EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Closing in on ^{100}Sn: Mass Measurements of the Neutron Deficient N=51-53 Tin Isotopes

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Abstract:

The direct neighborhood of the doubly magic ^{100}Sn is of great interest to test our understanding of the nuclear structure and state-of-the-art many-body calculations. To probe this region, we therefore propose to accurately and precisely measure the ground-state masses of $^{101-103}$Sn using the high-precision mass spectrometer ISOLTRAP at CERN-ISOLDE. The mass values of these isotopes are currently only known with high uncertainties through indirect determination via beta-decay Q-values. A mass measurement of ^{101}Sn directly probes the neutron binding energy of the closed ^{100}Sn core and is of importance for bench-marking shell model and *ab initio* calculations. By measuring the masses of $^{102-103}$Sn the recently emerging local inconsistency on the mass surface at $N = 53$ can be resolved. Additionally, the mass measurements will reduce mass uncertainties of nine alpha and proton emitters north-east of ^{100}Sn which are linked to the tin masses via their decays.

Requested shifts: 18 shifts in one run with a LaC_x target and RILIS in broadband mode.

1 Motivation

Being on the edge of the proton drip line, one of the heaviest known self-conjugate nuclei, ^{100}Sn, not only exhibits the strongest super-allowed Gamow-Teller $\beta-$decay and is the end point for $\alpha-$decays, but is also considered doubly magic with closed $N = 50$ and $Z = 50$ shells[1].

Due to its poor production cross-section, experimental knowledge on ^{100}Sn and its direct neighbors is sparse. Most investigations in this neutron-deficient area of the nuclear chart have been performed at facilities such as GSI and RIKEN using heavy primary beams such as ^{112}In or ^{124}Xe to produce rare isotopes through fragmentation processes [2, 3, 4] or fusion-evaporation reactions using the IGISOL technique [5]. In recent experiments at CERN-ISOLDE, masses of indium isotopes and their long-lived excited states were measured all the way to ^{99}In, one proton below ^{100}Sn [6, 7], while laser spectroscopy has been performed on tin isotopes out to ^{104}Sn [8].

Neutron-deficient proton-magic tin isotopes provide a good case to study our understanding of the shell model with respect to the expected double shell closure in ^{100}Sn. Here, the $I^{\pi} = 0^{+}$ ground states in even-even tin isotopes can be described as having pairs of valence neutrons above the closed $N = 50$ shell while the lowest-lying states in odd-even isotopes are viewed as one-particle states whose spins are determined by the occupied shell of the unpaired neutron. For the latter, the single-particle orbitals involved are the $d_{5/2}$ and

[1] For an extensive overview on ^{100}Sn, we refer to Ref. [1]

