10)% was reported as evidence of a proton halo in ^{26}P [14]. This was reproduced by shell-model calculations including isospin-nonconserving (INC) forces related to the $s_{1/2}$ orbit [15], thus supporting the existence of a proton halo structure.

The experimental study of the β-delayed proton branches in the decay of ^{27}S has recently provided information on the β feeding to the first $3/2^+$ and $5/2^+$ states in ^{27}P [8, 9]. When compared with the corresponding β intensities of the decay of the mirror nucleus ^{27}Na, mirror asymmetries of $\delta(3/2^+)$=38(26)% and $\delta(5/2^+)$=48(18)% are found [9], which could be interpreted as evidence of a proton halo structure in ^{27}S. However, as will be discussed in detail later, the possible incompleteness in the β intensities of the decay of ^{27}Na discourages any firm conclusion.

A very recent study of the decay of ^{22}Si [16] has found the largest reported mirror asymmetry value up to now in low-lying states, amounting to 209(96)% for the first 1^+ excited state in the ^{22}Si-^{22}O pair. It has been interpreted as evidence of a proton halo structure in the daughter nucleus ^{22}Al, endorsed by shell-model calculations with INC forces that account for such an asymmetry by predicting a larger s-orbit occupation for the 1^+_1 level. However, as in the case of ^{27}Na, the available information about the β^- decay of ^{22}O does not seem to be complete, which calls for clarification before one can draw any firm conclusion.

2 Previous studies and proposed physics cases

The goal of this proposal is to improve our knowledge of the β decays of ^{27}Na and ^{22}O, so that a clear picture can be established on the proton halo structure of ^{27}S and ^{22}Al. In order to confirm the recent conclusions for ^{22}Al [16] and to point firmly to a proton halo in ^{27}S, fully reliable β-decay information for the mirror decays is needed.

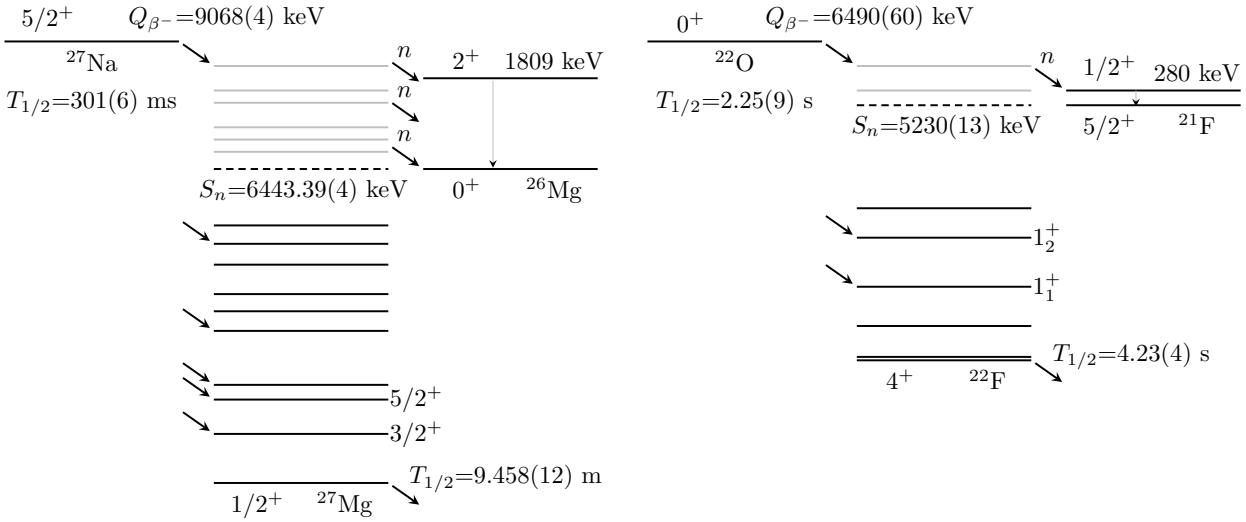

Figure 2: Schematic decay schemes for ^{27}Na (left) and ^{22}O (right). Half-lives, Q_β and S_n values and spin-parities for the most relevant levels are shown based on the information from NNDC [17] and ENSDF [18, 19].

2.1 ^{27}Na

The most complete γ-spectroscopy study of the β decay of ^{27}Na so far was performed at ISOLDE based on Ge(Li) detectors [20], where up to ten excited states were identified to be populated in the daughter nucleus ^{27}Mg, the last one of them at an excitation energy of 4992.6 keV. The β intensity distribution determined is dominated by 85.8(11)% feeding to a $3/2^+$ at 984.7 keV excitation energy (see the schematic level scheme on Figure 2). No direct feeding to excited states above the neutron separation energy S_n was reported, but a neutron emission probability P_n of 0.13(4)% was deduced from the absolute intensity of the 1809 keV γ transition in ^{26}Mg, connecting the first excited state to the ground state (see Figure 2). This is in conflict with a neutron spectroscopy measurement also performed at ISOLDE [21] where β delayed neutrons were observed up to 1.3 MeV, that were attributed solely to transitions to the 0^+ ground state in ^{26}Mg (see Figure 2). It is expected that neutron emission is suppressed up to S_n+1809 keV, since positive parity 3/2, 5/2 and 7/2 states populated in the β decay of ^{27}Na require neutrons with angular momentum l=2,4 to populate the 0^+ ground state in ^{26}Mg, leaving room for undetected

competition with γ de-excitation. From S_n+1809 keV up to the Q_β value, however, no competition is expected, since l=0 neutrons can populate the 2^+ state in ^{26}Mg.

