EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Employing ROC to explore astrophysics milestones: nuclear structure of the $N = Z$ nucleus ^{76}Sr

April 9, 2024

L. V. Rodríguez[1,2], T. Lellinger[2,3], M. Au[4], A. Arcones[1,3], K. Blaum[1], H. Bodnar[3], B. Cheal[5], K. Chrysalidis[5] S. Dutton[1], T. Fabritz[3], R. F. Garcia Ruiz[7], J. Hughes[5], P. Imgram[8], F. Koehler[3], K. Koenig[3], D. Lange[1], B. Maaß[3], E. Matthews[2,3], P. Müller[3], R. Neugart[2,9], G. Neyens[8], W. Nörtershäuser[3], J. Palmes[3], P. Plattner[1], L. Renth[3], S. Rothe[4], R. Sánchez[10], C. Schweiger[1], J. Spahn[3], X. Yang[11] and D. T. Yordanov[1,12]

[1] *Max-Planck-Institut für Kernphysik, Heidelberg, Germany.*
[2] *Experimental Physics Department, CERN, Geneva, Switzerland*
[3] *Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany*
[4] *Engineering Department, CERN, Geneva, Switzerland.*
[5] *Oliver Lodge Laboratory, University of Liverpool, United Kingdom*
[6] *Accelerator Systems Department, CERN, CH-1211 Geneva 23, Switzerland*
[7] *Massachusetts Institute of Technology, Cambridge, MA, USA*
[8] *Instituut voor Kern- en Stralingsfysica, KU Leuven, Leuven, Belgium*
[9] *Institut für Kernchemie, Universität Mainz, Mainz, Germany*
[10] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*
[11] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[12] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*

Spokesperson: L. V. Rodríguez, liss.vazquez.rodriguez@cern.ch
Contact person: L. V. Rodríguez, liss.vazquez.rodriguez@cern.ch

CERN-INTC-2024-041 / INTC-P-706
09/04/2024

Abstract: We aim to explore neutron deficient strontium isotopes near the proton drip line. This study will focus on determining the charge radius of the $N = Z$ nucleus ^{76}Sr, anticipated to be a waiting point for astrophysical mechanisms. To address the challenge of low production yields, we will employ the recently developed ROC technique. Additionally, we plan to extend the existing mass measurements to the exotic ^{75}Sr isotope, important in refining astrophysics models. In collaboration with the RILIS and target groups we propose to perform yield measurements and efficiency tests of a RILIS scheme that has been successfully implemented at the TRIUMF facility yet remains unexplored at ISOLDE.

Summary of requested shifts: 9 shifts of radioactive beam and 1 shift of stable beam, in 1 run.

1 Introduction

Type-I X-ray bursts are highly luminous events that occur as intense nuclear explosions on the surface of a neutron star. These explosions are driven by the rapid proton capture process (rp-process). The path of the rp-process consists of a sequence of proton captures and β^+ decays along the proton drip line [1-3]. Along the path, waiting-point (WP) nuclei play an important role. These nuclei represent points where rapid proton capture reactions can no longer occur due to energy constraints, causing the process to pause. The sequence resumes only when a slower β^+ decay facilitates an alternative pathway.

In the path from ^{56}Ni to the predicted rp-process end point above ^{100}Sn, eleven waiting points are expected [4], namely, ^{56}Ni ($T_{1/2} = 6$ d), ^{60}Zn ($T_{1/2} = 1.38$ min), ^{64}Ge ($T_{1/2} = 64$ s), ^{68}Se ($T_{1/2} = 35.5$ s), ^{72}Kr ($T_{1/2} = 17$ s), ^{76}Sr ($T_{1/2} = 7.89$ s), ^{80}Zr ($T_{1/2} = 4.6$ s), ^{84}Mo ($T_{1/2} = 2.3$ s), ^{88}Ru ($T_{1/2} = 1.2$ s), ^{92}Pd ($T_{1/2} = 1$ s) and ^{96}Cd ($T_{1/2} = 1.03$ s). The nuclear properties of these $N = Z$ nuclei, in particular the mass and the charge radius, impact how these nuclei interact and fuse, affecting the synthesis of heavier elements, and are therefore key for studying stellar evolution and nucleosynthesis mechanisms. However, the experimental investigation of these very exotic nuclei is extremely challenging due to their short half-lives and small production yields. Furthermore, experimental methods like laser spectroscopy have not been fully utilized in their study.