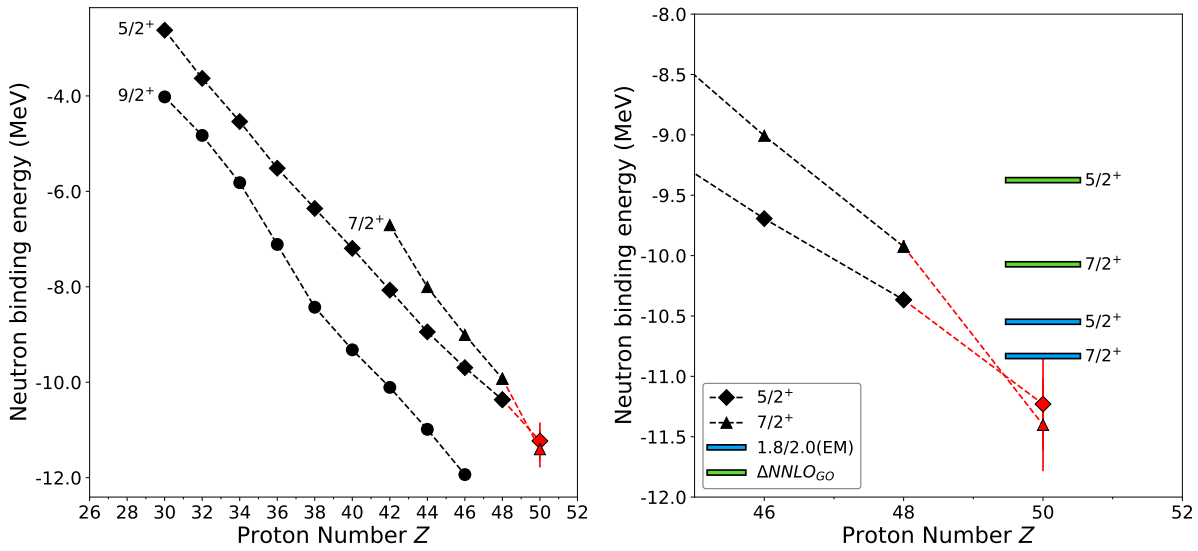
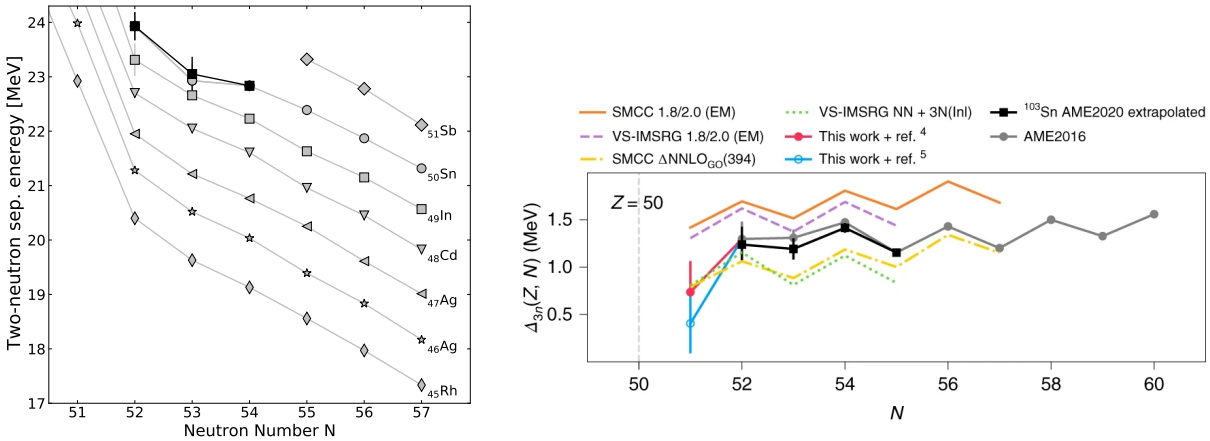


Figure 1: Neutron binding energy for the $N = 49$ and $N = 51$ isotones south of the ^{100}Sn region. The highlighted data points in red represent the current AME data on the ground state mass of ^{101}Sn. The excitation energy for the $7/2^{+}$ state in ^{101}Sn is taken from [9]. The *ab initio* calculations of the single particle states shown in the right hand plot for two different $NN+3N$ Hamiltonians, 1.8/2.0(EM) and $\Delta NNLO_{GO}$, are taken from [10].

$g_{7/2}$.

Towards the valley of stability, it is known that the ground-state configuration for odd-even tin isotopes is formed by the $d_{5/2}$ orbital. Experimental studies accompanied by shell model calculations suggest that the level ordering breaks down in ^{101}Sn and the $g_{7/2}$ configuration becomes the ground state [11]. However, this working theory is challenged by a more recent γ-ray spectroscopy study in Ref. [12]. The two plots in Figure 1 trace the development of the neutron binding energy $S_{1n} = B(Z,N-1) - B(Z,N)$ (with $B(Z,N)$ being the total binding energy) for the $N = 49$ and $N = 51$ isotonic chains forming the $N = 50$ shell gap. For the data points highlighted in red, ^{101}Sn, the ground-state mass is estimated through its beta-delayed proton decay channel via ^{101}In into ^{100}Cd, with a dominating mass uncertainty assigned from a measurement of the proton emission energy [13]. This value suggests that the single neutron is slightly more bound than one would expect from the local trend. A direct mass measurement of the ground-state of ^{101}Sn cannot absolutely resolve the state-ordering question definitely, but would provide valuable input to benchmark the expected single-particle energies, as calculated in Ref. [14, 10], and would give an additional data point to test the nucleon-number dependence of single-nucleon energy trends across the whole nuclear chart, recently reviewed in Ref. [15].

