New Proposal to the ISOLDE Neutron Time of Flight Committee

A Study of the r-Process Path Nuclides, $^{137,138,139}\text{Sb}$ Using the Enhanced Selectivity of Resonance Laser Ionization

W. B. Walters, 1 K.-L. Kratz, 2,3,4 A. Aprahamian, 4 A. Wöhr, 4 U. Köster, 5 V. Fedosseev, 5 A. Hecht, 1
N. Hoteling 1 B. Pfeiffer, 2 O. Arndt, 2 S. Hennrich, 2 C. Jost, 2 O. Keller, 2 T. Griesel, 2,4 S. Falahat, 2,4
R. Kessler, 2,3 F. Schertz, 2,3 T. Berg, 2 J. Barth 2,3

1 Department of Chemistry, University of Maryland, College Park, MD 20742 USA
2 Institut für Kernchemie, Universität Mainz, 55128 Mainz, Germany
3 Virtual Institute for Nuclear Structure and Astrophysics, http://www.vistars.de, Germany
4 Physics Department, University of Notre Dame, Notre Dame, IN 46556 USA
5 ISOLDE, CERN, Geneva, Switzerland

Spokesperson: W. B. Walters
Contact Person: Valentin Fedosseev

Abstract

The particular features of the r-process abundances with $100 < A < 150$ have demonstrated the close connection between knowledge of nuclear structure and decay along the r-process path and the astrophysical environment in which these elements are produced. Key to this connection has been the measurement of data for nuclides (mostly even-N nuclides) that lie in the actual r-process path. Such data are of direct use in r-process calculations and they also serve to refine and test the predictive power of nuclear models where little or no data now exist. In this experiment we seek to use the newly developed ionization scheme for the Resonance Ionization Laser Ion Source (RILIS) to achieve selective ionization of neutron-rich antimony isotopes in order to measure the decay properties of r-process path nuclides $^{137,138,139}\text{Sb}$. These properties include the half-lives, delayed neutron branches, and daughter gamma rays. The new nuclear structure data for the daughter Te nuclides is also of considerable interest in view of the new, surprisingly low, B(E2) value reported for $^{136}\text{Te}$ from the Radioactive Ion Beam work at Oak Ridge. Nine shifts are requested for 2005 and 15 shifts for 2006.
I. Introduction

Over the past decade we have taken great advantage of the development of the Resonance Ionization Laser Isotope Separation (RILIS) to study the decay of nuclides lying in and near the r-process path by which heavy elements are synthesized in explosive nucleosynthesis (the r-process). In 2002, we submitted a “Letter of Intent” [I-043 (CERN/INTC 2002-016) minutes INTC, May 13, 2002 meeting] indicating an interest in a study of the decay of neutron-rich Sb isotopes once a laser ionization scheme had been tested and a realistic estimate for ionization efficiency could be provided. The following statement was approved in the closed session "The proposed measurements on the heavy Sb-nuclei were judged interesting both from the point of view of nuclear structure and astrophysics. Consequently, the committee expressed its support for the needed beam developments." That “ionization scheme” has now been identified and tested and an ionization efficiency of 2.7% is listed, as is shown in the excerpt from this paper that is reproduced in the Appendix. In comparison with the adjacent Sn isotopes, the efficiency would be approximately 1/3 that observed for Sn, and quite adequate for the proposed study, given the very successful results from the two RILIS studies for neutron-rich r-process Sn isotopes where nuclides as heavy as $^{138}\text{Sn}$ were observed.

The primary goals of this experiment, as well as the past experiments, are the measurement of the decay properties of r-process path nuclides for use in various calculations which attempt to determine the conditions under which the r-process takes place, as well as the discovery of new nuclear physics properties of the nuclides under study. The important experimental features of these experiments unique to ISOLDE have been the development of the RILIS techniques that dramatically enhance the nuclidic selectivity for study of a specific isotope. The new aspects of nuclear structure and decay are, in turn, used in making better calculations of the properties of other unknown nuclei of importance to r-process nucleosynthesis. For these Sb nuclides in particular, the estimate for the $P_n$ values are subject to considerable uncertainty.

