Decay spectroscopy with RILIS
Resonance Ionization Laser Ion Source

W. B. Walters, Chemistry, University of Maryland

Encompass work performed at ISOLDE (Ravn, Mishin, Fedeyosev, Köster) in collaboration with the Institute for Kernchemie in Mainz (Kratz, Pfeiffer, Wöhr, Wendt) & the IKS, Leuven, (Huyse and Van Duppen)

Motivation in Mainz was clearly to investigate the decay properties of neutron-rich nuclides involved in r-process nucleosynthesis.

Let me start by thanking DOE for many years of support, and also the Alexander von Humboldt Foundation for funding last year that permitted a 6-month stay in Mainz.

The start of RILIS work at ISOLDE was the recognition by Karl-Ludwig Kratz that the **CHEMICAL SELECTIVITY** needed to isolate r-process nuclides could be achieved via resonance-laser ionization. The first experiments with resonance laser ionization were conducted at GSI to separate ^{101}Sn where the advantage over other methods was not encouraging. But, a fortuitous combination of people in Mainz, Troitsk and CERN made much more successful implementation at ISOLDE possible. Those involved included Viatcheslav Mishin and Valentin Fedoseyev from the Russian Institute for Spectroscopy, Troitsk , along with Helge Ravn and Ulli Köster at CERN/ISOLDE, Jürgen Kluge, Klaus Wendt, Andreas Wöhr, and other laser physicists in Mainz. [NIM **B73**, 550 (1993);ZP A **353**, 9 (1995); Phys. Scr. **T56**, 262(1995)]

There were also parallel developments of laser ion sources led by Mark Huyse and Piet Van Duppen from the University of Leuven for Co and Ni. [NIM B **114**,350(1996)] Note that the work in Leuven was performed with an Ion Guide, not a chemical ion source. In that regard, it was possible to study the decay of heavy short-lived Ni isotopes whose release in a chemical ion source is quite slow.

Two key advantages are associated with ionization enhanced by the use of a RILIS, ...it can be turned off, and it can be tuned.

The first slide shows the gamma spectrum for Ag-126 taken last August, with the laser-on spectrum and laser-off spectrum shown together

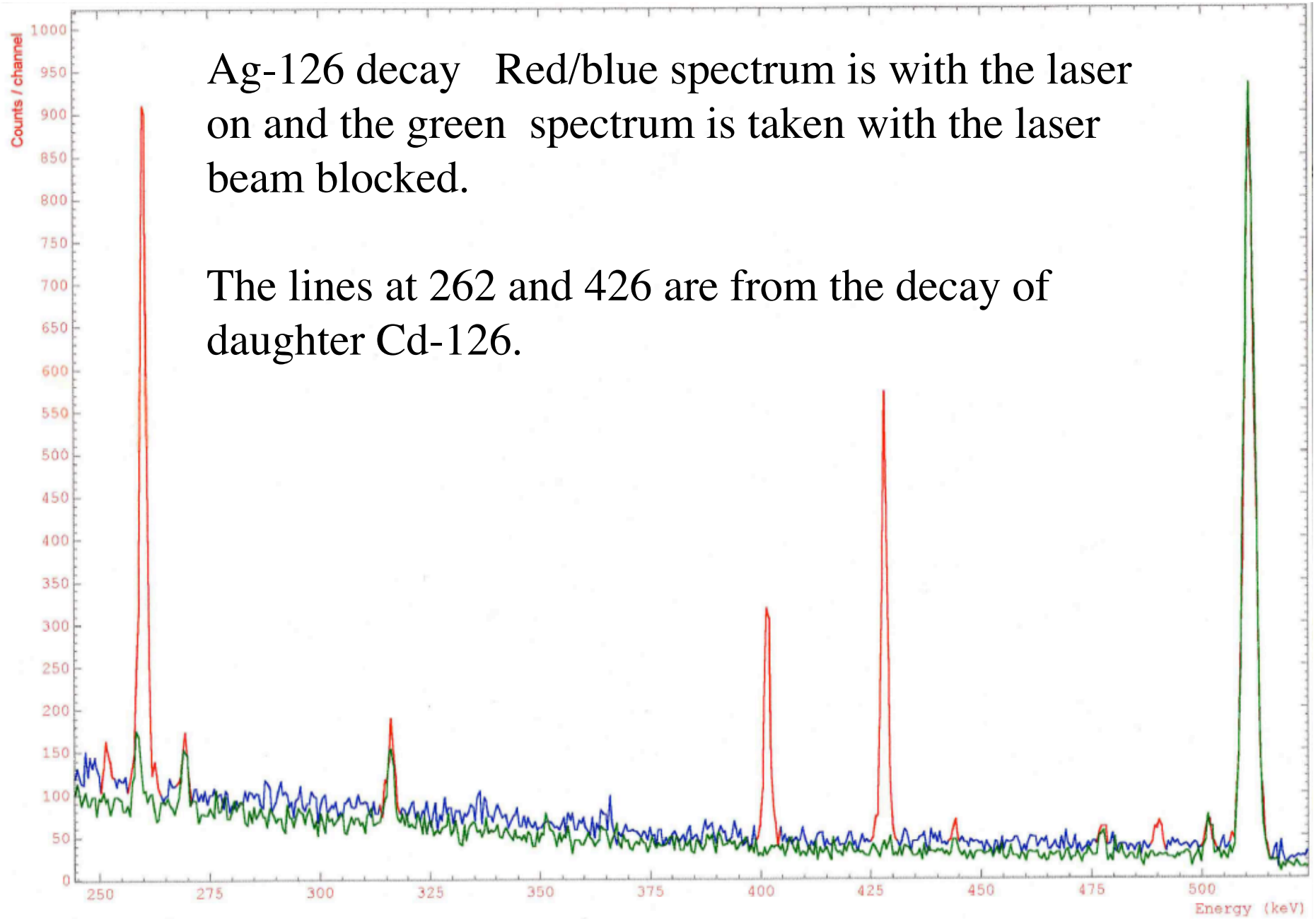
Tuning means that it is possible to separate isomers.

I will show the old Ag-122 spectrum from 1997 along with the neutron counting-rate as a function of laser frequency. Later on, I will present some data showing the presence of similar isomers in Ag-124 and Ag-126.

Perhaps the most impressive use of this technique has been in Leuven where the presence of 3 isomers was identified in Cu-70.

Ag-126 decay Red/blue spectrum is with the laser on and the green spectrum is taken with the laser beam blocked.

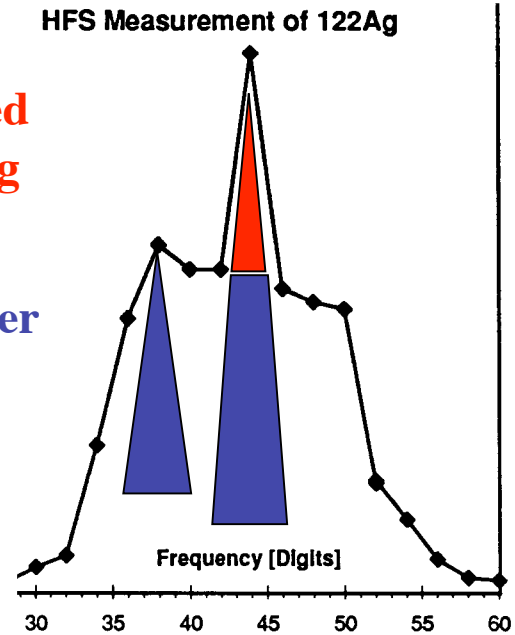
The lines at 262 and 426 are from the decay of daughter Cd-126.

