EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

γ spectroscopy and fast timing study of the doubly magic ^{132}Sn system and its 1n particle/hole and 2n particle/hole neighbours

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Abstract: We propose to use fast timing and γ spectroscopy to study five nuclei including the doubly magic ^{132}Sn and its four neighbours: two-neutron hole ^{130}Sn, one-neutron hole ^{131}Sn, one-neutron particle ^{133}Sn and two-neutron particle ^{134}Sn. There is enormous interest in these nuclei as they serve to test nuclear models, deduce single particle states and interaction strength, and moreover, properties of these nuclei are very important to the modeling of the astrophysical r-process. Sn nuclei will be produced from the β-decay of In isomers using the UC$_x$ target equipped with neutron converter and RILIS. We will use the Isolde Decay Station (IDS), which will be slightly modified to increase the efficiency for the fast timing measurements. The present ISOLDE facility provides unique capabilities to study these nuclei from the β decay of Indium. For example it will provide about 200 times higher yield than available in the previous seminal study on ^{132}Sn performed at the OSIRIS separator in 1994. Sensitivity of our measurements will be further enhanced by the use of the highly-efficient clover-type Ge detectors and the new generation fast timing LaBr$_3$ crystals. We request 24 shifts in total: 3 shifts for ^{130}In, 3 for ^{131}In, 4 for ^{132}In, 5 for ^{133}In, 7 for ^{134}In, and 2 shifts for the in-beam time response calibrations.

Requested shifts: 24 shifts, (split into 1 runs over 1 years)

1 The Physics Case

Doubly magic nuclei and their immediate neighbours command a strong interest for both theoretical and experimental investigations. They represent the best regions to deduce the single particle energies and the interaction strength, which are then used in model calculations over an extended range of nuclei. For the vast region of the medium heavy nuclei, there are only two magic nuclei, stable ^{208}Pb and exotic ^{132}Sn, which can be studied in greater detail. However, Sn isotopes are very special since those that can be studied experimentally span a long range, starting from the doubly magic ^{100}Sn to ^{132}Sn, and now extending even to ^{138}Sn [1]. We propose to use fast timing and γ spectroscopy to study five nuclei: ^{130,131,132,133,134}Sn, the doubly magic ^{132}Sn and its neighbours: two-neutron hole, one-neutron hole, one-neutron particle and two-neutron particle systems. The enormous interest in the ^{132}Sn nucleus and the difficulty in accessing it, can be best seen from the following facts: in the last 20 years there were about 500 theoretical studies on this nucleus and only a few experimental investigations of its excited states. This nuclear region is also very important to understanding the r-process and the synthesis of heavy elements. Figure 1 shows the results of a sensitivity studies performed by Mumpower *et al.* [2] to identify the most important nuclei to measure in a given astrophysical scenario. Nuclei east of ^{132}Sn are prominently marked.

The experimental studies on exotic Sn nuclei, which include: γ spectroscopy from β-decay, fast timing spectroscopy from β decay, prompt-fission, decay from isomeric states, Coulomb excitation and particle transfer reactions in inverse kinematics, mass measurements and laser spectroscopy, provide key complementary information. However, so far

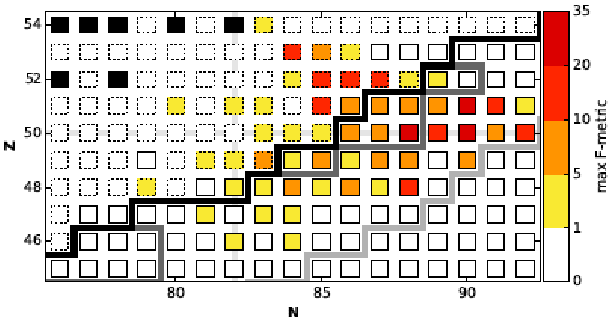

Figure 1: Nuclei which mass values significantly impact r-process abundances in the N=82 region. Nuclear masses listed in AME 2012 (black line) and accessibility limits for CARIBU (dark grey) and FRIB (light grey). It shows the importance of the properties of heavy Sn nuclei for the r-process. Figure is taken from [2].

due to the technical difficulties only the β-decay studies, isomeric studies and mass measurements were systematically done on these nuclei.

Altogether, there were only a very few experimental studies done on each of these Sn nuclei. Most of the experimental information on the excited states comes from the β-decay studies, which were performed between 1980 and 2004 at the (now closed) fission-product mass separator OSIRIS located at Studsvik in Sweden. During that period of time, the proton beam at ISOLDE was sent directly to hit the target creating enormous contaminating beams of mainly Cs, whose production exceeded by several orders of magnitude the desired In activities making such measurements impossible. The introduction of the neutron converter and laser ion source (RILIS) at ISOLDE drastically changed the experimental capabilities and allowed the investigation of exotic In decays.

