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Report to the INT Committee

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

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Abstract

An experiment was undertaken in July 2000 to study the decay of the neutron-rich Sn nuclides using the Resonance Ionization Laser Ion Source. A half-life of 535(25) milliseconds and a delayed-neutron branch of 22(5)% have been determined for ^{135}Sn. A number of gamma-ray transitions are identified including the strongest at 282 keV which suggests a $5/2^+$ first excited state in ^{135}Sb at that energy. A half-life of 280(30) ms is indicated for ^{136}Sn with a Pn value of 25(5)%. At mass 137, a half-life of 260(40) ms is determined for ^{137}Sn and a half life of ~800 ms is suggested for its unknown daughter ^{137}Sb At A = 138 a product observed with the laser off, most likely ^{138}Te, completely dominated the neutron spectrum and covered up any possible delayed neutrons from the decay of ^{138}Sn. In this report/proposal, we ask for 15 shifts to be devoted to this project in 2001 to make improved gamma-ray measurements for A = 135 to 137, and improved delayed neutron measurements for A = 136 and 139.

1. Introduction

The experiment, approved as IS-378, to use the Resonance Ionization Laser Ion Source (RILIS) to achieve high selectivity for the study the decay of very neutron-rich Sn nuclides was performed in July 2000.

2. Experimental setup

The experimental setup was quite close to that presented to the INTC in September, 1999. Three large Ge detectors, each shielded by a cylindrical Pb shield were mounted as close as possible to the tape on the Moving Tape Collector (MTC). The absolute efficiency of each Ge detector was ~1% at 900 keV. The Mainz neutron detector was mounted as planned.

3. Results

The chart of nuclides in the A = 130 to 145 mass region from the initial proposal is shown in Figure 1. Two new lines added below to show the new data in comparison with the expectations presented last year. The important new results include the half-life and Pn values for ^{135,136,137}Sn with levels of uncertainty that increase with mass. We also have an estimate for the half-life of ^{137}Sb that is produced in the decay of ^{137}Sn, but there is a large uncertainty in this value. In addition, a partial decay scheme for ^{135}Sn to levels of ^{135}Sb can be constructed from the gamma-gamma coincidence data.

These results are consistent with previous first attempts at RILIS studies of a new element. In the first year with Ag nuclides, new data were obtained for ^{125,126,127}Ag, with data for ^{128}Ag and ^{129}Ag coming after further development. [1] For Cd nuclides in 1999, the first experiments yielded a much better half-life for ^{130}Cd and new half-life values for ^{131,132}Cd. [2]

138 STAB	139 1.4 h	140 13 d	141 18 m	142 11 m	143 14 s	144 11 s	145 4 s	146 2.2 s	56 Ba
137 30 y	138 32 m	139 9 m	140 1.1 m	141 .03 25 s	142 0.1 1.8 s	143 1.6 1.8 s	144 3 1.0 s	145 14 0.6 s	55 Cs
136 STAB	137 3.8 m	138 14 m	139 40 s	140 14 s	141 .04 1.7 s	142 0.4 1.2 s	143 >0 1.0 s	144 >0 1.2 s	54 Xe
135 6.6 h	136 1.4 m	137 7 25 s	138 6 6.5 s	139 10 2.3 s	140 10 0.9 s	141 21 0.5 s	142 >0 0.2 s	143	53 I
134 42 m	135 19 s	136 1 18 s	137 3 2.5 s	138 6 1.4 s	139	140	141	142	52 Te
133 2.5 m	134 0.1 0.8 s	135 16 1.7 s	136 24 0.8 s	137	138	139	140	141	51 Sb
132 40 s	133 2.9 1.4 s	134 17 1.0 s	135 40 0.4 s	136 33 0.6 s	137 65 0.1 s	138 40 0.2 s	139 75 0.1 s	140 50 0.1 s	50 Sn
131 0.3 s	132 0.1 0.2s	133 0.1 0.2 s	134	135	136	137	138	139	49 In

A P_n value in %

Half-life

Figure 1. Half-lives and P_n values for heavy Sn & daughter nuclides. Measured half-lives and P_n values are in green and blue, estimated half-lives and P_n values are in turquoise, new results are shown below in red.