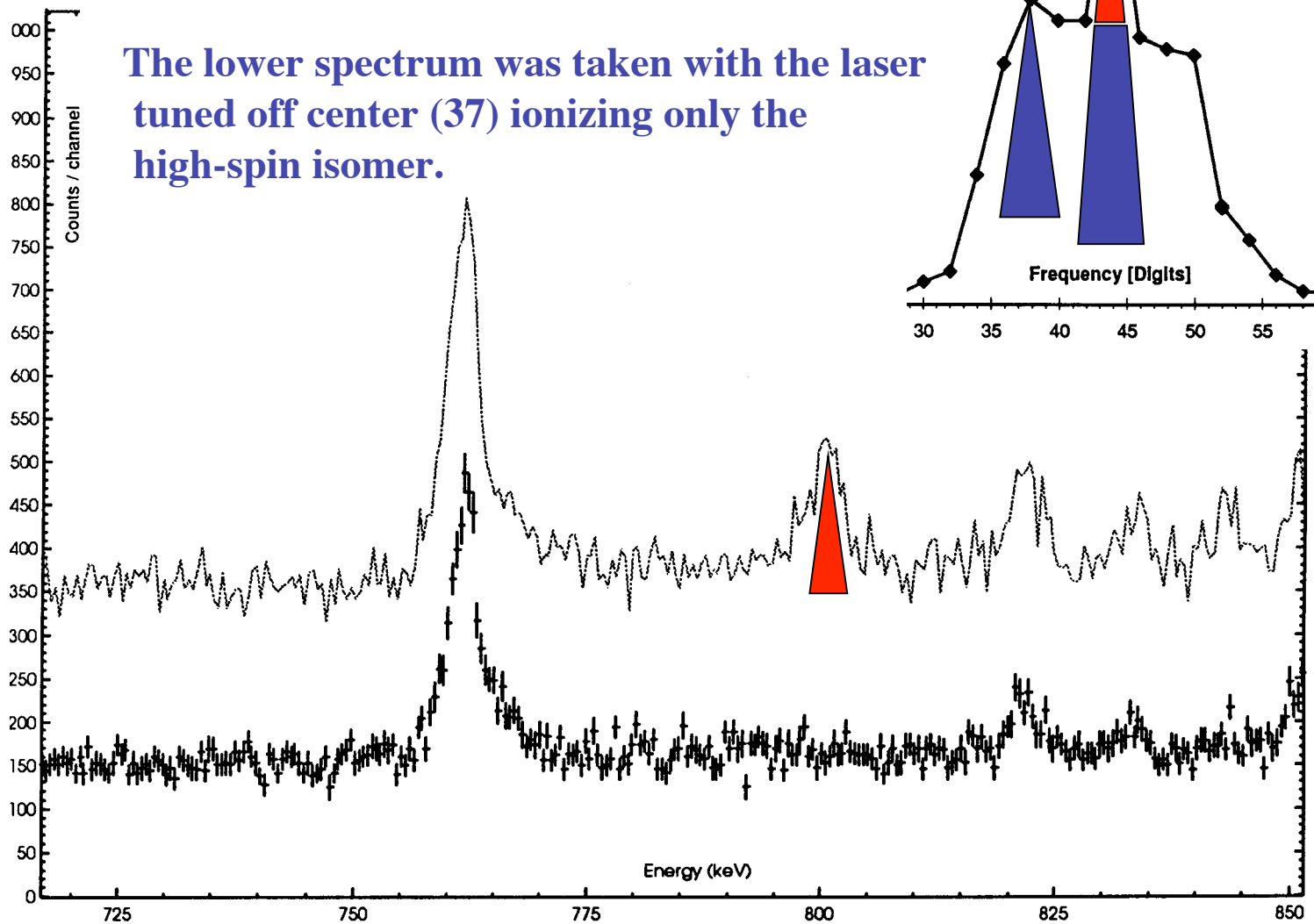


Separation of isomers with hyperfine tuning of the Resonance Ionization Laser Ion Source.

The upper specrum was taken with the laser tuned to the central frequency (44 on this scale) ionizing both isomers.

The lower spectrum was taken with the laser tuned off center (37) ionizing only the high-spin isomer.





First shown in Sanibel in 1997.

T. Kautzsch et al., Proc Conf. Neutron-Rich Nuclides, Seyssins, AIP Conf. Ser. 447, 183 (1998).

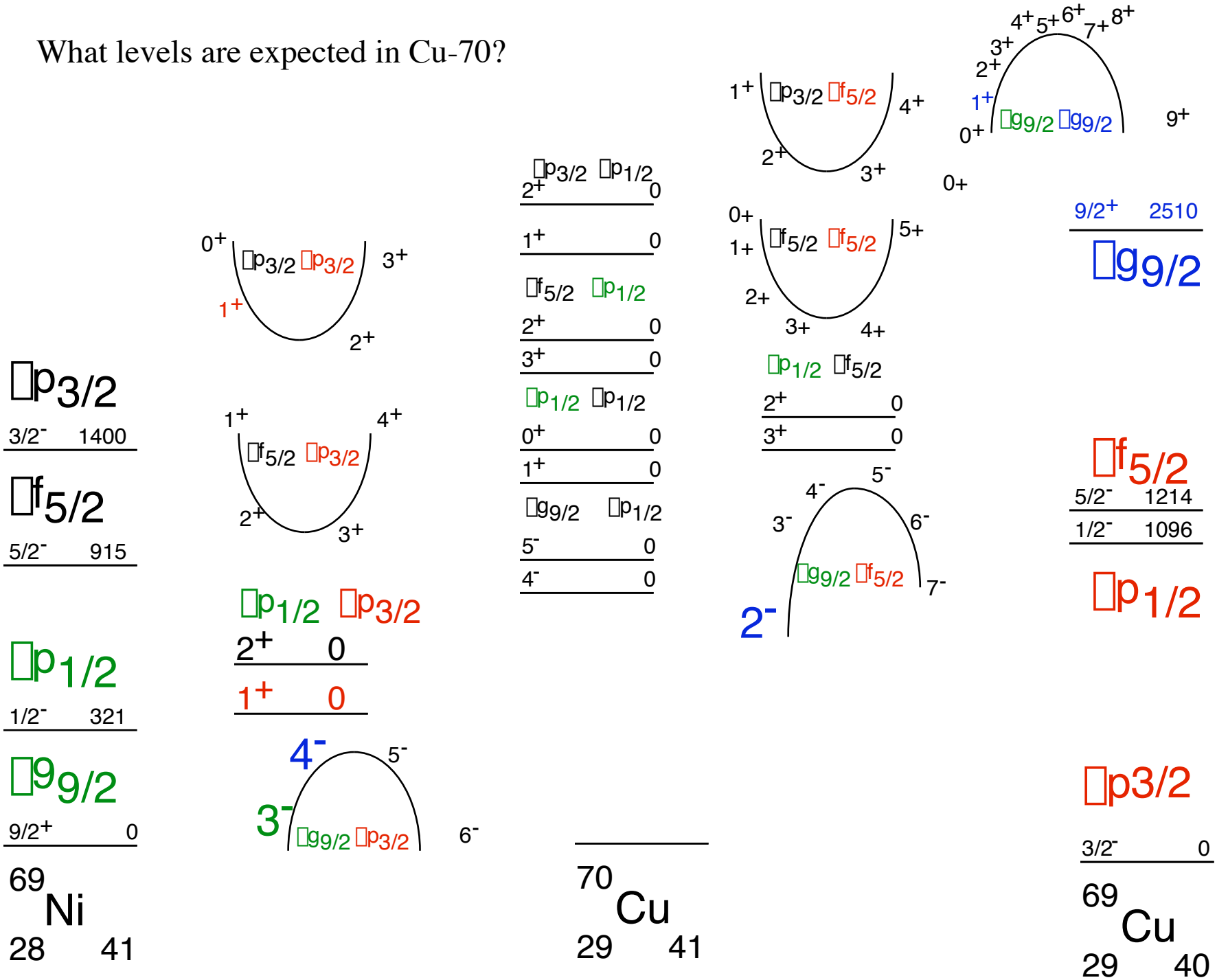
I want to start with a RILIS story of the decay of Cu-70 levels where the miracle of the hyperfine studies made it possible to make sense of the decay of Ni-70 to levels of Cu-70 studied by Serge Franchoo in his thesis work in Leuven.

