Radioactivity decay studies of heavy fission products at TRISTAN and ISOLDE

from Coryell to CARIBU

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This work has been supported by the US Department of Energy under grant DE-FG02-94-ER40834.
This is a photograph of Charles Coryell taken in about 1954. Charles was in Inorganic Chemist recruited from UCLA in 1942 to head the effort at ORNL to study the fission-produce yields.

At Cal Tech, he had become and remains famous for a paper… “Pauling and Coryell” that opened Pauling’s life-long study of hemoglobin and blood chemistry.

Charles’ group discovered element 61 during the war, and named it Promethium, Pm, for the god of fire. The work was published in a 3 volume series with Sugarman.

And, in 1956, he was the first to identify the solar abundance peaks at N = 50, 82, and 126 with closed neutron shells to provide a basis for r- and s-process nucleosynthesis.
My plan is to follow the study of fission-product decay from:

MIT via chemical methods

TRISTAN on-line mass separation with limited ion-source selectivity

ISOLDE on-line mass separation with laser ionization,

    ion-source selectivity and suppression of some elements,

    and molecular-ion selectivity
Two theses were prepared in the 1970 time frame at MIT, one by my student, Ken Apt, and one by Coryell’s student, Hasan Erten.
SHORT-LIVED FISSION PRODUCTS:  
IODINE, ANTIMONY, BROMINE

by

HASAN N. ERTEN

Submitted to the Department of Chemistry on December 3, 1970
in partial fulfillment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

The decay of species in iodine fractions rapidly separated from fission products have been studied using Ge(Li) and NaI(Tl) detectors in conjunction with 4096-channel multiparameter pulse-height analyzer and a buffer memory unit. A γ ray of 271.9 ± 0.2 keV decaying with a 3.8-min half-life and growth with a 3.8-min half-life of the prominent γ rays of 55-min 134I, at 847, 885, and 1073 keV were observed. These findings characterize the isomeric transition of 134I. The new isomer 3.8-min 134mI decays by two modes of isomeric transition (E3 and M4), as well as a minor β− decay mode.

A total of 17 γ rays are attributed to the decay of 85-sec 136I. Another species was observed which decayed with 45-sec half-life by emission of 197.3-, 220-, 370-, 381.8, and 1313.3-keV γ rays. The 1313.3-keV γ ray belonging to the decay of 85-sec 136I was found to have a 45-sec component. These observations characterize the 45-sec species as an isomer of 136I. Decay schemes are constructed for 45-sec and 85-sec 136I isomers populating 14 levels in 136Xe. The results are compared with those from previous decay scheme and nuclear excitation studies.

The decay of short-lived antimony fission products were studied using Ge(Li) detectors in singles and in γ coincidences. Some 23 γ rays have been assigned to the decay of the 40-min 130Sb and 5 of these plus 11 new γ rays have been assigned to the decay of the 5.7-min isomer. Thirteen levels are established in 130Te. The levels are compared with those from reaction studies and the systematics of even-A tellurium levels are discussed.

The first detailed decay scheme is constructed for 23-min 131Sb. Sixty γ rays populating 24 levels in 131Te are attributed to the decay of 131Sb. Some of these levels are identified as single quasi-particle states coupled to the first 2+ phonon of the core. Others can be explained as single quasi-particle states coupled to the second phonon and/or the two-particle-neutron levels.

The γ-ray spectra of antimony samples, when counting was started about 1 min after irradiation, showed that the decay of the γ rays of 108.2-, 897.4-, and 974.8-keV energy are complex. The half-lives of the two species involved are found to be 2.1 and 4.1 min. Other γ rays were observed which decayed with only 2.1 min or 4.1 min half-life. The two isomers of 132Sb were characterized from the above observations and the γ-γ coincidence relationships among these γ rays. Ten γ rays have been assigned to the decay of 2.1-min 132Sb and 3 of these plus 7 new ones have been assigned to the decay of 4.1-min 132Sb. Five levels are established in 132Te. A previously reported 45-sec species was not observed in any of our γ-ray spectra.

The half-life of 133Sb is found to be 2.3 ± 0.2 min by following the decay of its prominent γ rays of 1096.4-, 1732.2-, and 2751.7-keV energy. A total of 70 γ rays are attributed to the decay of 2.3-min 133Sb populating 17 levels in 133Te. The proposed levels can be explained to be single-hole states in the d3/2, h11/2, and s1/2 single-particle orbitals, single-hole states coupled to the first and second phonon levels, and two-proton levels coupled to single-hole states. The levels of odd-A tellurium isotopes are discussed.