133 2.5 m	134 0.1 0.8 s	135 16 1.7 s	136 24 0.8 s	137 50 0.9 s	138	139	140	141	51 Sb
132 40 s	133 2.9 1.4 s	134 17 1.0 s	135 23 0.53 s	136 25 0.28 s	137 60 0.26 s	138 40 0.2 s	139 75 0.1 s	140 50 0.1 s	50 Sn

The proposed partial decay scheme for ^{135}Sn is shown in Figure 2 along with previously available data for both the core nucleus, ^{134}Sn, and data for ^{135}Sb yrast levels from in-beam fission fragment measurements. [3,4] New calculations of the ^{135}Sb levels performed by Alex Brown are also shown. These calculations were performed with the OXBASH code that provided good fits for the experimental data for the levels of ^{134}Sn. All calculated levels are shown up through the $19/2^+$ level at 1257 keV. Excellent OXBASH fits are found for all of the observed levels in both the in-beam study and in our study, except for the surprisingly low energy of the first excited state that we tentatively assign as the $d_{5/2}$ single-proton state. A least-squares fit for the delayed-neutron data from which the half-life and Pn values were obtained is also shown.

The delayed-neutron decay data for A = 136 are shown in Figure 3 from which the half-life for ^{136}Sn is found to be 280(30) ms and the Pn value is 25(5)%. For ^{136}Sn, both the beta-decay daughter, ^{136}Sb, and the delayed-neutron decay daughter, ^{135}Sb have delayed-neutron branches. Hence, the Pn value serves to determine the ratio of these two activities.

The delayed-neutron decay data for A = 137 are also shown in Figure 3. At this mass there are four unknown variables as there exist in the literature no data for ^{137}Sb decay. Hence, a wide choice in half-life and Pn values was possible. We determined a maximum half-life for ^{137}Sn by assuming a 100% Pn value and then using the known half-life and Pn values for ^{136}Sb to determine a single growth and decay component. That maximum value was 480 ms. We also determined a minimum half-life value for ^{137}Sn by assuming a very short half-life of 500 ms for ^{137}Sb. That minimum value was 180 ms. The best fit for the data was obtained with a half-life of 260(40) ms and a Pn value of 60(10)% for ^{137}Sn and a half-life of ~900 ms for ^{137}Sb and a 50(20)% Pn value. No gamma rays were observed for ^{137}Sn decay

The delayed-neutron data taken with the laser off at A = 138 are shown in Figure 4. No difference at between the laser-on and laser-off data were found.