Since the beginning of these experiments, it has been possible to make significant improvements in the ability to fit the r-process abundance peak in the $A = 130$ region by using actual experimental data obtained at ISOLDE. The general background for this work was summarized in the ISOLDE Laboratory Report in Hyperfine Interactions, and in a recent Nuclear Physics review article. 2,3
In almost all cases, surprises have been found for the observed nuclear structure.

For example, the study of the r-process seed Mn nuclides revealed, for the first time, evidence for a new region of deformation near \( N = 40 \) in the \( 20 \leq Z \leq 28 \) nuclides.\(^4\)

The study of the r-process Ag nuclides, including the critical waiting-point nucleus \(^{129}\)Ag, revealed unexpectedly low \( 2^+ \) energies for the Cd nuclides near \( N = 82 \) that served as early concrete evidence for the weakening of the \( N = 82 \) closed shell below \( Z = 50 \).\(^5\)

The study of the decay of the key r-process waiting-point nuclide \(^{130}\)Cd revealed a surprisingly high energy of 2120 keV for the lowest 1+ level in daughter \(^{130}\)In, far above the recent shell-model predicted position between 1380 and 1555 keV. And, the measured \( Q_\beta \) was found to be higher than predicted by most mass models.\(^6\)

The study of the r-process Sn nuclides \(^{135,136,137}\)Sn revealed a totally unexpected low energy for the \( d_{5/2} \) level in daughter \(^{135}\)Sb, which can be interpreted to arise from neutron skin effects.\(^7\)

Moreover, none of the model calculations for the Sn half-lives provided consistent results when compared with our new values that we show in Table I in the Appendix at the end of this proposal. To emphasize this point, the closest calculated value is shown in bold for \(^{135,136,137}\)Sn and it can be seen that those values come from three different models.

\section*{II. This experiment}

In this experiment, we are seeking to measure the decay properties of the very neutron-rich \(^{137,138,139}\)Sb nuclides that lie directly in the path of the r-process. A chart of the region is shown in Figure 1 that includes existing data, new data from ISOLDE Sn, Xe, and In studies, along with the expected half-lives and \( P_n \) values for these Sb nuclides.\(^6,8,9\) In our study of the Sn nuclides mentioned above, we observed no activity at \( A = 135 \) and \( A = 136 \) with the laser off that might have come from surface ionization of those Sb nuclides.\(^6\) Hence, use of RILIS techniques should permit definite determination of the properties of the Sb nuclides by comparison of spectra taken with the laser on and laser off. In those studies, we did observe some surface ionization of the daughter Te nuclides at masses 137, 138, and 139 in the delayed neutron spectra when the target was directly bombarded by the PSB proton beam in 2000, probably induced by a high-temperature burst following bombardment by the proton beam. In contrast, when the neutron converter was used in 2002, almost no identifiable activity at any of the masses, 135,136,137,138 was observed with the laser off.
Figure 1. Chart of nuclides in and near the r-process path beyond $A = 132$. Our estimated values for the half-lives and $P_n$ values for the three Sb nuclides that we seek to study are shown in red, our new data for the neighboring Sn nuclides are shown in green, and properties of important daughter nuclides are shown in blue. The key r-process nuclides are marked by an "r".

### III. Astrophysics

The calculated abundances for the Sb isotopes at freeze-out at various neutron densities using our new data from the Sn experiment are shown in Figure 2 below. A similar plot is presented by Shergur et al.,$^6$ for the Sn nuclides and by Dillmann et al.,$^8$ for the neutron-rich In nuclides. As expected, the even-N nuclides with a higher neutron binding energy dominate the yields.
Figure 2. Sb isotope r-process abundances under freeze-out conditions at various neutron densities.

