EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Gamma spectroscopy of n-rich ^{95,96}Rb nuclei by the incomplete fusion reaction of ^{94}Kr on ^{7}Li: Introduction to HIE-ISOLDE studies of n-rich Sb and Tl isotopes with Sn and Hg radioactive beams.

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Abstract

We propose an experiment with MINIBALL coupled to T-REX to investigate n-rich ^{95,96}Rb nuclei by the incomplete fusion reaction of ^{94}Kr on ^{7}Li. The nuclei of interest will be populated by transfer of a triton into ^{94}Kr, forming the excited ^{97}Rb nucleus, followed by the emission of an alpha particle, which will be detected in the Si telescopes of T-REX. The ^{97}Rb product will evaporate 1 or 2 (with the highest probability) neutrons leading to ^{96}Rb or ^{95}Rb, respectively. The aim of the experiment is twofold: i) to perform a gamma spectroscopy study of ^{95,96}Rb nuclei with N=58,59, the structure of which is of particular interest in investigating the transition towards stable deformation at N=60, ii) to acquire experience in using incomplete fusion reactions with the weakly bound ^{7}Li target, in order to perform, at later stage with HIE-ISOLDE, similar measurements induced by n-rich radioactive beams of Sn and Hg, for which at least 5 MeV/nucleon are needed to overcome the Coulomb barrier.

The present experiment is therefore meant as a first step of a research program aiming at gamma spectroscopic studies of the low-lying structures in Sb and Tl isotopes located close to ^{132}Sn and ^{208}Pb, respectively.

Requested shifts: 12 shifts (split into 1 run over 1 year)

Nuclei around doubly closed shells play a crucial role in determining both the nucleonic single-particle energy levels and the two-body matrix elements of the effective nuclear interactions. Of particular importance is a comparison of experimental data with calculations in which the effective interaction is derived from the free nucleon-nucleon potential - such comparison may deliver information on some basic aspects of the nucleon-nucleon interaction or on the renormalization procedure [Cov]. In this respect, the region around doubly magic ^{132}Sn and ^{208}Pb is particularly attractive as these nuclei are considered the best doubly closed cores. Until now, however, the knowledge on the structure of nuclei from the vicinity of ^{132}Sn has not been sufficient to determine a complete set of the empirical two-body matrix elements (TBME's) for the active orbitals. Similarly, information on the TBME's for the proton-hole neutron-hole and proton-hole neutron-particle interaction with respect to ^{208}Pb is far from being complete. This situation has resulted mainly from the inaccessibility of the regions in standard fusion-evaporation reactions with stable projectiles and targets.

Having in mind the future availability of radioactive beams with energies up to 10 MeV/nucleon at HIE-ISOLDE, we would like to propose a research program aimed at gamma spectroscopic studies of the low-lying structures in Sb and Tl isotopes located close to ^{132}Sn and ^{208}Pb, respectively. A special emphasis will be put on ^{132}Sb and ^{134}Sb which are one-proton-particle, one-neutron-hole and one-proton-particle, one-neutron-particle systems, respectively. Along the same way, we would like to access one-proton-hole, one-neutron-hole and one-proton-hole, one-neutron-particle multiplets in ^{206}Tl and ^{208}Tl nuclides.

We plan to employ the incomplete fusion reactions induced by radioactive beams of Sn and Hg on a ^{7}Li target. The nuclei of interest will be populated in ^{7}Li(^{A}Sn,α2n) and ^{7}Li(^{A}Hg,α2n) processes, respectively. The gamma spectroscopic data collected in such measurements will be used to extract empirical diagonal two-body matrix elements of proton-neutron interaction in the vicinity of ^{132}Sn and ^{208}Pb. Comparison of these empirical TBME's with the ones derived from the free nucleon-nucleon potentials, by using for example the $V_{\text{low-k}}$ approach, may deliver information on basic ingredients of the nucleon-nucleon interaction or on the renormalization procedure.