By observing the spectra of short-lived bromines separated from fission at different times after irradiation it was possible to differentiate between some of the γ rays belonging to the decay of 54-sec 86Br and 55-sec 87Br. Three γ rays of 801.6, 832.0, and 925.1 keV were found to decay with a 3.0-min half-life and they are assigned to the decay of 3-min 85Br. A decay scheme is constructed for 3.0-min 85Br based on these results and on the results of nuclear excitation studies in 85Kr.

The γ-ray spectrum of equilibrium sources of 99Zr - 95Nb, and pure 95Nb sources were observed using a Compton-suppressed Ge(Li) detector. Energies and relative intensities of the γ transitions as well as percent β− branchings were determined. Two new weak β− transitions were found in the decay of 90-h 95mNb leading to levels at 204.2 and 790.2 keV in 95Mo.

Thesis Supervisor: Charles D. Coryell
Title: Professor of Chemistry

Sb chemistry: 130, 131, 132, 133Sb decay  fast gas chemistry SbH3
Halogen chemistry, 134, 136I 86, 87Br
REMOTELY OPERATED FISSION-PRODUCT TIN EXTRACTION APPARATUS

75 ml 2.5 M HClO₄ and 2.5 M NaI Wash Solution

Br₂-H₂O Wash Solution and Sn Carrier

100 ml Pre-equilibrated Benzene

Fission-Product Solution

75 ml 2.5 M HClO₄ and 2.5 M NaI Sb and Te Carriers

Waste Solution

Benzene Fraction Containing Extracted Sn

To Vacuum
Three-Quasiparticle $15/2^-$ Isomer in $^{127}\text{Sb}^+$

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and

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(Received 30 March 1973)

The $\beta$ decay of 2.2-h, $^{119}\text{Sn}$ has been found to populate an 11-μsec isomer of $^{127}\text{Sb}$

\[
\begin{array}{c|c}
3^- & 2720 \\
2^+ & 2378 \\
7^- & 2222 \\
6^+ & 2167 \\
5^- & 2054 \\
\end{array}
\]

\[
\begin{array}{c|c}
15/2^- & 2358.4 \\
& 824.7(16) \\
& 605.9(16) \\
& 1920.2 \\
(7/2^+) & 1711.4 \\
(9/2^+) & 1584.3 \\
(7/2^+) & 1471.2 \\
9/2^+ & 114.3 \\
11/2^+ & 1095.6 \\
5/2^+ & 490.9 \\
0^+ & 0 \\
\end{array}
\]

$^{124}\text{Sn}(t,p)^{126}\text{Sn}$
This is a “big picture chart” showing the location of the MIT work.
At Maryland during the 1970's, we had been working with 3-detector angular correlations and proposed an extension to 4 detectors for the work at TRISTAN.

The isotopes that could be studied were the thermal-neutron fission products of $^{235}$U.

Fig. 2. Schematic description of the detectors and angles.

Fig. 1. The experimental system at TRISTAN. Two detectors are installed at the "parent" port, where the fission products are deposited on the aluminized mylar tape. The four-detector system is located at the "daughter" port.
A FOUR-DETECTOR SYSTEM FOR $\gamma-\gamma$ ANGULAR CORRELATION STUDIES

