EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Spectroscopic factors in the r-process nucleus ^{135}Sn

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Abstract: We propose to study states in the isotope ^{135}Sn populated by a ^{134}Sn(d,p) one-neutron transfer reaction at 7.5 MeV/u in inverse kinematics. Outgoing protons will be measured by the ISS. We aim for identification and spin-parity assignments for excited states and to determine spectroscopic factors. This data will allow for a stringent test of predictions by state-of-the-art shell model calculations in this region.

Requested shifts: [24] shifts, (split into [1] runs over [1] years)
Installation: [ISS]

1 Physics case

The understanding of doubly-magic shell closures is the benchmark for any nuclear theory. On the neutron-rich side of the nuclear chart, the region around ^{132}Sn is the focus of many efforts in both experimental and theoretical nuclear physics. Additional interest comes from nuclear astrophysics as the r-process[1] approaches ^{132}Sn from the neutron-rich $N = 82$ waiting point nuclei, and then proceeds along the $Z = 50$ isotopic chain towards more neutron-rich nuclei. Masses, β half-lifes and (n,γ) cross sections, all directly linked to the nuclear structure of the involved isotopes, are crucial inputs for the description of the $A \approx 130$ peak in the solar element abundances [1, 2]. Extrapolation towards heavier Sn isotopes therefore requires a strong anchor point at the doubly-magic ^{132}Sn. Spectroscopy and neutron spectroscopic factors for ^{135}Sn will serve as a benchmark for nuclear theory and also give important information on the direct neutron capture process. (d,p) can serve as a surrogate reaction for (n,γ) which experimentally cannot be measured for short-lived isotopes [1].
Our programme to investigate the nuclear structure in this region at HIE-ISOLDE is sketched in our LoI which has been endorsed by the INTC in 2010 [4], although restricted at this time to the only available set-up suited for such studies, Miniball + T-REX.
Single-particle properties are investigated most directly by nucleon transfer reactions, e.g (d,p) or (t,p). Main observables are the differential cross sections as well as the energies of the outgoing protons which allow for the determination of excitation energies, transferred orbital angular momenta, $\Delta\ell$, and spectroscopic factors. For heavy beams around ^{132}Sn well-pronounced angular distributions require beam energies available at HIE-ISOLDE which was designed to meet these conditions.
Transfer reactions in this region have been pioneered at Oak Ridge National Laboratory some years ago [5]. ^{132}Sn(d,p) has been investigated at a beam energy of 4.77 MeV/u. A new measurement of this reaction has been proposed for ISS recently [6]. The ground state and three excited states at 854 keV, 1363 keV, and 2005 keV were populated. The energy resolution was just sufficient to resolve these states. Although the angular distributions of the emitted protons were rather smooth at this beam energy, for the two lowest states an assignment of $\Delta\ell = 1$ or 3 was possible. Guided by shell model predictions spin-parity assignments of $7/2^-$ and $3/2^-$ for the ground state and the first excited state could be concluded. The tentative $(1/2^-)$ and $(5/2^-)$ assigments for the other two excited states as the respective spin-orbit partners are reasonable, but experimentally not confirmed. The $(9/2^-)$ candidate at 1561 keV was not populated (or only weakly populated and therefore not resolved within the given energy resolution). Theory expects also two further states with $11/2^-$ and $13/2^+$. The $11/2^-$ state was found at 3570 keV recently populated in one-neutron knockout from ^{134}Sn and turned out to be neutron-unbound ($S_n = 2402$ keV) [7]. Nevertheless, a γ-branch to the ground state was observed. Being a hole-state in the $N = 82$ neutron core, it is not populated in one-neutron transfer anyway.
Excited states in ^{133}Sn have been also observed with γ-rays following a ^{132}Sn(^{9}Be, ^{8}Be) one-neutron transfer reaction [8]. In heavy-ion sub-barrier transfer only a selectivity of the *total* cross section on $j = l + s$ or $j = l - s$ exists [9], but *differential* cross sections are not

[1] In 2017, for the first time observations confirmed a binary neutron star merger as an astrophysical site of the r-process with the light curves as indicator for the composition of isotopes produced and their decay [3].