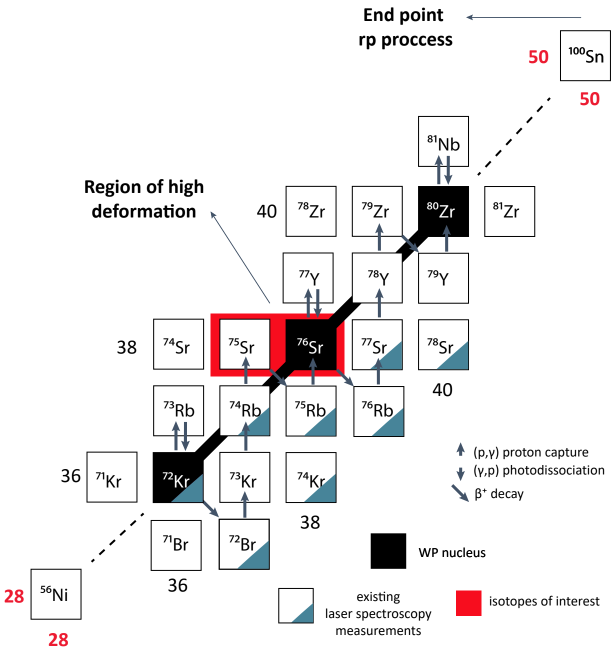

Figure 1: Nuclear chart around the rp-process WP ^{76}Sr. The pathway of the rp-process nucleosynthesis is shown with the black arrows.

In Fig.1, the region of the nuclear chart around ^{72}Kr, the only waiting point nucleus reached by laser spectroscopy so far, is shown. The WP nuclei, ^{76}Sr and ^{80}Zr are also

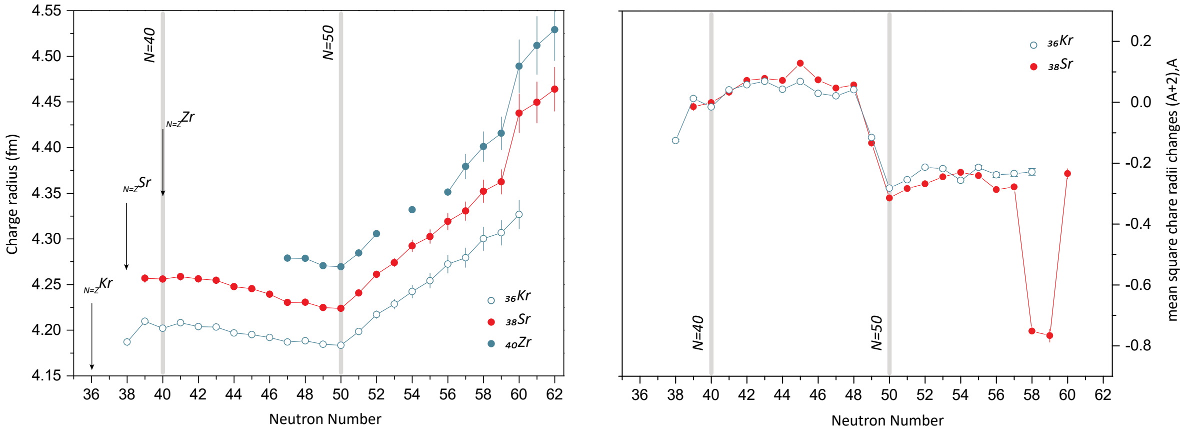

Figure 2: **a.** Changes in mean square charge radii for the Sr ($Z = 38$) [9] isotopes compared with the neighbouring Kr ($Z = 36$) [10] and Zr ($Z = 40$) [11] isotopic chains. The $N = Z$ nuclei in Kr, Sr and Zr are highlighted with black arrows. **b.** The differential change of the mean square charge radii in Kr and Sr. The subshell closure at $N = 40$ and the $N = 50$ shell closure are shown with vertical grey lines.

shown, together with the pathway of the rp-process. Previous laser spectroscopy measurements in the region are shown with small blue triangles. No measurements exist above the strontium chain due to the starting of the refractory island, and below, the isotopes are very poorly produced and not reachable with conventional laser spectroscopy techniques. Previous strontium measurements at COLLAPS yielded the nuclear information down to ^{77}Sr [5]. In this proposal, we aim to extend the laser spectroscopy measurements to ^{76}Sr placed at the border of the proton dripline. For this we will use the recently implemented radioactive detection of optically pumped ions after state selective charge exchange technique, later referred to as ROC.

