EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

# Study of single-particle structure utilising long-lived radioactive beams during LS2

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**Abstract:** We propose to measure the ($d$,$p$) neutron-adding reactions using long-lived radioactive beams that can be extracted from the ISOLDE target during LS2. We will use the ISOLDE Solenoidal Spectrometer to study the low-lying single-particle strength in $^{127}$Sn, $^{211}$Po and $^{211}$Pb. All these cases enable the study of the evolution of single-particle structure away from stability, along chains of isotopes and isotones near shell closures. A systematic study of the stable Sn isotopes will be extended towards $^{132}$Sn, measuring the single-particle states approaching $N = 82$. Whilst the study of states in $^{211}$Po will allow an investigation of the evolution of neutron single-particle energies along Z=83, with the long-term aim of extending this study further from stability. Single-particle states in $^{211}$Pb will serve as a test of shell-model calculations near a doubly-magic shell closure.

**Installation:** ISOLDE Solenoidal Spectrometer (ISS)

# 1 Physics cases

Single-particle behaviour underpins much of our understanding of nuclear structure. Studying the evolution of single-particle structure across chains of isotopes/isotones can highlight the roles of different components of the nucleon-nucleon interaction in driving the observed changes and provide tests of the predictive power of modern shell-model calculations. Measurements of transfer reactions, an ideal tool for probing single-particle states, across chains of stable isotopes and isotones have been carried out in recent years [1, 2, 3, 4]. These studies elucidated on the role of the tensor interaction in driving changes in high-$j$ single-particle energies for both neutrons and protons. The energies and intensities of radioactive beams at HIE-ISOLDE, conducive to robust transfer-reaction measurements, allow an extension of these studies to more exotic regions of the nuclear chart away from stability. The ISOLDE Solenoidal Spectrometer (ISS) is being commissioned to take full advantage of these beams for direct-reaction studies. The ISS magnet has recently been successfully energised to 2.75 T and has since been moved into the HIE-ISOLDE hall. Plans are underway to use the HELIOS silicon array from Argonne National Laboratory for science exploitation before LS2.

Several cases are presented here to utilise long-lived beams offline from the ISOLDE production targets (i.e. no protons on target) during LS2.

## 1.1 Evolution of single-neutron states in the Sn isotopes - $^{126}$Sn($d$,$p$)

It is proposed to study the $^{126}$Sn($d$,$p$)$^{127}$Sn in inverse kinematics. This will extend a recent systematic study of the even Sn isotopes made using stable targets [5]. Neutron-adding and -removing reactions have been measured systematically on the stable even Sn isotopes to robustly determine the neutron occupancies and vacancies of these systems. The ($d$,$p$) reaction will be used to probe the vacancy of the orbitals in $^{126}$Sn as well as confirming the location of the low-lying single-particle states in $^{127}$Sn. The orbitals of interest in this region are the $2s_{1/2}$, $1d$ and $0h_{11/2}$. These data will help complete the picture of the evolution of these single-particle orbitals away from the stable tins towards the shell closure at $^{132}$Sn. The relative location of the $1f_{7/2}$ strength to the $0h_{11/2}$ is also of interest as an indication of the evolution of single-particle states above $N = 82$ towards $^{132}$Sn.

These data will also be necessary to ascern the participating orbitals in driving the evolution of the effective single-particle energies of the single proton outside the $Z = 50$ core.

## 1.2 Single-particle evolution along $N = 126$ - $^{210}$Po($d$,$p$)

The $N = 126$ isotones provide another location in the nuclear chart where the evolution of single-neutron behaviour can be studied. Along $N = 126$, transfer reations have been performed on the stable $^{208}$Pb and $^{209}$Bi, but there is little data elsewhere which is directly sensitive to the single-particle behaviour. HIE-ISOLDE is uniquely able to provide access to radioactive beams in this region at intensities and energies with which to probe single-particle properties using transfer reactions. Measurements of the single-neutron properties of $^{211}$Po using a long-lived $^{210}$Po beam is the first step in probing along this isotonic chain north of $^{208}$Pb - with $^{212}$Rn and $^{214}$Ra also tantalising prospects at HIE-ISOLDE in the future. Measurements have been made in the past using a radioactive $^{210}$Po target [6], however, only the strongest low-lying states were assigned with many observed states left with no spin-parity assignments and so there are questions remaining on the distribution of single-particle strength. Although the ($d$,$p$) reaction allows a robust study of low-$\ell$ states in the residual nucleus, it will also populate higher-$\ell$ orbitals with distinctive angular distributions. These states will have large overlaps with the $h_{9/2}$ proton orbital and so the evolution of the high-$j$ neutron states as a function of high-$j$ protons filling the core will give insight into the role of the tensor interaction in this region. Proton-removal reactions on $^{210}$Po suggest that the majority of the proton occupation is in the $h_{9/2}$ orbital [7].