During the last two decades or so, incomplete fusion reactions induced by a ^{7}Li beam have extensively been exploited for γ-ray spectroscopic studies [e.g., Cla, Dra, Mul, Jun, Jut, Wat]. The success of these studies relied on the fact that incomplete fusion processes offer access to states at relatively high angular momentum in neutron-rich heavy nuclei, which are otherwise inaccessible by standard fusion evaporation reactions involving stable beam-target combinations. Indeed, there is a significant probability of a ^{7}Li beam nucleus breaking up, with a triton being captured while an α is emitted. It has also been shown that in such processes it is possible to populate states with a significantly higher angular momentum than can be reached with ^{7}Li-induced fusion-evaporation reactions [Dra]. For example, recently, excited states in ^{125}Sb with spins up to 23/2 have been studied following the ^{124}Sn(^{7}Li,α2n)^{125}Sb incomplete fusion reaction at beam energy 37 MeV [Jud].

At REX-ISOLDE, the available energies of the Sn or Hg beams are not sufficient to overcome the Coulomb barrier if scattered on a ^{7}Li target and, as a result, the measurement proposed above cannot be performed at the present time. In turn, such studies will be doable at HIE-ISOLDE and we plan to propose the appropriate beam requests in the future. At the present stage, however, we would like to acquire experience in performing similar measurements with a lighter mass radioactive beam. We concluded that one of the test cases in this respects offers a beam of ^{94}Kr that can be delivered from REX-ISOLDE with a sufficient energy and intensity to study the incomplete fusion processes on a ^{7}Li target. One of the main channels of this reaction, ^{7}Li(^{94}Kr,αxn), will lead to ^{95,96}Rb nuclei with N=58,59 the structure of which is of particular interest in investigating the transition towards stable deformation at N=60.

In the following, we propose the study of neutron-rich ^{95,96}Rb nuclei, in particular ^{95}Rb, which we intend to populate by the incomplete-fusion reaction induced by a radioactive beam of ^{94}Kr at 2.84 MeV/A delivered from REX-ISOLDE on a ^{7}Li target.

The proposed reaction has two distinct features that greatly facilitates detection of the discrete gamma rays and their identification:

- Firstly, the very inverse kinematics guarantees that the product nuclei all travel downstream in a very small recoil cone, thus Doppler reconstruction of the gamma-ray data does not require recoil detection.

- Secondly, reaction channel of interest here will be uniquely associated with emission of an alpha particle. By detecting this alpha particle, we will be able to produce a very clean trigger of the ^{7}Li(^{94}Kr, αxnγ) processes.

The Rb nuclei of interest (Z=37, N=58-59) are placed in a mass region where a transition from a partial sub-shell closure at N=56 and a stable deformation at N=60 is expected to take place [Buc]. This is confirmed by the experimental measurement of the first 2^{+} state energy in even-even isotopes of Kr, Sr, Zr and Mo (Z= 36, 38, 40 and 42). As shown in Figure 1, in each isotopic chain the energy of the 2^{+} state shows a pronounced peak at N=50 (shell closure) and the onset of a deep minimum at N=60, a clear indication of a transition towards a well deformed shape. In the Zr case, a second peak is also observed at N=56, while in Kr and Sr nuclei with N~56 the 2^{+} energies exhibit a rather smooth plateau. This can be interpreted as a partial neutron sub-shell closure in the transitional region between spherical and deformed shapes, although preliminary results from ISOLDE do not agree in the case of the 2^{+} energy of ^{96}Kr [Alb].

To investigate further this region of shape changes, detailed information on higher spin states not only in even-even nuclei, but also in the odd adjacent nuclei (as for example Rb isotopes) are very much needed. In particular, in odd nuclei the observation of multiplets of states arising from the coupling between single particles and elementary modes of core excitations would probe the robustness of the collectivity of the core-nuclear system. Indeed, for example, problems with identifying the 27/2- isomer in ^{95}Rb of a $\pi g_{9/2}\nu h_{11/2}g_{7/2}$ character, which is expected on the basis of systematics (such an isomer exists in the isotopes ^{91}Rb, ^{93}Rb and the isotone ^{97}Y) and shell model calculations [Sim], points toward development of structures that cancel the isomerism in this nucleus. In the study proposed here, we will be able to populate yrast and non-yrast states, up to a spin of at least 15ħ in ^{95}Rb and ^{96}Rb nuclei. This should provide an answer to the question that was posed above as well as give a deeper insight into the competition between various structures in the nuclides of interest. From a broader perspective, the investigation planned here will provide information on ^{95}Rb that is complementary to the results obtained by neutron-induced fission of [Sim10] and by a previous ISOLDE experiment [IS493] in which Coulomb excitation of the ^{93,95,97,99}Rb nuclei was successfully studied with MINIBALL. In these cases, yrast and near-yeast states have been populated, at variance from the proposed ^{94}Kr+^{7}Li reaction which is expected to get access to higher excited states.