His thesis was defended in 1999 and there were data for Ni-70 that just did NOT make sense.

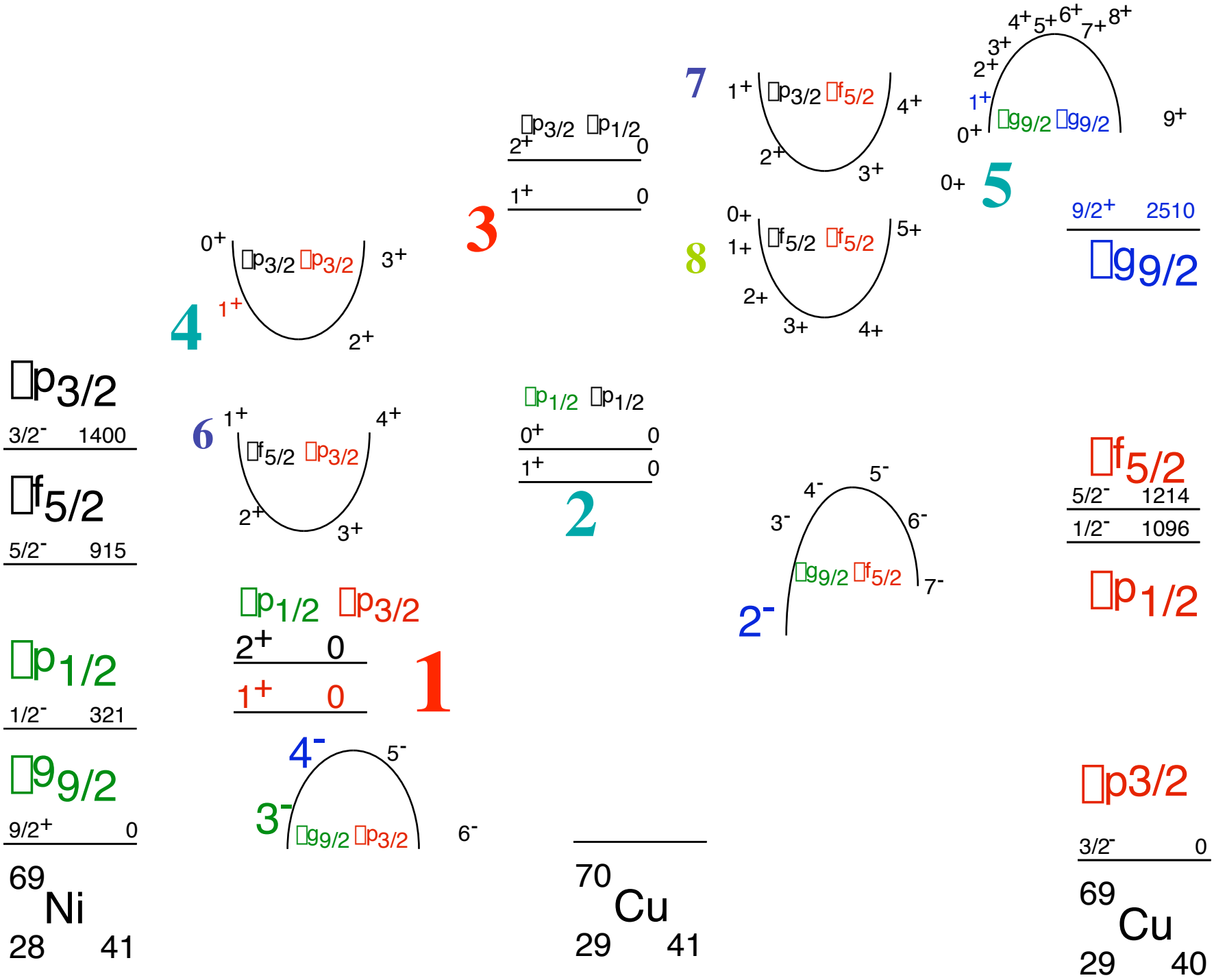
Finally, the RILIS hyperfine study of the Cu-70 decay made sense of the data.

AND….make it possible to make some good sense of what might be going on in Cu-76 and Cu-78.

What levels are expected in Cu-70?



- Eight 1+ levels are expected. Strong beta decay should be observed to those numbered 1 through 5. Those numbered 6 and 7 are L-forbidden, and #8 should lie at a very high energy and play little role in Ni-70 decay.
- Five 1+ levels were observed at just about the energies and log ft values as will be suggested in the next several slides. 3 of the four members of the g-9/2 p-3/2 multiplet were identified with the aid of the laser hyperfine studies.
- A paper presenting these results is in preparation and should be available soon as J. Van Roosbroeck et al.


p3/2
3/2- 1400
f5/2
5/2- 915
p1/2
1/2- 321
g9/2
9/2+ 0
69 Ni 28 41
0+ p3/2 p3/2 3+
1+ 2+
4
1+ f5/2 p3/2 4+
2+ 3+
6
p1/2 p3/2
2+ 0
1+ 0
1
4- 5-
3- g9/2 p3/2 6-
p3/2 p1/2
2+ 0
1+ 0
3
p1/2 p1/2
0+ 0
1+ 0
2
70 Cu 29 41
7
1+ p3/2 f5/2 4+
2+ 3+
0+ f5/2 f5/2 5+
1+ 2+ 3+ 4+
8
4+ 5+ 6+ 7+ 8+
3+
2+
1+ g9/2 g9/2 9+
0+ 0+
5
9/2+ 2510
g9/2
f5/2
5/2- 1214
1/2- 1096
p1/2
5- 4- 6-
3- g9/2 f5/2 7-
2-
p3/2
3/2- 0
69 Cu 29 40

PHYSICAL REVIEW C, VOLUME 65, 024315

Magnetic moments of $^{68}Cu^{g,m}$ and $^{70}Cu^{g,m_1,m_2}$ nuclei measured by in-source laser spectroscopy