In the current Atomic Mass Evaluation (AME) of input data [16], the ground-state mass of ^{102}Sn is extracted from the ^{102}In ground-state mass using a beta-decay Q-value measured in [17], incorporating the 100 keV measurement uncertainty. Additionally, ^{103}Sn was deemed a "seriously irregular mass" determined only from the ^{103}In ground-state mass through a β^- Q-value measurement [18]. The AME authors thus recommend using the mass value determined by systematic trends on the mass surface and call for a direct measurement to resolve the irregularity. The problem can readily seen by plotting the two-neutron separation energy $S_{2n} = B(Z,N-2) - B(Z,N)$ for different isotopic chains as plotted in Figure 2(a). The dip at



(a) Two-neutron separation energy for different neutron deficient isotopes south of the ^{100}Sn region.

(b) Three-point estimator for neutron-deficient tin chain compared to ab initio shell model calculations, taken from [6].

Figure 2: Comparison of two mass filters with current mass knowledge in neutron deficient tin region. In both figures the experimental data (grey symbols) is taken from the AME2016 and the extrapolated values from the mass surface are from AME2020 (black squares).

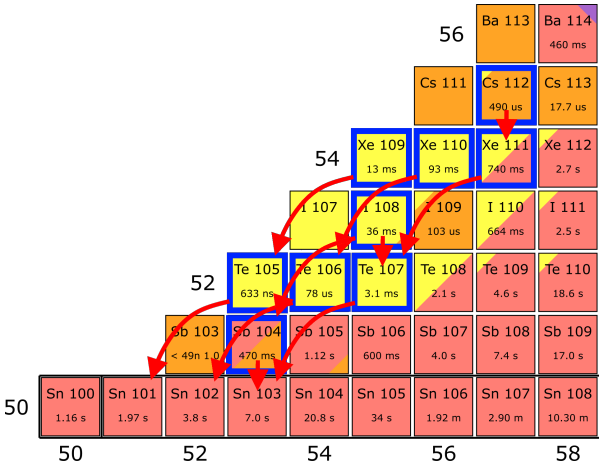


Figure 3: Excerpt of nuclear chart northeast of ^{100}Sn. The blue boxes show isotopes whose masses are linked through α-decays and proton emissions to $^{101-103}$Sn. The decay chains are indicated by red arrows. They include ^{109}Xe(α)^{105}Te(α)^{101}Sn, ^{110}Xe(α)^{106}Te(α)^{102}Sn, ^{112}Cs(p)^{111}Xe(α)^{106}Te(α)^{103}Sn, ^{108}I(α)^{104}Sb(p)^{103}Sn, and ^{108}I(p)^{107}Te.

$N = 53$ is not expected and results from the inaccurate mass determination from the Q-value measurement. This problem is also illustrated by plotting the so-called three-point estimator for the odd-even staggering $\Delta_{3n}(Z,N) = 0.5\times(-1)^N\,[B(Z,N-1) - 2B(Z,N) + B(Z,N+1)]$, see Figure 2(b). In this work [6], *ab initio* calculations disagree with the mass determined through the Q-value measurement. By directly measuring ^{103}Sn, we will contribute to a more accurate experimental description of the shell gap and the odd-even staggering above ^{100}Sn. This is particularly important due to the sharp cusp on the mass surface for $N = Z$ nuclides referred to as the Wigner energy.