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C. CHUNG and W.B. WALTERS

University of Maryland, College Park, Maryland 20742, USA

G. PEASLEE

SUNY at Stony Brook, Stony Brook, New York 11794, USA

R.I. GILL, M. SHMID, V. MANZELLA, E. MEIER, M.L. STELTS,** H.I. LIOU and R.E. CHRIEN

Brookhaven National Laboratory, Upton, New York 11973, USA

D.S. BRENNER

Clark University, Worcester, Massachusetts 01610, USA

Received 28 September 1982

A multiple detector system for $\gamma-\gamma$ coincidence and angular correlation measurements is described. The system consists of four large coaxial Ge detectors set at fixed positions, enabling the measurement of $\gamma-\gamma$ coincidences between any pair. Thus, six distinct angles are measured simultaneously. The performance of the system was studied with a $^{152}$Eu source. An application for $\gamma-\gamma$ correlation studies in $^{146}$Ce is described. Systematic errors, if present, are shown to be less than 0.03 and 0.05 for $A_2$ and $A_4$, respectively. The extension of this system to more than four detectors is straightforward.
This is a summary of work out group performed at TRISTAN. Craig Stone studied the Sn isotopes, Scott Faller worked on the Xe decay, and Dave Robertson worked on the Ba decay. Ion source development started with Re ionizer for Ba nuclei, then plasma for the Sn isotopes and LaBr$_6$ for Iodine. Finally, we could do the short-lived $^{127}$Sn decay. Overall, decays from 27 nuclei were studied.
IBA CALCULATIONS NEAR THE Z = 64 SUBSHELL

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Received 25 January 1982
Revised manuscript received 25 April 1982

It has recently been shown that the effects of the Z = 64 subshell are important for nuclides with N ≤ 88 but disappear as N approaches 90, due to the influence of neutron–proton interactions. IBA-2 calculations show excellent agreement with experimental energy systematics if the effective reduction in valence bosons caused by the Z = 64 subshell closure is explicitly included. The deduced parameters then behave as predicted by the microscopic basis of the IBA-2 model, in contrast with previous studies.
Our initial interest was in the $^{144}\text{Ba}$ decay to odd-odd $^{144}\text{La}$, which has been published, and opened our interest in Vladimir Paar’s parabolas. In the process, we also studied $^{144}\text{Ce}$. 
Chien Chung had worked out this decay scheme containing 400 gamma rays and 80 levels. We had no idea how to publish it, so the data were sent to the Nuclear Data Center. PC’s and Lotus 1-2-3 came along just in time to make it possible to organize the data in a useful way.
When high-energy beta’s are placed, more neutrino energy is lost compared to the real “lower-energy” beta for which less neutrino energy is lost.
In the mid 90's Reg Greenwood asked for the spreadsheet with the gamma list in order to make a comparison with their Total Absorption Spectrum

Measurement of $\beta^-$-decay intensity distributions of several fission-product isotopes using a total absorption $\gamma$-ray spectrometer

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$^c$Idaho National Engineering Laboratory, Idaho Falls, ID 83415-2114, USA

Received 6 June 1996

Abstract

A total absorption $\gamma$-ray spectrometer coupled to the $^{252}$Cf-based INEL ISOL facility has been used in a program of systematic study of the distributions of $\beta^-$-decay intensities of fission-product radionuclides. Cascade-summed $\gamma$-ray spectra measured with the system have been compared with the spectrum simulated from the corresponding decay schemes, as a test of the completeness and correctness of these schemes. New $\beta^-$-decay intensity distributions have been deduced for the decay of these radionuclides. Radionuclides which have been studied in this manner include $^{87}$Rb, $^{90}$Rb, $^{90a}$Rb, $^{91}$Rb, $^{93}$Rb, $^{93}$Sr, $^{94}$Sr, $^{94}$Y, $^{95}$Sr, $^{95}$Y, $^{138}$Cs, $^{138a}$Cs, $^{139}$Cs, $^{140}$Cs, $^{141}$Ba, $^{142}$Ba, $^{142}$La, $^{143}$Ba, $^{143}$La, $^{144}$Ba, $^{144}$La, $^{145}$Ba, $^{145}$Ce, $^{146}$Ce, $^{146}$Pr, $^{147}$Ce, $^{147}$Pr, $^{148}$Ce, $^{148}$Pr (2.0 min), $^{148}$Pr (2.27 min), $^{149}$Pr, $^{149}$Nd, $^{151}$Pr, $^{151}$Nd, $^{152}$Nd, $^{152}$Pm (4.1 min.), $^{153}$Nd, $^{153}$Pm, $^{154}$Nd, $^{154}$Pm (1.7 min), $^{155}$Nd, $^{155}$Pm, $^{156}$Pm, $^{157}$Pm, $^{157}$Sm, $^{158}$Sm, and $^{158}$Eu.
\textbf{144}La $3^-$

\textbf{Literature}

Fig. 23. Comparison of measured singles spectrum for $^{144}$La with the simulated spectrum for the NDS decay scheme [30].

\textbf{Chung et al.}

\textbf{Four $\sim$25\% Ge detectors}

Fig. 24. Comparison of measured singles spectrum for $^{144}$La with the simulated spectrum for the Walters decay scheme [31].