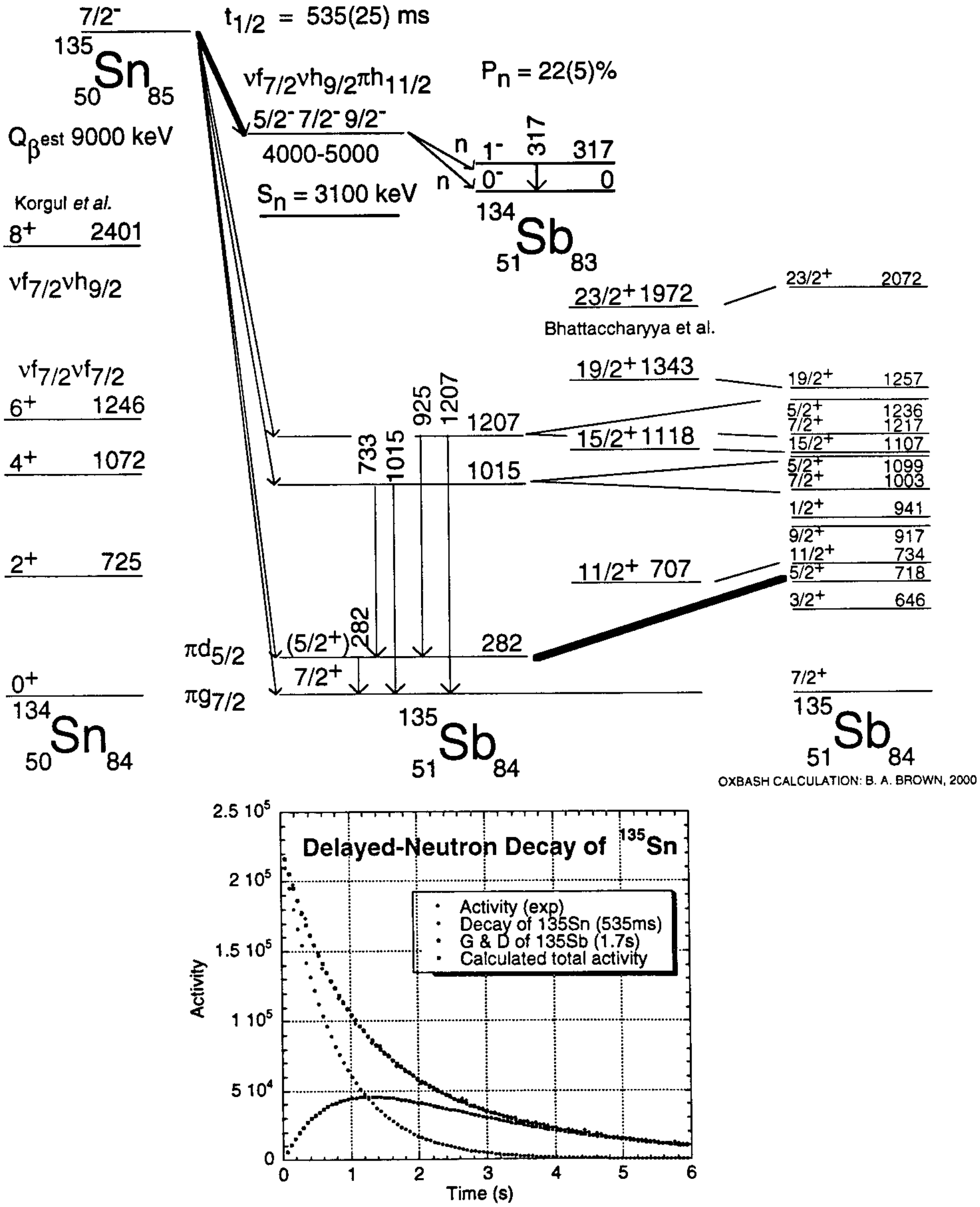


Figure 2. New data for the decay of ^{135}Sn along with data for levels in ^{134}Sn and ^{135}Sb from fission studies.