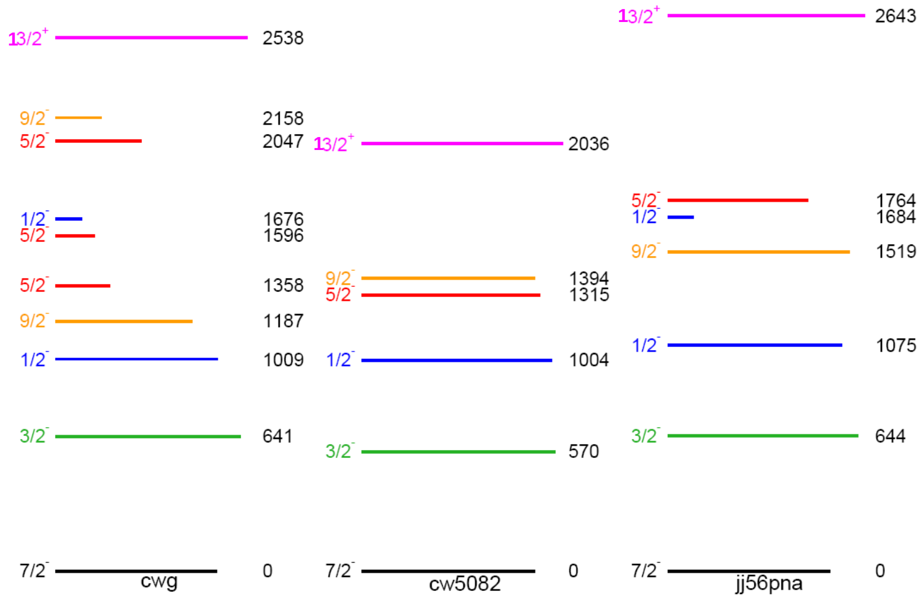

Figure 1: *Shell model predictions for ^{135}Sn with three different interactions (see text). The length of the coloured bars for each level corresponds to the spectroscopic factor.*

sensitive on $\Delta\ell$. Due to the more complicated wave function, in particular the α cluster structure of C (and Be, see below), the extracted (relative) spectroscopic factors may be affected. In addition to the states populated in (d,p), with much smaller intensities γ-rays depopulating the $(9/2^-)$ state as well as a few counts which may indicate the "missing" $13/2^+$ state to be at 2792 keV were observed. These complete the expected level scheme. The region north-east of ^{132}Sn has been studied at Oak Ridge as well by (^{9}Be, ^{8}Be) and (^{13}C,^{12}C) reactions on the more abundant beams of ^{134}Te and (stable) ^{136}Xe at 4.2 MeV/u and 4.1 MeV/u, respectively [9]. The higher statistics allowed not only for particle-γ-γ coincidences but also for particle-γ angular correlations giving further confidence in the spin-parity assignments. Noteworthy, the properties of the three excited states populated in ^{137}Xe only partially agree with states among the 18 excited states from ^{136}Xe(d,p) in inverse kinematics at 10 MeV/u performed at Argonne National Laboratory with HELIOS, a set-up similar to ISS [10].

In conclusion, nucleon transfer reactions in inverse kinematics, in particular (d,p), are a valuable tool to populate states in exotic nuclei in this region which offer access to the single-particle properties of the states[2].

Fig. 1 shows the shell model predictions obtained with three different interactions concerning the neutron sector [11, 12, 13] which are used in this region of the nuclear chart[3]. For clarity, only states with a spectroscopic factor larger than 0.1 are plotted. The excitation energies of the first two excited states do not differ much, whereas for the next states, i.e. the $5/2^-$ and the $9/2^-$, even the ordering is predicted differently. Only one of the interactions predicts the $13/2^+$ state to be bound ($S_n(^{135}\text{Sn}) = 2271$ keV). Mostly, the spectroscopic factors are well above 0.5 indicating that a strong population of these states can be expected. The fragmentation of the $f_{5/2}$ strength predicted by one of the calculations is a noteable exception.

[2] For completeness: spectroscopic information for even Sn isotopes beyond ^{132}Sn is known from Coulomb excitation of ^{134}Sn [22] and decay spectroscopy [23, 28, 33].

[3] Other calculations with similar predictions can be found in Refs. [26, 14].

It is worth to mention that a very new calculation predicts a significant reduction of spectroscopic factors from ^{133}Sn to ^{135}Sn, see Fig. 2 [15]. This is for the $3/2^-$ level not in agreement with all three interactions in Fig. 1 and for the $5/2^-$ level only in agreement with one of the three interactions in Fig. 1. The spectroscopic factor for the ground state is predicted with similarly large value as by the calculations in Fig. 1.

