EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Exploring shape coexistence across N=60 in $^{100}\mathrm{Sr}_{62}$ using IDS

January 5, 2022

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Abstract: This proposal aims to locate excited 0^+ state(s) in $^{100}\mathrm{Sr}_{62}$ in order to unravel the nuclear structure responsible for the sudden change in deformation characteristic of the region. The excited states of Sr isotopes will be populated via β and β-n decay using $^{100,101}\mathrm{Rb}$ beams at the ISOLDE Decay Station (IDS). The 0^+ state(s) will be firmly identified using $\gamma-\gamma$ angular correlations and by directly observing E0 transitions using the SPectrometer for Electron DEtection (SPEDE) ancillary detector. Secondary goals include measuring the P_n / P_{2n} values and nuclear level lifetimes by using fast-timing $\mathrm{LaBr}_3(\mathrm{Ce})$ detectors. The proposed experimental data will provide critical information about the shape co-existence beyond $N=60$ in Sr isotope.

Requested shifts: [11] shifts, (split into [1] runs over [1] years)
Installations: IDS with 5 clovers and SPEDE

1 Scientific value

The interaction between nucleons in an effective mean field can cause a sudden change in nuclear structure just by adding a few extra particles, either leading to a shell closure or a rapid onset of deformation. A well-known example of such an effect is the dramatic ground-state shape transition that has been observed in Sr and Zr isotopes when crossing $N \sim 60$. Figure 1 (taken from Ref. [1]) shows a comparison of the measured isotope shift from Kr ($Z = 36$) to Mo ($Z = 42$) isotopes. From Fig. 1 it is clear that in the case of Sr ($Z = 38$), Y ($Z = 39$) and Zr ($Z = 40$), the maximum change in charge radii is attained at $N = 60$, which has been interpreted as a shape transition. Further evidence of this effect includes the sudden drop in the excitation energy of the 2_1^+ state and the increase in $B(E2 : 2_1^+ \rightarrow 0_1^+)$ values (as can be seen, for example, in Fig. 2 of Ref. [2]) and the lowering of the excited 0^+ deformed bandhead (see Fig. 2 for the Sr isotopic chain). The spherical (*noral*) and prolate (*intruder*) configurations invert when going from $N = 58$ to $N = 60$, similarly to the so-called "islands of inversion" [3, 4]. Reduced transition probabilities and the spectroscopic quadrupole moments, which have been extracted from Coulomb excitation experiments, indicate the coexistence of highly deformed prolate and spherical configurations in ^{96,98}Sr nuclei [5]. Figure 3, taken from Ref. [2], shows the deformation energy surfaces of Sr and Zr isotopes from $N = 58$ to $N = 62$ in the β-γ plane from constrained mean-field calculations using the SLy4 force. These calculations also predict that there is always a weakly deformed oblate minimum coexisting with a prolate minimum. The details of the calculations can be found in Ref. [2].

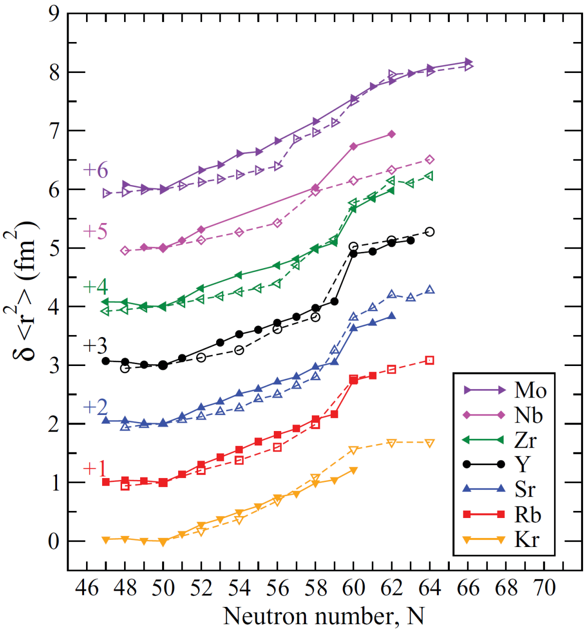

Figure 1: Comparison of the measured isotope shifts ($\delta < r_c^2 >$) from Kr to Mo isotopes and Gogny-D1S-HFB results. Solid symbols correspond to experimental data, while open symbols correspond to calculated values. Figure was taken from Ref. [1].

