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.

1912 - 1971

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:

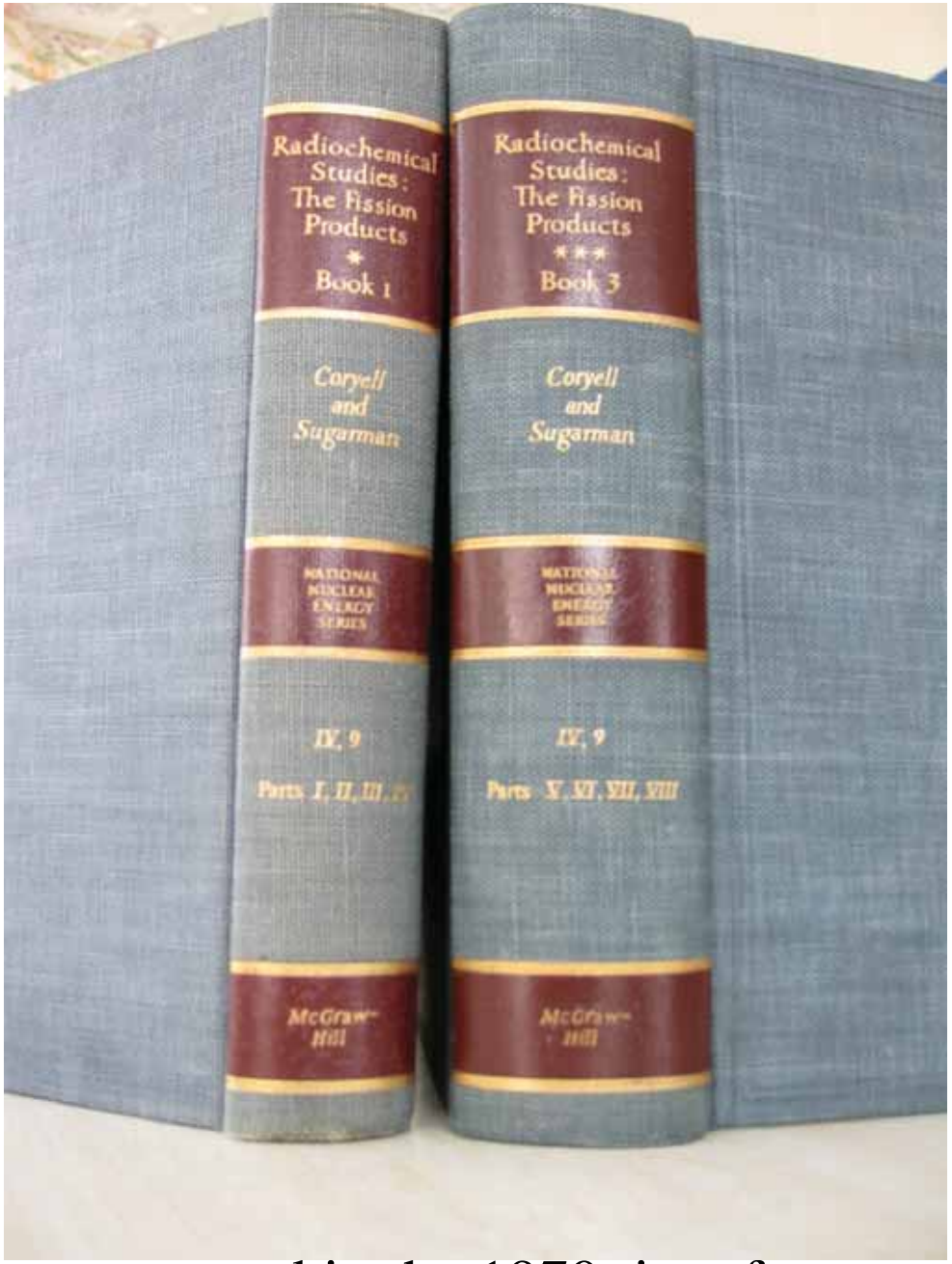
MIT via chemical methods

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 53-min ^{134}I at 847, 885, and 1073 keV were observed. These findings characterize the isomeric transition of ^{134m}I. The new isomer 3.8-min ^{134m}I 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 83-sec ^{136}I. 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 83-sec ^{136}I was found to have a 45-sec component. These observations characterize the 45-sec species as an isomer of ^{136}I. Decay schemes are constructed for 45-sec and 83-sec ^{136}I isomers populating 14 levels in ^{136}Xe. 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 ^{130}Sb 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 ^{130}Te. 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 ^{131}Sb. Sixty γ rays populating 24 levels in ^{131}Te are attributed to the decay of ^{131}Sb. 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 103.2-, 697.4-, and 974.6-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 ^{132}Sb 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 ^{132}Sb and 3 of these plus 3 new ones have been assigned to the decay of 4.1-min ^{132}Sb. Five levels are established in ^{132}Te. A previously reported 45-sec species was not observed in any of our γ-ray spectra.

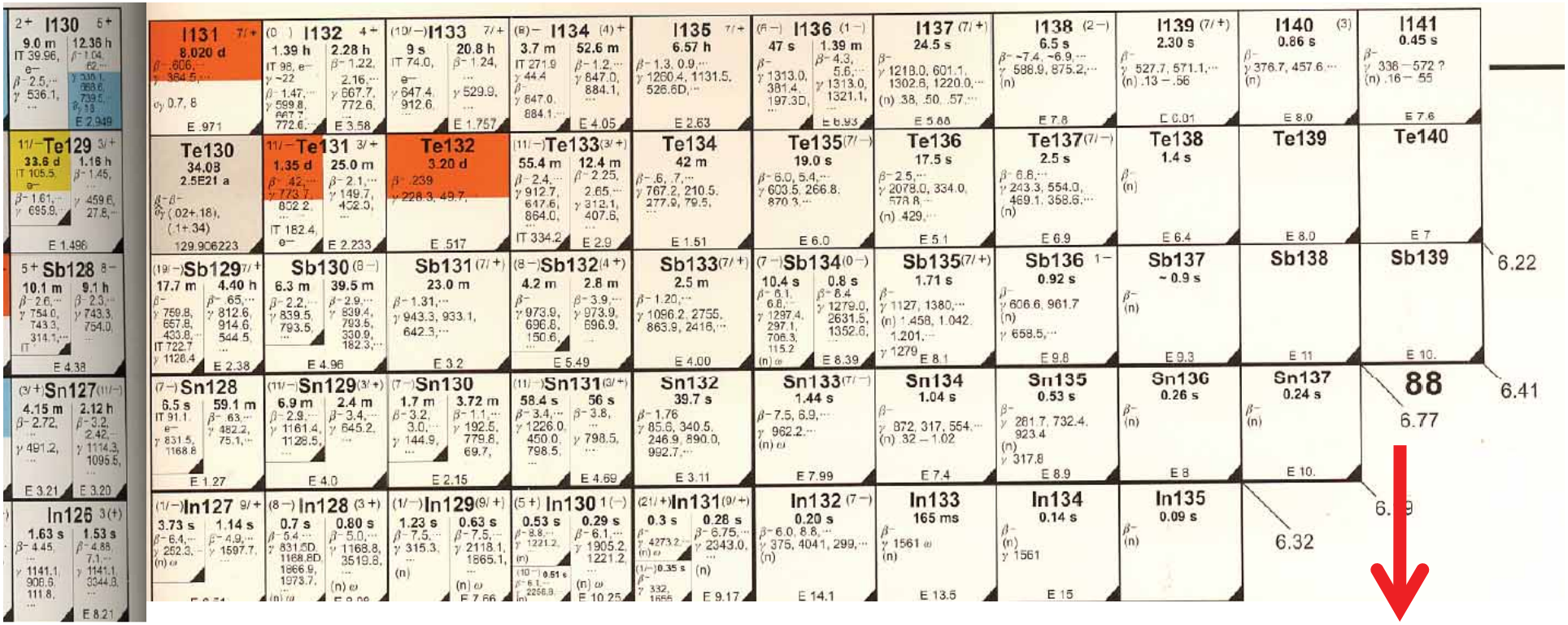
The half-life of ^{133}Sb is found to be 2.3 ± 0.2 min by following the decay of its prominent γ rays of 1096.4-, 1728.2-, and 2751.7-keV energy. A total of 70 γ rays are attributed to the decay of 2.3-min ^{133}Sb populating 17 levels in ^{133}Te. The proposed levels can be explained to be single-hole states in the $d_{3/2}$, $h_{11/2}$ and $s_{1/2}$ 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.

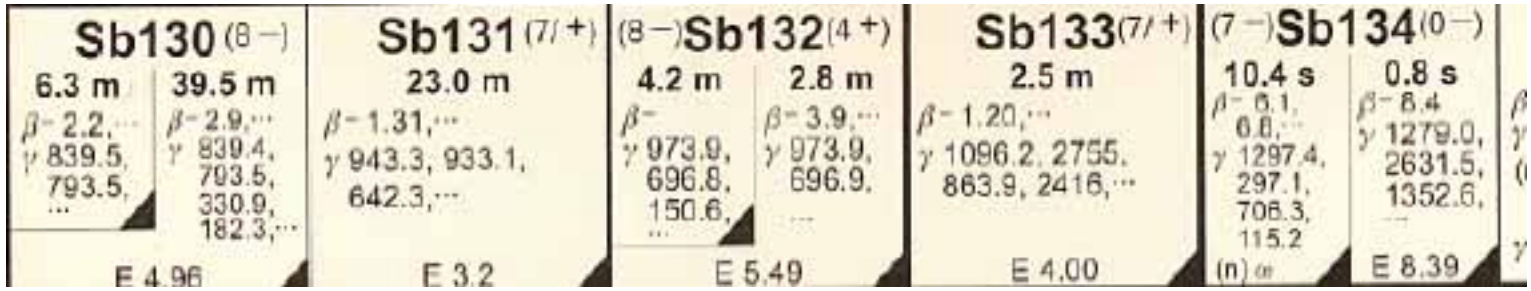
By observing the spectra of short-lived bromines separated from fission at different times after irradiation it was possible to differentiate between some of the γ rays belonging to the decay of 54-sec ^{86}Br and 55-sec ^{87}Br. Three γ rays of 801.6, 832.0, and 925.1 keV were found to decay with a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

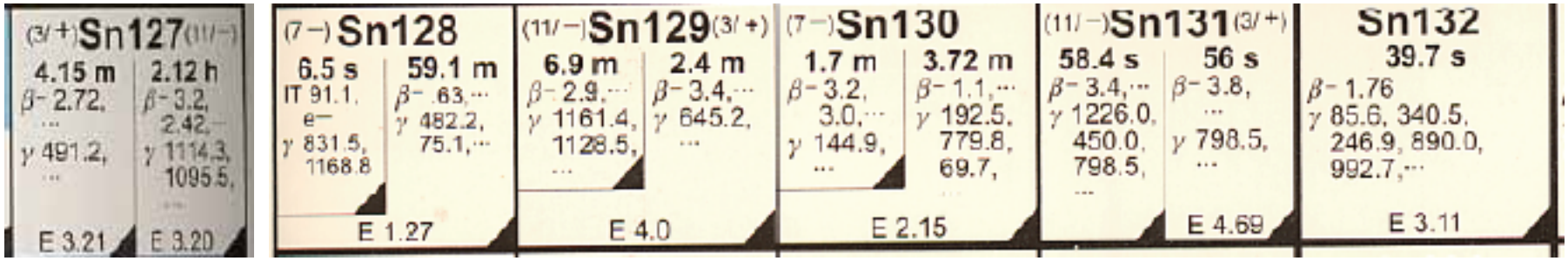
The γ-ray spectrum of equilibrium sources of ^{95}Zr - ^{95}Nb, and pure ^{95}Nb sources were observed using a Compton-suppressed Ge(Li) detector. Energies and relative intensities of the γ transitions as well as percent β^- branchings were determined. Two new weak β^- transitions were found in the decay of 90-h ^{95m}Nb leading to levels at 204.2 and 789.2 keV in ^{95}Mo.

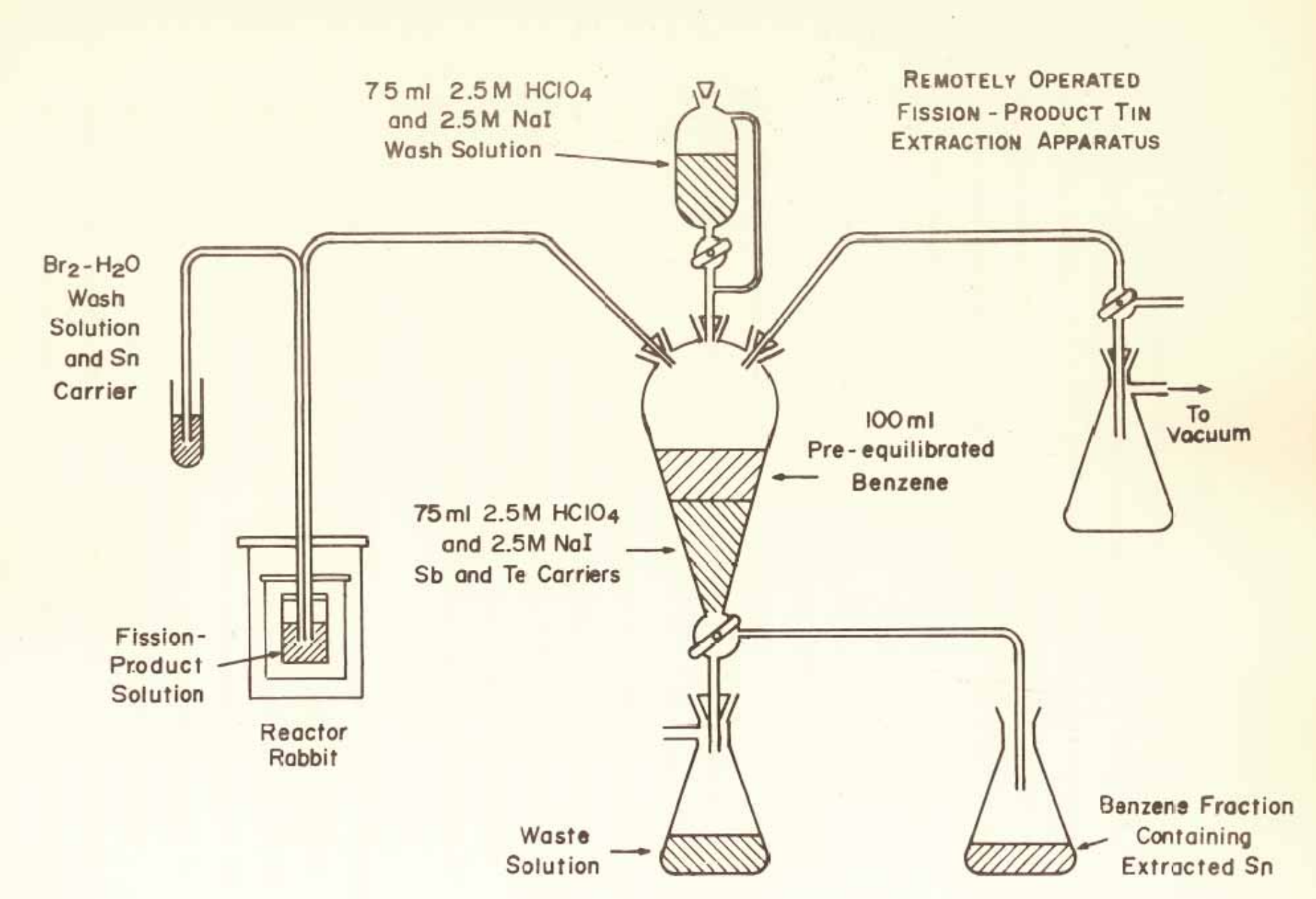
Thesis Supervisor: Charles D. Coryell
Title: Professor of Chemistry

Sb chemistry: ^{130,131,132,133}Sb decay fast gas chemistry SbH_3
Halogen chemistry, ^{134,136}I ^{86,87}Br


I130
I131 8.020 d
I132
I133
I134
I135 6.57 h
I136
I137
I138
I139
I140 0.86 s
I141 0.45 s
Te129
Te130 34.08 2.5E21 a
Te131
Te132 3.20 d
Te133
Te134 42 m
Te135
Te136 17.5 s
Te137
Te138 1.4 s
Te139
Te140
Sb128
Sb129
Sb130
Sb131
Sb132
Sb133
Sb134
Sb135
Sb136
Sb137
Sb138
Sb139
Sn127
Sn128
Sn129
Sn130
Sn131
Sn132 39.7 s
Sn133
Sn134 1.04 s
Sn135 0.53 s
Sn136 0.26 s
Sn137 0.24 s
88
In126
In127
In128
In129
In130
In131
In132
In133 165 ms
In134 0.14 s
In135 0.09 s
6.22
6.41
6.77
6.32


Sb130 (8−)
6.3 m
39.5 m
E 4.96
Sb131 (7/+)
23.0 m
E 3.2
(8−)Sb132 (4+)
4.2 m
2.8 m
E 5.49
Sb133 (7/+)
2.5 m
E 4.00
(7−)Sb134 (0−)
10.4 s
0.8 s
E 8.39


(3/+)Sn127 (11/−)
4.15 m
2.12 h
E 3.21
E 3.20
(7−)Sn128
6.5 s
59.1 m
E 1.27
(11/−)Sn129 (3/+)
6.9 m
2.4 m
E 4.0
(7−)Sn130
1.7 m
3.72 m
E 2.15
(11/−)Sn131 (3/+)
58.4 s
56 s
E 4.69
Sn132
39.7 s
E 3.11


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
To
Vacuum
75 ml 2.5 M HClO4
and 2.5 M NaI
Sb and Te Carriers
Fission-
Product
Solution
Reactor
Rabbit
Waste
Solution
Benzene Fraction
Containing
Extracted Sn