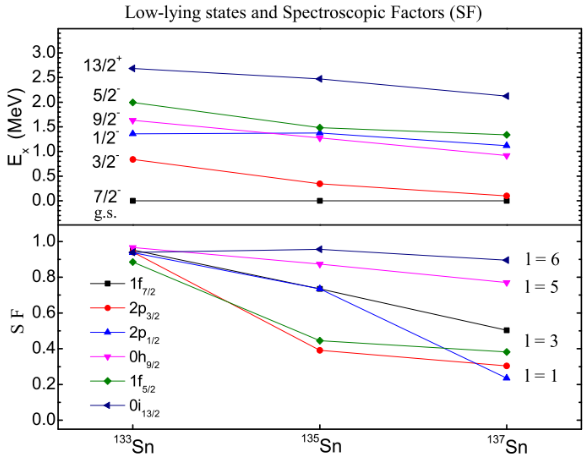

Figure 2: *Excitation energies of low-lying states (top) and spectroscopic factors (bottom) for ^{133,135,137}Sn from Ref. [15].*

Various approaches have been used to generate shell-model interactions capable of prediciting the behavior of neutron-rich nuclei beyond $N = 82$. Calculations with empirical interactions even predict a new shell closure at $N = 90$ when the $\nu f_{7/2}$ orbital is filled, e.g. Ref. [25]. Such an effect is not found in calculations with realistic interactions based on nucleon-nucleon potentials, e.g. Refs. [26, 24]. Including three-body forces, the new shell closure occurs with realistic interactions too [27].

Shell model calculations need, apart from a set of interaction matrix elements, also spectroscopic information from the nuclei neighbouring the doubly-magic cores. E.g. the region north-east of ^{132}Sn requires the single-particle energies of states in ^{133}Sn and ^{133}Sb as input. The validity of the calculations can be tested only with nuclei further away from the core and therefore, keeping the magic closure at $Z = 50$, the spectroscopy of ^{135}Sn is the straightforward challenge for the predictive power towards neutron-rich isotopes.

The structure of the Sn isotopes is particularly important to test the neutron-neutron part of shell-model interactions as proton-proton and proton-neutron terms do not contribute at low energies and, therefore, low-lying states have a pure neutronic character. The results of the proposed experiment will aid the understanding of the evolution of neutron-neutron two-body matrix elements in nuclei with large neutron excesses.

The physics case of the proposed measurement has already been presented and experiment IS654 with the γ-ray spectrometer Miniball and the particle detector T-REX has been approved by the INTC already in 2018 [30]. At REX-ISOLDE several transfer reactions have been studied in the past showing the power of the method, e.g. [16, 17, 18, 19, 20, 21]. However, experiment IS654 performed before LS2 in 2018 failed because the beam could not be delivered (status report to the INTC [31]). Meanwhile after LS2 in 2023, two very successful experiments with ^{130,132}Sn beams, IS595[4] and IS702, were performed. Therefore, the problems with Sn beams in 2018 can be considered to be solved by the ISOLDE target group. In 2022/23 Miniball was refurbished and upgraded, e.g with a new DAQ. T-REX is not compatible with this new DAQ. It was decided to go for a new T-REX, HI-TREX [32], which also addresses the limitations of T-REX like moderate energy resolution due to high noise and high sensitivity to δ electrons. It is planned that HI-TREX will be ready for commissioning in 2024 and after coupling to the Miniball DAQ for experiments

[4]Also IS595 was scheduled in 2018 and then had to be cancelled because of the problems to deliver Sn beams.

with Miniball in 2025 before LS3.
In 2018, no information on excited states in ^{135}Sn was available. Meanwhile, a decay experiment at IDS reported on two γ-rays attributed to states at 950 keV and 1221 keV with only a range $9/2^- - 11/2^-$ of tentative spin-parity assigments [33]. Hence, these are no candidates for members of the low-spin part of the level scheme shown in Fig. 1.
The game changer which motivated us to propose this measurement now also for ISS was that recently the excitation energy of first excited state in ^{135}Sn was measured at RIKEN [34]. Its excitation energy lies in the range as expected by our shell model calculations (Fig. 1) with consequences for our experimental approach as discussed in the following.