2 Nuclear Physics Motivation

The region of the nuclear chart shown in Fig.1, equal proton and neutron number around the shell gaps at $Z, N = 36, 38$ and 40, is known to exhibit a coexistence of strong prolate and strong oblate deformations in connection with a rapid transition from spherical to deformed shapes [6-7]. The isotope of interest in this proposal (^{76}Sr) is expected to be the most deformed nucleus in the region according to beta-decay studies [8], this places it centre stage in the investigation of this behaviour.

In Fig.2a, the absolute charge radius of Kr ($Z = 36$) [10], Sr ($Z = 38$) [9] and Zr ($Z = 40$) [11] between $N = 38$ and $N = 62$ are shown. Several common features in the behaviour are observed in all set of data: a decreasing charge radius as the $N = 50$ shell gap is reached from the neutron deficient side and a characteristic kink at the magic number of 50 neutrons. A large kink is also observed in strontium and zirconium at $N = 60$ previously linked to a strong ground state deformation in ^{98}Sr and ^{100}Sr. β decay studies

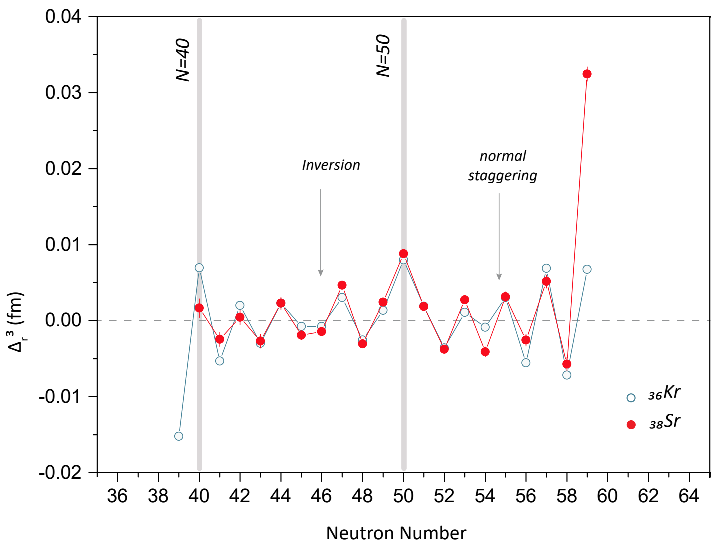

Figure 3: Odd-even staggering in the charge radius of Sr and Kr isotopes.

confirmed a smilar strong prolate deformation for ^{76}Sr. However, due to the lack of data around $N = 40$ in this region of Z, there is no indication of such an effect in the trend of the charge radius. Our measurement will add the missing experimental point at $N = 38$ in the strontium chain.

In order to reveal the finer details at $N = 40$, and a possible weak subshell gap, Fig.2b displays the mean square changes for isotopes that differ by two units on the mass scale. The advantage of such a differential plot (Brix-Kopfermann plot) is that the effect of the odd-even staggering is eliminated. The plot corroborates the distinct drop at $N = 50$ and shows a small drop at $N = 40$ in krypton. The hypothesis of a weak subshell closure, not seen in the lower mass chains (Cu, Zn, Ga, Ge) can not be confirmed in strontium as there is only one data point below $N = 40$ measured. Therefore, we propose to extend the strontium measurements using ROC at COLLAPS. Zirconium data in the vicinity of $N = 40$ is unavailable and, therefore, has been omitted from the graph.

The investigation of the anomalous odd-even staggering observed in this region is also of interest to this proposal. The staggering in the charge radius for strontium and krypton is displayed in Fig.3. In the figure, a normal staggering is observed for those isotopes above $N = 50$ but an inversion occurs at $N = 45$ in both isotopic chains. The inversion remains all the way to the more neutron-deficient side towards $N = 40$. While the trend of the staggering seems to remain the same for both isotopic chains, it becomes more pronounced in krypton towards the more neutron-deficient side. In contrast, shape staggering becomes less severe for Sr in the same (neutron deficient) region. The question of whether the staggering will completely disappear when crossing the $N = 40$ gap in