One should also keep in mind that the main channel of the studied reaction, ^{94}Kr+^{7}Li, will be the fusion-evaporation channel. According to the PACE calculations, it will lead to ^{97}Y and ^{98}Y nuclei with cross-section of the order of 200 mb and 70 mb, respectively. By using gamma-gamma coincidence data with gates set on the known gamma transitions, one might be able to extend the spectroscopic information on medium-high spin states in ^{97}Y and ^{98}Y as well.

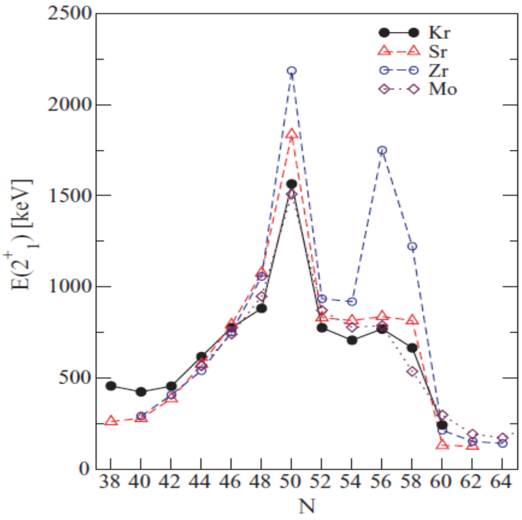

Figure 1. *Experimental energy of the first 2^+ state in neutron-rich even-even isotopes of Kr, Sr, Zr and Mo [Marg]. Please note that preliminary results from ISOLDE do not agree in the case of ^{96}Kr – a higher energy, ~500 keV, was suggested for the 2+ state.*

It is important to note that structural information on the proposed nuclei (in terms of shape changes and deformation) is also very relevant for astrophysics, in particular for the nucleosynthesis of heavy-elements in this region of mass. As shown in Figure 2, some models show that the astrophysical r-process is expected to pass through those Rb nuclei which we intend to study. However, the location of this path is very uncertain since it is strongly affected by quantities, such as the beta-decay lifetimes $T_{1/2}$ and the beta-delayed neutron emission P_n, which, in turn, are strongly influenced by the shape of the nucleus [Mol].

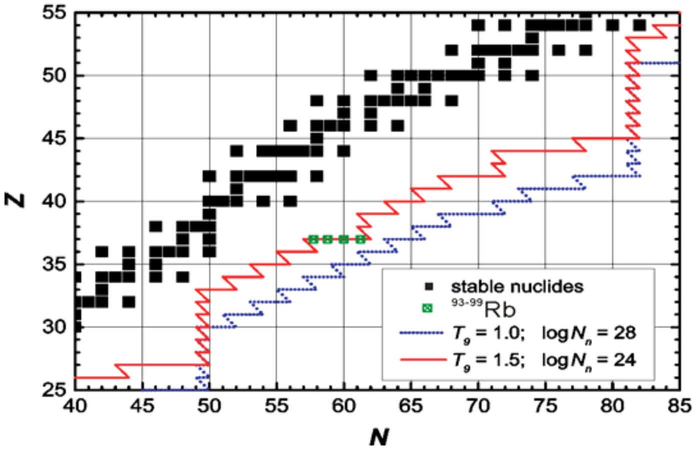

Figure 2. *Theoretical predictions for the location of the r-process in the neutron rich mass region around ^{94}Kr. The red and blue lines indicate different paths, for two different temperature and neutron density [Rah,Del].*

As it was mentioned above, the ^{94}Kr+^{7}Li reaction that we intend to employ will allow to populate $^{95\text{-}96}$Rb species in the process associated with transfer of a triton into ^{94}Kr, followed by emission of an α particle:

^{94}Kr + ^{7}Li → ^{97}Rb + α, Q=+9.706 MeV.

This will lead to production of the excited ^{97}Rb and the subsequent evaporation of one or two neutrons will populate ^{96}Rb and ^{95}Rb nuclei.

In the considered experiment, one will observe also α and t particles arising from other processes:

a) transfer of α: ^{94}Kr + ^{7}Li → ^{98}Sr + t, Q = + 5.445 MeV.

b) breakup of the weakly bound ^{7}Li target (binding energy S_α ~ 2.5 MeV): ^{7}Li → α + t.