2 Experimental method and set-up

We propose to use the ISOLDE Solenoidal Spectrometer (ISS) to detect the protons following (d,p) reactions on ^{134}Sn in inverse kinematics.
The level density (Fig. 1) and, in particular, the alternative prediction to have the $3/2^-$ state at higher excitation energies in the region of high level densities (as it could be expected with a new shell closure at $N = 90$ with a large separation between the $f_{7/2}$ and $p_{3/2}$ neutron orbitals), made the approach using high-resolution γ-ray spectroscopy with Miniball to tag the protons detected by T-REX advantageous for a first experiment on this nucleus. The limited energy resolution of T-REX and the dynamic compression made a T-REX-only attempt not promissing. Taking into account the new knowledge that the first excited state is well separated from other excited states, the energy resolution of ISS in the range of around 200 keV allows to measure the angular distributions, leading to orbital angular momentum transfer Δl determinations, and the spectroscopic factors at ISS without γ-ray tagging.
The clear benefits of using ISS are higher statistics as the coincidence with Miniball reduces the statistics by roughly a factor 10. In addition, the measurement of the direct population of the states of interest is guaranteed whereas Miniball may miss a feeding of the state of interest from a state above which actually has been populated. Depending on the actual level spacing, also other states can be analysed from the ISS data. If the spacing is too small, then the following IS654 will do the spectroscopy and fix the excitation energies which then allows for multiple-peak fits to the ISS data.

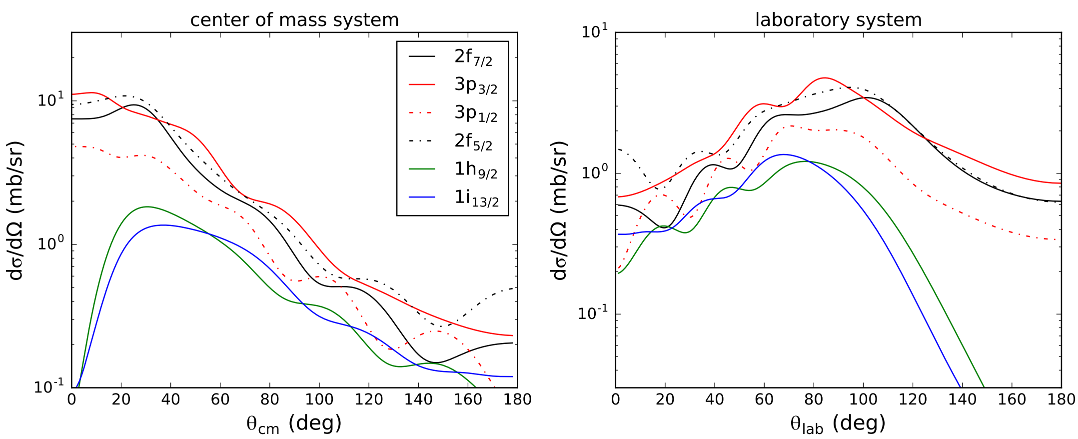

Figure 3: *Differential cross sections for the ^{134}Sn(d,p) reaction at 7.5 MeV/u. Excitation energies and spectroscopic factors are calculated with the cw5082 interaction.*

Fig. 3 shows the differential cross sections for the ^{134}Sn(d,p) ($Q_0 = 45.2$ keV) reaction in inverse kinematics at 7.5 MeV/u. The optical model parameters from Ref. [40] have been used. The main part of the transfer cross section is in the backward hemisphere in the laboratory system (Fig. 3, right) where the ISS Si array is placed.

Fig. 4 shows the kinematics of the outgoing protons in ISS. Assumed was a beam energy of 7.5 MeV/u, a magnetic field of 1.8 T, a threshold on the proton energy of 1 MeV and a separation between the target and the ISS Si array of 55 mm. For the population of the ground state, a range of polar angles between $10° - 42°$ im the CM system is covered. This range is reduced to $10° - 35°$ for an excitation energy of 3 MeV.

