EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Determination of single-neutron energies and spectroscopic factors outside ^{132}Sn

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B. P. Kay[1], S. J. Freeman[2,3], D. K. Sharp[2], Y. Ayyad[4], D. Bazin[5], F. Browne[3], P. A. Butler[6], J. Cederkall[7], A. Ceulemans[8], J. Chen[9], K. A. Chipps[10], D. J. Clarke[2], A. J. Dolan[6], L. P. Gaffney[6], R. Grzywacz[10,11], A. Heinz[12], C. R. Hoffman[1], H. T. Johansson[12] B. R. Jones[6], K. L. Jones[11], A. Kawecka[12], M. Labiche[13], I. Lazarus[13], A. Lopez[7] A. O. Macchiavelli[10], P. T. MacGregor[3], M. V. Managlia[12], R. Page[6], S. D. Pain[10], M. Piersa-Siłkowska[3], O. Poleshchuk[8] R. Raabe[8], S. Reeve[2], F. Recchia[14,15], G. Savard[1], J. F. Smith[16], T. L. Tang[17], H. T. Törnqvist[12], A. H. Wuosmaa[18], and Z. Y. Xu[11].

[1]*Physics Division, Argonne National Laboratory, Lemont, IL 60439, USA*
[2]*Schuster Laboratory, The University of Manchester, Oxford Road, Manchester M13 9PL, UK*
[3]*ISOLDE, CERN, CH-1211 Geneva 23, Switzerland*
[4]*IGFAE, Universidade de Santiago de Compostela, E-15782, Santiago de Compostela, Spain*
[5]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*
[6]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK*
[7]*Physics Department, Lund University, Box 118, Lund SE-221 00, Sweden*
[8]*Instituut voor Kern- en Stralingsfysica, KU Leuven, Belgium*
[9]*College of Science, Southern University of Science and Technology, Shenzhen, China*
[10]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[11]*Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA*
[12]*Institutionen för Fysik, Chalmers Tekniska Högskola, S-412 96 Göteborg, Sweden*
[13]*STFC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK*
[14]*Dipartimento di Fisica e Astronomia, Universitá degli Studi di Padova, I-35131 Padova, Italy*
[15]*INFN, Sezione di Padova, I-35131 Padova, Italy*
[16]*Nuclear Physics Group, The University of the West of Scotland, Paisley PA1 2BE, UK*
[17]*Department of Physics, Florida State University, Tallahassee, FL 32306, USA*
[18]*Department of Physics, University of Connecticut, Storrs, CT 06269, USA*

Spokespersons: B. P. Kay (kay@anl.gov), S. J. Freeman (sean.freeman@cern.ch), and D. K. Sharp (david.sharp@manchester.ac.uk)
Contact person: P. T. MacGregor (patrick.macgregor@cern.ch)

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Abstract: We propose a study of the (d,p) reaction on ^{132}Sn at an energy of $\geq$7 MeV/u, several MeV/u above the Coulomb barrier, to provide a determination of single-neutron energies and spectroscopic factors outside of ^{132}Sn. These are the valence neutron orbitals $1f_{7/2}$, $2p_{3/2}$, $2p_{1/2}$, $0h_{9/2}$, $1f_{5/2}$, and $0i_{13/2}$. The location of the $0i_{13/2}$ strength, likely carried by a single $13/2^+$ state is not decisively known, with speculations as to whether it is bound or not. The $0h_{9/2}$ strength has not been probed via single-nucleon transfer either, though its energy is known. The combination of the HIE-ISOLDE beam intensity and energy for ^{132}Sn, and the ISOLDE Solenoidal Spectrometer (ISS), make this the only

practical facility in the world where this measurement can currently be done, expanding on the pioneering measurement of Jones *et al.* [Nature **465**, 454 (2010)] for the first time. Knowledge of the location of these single-neutron excitations and their overlaps is essential to robustly define effective interactions in this region, foundational for our understanding r-process nucleosynthesis around $N = 82$, and enhancing our knowledge of weak-binding effects on low-ℓ spin-orbit partners.

