Proposal to the IST Committee

Decay study for the very neutron-rich Sn nuclides, $^{135-140}$Sn separated by selective laser ionization

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Abstract

In this investigation, we wish to take advantage of chemically selective laser ionization to separate the very-neutron-rich Sn nuclides and determine their half-lives and delayed-neutron branches ($P_n$) using the Mainz $^3$He-delayed neutron spectrometer and close-geometry gamma-ray spectroscopy system. The beta decay rates are dependent on a number of nuclear structure factors that may not be well described by models of nuclear structure developed for nuclides near stability. Determination of these decay properties will provide direct experimental data for r-process calculations and test the large number of models of nuclear structure for very-neutron rich Sn nuclides now in print.
1. Introduction

The determination of the nuclear structure and decay properties of the very-neutron-rich Sn nuclides will simultaneously provide crucial experimental input data for astrophysical r-process calculations and provide incisive tests for models of nuclear structure where the neutron/proton ratio moves toward a value of 2/1. The development of highly selective Resonance Ionization Laser Ion Sources (RILIS) at ISOLDE in the last several years has resulted in the discovery of a number of new Ag, Cd, and Mn nuclides using the General Purpose Separator (GPS). Several of these nuclides lie directly in the path of the r-process. The new half-lives for Ag and Cd nuclides have made a significant impact on a better understanding of the astrophysical conditions that determine the $A = 130$ r-process abundance peak.\(^1\) Moreover, the decay of the odd-odd Mn nuclides populated levels in even-even Fe nuclides that led to the identification of a new region nuclear deformation at $N = 40$ for $^{66}$Fe.\(^2\) Part of this success of these experiments must be attributed to the well-developed Mainz $^{3}$He neutron detector that has both high sensitivity and low background, as well as the Mainz close-geometry gamma-ray detection setup. In this investigation, these detectors will be combined with laser ionization to extend study of the heavy Sn nuclides out toward $^{140}$Sn. The principal goals of these experiments are the measurement of the half-lives and delayed neutron branching values ($P_n$) for $^{135,136,137,138,139,140}$Sn. In addition, new half-life and $P_n$ values for daughter Sb and Te nuclides will be determined. Level structure data are also expected from the gamma-ray measurements, including the energy of the first $2^+$ level in $^{136}$Te.

This experiment, however, remains an adventure into the unknown. When the study of the decay of Mn nuclides separated via the RILIS was conceived, there was no hint of a new region of deformation. Neither did we expect laser hyperfine separation of nuclear isomers to prove quite important to the studies of the heavy Ag nuclides.\(^3\)
2. Nuclear structure factors

The basic factors that influence the decay of the heavy Sn nuclides are established in the decays of $^{133,134}$Sn shown in Figure 1, along with the single-particle levels of $^{133}$Sn. Decay of both $^{133}$Sn and $^{134}$Sn is dominated by forbidden transitions with log ft values of 5.4 and 5.1, respectively, in which an $f_{7/2}$ neutron undergoes beta decay to either the $g_{7/2}$ proton ground state or $d_{5/2}$ first excited state. In addition, a strong the Gamow-Teller spin-flip decay is observed for $^{134}$Sn decay in which an $h_{9/2}$ neutron is converted into an $h_{11/2}$ proton. This transition populates a $1^+$ level at 3850 keV that lies well above the neutron separation energy $S_n$ and gives rise to a 13% delayed neutron branch. As neutron number increases, this Gamow-Teller spin-flip transition will play a role that is highly dependent on how nuclear properties shift with increasing neutron number in these very neutron-rich nuclides.

The properties of Sn nuclides beyond $N = 82$ have proven to be an interesting challenge for theoretical calculations. For example, the known structure of $^{134}$Sn is shown in Figure 2 where $2^+$, $4^+$, and $6^+$ levels are found at lower energies than calculated either by Chou and Warburton or by Erokhina and Isakov. Calculations for other important properties of heavy Sn nuclides have also been presented in the literature that are important to the evolution of the decay properties. In Figure 3, we show the results of two recent calculations, one for the changes in proton and neutron radii published by Hoffman and Lenske, and one for two-neutron separation energies published by Chabanat et al.