Three-Quasiparticle 15/2⁻ Isomer in ^{127}Sb†

K. E. Apt

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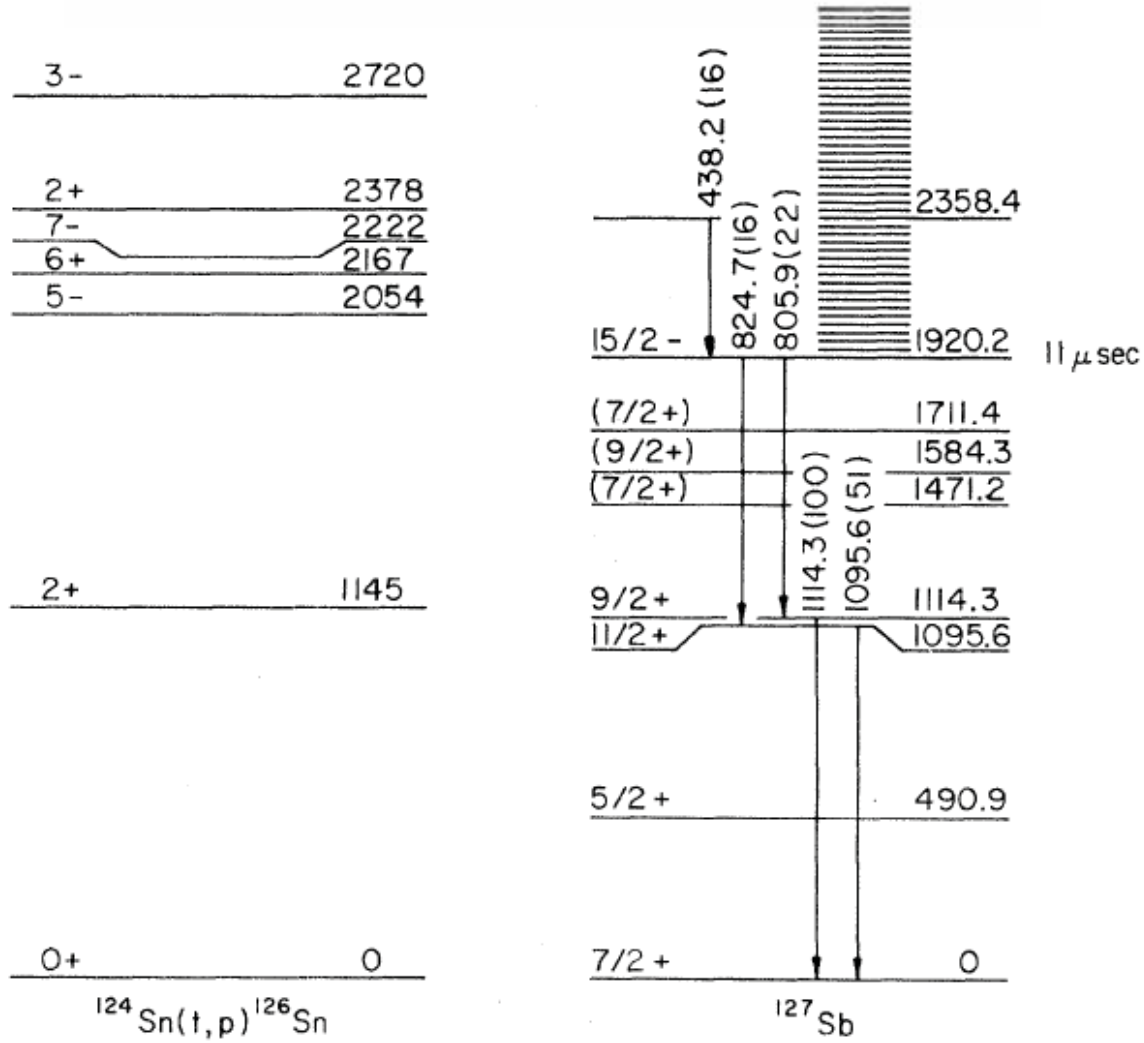
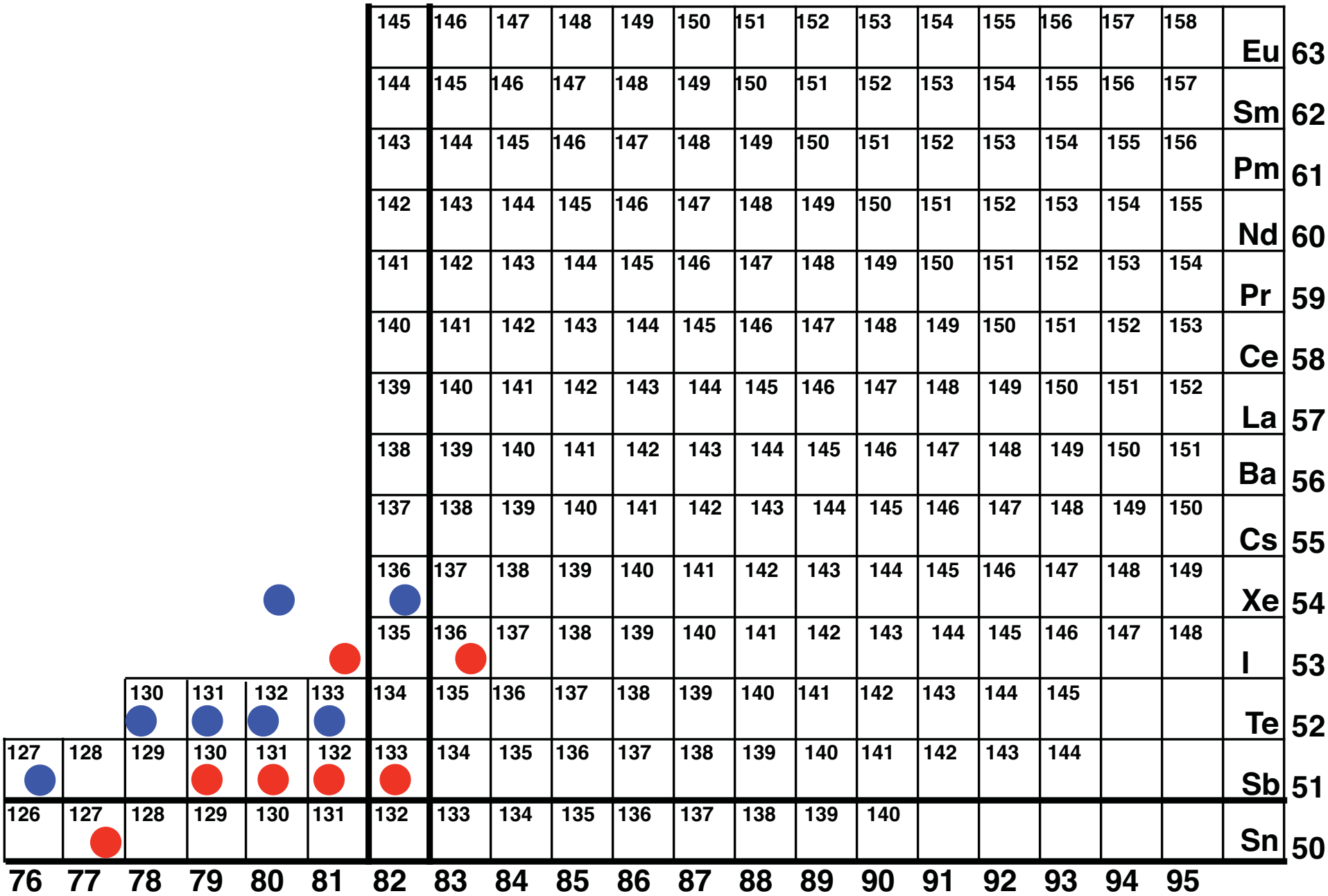
(Received 30 March 1971)

The β decay of 2.2-h, $\frac{11}{2}^-$ ^{127g}Sn has been found to populate an 11-μsec isomer of ^{127}Sb



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.

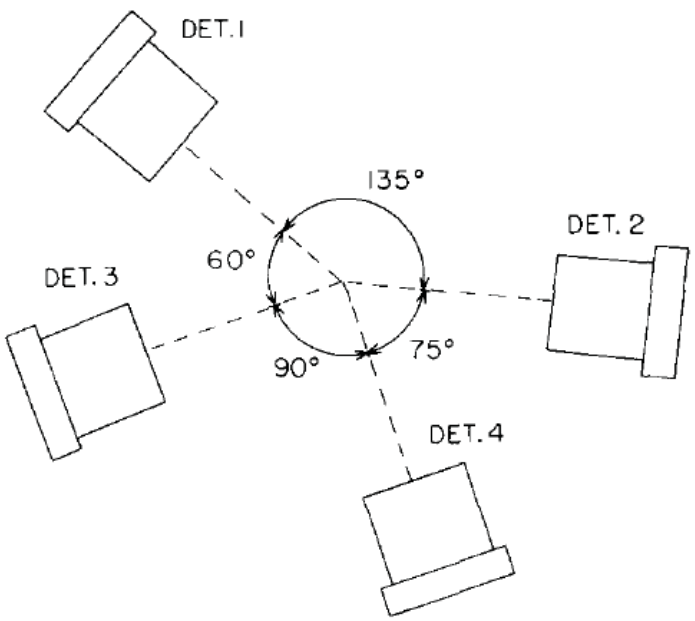


Fig. 2. Schematic description of the detectors and angles.

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.

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A FOUR-DETECTOR SYSTEM FOR γ–γ ANGULAR CORRELATION STUDIES†

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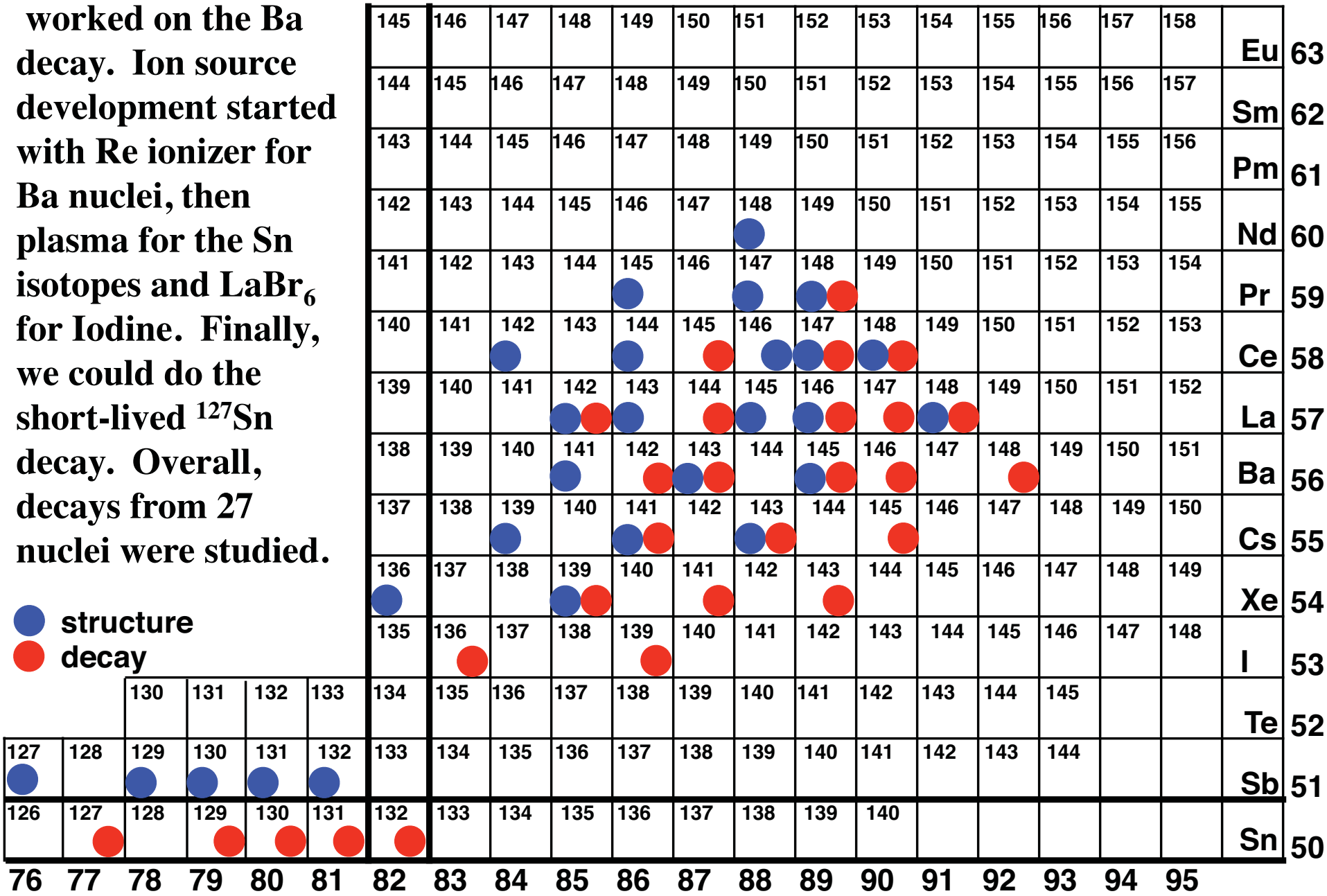
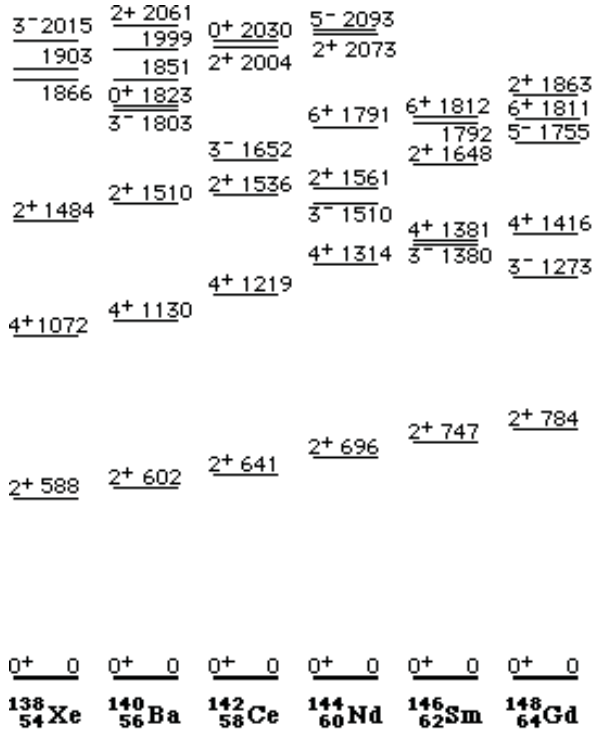
Received 28 September 1982

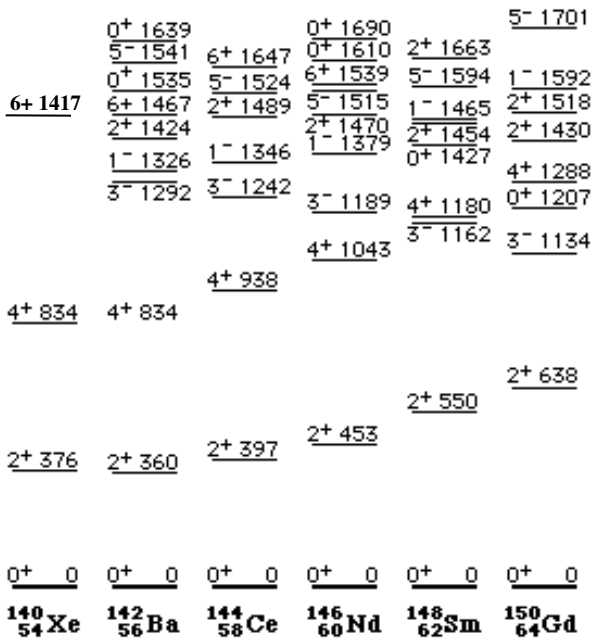
A multiple detector system for $\gamma-\gamma$ coincidence and angular correlation measurements is described. The system consists of four large coaxial Ge detectors set at fixed positions, enabling the measurement of $\gamma-\gamma$ coincidences between any pair. Thus, six distinct angles are measured 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.