Requested shifts: 21 shifts
Installation: ISOLDE Solenoidal Spectrometer

Physics Case (draft)

The pattern of single-particle excitations outside of ^{132}Sn has held a long-standing fascination in the field. Outside of the five stable doubly magic nuclei, ^{4}He, ^{16}O, ^{40,48}Ca, and ^{208}Pb, ^{132}Sn is the heaviest short-lived doubly magic nucleus making the study of excitations built up on it challenging. For example, performing transfer reactions such as the (d,p) neutron-adding reaction is more challenging than for stable species. The development of the solenoidal-spectrometer technique was strongly motivated by this physics case [1–3], providing both the means to resolve all the low-lying states and the efficiency to reveal the high-j states which are weakly populated in (d,p) reactions. We propose a measurement of the ^{132}Sn(d,p) reaction at $\geq$7 MeV/u using the ISS—the beam energy and intensity at ISOLDE offer a combination that will not be rivaled for many years elsewhere [4–6].

Over the decades, there have been many attempts to identify valence $1f_{7/2}$, $2p_{3/2}$, $2p_{1/2}$, $0h_{9/2}$, $1f_{5/2}$, and $0i_{13/2}$ single-neutron excitations outside of ^{132}Sn, generally believed to be "pure" single-particle states. β decay and β-delayed neutron emission have been among the most powerful approaches, with data from, among others, the ISOLDE Decay Station playing a key role in identifying a subset of these states [7–12], including states above the neutron separation energy.

In 2010, a pioneering measurement of the ^{132}Sn(d,p) reaction was carried out at Oak Ridge National Laboratory at a beam energy of 4.77 MeV/u using a barrel-like array of silicon detectors [13]. The measurement allowed for the first time a determination of the single-particle strength of the levels corresponding to the $1f_{7/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ orbitals. These states appear to carry all the single-particle strength [14], confirming the doubly magic nature of ^{132}Sn. However, due to the low beam energy, below the barrier in the outgoing channel for all bar the ground state, the high-j states were not populated and in the case of the $0h_{9/2}$ excitation, could not be observed due to the limited resolution. The $9/2^-$ was seen in a later sub-barrier heavy-ion transfer experiment apparently with a lower spectroscopic factor than the $1f$ and $2p$ states observed in the (d,p) study [15]. This proposed measurement aims at observing the $9/2^-$ and $13/2^+$ states and extracting their spectroscopic factors.

Theoretical calculations suggest that these states will carry a significant fraction of the single-particle strength, for example, Refs. [16, 17], as naively expected. Effective interactions developed for this region typically assume the energy of the $13/2^+$ to be 2600 or 2700 keV, including advanced Monte Carlo Shell Model calculations [18]. There have been numerous estimates made from existing data in the region and extrapolations [19–22], with most being around ∼2680 keV, though the range is around 2330–2800 keV. We note that Ref. [15] made a passing comment on an observed 2792-keV γ ray as a possible candidate for the $13/2^+$ state, though ruled it out, and the recent work of Piersa-Siłkowska *et al.* [10] make a tentative assignment at 2434 keV, very close to S_n.

The evolution of single-neutron states outside of $N = 82$ has been robustly tracked from ^{145}Sm ($Z = 62$) to ^{137}Xe ($Z = 54$) experimentally [21–32]. The changes in the location of the high-j $9/2^-$ and $13/2^+$ strength — which have characteristic fragmentation patterns [33] demanding the centroids to be determined via single-nucleon transfer reactions — is an emphatic demonstration of the action of the tensor force in the evolution of effective single-particle energies [34], as protons predominately fill the $0g_{7/2}$ and $1d_{5/2}$ orbitals above $Z = 50$ to the $Z = 64$ subshell closure [35, 36]. These trends have yet to be extended through ^{135}Te to ^{133}Sn, though limited information is available, as shown in Figure 1. The fragmentation of the $0h_{9/2}$ and $0i_{13/2}$ strength into two or three fragments observed from Sm to Xe, and expected in Te, is predicted to collapse into a single state in ^{133}Sn, as appears to be the case with the $2p$ and $1f$ strength demonstrated by Jones *et al.* [13].