While the inversion of the spherical and deformed shapes is well documented, our knowledge of the *intruder* structure is limited to the $N = 60$ isobars, with scarce information for any of the heavier isotopes above it. The goal of this proposal is to search for excited 0^+ state(s) in ^{100}Sr ($N = 62$) populated in the β and β-n decays of ^{100}Rb and ^{101}Rb, respectively. The experiment will run at at the IDS experimental setup and will focus on the $0_i^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ angular correlations and a direct observation of the $0_i^+ \rightarrow 0_1^+$ E0 transitions.

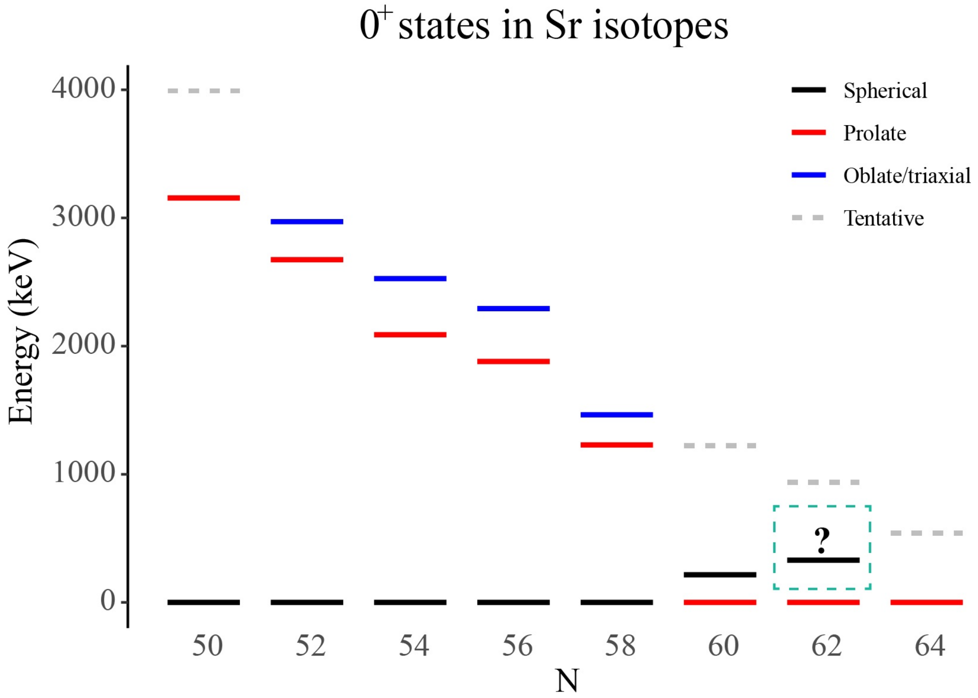

Figure 2: Experimental energy systematics of the 0^+ states in even-mass Sr isotopes. Levels in black are spherical, red are prolate and blue have oblate/triaxial deformation. The dashed levels are tentative and it is unclear to which band they belong, although the energy trend seems to suggest they belong to the oblate/triaxial one. The level at 300 keV in ^{100}Sr (N=62) marked with a question mark has not been observed, but it is predicted by theoretical calculations, see text for details. All data are from ENSDF [6].

2 Previous work

The nuclear structure of ^{100}Sr has been previously studied via β-decay of neutron-rich ^{100}Rb at ISOLDE [7]. The setup consisted of a planar and a coaxial Ge detectors of 27% relative efficiency, but no conversion electron detectors were employed [7]. The 938-keV level was tentatively assigned as an excited (0^+) state based on the systematic of neighboring $N = 62$ isotones and the lack of a γ transition to the 0^+ g.s. (see Figs. 2 and 4). However, no firm conclusions can be drawn about the nature of this state based on their experimental results [7]. The ground state spin-parity of ^{100}Rb is (4^-), making feeding of 0^+ states highly unlikely. However, the presence of a 1^- beta-decaying state has