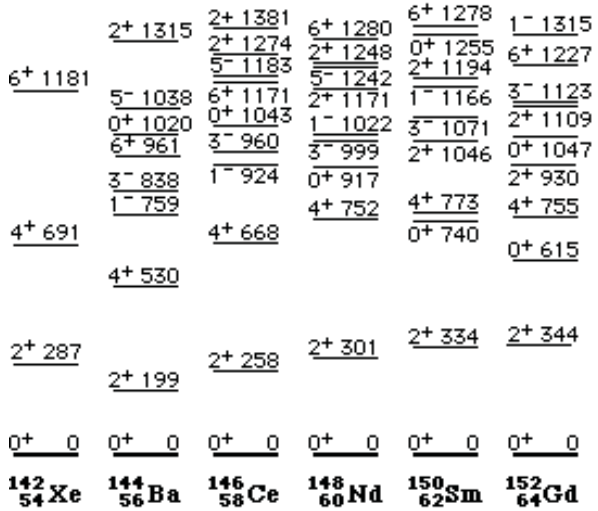




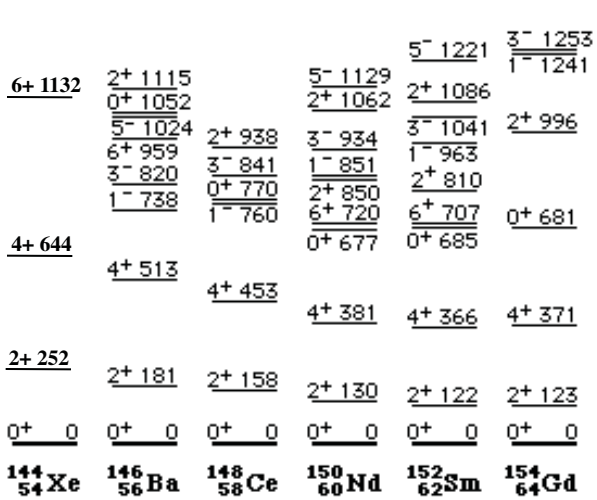
N=84



N=86



N=88



N=90

IBA CALCULATIONS NEAR THE $Z = 64$ SUBSHELL

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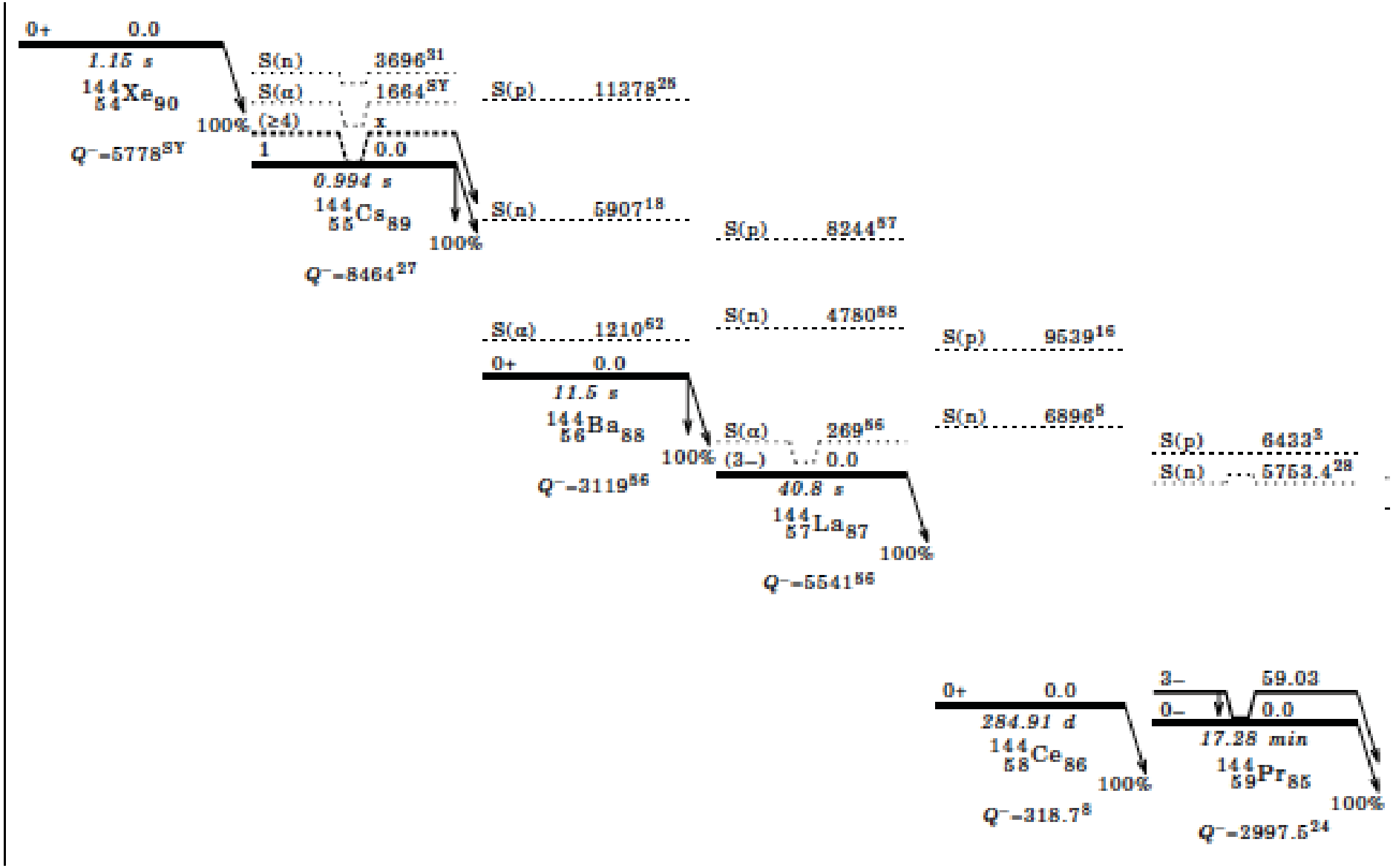
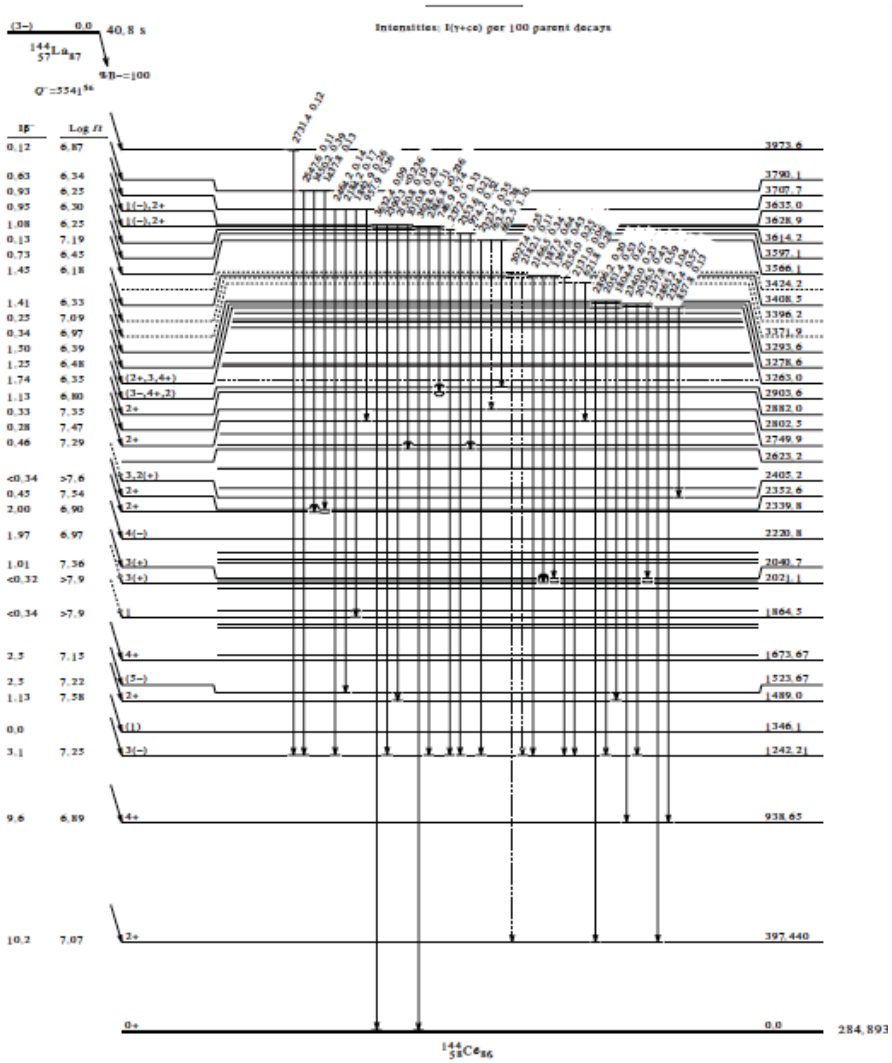
Received 25 January 1982
Revised manuscript received 25 April 1982

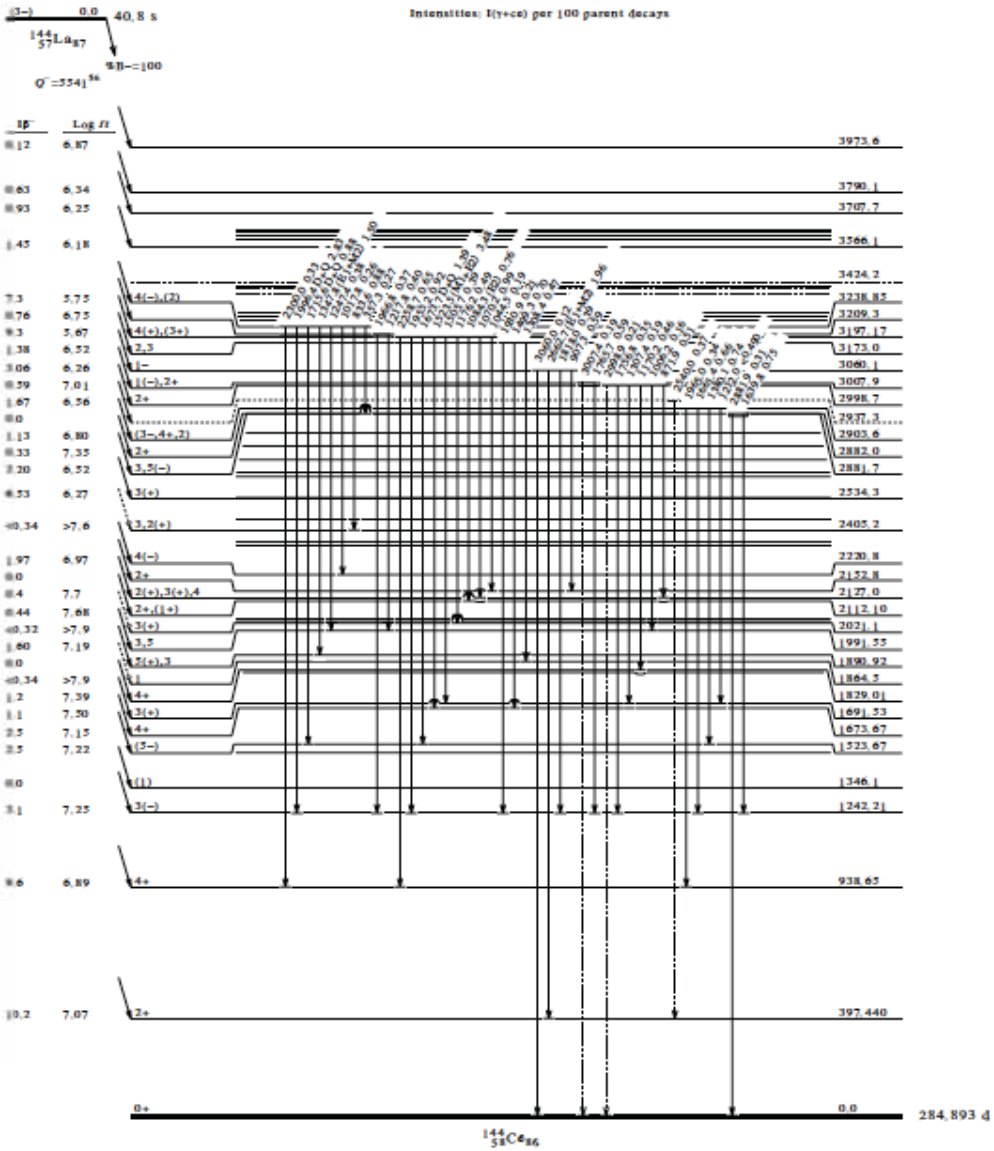
It has recently been shown that the effects of the $Z = 64$ subshell are important for nuclides with $N \leqslant 88$ but disappear as N approaches 90, due to the influence of neutron–proton interactions. IBA-2 calculations show excellent agreement with experimental energy systematics if the effective 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}Ba decay to odd-odd ^{144}La, which has been published, and opened our interest in Vladimir Paar's parabolas. In the process, we also studied ^{144}Ce.

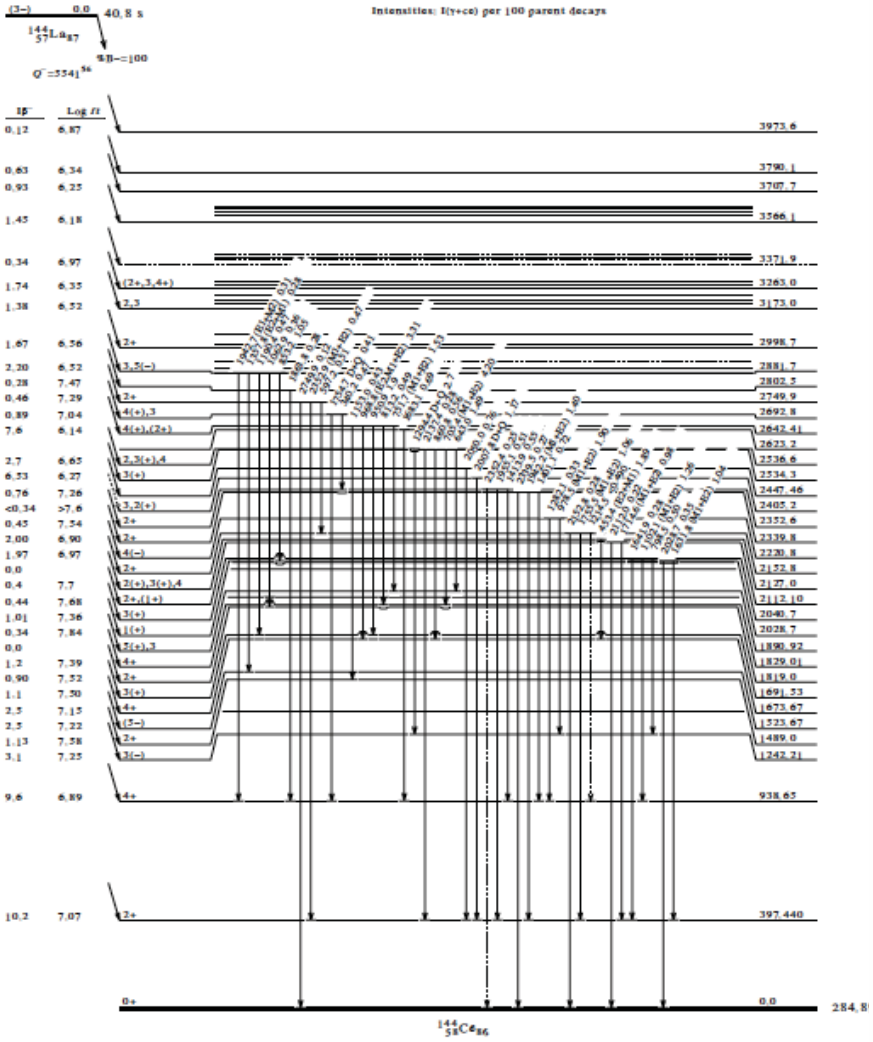


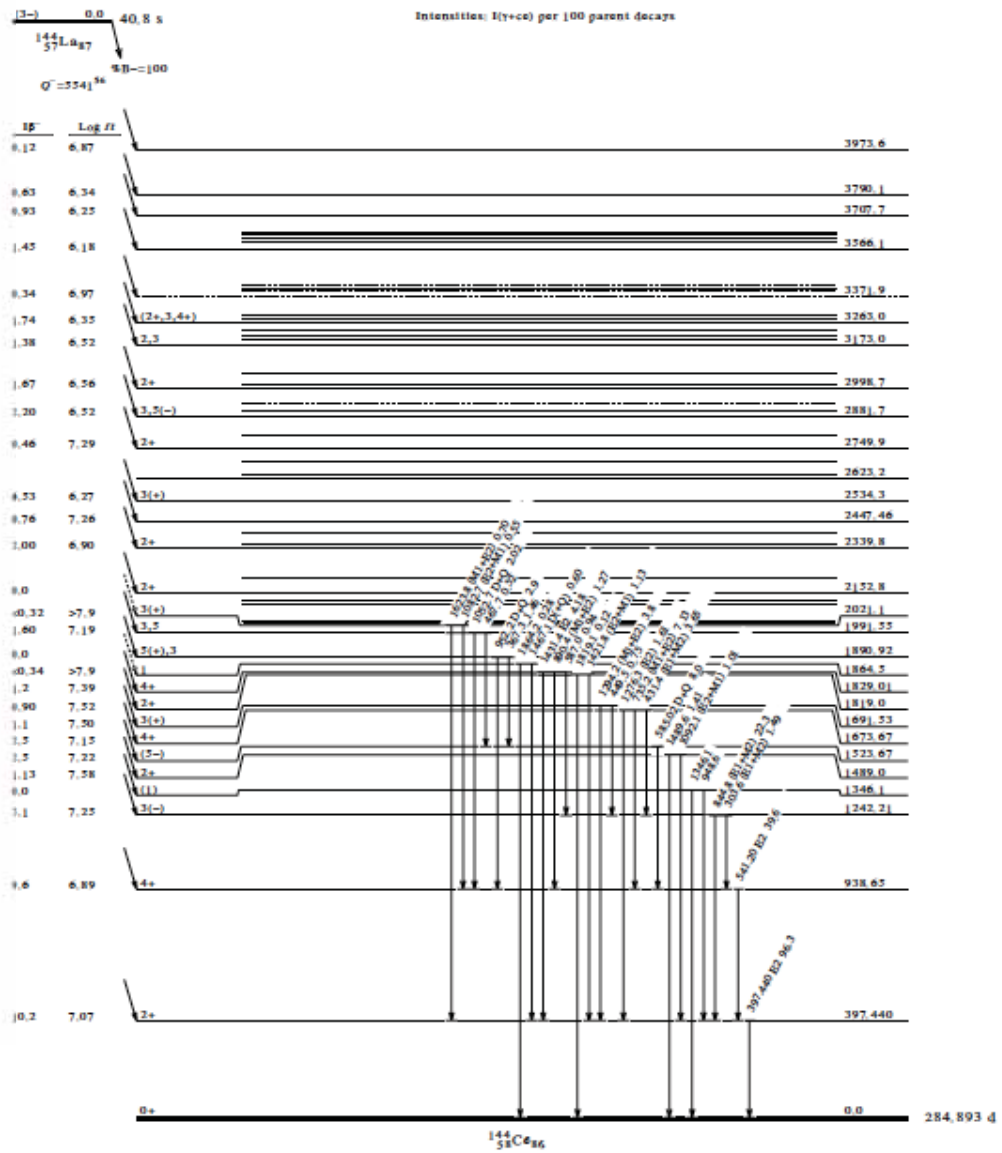
Chien Chung had worked out this decay scheme containing 400 gamma rays and 80 levels. We had no idea how to publish it, so the data were sent to the Nuclear Data Center. PC's and Lotus 1-2-3 came along just in time to make it possible to organize the data in a useful way.





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

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 390 (1997) 95–154

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Measurement of β^--decay intensity distributions of several fission-product isotopes using a total absorption γ-ray spectrometer

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[b]*Retired, Idaho National Engineering Laboratory, Idaho Falls, ID 83415-2114, USA*
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Received 6 June 1996

Abstract

A total absorption γ-ray spectrometer coupled to the ^{252}Cf-based INEL ISOL facility has been used in a program of systematic study of the distributions of β^--decay intensities of fission-product radionuclides. Cascade-summed γ-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 β^--decay intensity distributions have been deduced for the decay of these radionuclides. Radionuclides which have been studied in this manner include ^{89}Rb, ^{90g}Rb, ^{90m}Rb, ^{91}Rb, ^{93}Rb, ^{93}Sr, ^{94}Sr, ^{94}Y, ^{95}Sr, ^{95}Y, ^{138g}Cs, ^{138m}Cs, ^{139}Cs, ^{140}Cs, ^{141}Cs, ^{141}Ba, ^{142}Ba, ^{142}La, ^{143}Ba, ^{143}La, ^{144}Ba, ^{144}La, ^{145}Ba, ^{145}La, ^{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.

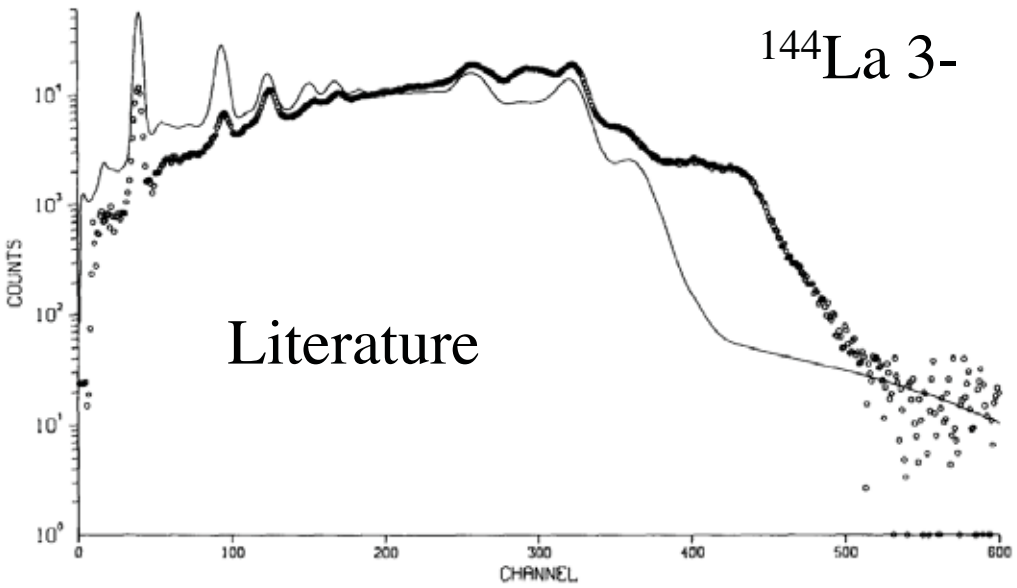

Fig. 23. Comparison of measured singles spectrum for ^{144}La with the simulated spectrum for the NDS decay scheme [30].