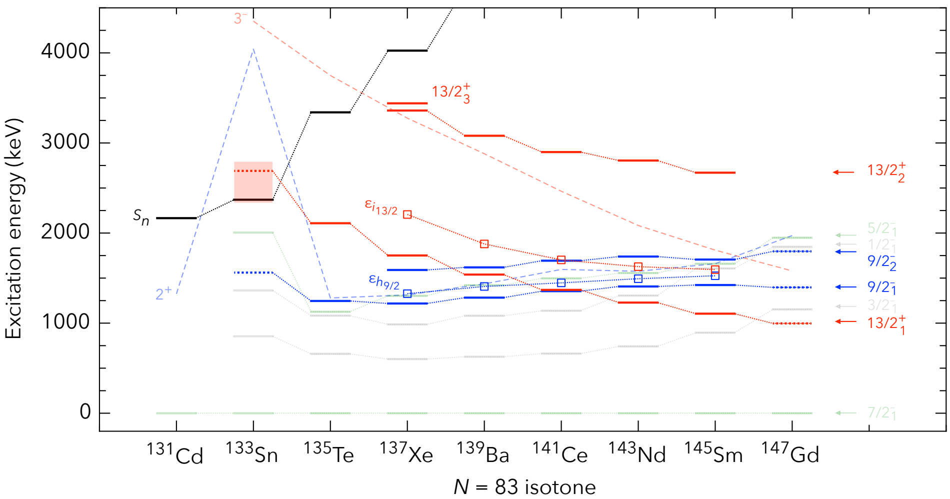

Figure 1: Excitation energy of core 2^+_1 and 3^-_1 excitations in the respective $N = 82$ isotones (dashed lines). For the $N = 83$ isotones, the neutron separation energy (S_n, black), the first $\ell = 3$ ($7/2^-_1$, $5/2^-_1$, faded green), $\ell = 1$ ($3/2^-_1$, $1/2^-_1$, faded gray), and the characteristic fragments of the high-j $0h_{9/2}$ (blue lines) and $0i_{13/2}$ (red) strength and the respective centroids, ε, shown by the empty squares. The dashed horizontal levels have not been observed in light-ion transfer reactions. Data from Refs. [37, 38]. The shaded region at ^{133}Sn shows the range of estimates (including the recent tentative claim) for the $13/2^+$ state.

The crossing of the $N = 82$ shell gap in the r process has been the focus of extensive experimental and theoretical study around the $Z \sim 50$, $N \sim 82$ region (Ref. [39], and those within), with ^{133}In, which β decays into ^{133}Sn, being recently dubbed a Rosetta Stone for decays in r-process nuclei [11]. While the attribution is made with emphasis on the more complex states above threshold, it still exemplifies the need for robust data on single-particle excitations in the region.

We consider the proposed ^{132}Sn(d,p) measurement as a keystone for the region, and a precursor to revisiting the ^{134}Te(d,p) measurement done at Oak Ridge [40], likely possible at ISOLDE or FRIB in the coming years. Furthermore, there is the exciting prospect of measuring the low-ℓ states in ^{131}Cd using, for example, a ^{130}Cd beam on an active deuterium target in the ISS, where the weak binding of the p-states (see Fig. 1) already at ^{133}Sn show hints of deviation from the Mairle [41] trends [42], similar to what is seen in the $N = 20$ region [43].

Experimental Approach

We will use the ISOLDE solenoidal spectrometer to analyze protons from the (d,p) reaction on ^{132}Sn at $\geq$7 MeV/u and an estimated intensity between $1 \times 10^{6-7}$ pps [44] at the ISS target position. We consider 7 MeV/u and 10^6 pps as practical lower limits for the beam energy and intensity.

Beam energy—Figure 2(a) shows the estimated counts integrated across the ISS silicon detector per shift (8 hours) of beam time for each of the states expected to be populated below 3 MeV in excitation energy in the ^{132}Sn(d,p) reaction as a function of beam energy. The calculations were carried out using the distorted-wave Born approximation (DWBA) with the Ptolemy code [45]. Typical bound-state form factors were used along with global optical-model parameters (Ref. [46] for deuterons and Ref. [47] for protons) to describe the distorting potentials. A beam intensity of 1×10^6 pps, a target thickness of 100 μg/cm^2, a 70% geometrical acceptance in azimuthal angle, and $10^\circ \lesssim \theta_{\text{c.m.}} \lesssim 40^\circ$ angular coverage (slightly less above S_n, around $10^\circ \lesssim \theta_{\text{c.m.}} \lesssim 35^\circ$).

The work of Ref. [13], done at 4.77 MeV/u, was essentially at the Coulomb barrier for transfer to the ground state, and below the barrier in the exit channel for excited states. At 7 MeV/u, the reaction is a few MeV/u above the barrier in the entrance and exit channels over the excitation range of interest. This beam energy is close to optimal, in terms of yield, for $\ell = 1$ and 3 transfers. Going from 4.77 to 7 MeV/u gives a remarkable order-of-magnitude increase in yield for $\ell = 5$ and 6 transfers, times 9.5 and 14.7, respectively. This makes the measurement feasible for the first time and allows for the reliable extraction of spectroscopic factors using models, such as DWBA, ideally suited for this energy regime [48]. We stress that, of course, pushing to higher energies only benefits the measurement—7 MeV/u is used as a practical lower limit in our simulations and calculations [49].