Another drastic improvement came from the use of a new generation of detectors and experimental techniques. In particular clover detectors are much more efficient than the single crystal Ge used more than 20 years ago. Moreover in the fast timing measurements, the $LaBr_3$(Ce) crystals are characterized by 3 times better energy resolution while keeping the same time resolution, thus they allow, next to the standard $\beta\gamma\gamma$(t) measurements using the β-Ge-$LaBr_3$ detectors, also $LaBr_3$-$LaBr_3$(t) measurements, which are particularly useful for the levels located below long-lived isomers.

The present study is complementary to those that probe this region using other techniques, like the “Coulomb excitation of doubly magic ^{132}Sn at HIE-ISOLDE” (IS551), “Coulomb excitation of the neutron-rich ^{134}Sn and ^{136}Sn at HIE-ISOLDE” (IS549), and the “Laser spectroscopy of Tin and Cadmium” (IS573).

2 Theoretical Perspective

During the last two decades, there has been substantial progress in gaining experimental information on nucleon-rich nuclei far from the stability line, which has given evidence for changes in the shell structure when approaching the neutron drip line. In this context, nuclei in the regions of the shell closures with a large N/Z ratio, as for instance ^{132}Sn neighbours, are a subject of great interest, opening the opportunities for a better understanding of the forces that bind nucleons together.

New data have been acquired for nuclei around ^{132}Sn but until now no clear evidence for changes in the shell structure have been observed, as was the case in lighter mass regions. However, the available data have shown some anomalies, one of the most notable ones being the asymmetry in the behavior of the properties of the yrast 2^+ state in Sn and Te isotopes with respect to the 82 neutron shell closure. Further information is needed to clarify the nature of this feature.

A proposed explanation for the asymmetry in the energy behavior of the 2^+ state is the reduction of the neutron pairing when crossing N=82 and in this connection it may be very useful to investigate the semi-magic Sn isotopes. These nuclei, which are good candidates to be studied within the shell model, may give information on the neutron-neutron interaction. In particular, by focusing on the two nearest neighbours below and above the doubly-magic ^{132}Sn, we may test this interaction for neutron holes in the 50-82 shell and neutron particles in the 82-126 shell, respectively.

The one-body components of the two shell-model Hamiltonians, below and above the shell closure, can be taken from the experimental spectra of the two odd nuclei ^{131}Sn and ^{133}Sn. Then one can study the two even-even systems ^{130}Sn and ^{134}Sn, whose properties are directly related to the two-body matrix elements of the effective interactions. However, as mentioned above, a better comprehension of this region requires not only more data but in some cases also more precise data.

The single-particle structure of ^{133}Sn has been investigated through the ^{132}Sn(d,p) reaction recently performed at the Holifield RIBF facility at Oak Ridge National Laboratory [3, 4]. In this experiment, the spectroscopic factors of the $7/2^-$, $3/2^-$, and $5/2^-$ states, previously observed in β-decay studies [5], were extracted, evidencing a little fragmentation of the single-particle strength. Furthermore, a strong candidate for the $2p_{1/2}$ single-particle orbit was identified at 1.363 MeV excitation energy, which is about 300 keV lower than the previously proposed value [5]. The observed state at 1.561 MeV, not significantly populated, was associated with the $9/2^-$ state of Ref. [5], expected to correspond to the $0h_{9/2}$ orbit. It is worth noting that no $13/2^+$ state has yet been observed in ^{133}Sn. Clearly, in this context, it would be very interesting to get information of the position of the $13/2^+$ state as well as to have a confirmation of the new value of the $1/2^-$ state.

As for ^{131}Sn, information on the single-particle nature of the observed states is not available, since no one-particle transfer experiments have been performed up to now, although all the levels with angular momentum and parity corresponding to the five orbits of the 50-82 shell have been identified. However, a more precise value of the the position of the $h_{11/2}$ neutron-hole orbit is certainly desirable. In recent shell-model calculations [6, 7], the adopted energy of this orbit arises from the β-decay experiment of Ref. [8], where the value of 69 ± 14 keV was measured.