Breakup will occur with the cross section of the order of 30 mb. In this case, emission of light particles at forward angles is expected – it might be accompanied by gamma rays from inelastic excitation of ^{94}Kr.

What regards transfer processes taking place in the reaction of ^{94}Kr on ^{7}Li, Figure 3 (left) shows results, as a function of detection angle, of the DWBA calculations for the emission of α, t and ^{6}Li particles. The calculations are done at E_{lab} = 232 MeV and correspond to the transfer of t, α and one neutron. In the calculation, the optical model potential for the system ^{94}Kr + ^{7}Li has been taken from the global prescription of Julian Cook [Cook].

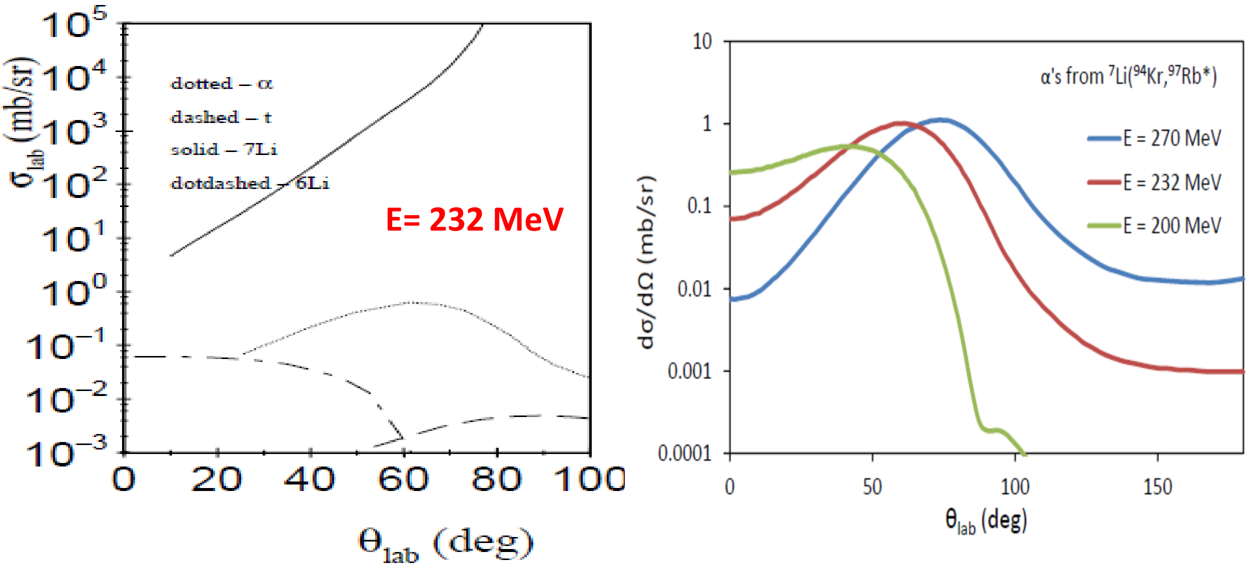

Figure 3. *Left: DWBA calculations for emission of α, t and ^{6}Li for the reaction ^{94}Kr + ^{7}Li at E_{lab}=232 MeV, as a function of scattering angle in the laboratory frame. The solid line shows the elastic scattering cross section of ^{7}Li. Right: DWBA calculations for emission of α particles for different energies of the ^{94}Kr beam (E_{lab}=200, 232 and 270 MeV).*

In the α–transfer process leading to Sr isotopes (dashed line), the residual nucleus will be produced mainly in high excited states, because the Q-value of the reaction is high and positive and α–cluster states in nuclei are typically placed at high excitation energies (see for example [Gold]). The calculation assumes that the four nucleons forming α-cluster are placed at the $2p_{3/2}$ (two protons) and $1g_{7/2}$ (two neutrons) orbitals in the residual nucleus ^{98}Sr, at excitation energy of ~7.5 MeV. In addition, the potential binding α + core nucleus is of a Wood-Saxon form (with standard geometry), while the triton optical potential is taken from Ref. [Fly].

The conditions for the t-transfer process (thin solid line), leading to Rb isotopes, are very similar (very high and positive Q value), so the residual nucleus ^{97}Rb will be produced mainly at an excitation energy of ~14.5 MeV. In this case, the optical potential for α + ^{97}Rb is taken from the global prescription of Ref. [Avr].