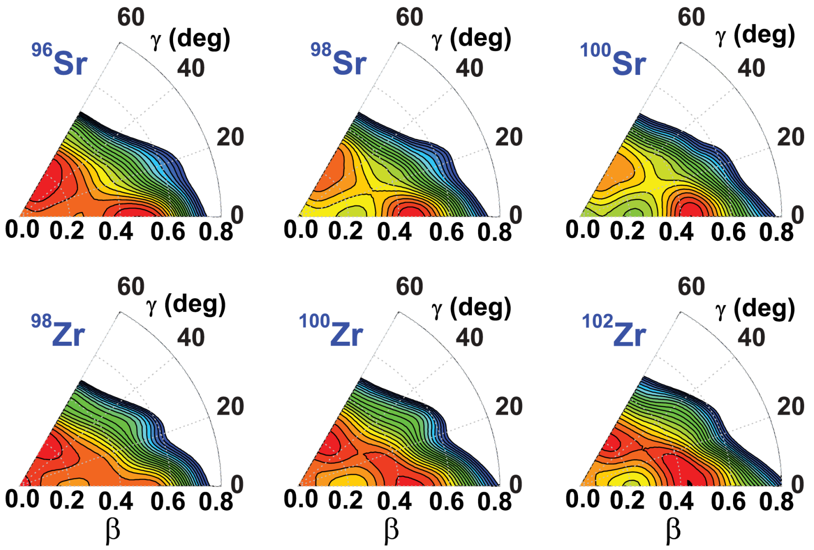

Figure 3: Total energy surfaces of the Sr and Zr isotopes in the β-γ plane from constrained SHF + BCS calculations using SLy4 force for the ph channel and density-dependent δ force for the pp channel. All the energies are normalized to the absolute minima and each contour line is separated by 0.5 MeV. This Figure was taken from [2].

been hypothesized in ^{100}Rb. This isomer could populate the 2^+ and excited 0^+ (938 keV) states via first-forbidden transitions [7]. On this regard, it should be noted that the masses of neutron-rich Rb isotopes were recently measured by ISOLTRAP [8] and TITAN [9, 10], which found an 80 keV isomer in ^{98}Rb, but no sign of one in ^{100}Rb.

It is worth mentioning that NNDC notes: *"The decay scheme is not normalized as it is considered incomplete in several ways."* [6]. It is thus, clear, that a higher statistics and more detailed study is necessary to unravel the underlying structure of ^{100}Sr to better understand the shape inversion across $N = 60$.

On the theoretical side, Mei *et al.* [2] predicted a first excited 0^+ at 907 keV using the Sly4 force, very close to the tentative 938-keV state observed experimentally (see Fig. 3). On the other hand, when employing a five-dimensional collective Hamiltonian (5DCH) and the PC-PK1 force, they obtained the first excited 0^+ at only $\sim$ 300 keV. No candidate currently exists for a 0^+ state near that energy. However, Fig. 2 shows that there are two low-lying excited 0^+ states in each Sr isotope firmly identified up to $N = 58$ and tentatively assigned for $N = 60$. Following the systematics, another 0^+ state can be expected at low energy for ^{100}Sr, probably around 300 keV. A likely explanation is that it would correspond to the spherical *normal* configuration that now lies above the prolate one.

3 Goals of the experiment

The main goal of the experiment is to locate excited 0^+ states in ^{100}Sr, a key ingredient to understand shape coexistence in the region. While this was done tentatively from γ feeding considerations, we plan to perform $\gamma - \gamma$ angular correlations and to use SPEDE to