\textbf{Table 22}

$^{144}$La $\beta^-$-decay intensities

<table>
<thead>
<tr>
<th>Level energy (keV)</th>
<th>$I_\beta$ (%)</th>
<th>NDS [30]</th>
<th>Walters [31]</th>
<th>TAGS</th>
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<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.2 ± 1.0</td>
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<td>397.4</td>
<td>2+</td>
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<td>4+</td>
<td>9.6</td>
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<td>3-</td>
<td>3.1</td>
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<td>0.0</td>
<td>1.21</td>
<td>0.25</td>
</tr>
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<td>1.13</td>
<td>0.73</td>
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<td>1592.0</td>
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<tr>
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<td>0.55</td>
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<td>0.29</td>
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<tr>
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<td>0.27</td>
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<td>0.0</td>
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New Cold and Ultra Hot Binary and Cold Ternary Spontaneous Fission Modes for $^{252}$Cf and New Band Structures with Gammasphere

J. H. HAMILTON$^1$, A. V. RAMAYYA$^1$, J. K. HWANG$^1$, J. KORMICKI$^1$, B. R. S. BABU$^1$, A. SANDULESCU$^{1,3,4}$, A. FLORESCU$^{1,3,4}$, W. GREINER$^{1,3,4}$, G. M. TER-AKOPIAN$^{1,2,5}$, Yu. Ts. OGANESSIAN$^5$, A. V. DANIEL$^{1,2,5}$, S. J. ZHU$^{1,2,6}$, M. G. WANG$^6$, T. GINTER$^1$, J. K. DENG$^{1,6}$, W. C. MA$^7$, G. S. POPEKO$^5$, Q. H. LU$^2$, E. JONES$^3$, R. DODDER$^1$, P. GORE$^1$, W. NAZAREWICZ$^9$, J. O. RASMUSSEN$^9$, S. ASZTALOS$^9$, I. Y. LEE$^2$, S. Y. CHU$^9$, K. E. GREGORICH$^9$, A. O. MACCHIAVELLI$^9$, M. F. MOHAR$^9$, S. PRUSSIN$^{10}$, M. A. STOYER$^{10}$, R. W. LOUGHEED$^{10}$, K. J. MOODY$^{10}$, J. F. WILD$^{10}$, L. A. BERNSTEIN$^{10}$, J. A. BECKER$^{11}$, J. D. COLE$^{12}$, R. ARYAINEJAD$^{12}$, Y. X. DARDENNE$^{12}$, M. W. DRIGERT$^{12}$, K. BUTLER-MOORE$^{12}$, R. DONANGELO$^{13}$ and H. C. GRIFFIN$^{14}$
OSTIS at Grenoble

1979RI09  Z.Phys. A290, 311 (1979)

C.Ristori, J.Crancon, K.D.Wunsch, G.Jung, R.Decker, K.-L.Kratz

Half-Lives and Delayed Neutron Emission Probabilities of Short-Lived Rb and Cs Precursors

RADIOACTIVITY 94,95,96,97,98Rb, 143,144,145,146,147Cs [from on-line separator]; measured T1/2, delayed-neutron emission probabilities.

OSTIS at Grenoble


M.Epherre, G.Audi, C.Thibault, R.Klapisch, G.Huber, F.Touchard, H.Wollnik

Direct Measurements of the Masses of Rubidium and Cesium Isotopes Far From Stability

NUCLEAR STRUCTURE 74,75,76,77,78,79,90,91,92,93,94,95,96,97,98,99Rb; 117,118,119,120,121,122,123,124,126,138,140,141,142,143,144,145,146,147Cs; measured masses; deduced two-neutron separation energies, evidence for deformation around N=60.


OSTIS at Grenoble


The Neutron-Rich Barium Isotopes

RADIOACTIVITY 142,144,146Cs [from 235U(n, F), mass separation]; measured Eγ, Iγ, γγ(θ). 142,144,146Ba levels deduced J, π, δ. Interacting boson model.

TRISTAN at BNL


P.L.Reeder, R.A.Warner

Delayed Neutron Precursors at Masses 97-99 and 146-148

RADIOACTIVITY 97,98,99Rb, 97,98,99Sr, 97,98,99Y, 146,147Cs, 147,148Ba, 147,148La(β-n) [from 235U(n, F), E=thermal]; measured T1/2, β-delayed neutron emission probabilities. On-line mass separation, multiscaling technique.