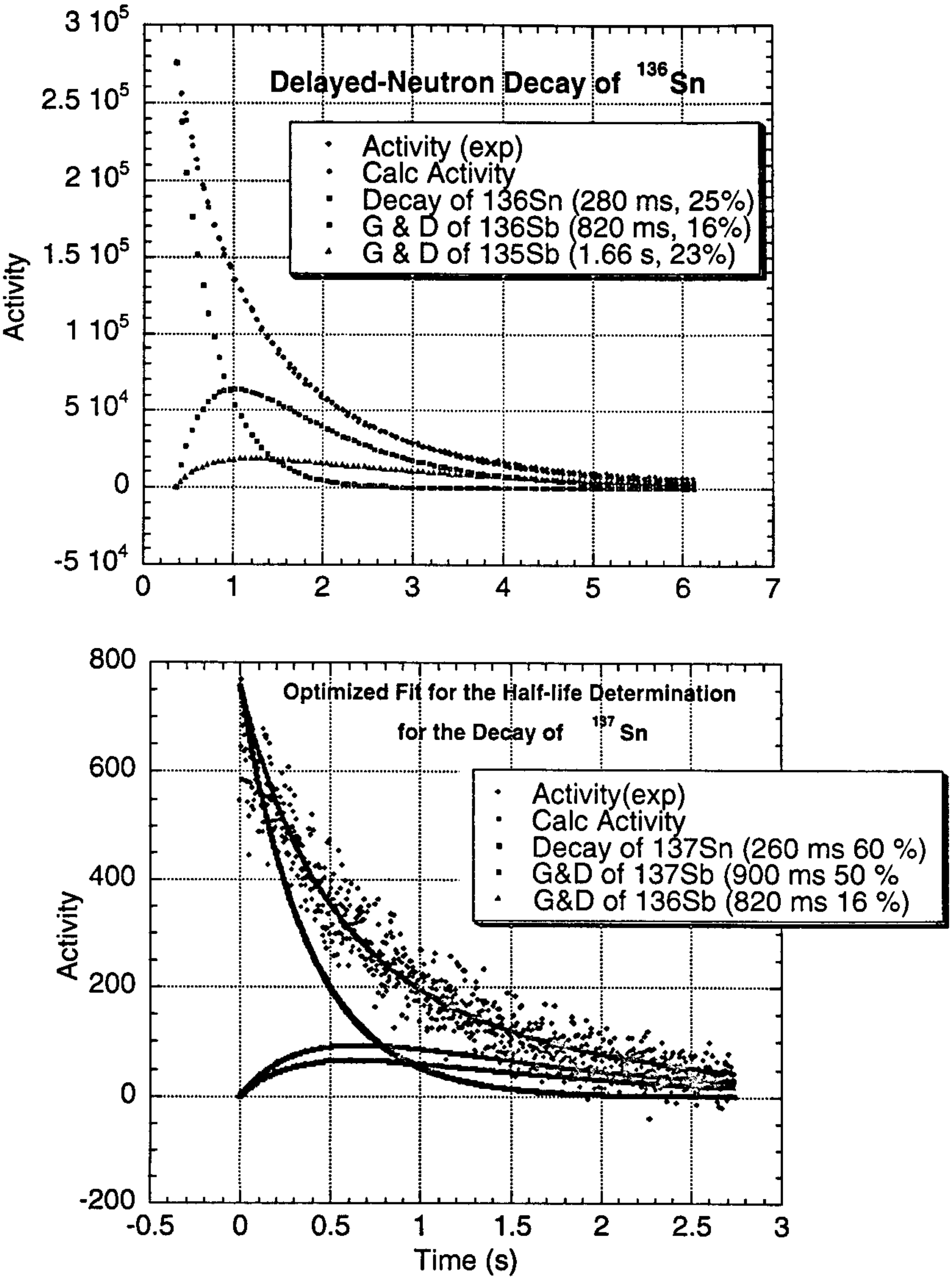


Figure 3. Delayed-neutron decay data for A = 136 and A = 137.

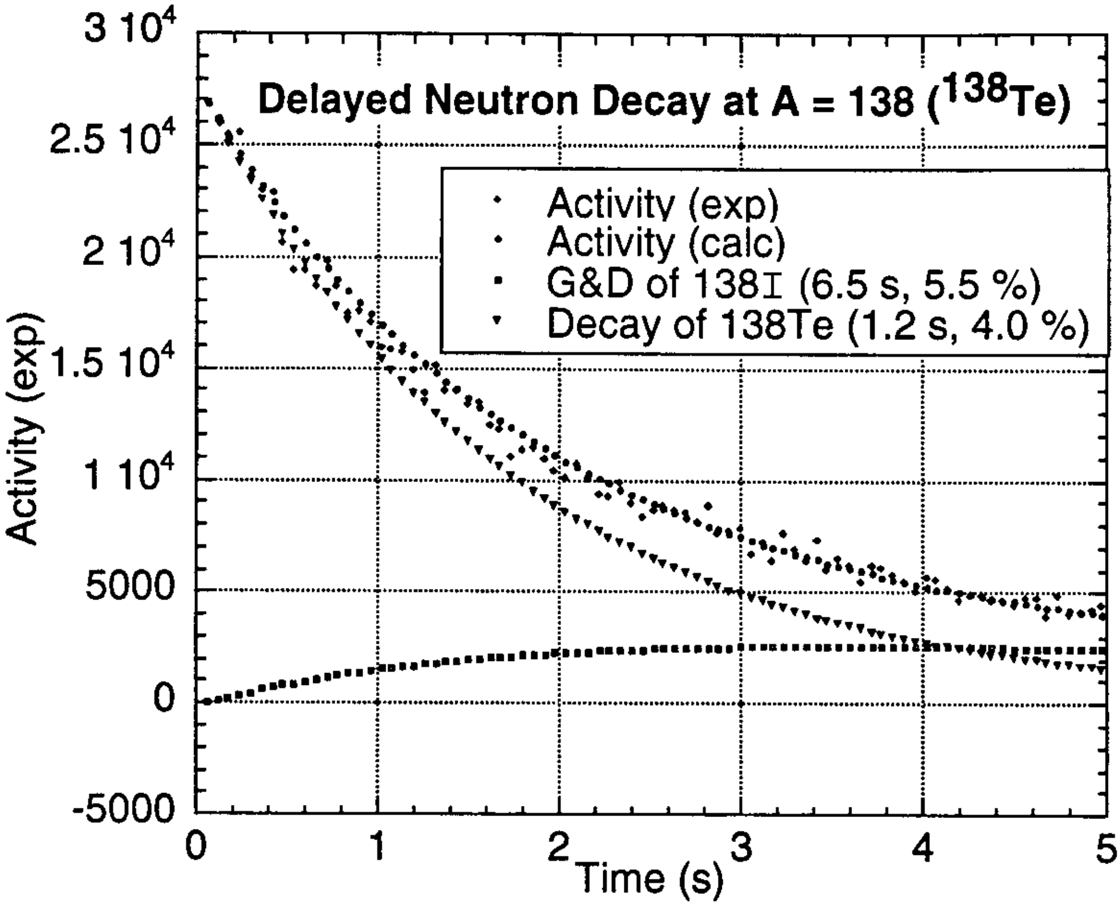


Figure 4. Observed laser-off delayed-neutron decay at A = 138.