Figures 2(b-e) show that at $\geq$7 MeV/u, robust identification of the $13/2^+$ state can be made. Figure 2(b) is the characteristic energy versus position plot showing the kinematic lines for each state, where the angular-distribution shape can be noted in from the intensity of the counts along the loci—this is particularly evident for the predicted $13/2^+$, shown here at 2.68 MeV (but as discussed above, could be in the range of approximately 2.33-2.79 MeV). These are simulated using the well-established DIGIOS software package [50]. This will be discussed more below.

The resulting excitation-energy spectrum, Fig. 2(c), shows that the yield alone is indicative of the spin-parity of a given state (here $S = 1$, which is known to be the case for the $1f$ and $2p$ states [13] and expected to be the case for all states from theoretical calculations [16, 17]). It also demonstrates the power of the solenoidal-spectrometer technique, allowing all states to be resolved (a FWHM of 175 keV is assumed; a typical value for the ISS). DWBA calculations of the differential angular distributions show distinctive features for $\ell = 1$, 3, 5, and 6 transfer at 7 MeV/u [Fig. 2(d)], with the simulated minimum counts over 15 shifts of beam time as a function of center-of-mass angle in Fig. 2(e).

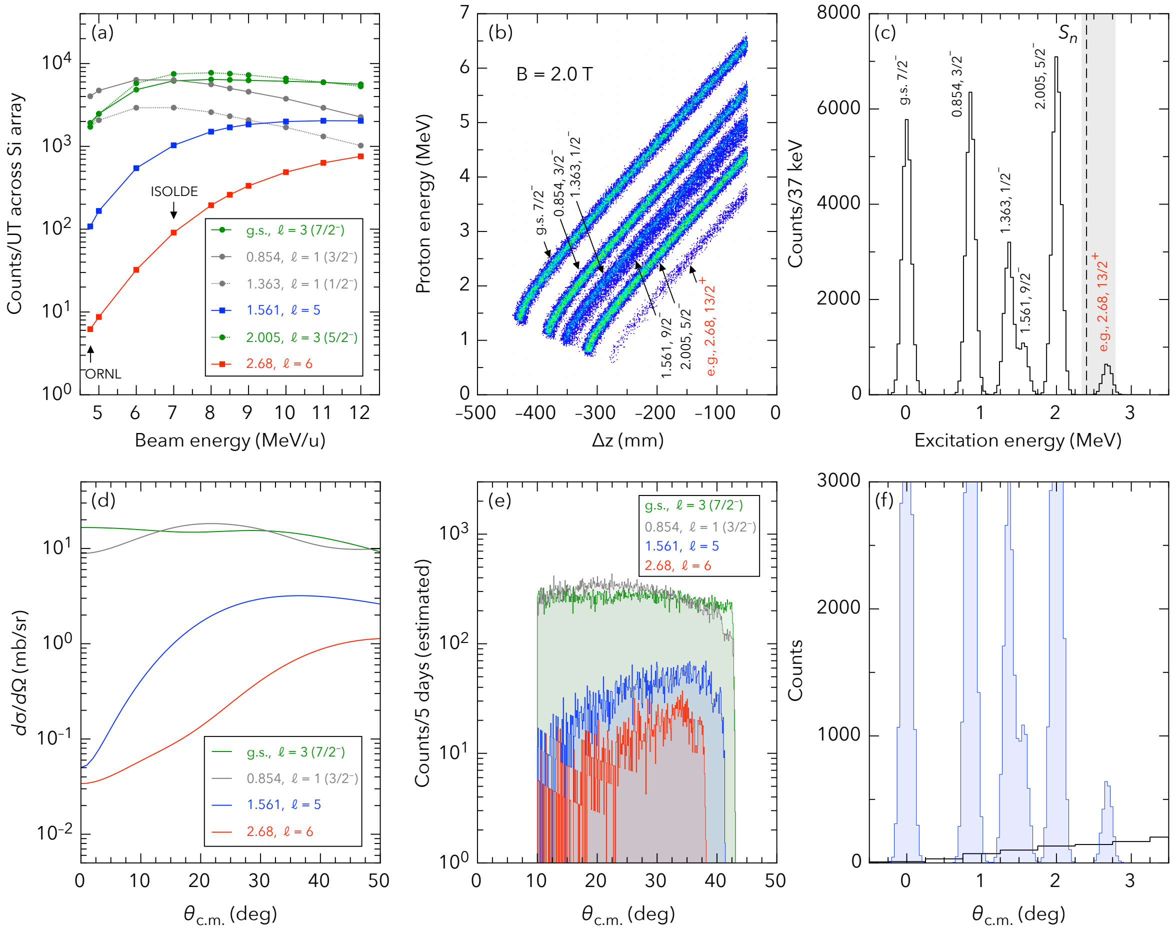

Figure 2: (a) Estimated (using DWBA and the parameters discussed in the text) counts per shift (8 hours) of beam on target across the silicon detector for states populated in the ^{132}Sn(d,p) reaction at different beam energies. The proton energy versus distance from the target (Δz) for states populated (b), assuming 175 keV FWHM and a 2 T B field, and the resulting excitation energy spectrum is shown in (c). DWBA calculations of the angular distributions for $\ell = 1$, 3, 5, and 6 transfer are shown in (d) and the resulting counts as a function of center-of-mass angle, taking into account the acceptance in (e). An estimate of the yield of protons from fusion-evaporation reactions (f) contrasted with the spectra in (c).

ISOLDE solenoidal spectrometer—The ISOLDE Solenoidal Spectrometer [51] has been prolific in its use as an instrument for (d,p)-reaction studies over the last five years, spanning the chart of nuclides with beams of ^{11}Be, ^{27}Na, ^{28}Mg [52], ^{30}Mg, ^{49,50}Ca, ^{61}Zn, ^{68}Ni, ^{94}Kr, ^{110}Sn, ^{206}Hg [53], and ^{212}Rn. A good Q-value resolution of around 150-175 keV

