EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Probing the largest core-breaking prediction towards ^{100}Sn: proton single-particle strength in ^{110}Sn

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Abstract:

The Sn isotopic chain is a formidable testing ground for the study of shell evolution in different nuclear models. Even though the energies of the first 2^+ states in even-even isotopes between ^{102}Sn and ^{130}Sn are quite similar, in agreement with the seniority scheme for this valence neutron space, the significant increment of the $B(E2; 0^+ \rightarrow 2^+)$ value approaching ^{100}Sn has remained a major puzzle over decades. Recently, the result of state-of-the-art Monte Carlo shell model (MCSM) calculations on Sn isotopes, performed in a large model space including single-particle orbits below and above the Z=50 and N=82 magic numbers, has explained the anomalous trend of $B(E2; 0^+ \rightarrow 2^+)$ by considering a core breaking contribution, involving the $g_{9/2}$ proton orbits to the *gds* valence space. The MCSM calculations also suggested that the number of proton holes for the first 0^+, 2^+ and 4^+ states in even-even Sn isotopes will increase when approaching $N = 60$, i.e. ^{110}Sn, being maximum for the 4^+_1 state. In this proposal, we aim at measuring the proton single-particle strength, by probing directly the $\Delta\ell$=2 contribution in the proton transfer to the 4^+_1 state in ^{110}Sn. This will be achieved using the ^{109}In(^{3}He,d)^{110}Sn one-proton transfer reaction, with the light ejectiles being measured using the solenoidal spectrometer at ISOLDE.

Requested shifts: 21 shifts (7 days, 1 run over 1 year)

1 Motivations

The self-conjugated and doubly-magic ^{100}Sn nucleus has been regarded as one of the milestones in present and future nuclear structure research. Consequently, a great experimental effort has been devoted to ^{100}Sn and the nearby nuclei, employing different techniques. Up to now, only the β-decay spectroscopy of ^{100}Sn has been experimentally studied, providing indication about a doubly-magic nature [1, 2]. Yet, single-particle energies are poorly known, due to the difficulty of studying ^{101}Sn, given also the controversy regarding the spin-parity assignments of ground and first excited states [3].
The whole tin isotopic chain, from ^{102}Sn to ^{130}Sn (neutron number 52–80), roughly exhibits the typical behavior predicted by the generalized seniority scheme for neutrons in the $g_{\frac{7}{2}}$ and $h_{\frac{11}{2}}$ orbitals, for N < 64 and >64, respectively. See Ref. [4] for details.
The energies of the first 2^+ states in even-even isotopes between ^{102}Sn and ^{130}Sn are quite similar, in agreement with the prediction of the seniority scheme for this valence neutron space.
However, the experimental $B(E2; 0^+ \rightarrow 2^+)$ values suggested a *presumed* deviation from the expected parabolic behavior, as shown in Fig. 1 (a) (taken from Ref. [5]). From a theoretical point of view, various attempts have been made to explain the experimental results, in particular by including core-breaking excitations in the shell-model calculations [6, 7]. The predicted *flat* trend is not firmly established experimentally, because limited data are available on the extremely neutron-deficient nuclei beyond ^{104}Sn. Recently, Togashi et al. [5] claimed that Monte Carlo shell-model (MCSM) calculations have explained the $B(E2; 0^+ \rightarrow 2^+)$ trend (see the red curve in Fig. 1 and Ref. [5]) by promot-

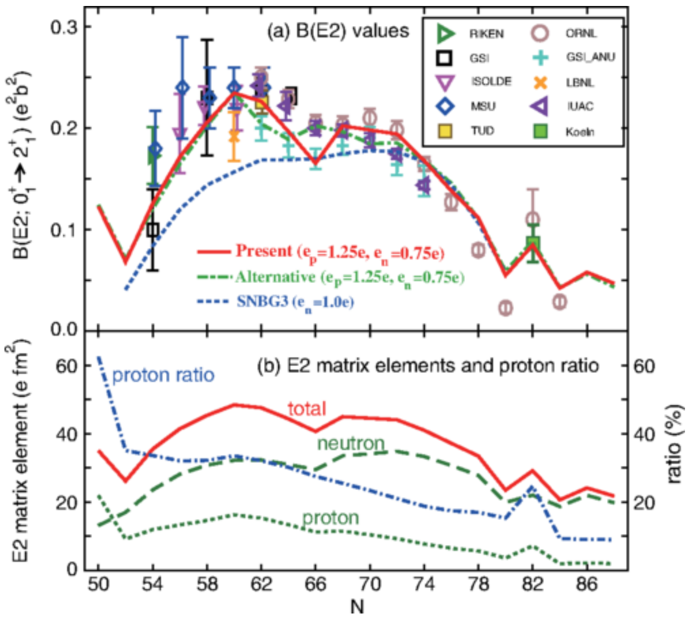

Figure 1: (a) Calculated and measured $B(E2)$values and (b) $E2$ matrix elements as well as their decomposition in proton and neutron contribution ratios (%). The figure is taken from Ref. [5].