The nucleus of ^{134}Sn is the most interesting case of a two-valence system. Here only the ground and the yrast 2^+, 4^+, 6^+, and 8^+ states have been observed, the first four states

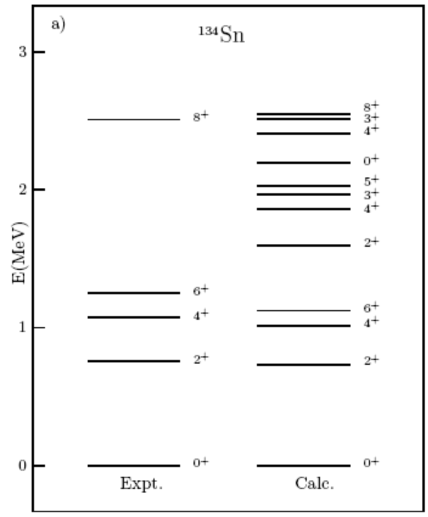

Figure 2: The level scheme in ^{134}Sn from experiment and model calculations, showing the positions of the predicted low spin states, which are of interest to this proposal.

being separated by an energy gap of about 1.5 MeV from the 8^+ state. This experimental spectrum is very well reproduced by the realistic shell-model calculation of Ref. [9], where the four lowest states have been interpreted as the members of the $(\nu f_{7/2})^2$ multiplet while the highest one as the maximum-aligned state of the $\nu f_{7/2}h_{9/2}$ configuration. In the energy interval between the 6^+ state at 1.1 MeV and the 8^+ state at 2.5 MeV, this calculation predicts the existence of other states, namely the members of the $\nu f_{7/2}p_{3/2}$ and $\nu f_{7/2}p_{1/2}$ multiplets and of the 0^+ state of the $(\nu p_{3/2})^2$ configuration. The identification of these missing states above the 6^+ state is critical as it gives us the possibility to test other matrix elements of the effective interaction besides those related to the $(\nu f_{7/2})^2$ and $\nu f_{7/2}h_{9/2}$ configurations. A better insight into the structure of this exotic nucleus may be provided also by the measurements of other properties as the electromagnetic transition rates. Only the $B(E2)$ for the 6^+ to 4^+ and 2^+ to 0^+ transitions are presently known.

3 Experimental Details

Detectors: The IDS station will include a modified T-section, two LaBr$_3$(Ce) and two clover detectors and a 2-inch β detector positioned at the tape station in a close geometry.

Indium yields: Table I indicates the expected intensities at the IDS station. The In yields are taken from Ref. [10] and increased by 50% due to the recent changes in the neutron converter, proton beam of 2μA and the transmission of 86% to the IDS station.

Expected results:

^{130}**Sn:** Test measurements conducted in 1991 indicated that substantial modifications are needed to the level scheme from the β decay of ^{130}In published in 1980. There are also several level lifetimes in ^{130}Sn measurable by the fast timing technique.

^{131}**Sn:** We expect an increase in the measurement sensitivity by a factor of ~20 in com-

Table 1: Production yields of In and intensities at IDS for $^{130-134}$In.

Isotope	Yield [10]	Intensity at IDS	Requested shifts
	per *mu*C	pps	
^{130}In	$>3.5\times10^5$	$>9\times10^5$	3
^{131}In	$\sim5\times10^4$	$\sim1.3\times10^5$	3
^{132}In	8000	20000	4
^{133}In	900	2300	5
^{134}In	$\sim$95	$\sim$250	7

parison to the previous study from 2004. The key aspect is to confirm by coincidence measurements the $h_{11/2}$ single particle level at 65.1 keV. We will also measure lifetimes of the excited states including the 331-keV $1/2^-$ level and a few levels at about 4.5 MeV populated from the high-spin $(21/2^+)$ isomer in In.

^{132}**Sn:** The sensitivity of our study will be 100 times higher than in the previous measurement from 1994. More than 50% of the expected particle-hole multiplet states have not been identified yet. Several level lifetimes will be measured with high precision giving critical transition rates.

^{133}**Sn:** Our sensitivity will $\sim$20 times higher than in the previous work from 1996. This will allow to measure $\gamma\gamma$ coincidences for selected transitions. The issue of single particle states remain open. We expect to measure 1-2 level lifetimes.

^{134}**Sn:** The aim of this study is to identify low-spin non-yrast states in this nucleus. We also expect to measure lifetimes or significant lifetime limits for a few levels.

Summary of requested shifts: we request 24 shifts: 3 shifts for ^{130}In, 3 for ^{131}In, 4 for ^{132}In, 5 for ^{133}In, 7 shifts for ^{134}In, and 2 shifts for the in-beam time calibrations (^{138}Cs).

References

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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
IDS	☒ 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 IDS 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]