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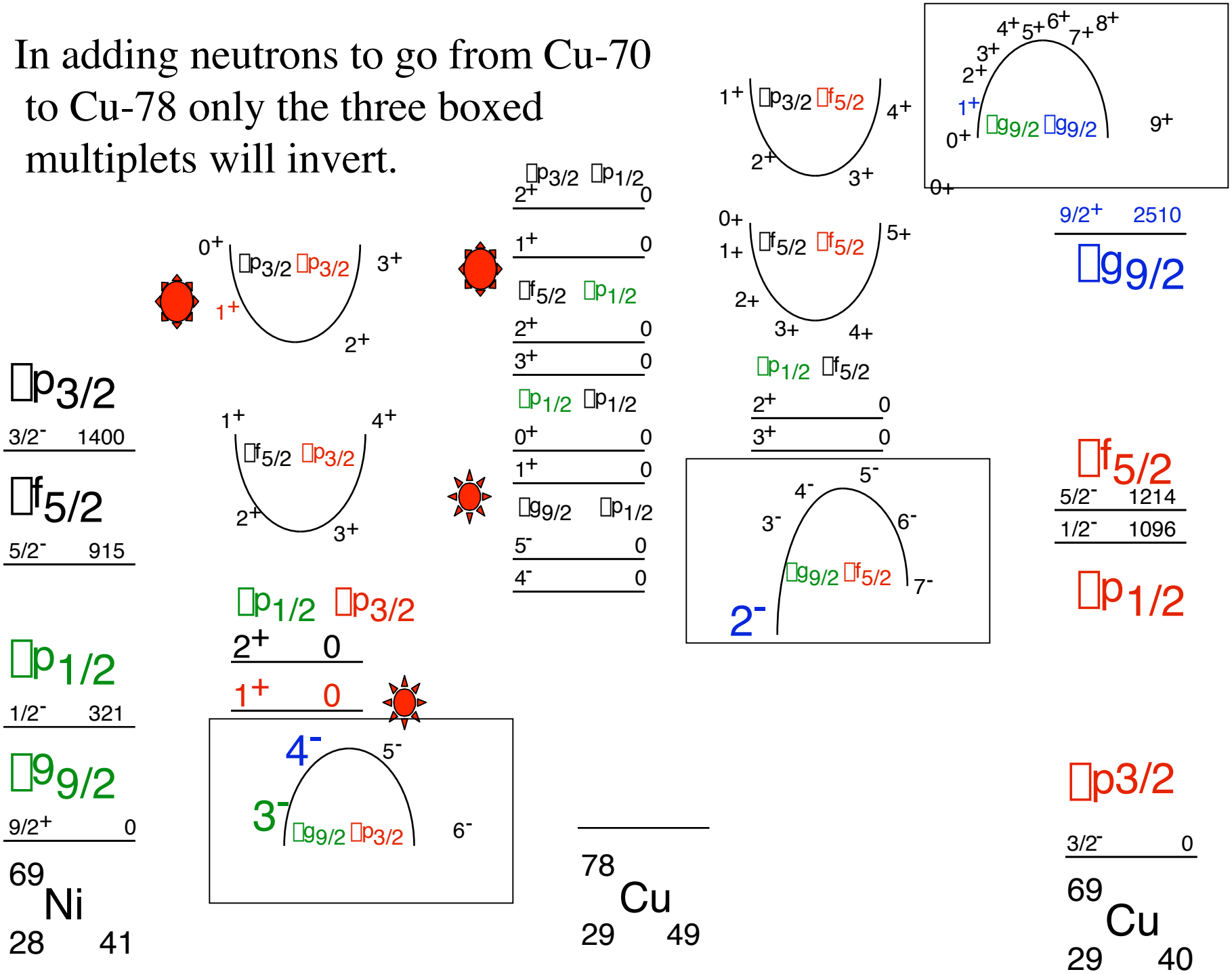
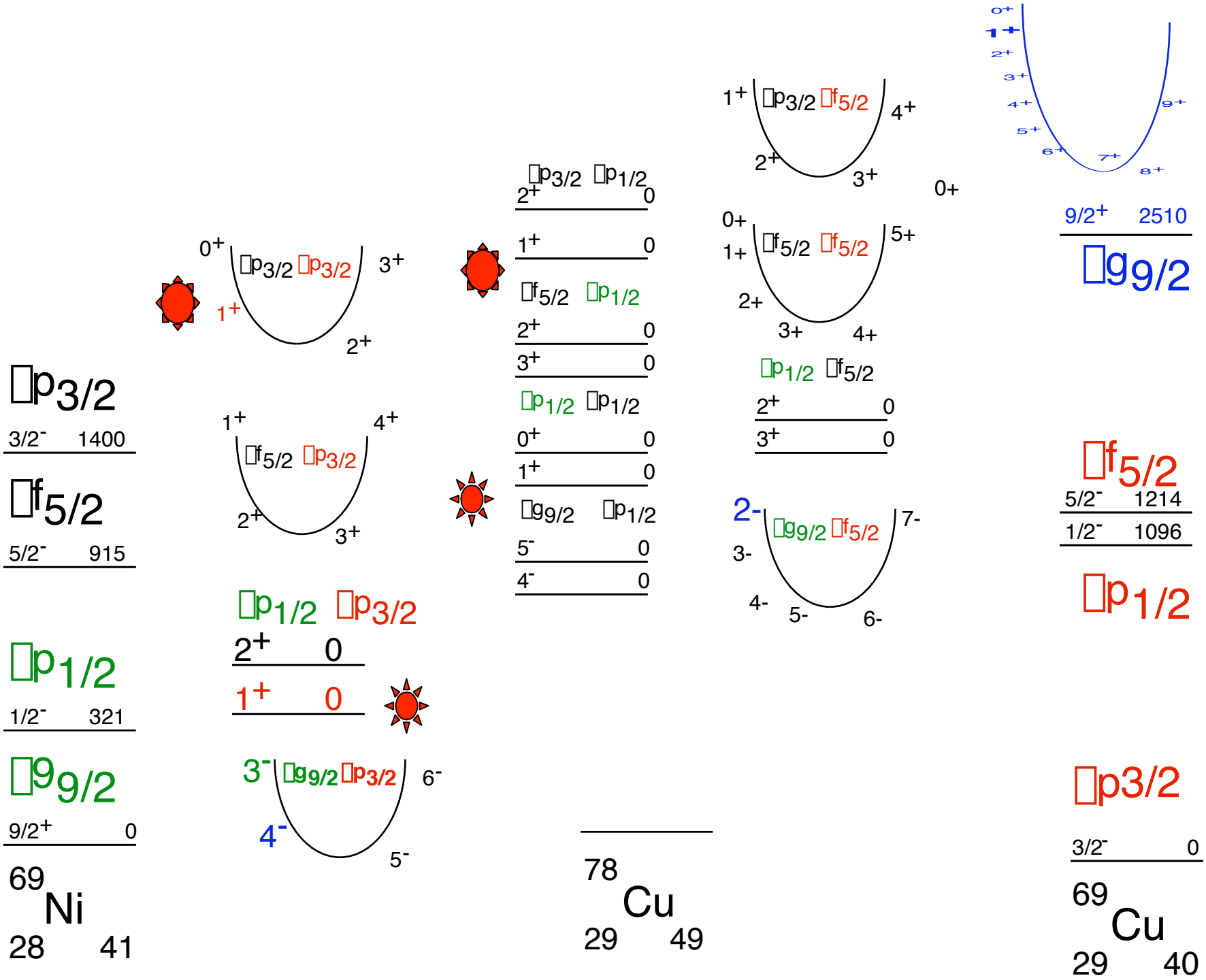
J. Van Roosbroeck, S. Gheysen, M. Huyse, K. Kruglov, G. Neyens, and P. Van Duppen
Instituut voor Kern-en Stralingsfysica, University of Leuven, B-3001 Leuven, Belgium

(IS365 Collaboration and ISOLDE Collaboration)
(Received 18 September 2000; revised manuscript received 13 September 2001; published 16 January 2002)

We have obtained information on the atomic hyperfine splitting and, hence, on magnetic moments in neutron-rich $^{68,70}Cu$ isotopes by scanning the frequency of the narrow-band laser of the first excitation step in the resonance ionization laser ion source. The deduced magnetic moments are $\mu(^{68}Cu^{g},I^{\pi}=1^{+})=+2.48(2)\times(7)\mu_N$, $\mu(^{68}Cu^{m},I^{\pi}=6^{-})=+1.24(4)(6)\mu_N$, and $\mu(^{70}Cu^{m_2},I^{\pi}=1^{+})=+1.86(4)(6)\mu_N$, $\mu[^{70}Cu^{g},I^{\pi}=(6^{-})]=(+)1.50(7)(8)\mu_N$. The results of the scans analysis points out the existence of a new isomer, $^{70}Cu^{m_1}$. Its deduced magnetic moment is $(-)3.50(7)(11)\mu_N$, in good agreement with the $I^{\pi}=3^{-}$ assignment. The method of in-source atomic spectroscopy, as well as the analysis of the obtained data, is described. The results are discussed in terms of single-particle configurations coupled to the ^{68}Ni core.

In adding neutrons to go from Cu-70 to Cu-78 only the three boxed multiplets will invert.