A unique feature of the nuclear landscape is a small island of α-emitters with decay chains ending in tin isotopes. Most of the mass data in this region is indirectly known based from the anchoring tin masses through successive α-decays by measuring the α-particle energies, see for example Ref. [11, 19]. By directly measuring $^{101-103}$Sn, we can significantly reduce the mass uncertainties for ^{104}Sb, ^{105}Te, ^{106}Te, ^{107}Te, ^{108}I, ^{109}Xe, ^{110}Xe, ^{111}Xe, and ^{112}Cs. See Figure 3 for a visualization of the decay chains.

Extracting masses through β end-point energies requires a complete knowledge of the feeding into excited states in the daughter nucleus to reliably fit the β-decay spectrum. High-resolution γ-spectroscopy of the decay is needed to account for all internal transitions as well as total absorption spectroscopy and energy measurements of the delayed proton emission to draw a full picture of the decay. However, incomplete knowledge on the full decay caused by internal γ conversion or undetected weak decay branches may lead to significant systematic errors. We therefore propose to perform direct mass measurements using the ISOLTRAP mass spectrometer by employing the Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS) and Phase-Imaging Ion-Cyclotron Resonance (PI-ICR) techniques. Direct measurements are not only much more reliable, they also provide stringent decay energy windows. Accurate masses will also benchmark state-of-the-art calculations of single-neutron energies in ^{101}Sn, shed light on the local mass trend around ^{103}Sn, and indirectly reduce the mass uncertainty on many nuclei in the island of enhanced α- and proton-emitters northeast of ^{100}Sn.

2 Experimental techniques

Analogous to the recently measured $^{99-101}$In [6, 7], the ISOLTRAP high-precision mass spectrometer [20] will be used for $^{101-103}$Sn. Currently, the apparatus consists of four ion traps optimized for different purposes: accumulation, bunching, separation, cleaning, and mass determination. In Figure 4(top) a schematic view of the apparatus is presented. The quasi-continuous ion beam provided by ISOLDE is cooled and bunched in a linear radio-frequency quadrupole (RFQ) to improve the beam's ion-optical quality. Ion bunches are ejected from the RFQ into a Multi-Reflection Time-of-Flight device [21] which is used in combination with a ToF-detector to identify (mass-spectrometry mode) and clean (mass-separation mode) undesired ion species from the ion bunch. Selected ions are then guided to the two Penning traps: The preparation Penning trap is used to further reduce the beam emittance while in the precision Penning trap the ion mass is determined by either the Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR) [22] or the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) [23, 24] techniques.

The bottom left plot in Figure 4 shows the $A = 101$ MR-ToF MS spectrum from which the mass of ^{101}In was recently determined [7] as compared to the earlier PI-ICR measurement from [6]. The thick red bar in the ToF spectrum shows the expected time-of-flight for ^{101}Sn. This clearly demonstrates that the ions of interest ^{101}Sn, can be well separated from isobaric contaminants for the proposed measurement. This is similar for the other proposed tin cases as well. In case the production of the tin isotopes is too low and can-