For neutron densities in the range of $10^{24}$ n/cm$^3$ to $10^{25}$ n/cm$^3$ which are required to move beyond the N = 82 waiting point nuclides, $^{133}$In, $^{136}$Sn and $^{139}$Sb are expected to be the most abundant nuclides, whereas at higher neutron densities $\sim 10^{27}$ n/cm$^3$ required to move beyond the N = 126 waiting-point nuclides, the most abundant nuclides will be shifted to the shorter-lived $^{137}$In, $^{138}$Sn and $^{141}$Sb. When $^{136}$Sn is the waiting-point nuclide, then the decay will produce $^{135}$Sb and $^{136}$Sb, which will, in turn, capture neutrons until the next waiting point $^{139}$Sb nuclide is reached. The nuclides that we propose to study are those directly involved in the r-process. Because of the large number of beta-delayed neutrons found in the decay of surface-ionized $^{141}$Cs, study of $^{141}$Sb is not considered feasible at this time. Nonetheless, with the data from these measurements available, much better estimates should be possible for the properties of $^{141}$Sb.

The r-process abundances calculated using the latest new experimental data through $^{136}$Sn are shown in Figure 3. As can be seen, in the region from $127 \leq A \leq 133$ where our new data have been used, it is possible to obtain good agreement between the calculated and observed yields. The major discrepancies involve the abundances at $A = 136$, 138, and 140 for which the calculations indicate values that are a factor of 2 or 3 higher than observed. In contrast, the abundance for $A = 137$ is underpredicted. These
calculations use global models with parameters that are consistent over a wide range of nuclides where experimental data are not available. As the discrepancies shown below involve adjacent nuclides, it is possible that the difficulty lies in the calculated $P_n$ values. For example, a high $P_n$ value for the $A = 137$ waiting-point progenitor ($^{137}\text{Sb}$ in this case) would lead to less mass at $A = 137$ and more at $A = 136$. In Figure 1, we show a systematic estimate of 500 ms for the half-life of $^{138}\text{Sb}$, whereas, a global calculation that includes some deformation indicates a half-life as low as 98 ms, but only a 16% $P_n$ value, and for $^{139}\text{Sb}$, a half-life of 115 ms and a $P_n$ value of 94%. With a $P_n$ value of that magnitude, it can be seen that little mass would accumulate at $A = 139$ and more would be found at $A = 138$.

![Graph](image)

Figure 3. Observed r-process yields are shown as dots along with our best current calculated values that are shown as a solid line.

Recent abundance data from old halo stars that show similar relative abundances for nuclides with $Z > 56$ and $A > 130$ have provided strong support to the notion that there is a "single r-process" responsible for nucleosynthesis for these elements. Other measured and calculated abundances for lighter elements have led to the notion that there may exist a second "weak r-process" that does not produce elements above $Z = 56$ and $A = 138$. If so, then nuclides in the region with $125 \leq A \leq 140$, including these particular nuclides, $^{137,138,139}\text{Sb}$ would be the "waiting point nuclides" beyond which the weak r-process would not be able to
move. Hence, as that debate continues, these data are expected to play a crucial role in identifying how and why a "weak r-process" nucleosynthesis terminates in this region.

IV. New Nuclear Physics

In the appendix, we show the structures of the important Te daughter nuclides in Figure A. The daughter Te nuclides $^{136,137,138,139}$Te are interesting as their yrast structures have been determined from gamma-ray coincidences with fragments from spontaneous fission. The structure of $^{136}$Te has been of interest for some time as the valence nucleons consist of only 2 neutrons and 2 protons beyond the double magic nuclide $^{132}$Sn. Moreover, a new B(E2) measurement has been performed with the Radioactive Ion Beam facility at Oak Ridge. The data have, so far, been interpreted to show a B(E2) value for $^{136}$Te lower than that for the closed neutron-shell nuclide $^{134}$Te, and significantly lower than would be predicted from shell-model calculations. For $^{138}$Te, Hoellinger et al., argue against strong deformation, while Urban et al., suggest a transitional shape for $^{139}$Te. More details are known for the structure of $^{137}$Te and other $N = 85$ isotones. Urban et al., suggest that low-energy $5/2^-$ and $3/2^-$ states should be observed as such states are also found in the higher $N = 85$ isotones, all of which have 3 neutrons beyond the $N = 82$ closed shell.