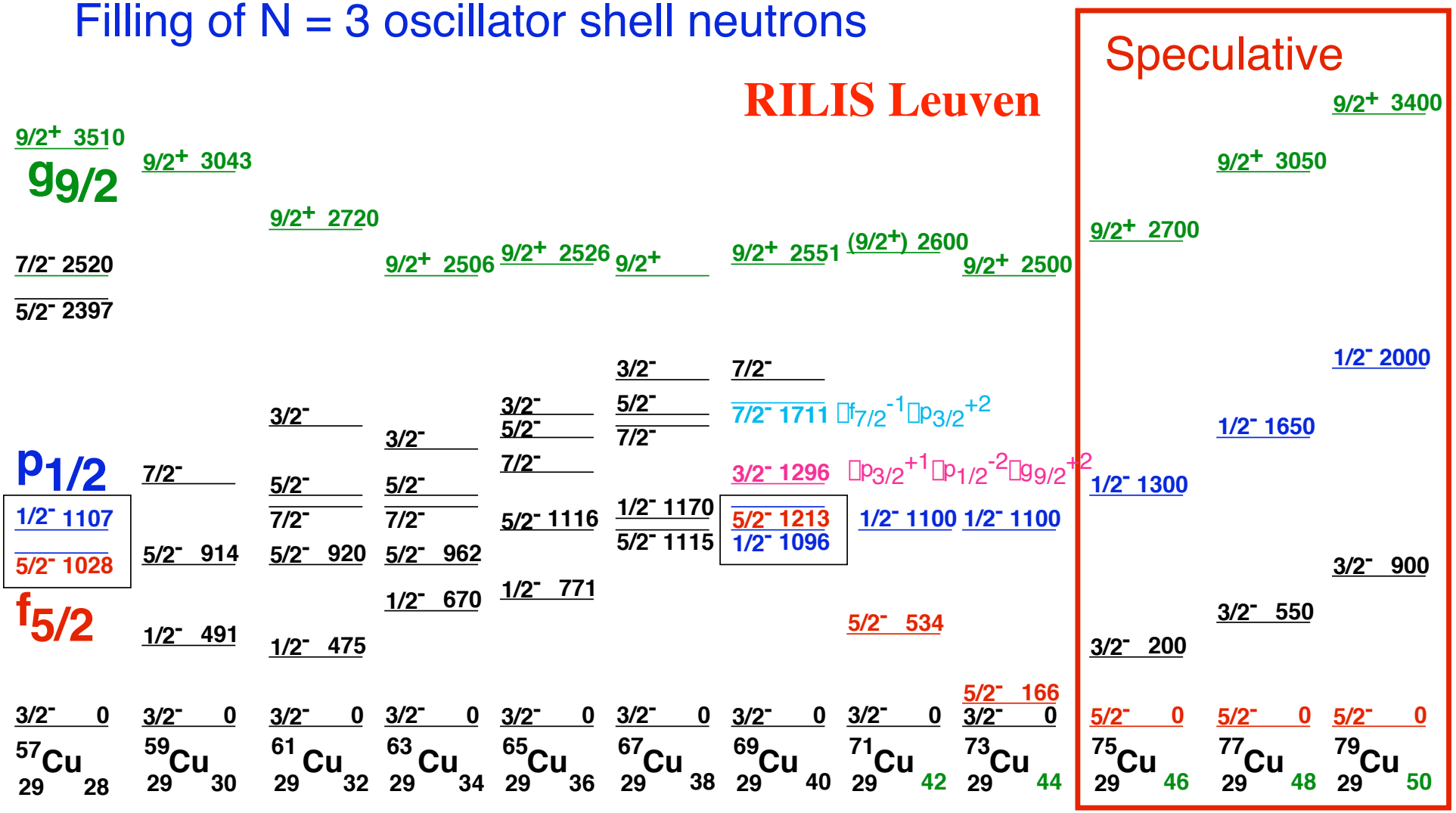

p3/2
3/2- 1400
f5/2
5/2- 915
p1/2
1/2- 321
g9/2
9/2+ 0
69 Ni 28 41
0+ p3/2 p3/2 3+
1+ 2+
1+ f5/2 p3/2 4+
2+ 3+
p1/2 p3/2
2+ 0
1+ 0
3- g9/2 p3/2 6-
4- 5-
p3/2 p1/2
2+ 0
1+ 0
f5/2 p1/2
2+ 0
3+ 0
p1/2 p1/2
0+ 0
1+ 0
g9/2 p1/2
5- 0
4- 0
78 Cu 29 49
1+ p3/2 f5/2 4+
2+ 3+
0+
0+ f5/2 f5/2 5+
1+ 2+ 3+ 4+
p1/2 f5/2
2+ 0
3+ 0
2- g9/2 f5/2 7-
3- 4- 5- 6-
0+ 1+ 2+ 3+ 4+ 5+ 6+ 7+ 8+ 9+
9/2+ 2510
g9/2
f5/2
5/2- 1214
1/2- 1096
p1/2
p3/2
3/2- 0
69 Cu 29 40

Single odd proton levels in Cu nuclides

$g_{9/2}$ neutrons N = 4 oscillator shell neutrons

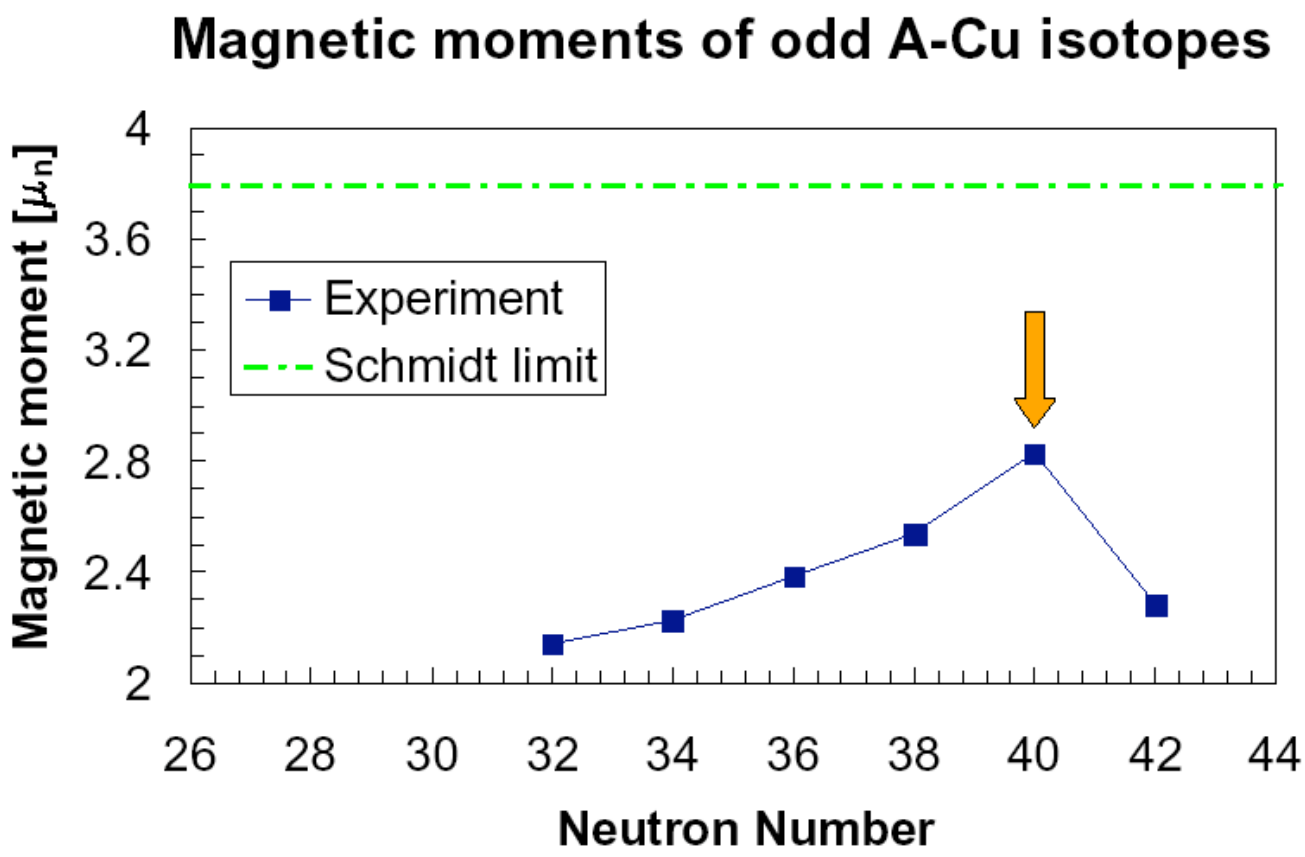
Filling of N = 3 oscillator shell neutrons

RILIS Leuven



Levels in odd-PROTON Cu nuclides.