The crucial factors for the decay of the heavy Sn nuclides will be the $Q_p$ values as well as both the position and occupancy of the $h_{9/2}$ and $p_{3/2}$ neutron orbitals which lie at 1561 and 854 keV, respectively, in $^{133}$Sn, and the position of the daughter $h_{11/2}$ proton orbital that lies at 2791 keV in $^{133}$Sb.
Figure 1. Data for $^{133}\text{Sn}$ levels and decay and $^{134}\text{Sn}$ decay.
Figure 2. Experimental and Calculated levels for $^{134}\text{Sn}$. 
Root mean square radii of the tin isotopes from density dependent Hartree-Fock calculations using the D3Y interaction with \( r_0 = 5 \) for neutrons (squares) and protons (triangles). The lines are drawn to guide the eye.

HF + BCS two neutron separation energies (in MeV) for Sn isotopes as a function of the neutron number. The results with the SkM* force is reported for comparison.

Figure 3. Calculated radii and separation energies for Sn nuclides.
In Figure 4 we show shifts in single-particle levels that might occur for very neutron-rich nuclides. This change has been discussed by Casten, and by Pfeiffer et al., and is accomplished by reducing the $\ell^2$ term in the Nilsson Hamiltonian.\textsuperscript{9,10} This reduced $\ell^2$ term has the effect of shifting the nuclear potential away from a square well toward more of a harmonic oscillator shape.\textsuperscript{11} Such a shift might be expected for a nuclide with a more diffuse surface resulting from the increasingly larger neutron radius as suggested in Figure 3. The principal consequence is the upward movement of the high- $\ell$ orbitals. For the heavy Sn nuclei, the crucial $\pi h_{11/2}$ and the $\nu h_{9/2}$ orbitals would both be shifted upward in energy. As these are the only orbitals available for Gamow-Teller transitions at low energy, an upward shift in energy would raise the energy of the 2- and 3-particle daughter states populated in G-T transitions, and lower the occupancy of $h_{9/2}$ neutrons in the ground states of the Sn nuclides, both of which would serve to lengthen the observed half-lives.

In Figure 5, we show projected level schemes for $^{135,136}$Sn. In contrast to $^{133}$Sn decay, $^{135}$Sn has three neutrons beyond the N = 82 closed shell, and occupancy of the excited $h_{9/2}$ orbital is possible which should give rise to a strong Gamow-Teller spin-flip transition to 3-particle level near 4300 keV. As the neutron separation energy $S_n$ of \textasciitilde4.2 MeV for $^{135}$Sb, is quite close to the positions of the 3-particle, the $\beta$-delayed neutron branching $P_n$ will be quite sensitive to their location. How the half-life and $P_n$ values differ from the values shown in Table I and Figure 6 will depend on the actual location of those levels. In the decay of the heavier Sn nuclides, the $P_n$ values will be highly dependent upon the degree to which the 2-particle $1^+ \ell$ level and 3-particle $5/2^-, 7/2^+$, and $9/2^-$ levels either shift downward, possibly moving below the $S_n$ value, or rise well above $S_n$. As for $^{136}$Sn, the decay pattern should be quite similar to that of $^{134}$Sn with the actual position of the $1^+$ level again determining the delayed-neutron branch and deviation from the half-life shown in Table I. As N increases, the neutron separation energy $S_n$ will be lowered more rapidly than the position of the daughter levels populated in GT decay and, hence, $P_n$ values will continue to increase.
Figure 4. Nilsson Neutron Potentials, $^{133}$Sn$^{83}$
Figure 5. Projected decay schemes for $^{135,136}$Sn.
In Table I, we show experimental and calculated half-lives for the very-neutron-rich Sn nuclides. The last line shows our predicted operational values taken by assuming "normal" nuclear physics and first-forbidden ground-state transitions similar to those shown in Figure 1 for $^{133}$Sn and $^{134}$Sn. By operational values, we mean those that we will use to plan the experiment. The "normal" filling of neutrons will bring the $h_{\nu/2}$ level closer to the ground state, which will, in turn, lower the energy of the $1^+$ level populated in Gamow-Teller decay and lead to increased dominance of the beta decay by that branch. Hence, the difference between $T_m$ values and the other calculations diminishes as N increases.