As it is seen in Fig. 3 (left), α emission (associated with triton transfer) is expected to be much favored with respect to the emission of tritons (following α transfer) and ^{6}Li. It has also been found that the cross section for α emission varies rather rapidly with the beam energy – it is shown in the right panel of Fig. 3: for E_{lab} = 200, 232 and 270 MeV, the maximum of the expected distribution moves from ~47° to 77° in the laboratory frame and the total cross section increases from 1.5 to 4.5 mb.

It is worth noting that the values of the cross-section for α emission that are quoted above, correspond to a triton transfer process that populates only one state around 14.5 MeV in the ^{97}Rb product. By integrating over all the excited states which should be populated in ^{97}Rb, an increase of a factor 10-20 is expected for the total ^{7}Li(^{94}Kr,αxn) reaction cross section. **In the case of the reaction at E_{lab} = 232 MeV, this means a total of ~35-70 mb for ^{97}Rb**

and presumably also for ^{95}Rb, due to the high probability for evaporation of two neutrons after the emission of the α particle [Cla,Dra,Das]. Production yield of ^{96}Rb that is associated with evaporation of 1 neutron will be lower by a factor of a few. The calculations indicate that both α and t will have energy up to 40 MeV. Emission of alphas and tritons with higher energies (by 10-15 MeV, in particular for the α particles), although with rather low probability, is also expected because of the transfer process to the ground state of the residual nucleus.

Experimental Setup

The experimental setup which we propose to use requires the MINIBALL array coupled to the T-REX apparatus, for the detection of α and t particles in coincidence with γ transitions. T-REX should be in the Coulex barrel configuration, consisting in CD and Barrel telescopes in forward direction, thus allowing to optimize the detection of the emitted α particle. By gating on α particles and requiring a coincidence with γ transitions in the Ge array, the background from break-up contributions will be largely reduced and the Rb nuclei of interest will be selected.

Monte Carlo simulation calculations for the ^{94}Kr + ^{7}Li reaction at E_{lab}=232 MeV (see Fig. 4) show that the ΔE-E Si telescopes are able to separate and detect with high efficiency the α and t particles produced at forward angles. In the simulation, a mylar foil of 25 μm has been used in front of the Si detectors of the Barrel of T-REX, in standard configuration (i.e. 140+1000 μm for the Barrel and 500+1500 μm for the CD detectors).