PRE dicted at Sanibel 1992



N.J. Stone et al., DNP MSU 2002 RILIS NICOLE nuclear orientation data.

Weissman et al DNP 2002 Cu-73 and Cu-75 showed lower moments that support the notion that Cu-75 has a 5/2- spin and parity.

(1+, 6-)

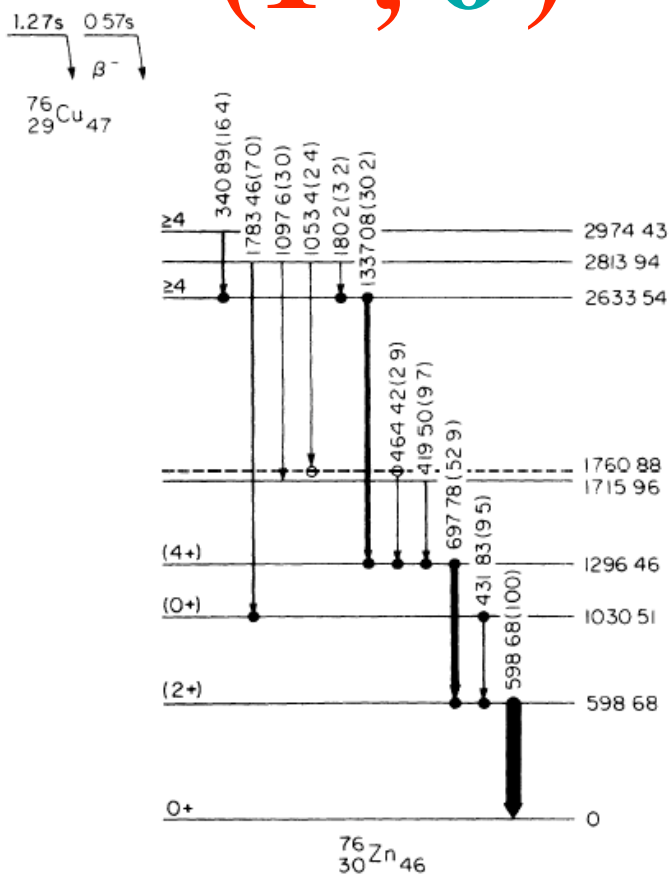
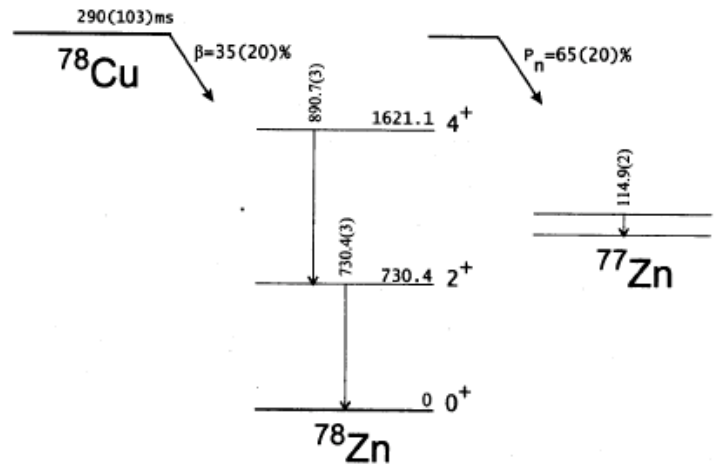


FIG. 4. Decay scheme for ^{76}Cu with energies in keV. The 0.57 s half-life is probably from the decay of a high-spin isomer while the 1.27 s half-life is probably from the decay of a low-spin isomer.

(5-)



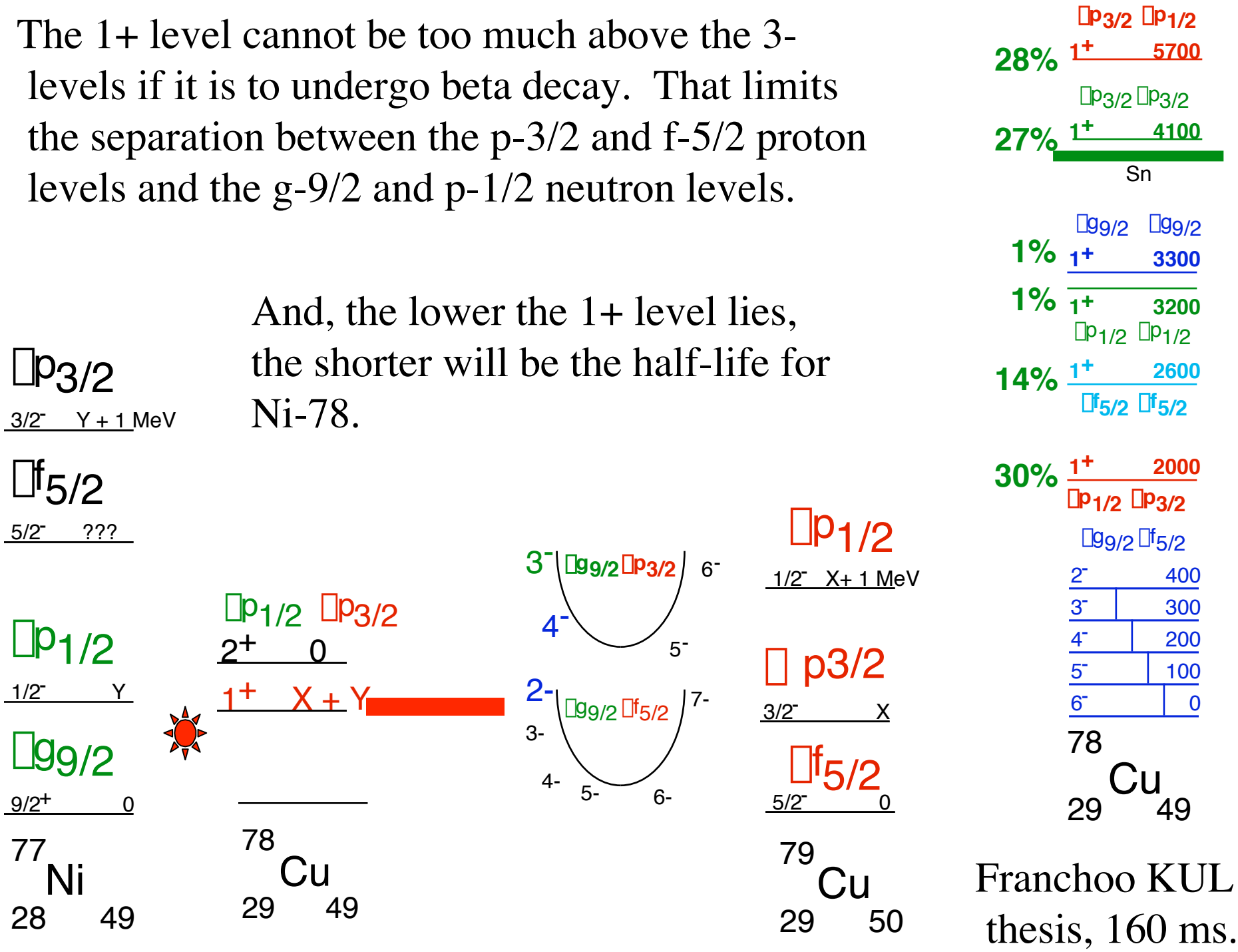
g. 1. Deduced decay scheme for the β-decay of ^{78}Cu.