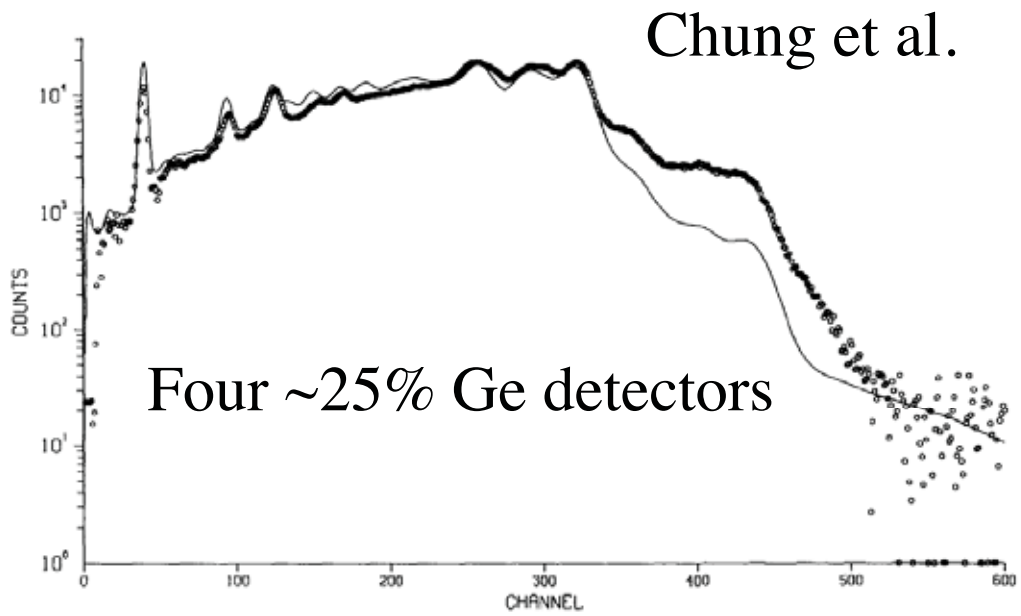

Fig. 24. Comparison of measured singles spectrum for ^{144}La with the simulated spectrum for the Walters decay scheme [31].

Table 22
^{144}La β^--decay intensities

Level energy (keV)		I_β (%)		
		NDS [30]	Walters [31]	TAGS
0.0		0.0	0.0	1.2 ± 1.0
397.4	2+	10.2	0.0	0.0
938.6	4+	9.6	0.57	0.0
1242.2	3-	3.1	0.65	0.64
1346.0		0.0	1.21	0.25
1489.7		1.13	0.73	0.0
1523.6		2.5	0.43	0.20
1647.1			0.085	0.0
1673.9		2.5	1.03	0.0
1692.0		1.1	0.094	0.69
1819.6		0.90	0.75	0.111
1829.5		1.2	1.54	0.23
1864.5		< 0.34	0.55	0.080
1891.1		0.0	0.29	0.043
1991.5		1.60	0.0	0.0
2022.0		< 0.32	0.76	0.25
2029.3		0.34	0.38	0.092
2038.7			0.028	0.007
2041.3		1.01	0.67	0.164
2111.9		0.44	0.95	0.234
2127.4		0.4	0.60	0.148
2142.7			0.27	0.067
2150.9			0.047	0.012
2153.7		0.0	0.76	0.188
2191.6			0.0	0.0
2203.7			0.0	0.0
2221.1		1.97	1.88	0.83
2242.1			0.64	0.28
2329.2			0.31	0.168
2331.7			0.179	0.096
2340.7		2.00	0.84	0.45
2352.3		0.45	0.60	0.33
[illegible]			0.066	0.035

Pergamon

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S0146-6410(97)00037-9

New Cold and Ultra Hot Binary and Cold Ternary Spontaneous Fission Modes for ^{252}Cf and New Band Structures with Gammasphere

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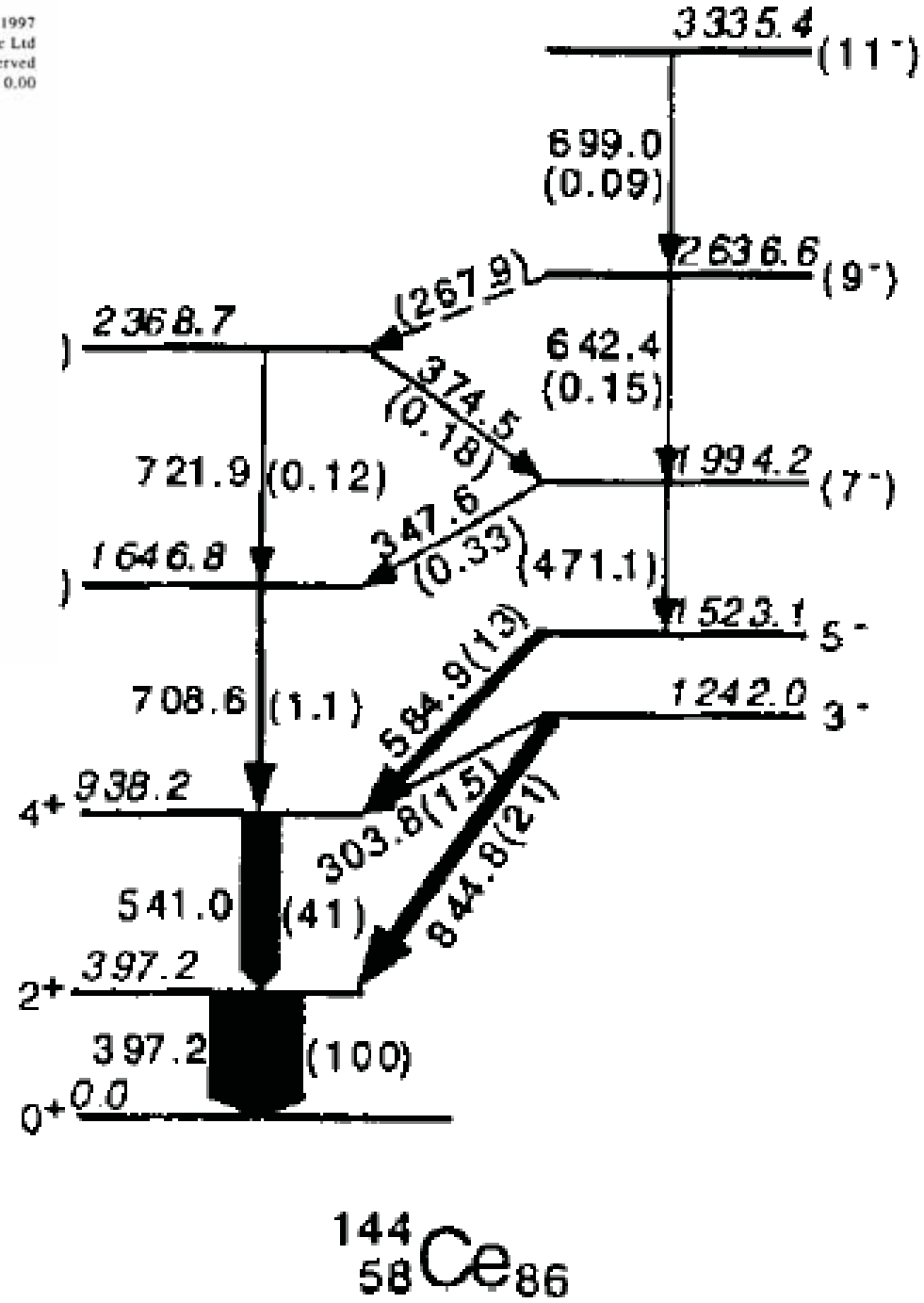


1979RI09 Z.Phys. A290, 311 (1979)

OSTIS at Grenoble

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.

1979EP01 Phys.Rev. C19, 1504 (1979)

ISOLDE at CERN

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.

doi: 10.1103/PhysRevC.19.1504

OSTIS at Grenoble

1980SC16 J.Phys.(London) G6, 1291 (1980)

S.M.Scott, W.D.Hamilton, P.Hungerford, D.D.Warner, G.Jung, K.D.Wunsch

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.

1983RE10 Phys.Rev. C28, 1740 (1983)

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.

doi: 10.1103/PhysRevC.28.1740

1976LU02 Phys.Rev. C13, 1544 (1976)

OSIRIS at Studsvik

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.

doi: 10.1103/PhysRevC.13.1544

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.

REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 1 JANUARY, 1956

Abundances of the Elements*

HANS E. SUESS,† *U. S. Geological Survey, Washington, D. C.*

AND

HAROLD C. UREY, *Department of Chemistry and Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Laboratory for Nuclear Science
ANNUAL PROGRESS REPORT
June 1, 1955 to May 31, 1956

VI. NUCLEAR CHEMISTRY

A. Neutron Shell-Numbers and the Aggregate Total β Decay in the Creation of the Elements of Mass Number Above 70

Several conclusions are fairly well established about the abundances in nature of nuclear species above 70 in mass number A. Isotopic abundances indicate that β decay was the principal last mode of formation of the stable and long-lived nuclides. Nuclides of even A not shielded from formation by β decay are roughly twice as abundant as their odd-A neighbors. Some authors have noted an inverse dependence[21] of cosmic abundance in fast neutron (~1 Mev) cross sections suggesting multiple neutron condensation in competition with β decay.

-29-

It is postulated that the broad abundance peaks in Figure 2.1 at A = 79 and 81 ($_{35}$Br) corresponds to the now stable β decay products of the primordial species with N* = 50. Thus Δ values of 6 and 4 are prominent, and two prominent primordial species are $^{50}_{29}Cu^{79}$ and $^{50}_{31}Ga^{81}$. The height of this peak is about five times the roughly estimated base abundance curve (broken line in Figure 2.1), and it is fairly broad, suggesting a wide Z band for the nucleogenesis reaction paths.

Correspondingly, it is postulated that the moderately sharp peak near $_{54}Xe^{129}$ corresponds to β decay of $^{82}_{47}Ag^{129}$, corresponding to a Δ value of 7. The peak stands out quite strong (about 12X) above the nominal base line.

The next peak of similar shape is that for $^{116}_{77}Ir^{193}$ and $^{117}_{78}Pt^{195}$ which also stands out very strongly, about 15X the nominal base line. The N* value 126 postulated leads to identification of the primordial species as $_{67}Ho^{193}$ and $_{69}Tm^{195}$. The Δ values of 10 and 9 respectively seem surprisingly high, but the valley of stability is known to be much wider for high masses[26], corresponding to lower fall of neutron affinity with N and to less time sensitivity (higher half-life for given Δ).

-30-

This report by Coryell came almost immediately after a Seuss and Urey paper reporting good solar abundances..

Correspondingly, it
β decay of $^{82}_{47}Ag^{129}$, corr

^{129}Ag 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

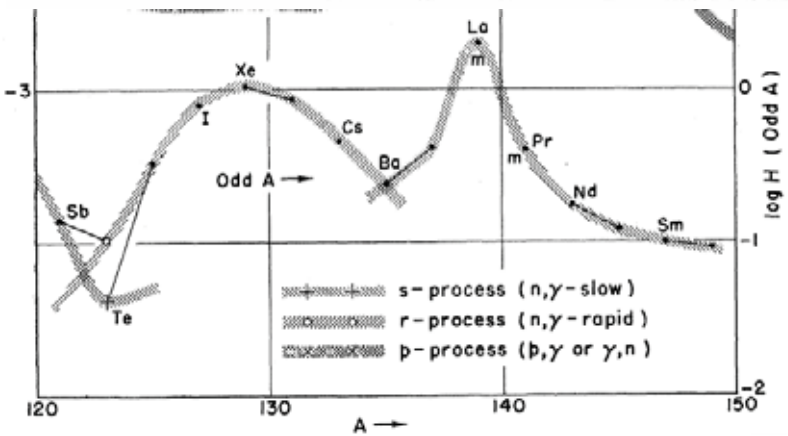
The major BBFH paper appeared in 1957, but was preceded in October, 1956, by an article in Science.

5 October 1956, Volume 124, Number 3223

SCIENCE

Origin of the Elements in Stars

F. Hoyle, William A. Fowler,
G. R. Burbidge, E. M. Burbidge



are in the contributing curves. It is already clear that both the slow and rapid neutron-capture processes operated under conditions of "steady streaming." For instance, in the case of the *s*-process, it appears that the products obtained by multiplying the abundances built through the *s*-process by the appropriate (n,γ) cross sections of the stable nuclei are remarkably constant from isotope to isotope, as would be expected on the basis of steady streaming. There is one notable

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.

References and Notes

1. W. A. Fowler *et al.*, *Bull. Am. Phys. Soc. Ser.* 2 1, 191 (1956).
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2. P. W. Merrill, *Science* 115, 484 (1952).
3. J. L. Greenstein, *Mém. soc. roy. sci. Liège* 14, 307 (1954); E. M. Burbidge and G. R. Burbidge, *Astrophys. J.* 124 (1956).
4. J. P. Wild, J. D. Murray, W. C. Rowe, *Nature* 173, 532 (1954).
5. G. R. Burbidge *et al.*, *Phys. Rev.* 103, 1145 (1956).
6. P. R. Fields *et al.*, *ibid.* 102, 180 (1956).
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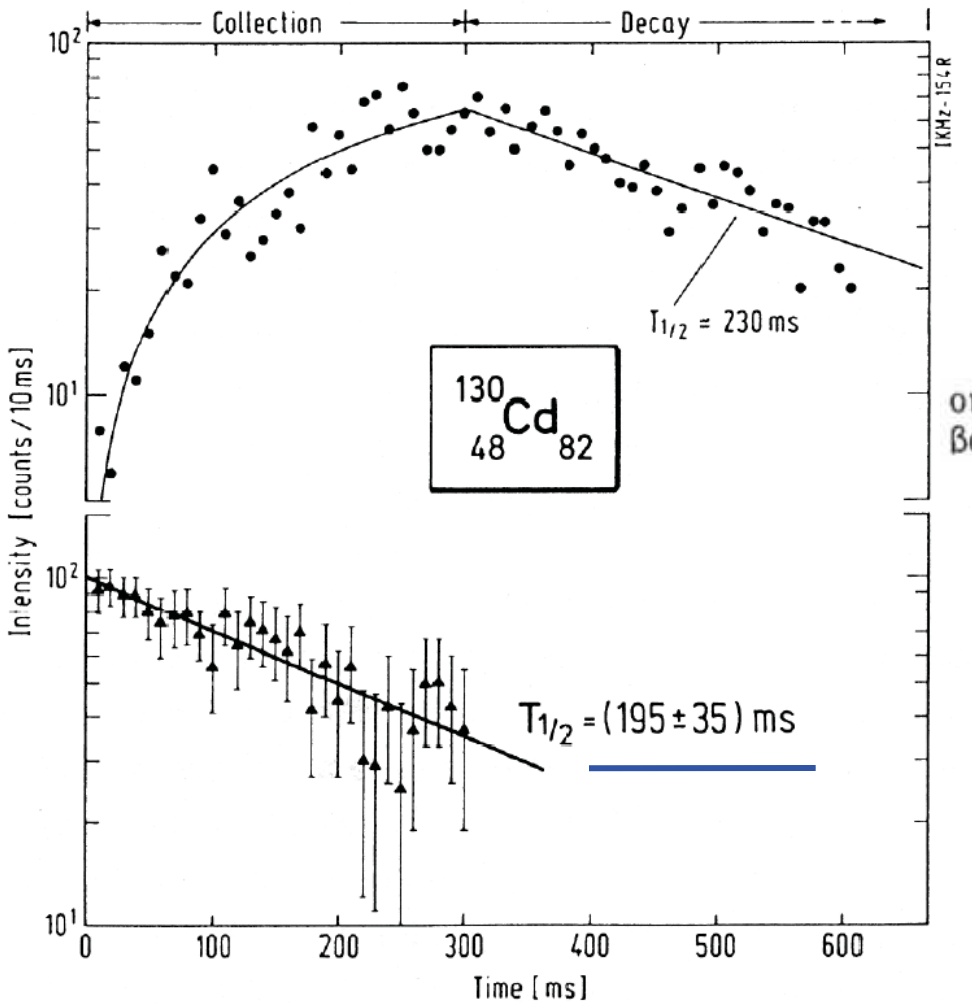
12. A detailed quantitative account of this work is in preparation. This work was supported in part by the joint program of the Office of Naval Research and the U.S. Atomic Energy Commission. We wish to take this opportunity to thank Stanley Thompson and Rosemary Barrett of the University of California, Berkeley, for helpful discussions of material to be published on the properties of the transuranium nuclei including Cf^{254}.
13. C. D. Coryell, *Lab. for Nuclear Sci. Ann. Rept.* (1956).

Stated another way, BBFH were aware of the Coryell work prior to this article and their seminal article in 1957.

Z. Phys. A – Atomic Nuclei 325, 489–490 (1986)

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.



The Beta-Decay Half-Life of $^{130}_{48}Cd_{82}$ and its Importance for Astrophysical *r*-Process Scenarios

K.-L. Kratz [1], H. Gabelmann [2], W. Hillebrandt [3], B. Pfeiffer [1], K. Schlösser [2], and F.-K. Thielemann [4]
and the ISOLDE Collaboration, CERN
[1] Institut für Kernchemie, Universität Mainz, D-6500 Mainz, Federal Republic of Germany
[2] CERN-ISOLDE, CH-1211 Geneva, Switzerland
[3] MPI für Physik und Astrophysik, D-8046 Garching, Federal Republic of Germany
[4] Department of Astronomy, Harvard University, Cambridge, MA 02138, USA

Received October 10, 1986

order to enhance ^{130}Cd and minimize the 1.9 s βdn-background from ^{40}Ca^{90}Br$^+$ at A = 130. Data

^{130}Ag	0.0		~50 ms	%β⁻=?
^{130}Cd	0.0	0+	0.20 s *4*	%β⁻=100; %β⁻n=4
^{130}In	0.0	1(−)	0.29 s *2*	%β⁻=100; %β⁻n=0.93 *13*
	50	(10−)	0.54 s *1*	%β⁻=100; %β⁻n=1.65 *15*
	400	(5+)	0.54 s *1*	%β⁻=100; %β⁻n=1.65 *15*
^{130}Sn	0.0	0+	3.72 min *7*	%β⁻=100
	1946.88	(7−)	1.7 min *1*	%β⁻=100

Fig. 8: Growth and decay curve of β-delayed neutron activity of ^{130}Cd. Data from about 36,000 multiscaling cycles were accumulated at 10 ms intervals.

Physica Scripta. Vol. T56, 262–265, 1995

Beta Decay of the New Isotope ^{101}Sn

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M. Huyse, J. von Schwarzenberg, J. Szerypo[1], P. Van Duppen and L. Vermeeren

Instituut voor Kern- en Stralingsfysica, K. U. Leuven, B-3001 Leuven, Belgium

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Institute of Experimental Physics, Warsaw University, PL-00-681 Warsaw, Poland

Received October 15, 1994; accepted October 31, 1994

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.

Along came this report from GSI that chemical selectivity could be achieved by the user of laser ionization.