Below in Figure 4 are shown the decay data for $^{135}$Sb decay to levels of $^{135}$Te that serve as a basis for a systematic method to extrapolate half-lives and $P_n$ values for $^{137,138,139}$Sb decay. Forbidden decay is seen to exhibit a strong ground state, $\nu f_{7/2}$ to $\pi g_{7/2}$ branch with a log $ft$ value of 5.82. We simulate the numerous weaker branches that populate many levels between 0.5 and 2.5 MeV with a single transition lying 1 MeV above the ground state. The measured 17% $P_n$ value for $^{135}$Sb decay is simulated with a single Gamow-Teller $\nu h_{9/2}$ to $\pi h_{11/2}$ transition to 3-quasi-particle levels near 4.5 MeV that are consistent with such levels in an OXBASH calculation for the structure of $^{135}$Te. The half-lives and $P_n$ values shown in Figures 1 and 4 were obtained by using the Audi-Wapstra Q values and keeping the three daughter levels at approximately the same position.

The calculated $P_n$ values shown in Figures 1 and 4 for these three Sb nuclides are subject to considerable uncertainty. Indeed, that is a major motivation for this proposal. It is possible to make reasonably reliable estimates for the forbidden beta transition from ground state to ground state. But, the $P_n$ values are largely determined by the Gamow-Teller beta branching to levels above the neutron separation energy that have configurations involving the high-$L$ $\nu h_{9/2}$ and $\nu h_{9/2}$ orbitals. As noted above and in our recent paper on $^{135}$Sn decay, the positions of these high-angular momentum orbitals in nuclei where some evidence exists for a neutron skin is more difficult to determine. "Surprises" can occur if, as is suggested by some models, the high-angular momentum $\pi h_{11/2}$ and $\nu h_{9/2}$ orbitals move up in energy as $N/Z$ increases. Indeed,
Figure 4. Schematic data for $^{135}$Sb decay to $^{135}$Te that serve as a basis for a systematic estimate for the half-lives and $P_n$ values for $^{137}$Sb and $^{139}$Sb decay.

if the high-angular momentum $\pi h_{11/2}$ and $\nu h_{9/2}$ orbitals rise above the energies expected in several current models, then the observed $P_n$ values could be significantly lower and the half-lives longer. On the other hand, the lowering of low-K orbitals from these high-angular momentum states via deformation could result in much shorter half-lives. In such cases, the $P_n$ value is critically dependent on the relationship of the beta-strength distribution relative to the neutron separation energy. If the beta strength remains above $S_n$, then a higher $P_n$ is found, whereas, if the GT beta strength is shifted below $S_n$ then a strange combination of both a shorter half-life and lower $P_n$ value would be observed. Although not caused by deformation, such a situation is known for $^{131}$Cd decay which has a short 68-ms half life and, at the same time, a low 3.5% $P_n$ value, contrasted with $^{132}$Cd which has a 97-ms half-life and a 60% $P_n$ value. In $^{137}$Te we should be able to observe the proposed low-energy 3/2- and 5/2- levels in beta decay from the expected 7/2+ ground state of $^{137}$Sb.
V. Experimental considerations and request for beam time

We request 9 shifts for 2005 and an additional 15 shifts for 2006, using a uranium carbide target. In 2005, we plan to evaluate the impact of the neutron converter on the Sb yields relative to Cs as well as for the absolute yields for the Sb nuclides. We would plan to start the experiment using the converter, particularly for $^{137}$Sb where buildup of long-lived $^{134,135,136,137}$Cs is to be avoided. For $A = 138$ and $139$, where Cs is produced more strongly in fission, use of the converter may not provide the advantage that is found at lower masses. Thus, at the end of the experiment, comparative yields could also be measured by direct bombardment of the target with PSB protons.