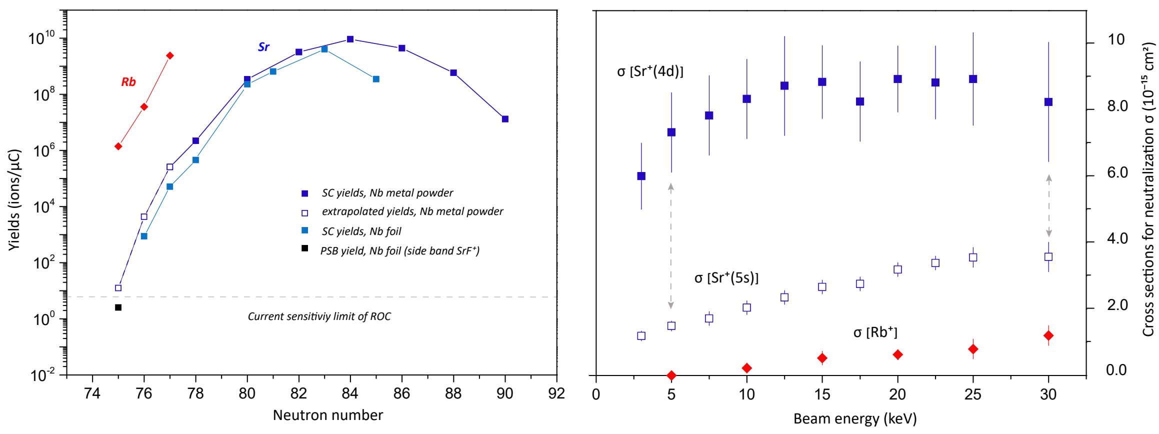

Figure 4: **a.** Strontium yields measured, at the SC and PSB, using Nb metal powder and Nb foil targets and a W ion surface ion source. Extrapolated yields are shown with empty blue squares. The expected Rb contamination is shown with red diamonds. **b.** Cross sections for neutralization of ground state and metastable state of Sr ions on Na as a function of the impact energy. The cross-section for the neutralization of Rb ions is shown with red diamonds.

strontium would be answered by our measurements. In addition, our results would help to benchmark nuclear theory, as the neutron – neutron (nn) and proton – proton (pp) pairing correlations, which are magnified in $N = Z$ nuclei, are expected to be crucial for explaining the OES in charge radii [12].

3 Experimental Method

Experimental technique: We propose to employ the ROC technique [13-16] to assess the nuclear properties of ^{76}Sr. A new setup for this method has been recently developed at COLLAPS and was successfully utilized in August 2023 to determine the electromagnetic moments of ^{53}Ca [17], produced at ISOLDE at rates of about 10 ions/s. ROC operates on the principle of state-selective particle detection, exploiting the fact that ions in different atomic states possess different cross-sections for charge-exchanging collision processes. Consequently, when an ion beam interacts with a laser and passes through a suitable vapour, the charge-state distribution of the resulting beam can undergo significant alterations. This occurs when, at resonance, ions are efficiently pumped into an atomic state whose collisional cross section diverges sufficiently from that of the ground state. Under such conditions, a resonant interaction between the particle and laser beams can be observed as a variation in the particle intensity within one of the charge-state channels.

Production: The beam will be produced by proton-induced spallation in a Nb metal powder (or foil) target at the GPS station. The measured yields [18], from the SC and the PSB using a tungsten surface ionization source, are plotted in Fig.4a. The yield of ^{76}Sr is a factor of 100 higher than the current sensitivity limit of ROC (rate of ions observed at the ROC detectors: 6 ions/s for ^{53}Ca, with hyperfine structure). Nevertheless, we expect an increase in the yields by using the Resonance IOnization Laser Ion Source. Ionization schemes for strontium have been developed and tested in Mainz and TRIUMF and are available on the RILIS website [19] (with the one recently developed at TRIUMF being expected to be the most efficient). We would like to include a test of the laser schemes using RILIS. Two shifts at the beginning of the experiment will be added to the request to test the ionization scheme .