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PROPOSAL TO THE ISC

NEUTRON-RICH SILVER ISOTOPES PRODUCED BY A CHEMICALLY SELECTIVE LASER ION-SOURCE: TEST OF THE R-PROCESS "WAITING-POINT" CONCEPT

Kernchemie Mainz[1]-Troitzk[2]-Physik Mainz[3]-Astrophysics Harvard[4]-ISOLDE[5] Collaboration

W. Böhmer[1], V. N. Fedoseyev[2], Y. Jading[1], H.-J. Kluge[3], K.-L. Kratz[1], V. S. Letokhov[2], J. Lettry[5], V. I. Mishin[2], H. L. Ravn[5], F. Scheerer[3], A. Wöhr[1], and F.-K. Thielemann[4]

Spokesman: K.-L. Kratz
Contactman: O. Tengblad

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CERN/ISC 96-4
ISC/P34 Add.1
Date: January 19, 1996

Status Report on Experiment IS333 part II and Request for Beam Time

NEUTRON-RICH SILVER ISOTOPES PRODUCED BY A CHEMICALLY SELECTIVE LASER ION-SOURCE:

Kernchemie Mainz – Russian Academy of Sciences Troitzk – Nuclear Chemistry Maryland – KU Leuven – ISOLDE Collaboration

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

3

Mass separator:
GPS/ HRS

Distance to Target: 20m

Laser System

ISOLDE Laser System: 2

- 3 copper vapor lasers
- 2 dye lasers (cw, frequency tripling by two BBO cristals → UV)

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

Target

Transfer line (Nb)
~2200 K

Extraction Electrode

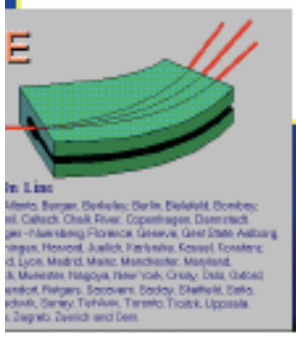
Laser

UC_2-C-Target

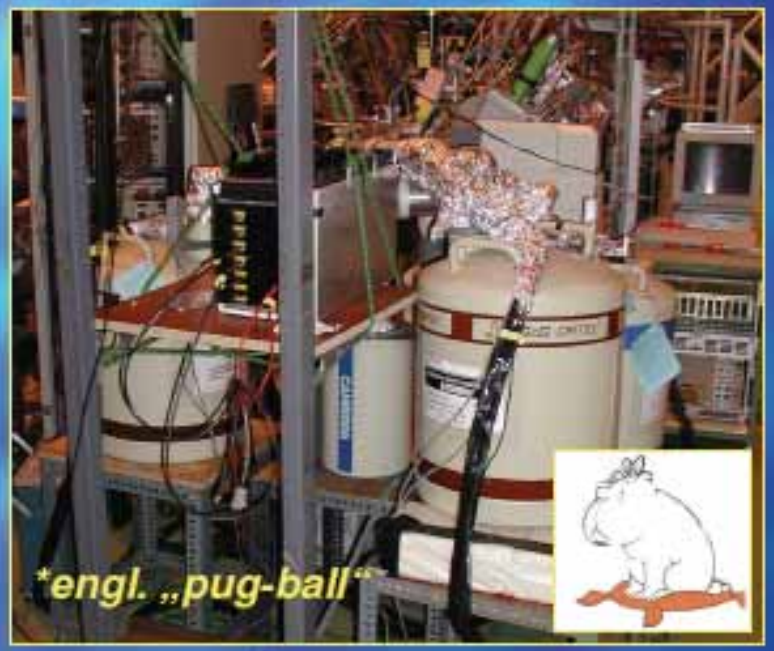
1

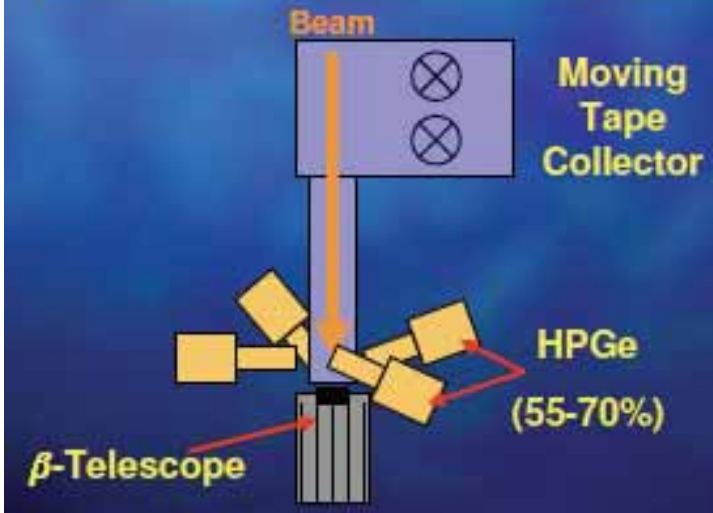
Converter (Ta or W)

60 kV

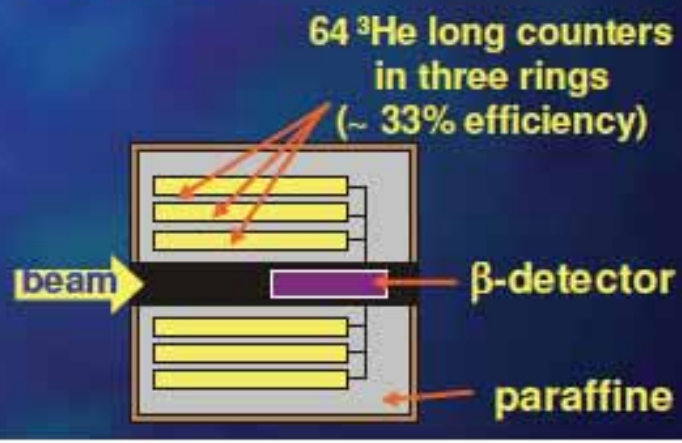


The MOPSBALL* $\beta\gamma\gamma$-detector setup





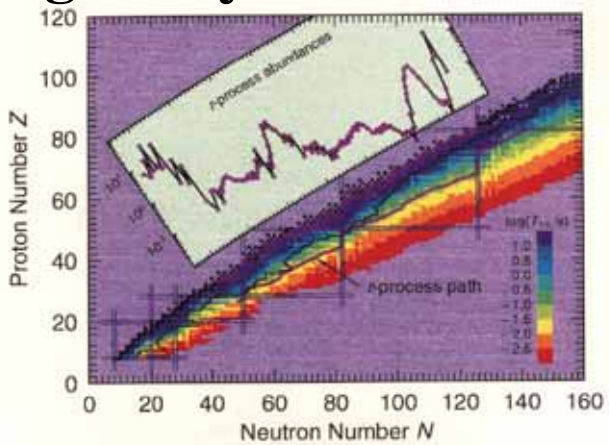
The Mainz βdn-detector setup



Institut für Kernchemie JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Towards the "Waiting-Point" Nucleus ^{129}Ag

Figure by P. Moller



Y. Jading

1996

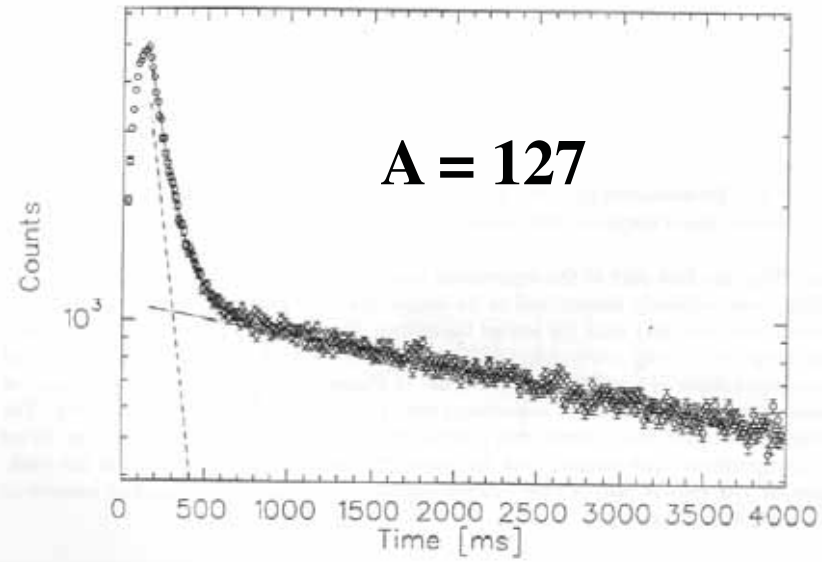


Figure 4.8: Beta-delayed neutrons from ^{127}Ag and ^{127}In (solid line). The short broken line represent the Ag component and the long broken line the In component.

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

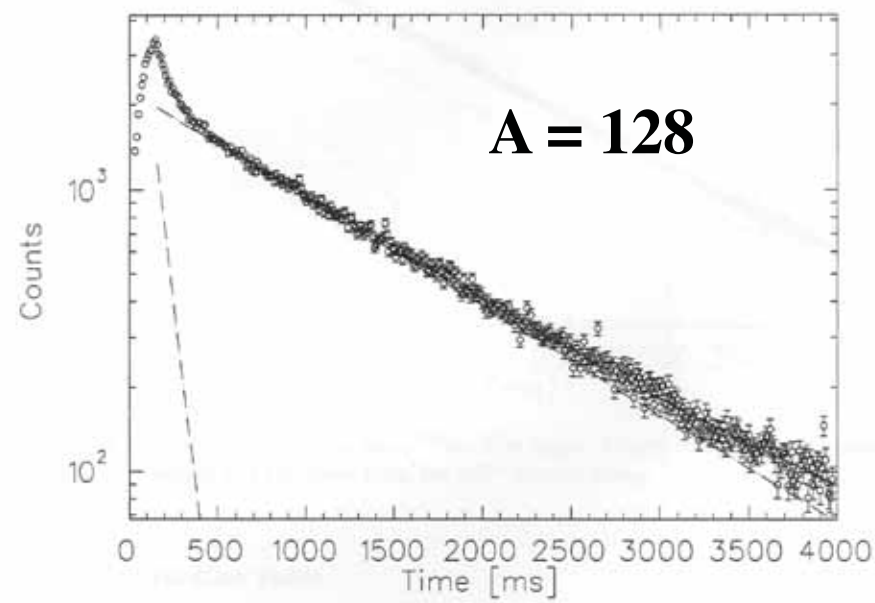


Figure 4.9: Beta-delayed neutrons from ^{128}Ag and ^{128}In. The short broken line is the silver component and the long broken line is the average indium component.

4.3 Results

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

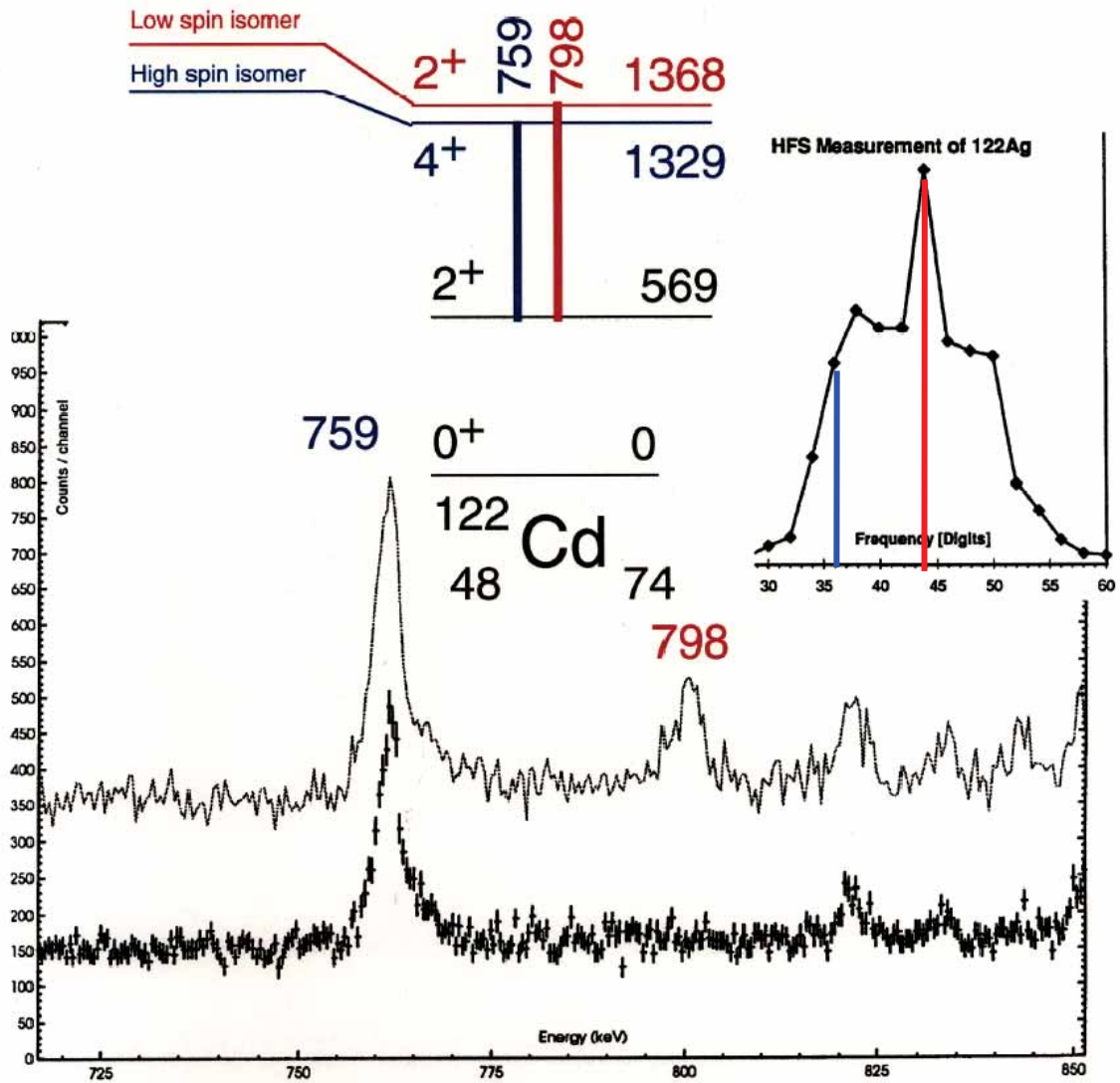
In Table 4.3 the results from the halflife analyses for $^{120-128}$Ag have been listed, togethe with earlier halflife measurements made with β-delayed neutrons, β- or γ-detection.

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

Isotope	Halflives [ms]	Method	Reference
^{120}Ag	1350 ± 200	n	This thesis
	1250 ± 30	β	[Ree83]
	1170 ± 50	γ	[Fog71]
^{121}Ag	1010 ± 100	n	This thesis
	910 ± 60	n	[Ree83]
	780 ± 10	β	[Ree83]
	720 ± 100	β	[Fog82]
	800 ± 100	γ	[Gra74]
^{122}Ag	520 ± 20	n	This thesis
	570 ± 30	n	[Ree83]
	480 ± 80	γ	[Shi78]
	1500 ± 500	γ	[Fog71]
^{123}Ag	293 ± 6	n	This thesis
	300 ± 10	n	[Ree83]
	390 ± 30	n	[Lun76]
	300 ± 20	γ	[Mac86]
^{124}Ag	172 ± 5	n	This thesis
	540 ± 80	n	[Ree83]
	170 ± 30	γ	[Hil84]
^{125}Ag	155 ± 7	n	This thesis
^{126}Ag	98 ± 3	n	This thesis
^{127}Ag	79 ± 3	n	This thesis
^{128}Ag	58 ± 5	n	This thesis

Part of the γ-ray spectrum of the decay of Ag-122 isomers.

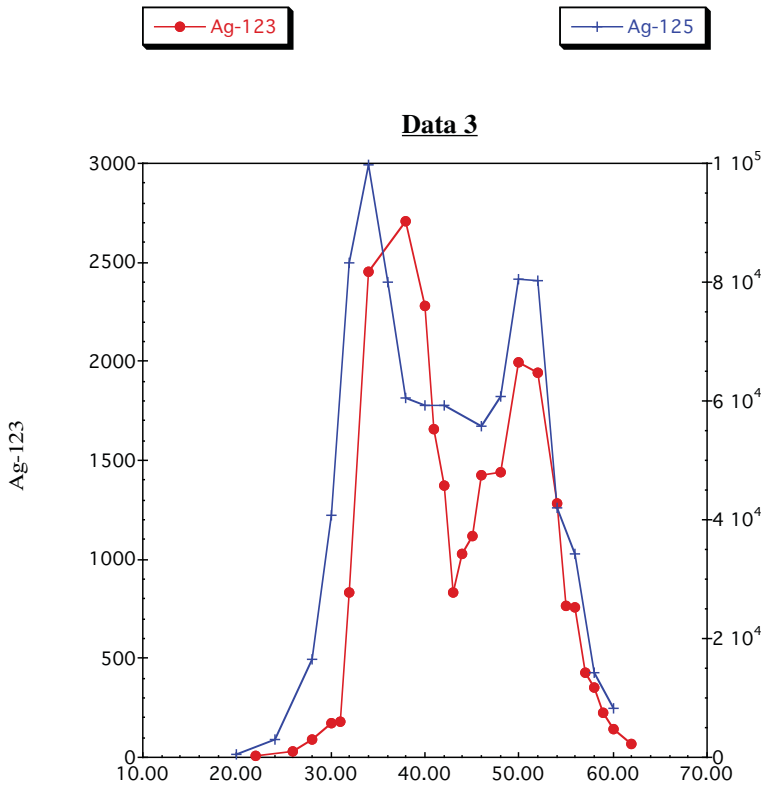
The upper spectrum was taken with the laser frequency set at 44 and may be compared with the lower spectrum which was taken with the laser set at 36. The gamma ray at 798.4 keV is attributed to the decay of the 2_2^+ level to 2_1^+ level whereas the line at 759 keV is attributed to the decay of the 4_1^+ level to 2_1^+ level.



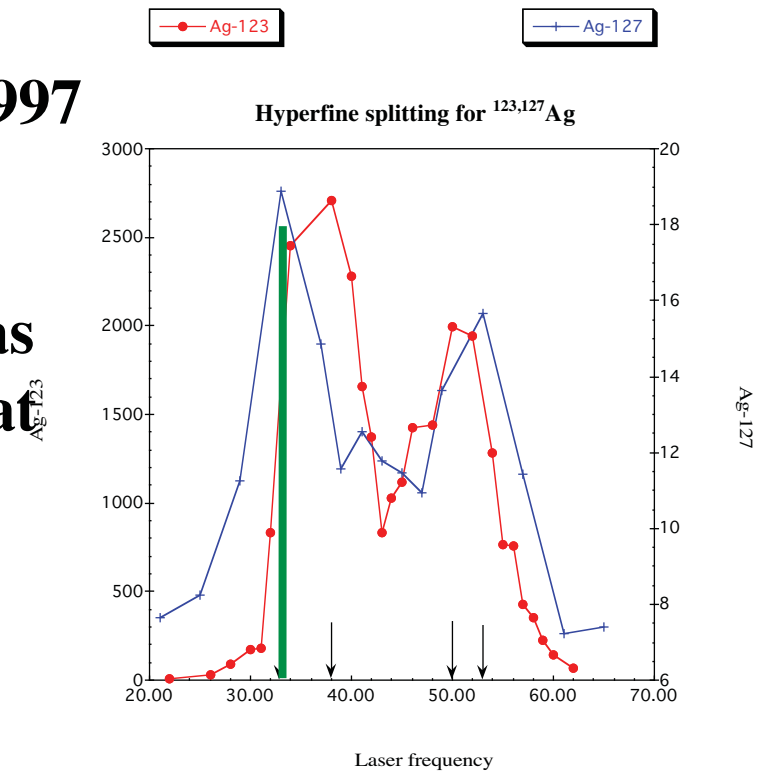
August 1997

Setup in 1996 had been done with stable ^{107}Ag which has a ½- 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.