ing protons and neutrons from the $g_{\frac{9}{2}}$ orbital to those at higher energy. Such state-of-art theoretical prediction opens a new perspective for the study of core-breaking effects in Sn isotopes especially for the neutron-deficient ones. In the bottom panel of Fig. 1, proton and neutron contributions to the E2 matrix elements are shown. The proton contribution becomes larger approaching the most neutron-deficient ^{100}Sn: the proton/neutron ratio of the calculated matrix element exceeds 30% for N = 50-64, with the $1g_{9/2} \rightarrow 2d_{5/2}$ excitation being dominant, and the proton contribution reaches a maximum at N=60 in ^{110}Sn.

Further to the $B(E2; 0^+ \rightarrow 2^+)$ measurement, which are still out of reach for the most exotic neutron-deficient Sn isotopes, a powerful alternative way to investigate the robustness of the ^{100}Sn core is to directly probe the proton single-particle occupation above the Z=50 shell closure. For the low-lying states, this would imply a partial occupation of the $g_{\frac{7}{2}}$, $d_{\frac{5}{2}}$, $d_{\frac{3}{2}}$, $s_{\frac{1}{2}}$ proton valence orbitals., if core-breaking effects are present. In particular from Ref. [5], the main core-breaking contribution is expected from proton excitation to the $d_{\frac{5}{2}}$ orbital which is predicted to reach a maximum at N=60, corresponding to ^{110}Sn, see Fig. 2. Such a contribution is also expected to become larger with increasing spin, making the 4^+ state in ^{110}Sn the best candidate for testing the possible ℓ=2 proton component of its wave function. In addition, to the best of our knowledge, this will represent the first time a neutron deficient Sn isotope is probed against the proton degree of freedom via direct reactions.

This will be possible by measuring the ^{109}In(^{3}He,d)^{110}Sn single-proton transfer reaction using the ISOLDE Solenoidal Spetrometer, which will allow us to populate the 4^+ state at 2.197 MeV in ^{110}Sn. Deuterons, which will be detected at backward angles, will show

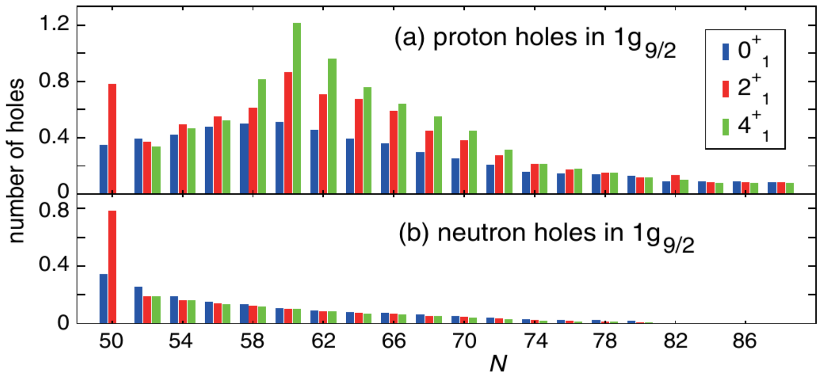

Figure 2: Occupation numbers of (a) proton and (b) neutron holes in the $1g_{9/2}$ orbit. For each value of N, histograms for the 0^+, 2^+, and 4^+ states are shown from left to right. The maximum is expected in correspondence of the 4^+ state in ^{110}Sn. The figure is taken from Ref. [5].

a characteristic angular distribution depending on the $\Delta\ell$ transfer, providing information on the occupancy of proton orbitals above the Z=50 shell closure. This will shed light on possible proton excitations across the shell gap, as a consequence of core-breaking effects in ^{110}Sn. In summary, we aim at:

1. getting insights into the possible core-breaking effects in ^{110}Sn by measuring absolute integral cross section for the proton-adding (^{3}He,^{2}H) reaction, predicting to be mainly from a $\Delta\ell$=2 transfer.