Contamination After production, the ion beam will be mass separated and guided to the ROC experimental setup where strontium ions will be optically pumped from the $5s^2\,S_{1/2}$ ground state to the $4d^2\,D_{3/2}$ metastable state. Afterwards, they will be neutralized in a CEC with sodium. The isobaric ^{75,76}Rb contamination is expected to be about 10^4 times higher than the strontium beams [20]. This would render a straight forward particle detection scheme unfeasible, as the signal would be indistinguishable from statistical fluctuations of the background.
However, we expect to reduce the background to manageable levels through several measures: The neutralization cross section for rubidium drops to near zero at a beam energy of 5 kV (see Fig. 4b). Since this beam energy also offers a high cross section ratio between the $5s^2\,S_{1/2}$ ground state and the $4d^2\,D_{3/2}$ metastable state, this will reduce the rate of rubidium ions in the neutral detector by at least two orders of magnitude without sacrificing signal-to-noise ratio. Additionally, the strontium isotopes have shorter half-lifes than their rubidium isobars, so an appropriately chosen measurement interval suppresses the β-detection rate by another factor of four (^{76}Sr, interval 10 seconds) and 65 (^{75}Sr, interval 300 ms). Finally, since the ionization of the strontium isotopes will be provided by RILIS, a quartz line target can be used to suppress the rubidium contaminants an additional two orders of magnitude.
Combined, these measures should reduce the rate of rubidium isotopes in the neutral detector by four to five orders of magnitude. With these suppression factors, the detected rate of strontium β-events compared to the rubidium background would be about one-to-one. This is comparable with the recent measurements of neutron rich calcium, in which a rate of 58 events/s of ^{52}Ca was observed on top of a background of 69 events/s of (most likely) ^{52}K. Similarly, the hyperfine spectrum of ^{53}Ca was measured at a rate of 4.8 events/s with a background of 4.2 events/s.

Yield measurements and laser scheme tests: Considering the reported yields and the contaminants present in the beam, the isotope ^{76}Sr will be accessible with the ROC setup. However, if we consider the extrapolated yields, ^{75}Sr would be on the limit of feasibility. Since no yields from the PSB are available for the Sr element, we propose to incorporate yield measurements and the RILIS scheme before or after the experiment. These measurements would be done with the ISOLTRAP collaboration and would benefit of the measurement of the mass of ^{75}Sr of astrophysics importance.

Summary of requested shifts:
- 2 shifts for resonance ionization scheme developments using RILIS
- 2 shift for yield measurements using a Nb powder/foil target with the quartz line and

RILIS.
- 1 shift to investigate the beam composition using ISOLTRAP and the feasibility of ^{75}Sr.
- 1 shift for beam tuning and detector optimization
- 3 shifts to measure the charge radius of ^{76}Sr.

In summary, one experiment of 9 shifts of radioactive beam and 1 shift of stable beam are requested for the study of neutron-deficient strontium isotopes.

References

[1] van Wormer, L., Gorres, J., Iliadis, C., Wiescher, M. and Thielemann,F.-K. Reaction rates and reaction sequences in the rp-process. **Astrophys. J. 432, 326–350 (1994)**.

[2] Schatz, H. et al. rp-process nucleosynthesis at extreme temperature and density conditions. **Phys. Rep. 294, 167–263 (1998)**.

[3] Schatz, H. et al. End point of the rp process on accreting neutron stars. **Phys. Rev. Lett. 86, 3471–3474 (2001)**

[4] Zhou, X., Wang, M., Zhang, Y.H. et al. Mass measurements show slowdown of rapid proton capture process at waiting-point nucleus ^{64}Ge. **Nat. Phys. 19, 1091–1097 (2023)** .

[5] P. Lievens et al. Spin, moments, and mean square nuclear charge radius of Sr. **Phys. Rev. C 42, 2 (1992).**

[6] K. W. Schmid, A. Faessler, J. H. Hamilton and A. V. Ramayya. Shape Coexistence Phenomena in Medium Mass Nuclei. **Prog. Part. Nucl. Phys.43 (1999) 485-535.**

[7] C. J. Lister et al. Shape changes in N Z nuclei from germanium to zirconium. **Phys. Rev. C 42, 4, 1990.**

[8] E. Nacher, et al. Deformation of the $N = Z$ Nucleus ^{76}Sr using β-Decay Studies. **Phys. Rev. Lett. 92, 23, 2004.**

[9] F. Buchinger et al. Systematics of nuclear ground state properties in $^{78-100}$Sr by laser spectroscopy. **Phys. Rev. C. 41, 6 (1990)**.

[10] F. Buchinger et al. Laser-spectroscopy measurements of $^{72-96}$Kr, spins, moments and charge radii. **Nucl. Phys. A 586 (1995) 219-239.**

[11] https://www-nds.iaea.org/nuclearmoments/.