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The lines $Q_M$ and $T_{\text{M(GT)}}$ are the published values from Moeller, Nix and Kratz. The $T_{\text{M(GT)}}$ half lives include only for the Gamow-Teller branches. The values labeled $T_{\text{Hilf}}$ and $T_{\text{Groote}}$ were taken from the compilation of Staudt et al.
3. New Nuclear Physics Information

The new nuclear physics information that is expected to come from the gamma-ray data includes the systematic shift of the single-particle d_{5/2} proton orbital in the neutron-rich Sb nuclides and the 2+ energies in $^{136}$Te and hopefully, $^{140}$Te as well. A sharp downward movement of the $\ell = 2$ d_{5/2} orbital (963 keV in $^{135}$Sb) relative to the $\ell = 4$ g_{7/2} ground state orbital in the heavy Sb nuclides as N increases could be interpreted as support for the $\ell^2$ reduction discussed above.

4. Astrophysics Factors

These six Sn nuclides lie in the path of the astrophysical r-process by which neutron-rich heavy elements are formed in explosive nucleosynthesis. The successive capture of neutrons above $^{134}$Sn marks the breakout from the "waiting-point" nuclides at N = 82 during the r-process and is expected to continue until the beta decay rate competes with the forward shift of the (n,$\gamma$) = ($\gamma$,n) equilibrium. The calculated specific "waiting-point" nuclides above $^{132}$Sn are $^{136,138}$Sn, $^{137,139}$Sb, and $^{138,140}$Te. By unfolding the delayed-neutron decay curves as well as the study of the gamma-ray spectra, we should be able to obtain data for a number of these nuclides. In current models for r-process nucleosynthesis, theoretical estimates that are not always consistent or in agreement with each other are often used. The known nuclear properties of the daughter nuclides as well as the positions of the nuclide to be studied are shown in Figure 6.
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Figure 6. Half-lives and $P_n$ values for heavy Sn & daughter nuclides. Measured half-lives and $P_n$ values are shown for nuclides except $^{135-140}$Sn where estimated half-lives, including forbidden branches and $P_n$ values are shown.
5. Experimental plans and approaches

Neutron-rich Sn isotopes are produced at ISOLDE using a UC$_2$-target with the Resonance Ionization Laser Ion Source. In the RILIS ions are produced inside a hot metal cavity due to step-wise resonance excitation of atomic transitions and ionization by laser light.

Laser ionization of Sn can be performed by three-step excitation of an auto-ionizing state with $\lambda_1 = 300.91$ nm, $\lambda_2 = 811.40$ nm, and $\lambda_3 = 823.50$ nm. Using the RILIS technique the study of neutron-deficient Sn isotopes has been carried at GSI/Darmstadt. There the total efficiency of tin ionization was determined to be 8.5%. As the ISOLDE setup is rather different in many ways, the efficiency is not expected to be exactly the same.

The Mainz $^3$He-neutron detector system will be used for the detection of beta-delayed neutrons. This apparatus consists of 60 - 64 $^3$He proportional counters mounted in paraffin in three rings with a total efficiency of ~32% for thermalized neutrons. The background counting rate on the ISOLDE floor is ~ 1 neutron/counter/minute or ~ 1 neutron/sec total. Thus, even for a nuclide with a yield as low as 10 atoms/sec that has a $P_n$ value of 20%, the real count rate is > 50% of the background rate and could be observed. The system is equipped with the new Mainz Moving Tape system that is used to remove accumulated activity between PSB pulses.