OSTIS at Grenoble


E.Lund, G.Rudstam

Delayed-Neutron Activities Produced in Fission: Mass Range 122-146

RADIOACTIVITY 123,122Ag, 127,128,129,130,131,132In, 128Cd, 133,134Sn, 134,135,136Sb, 136Te, 137,138,139,140,141I, 141,142,143,144,145,146Cs; measured delayed neutrons, T1/2.


OSIRIS at Studsvik

1979RI09  Z.Phys. A290, 311 (1979)

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RADIOACTIVITY 97,98,99Rb, 97,98,99Sr, 97,98,99Y, 146,147Cs, 147,148Ba, 147,148La(β-n) [from 235U(n, F), E=thermal]; measured T1/2, β-delayed neutron emission probabilities. On-line mass separation, multiscaling technique.


E.Lund, G.Rudstam

Delayed-Neutron Activities Produced in Fission: Mass Range 122-146

RADIOACTIVITY 123,122Ag, 127,128,129,130,131,132In, 128Cd, 133,134Sn, 134,135,136Sb, 136Te, 137,138,139,140,141I, 141,142,143,144,145,146Cs; measured delayed neutrons, T1/2.

The TRISTAN operation ground to a halt in the late 1980’s owing to safety concerns at the HFBR. OSTIS also was closed.

Meantime…..

The data flowing in from Supernova 1987a fueled a new interest in r-process nucleosynthesis that provided motivation for added measurements of the decay and structure properties of nuclei that lie in the path of the r-process.

Since the Seuss and Urey paper in 1956, there had been much interest in the astrophysical production of heavy elements.
This report by Coryell came almost immediately after a Seuss and Urey paper reporting good solar abundances.

Correspondingly, it
\[ \beta \text{ decay of } {}^{\text{82}}_{\text{47}} \text{Ag}^{\text{129}}, \text{ corr} \]

\[ {}^{129}\text{Ag} \text{ was deemed important on DAY ONE.} \]

In other words, there were two waiting points, one for capture of neutrons on a slow time scale on elements near stability, and one for nuclei much farther from stability that must be on a faster time scale.
The major BBFH paper appeared in 1957, but was preceded in October, 1956, by an article in Science.

We have distinguished two conditions under which the neutron capture can take place, a slow (s) process and a rapid (r) process. Suess and Urey (11) and Coryell (13) have already pointed out that the peaks in the abundance curves at stable nuclei with filled neutron shells \((A=90, N=50; A=139, N=82; A=208, N=126)\) strongly indicate the operation of the \(s\)-process in element synthesis and that the nearby peaks at \(A=82, 130,\) and \(194,\) shifted by \(\delta A \sim 8\) to 14, similarly require the operation of the \(r\)-process.

Stated another way, BBFH were aware of the Coryell work prior to this article and their seminal article in 1957.
It was THIRTY years after Coryell, and BBFH before the first successful measurement for the $^{130}$Cd half life emerged at ISOLDE. This was a very hard measurement, and did not bode well for further work with the plasma ion source.

**Fig. 8:** Growth and decay curve of $\beta$-delayed neutron activity of $^{130}$Cd. Data from about 36,000 multiscaling cycles were accumulated at 10 ms intervals.
Along came this report from GSI that chemical selectivity could be achieved by the user of laser ionization.

**Beta Decay of the New Isotope $^{101}$Sn**

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**Abstract**

The very neutron-deficient isotope $^{101}$Sn was produced in a $^{50}$Cr($^{58}$Ni, 2p5n) reaction and its decay properties were determined for the first time. By using chemically selective ion sources of an on-line mass separator, the energy spectrum and the half-life (3 ± 1 s) of beta-delayed protons of $^{101}$Sn were measured. These results are compared to theoretical predictions.
Recently, a laser ion source was developed for the CERN/ISOLDE on-line facility which can meet these requirements. The ionization of Sn, Tm, Yb and Li was investigated in off-line and on-line studies. An ionization efficiency of up to 15% was obtained [15]. The laser ion source based on resonance ionization spectroscopy of atoms in a hot cavity has proved to be a powerful technique for sensitive and chemically selective detection of atoms. The key features of this technique, high selectivity and high efficiency are also required for the proposed experiments on neutron-rich Ag isotopes.
Neutron-rich beams at CERN/ISOLDE