J. Van Roosboeck et al.
Hameenlinna p.327
ISOLDE RILIS Cu

Jeff Winger et al., PRC 42,958(1990).

The 1+ level cannot be too much above the 3- levels if it is to undergo beta decay. That limits the separation between the p-3/2 and f-5/2 proton levels and the g-9/2 and p-1/2 neutron levels.

And, the lower the 1+ level lies, the shorter will be the half-life for Ni-78.



Franchoo KUL thesis, 160 ms.

Next, I want to review the status of the data for the RILIS studies in the Sn-132 region.

A P_n value in %
Half-life in milliseconds

new values in red
old values in black
hopeful values in green
new structure in blue

						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
						135 6.6 h	136 1.4 m	137 7 25 s	138 6 6.5 s	139 10 2.3 s	140 10 0.9 s	141 21 0.5 s	142 15 0.2 s	143			53 I
						134 42 m	135 19 s	136 1 18 s	137 3 2.5 s	138 6 1.4 s	139 12 0.4 s	140	141	142			52 Te
						133 2.5 m	134 0.1 0.8 s	135 16 1.7 s	136 24 0.8 s	137 49 0.33 s	138 50 0.25 s	139 90 0.15 s	140	141			51 Sb
126	127	128	129	130	131	132 40 s	133 2.9 1.4 s	134 17 1.0 s	135 21 0.53 s	136 30 0.28 s	137 58 0.18 s	138 50 0.20 s	139 75 0.1 s	140 50 0.1 s			50 Sn
125	126	127	128	129	130	131 0.3 s	132 0.1 0.20s	133 85 0.17 s	134 90 0.14 s	135 95 92	136	137	138	139			49 In
124	125	126	127	128	129	130 195 160	131 68	132 95	133	134							48 Cd
123	124	125 155	126 95	127 79	128 58	129 46	130 50	131	132	133							47 Ag

Y. Jading et al., Nuclear Instruments and Methods B **126**, 76 (1997).

T. Kautzsch, W. B. Walters, and K.-L. Kratz, AIP Conference Series **447**, 1183 (1998).

M. Hannawald et al., Physical Review C **62**, 054301 (September 25, 2000).

I. Dillmann et al., European Physics. Journal A **13**, 281 ((March 2002).

T. Kautzsch et al., Physical Review C **54**, R2811-R-2814 (December 1996).

T. Kautzsch et al., European Physics Journal A, **9** 201-206 (October 2000).

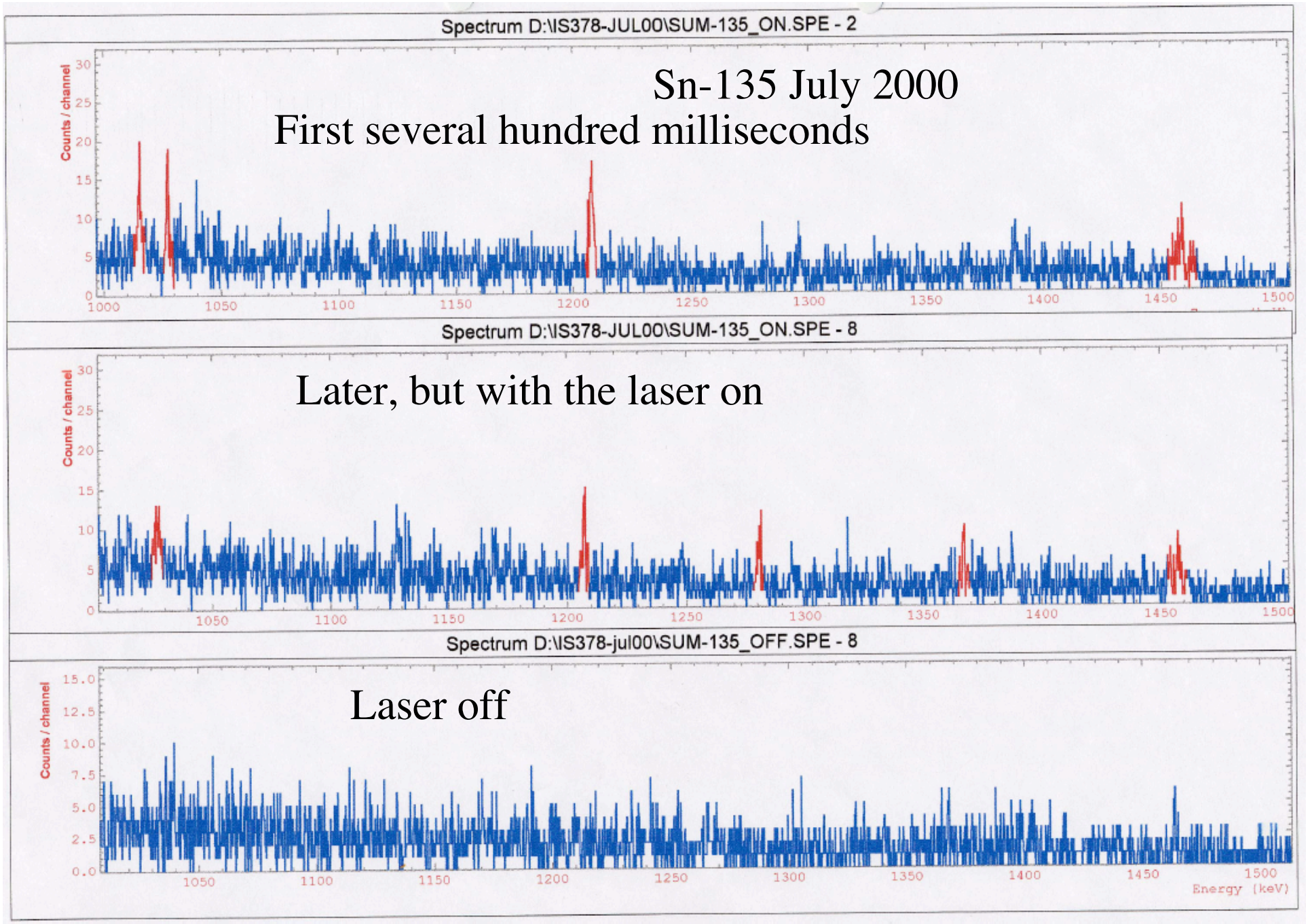
J. Shergur et al., Physical Review C **65**, 034313 (March 2002).