[12] Chong Qi and Ramon Wyss. $NN = Z$ nuclei: a laboratory for neutron–proton collective mode. **Phys. Scr. 91 (2016) 013009**.

[13] P. Lievens et al. Very high sensitivity in collinear laser spectroscopy : resonance detection by particle counting techniques. **Nucl. Instrum. Methods Phys. Res. B70 (1992) 532-536.**

[14] L. Vermeeren, P. Lievens and R.E. Silverans. Sensitive laser spectroscopy of ions with hyperfina structure. **Hyperfine Interact. 61 (1990) 1391402 1399**.

[15] L. Vermeeren et al. Ultrasensitive Radioactive Detection of Collinear-Laser Optical Pumping: Measurement of the Nuclear Charge Radius of Ca. **Phys. Rev. Lett. 68, 11 (1992)**.

[16] R F Garcia Ruiz et al. Development of a sensitive setup for laser spectroscopy. **J. Phys. G: Nucl. Part. Phys. 44 044003 (2017)**.

[17] T. E. Lellinger. PhD thesis. In writing.

[18] https://isoyields2.web.cern.ch/YieldBasic.aspx?Z=38

[19] https://riliselements.web.cern.ch/index.php?element=Sr

[20] https://isoyields2.web.cern.ch/YieldBasic.aspx?Z=37

4 Details for the Technical Advisory Committee

4.1 General information

Describe the setup which will be used for the measurement. If necessary, copy the list for each setup used.

- ☒ Permanent ISOLDE setup: *COLLAPS/ROC*
  - ☒ To be used without any modification
  - ☐ To be modified: *Short description of required modifications.*
- ☐ Travelling setup (*Contact the ISOLDE physics coordinator with details.*)
  - ☐ Existing setup, used previously at ISOLDE: *Specify name and IS-number(s)*
  - ☐ Existing setup, not yet used at ISOLDE: *Short description*
  - ☐ New setup: *Short description*

4.2 Beam production

- Requested beams:

Isotope	Production yield in focal point of the separator (/μC)	Minimum required rate at experiment (pps)	$t_{1/2}$
^{76}Sr	870 ions/μ C	1 ion/μ C	8.79 s

- Yield of ^{76}Sr was taken from the ISOLDE yield database and yield of ^{75}Sr has been extrapolated.
- Target - ion source combination: Nb metal powder or Nb foil.
- RILIS?: Yes
  - ☐ Special requirements: (*isomer selectivity, LIST, PI-LIST, laser scanning, laser shutter access, etc.*)
- Additional features?
  - ☐ Neutron converter: (*for isotopes 1, 2 but not for isotope 3.*)
  - ☒ Other: *quartz transfer line.*
- Expected contaminants: ^{76}Rb: 10^7 ions/μC, ^{75}Rb: 10^6 ions/μC,
- Acceptable level of contaminants: factor of 10^5 with respect to beam of interest.
- Can the experiment accept molecular beams?
- Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of?

4.3 Shift breakdown

The beam request only includes the shifts requiring radioactive beam, but, for practical purposes, an overview of all the shifts is requested here. Don't forget to include:

- Isotopes/isomers for which the yield need to be determined
- Shifts requiring stable beam (indicate which isotopes, if important) for setup, calibration, etc. Also include if stable beam from the REX-EBIS is required.

An example can be found below, please adapt to your needs. Copy the table if the beam time request is split over several runs.

Summary of requested shifts:

With protons	Requested shifts
Optimization of RILIS laser scheme	2 shifts
Yield measurements	2 shifts
Beam composition investigation using ISOLTRAP	1 shift
ROC CEC heating, neutralization testing, and detector optimization	1 shift
Data taking, ^{76}Sr	2 shifts
Time for CEC heating and neutralization testing	1 shift
Without protons	Requested shifts
Stable Na/Rb beams for tunning	1 shift

4.4 Health, Safety and Environmental aspects

4.4.1 Radiation Protection

- If radioactive sources are required:
  - Purpose?
  - Isotopic composition?
  - Activity?
  - Sealed/unsealed?
- For collections:
  - Number of samples?
  - Activity/atoms implanted per sample?
  - Post-collection activities? (*handling, measurements, shipping, etc.*)

4.4.2 Only for traveling setups

- Design and manufacturing

  ☒ Consists of standard equipment supplied by a manufacturer

  ☐ CERN/collaboration responsible for the design and/or manufacturing

- Describe the hazards generated by the experiment:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]

Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			