Technical improvements:
1: Neutron converter
2: Laser Ion Source
3: High Resolution Separator

Primary beam:
1 - 1.4 GeV protons, intensity: ca. $10^{13}$ p/pulse

Transfer line (Nb)
~2200 K

UC$_2$-C-Target

Converter (Ta or W)

ISOLDE Laser System:
- 3 copper vapor lasers
- 2 dye lasers (cw, frequency tripling by two BBO crystals → UV)

Distance to Target: 20m

Mass separator:
GPS/HRS

60 kV
The MOPSBALL* \(\beta\gamma\) detector setup

\*engl. „pug-ball“

The Mainz \(\beta\)dn-detector setup

64 \(^3\)He long counters in three rings (~33% efficiency)

Beam

Moving Tape Collector

HPGe (55-70%)

\(\beta\)-Telescope

\(\beta\)-detector

paraffine

Institut für Kernchemie

Johannes Gutenberg Universität Mainz
Towards the “Waiting-Point” Nucleus $^{129}$Ag

Dissertation zur Erlangung des Grades
“Doktor der Naturwissenschaften”

am Fachbereich Physik
der Johannes Gutenberg-Universität
in Mainz

Ylva Jading
geboren in Västervik
Mainz 1996

Figure 4.8: Beta-delayed neutrons from $^{127}$Ag and $^{127}$In (solid line). The short broken line represents the Ag component and the long broken line the In component.

Figure 4.9: Beta-delayed neutrons from $^{128}$Ag and $^{128}$In. The short broken line is the silver component and the long broken line is the average indium component.
4.3 Results

Before going into details of the analysis for the different isotopes a few general remarks have to be made on the spectra themselves.

In Table 4.3 the results from the half-life analyses for $^{120-128}$Ag have been listed, together with earlier half-life measurements made with $\beta$-delayed neutrons, $\beta$- or $\gamma$-detection.

Table 4.3: Half-lives for silver isotopes $^{120-128}$Ag from this and earlier publications.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-lives [ms]</th>
<th>Method</th>
<th>Reference</th>
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<td>1350 $\pm$ 200</td>
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<td></td>
<td>1250 $\pm$ 30</td>
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<td>1170 $\pm$ 50</td>
<td>$\gamma$</td>
<td>[Fog71]</td>
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<td>[Fog82]</td>
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<td></td>
<td>570 $\pm$ 30</td>
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<td>480 $\pm$ 80</td>
<td>$\gamma$</td>
<td>[Shi78]</td>
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<td>300 $\pm$ 10</td>
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<td>390 $\pm$ 30</td>
<td>n</td>
<td>[Lun76]</td>
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<td>300 $\pm$ 20</td>
<td>$\gamma$</td>
<td>[Mac86]</td>
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<td>$^{124}$Ag</td>
<td>172 $\pm$ 5</td>
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<td>540 $\pm$ 80</td>
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<td>170 $\pm$ 30</td>
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<td>$^{125}$Ag</td>
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<td>$^{126}$Ag</td>
<td>98 $\pm$ 3</td>
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<td>$^{127}$Ag</td>
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<td>$^{128}$Ag</td>
<td>58 $\pm$ 5</td>
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August 1997

Setup in 1996 had been done with stable $^{107}$Ag which has a $\frac{1}{2}^-$ ground-state spin. The question was raised about hyperfine interactions and whether some adjustment would help yields for the expected $9/2^+$ spin for $^{129}$Ag. The answer was yes. In other words, hyperfine tuning could provide “isomer-specific” ionization.
November 1997

The search for $^{129}\text{Ag}$ was performed at the “green” setting.

These $\beta$-delayed neutron data support the presence of $\beta$-decaying $\frac{1}{2}-$ isomers in $^{125,127}\text{Ag}$, but not necessarily $^{123}\text{Ag}$, but $P_n$ could be a factor.