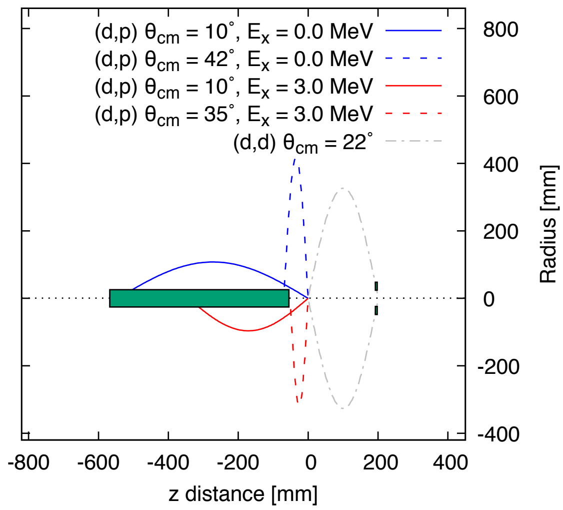

Figure 4: *Kinematical acceptance of the ISS Si array*

Comparing Figs. 3 and 4, clearly for the most interesting cases, transferred orbital angular momenta $\Delta\ell = 1$ and 3, the maxima of the differential cross sections are covered and can be clearly distinguished. For larger $\Delta\ell = 5$ and 6, the states are expected at larger excitation energy. The differential cross section are much less pronounced and the maxima may not be covered by our acceptance. Here, a currently not existing second ISS Si array in forward direction or experiment IS654 with HI-TREX are required.

Also shown in Fig. 4, in forward direction the luminosity monitor of ISS, ELUM, detects elastically scattered deuterons for normalisation. Further information on the shape of the optical potentials and the impact on the interpretation of the cross sections will come also from elastic scattering measured with HI-TREX (IS654) which covers both hemisspheres.

Fig. 5 shows the simulated energy distribution of the protons along the axis of the ISS Si array for 6 states populated. We assumed the excitation energies given in Table 1 within the range of predicted values (see Fig. 1 and 2). As energy resolution 200 keV (FWHM) was assumed, adaquate for the intended target thickness of 200 μg/cm^2. Clearly, the states are separated profiting from

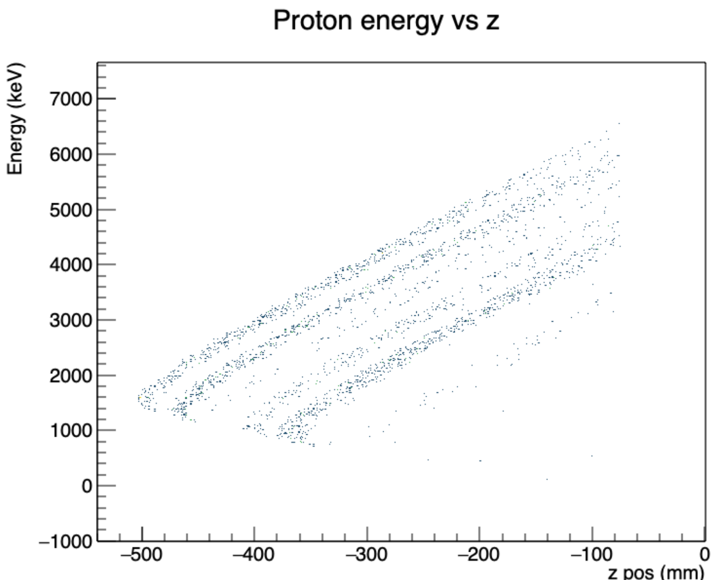

Figure 5: *Simulated proton energy versus z-position on the Si array of ISS for a magnetic field of 1.8 T.*

the fact that ISS does not suffer from dynamic compression and has a better energy resolution for protons compared to T-REX/HI-TREX.

The differential cross sections shown in Fig. 3 integrated over the solid angle covered by ISS are given in Table 1. Assuming a beam intensity of 10^4/s and a target thickness of 200 μg/cm^2 CD_2, the rate of detected protons per 8-h shift is given in the last column. Here, the dead areas of the Si detectors are included which result in about 66% of the covered solid angle being active detector area.