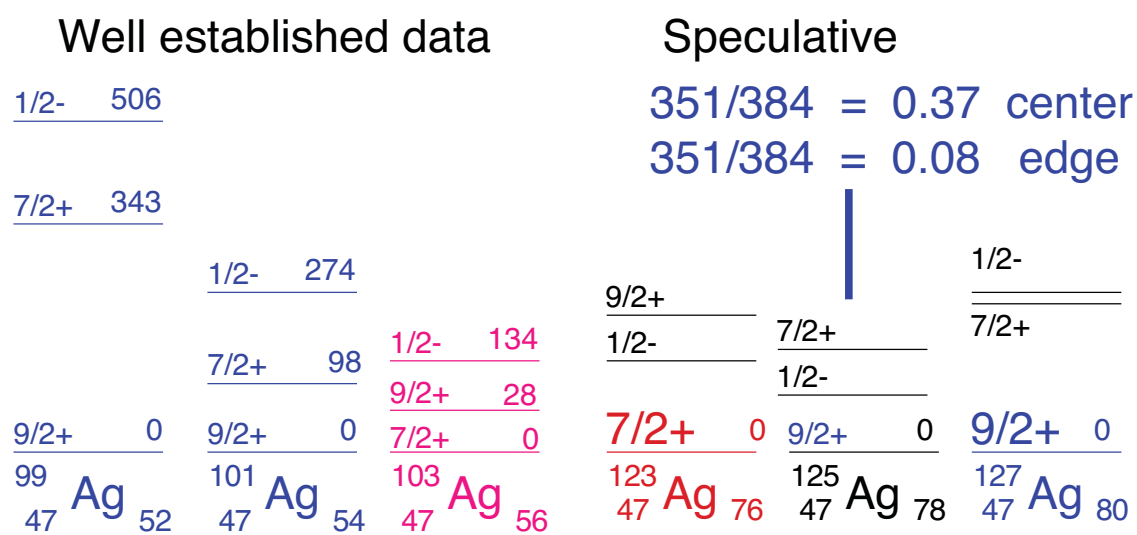
November 1997

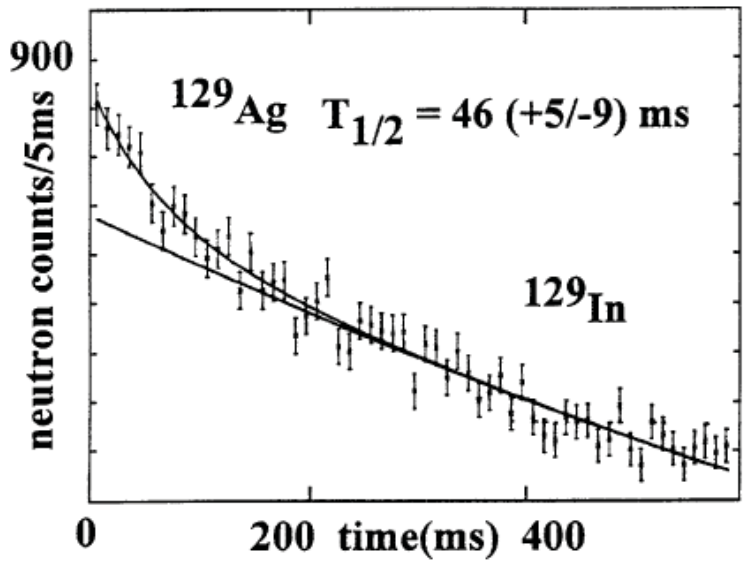


The search for ^{129}Ag was performed at the "green" setting.



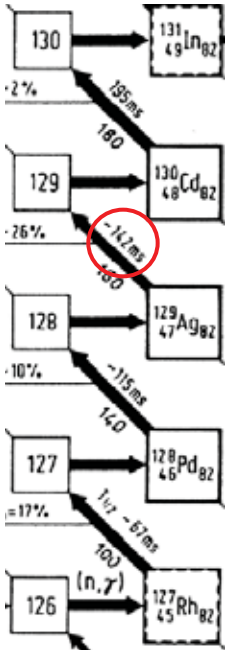
These β-delayed neutron data support the presence of β-decaying ½- isomers in ^{125,127}Ag, but not necessarily ^{123}Ag, but P_n could be a factor.





Isotope	Beta-Decay Half-Life. $T_{1/2}$ ms Exp.	RPA-S. M.	Beta-Flow	
^{133}In	180±20	123		
^{131}In	278± 3	240		
^{130}Cd	195±35	235	180	
^{129}Ag		172	160	
^{128}Pd		115	140	
^{127}Rh		67	100	
^{83}Ga	308± 4	288		
^{81}Ga	1218± 4	1070		
^{80}Zn	540±30	502	750	
^{79}Cu		193	200	+)
^{78}Ni		207	185	+)
^{77}Co		6.3	< 11.5	+)

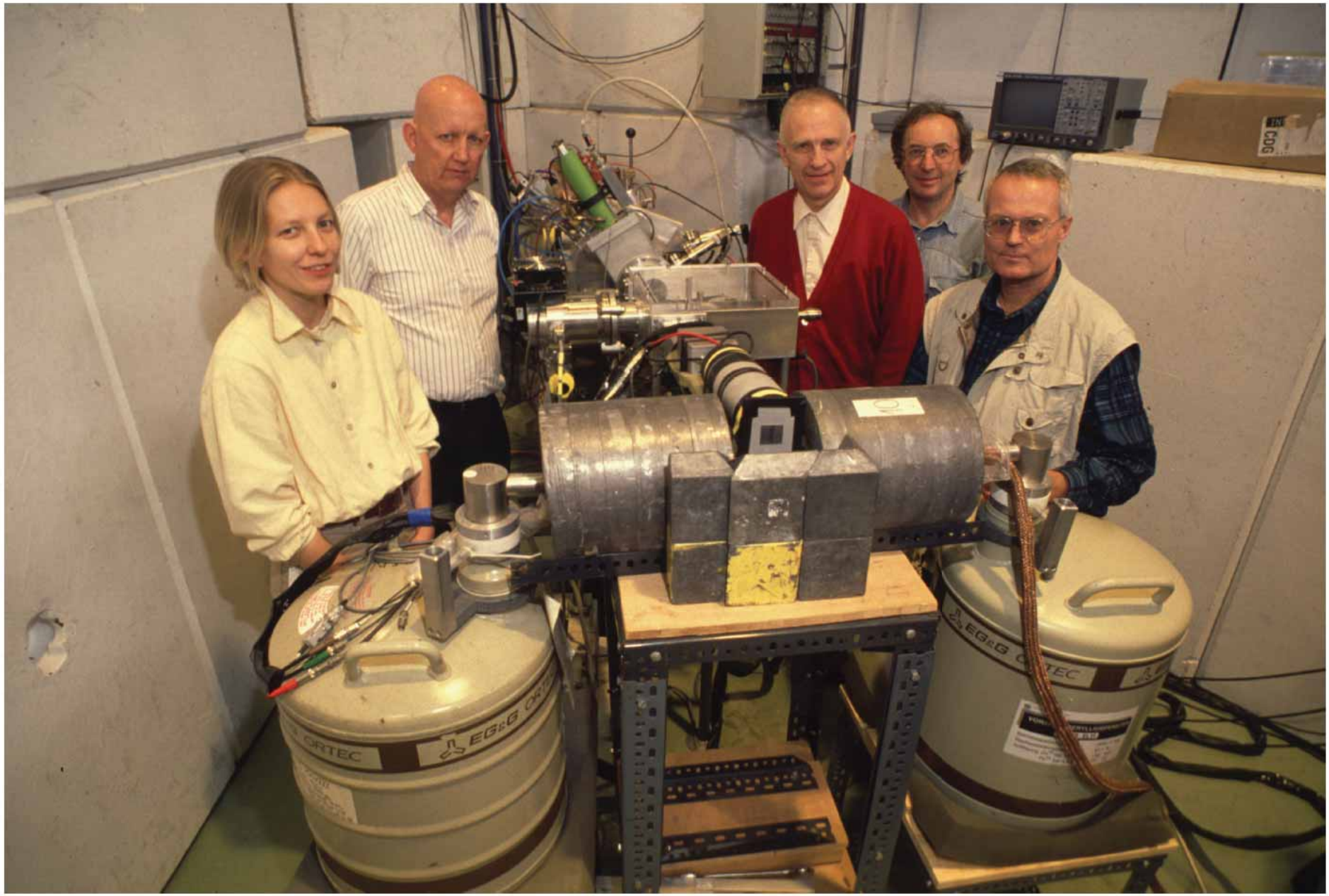
Reviews in Modern Astronomy, Vol.1 Cosmic Chemistry
Editor: G. Klare © Springer-Verlag Berlin Heidelberg 1988



The astrophysical impact was large as the short half life "lowered the impact of" ^{129}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.

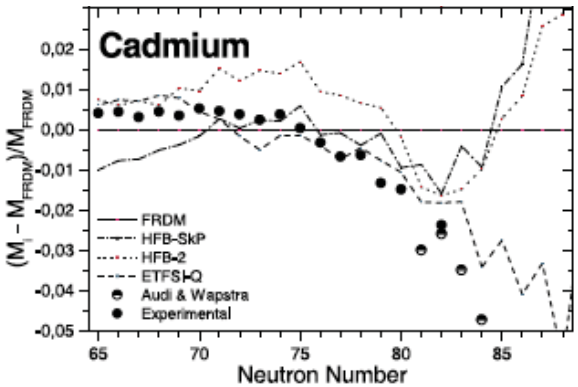
The successful development and utilization of the Resonance Ionization Laser Ion Source (RILIS) then paved the way to develop ionization schemes for Cd, In, Sn, and Sb.

<u>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.</u>



Jading, Moller, Walters, Mishin, Kratz…. For the CERN Courier

162503-1



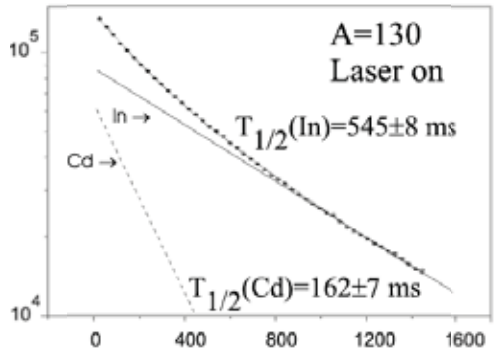
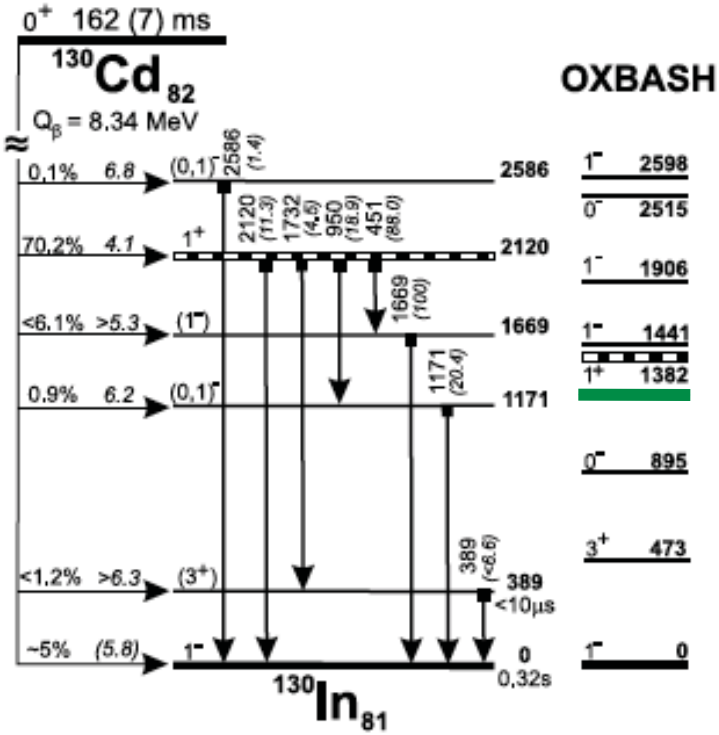


FIG. 3 (color online). Comparison of normalized mass deviations of $_{50}$Sn and $_{48}$Cd isotopes from model predictions with "shell quenching" [25,26,28], experimental values, and very recent short-range extrapolations for $^{135-137}$Sn and $^{129-132}$Cd [15,21] relative to the "unquenched" FRDM [22]. The deviation to our experimental value of ^{130}Cd corresponds to a mass difference of 1.57 MeV.



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.

PHYSICAL REVIEW C, VOLUME 62, 054301

Selective laser ionization of very neutron-rich cadmium isotopes: Decay properties of $^{131}Cd_{83}$ and $^{132}Cd_{84}$

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(Received 4 May 2000; published 25 September 2000)

A chemically selective laser ion source has been applied in a decay study of the very neutron-rich isotopes ^{131}Cd and ^{132}Cd at CERN/ISOLDE. For the β^- decay of the $N=83$ nuclide ^{131}Cd a surprisingly short half-life of (68 ± 3) ms and a weak delayed-neutron branch of $P_n=(3.5\pm1.0)\%$ were observed. For the $N=84$ nuclide ^{132}Cd a half-life of (97 ± 10) ms and a P_n value of $(60\pm15)\%$ were obtained. Schematic features of both decay schemes are developed. We find that our new data are not reproduced by current global models used for *ab initio* calculations of β-decay properties without significant changes.

^{131}Cd: 68(3) ms **^{132}Cd 97 (10) ms** **^{133}Cd 57(10)**

The 68 (3) ms half-life and 3.5% P_n values for ^{131}Cd remain somewhat anomalous and deserve more attention.

ELSEVIER

Nuclear Physics A621 (1997) 307c–310c

Microscopic calculations of β–decay characteristics near the A=130 r-process peak

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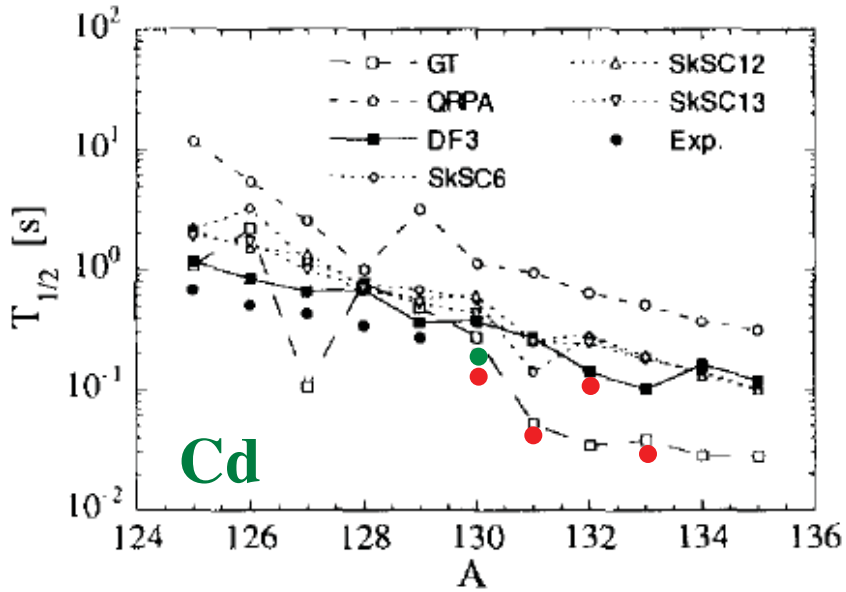
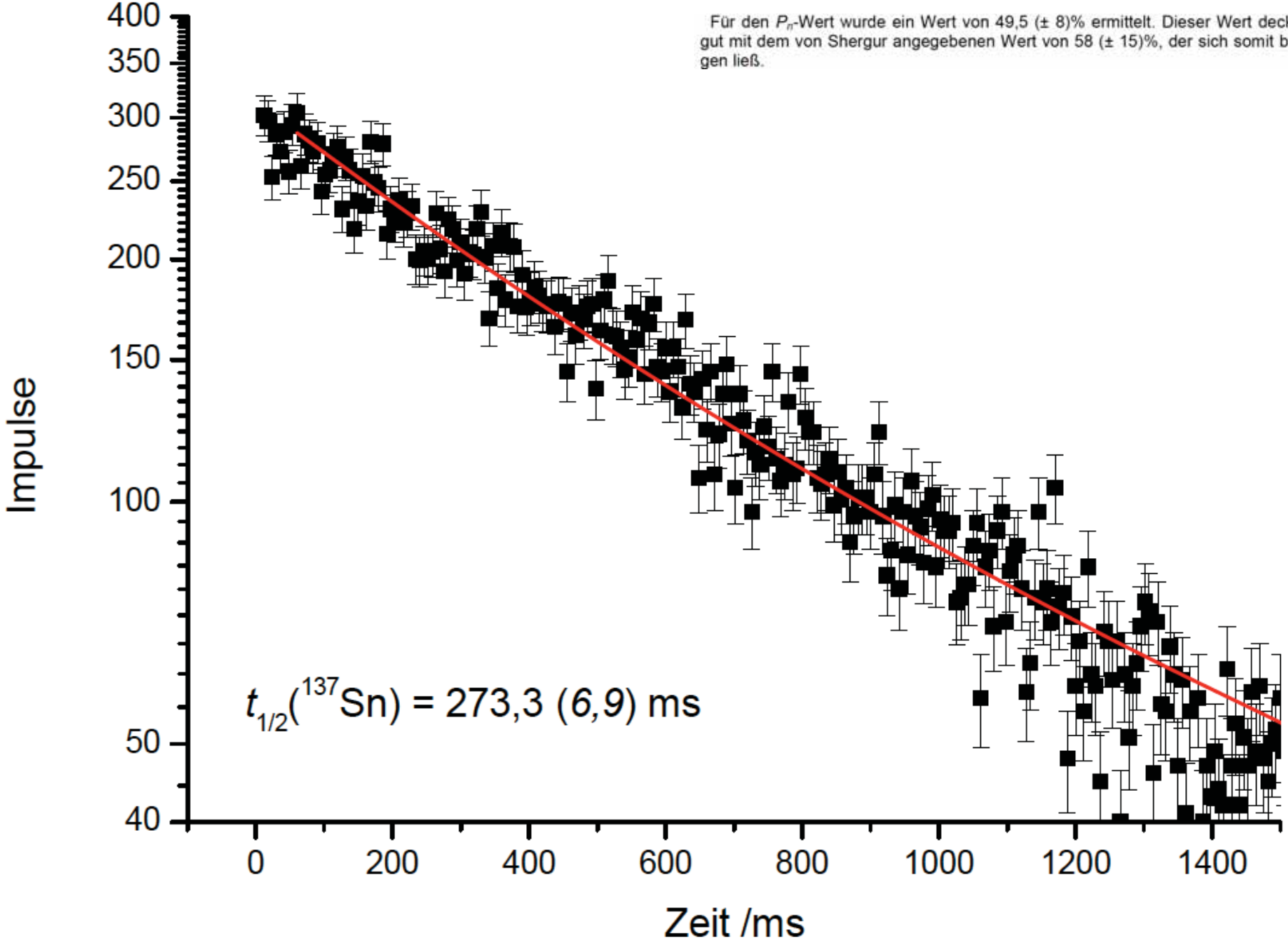


Figure 1. Comparison of experimental half-lives with the ones calculated with the ETFSI potentials (SKSC6-13) and with GT, QRPA and DF3 models.

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.

Für den P_n-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.