The detection setup would be similar to that used in the recent Sn and Cd experiments including the Mainz neutron counter and one Moving Tape Collector (MTC) on one beam line, and a gamma-ray detection station and second MTC on a second beam line. The 4 gamma detectors would each be ~1% efficient for 1 MeV gamma rays and the neutron counter has an efficiency of ~40%.

The beam-time requirements are based on the comparisons with the yields of the isobaric Sn nuclides with the recognition that the ionization efficiency is about 50% of that of Sn. Nine shifts would be used in 2005 for $^{135,136,137,138}$Sb. As this is the first on-line experiment with the RILIS Sb ionization scheme, we would expect the first 3 shifts to be devoted to characterization of the ion source and operation of the RILIS with study of the decay of $^{135,136}$Sb whose decay schemes are known and where we estimate yields of $10^5$ ions/second or greater. This time would also be used to calibrate the neutron detector for $P_n$ value measurements. Six shifts would be used for $^{137,138}$Sb where we estimate yields of $10^4$ and $10^3$, respectively, based on the trends in fission yields and the observation of a yield of $>10^4$ atoms of $^{138}$Sn per PSB pulse and about $10^2$ atoms per PSB pulse for $^{137}$Sn. Delayed-neutron measurements would be performed for both nuclides, and limited gamma-ray data for $^{137}$Sb decay, aimed primarily at growth and decay of Sb and its Te, I, and Xe daughters to assist in the determination of the $P_n$ value. Hence, the goal for 2005 is to determine the half-lives for $^{137,138}$Sb, and obtain good data for the $P_n$ value for $^{137}$Sb as well as to make a first attempt for a $P_n$ measurement for $^{138}$Sb. These experiments could be performed with either the General Purpose Separator (GPS) or the High-Resolution Separator (HRS), depending on scheduling efficiency.

In 2006, we would plan to use the HRS. Three shifts would be devoted to the detailed study of $^{137}$Sb decay with a focus on the structure of daughter $^{137}$Te. The remaining 12 shifts would be used for the measurement of the half-life of $^{139}$Sb and the $P_n$ values for $^{138,139}$Sb. Based on the observation of a yield of 100 $^{137}$Sn nuclides/PSB pulse, we would estimate ~30 nuclides/PSB pulse for $^{139}$Sb. The high yields of Cs and Ba isotopes from surface ionization would saturate the beta detector in the delayed-neutron counter and also
provide high gamma-ray count rates that would also cover up the decay from the lower-Z nuclides along the 2 isobaric chains. We anticipate that spending approximately three shifts in order to set up the HRS and tune it to maximize the yield of the Sb nuclide and minimize the Cs and Ba nuclides. These nuclides are all on the same side of the valley of stability, hence the separation is in all cases over 20 MeV. For such a separation, a mass resolution of 1/6000 would be sought.

The strong odd-even effect shown in the calculated r-process abundances suggests that the $P_n$ values used in the calculations may be quite uncertain, as it is the delayed-neutron emission after freeze-out during the decay process that smoothes out the r-process abundances. Thus, we plan to determine the $P_n$ values both by comparison of beta and neutron rates in the neutron counter, and by following the decay of samples collected for longer periods to determine the ratios of adjacent isobars closer to stability. For example, for $^{137}$Sb decay which is expected to have a $P_n$ value of ~30%, we would follow the decay down the chain to observe the gamma-ray decay of the $^{136,137}$Te daughters and $^{136,137}$I granddaughters. These experiments are low duty-cycle measurements in which one PSB pulse is used and decay followed for up to 2 min before another pulse is used to build a new sample.
Appendix

Below in Figure A are shown some of the known nuclear structure properties of the Te daughter nuclides to be encountered in this experiment.