FWHM is readily achievable and with relatively pure beams, clean spectra can be extracted without recoil detection—indeed there is no practical solution for medium mass beams at this intensity. Of particular relevance to the experimental approach proposed here are the data reported in Ref. [53], where proton yields from the ^{206}Hg(d,p) reaction at 7.38 MeV/u and $\sim 5 \times 10^5$ pps were measured cleanly without recoil detection at ISS. Similarly, IS689, explored the same reaction on ^{212}Rn at a higher intensity of $\sim 1\times10^6$ pps, observing the $\ell = 6$, $0i_{11/2}$ strength—the spin-orbit partner to the $0i_{13/2}$ we seek in this measurement. A demonstration of the capabilities of solenoidal spectrometers with beams in this mass region was done using HELIOS at Argonne with the ^{136}Xe(d,p) reaction at similar beam energies and intensities as proposed here [31], revealing the $\ell = 5$ and $\ell = 6$ strength in a much more complex and fragmented system. We note that spectroscopic factors for the $\ell = 5$ and 6 strength extracted from Ref. [31], matched very favorably with those from a higher energy (α,^{3}He)-reaction study [22], where simple arguments suggest ideal momentum matching (see also Ref. [49]). The feasibility of the proposed measurement is therefore not in doubt.

Reaction kinematics and experimental setup—We will use a conventional "(d,p) set up." Protons emitted at forward center-of-mass angles from the (d,p) reaction in inverse kinematics are emitted at backward angles in the laboratory. The ISS silicon array will be placed upstream of the target position, with a small separation of $\Delta z = -50$ mm. The small Q-value for this reaction and the beam energy of 7 MeV/u mean that the outgoing protons are of relatively low energy, between about 500 keV and less than 7 MeV over the range of the detector. The magnetic field of 2.0 T is chosen to ensure that protons do not hit the bore (higher field needed) of the solenoid and that they are sufficiently dispersed in angle (lower field desired). The diameter of the array is such that, at $\Delta z = -50$ mm, we see angles of $\theta_{\text{c.m.}} > 10^\circ$ for all excitations. Figures 2(b,c, and e) show the proton energy versus Δz for this setup, the resulting excitation energy spectrum, and angular acceptance per state, respectively.