2. establishing the individual contribution of each proton component by measuring differential cross sections and extracting spectroscopic factors.

2 Experimental details and rate estimation

The ^{109}In(^{3}He,d)^{110}Sn single-proton transfer reaction is proposed to investigate the core breaking effects, which manifests via the occupation of the valence orbitals above Z=50. The deuterons emitted at backward angles will be measured along the Z axis by the ISOLDE Solenoidal Spectrometer (ISS) silicon detectors.
The $^{109}In_{gs}$ isotope is produced from a UC_X target irradiated with the proton beam from the PS Booster. The expected production yield is 5x10^9 pps, as recently measured at the COLLAPS experiment [8]. Considering transmission efficiency and post acceleration, we expect a beam intensity on secondary target of at least ∼1x10^7 pps. Possible 10÷20% contamination, presumably from ^{109}Pd, might also be present. For such $^{109}_{46}$Pd, ℓ=4 would be the most probable ℓ transfer, being the Z=50 core open, but this will be largely suppressed because of the high ℓ value. As a consequence, no significant effect to the aim of the experiment is expected from Pd contaminants, considering also that the estimated statistical error on the final cross section is expected to be around 20%. Please see further below for details.

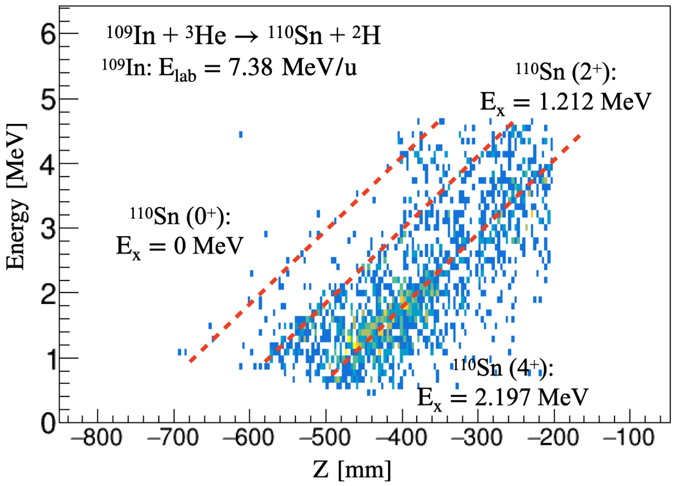

Figure 3: Realistic MC simulation of ISS energy vs Z axis position for the deuteron ejectiles. According with the calculated cross section, the 4^+ state is the most abundantly populated, followed by the 2^+ state, whilst the ground state is barely visible. Dashed lines suggest the centroid of each state: the 4^+ state could be unambiguously selected.

A beam energy of 7.38 MeV/u from HIE-ISOLDE is suited to enhance the probability of single-particle proton transfer. The transfer will populate low-lying states, in particular the 4^+ state, and will enable the determination of the total and differential cross section, which is predicted to be dominated by the $\Delta\ell$=2 transfer.
Cross sections were calculated using a one-step DWBA approach for the 0^+, 2^+, 4^+ states [9]. The optical parameters of the ^{109}In+^{3}He incoming and the ^{110}Sn+d outgoing scattering potentials were taken from Ref. [10] and Ref. [11], respectively. The ^{3}He wave function was obtained with a Woods Saxon potential and fitted to the $<^3 He|d + p>$ overlap calculated with VMC techniques, using the the AV18+UX interaction (see Ref. [12]). The parameters of the potential were adjusted to match the ANC and the proton binding energy. The calculated integral cross section is 0.75 mb and 0.25 mb, for the 4^+_1 and 2^+_1 state, respectively. The total cross section calculated for the transfer to the ground state is only 0.01 mb. Unitary spectroscopic factors have been considered in all the calculations.
For the secondary target, we plan to use a solid ^{3}He target on a W substrate, developed within our collaboration, which accounts for a density of $\sim$0.3x10^{18} atoms/cm^2. Substrate thickness, 0.6 μm, is necessarily limited due to the beam energy straggling, and so the maximum density of the sputtered ^{3}He. Please see Ref. [13] for any further detail.
We performed a commissioning run of a similar target prototype with an intense Zn stable beam delivered by the LNL-INFN Tandem, at a variable intensity ranging from $(0.3 \div 5) \times 10^{10}$ pps for 22 hrs. After 11 hours, during which the beam intensity was increased, the density of ^{3}He decreased by a factor of $\sim$3. In conclusion, we do not expect any significant loss with an intensity of 10^7 as expected for ^{109}In beam.
At the chosen beam energy, 7.38 MeV/u, the centre of mass energy is 50% above the Coulomb barrier for W. Nevertheless, the expected reaction mechanism will be (quasi) fusion-fission process, which hinders any light-charged particle background.