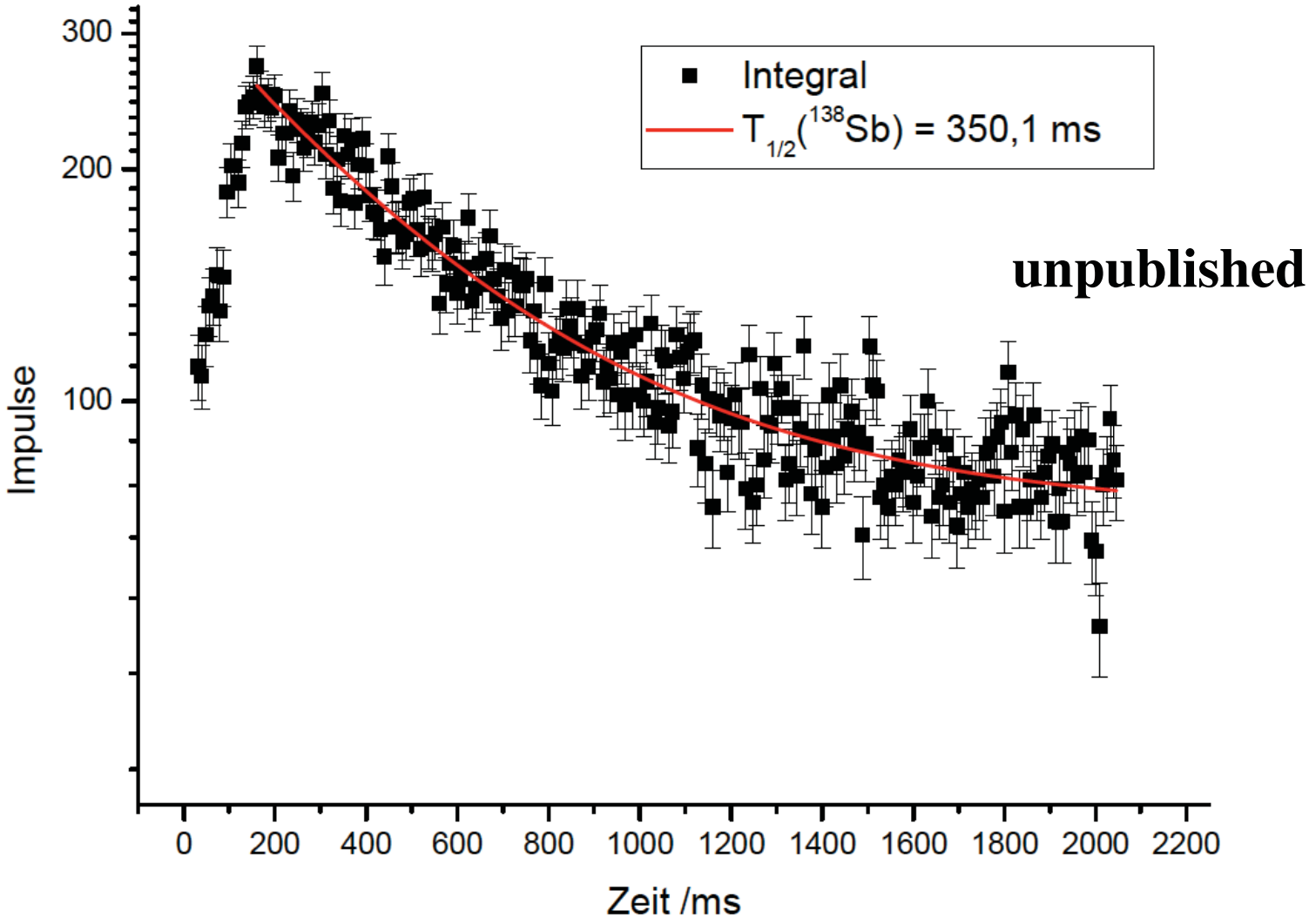


Abb. 76 **Differenzspektrum für ^{138}Sb mit einer Halbwertszeit von $T_{½}$ = 350,1 (+16,8/-15,8) ms. Bis 200 ms nach dem Eintreffen des Protonenpulses ist das Anwachsen der Aktivität bei geöffnetem Beamgate beobachtbar. Mit dem Schließen des Beamgates beginnt der Zerfall der gesammelten Aktivität. Der Untergrund besteht im Wesentlichen ^{137}I ($T_{½}$ = 24,5 (± 0,2) s).**

	135 28 h STAB	136 STAB 300 ms	137 2.5 m STAB	138 STAB	139 83 m	140 13 d	141 18 m	142 11 m	143 14 s	144 11 s	145 4 s	146 2.2 s	56 Ba
	134 3 h 2 y	135 53 m STAB	136 19 s 13 d	137 30 y	138 3 m 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
	133 2 d 5 d	134 STAB	135 15 m 9 h	136 STAB	137 3.8 m	138 14 m	139 40 s	140 14 s	141 .04 1.7 s	142 0.2 1.25 s	143 1.0 0.5 s	144 3.0 0.4 s	54 Xe
	132 1.5 h 2.3 h	133 9 s 20 h	134 4 m 52 m	135 6.6 h	136 49 s 83 s	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 15 0.2 s	143	53 I
	131 30 h 25 m	132 3 d	133 55 m 15 m	134 42 m	135 19 s	136 1 18 s	137 3 2.5 s	138 6 1.4 s	139 12 0.4 s	140	141	142	52 Te
	130 39 m 6 m	131 23 m	132 4 m 3 m	133 2.5 m	134 0.1 10 s 0.8 s	135 16 1.7 s	136 24 0.9 s	137 40 0.5 s	138 50 0.35 s	139 90 0.1 s	140	141	51 Sb
	129 7 m 2. m	130 3.7 m 1.7 m	131 58 s 56 s	132 40 s	133 2.9 1.4 s	134 17 1.0 s	135 22 0.53 s	136 30 0.25 s	137 58 0.27 s	138 0.1 s	139 75	140 50 0.1 s	50 Sn
	128 0.8 s 0.8 s	129 1.2 s 0.60s	130 0.3 s 0.5 s	131 3 0.3 s 0.3 s	132 0.1 0.20s	133 85 0.17 s	134 90 0.14 s	135 95 92 ms	136	137	138	139	49 In
	127 0.4 s	128 0.3 s	129 242 104	130 162	131 68 ms	132 97 ms	133 57 ms						48 Cd
125 155	126 98 ms	127 79 ms	128 58 ms	129 46 ms	130 35 ms	131							47 Ag

News from r-Process Nucleosynthesis: Consequences from the ESS to Early Stars

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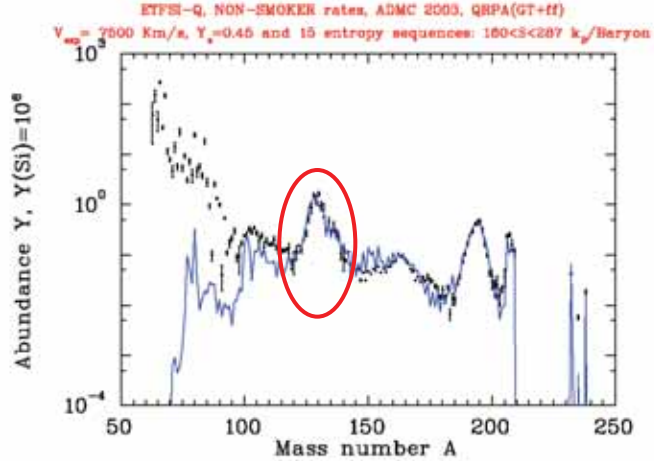
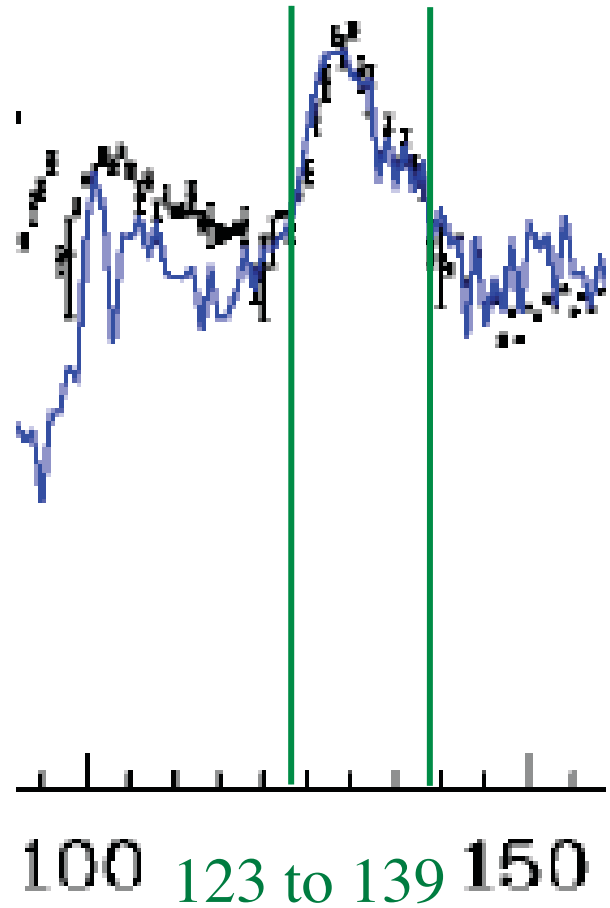


FIGURE 1. Comparison of the $N_{r,\odot}$ distribution (data points [27]) with predicted isotopic abundances (full line) from a weighted superposition of 15 HEW entropy components in the range $160 \leq S \leq 287$. For further details and discussion, see text.



During the past 15 years, the half-lives have been measured from ^{129}Ag to ^{139}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.

Eur. Phys. J. A **25**, s01, 531–534 (2005)
DOI: 10.1140/epjad/i2005-06-057-5

EPJ A dir
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Self-consistent relativistic QRPA studies of soft modes and spin-isospin resonances in unstable nuclei

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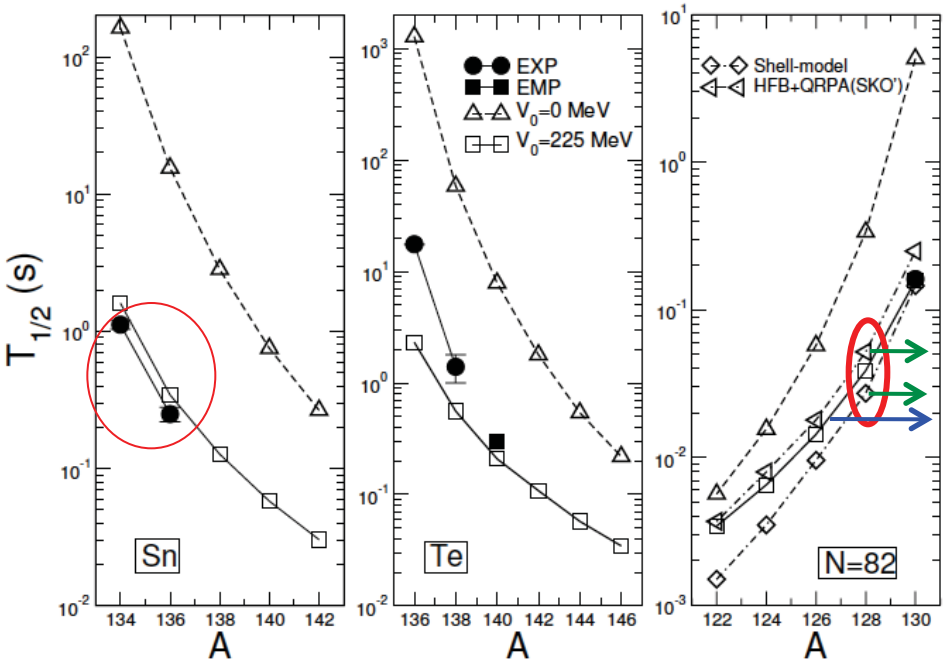
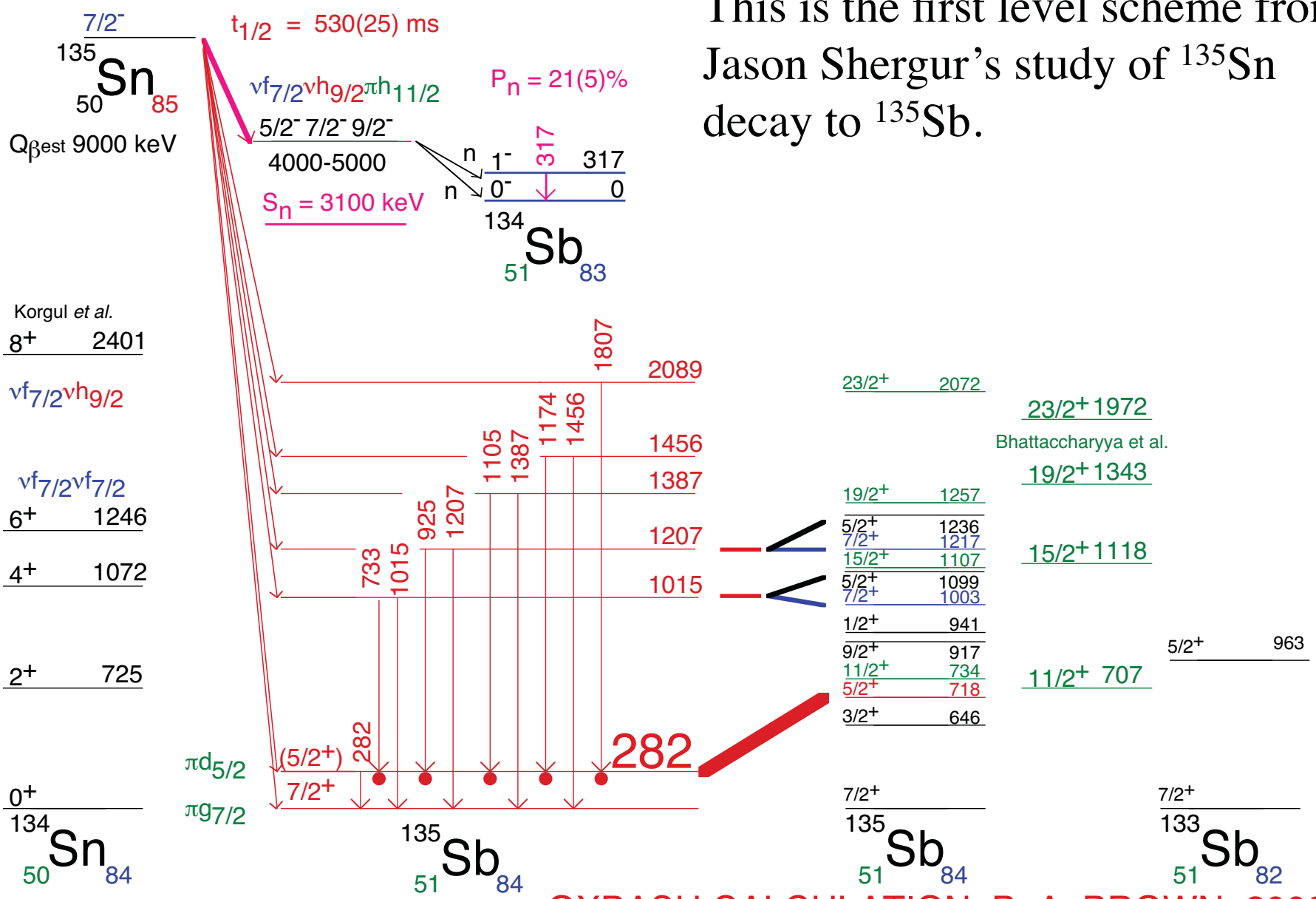


Fig. 3. Calculated half-lives of Sn and Te isotopes with ($V_0 = 225$ MeV), and without ($V_0 = 0$ MeV) $T = 0$ pairing, in comparison with experimental data [34,35]. In the right panel the results for the $N = 82$ isotones are compared with the shell-model [36], and non-relativistic HFB + QRPA results [23].

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}Pd, the range is from 30 to 50 ms. For ^{126}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.



OXBASH CALCULATION: B. A. BROWN, 2000

The 718-keV level is ~ 70 % single-particle $d_{5/2}$.

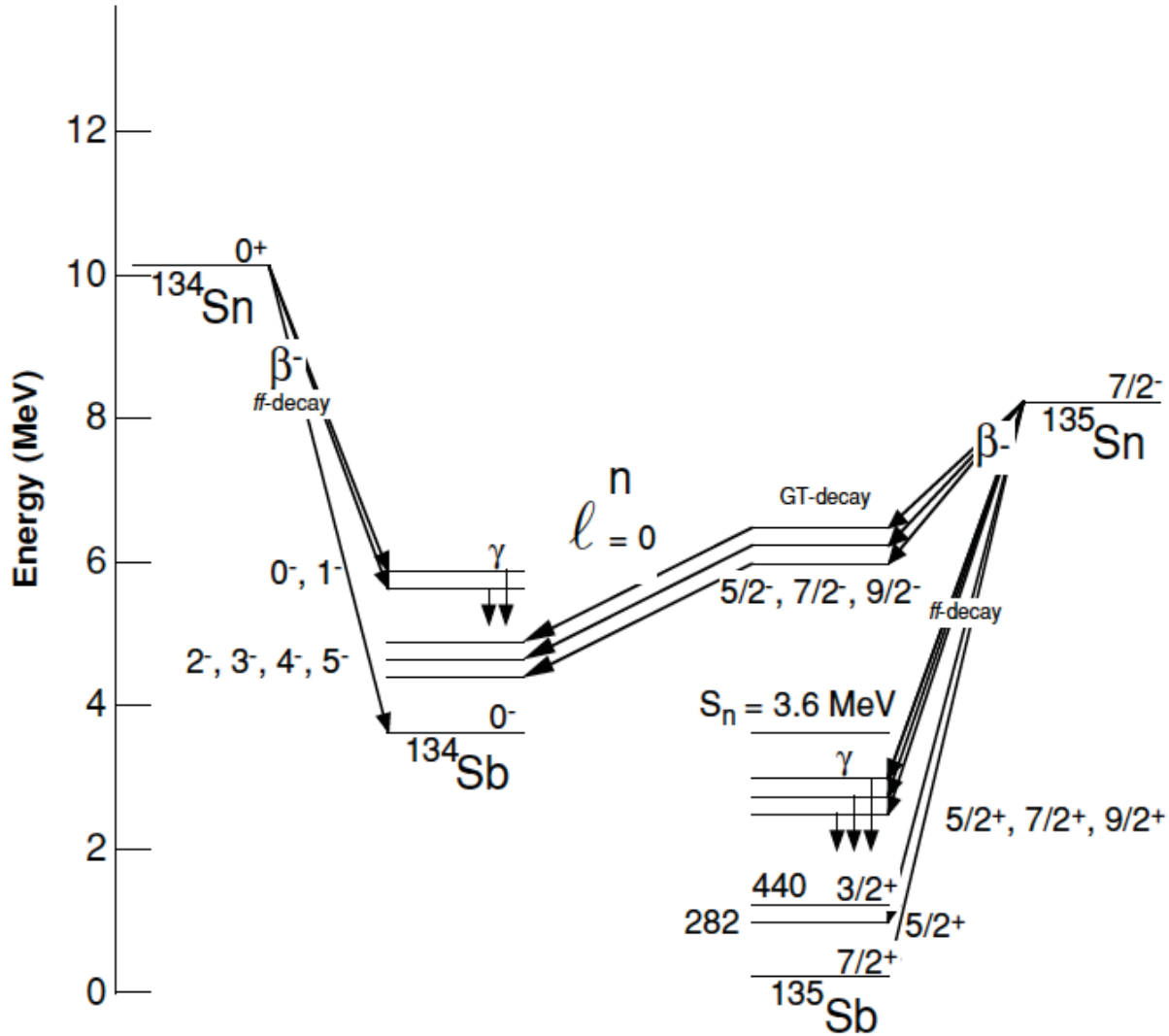
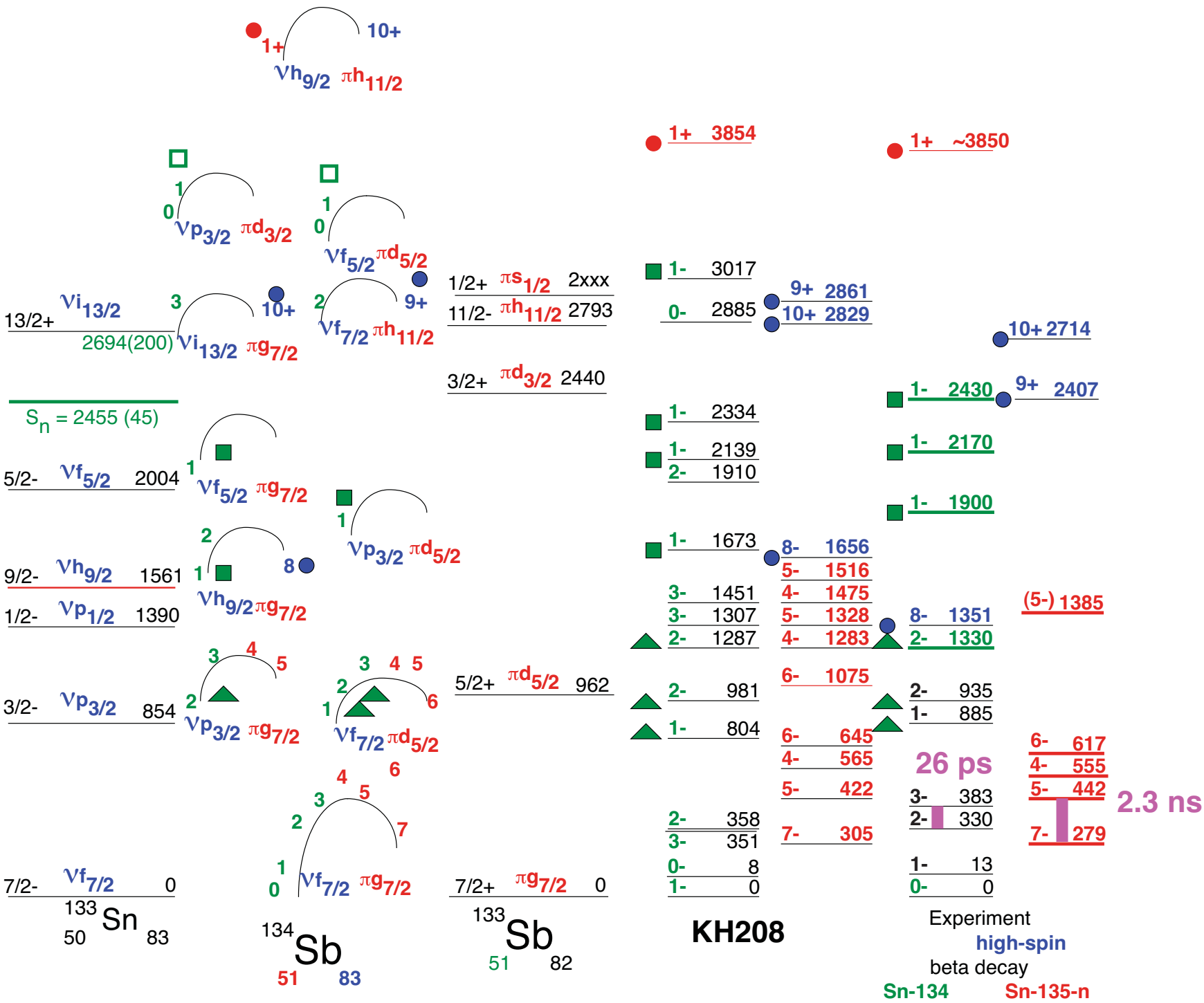