\[
\begin{align*}
Q &= 8.1 \text{ MeV} \\
1.68 \text{ seconds}
\end{align*}
\]

\[
\begin{array}{c}
\text{135} \text{Sb}^{84} \quad \beta^- \\
\text{5/2},7/2,9/2^+ \\
\sim 6.4 \text{ MeV} \\
\text{5/2, 7/2, 9/2}^+ \\
\end{array}
\]

\[
\begin{array}{cccc}
10^+ & 2792 & 23/2^- & 2490 \\
10^+ & 2761 & 21/2^- & 1996 \\
19/2^- & 1555 & 15/2^- & 1505 \\
21/2^- & 1599 & 21/2^- & 1723 \\
21/2^- & 1723 & 19/2^- & 1723 \\
6^+ & 1383 & 11/2^- & 1180 \\
13/2^- & 1180 & 15/2^- & 1141 \\
17/2^- & 1777 & 6^+ & 1440 \\
6^+ & 1440 & 21/2^- & 1599 \\
15/2^- & 1141 & 17/2^- & 1064 \\
4^+ & 905 & 17/2^- & 1064 \\
4^+ & 905 & 13/2^- & 627 \\
9/2^- & 271 & 13/2^- & 627 \\
2^+ & 443 & 9/2^- & 271 \\
3/2^- & 659 & 2^+ & 606 \\
5/2^- & 1083 & 11/2^- & 608 \\
13/2^- & 608 & 2^+ & 443 \\
13/2^- & 608 & 3/2^- & 443 \\
9/2^- & 271 & 13/2^- & 627 \\
7/2^- & 0 & 0^+ & 0 \\
135 \text{Te}^{83} & 136 \text{Te}^{84} & 137 \text{Te}^{85} & 138 \text{Te}^{86} & 139 \text{Te}^{87}
\end{array}
\]

Figure A. Structure of the Te daughters that should be observed in this experiment.
Table I. Measured and calculated half-lives for very neutron-rich Sn nuclides.

<table>
<thead>
<tr>
<th>A</th>
<th>133</th>
<th>134</th>
<th>135</th>
<th>136</th>
<th>137</th>
<th>138</th>
<th>139</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{meas} (s)</td>
<td>1.44</td>
<td>1.12</td>
<td>538(9)</td>
<td>300(15)</td>
<td>260(40)</td>
<td>100(50)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pn(%)</td>
<td>2.9(2)</td>
<td>13(1)</td>
<td>20(2)</td>
<td>27(4)</td>
<td>58(10)</td>
<td>60(20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q_M (MeV)</td>
<td>8.0</td>
<td>7.1</td>
<td>9.4</td>
<td>8.2</td>
<td>10.5</td>
<td>8.4</td>
<td>10.9</td>
<td>9.5</td>
</tr>
<tr>
<td>Q_{Audi}</td>
<td>7.6</td>
<td>7.2</td>
<td>8.6</td>
<td>8.0</td>
<td>9.7</td>
<td>8.9</td>
<td>10.7</td>
<td>9.8</td>
</tr>
<tr>
<td>T_{M(GT)} (ms)</td>
<td>10.3 s</td>
<td>3.5 s</td>
<td>3000</td>
<td>950</td>
<td>800</td>
<td>480</td>
<td>390</td>
<td>120</td>
</tr>
<tr>
<td>T_{Hilf} (ms)</td>
<td>731</td>
<td>189</td>
<td>110</td>
<td>49</td>
<td>28</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{Groote} (ms)</td>
<td>312</td>
<td>493</td>
<td>327</td>
<td>116</td>
<td>77</td>
<td>37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{ff+GT} (ms) [1996]</td>
<td>300</td>
<td>209</td>
<td>186</td>
<td>162</td>
<td>62</td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{ff+GT} (ms) [this work]</td>
<td>400</td>
<td>600</td>
<td>120</td>
<td>200</td>
<td>80</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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


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.