Well established data

$^{1/2-} 506$
$^{7/2+} 343$

Speculative

$351/384 = 0.37$ center
$351/384 = 0.08$ edge

$^{1/2-} 134$
$^{7/2+} 28$
$^{9/2+} 0$
$^{1/2-} 78$

$^{9/2+} 0$
$^{7/2+} 0$
$^{1/2-} 0$
$^{7/2+} 0$

$^{9/2+} 0$
$^{123} 47$
$^{125} 47$
$^{127} 47$

$^{47} 47$
$^{52} 54$
$^{76} 78$
$^{80} 80$
The astrophysical impact was large as the short half life "lowered the impact of" $^{129}\text{Ag}$ as a major waiting-point nucleus, and also strongly suggested that the lower $N = 82$ isotones would also have shorter half-lives and also not be major waiting points. Although it was a "theoretical surprise", any look at the half-lives for the lighter Ag nuclei measured in 1996 could see...... 150.... 100..... 80..... 60.... 40.

The successful development and utilization of the Resonance Ionization Laser Ion Source (RILIS) then paved the way to develop ionization schemes for Cd, In, Sn, and Sb.

The study of the decay of the Cd isotopes was improved significantly by the development of means to suppress ionization of daughter In isotopes. This was done by using a quartz transfer tube onto which the In stuck.
Jading, Moller, Walters, Mishin, Kratz…. For the CERN Courier
This drawing exhibits the difference between the measured mass of $^{130}$Cd and the value calculated by the FRDM, showing that $^{130}$Cd is 1.6 MeV less bound than expected.

Also shown is the measured position of the 1$^+$ level in $^{130}$In that is 740 keV higher in energy than the value calculated prior to the measurement. The measured value can be fitted by a 30% reduction in the proton-neutron interaction strength.

Hence, there is now evidence that some reduction in both “neutron-neutron” and “proton-neutron” interactions may be needed.
The 68 (3) ms half-life and 3.5% \( P_n \) values for \(^{131}\text{Cd}\) remain somewhat anomalous and deserve more attention.
Microscopic calculations of $\beta$–decay characteristics near the $A=130$ $r$-process peak

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*Institut d’Astronomie et d’Astrophysique, Université Libre de Bruxelles
CP 226 Campus de la Plaine, Bvd. du Triomphe, 1050 Brussels – Belgium

The green dot is the 1986 point whereas the red dots are from the 1999 measurements performed with RILIS. One observation is that, at that time, nearly all calculated half-lives were HIGHER the values eventually observed.

Figure 1. Comparison of experimental half-lives with the ones calculated with the ETFSI potentials (SKSC6-13) and with GT, QRPA and DF3 models.
Für den $P_{\alpha}$-Wert wurde ein Wert von 49,5 (± 8)\% ermittelt. Dieser Wert deckt sich gut mit dem von Shergur angegebenen Wert von 58 (± 15)\%, der sich somit bestätigen ließ.

\[ t_{1/2}^{\text{\tiny 137Sn}} = 273,3 (6,9) \text{ ms} \]
Abb. 76 Differenzspektrum für $^{138}\text{Sb}$ mit einer Halbwertszeit von $T_{1/2} = 350,1 \, (+16,8/-15,8) \, \text{ms}$. Bis 200 ms nach dem Eintreffen des Protonenpulses ist das Anwachsen der Aktivität bei geöffnetem Beamgate beobachtbar. Mit dem Schließen des Beamgates beginnt der Zerfall der gesammelten Aktivität. Der Untergrund besteht im Wesentlichen $^{137}\text{I}$ ($T_{1/2} = 24,5 \, (\pm 0,2) \, \text{s}$).
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During the past 15 years, the half-lives have been measured from $^{129}\text{Ag}$ to $^{139}\text{Sb}$. The work at N = 82 has improved the ability to extrapolate “down the N = 82 chain” to make better estimates for the other N = 82 “likely waiting-point isotopes”. The IMPACT is that it is now possible to provide a “reasonable” model fit for the r-process yields!!!! These data make it possible to account for the “steep” left slope of the peak owing to the shorter-than-expected half-lives up the N = 82 chain, and, perhaps, somewhat longer-than-expected half-lives for the Sn and Sb nuclei.
One major impact of these measurements has been the ability to identify model calculations that do not provide good fits to the data. For $^{128}\text{Pd}$, the range is from 30 to 50 ms. For $^{126}\text{Ru}$, the maximum is only about 20 ms…..not much waiting with that half-life.
This is the first level scheme from Jason Shergur’s study of $^{135}$Sn decay to $^{135}$Sb.