The spectrum of the reconstructed excitation energies is shown in Fig. 6. The statistics shown is based on the rates given in Table 1 and assuming 20 shifts of measuring time.

state	E_x [keV]	σ [mb]	rate [/shift]
$2f_{7/2}$	0	11.2	32
$3p_{3/2}$	500	11.6	33
$3p_{1/2}$	1500	5.6	16
$2f_{5/2}$	2000	13.1	37
$1h_{9/2}$	950	2.1	6
$1i_{13/2}$	3000	1.5	4

Table 1: *States in ^{135}Sn (labels as in Fig. 3), assumed excitation energies, simulated cross sections and expected proton rates.*

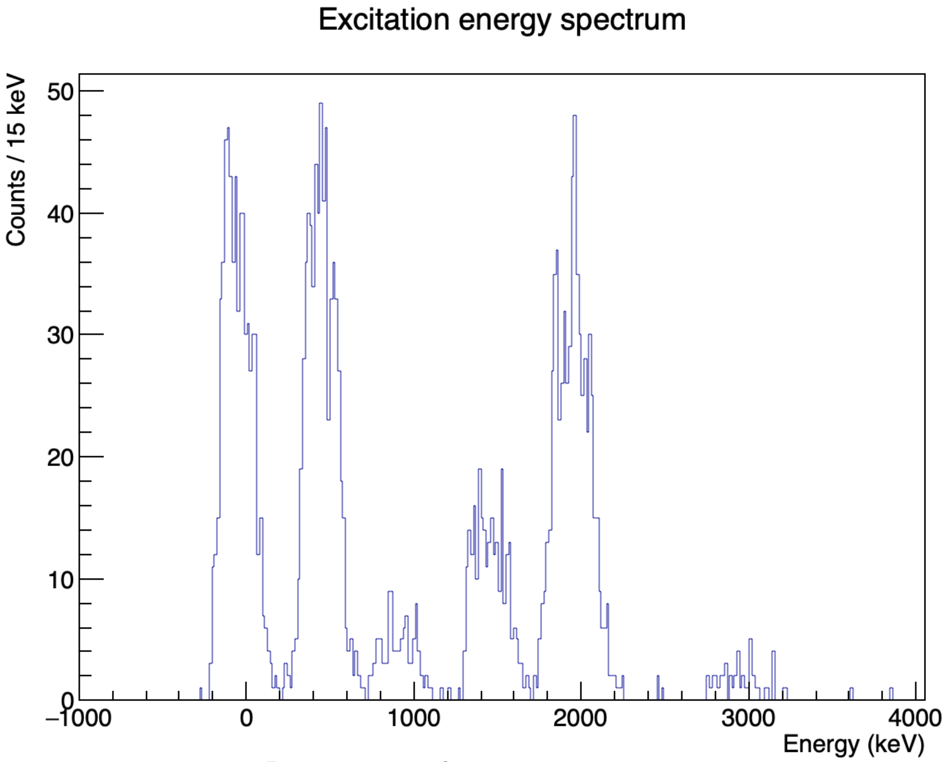

Figure 6: *Reconstructed excitation energy spectrum.*

In order to obtain an angular distribution, the data set is split into $5° - 10°$ angular bins. For the strongly populated states, this assures in the order of 100 counts per bin and, hence, a statistical error of 10%. For the more weakly populated states with large orbital angular momentum transfer, the maximum of the angular distribution may not be covered and only from the slope a tentative assigment may be possible.

3 Beam time request

The Sn isotope is produced with a standard UC_x/graphite target irradiated with the proton beam from the PS Booster. In order to eliminate the Cs contamination, as used

in experiment IS595/IS702 (2023), we will extract SnS^+ molecules which will be cracked afterwards in the EBIS [41]. Natural sulphur contains the isotopes $^{32,33,34,36}S$ (94%, 0.75%, 4.2%, 0.02%). To produce ^{134}Sn, a $A = 166$ beam would contain $^{134}Sn^{32}S^+$ but also a strong contamination from the more abundant Sn isotope, hence $^{132}Sn^{34}S^+$. Therefore, we will use isotopically enriched ^{34}S and produce a very clean $A = 168$ beam containing only $^{134}Sn^{34}S^+$ molecules [41]. Newer developments of the ISOLDE target group with the VADIS ion source enable a yield of about $10^5/\mu C$ for ^{134}Sn [42].
The isotope ^{134}Sn ($T_{1/2} = 1.05$ s) decays subsequently to the stable Xe isobar. The decay products involved with longest half-lifes are ^{134}I (52 min) and ^{134}Te (41.8 min). Therefore, activation by long-lived decay products is no issue for radiation protection.
The latest experiments with Sn beam confirmed pure beams, e.g. [29], except for the unavoidable decay products of the ^{134}Sn. As strongest isobaric contaminant ^{134}Sb would be expected. The Q value ($Q_0 = 1518$ keV) for (d,p) is much different and the most protons are unlikely to fit into the acceptance of ISS. However, we plan to mount the IC telescope as well, which was useful in 2023 in several experiments with lighter beams, but the resolution may not be sufficient to separate umambiguously isotopes in the $A \approx 130$ range. Being neutron-rich, from our experience from several experiments with T-REX, we do not expect a large background from protons evaporated following fusion-evaporation reactions with carbon (was much worse for tritium-loaded Ti).
Assuming a proton current of 2 μA and, conservatively, an efficiency of HIE-ISOLDE of 5% the expected beam intensity will be 10^4/s. We require the slow extraction from the EBIS to reduce the instantaneous particle rate. Assuming a standard deuterated PE target of 200 $\mu g/cm^2$ thickness the expected count rates are given in Table 1.
We request 24 shifts of beam time to obtain the statistics shown in Fig. 6 including 3 shifts for setting up the detectors, e.g. thresholds, in-beam and 1 shift for background check with a pure C target.
The obtained statistics will allow to confirm spin assigments, measure cross sections with good statistics and extract spectroscopic factors at least for the strongly populated states in ^{135}Sn. This will greatly enhance the knowledge of this r-process isotope and challenge the theory descriptions in this region of the nuclear chart.