A. Staudt et al., Atomic Data and Nuclear Data Tables, 44, (1990) 79.

Except for the values shown in red and blue (underlined for the black and white readers), this is the table of predictions presented in the initial proposal for RILIS Sn work in 1999. An estimate for the predicted P_n value can be obtained by dividing the Gamow-Teller half-life, T_{M(GT)} by the total half-life, as all of the states populated in Gamow-Teller allowed transitions are above the neutron separation energy in the daughter Sb nuclide. The large uncertainty values for the half-life and P_n values for \(^{137}\)Sn and \(^{138}\)Sn, are a consequence of using a range of calculated values for the daughter \(^{137}\)Sb and \(^{138}\)Sb half-life and P_n values. The calculated values shown in **bold** are those nearest the observed values and are seen to come from 3 different models.
Recent developments in production of radioactive ion beams with the selective laser ion source at the on-line isotope separator ISOLDE

R. Catherall, V. N. Fedosseev, U. Köster, J. Lettry, G. Suberluq, and the ISOLDE Collaboration
CERN, CH-1211 Geneva 23, Switzerland

B. A. Marsh
The University of Manchester, Manchester M13 9PL, United Kingdom

E. Tongborn
Chalmers University of Technology, Göteborg 41296, Sweden

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The resonance ionization laser ion source (RILIS) of the ISOLDE on-line isotope separation facility is based on the method of laser stepwise resonance ionization of atoms in a hot metal cavity. The atomic selectivity of the RILIS complements the mass selection process of the ISOLDE separator magnets to provide beams of a chosen isotope with greatly reduced isobaric contamination. Using a system of dye lasers pumped by copper vapor lasers, ion beams of 22 elements have been generated at ISOLDE with ionization efficiencies in the range of 0.5%–30%. As part of the ongoing RILIS development, recent on-line resonance ionization spectroscopy studies have determined the optimal three-step ionization schemes for yttrium, scandium, and antimony. © 2004 American Institute of Physics. [DOI: 10.1063/1.1691485]

<table>
<thead>
<tr>
<th>Element</th>
<th>$E_i$ (eV)</th>
<th>$\lambda_1$ (mm)</th>
<th>$\lambda_2$ (mm)</th>
<th>$\lambda_3$ (mm)</th>
<th>$\eta_{\text{tot}}$ (%)</th>
<th>Produced isotopes, mass number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>9.32</td>
<td>234.9</td>
<td>297.3</td>
<td>...</td>
<td>&gt;7</td>
<td>7.9–12, 14</td>
</tr>
<tr>
<td>Mg</td>
<td>7.65</td>
<td>215.2</td>
<td>552.8</td>
<td>578.2</td>
<td>9.8</td>
<td>24–33</td>
</tr>
<tr>
<td>Al</td>
<td>5.99</td>
<td>308.2, 309.3</td>
<td>510.6, 578.2</td>
<td>...</td>
<td>&gt;20</td>
<td>26–34</td>
</tr>
<tr>
<td>Ca</td>
<td>0.11</td>
<td>514.0, 578.2</td>
<td>510.6, 578.2</td>
<td>...</td>
<td>&gt;40</td>
<td>stable</td>
</tr>
<tr>
<td>Sc</td>
<td>6.58</td>
<td>317.4</td>
<td>719.8</td>
<td>510.6, 578.2</td>
<td>15–30</td>
<td>stable</td>
</tr>
<tr>
<td>Mn</td>
<td>7.44</td>
<td>279.8</td>
<td>628.3</td>
<td>510.6</td>
<td>19</td>
<td>48–69</td>
</tr>
<tr>
<td>Co</td>
<td>7.83</td>
<td>364.4</td>
<td>544.5</td>
<td>510.6, 578.2</td>
<td>&gt;3.8</td>
<td>stable</td>
</tr>
<tr>
<td>Ni</td>
<td>7.41</td>
<td>296.3</td>
<td>611.1</td>
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<td>&gt;6.4</td>
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