4. New Nuclear Physics

The most interesting new nuclear physics comes from the surprisingly low energy of 282 keV for the first excited state in ^{135}Sb. That this position is unexpected can also be seen in the recent OXBASH calculation performed by Alex Brown where the lowest 5/2+ level is indicated at 718 keV, just about where it was thought to be when this proposal was presented to INTC in 1999. Those expectations were based on the systematic behavior of the relative positions of the $g_{7/2}$ and $d_{5/2}$ levels in the lighter Sb nuclides shown in Figure 5. The expectation was that the $d_{5/2}$ level would rise slightly from its position at 963 keV in ^{133}Sb toward the 1806-keV separation found for the single proton hole nuclide, ^{207}Tl. And, that the $d_{5/2}$ single-proton level would mix with the particle + phonon levels near 700 keV and possible push the lower mixed state down in energy by as much as 100 keV. But, these data now suggest that the $d_{5/2}$ level now lies well below the 700-keV phonon region.

One possible interpretation for sharp drop in the position of the $d_{5/2}$ level relative to the position of the $g_{7/2}$ level is that the single proton bound to ^{134}Sn moves in a more diffuse nuclear surface when compared to the Sb nuclides with neutron numbers just below and at the N = 82 closed shell. [5] As shown in Figure 6, when the ℓ^2 term in the Nilsson potential to simulate a more diffuse nuclear surface and a more harmonic-oscillator-like potential, the low-ℓ levels are lowered relative to the higher ℓ levels. [6] Some evidence for such changes were presented at the Seyssins meeting on neutron-rich nuclides in 1998 for both the N = 83 and N = 29 isotones. A similar trend is observed in the Bi nuclides as the N = 126 closed shell is crossed. [7] None of the effects previously observed are as sharp or as dramatic as is shown in Figure 5. Similar lowering of low-ℓ orbitals relative to high-ℓ orbitals with increasing N/Z and increasing surface diffuseness has been presented in recent calculations by both Hamamoto et al., [8] and Tanahata. [9]