### 1.3 Single-particle structure along the Pb isotopes - $^{210}$Pb($d$,$p$)

Nuclei near doubly-magic shell closures provide good testing grounds for shell-model calculations. $^{210}$Pb is only two neutrons from the doubly-magic shell closure at $Z = 82$ and $N = 126$. Neutron-adding on this nucleus will probe the $1g_{9/2}$, $0i_{11/2}$, $0j_{15/2}$, $2d_{5/2}$, $3s_{1/2}$, $1g_{7/2}$ and $2d_{3/2}$ single-particle strength in $^{211}$Pb to varying degrees. The reaction is best suited to the study of the $2d$ and $3s_{1/2}$ states, but will also locate the higher-$j$ strength. These data will act as a test of modern shell model calculations and can be used to predict the evolution of single-particle structure further from doubly-magic $^{208}$Pb.

## 2 Experimental details

***Reaction and beam energy*** – We propose to use the ISOLDE Solenoidal Spectrometer (ISS) to analyze protons from single-neutron adding ($d$,$p$) reactions at an incident beam energy of 10 MeV/u to probe single-particle structure in $^{127}$Sn, $^{211}$Po and $^{211}$Pb. This energy has been chosen to maximise the cross-section for transfer to all states of interest, in particular high-$j$ states, whilst also achieving characteristic, forward peaked, angular distributions that enable assignments to be made.

***Beam production*** – In the decay chain of $^{228}$Th ($T_{1/2} = 1.9$ years), there is a waiting point at $^{210}$Pb ($T_{1/2} = 22.2$ years), which will have built up in UCx targets irradiated in the past. We propose using RILIS to extract $^{210}$Pb beams from previously irradiated UCx targets.
$^{210}$Po ($T_{1/2} = 138$ days), on the other hand, is directly produced and is volatile enough to be released from hot UCx targets. Therefore, irradiation of a cold target unit may be required at the very end of ISOLDE operation prior to LS2 to maximise the $^{210}$Po yield in the target. The yield expected and the irradiation time required will be calculated following discussions with the ISOLDE TISD team.
The case of $^{126}$Sn ($T_{1/2} = 2.3\text{E}5$ years) may also require the irradiation of a cold UCx target in a similar fashion to $^{210}$Po.

***Experimental set-up*** – We will use the ISS to momentum analyse the outgoing protons from the reactions of interest, measuring energies and yields of protons from population of final states within the residual nuclei. Radioactive beams of interest will be incident on a deuterated polyethylene ($CD_2$) positioned on the magnetic axis of the solenoid. The protons from the $(d,p)$ reactions are emitted in the backwards hemisphere of the magnet and follow helical orbits in the field of the solenoid returning to axis after a single cyclotron period where they are intercepted by a position-sensitive array. As with experiments IS621 and IS631 it is proposed to use the array and associated electronics from the HELIOS spectrometer at Argonne National Laboratory [8, 9]. A $Q$-value resolution of $\sim$75 keV is expected based on past performance of this array. Measurements made in the later part of LS2 could make use of the newly developed advanced ISS silicon array. This array is being constructed as part of the UK ISOL-SRS project with the array due to be shipped in stages to CERN from November 2019. The anticipated resolution of this device will be $\sim$20-30 keV. The extracted cross sections from the intended measurements will be compared to calculations using the DWBA code Ptolemy [10] in order to obtain information on the $\ell$ of the final state in the residual nuclei and the spectroscopic factor.

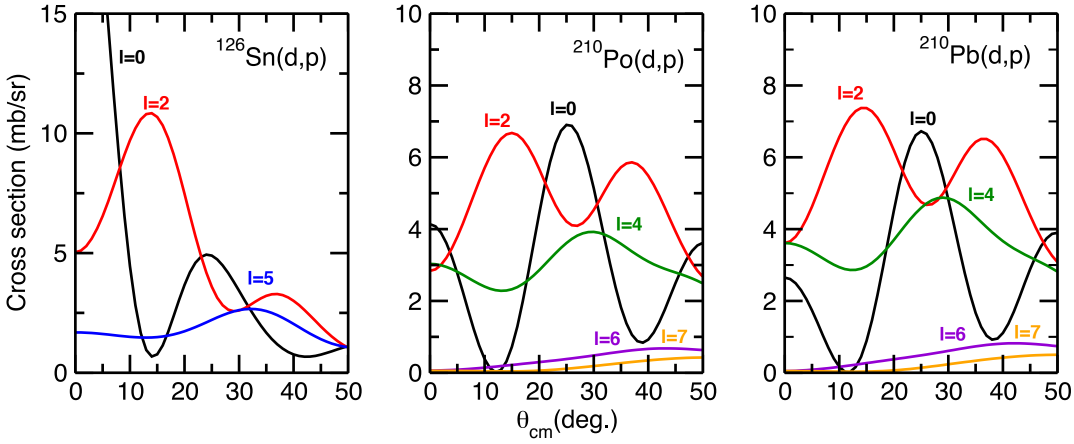

Figure 1: Angular distributions calculated for $^{126}$Sn($d$,$p$), $^{210}$Po($d$,$p$) and $^{210}$Pb($d$,$p$) reactions at 10 MeV/u using DWBA code Ptolemy. Distributions are labelled with the transferred angular momentum.