FIG. 1. Possible states in ^{134}Sb that can be populated by the β decay of ^{134}Sn and the $\beta^{-}n$ decay of ^{135}Sn.



1+ 10+
νh9/2 πh11/2
1 0 νp3/2 πd3/2
1 0 νf5/2 πd5/2
13/2+ νi13/2 2694(200)
3 10+ νi13/2 πg7/2
2 9+ νf7/2 πh11/2
Sn = 2455 (45)
5/2- νf5/2 2004
1 νf5/2 πg7/2
1 νp3/2 πd5/2
9/2- νh9/2 1561
2 1 8 νh9/2 πg7/2
1/2- νp1/2 1390
3/2- νp3/2 854
3 4 5 2 νp3/2 πg7/2
3 4 5 2 1 6 νf7/2 πd5/2
6 4 5 3 2 7 1 0 νf7/2 πg7/2
7/2- νf7/2 0
133 50 Sn 83
134 51 Sb 83
1/2+ πs1/2 2xxx
11/2- πh11/2 2793
3/2+ πd3/2 2440
5/2+ πd5/2 962
7/2+ πg7/2 0
133 51 Sb 82
1+ 3854
1- 3017
0- 2885
9+ 2861
10+ 2829
1- 2334
1- 2139
2- 1910
1- 1673
3- 1451
3- 1307
2- 1287
2- 981
1- 804
2- 358
3- 351
0- 8
1- 0
8- 1656
5- 1516
4- 1475
5- 1328
4- 1283
6- 1075
6- 645
4- 565
5- 422
7- 305
KH208
1+ ~3850
10+ 2714
1- 2430
9+ 2407
1- 2170
1- 1900
8- 1351
2- 1330
(5-) 1385
2- 935
1- 885
26 ps
3- 383
2- 330
1- 13
0- 0
6- 617
4- 555
5- 442
2.3 ns
7- 279
Experiment
high-spin
beta decay
Sn-134
Sn-135-n

Vol. 38 (2007) ACTA PHYSICA POLONICA B No

THE SINGLE-PARTICLE AND COLLECTIVE FEATURES IN THE NUCLEI JUST ABOVE ^{132}Sn*

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The Advanced Time Delayed method has been used to measure the lifetimes of excited states in the exotic nuclei ^{134}Sb, ^{135}Sb and ^{136}Te populated in the beta decay of ^{134}Sn, ^{135}Sn and ^{136}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}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.

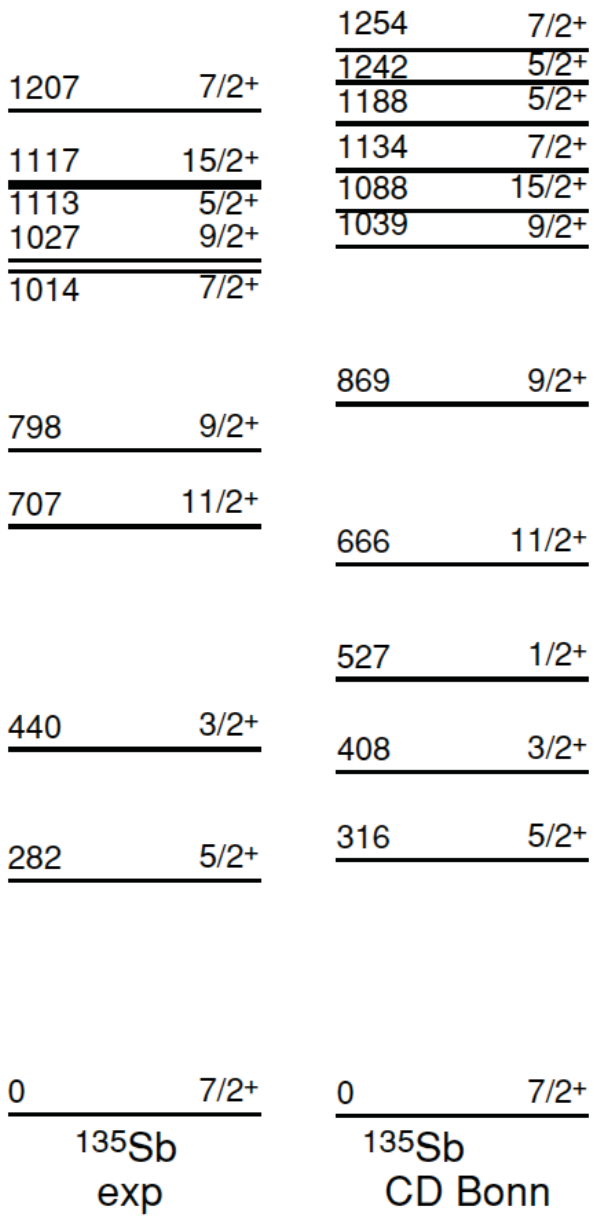
Table 1. Comparison of the experimental $B(M1)$ and $B(E2)$ values and the shell model calculations by A. Brown (labelled AB), A. Covello and A. Gargano (CG) and V.I. Isakov (IS). The B(M1) and B(E2) values are in the units of μ_N^2 and e^2fm^2, respectively.

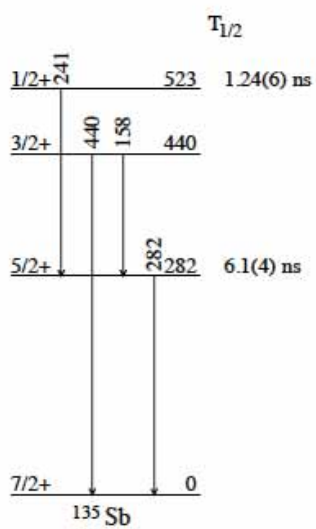
Nucleus	$J_i \rightarrow J_f$	$X\lambda$	$B(X\lambda)_{exp}$[a]	$B(X\lambda)_{th}^{AB}$	$B(X\lambda)_{th}^{CG}$	$B(X\lambda)_{th}^{IS}$
^{134}Sb	$3_1^- \rightarrow 2_1^-$	M1	2.0(4)	1.60	1.39	1.81
	$3_1^- \rightarrow 1_1^-$	E2	118(26)	84	115	116
	$2_1^- \rightarrow 0_1^-$	E2	429(238)	90	123	104
^{135}Sb	$1/2_1^+ \rightarrow 7/2_1^+$	E2	527(26)	678	566	
	$5/2_1^+ \rightarrow 7/2_1^+$	E2	$\leq$54	23	32	
	$5/2_1^+ \rightarrow 7/2_1^+$	M1	$\leq$0.00030	0.0022	0.0040	
^{136}Te	$2_1^+ \rightarrow 0_1^+$	E2	208(29)[b]			
	$2_1^+ \rightarrow 0_1^+$	E2	245(50)	452	360	

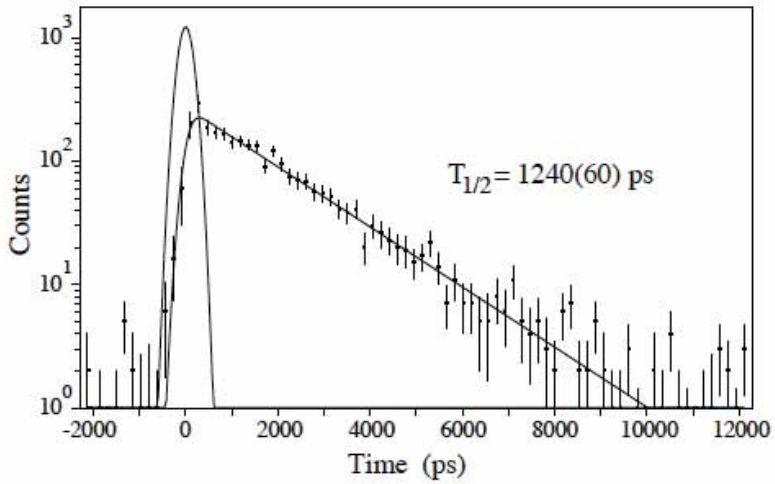
a: From this work unless noted otherwise.
b: From ^{12} obtained in Coulomb excitation in inverse kinematics.

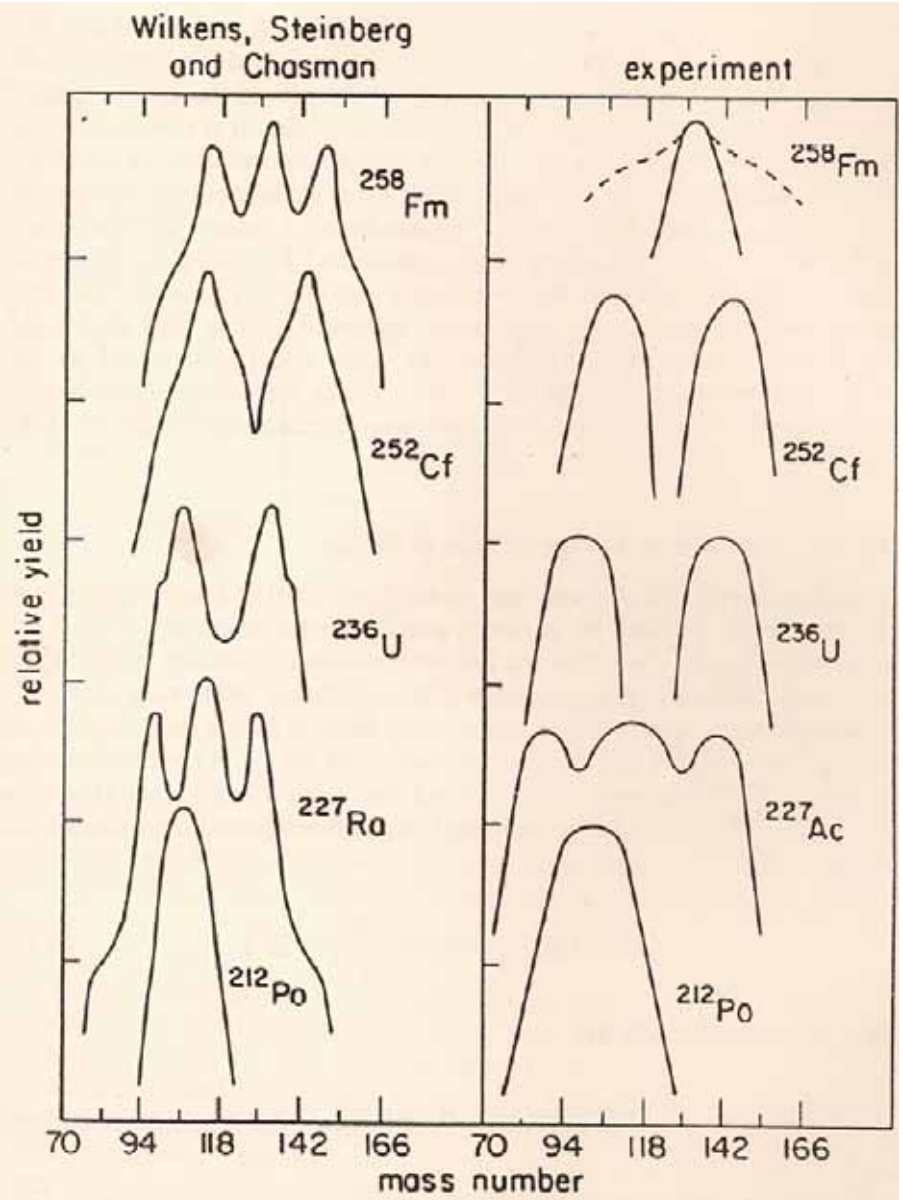
This result was obtained with an ISOLDE ion source using Sulfur gas, enriched in ^{34}S in the ion source, creating SnS+ ions that are 34 mass units heavier than the isobaric Cs that is strongly ionized. The ½+ level shown below was populated in beta-delayed neutron decay from ^{136}Sn decay. The calculation had been previously published indication the level should be at 527 keV…… ..it was found at 523 keV.

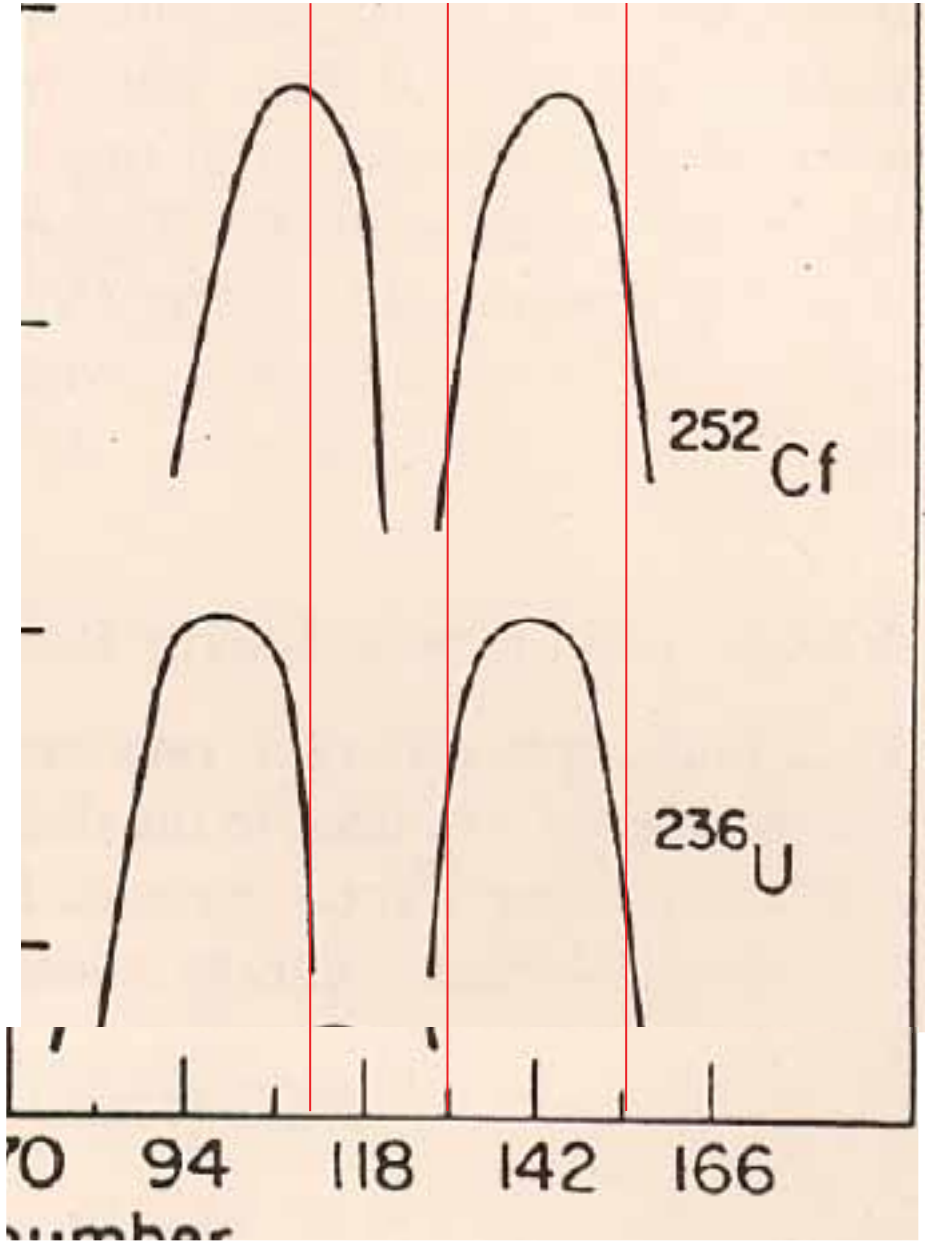
J. SHERGUR *et al.*











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.