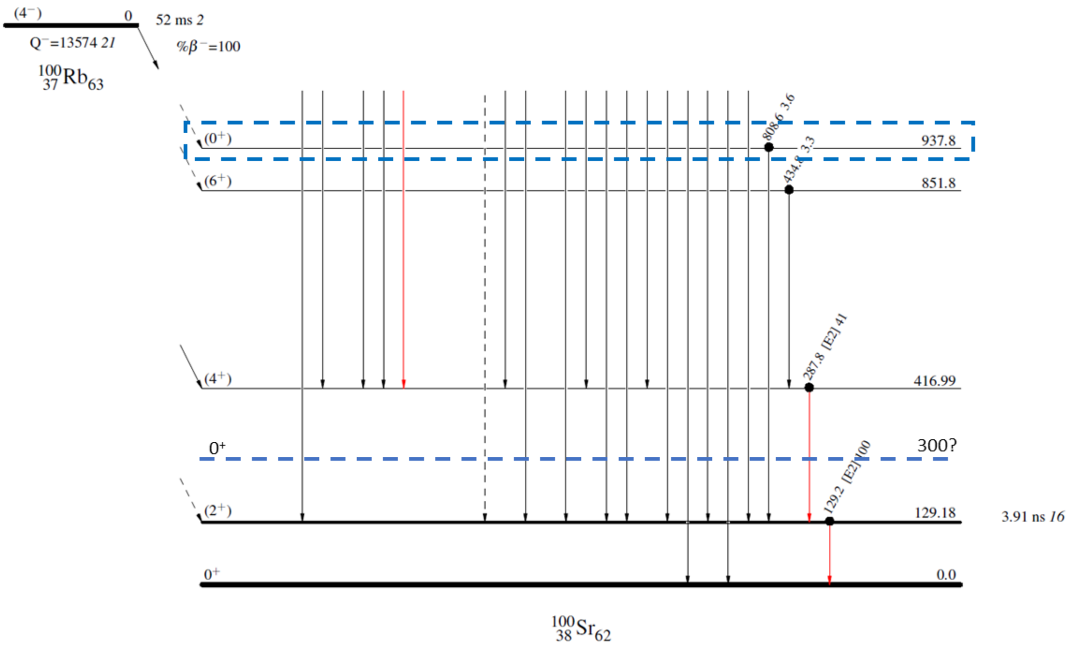

Figure 4: Partial level scheme of ^{100}Sr populated in the ^{100}Br β^- decay. In dashed blue lines, the tentative and calculated 0^+ levels, and the red lines indicate the most intense γ-ray transitions. Figure adapted from ENSDF [6].

directly observe E0 transitions between the 0^+ states and firmly establish their spin/parity.

Additionally, thanks to the versatility of IDS, several secondary observables can be measured simultaneously:

- **Expand level scheme:** The vastly superior efficiency of IDS with respect to that of the setup used in Ref. [7] ensures that many more orders of magnitude in statistics will be collected in a reasonable time. This is especially true for $\gamma-\gamma$ coincidences, the foundation on which level schemes are built. In the past experiment, only two Ge detectors were employed, while IDS uses several HPGe clovers. This greatly increases the number of crystal pairs that can detect $\gamma-\gamma$ coincidences.

- **Neutron emission:** The $1n$ and $2n$ emission channels are open for ^{100,101}Rb. The $\beta-n$ decay has been observed for both isotopes, but, so far, the $\beta-2n$ could only be measured once for ^{100}Rb. Moreover, the existing measurements suffer from large discrepancies (P_n ranging $5-35\%$ ^{100}Rb) [6].

- **The 1^- isomer in ^{100}Rb:** This experiment is specially well suited to disentangle the possible 1^- isomer/(4^-) g.s. ^{100}Rb decay. With the high statistics that will be collected, it will be possible to observe (or reject) the direct population of low-spin levels in ^{100}Sr. If populated, by gating on transitions decaying from such levels, we will be able to measure the 1^- isomer lifetime and separate it from the g.s. one.

- **Study of ^{101}Sr:** Although the main goal of the ^{101}Br beam is to measure states in

^{100}Sr, it will obviously yield abundant information on ^{101}Sr. This poorly understood nuclei can provide important information on single particle states in the region.

- **Fast timing:** By leveraging the fast component of the LaBr$_3$(Ce) scintillators signals, lifetimes down to 10's of ps can be measured. For ^{100}Sr, only the lifetimes of the 2_1^+ and 4_1^- states have been measured, each of them twice. However, there is a discrepancy of 5σ for the $\tau(2_1^+)$ (see Refs. [11, 12]) and of 3σ for $\tau(4_1^-)$ (Refs. [13, 14]). Since both lifetimes are in the nanosecond range, they are perfectly suited to be measured at IDS. Moreover, thanks to the γ-decay pattern, the 4_1^+ is strongly populated from the 4_1^- level (see Fig. 4). It is, thus, feasible to measure $\tau(4_1^+)$, which can be expected to be above 100 ps. The ratio $B(E2)_{4^+\to 2^+}/B(E2)_{2^+\to 0^+}$ is a key ingredient when trying to differentiate between vibrational and rotational bands. For the case of ^{101}Sr, 4 lifetimes of low-lying states have been measured with $T_{1/2} \sim 1$ ns, with large uncertainties, close to or even larger than 100%. All these lifetimes can easily be measured again to a much improved precision.