The limited efficiency of germanium detectors is known to impair the determination of the β intensities for complex de-excitation patterns, shifting the deduced β feeding to lower excitation energies, thus underestimating the β intensity at high excitation energies. This systematic error, known as the Pandemonium effect [22], can be overcome by means of the total absorption γ-ray spectroscopy (TAGS) technique, a high-efficiency approach that employs large scintillation crystals [23]. As was suggested in Ref. [8], the available decay data for ^{27}Na very probably suffer from the Pandemonium effect. Up to the last level seen in β decay (4992.6 keV) the level scheme of ^{27}Mg can be considered to be well known. However, even though it is a light nucleus where a modest level density is expected, there is evidence supporting the presence of many potentially undetected levels fed in β decay above that energy. Experimentally, the strongest one comes from the neutron measurement previously mentioned. In addition some $(3/2,\ 5/2,\ 7/2)^+$ levels at higher excitation energies were identified in (d,p) reactions [24, 25]. Shell-model calculations predicted up to 15 available levels above 4992.6 keV [26] and Hartree-Fock-Bogoliubov (HFB) plus combinatorial nuclear level densities [27] predict twenty six $3/2^+$, twenty six $5/2^+$ and eighteen $7/2^+$ states above 4992.6 keV excitation energy up to the Q_β value. In the light of all these facts, a TAGS measurement is the best choice to determine fully the β-intensity distribution of this decay, further justified by the proven sensitivity of this technique for detecting γ rays from neutron-unbound states [28–32]. The completeness of the TAGS results will allow one to refine the mirror asymmetry evaluation. If the value recently reported [8, 9] is confirmed, it would support the picture of a (di-)proton halo in ^{27}S. On the contrary, a large reduction of the order of 25% of the β intensity to the first $3/2^+$ state would rule out the mirror asymmetry, casting doubts on the existence of a proton halo structure in ^{27}S or on the apparent connection between halo structures and this asymmetry.

2.2 ^{22}O

The evaluated decay data for ^{22}O available at ENSDF [19] come from two high-resolution experiments performed at ISOLDE [33] and GANIL [34]. Only two levels were found to be clearly populated, at 1.625 and 2.572 MeV respectively. The 1_1^+ level involved in the large mirror asymmetry recently reported when compared with the decay of ^{22}Si [16] was fed with 29(4)% probability according to Ref. [33], and $\leq$34% according Ref. [34], while ENSDF adopts a value of 31(5)%. However, shell model calculations using the USD effective interaction predict a very low β intensity of 0.04% to this 1_1^+ state [26]. As discussed in Ref. [33], other effective interactions predict a β intensity ranging from 13 to 45%, in better agreement with both experimental values. The population of an experimentally unobserved 1_3^+ level between 2.7 and 4.2 MeV was also predicted by all these models.

An additional uncertainty in the decay scheme of ^{22}O concerns the β-delayed neutron branch. An upper limit of <22% was established for the neutron emission probability P_n in the only neutron measurement performed to date [35]. The 280 keV γ transition in

^{21}F (see Figure 2) was seen in Refs. [33,34], but contamination from the decay of ^{21}O and the limited statistics prevented any estimate of the P_n value, that was not considered in the normalization of the β intensities. No neutron-γ competition is expected in this case, since the low-lying $1/2^+$ level in ^{21}F can be populated by means of l=0 neutrons.

In this proposal we aim to clarify the picture of the β intensities to the 1^+ states, and also search for the possible population of a 1^+_3 state. In this case, above the 1^+_2 state up to the Q_β value only 3-6 levels are expected from shell-model calculations [26, 36] and the HFB plus combinatorial nuclear level densities [27] predict eleven 0^+ and five 1^+ levels. Given the very few levels involved and the scarce information about the level scheme of ^{22}F and about the β-delayed neutron branch, we think that the best experimental approach for this case is a measurement with modern germanium detectors.

3 Experimental details

For the measurement of the β decay of ^{27}Na we propose to use the Lucrecia total absorption spectrometer (TAS) installed at ISOLDE. It consists of a large NaI(Tl) cylindrical crystal with 38 cm height and diameter. This detector has been successfully used for the last 20 years [37] and has a total efficiency of 90 % for mono-energetic γ rays in the range of 300-3000 keV. A plastic detector will be used to require coincidences with β particles in order to reject environmental background. A new tape transport system under development will be employed to implant and remove the ^{27}Na activity inside the spectrometer. A set of collimators and slits is available to avoid the accumulation of activity in the set-up. Assuming a typical implantation cycle of four parent half-lives (see parent and daughter half-lives in Figure 2), less than 1% contamination coming from the decay of ^{27}Mg is expected, which means that there is no need to measure it separately. The interaction of neutrons with the NaI(Tl) crystal by means of inelastic scattering and neutron capture is known to produce a background that needs to be accounted for in the TAGS analysis. For this, we will consider two alternative strategies following the line of Ref. [32]: 1) the prompt-delayed γ discrimination based on the time difference between Lucrecia and the plastic β detector and 2) the Monte Carlo simulation of the response of Lucrecia to the β delayed-neutrons, taking advantage of the availability of the neutron spectrum data [21].