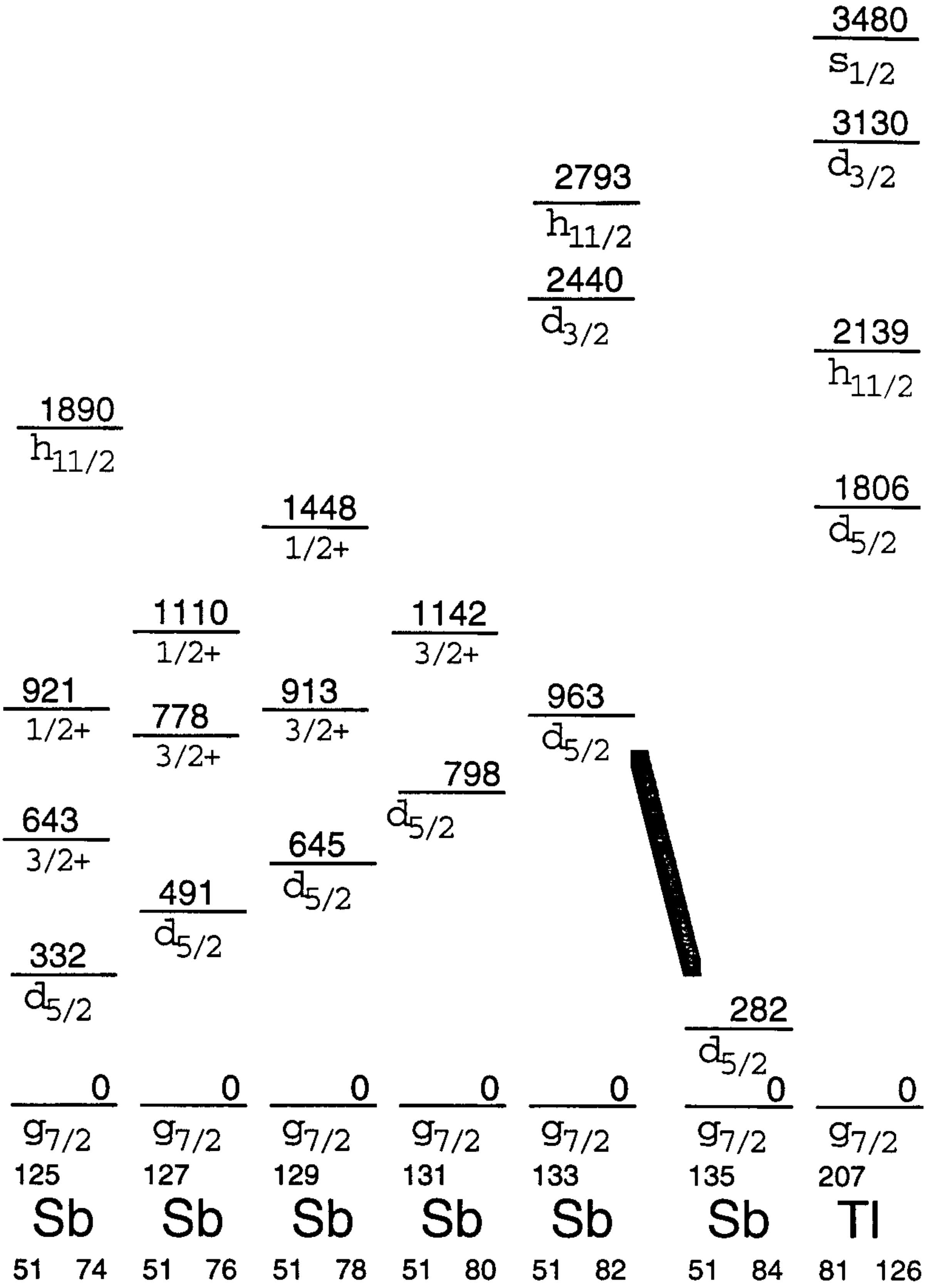


Figure 5. Low-energy and single-particle gddsh level structures.

5. Astrophysics

Below is shown the table presented with the initial proposal that will serve to illustrate how the new half-life values fit in to the theoretical expectations.

Table I. Measured and calculated half-lives for very neutron-rich Sn nuclides.

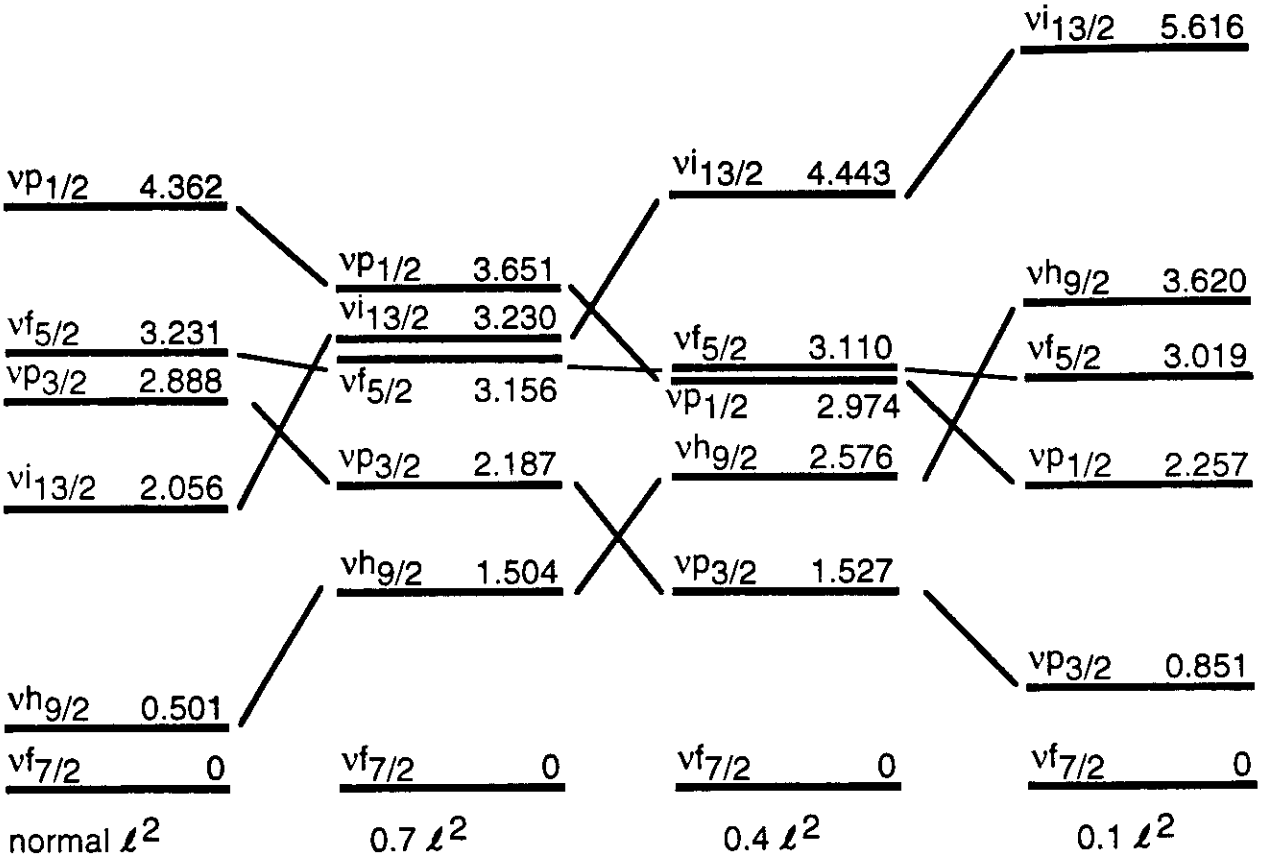
A	133	134	135	136	137	138	139	140
T_{meas} (s)	1.44	1.12	535(25)	280(30)	260(40)			
Pn(%)	2.9(2)	17(14)	22(5)	25(5)	60(20)			
Q_M (MeV)	8.0	7.1	9.4	8.2	10.5	8.4	10.9	9.5
Q_{Audi}	7.6	7.2	8.6	8.0	9.7	8.9	10.7	9.8
$T_{M(GT)}$ (ms)	10.3 s	3.5 s	3000	950	800	480	390	120
T_{Hilf} (ms)			731	189	110	49	28	16
T_{Groote} (ms)			312	493	327	116	77	37
T_{ff+GT} (ms) [1996]			300	209	186	162	62	57
T_{ff+GT} (ms) [this work]			400	600	120	200	80	100