***Beam time estimates*** – Rate estimates are calculated assuming an angular coverage of $\theta_{cm}$=10–40°, with a 50% efficiency in the azimuthal angle and 85% efficiency in the theta angle. Cross sections for transfer to the states of interest have been calculated using the DWBA code Ptolemy, shown in Fig. 1, and a minimum yield of 1000 counts in a low-$\ell$ peak of interest across the array. Assuming a beam intensity of at least $10^5$ pps and a target thickness of 100 $\mu g/cm^2$ then these measurements would require 6 days of beam on target of $^{126}$Sn, and 7 days for $^{210}$Po and $^{210}$Pb to achieve the minimum acceptable level of statistics. We would therefore require the requisite beams at HIE-ISOLDE energies with a minimum intensity of $10^5$ pps.

***Stable commissioning beams*** – In addition to the aforementioned long-lived beams, accelerated stable noble-gas beams will be required from HIE-ISOLDE at different stages of ISS commissioning. These will be used to prepare for radioactive beam runs - to test electronics and array alignment - as well as for commissioning the advanced ISS silicon array during LS2. Stable isotopes of Ne, Ar, Kr or Xe will be used for this purpose. As such stable beam running on HIE-ISOLDE will also be required during LS2. It is envisaged that at least a week is required for the stable commissioning of the new array plus a day of stable beam for calibration before a radioactive beam experiment. These noble-gas beams do not require the production target and can be produced directly from the EBIS.

# References

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# Appendix

## DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: The ISOLDE Solenoidal Spectrometer

| | Availability | Design and manufacturing |
|---|---|---|
| ISOLDE Solenoidal Spectrometer | ☒ Existing | ☐ To be used without any modification |
| Advanced silicon array | ☐ Existing | ☐ To be used without any modification<br>☐ To be modified |
| | ☒ New | ☐ Standard equipment supplied by a manufacturer<br>☒ CERN/collaboration responsible for the design and/or manufacturing |
| Fast ionisation detector | ☐ Existing | ☐ To be used without any modification<br>☐ To be modified |
| | ☒ New | ☐ Standard equipment supplied by a manufacturer<br>☒ CERN/collaboration responsible for the design and/or manufacturing |

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

| Hazards | | | |
|---|---|---|---|
| **Thermodynamic and fluidic** | | | |
| Pressure | | | |
| Vacuum | | | |
| Temperature | 4 K | | |
| Heat transfer | | | |
| Thermal properties of materials | | | |
| Cryogenic fluid | LHe, $\sim$1650 l, $LN_2$, $\sim$200 l, 1.0 Bar | | |
| **Electrical and electromagnetic** | | | |
| Electricity | 0 V, 300 A | | |
| Static electricity | | | |
| Magnetic field | 2.5 T | | |
| Batteries | | | |
| Capacitors | | | |
| **Ionizing radiation** | | | |
| Target material | Deuterated polyethylene | | |
| Beam particle type | $^{126}$Sn,$^{210}$Pb,$^{210}$Po | | |

| | | | |
|---|---|---|---|
| Beam intensity | $>1\times10^5$ | | |
| Beam energy | 10 Mev/u | | |
| Cooling liquids | | | |
| Gases | | | |
| Calibration sources: | ☒ | | |
| • Open source | ☒ ($\alpha$ calibrations source) | | |
| • Sealed source | | | |
| • Isotope | | | |
| • Activity | | | |
| Use of activated material: | | | |
| • Description | | | |
| • Dose rate on contact and in 10 cm distance | | | |
| • Isotope | | | |
| • Activity | | | |
| **Non-ionizing radiation** | | | |
| Laser | | | |
| UV light | | | |
| Microwaves (300MHz-30 GHz) | | | |
| Radiofrequency (1-300 MHz) | | | |
| **Chemical** | | | |
| Toxic | | | |
| Harmful | | | |
| CMR (carcinogens, mutagens and substances toxic to reproduction) | | | |
| Corrosive | | | |
| Irritant | | | |
| Flammable | | | |
| Oxidizing | | | |
| Explosiveness | | | |
| Asphyxiant | Helium | | |
| Dangerous for the environment | | | |
| **Mechanical** | | | |
| Physical impact or mechanical energy (moving parts) | | | |
| Mechanical properties (Sharp, rough, slippery) | | | |

| | | | |
|---|---|---|---|
| Vibration | | | |
| Vehicles and Means of Transport | | | |
| **Noise** | | | |
| Frequency | | | |
| Intensity | | | |
| **Physical** | | | |
| Confined spaces | | | |
| High workplaces | | | |
| Access to high workplaces | | | |
| Obstructions in passageways | | | |
| Manual handling | | | |
| Poor ergonomics | | | |

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above):