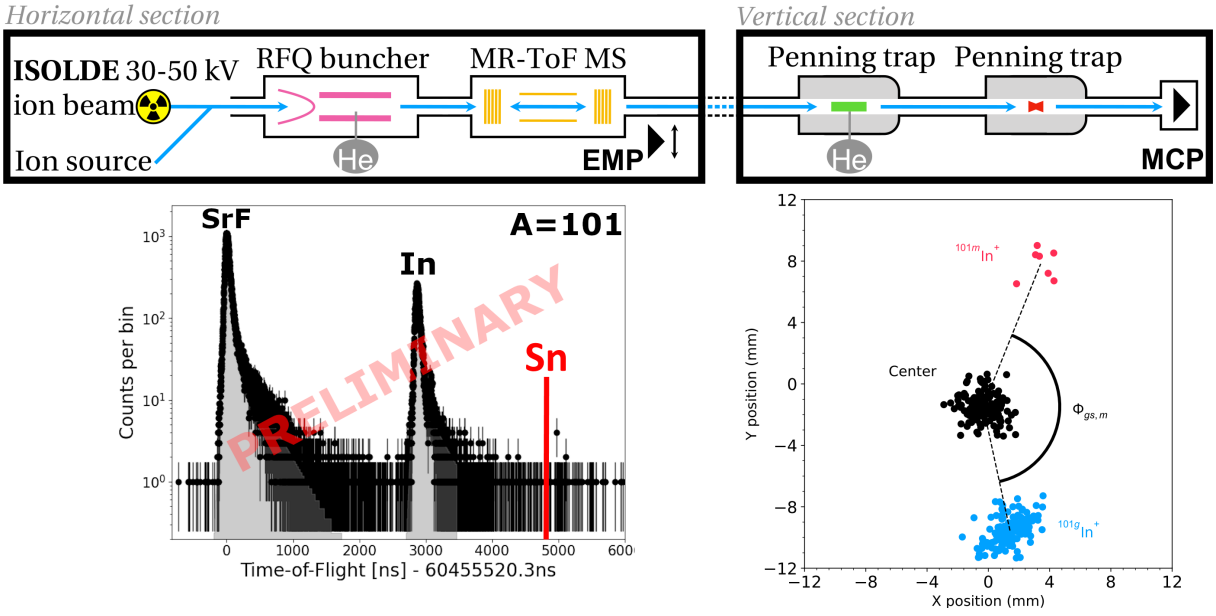


Figure 4: Top: schematic of the ISOLTRAP setup with its four ion traps and offline sources. Bottom left: ToF spectrum of $A = 101$ components of the ISOLDE beam with RILIS resonantly ionizing indium [7] with the expected time-of-flight for ^{101}Sn highlighted with a red bar. Bottom right: PI-ICR resonance of the ground and the 650 keV isomeric states of ^{101}In for comparison [6].

not be transported in sufficient quantities to the Penning traps, the MR-ToF MS provides in mass-spectrometry mode a precision of $\delta m/m = 10^{-6}$. Unwanted isobaric contamination can be removed using the well-proven in-trap lift method [25]. An absolute mass measurement of the isotope of interest can be performed by using several off-line ion sources in well-established cross-reference measurements [26]. In case that species like strontium-fluoride and indium (see bottom left insert in Figure 4) delivered online from ISOLDE are not sufficient for calibration purposes, $^{12}C_8$ and $^{12}C_9$ carbon clusters from a laser-ablation source or $^{85/87}$Rb and ^{133}Cs isotopes from a surface ion source will be used as mass references to reduce mass-dependent systematical shifts. If the production yield and the beam purity is sufficient, isotopes can be transported to the precision Penning trap. In the bottom right panel of Figure 4, a plot for a PI-ICR resonance of the resolved isomeric and ground states of ^{101}In proves the precision and the resolving power of the measurement procedure.

3 Beam time request

Neutron-deficient beams in the direct vicinity of ^{100}Sn are well studied at ISOL facilities [29]. At ISOLDE, as shown in the previous section, indium beams up to the $N = 50$ shell closure have recently been successfully measured by means of mass-measurements [6, 7]. In another experiment, tin was detected down to $N = 53$ [8].

Using a LaC_x target together with the Resonance Ionization Laser Ion Source (RILIS), yields for the around ^{100}Sn can be estimated from ISOLDE tape station measurements and Monte-Carlo simulations of in-target production [27] as well as from empirical fragmentation cross-sections between the primary beam and the target material [30]. Such a comparison is shown in Figure 5. The grey data points show the in-target yield based on the Monte-Carlo and empirical approaches while the blue diamonds represent measured data from the ISOLDE tape station and the laser-spectroscopy experiment. The blue line with error band represents our estimated yield in the central ISOLDE beam line based on the trends of the in-target production, target release and isotope half-lifes.