The 718-keV level is ~ 70% single-particle $d_{5/2}$.
FIG. 1. Possible states in $^{134}$Sb that can be populated by the $\beta$ decay of $^{134}$Sn and the $\beta^-n$ decay of $^{135}$Sn.
The Advanced Time Delayed method has been used to measure the lifetimes of excited states in the exotic nuclei $^{134}\text{Sb}$, $^{135}\text{Sb}$ and $^{136}\text{Te}$ populated in the beta decay of $^{134}\text{Sn}$, $^{135}\text{Sn}$ and $^{136}\text{Sn}$, respectively. High purity Sn beams were extracted at the ISOLDE separator using a novel production technique utilizing the molecular SnS$^+$ beams to isolate Sn from contaminating other fission products. Among the new results we have identified the $1/2^+$ state in $^{135}\text{Sb}$ and its E2 transition to the lower-lying $5/2^+$ state was found to be surprisingly collective. This measurement represents also one of the first applications of the LaBr$_3$ scintillator to ultra fast timing.

Table 1. Comparison of the experimental $B(M1)$ and $B(E2)$ values and the shell model calculations by A. Brown (labelled AB), A. Covello and A. Gargano (CG) and V.I. Isakov (IS). The $B(M1)$ and $B(E2)$ values are in the units of $\mu_N^2$ and $e^2 fm^2$, respectively.

<table>
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<tr>
<th>Nucleus</th>
<th>$J_i \rightarrow J_f$</th>
<th>$X\lambda$</th>
<th>$B(X\lambda)_{exp}^a$</th>
<th>$B(X\lambda)_{th}^{AB}$</th>
<th>$B(X\lambda)_{th}^{CG}$</th>
<th>$B(X\lambda)_{th}^{IS}$</th>
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<td>$^{134}\text{Sb}$</td>
<td>$3_1^- \rightarrow 2_1^-$</td>
<td>M1</td>
<td>2.0(4)</td>
<td>1.60</td>
<td>1.39</td>
<td>1.81</td>
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<td>$^{134}\text{Sb}$</td>
<td>$3_1^- \rightarrow 1_1^-$</td>
<td>E2</td>
<td>118(26)</td>
<td>84</td>
<td>115</td>
<td>116</td>
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<tr>
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<td>$2_1^- \rightarrow 0_1^-$</td>
<td>E2</td>
<td>429(238)</td>
<td>90</td>
<td>123</td>
<td>104</td>
</tr>
<tr>
<td>$^{135}\text{Sb}$</td>
<td>$1/2^+ \rightarrow 7/2_1^+$</td>
<td>E2</td>
<td>527(26)</td>
<td>678</td>
<td>566</td>
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</tr>
<tr>
<td>$^{135}\text{Sb}$</td>
<td>$5/2^+ \rightarrow 7/2_1^+$</td>
<td>E2</td>
<td>$\leq$54</td>
<td>23</td>
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</tr>
<tr>
<td>$^{135}\text{Sb}$</td>
<td>$5/2^+ \rightarrow 7/2_1^+$</td>
<td>M1</td>
<td>$\leq$0.00030</td>
<td>0.0022</td>
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<tr>
<td>$^{136}\text{Te}$</td>
<td>$2_1^+ \rightarrow 0_1^+$</td>
<td>E2</td>
<td>208(29)$^b$</td>
<td>452</td>
<td>360</td>
<td></td>
</tr>
<tr>
<td>$^{136}\text{Te}$</td>
<td>$2_1^+ \rightarrow 0_1^+$</td>
<td>E2</td>
<td>245(50)</td>
<td>452</td>
<td>360</td>
<td></td>
</tr>
</tbody>
</table>

$a$: From this work unless noted otherwise.

$b$: From $^{12}$ obtained in Coulomb excitation in inverse kinematics.
This result was obtained with an ISOLDE ion source using Sulfur gas, enriched in $^{34}$S in the ion source, creating SnS$^+$ ions that are 34 mass units heavier than the isobaric Cs that is strongly ionized. The $\frac{1}{2}^+$ level shown below was populated in beta-delayed neutron decay from $^{136}$Sn decay. The calculation had been previously published indication the level should be at 527 keV……… it was found at 523 keV.
The good news is that the most exotic nuclei will be at the highest mass and well separated from the the daughter, slower-decaying nucleus.
Thank you for your attention.