The decay of ^{22}O will be studied at the ISOLDE decay station (IDS). In particular we plan to use a high-efficiency β-γ set-up configuration consisting of five HPGe clover detectors in close geometry and a 3 cm-thick rectangular NE102 plastic scintillator covering almost 95% of the solid angle around the implantation point [38]. We plan to study $\beta\gamma$, $\beta\gamma\gamma$ and $\beta\gamma\gamma\gamma$ coincidences. The activity will be implanted in a movable tape and we plan to accumulate ^{22}O during one half-life (2.25 s, as shown in Figure 2) in order to reduce the contamination of the daughter ^{22}F to 10%.

4 Beam time request

For the production of both ^{27}Na and ^{22}O protons of 1.4 GeV will be used to induce fission in a uranium carbide graphite target.

^{27}Na: A surface ion source will be employed to ionize the radioactive atoms diffusing from the target. A yield of 8.5x10^6 ions/μC is expected according to the ISOLDE yield database and Ref. [39]. Assuming a current of 2 μA and a transmission of 70% to the TAS setup, a rate of $\sim$3x10^6 β-γ coincidences per second is expected, with 80% γ efficiency in the TAS and 40% efficiency in the β detector. We plan to adjust the beam gate to maintain the β-γ counting rate below 4 kHz (<10 kHz in Lucrecia in singles) in order not to have a large dead time in our acquisition system and to avoid a huge pileup distortion in Lucrecia, which will be treated as in previous works based on Ref. [40]. We request 3 shifts aiming at registering of the order of 100 million β-γ coincidences. This will allow us to study very precisely the β intensity at high-excitation energies. We took into consideration the $\sim$400 ms needed to move periodically the tape and that $\sim$10% of the time will be blocked by the tape rewind. Assuming a neutron efficiency for Lucrecia of 40% and the P_n value mentioned above only to the 2$^+$ level in ^{26}Mg, without neutron-γ competition, we expect $\sim$10^5 signals in Lucrecia coming from the interaction of neutrons.

^{22}O: A plasma ion source will be employed in this case. Oxygen will be extracted as a CO molecular ionic beam and a mass-separated $M = 34$ beam will be transported to the IDS. Based on previous measurements [33], we expect a dominant ^{12}C^{22}O component with a small contamination of ^{13}C^{21}O. We assume a yield of 1.3x10^3 ions/μC for ^{22}O from the ISOLDE yield data base and Ref. [41]. A counting rate of 1.8x10^3 ions/s is expected at the IDS, where a proton current of 2 μA and a transmission of 70% to the IDS station are assumed. In order to achieve enough sensitivity for 1% β feeding to a 1_3^+ state, we request 3 shifts of beam time. Considering the γ efficiency for five clovers (6% at 600 keV and 3% at 2000 keV) and a 90% β efficiency [38] this will translate into $\sim$100 $\beta\gamma\gamma\gamma$ coincidences for the most likely cascade de-exciting the possible 1_3^+ state. With such statistics, even with the possible contamination from ^{21}O, we could obtain a more constrained estimate of the P_n value of ^{22}O. For this, we will rely on the relative γ intensity of the 280 keV γ ray with respect to the most intense γ line (1730 keV) from the decay of ^{21}O [42].

The two measurements with Lucrecia and the IDS can take place independently during different campaigns. The ^{27}Na measurement can be grouped with one of the other TAGS experiments recently proposed under the umbrella of an international collaboration.

Summary of requested shifts: we request a total of 7 shifts: 3 shifts to measure the decay of ^{27}Na with Lucrecia, 1 shift to tune the beam, to measure background and to produce a ^{24}Na source for the calibration of Lucrecia, and 3 shifts to measure the decay of ^{22}O with the IDS.

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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
TAS	☒ Existing	☐ To be used without any modification ☒ To be modified: update of the tape station
IDS	☒ Existing	☒ To be used without any modification ☐ To be modified

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			
Vacuum	High vacuum [10^{-6} mbar]		
Temperature	LN_2 temperature [77 K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity	6.0 kV (HPGe det. HV supply)		
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)	Ions: ^{27}Na and ^{22}O		
Beam intensity	3000000 s^{-1}		

Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	^{152}Eu, ^{133}Ba, ^{22}Na, ^{241}Am, ^{60}Co, ^{137}Cs		
• Activity	1-10 kBq		
Use of activated material:			
• Description	☒ ^{24}Na samples on tape		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope	^{24}Na		
• Activity	50 kBq		
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]
2.5 kW