Summary of requested shifts: we request 8 days (24 shifts) of ^{134}Sn beam.

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Details for the Technical Advisory Committee

3.1 General information

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

- ☒ Permanent ISOLDE setup: *ISS)*
  - ☒ 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*

3.2 Beam production

For any inquiries related to this matter, reach out to the target team and/or RILIS (please do not wait until the last minute!). For Letters of Intent focusing on element (or isotope) specific beam development, this section can be filled in more loosely.

- Requested beams:

Isotope	Production yield in focal point of the separator (/μC)	Minimum required rate at experiment (pps)	$t_{1/2}$
^{134}Sn	10^5	10^4	1.05 s

- Full reference of yield information (*Beam estimates based on the same set of yield predictions for ^{130,132}Sn were confirmed 2023 in exps. IS702 and IS595, respectively.*)
- Target - ion source combination: U carbide + sulphur - VADIS
- RILIS? (*No*)
  - ☐ Special requirements: (*No*)
- Additional features?
  - ☒ Neutron converter: (*No*)
  - ☐ Other: (*sulphur for SnS molecular beams*)
- Expected contaminants: *decay products of ^{134}Sn from decays in EBIS, from experience with ^{142}Xe (IS548) with same lifetime about 10%; in IS702 no $A = 164$ contaminants (same mass as SnS molecule) were observed, hence we do not expect $A = 168$ contaminants.*
- Acceptable level of contaminants: (*Reactions on contaminants have different Q values, minor to no impact expected.*)

- Can the experiment accept molecular beams? No SnS will not survive the treatment in the EBIS ... I guess?
- Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of? Yes, a Letter of Clarification for the second part of IS702 will ask for ^{134}Sn as well.

3.3 HIE-ISOLDE

For any inquiries related to this matter, reach out to the ISOLDE machine supervisors (please do not wait until the last minute!).

- HIE ISOLDE Energy: *(MeV/u); 7.5 MeV/u ... similar or higher, but precise value needed for kinematical reconstruction (and potentially for setting the magnetic field of ISS).*
  - ☒ Precise energy determination required
  - ☒ Requires stable beam from REX-EBIS for calibration/setup? *May be required depending on the other experiments of the campaign, e.g. stable Xe offers similar mass*
- REX-EBIS timing
  - ☒ Slow extraction
  - ☐ Other timing requests
- Which beam diagnostics are available in the setup? Standard devices and diagnosis procedures in ISS.
- What is the vacuum level achievable in your setup? 10^{-6} mbar

3.4 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
Yield measurement of ^{134}Sn Optimization of experimental setup using ^{134}Sn Data taking, ^{134}Sn	? 24
Without protons	Requested shifts
Stable beam from REX-EBIS (after run) Background measurement	

3.5 Health, Safety and Environmental aspects

3.5.1 Radiation Protection

- If radioactive sources are required:
  - Purpose: calibration
  - Isotopic composition: Mixed alpha-source in ISS (4236RP)
  - Activity: 4 kBq (total)
  - Sealed/unsealed: Open
- For collections:
  - Number of samples? /
  - Activity/atoms implanted per sample? /
  - Post-collection activities? (*No*)