The RILIS was tested in August 1999 for ionization of Sn and proved quite successful. Delayed neutrons were observed at $A = 135$ and 136, but without the time resolution needed to unfold the half-life curves and make half-life estimates. The deposition rate at the neutron detector for $^{135}$Sn was estimated to be ~ $10^5$ atoms/sec. The rate was found to drop off by a factor of ~10 with each increase in mass. Hence, by this estimate, study of $^{138}$Sn decay should be possible, and, considering the high $P_n$ value for $^{140}$Sn, some activity
should be observed at that mass as well. There is also some indication that the yields are somewhat higher and drop off a bit more slowly with 1 GeV protons relative to 1.4 GeV protons. If this trend is thought to continue, then operation of ISOLDE with 600 MeV protons might produce a larger yield for the heaviest isotopes, $^{139,140}$Sn, should they prove elusive in this proposed experiment. We note that in a recent GSI fragmentation fission experiment for 750 MeV/A $^{238}$U ions, Sn nuclides up to $A = 137$ were identified, and Ag nuclides up to $A = 125$. As it has been possible with the RILIS source at ISOLDE to identify though $A = 129$ for Ag, keeping with that trend, we should, indeed be able to observe activity out as far as $A = 140$ for Sn.

We plan to use the second Mainz Moving Tape System to study gamma rays from the decay of nuclides lighter by 3 mass units than the nuclide whose delayed neutron emission is being investigated. This system consists of three 70% HPGe detectors in close geometry connected to the Mainz multispectra computer system that can accumulate gamma-ray singles data in up to 10 software-selected time bins of variable length between each PSB pulse. In addition, coincidence data are collected in event-by-event mode that includes the time after the PSB pulse. Data would be collected at the point of deposit and the tape would be used to move activity away between pulses. An example of the ability of this system to observe weak short-lived activity is illustrated in Figure 7 where two gamma lines identified in the decay of 98-ms $^{126}$Ag are shown on a background of surface-ionized isobaric In and Cs gamma rays. Other examples of the data accumulated with these two spectroscopic stations are available in the literature in our publication of the decay of the heavy Mn nuclides. In view of the large $P_1$ values, many of the observed gamma rays are expected to be coming from low-energy levels in the $A - 1$ daughter nuclides. For this experiment, we plan to add a neutron scintillation detector to permit identification of neutron-gamma-ray coincidences.
401 keV peak
62,000 counts

511-keV peak
5.7 million counts
  top slice:  50 to 150 ms after pulse
  middle slice:  350 to 450 ms after pulse
  bottom slice:  750 to 850 ms after pulse

651-keV peak
98,000 counts

Figure 7. Portion of the $\gamma$-ray spectrum of 98*-millisecond Ag-126 decay
The importance of the gamma-ray data in the unfolding of the delayed-neutron data cannot be underestimated. As is shown in Figure 6, the $^{135,136}$Sb daughter nuclides have large $P_n$ values, and that trend is likely to continue for the heavier Sb nuclides. It will be possible to estimate the $P_n$ values for all of the chains through the growth and decay of gamma rays from chains both 1 and 2 masses lighter than the chains under study. And it may be possible to obtain improved half-lives for these daughter nuclides as well, thereby reducing the number of variables and the uncertainties in these variables in unfolding the beta-delayed neutron spectra.

For this experiment, we ask for 15 shifts of beam time. Data analysis will require unfolding the delayed-neutron decay curves which, in turn, means following the decay for some time after the beam pulse and, in some cases, well beyond the point when the parent Sn nuclide has decayed. Consequently, the duty cycle will be low for some parts of the experiment.

We expect to devote 1 shift to $^{135}$Sn decay and the laser hyperfine scan of $^{135,135,137}$Sn to seek possible spin and deformation changes. Our plan is to make initial neutron measurements at high duty cycles for the other 5 masses which would also provide gamma-ray data at $A = 135$, 136, and 137 that is taken at the same time as neutron data for $A = 138$, 139, and 140. Then, depending on what is found, additional gamma-ray data will be accumulated for these latter three masses. Then, more neutron and gamma-ray data will be taken as needed, some at lower duty cycles, to achieve the stated objectives, namely half-lives and $P_n$ values. At each mass, there will also be measurements with the laser turned off to identify surface-ionized activities and activities that might come from molecular ions.