The spectrum in Fig. 2(c) assumes that a smooth background of protons from fusion evaporation reactions between the beam and carbon in the target has been subtracted. Without recoil detection, this background will be present. We will run up to six shifts of the 21 shifts requested using a pure carbon target to ensure we have a statistically significant characterization of this background. Accounting for the areal density of the pure carbon foil compared with a polyethylene target, and with a modest increase in thickness to $\sim$150 μg/cm^2, comparable statistics can be obtained in six shifts without a modified detector response. Because ^{132}Sn is so neutron rich these backgrounds will be low. Calculations using the PACE4 code [54] suggest that protons emitted at backward laboratory angles will be, for example, 200-300 times fewer than for the ^{110}Sn beam (8 MeV/u) used in the IS686 run.

Targets—We will use deuterated polyethylene targets of thickness $\sim$100 μg/cm^2. These targets will be provided by Argonne National Laboratory. We now have extensive experience in the use of such targets with beams in this mass, energy, and intensity regime (we could comfortably tolerate 10^7 pps, the upper end of the estimated yield), where targets are known to degrade under bombardment. A monitor detector will be used to provide information on the target degradation (see Ref. [31, 53] for a discussion of this method).

The target mechanism for the ISS can accommodate multiple targets. Once a target is damaged, the typical metric being the point where it has 50% of its original effective thickness, a new one can be moved into the beam path without breaking the vacuum. The continuous monitoring of the deuterium (and carbon) content of the target coupled with the beam current being integrated throughout allows for absolute cross sections to be extracted.

Previous ISOLDE runs with Sn beams—Sn-132 beams have been post-accelerated at ISOLDE many times. Achieving at least 7 MeV/u and an intensity of 1×10^6 pps or greater is important and appears possible [44]. The beam is expected to be highly pure—the transmission of sulfide molecules to the EBIS should ensure that any contamination from the target will be negligible.

Rate estimates and shifts required—Rate estimates are based on the angular ($\theta_{\text{c.m.}}$) coverage shown in Fig. 2(e), which includes a 70% coverage in the azimuthal angle. Cross sections were calculated using DWBA with the code PTOLEMY as discussed above. We considered pure single-particle states at 0.000 ($7/2^-$, $\ell = 3$), 0.824 ($3/2^-$, $\ell = 1$), 1.363 ($1/2^-$, $\ell = 1$), 1.561 ($9/2^-$, $\ell = 5$), 2.005 ($5/2^-$, $\ell = 3$), and 2.68 ($13/2^+$, $\ell = 6$) MeV. The total measured yield of protons over five days [Fig. 2(a)] of the beam on target at 1×10^6 pps, and a target thickness of 100 μg/cm^2, is about 90,000, 95,000, 44,000, 15,000, 110,000, and 1000 counts, respectively, for these states. The beam time request is driven by the weak population of the crucial $13/2^+$ state. With 1000 counts distributed across the array, and with background considerations, one should be able to make a definitive claim of an observation and characterization of the $13/2^+$ state. We request a total of 21 shifts.

Summary

We request 21 shifts of beam time to carry out the (d,p) reaction on ^{132}Sn at $\geq$7 MeV/u in inverse kinematics. We will use the ISOLDE Solenoidal Spectrometer to analyze the outgoing protons. The number of shifts is based on a beam of 1×10^6 pps of ^{132}Sn on target. We will use six shifts to robustly assess the background from fusion evaporation. We will use a deuterated polyethylene target of thickness $\sim$100 μg/cm^2. It is expected that a Q-value resolution of 175 keV will be achieved. The goal is to, for the first time, identify the full complement of valance neutron excitations outside of doubly-magic ^{132}Sn, including determining the spectroscopic factors for the $0h_{9/2}$ and $0i_{13/2}$ excitations.

References

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[5] Expected FRIB-ReA6 beam rates: https://groups.nscl.msu.edu/frib/rates/fribrates.html, with ^{132}Sn anticipated to be $\sim 1 \times 10^5$ pps at full power (3-5 years from now) with energies around 9 MeV/u.
[6] Expected HIE-ISOLDE beam rates: https://isoyields2.web.cern.ch, with ^{132}Sn anticipated to be $\sim 3 \times 10^8$ particles per μC. With transport through the linac, we conservatively estimate $\sim 1 \times 10^6$ pps at the ISS. See Ref. [44] below.
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DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
ISOLDE Solenoidal Spectrometer (ISS)	☒ To be used without any modification ☐ To be modified

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☒	2.0 T
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards	Open sources	☒	α calibrations sources
	Open sources	☒	^{148}Gd, ^{239}Pu, ^{241}Am, ^{244}Cm
	Open sources	☒	4 kBq