The lines Q_M and $T_{M(GT)}$ are the published values from Moeller, Nix and Kratz.[10]

The $T_{M(GT)}$ half lives include only for the Gamow-Teller branches.

The values labeled T_{Hilf} and T_{Groote} were taken from the compilation of Staudt et al.[11]

The expected "waiting-point" nuclides for the Sn isotopes are the even-even Sn nuclides, ^{136}Sn and ^{138}Sn. We have been using the 1996 value for ^{136}Sn that emerged from the ETFSI-Q mass value along with inclusion of first forbidden beta decay to calculate r-process yields. As can be seen the 280-ms measured half-life is reasonably close to this value. The Pn values are also interesting as they reflect the Gamow-Teller transitions to high-energy levels above the neutron separation energy. It can be seen that the T_M values which include only the Gamow-Teller strength are not far away from accounting for the observed partial half-lives for delayed neutron branching.



Nilsson Neutron Potentials, $^{133}Sn_{83}$

igure 6. Similation of a more diffuse nuclear potential by the lowering of the ℓ^2 term in the Nilsson Hamiltonian.

6. Challenges for future experiments and development

This experiment was clearly the first attempt at such measurements. Two serious difficulties were encountered. The first surprise was the appearance of one or more delayed-neutron emitting nuclides that provided interference for the study of ^{137}Sn decay and completely covered up any possible measurements for delayed neutron decay of heavier ^{138,139}Sn decay. In addition, the Cs and Ba gamma rays arising from surface ionization proved to be considerably more intense than expected.

As expected at all of these masses, there were only a few neutrons observed at A = 135 and A = 136 with the laser off. In 3-second experiments, there were less than 20 neutrons per PSB proton pulse observed at either mass, and the spectra appeared to be similar and consist of a burst of neutrons of about 400 ms, and then a longer-lived (~4 s) background. A similar, but more intense neutron activity (30 n/PSB pulse) was found with the laser off at A = 137. As a consequence, there is added uncertainty for the reported half-life and Pn values for A = 137. Serious interference is observed at A = 138 where the intensity in the 3-second run was over 60 neutrons/PSB pulse. Coming at just the point where the yield of the ^{138}Sn is small, these neutrons completely overwhelmed any ^{138}Sn that was produced and no net neutrons could be found between the neutron data taken with laser-on and laser off.