4 Proposed experiment at ISOLDE

The aim of the proposed experiment is to investigate shape co-existence in ^{100}Sr via ^{100,101}Rb β and β-n decay. Five IDS clovers will be arranged in order to maximize the number of different angles, as was successfully done in Ref. [15]. The ^{100,101}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. The LaBr$_3$(Ce) scintillators will be placed outside the implantation chamber, at a further distance, since measuring half-lives is a secondary goal of this experiment.

The search for 0^+ states in ^{100}Sr will be attempted with two different complementary approaches:

- **^{100}Rb decay:** This beam will use the same production method employed in Ref. [7], and thus we can expect similar relative intensities even if there were a low-spin isomer present. We will perform angular correlations to firmly establish the spin-parity state of the 938 keV state using the $(0_i^+) \to 2_1^+ \to 0_1^+$ cascade (see Fig. 4). This will unequivocally confirm or reject the 0^+ character of the state. The now much higher statistics will also help to disentangle g.s. and isomeric decays by their half-life.

- **^{101}Rb decay:** The βn decay of ^{101}Rb offers a much more likely opportunity to directly populate excited 0^+ states, owing to its $(3/2^+)$ g.s. and the fact that both the β^- and the neutron will carry angular momentum away, making it more likely to populate low-J states. Indeed, the βn decay of ^{97,99}Rb both significantly populate the 0_2^+ states in ^{96,98}Sr [6]. The larger $P_n = 28\%$ of ^{101}Rb should enhance the population of this level. We will use SPEDE to directly observe the E0 transition of the predicted 0_2^+ at ~ 300 keV. GEANT4 simulations carried out by the collaboration at U. of York, shows the ability of SPEDE to easily differentiate conversion electrons with absolute branching ratios of $\leq 1\%$ well over the β^- background [16].

5 Beamtime estimation

Neutron-rich Rb beams were measured in ISOLTRAP using an UC_X target with no RILIS, obtaining intensities of 1000 pps for A=100 and 40 pps for A=101 [17]. The only contaminants were isobaric Sr, with a factor ~ 2 higher yield. In both cases, the lifetimes of the Rb nuclei are 4 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.

In order to estimate the ^{100}Rb beamtime needed, we turn to the main goal for this beam: performing angular correlations in the $0^+_i \rightarrow 2^+_1 \rightarrow 0^+_1$ ($808 \rightarrow 129 \rightarrow 0$, see Fig. 4) cascade. The IDS configuration optimized for angular correlations has a total of 320 crystal pairs and an efficiency of 11% at 100 keV and 4% for 1 MeV [15]. Looking at Table I from Ref. [15], we can see that some of the angular bins were matched by only one of the crystal pairs. With 100 counts we can obtain a 10% statistical error, enough to differentiate a $0 \rightarrow 2 \rightarrow 0$ cascade, one of the most anisotropic of all angular distributions. We need a total of 32000 counts which, with the beam intensity and detection efficiency described before, would be obtained in 6 shifts.

While the βn decay of ^{101}Rb has been observed in a number of experiments, none of them measured the γ rays following it. Thus, to estimate the required beamtime for this mass, we will assume it is similar to that of $^{99}\text{Rb} \rightarrow ^{98}$ Sr + n. In this decay, the 0^+_2 is populated by a 1080 keV transition with a 20% absolute branching ratio [6]. The $0^+_2 \rightarrow 0^+_1$ E0 transition then has a $\sim 15\%$ relative branching. Additionally, it is desirable to tag on the plastic scintillator to greatly suppress the β^- background in SPEDE. Assuming a 4% efficiency for the first γ, 5% for the E0 and 30% for the β detector, with the 40 pps mentioned above, we estimate 20 counts per shift. In 5 shifts we would obtain 100 counts in very low-background conditions, enough to firmly establish an E0 transition.

We ask for a total of 11 shifts.

Note : A Letter of Intent (LOI) by K. Wimmer *et al.* [18] was endorsed by the INTC in the last meeting, (September 2021). That LoI aims to study shape co-existence along the neutron-rich Sr isotopic chain using Coulex with MiniBall and two nucleon transfer reactions with ISS, a perfect complementary study to this one. This shows the general interest to understand the nuclear structure in the region and the ability of ISOLDE to run complementary experiments that synergize each other.