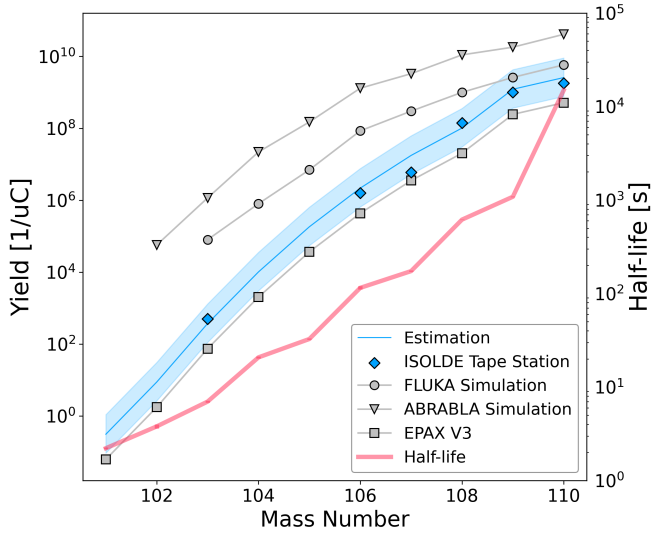


Figure 5: Measured, simulated, and estimated yields with half-lifes for neutron deficient tin isotopes produced from a lanthanum carbide target with a 1.4 GeV proton beam. The tape station measurements, FLUKA, and ABRABLA simulations are taken from [27], the EPAX V3 values are taken from [28], and the half-life information are taken from [16].

As seen in the indium campaigns at ISOLDE, one contaminant will be SrF which can be well separated by the MR-ToF MS and which can serve as an online mass reference. Going from $A = 101$ towards $A = 103$ it was seen that the SrF contamination is slightly increasing due to the in-target production cross-section for strontium. However, surface-ionized indium will be the dominant contamination. Based on our yield estimation for tin and the surface ionized indium yields detailed in [29], we expect indium to be ten- to hundred-fold more present in the beam as compared to tin. Both contaminants will require less than 2×10^4 of mass resolving power to be separated. The MR-ToF MS — using active and passive voltage stabilization [31] in combination with mass-selective ion ejection [25] — is fully capable of cleaning the radioactive ion beam from this contamination and has routinely be run with mass resolving powers exceeding 4×10^5. Furthermore, no loss of counts caused by in-flight or in-trap decay is expected due to the long half-lifes of the tin isotopes. This enables a high number of revolutions in the MR-ToF MS, increasing the separation capability if needed.

Considering the estimated yields, we believe that two and five shifts are required to perform the measurement on ^{103}Sn and ^{102}Sn, respectively, using the PI-ICR technique. We have shown that, with this technique, as little as a few counts are sufficient to perform a precise mass measurement. If the production yield is too low to allow for a Penning-trap measurement, the measurement will be performed with the ISOLTRAP MR-ToF MS. This is expected to be the case for ^{101}Sn, for which we estimate nine shifts to be needed to collect the necessary amount of statistics. The shift count is summarized in Table 1.

Table 1: Isotope properties and detailed summary of the shift request. Spins and parities are assigned based on nuclear structure arguments . Yields marked with # are estimated.

Isotope	Half-Life [h]	I^π	Yield in CA0 [ions/s]	Target / Ion source	Method	Shifts (8h)
^{101}Sn	2.2 s	$7/2^+$	0.1-1	LaC_x / RILIS	MR-ToF MS	9
^{102}Sn	3.8 s	0^+	10-100	LaC_x / RILIS	PI-ICR and MR-ToF MS	5
^{103}Sn	7.0 s	$5/2^+$	100-1000	LaC_x / RILIS	PI-ICR and MR-ToF MS	2
Beam optimization						2

Summary of requested protons: 18 shifts in one run with a LaC_x target, and RILIS in broadband mode.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: ISOLDE central beam line and ISOLTRAP setup. The ISOLTRAP setup has safety clearance, the memorandum document 1242456 ver.1 “Safety clearance for the operation of the ISOLTRAP experiment” by HSE Unit is released and can be found via the following link: `https://edms.cern.ch/document/1242456/1`.

Part of the	Availability	Design and manufacturing
ISOLTRAP setup	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed ISOLTRAP installation.