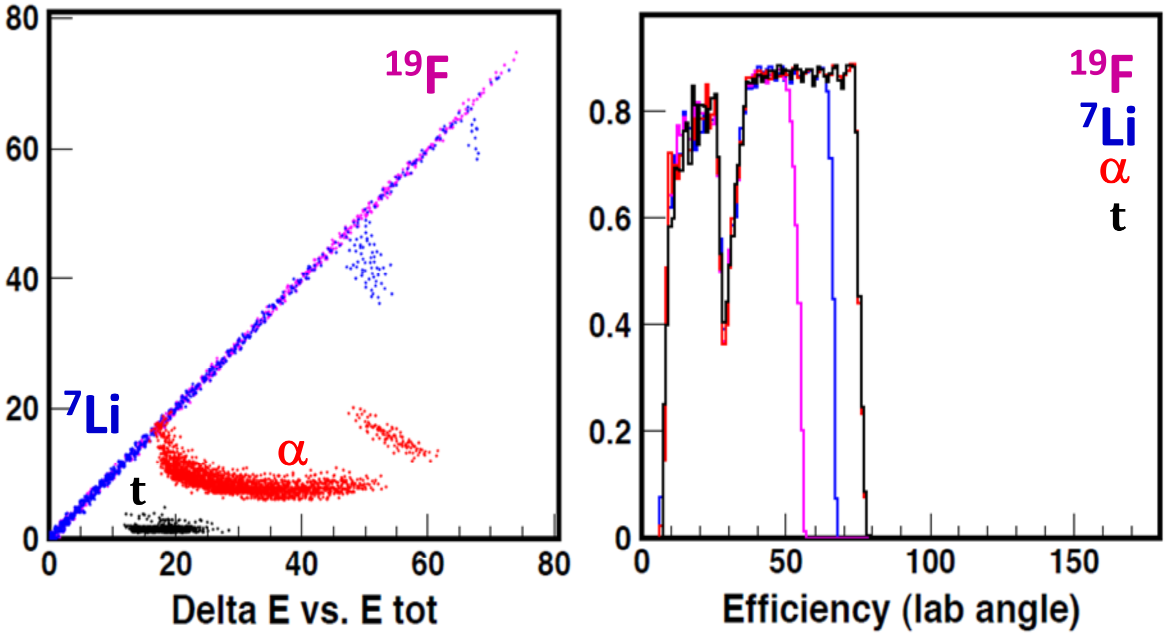

Figure 4. Left: *Monte Carlo calculations for the separation of α (red) and t (black) particles in the Si telescopes of T-REX.* ^{7}*Li and* ^{19}*F particles elastically scattered from the* ^{7}*LiF target are also shown in blue and violet, respectively.* ***Right:*** *Detection efficiency, as a function of the laboratory angle, for the different particles produced in the reaction. A mylar foil of 25μm has been considered in front of the Si telescopes of the Barrel.*

Considering a detection efficiency of T-REX for α particles at forward angles of the order of 90% (as obtained by simulation calculations), and assuming: i) a ^{94}Kr beam of 267 MeV with an intensity of ~2×10^5 pps (as measured at MINIBALL in experiment IS485 in June 2009), ii) a 1.5 mg/cm^2 thick ^{7}LiF target (leading to a beam energy of 232 MeV at mid-target) and iii) a total cross section of ~50 mb, we expect to be able to collect in T-REX ~0.08 α particles/second from incomplete-fusion. Further, assuming a typical 7% efficiency of MINIBALL for a γ transition in the 1 MeV range and an average gamma-ray multiplicity from the ^{95}Rb or ^{96}Rb products of the order of 5 (which is within the detection capability of the MINIBALL array), we may have ~0.03 events/s of α–γ coincidences associated with the production of $^{95\text{-}96}$Rb. Therefore, in a 4 day experiment a total of ~10000 events of α–γ coincidences from the ^{7}Li(^{94}Kr,αxn) reaction are expected. This should be sufficient to perform a basic γ-spectroscopic study of ^{95}Rb which will be the strongest (~80%) product. There will also be a chance to obtain some information on the structure of ^{96}Rb for which the production yield should be of the order of 10-20%. The high granularity of the MINIBALL detectors will also help considerably in reducing the Doppler broadening of the γ-rays emitted by the Rb nuclei (in flight with a velocity of ~7.5% speed of light), leading to an energy resolution of 12 keV at 1.3 MeV, at most.

Since we are going to use a LiF target, one may expect gamma rays from the products of fusion-evaporation reaction of ^{94}Kr on ^{19}F. However, at the beam energy of 232 MeV, that is expected in the middle of the target, the cross section for this process is negligible. Even at the highest beam energy of ~270 MeV, that will be available for reactions on ^{19}F in the superficial layer of the target, the largest part of the cross section, 130 mb, will be concentrated in ^{108}Rh, the product of 5n evaporation. There will be no charged particle emission from the ^{94}Kr+^{19}F fusion-evaporation processes.

Summary of requested shifts:

We ask for a total of 4 days beam time of ^{94}Kr at 2.84 MeV/nucleon and a beam intensity of at least 2 10^5 pps on target in MINIBALL. This corresponds to 12 shifts in one run.

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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 Choose an item.	Availability	Design and manufacturing
REX post-accelerator	☒ Existing	☒ To be used without any modification
MINIBALL + T-REX	☒ 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 [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	*REX*	*Miniball*	
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity			
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material		Secondary target: LiF_4 foil 1.5 mg/cm^2	
Beam particle type (e, p, ions, etc)	Heavy ions: tuning and calibrations : stable Kr, ^{22}Ne	Heavy ions: tuning and calibrations : stable Kr, ^{22}Ne	

	Measurement : ^{94}Kr	Measurement : ^{94}Kr	
Beam intensity	max 1 nA (injection plate REXTRAP)	max 10 pA (after EBIS)	
Beam energy		2.84 MeV/nucleon	
Cooling liquids			
Gases			
Calibration sources:	☐	☒ Standard alpha- and gamma-calibration sources from ISOLDE	
• Open source	☐		
• Sealed source	☐		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			
Intensity			
Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

Hazard identification

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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)*