These delayed neutron data at mass 138 with the laser off were shown in Figure 4. These data were studied extensively and it was concluded that they could be best fit by the assumption that they come from a small amount of unexpected surface ionization of ^{138}Te. The literature values for the half-life and Pn value come from a 1975 measurement and are 1.4(4) s and 6.3(2.4) %, respectively. [12] Hence, the best fit we could obtain of 1.2 s and 4% are well within the range reported.

For A = 135, the main Cs interference comes from the two gamma rays emitted in the decay of the 19/2+ isomer of ^{135}Cs. These gamma rays are at 846 and 798 keV. From the observation of ~1000 counts in the 282-keV peak in a 300 ms time period to the observation of ~16,000 counts in the 798-keV peak of 53-min ^{135}Cs^{m}, we estimate that this 19/2+ isomer of ^{135}Cs is produced over 10^5 times the intensity of Sn at A = 135. Beyond 846 keV, the background is lower and weaker gamma rays can be observed.

At A = 136, the interference is provided by an isomer in ^{136}Cs at 519 keV. The energy of this isomer is not listed in any data compilations. The overall yield of Sn at A = 136 is a factor of 7 to 10 times lower, hence the interference far more damaging. Indeed, it was not possible to observe any gamma rays undergoing decay below 519 keV. The one certain gamma ray that should be observed in ^{136}Sn decay would be the 282-keV line in the 25% delayed-neutron branch to levels of ^{135}Sb. In ^{134}Sn decay, the most intense low-energy line is at 317 keV. A similar transition, near 200 keV should also be expected in ^{136}Sn decay.

At A = 137, with the Sn yield down another factor of 7 to 10, no gamma rays could be observed above the interference provided at low energy by the 662-keV isomer in ^{137}Ba.

7. Proposal

In the experiment in July 2000, 11 of the 15 allotted shifts were used. Now, we are requesting **a total of 15 shifts for new work**, 11 new shifts added to the 4 remaining from last summer. These would be specifically used for the following measurements whose scientific goals are:

1. to identify and measure a half-life and Pn value for the "waiting-point" nuclide, ^{138}Sn;
2. to identify gamma rays in the decay of ^{137}Sn, and the growth and decay of ^{137}Sb, these will aid in a determining more precise half-lives and Pn values for ^{137}Sn and ^{137}Sb as well as to identify the lowest excited states in ^{137}Sb;
3. to improve the quality of the data for the delayed-neutron decay of ^{137}Sn and ^{137}Sb;
4. to improve the quality of the data for the gamma data for ^{136}Sn decay, particularly in the population of levels in ^{135}Sb through delayed-neutron-gamma-ray coincidences that would aid in establishing the low-energy structure of ^{135}Sb. In addition, new lines found in daughter ^{136}Sb should be strongly observed in the 60(10) % delayed-neutron decay of ^{137}Sn, thereby aiding in its identification half-life measruement;
5. to improve the quality of gamma-ray data for ^{135}Sn decay with the expectation of observing more levels at low energy;
6. to seek to identify the neutron decay of ^{139}Sn.

Tasks #1 and #5 can be done at the same time as the masses are 3 units apart and we request **4 shifts** for these measurements.

Tasks #2 and #3 on mass 137 cannot be performed with studies at other masses and a total of **6 shifts** is requested for these measurements, with 3 shifts devoted to each.

Tasks #4 and #6 can also be done at the same time and **4 shifts** are requested.

In addition, we wish to specifically ask for **1 shift** to be used for beam optimization.

We note that there was an expectation last summer that the new more powerful and stable lasers would be available, however these lasers did not arrive. As they have now arrived and are working, we expect that the yields will already be improved for future runs.

Considerable time was spent last summer in a more or less unplanned fashion to try to minimize both the Cs and Ba production as well as lower the intensity of the unknown interference observed at A = 138. In the next experiment, we would hope for strong involvement of the ISOLDE staff in seeking ways to accomplish the reduction of surface ionized Cs and Ba production for the gamma-ray studies and in the reduction of the surface-ionized ^{138,139}Te for the delayed neutron measurements.

Preparation of the ion source for this experiment and its operation during the run would need to take into account the type of ionization surface that would minimize surface ionization but retain the rapid diffusion and effusion of Sn from the ion source, inasmuch as the new Sn nuclides sought at A = 138 and 139 are likely to have half-lives < 200 ms.

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