Note 2: A study was just published this week studying shape coexistance in $^{90-96}$Sr isotopes [19]. That work highlighted the importance of $2^+_i \rightarrow 0^+_i$ transitions to explain the different shapes in a nucleus. It is also yet another example of the attention this region is currently attracting.

References

[1] R. Rodriguez-Guzman, P. Sarriguren, and L. M. Robledo. Shape evolution in yttrium and niobium neutron-rich isotopes. *Phys. Rev. C*, 83:044307, Apr 2011.

[2] H. Mei et al. *Phys. Rev. C*, 85:034321, 2012.

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

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

[5] E. Clément et al. *Phys. Rev. Lett.*, 116:022701, 2016.

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

[7] G. Lhersonneau, B. Pfeiffer, H. Gabelmann, and K.-L. Kratz. Identical transitions in the strongly deformed ^{99}Sr and ^{100}Sr. *Phys. Rev. C*, 63:054302, Apr 2001.

[8] A. de Roubin, D. Atanasov, K. Blaum, S. George, F. Herfurth, D. Kisler, M. Kowalska, S. Kreim, D. Lunney, V. Manea, E. Minaya Ramirez, M. Mougeot, D. Neidherr, M. Rosenbusch, L. Schweikhard, A. Welker, F. Wienholtz, R. N. Wolf, and K. Zuber. Nuclear deformation in the $a \approx 100$ region: Comparison between new masses and mean-field predictions. *Phys. Rev. C*, 96:014310, Jul 2017.

[9] R. Klawitter, A. Bader, M. Brodeur, U. Chowdhury, A. Chaudhuri, J. Fallis, A. T. Gallant, A. Grossheim, A. A. Kwiatkowski, D. Lascar, K. G. Leach, A. Lennarz, T. D. Macdonald, J. Pearkes, S. Seeraji, M. C. Simon, V. V. Simon, B. E. Schultz, and J. Dilling. Mass measurements of neutron-rich rb and sr isotopes. *Phys. Rev. C*, 93:045807, Apr 2016.

[10] I. Mukul, C. Andreoiu, J. Bergmann, M. Brodeur, T. Brunner, K. A. Dietrich, T. Dickel, I. Dillmann, E. Dunling, D. Fusco, G. Gwinner, C. Izzo, A. Jacobs, B. Kootte, Y. Lan, E. Leistenschneider, E. M. Lykiardopoulou, S. F. Paul, M. P. Reiter, J. L. Tracy, J. Dilling, and A. A. Kwiatkowski. Examining the nuclear mass surface of rb and sr isotopes in the $a \approx 104$ region via precision mass measurements. *Phys. Rev. C*, 103:044320, Apr 2021.

[11] R.E. Azuma, G.L. Borchert, L.C. Carraz, P.G. Hansen, B. Jonson, S. Mattsson, O.B. Nielsen, G. Nyman, I. Ragnarsson, and H.L. Ravn. The strongly deformed nucleus 100sr. *Physics Letters B*, 86(1):5–8, 1979.

[12] G. Lhersonneau, H. Gabelmann, N. Kaffrell, K. L. Kratz, B. Pfeiffer, K. Heyde, and ISOLDE Collaboration. K-isomeric state in even-even ^{100}Sr. *Z. Phys. A*, 337:143, 1990.

[13] B. Pfeiffer, G. Lhersonneau, H. Gabelmann, K. L. Kratz, and The ISOLDE Collaboration. K-isomeric state in even-even ^{100}Sr. *Z. Phys. A*, 353:1, 1995.

[14] D. Kameda and T. *et al.* Kubo. Observation of new microsecond isomers among fission products from in-flight fission of 345 mev/nucleon ^{238}u. *Phys. Rev. C*, 86:054319, Nov 2012.

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

[16] J. Cubiss. Spede simulations. *Private communication*, 2021.

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

[18] K. Wimmer, S. S. Bhattacharjee, et al. *INTC-I-237*, 2021.

[19] W. Urban, K. Sieja, T. Rzaca-Urban, J. Wiśniewski, A. Blanc, M. Jentschel, P. Mutti, U. Köster, T. Soldner, G. de France, G. S. Simpson, C. A. Ur, A. G. Smith, and J. P. Greene. Structure of even-even sr isotopes with $50 \leq n \leq 58$ neutrons. *Phys. Rev. C*, 104:064309, Dec 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]