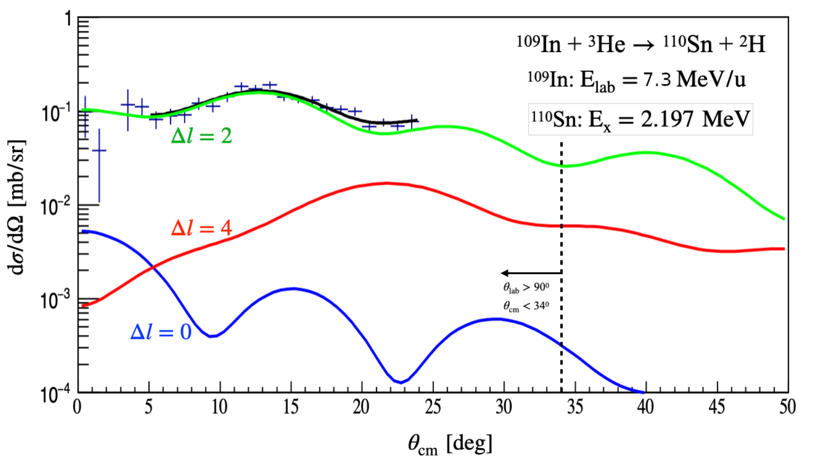

Figure 4: Realistic MC simulations of the differential cross section for the 4^+ state. A deconvolution of each $\Delta\ell$ transfer component is performed, revealing the main contribution of $\Delta\ell$=2, as a given input, in agreement with theoretical predictions.

Fig. 3 shows a realistic MC simulation where the first excited 4^+ and 2^+ states are the most abundantly populated states, whilst the ground state in ^{110}Sn is barely visible.
Two other states at 2058.0(4) and 2121.04(23)-keV energy are quoted in literature. However, the first one is only reported in a FE reaction in Ref. [14] as (0^+,2) but neither spectra are shown nor the character of the state discussed; the second one is reported in Ref. [15] to be a 2^+_2 marginally produced in the ϵ capture from ^{110}Sb and in Ref. [16] in a *neutron* transfer reaction, but the tiny cross section couldn't be quoted in the paper. Therefore, we expect these two states, if there, to be marginally produced also in our experiment.
The separation shown in the Energy *vs* Z plot of ISS is sufficient to gate on the 4^+ events and extract the differential cross section, which is shown in Fig. 4. Such angular distribution for the proton transferred to the 4^+ state was simulated considering the different ℓ contributions and the estimated number of counts. Spectroscopic factor are presently under calculation, consequently in our simulation, each contribution was provisionally taken proportional to the relative *s,d,g* composition of 4^+ wave function [17]. The relative weights used as input are 7%, 80% and 13% for $s_{1/2}$,$d_{5/2}$+$d_{3/2}$,$g_{7/2}$ components, respectively.
Due to the reaction kinematics, deuterons are emitted backward in the laboratory frame with a $\Delta\ell$=2 peaked at ∼120 degrees in the lab frame. This implies that, including also the presence of the target and Si detection system bore, an angular coverage of 3 ÷ 30 degrees in the CM frame remains available for the detection, see Fig. 4. Notwithstanding this limit, the result of the simulation gives for the deconvolution of the $\Delta\ell$=2 component a value of 80%, as a given input, with a relative error of ∼20%. This error sets also the sensitivity of the measurement to the core breaking effect, giving a lower detectable limit of ∼100 μb. For the extraction of the absolute cross section we plan to use a downstream Faraday cup and a monitor detector for the ^{3}He elastically scattered.

Summary of requested shifts: in total we request 21 shifts of beam on target, to be able to estimate a core breaking contribution with an error of 20% corresponding to a lower limit of $\sim$100 μb.

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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	Availability	Design and manufacturing
ISOLDE Solenoidal Spectrometer	☒ 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	**1.8 T**		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]	^{3}**He (solid, 0.6**μ**m W substrate)**		
Beam particle type (e, p, ions, etc)	$^{109}\mathbf{In}_{gs}$		
Beam intensity	$\mathbf{10}^{7}pps$		
Beam energy	**7.38 MeV/u**		
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]