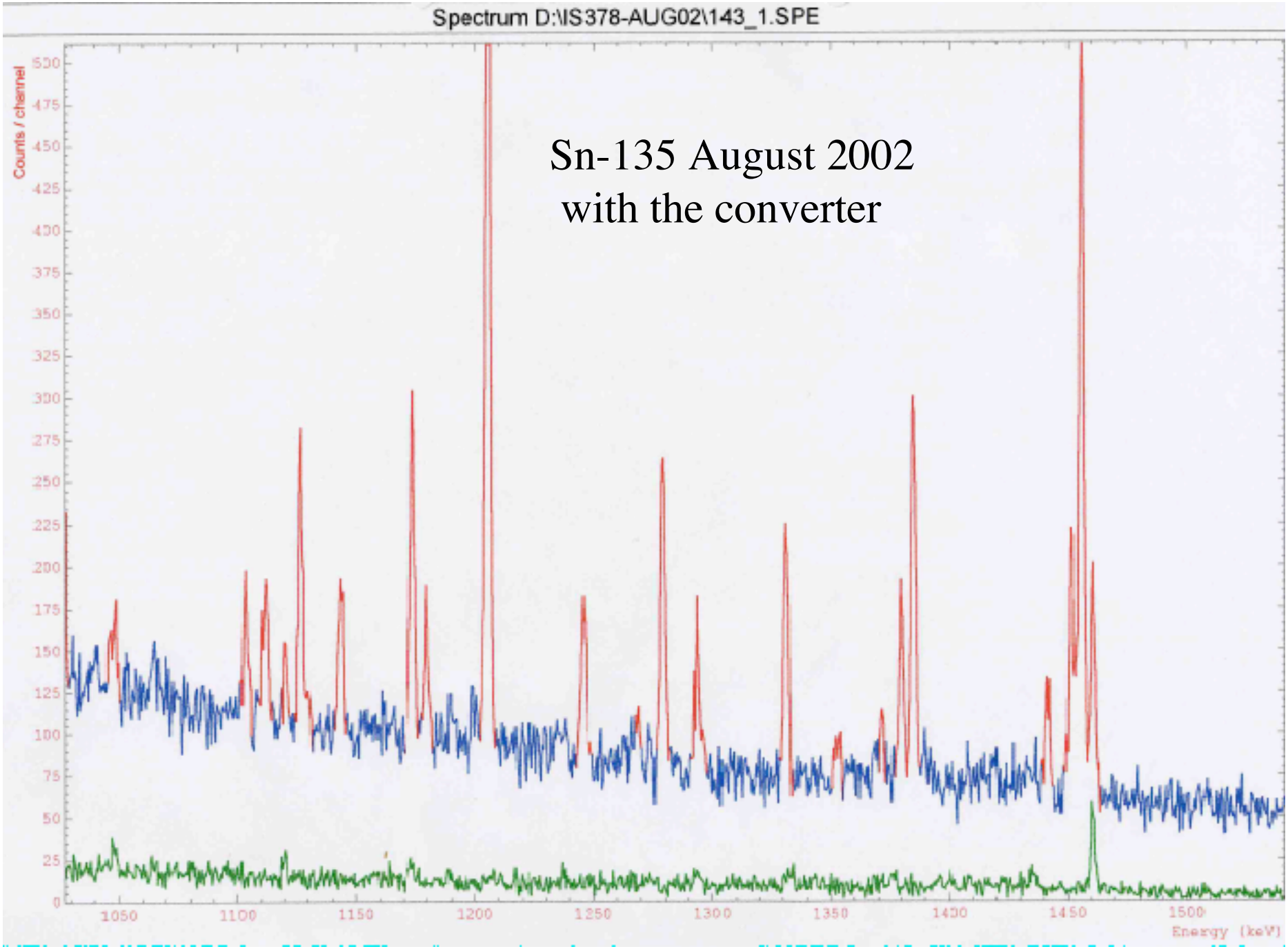
A. Wöhr et al., Proc. 11th Workshop on Nuclear Astrophysics, Ringberg Castle, Feb. 2002.

I. Dillmann et al., in press Physical Review Letters, 2003.

K.-L. Kratz, B. Pfeiffer, F.-K. Thielemann, and W. B. Walters, Hyperfine Interactions **129,** 185-221 (November 2000).

B. Pfeiffer, K.-L. Kratz, F.-K. Thielemann and W.B. Walters, Nuclear Physics A **693**, 282- 324 (October 8,2001)

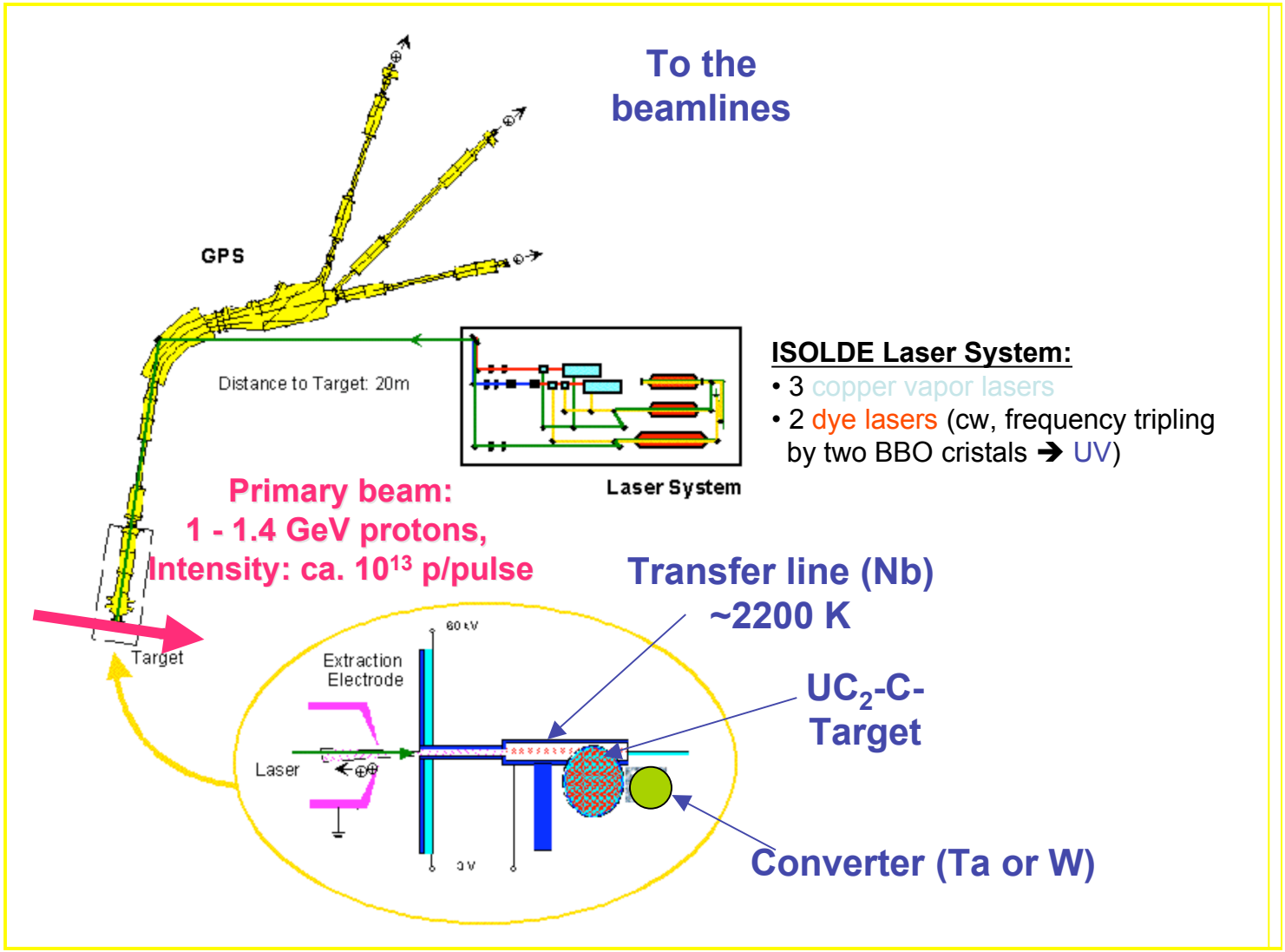

Spectrum D:\IS378-JUL00\SUM-135_ON.SPE - 2
Sn-135 July 2000
First several hundred milliseconds
Counts / channel
Spectrum D:\IS378-JUL00\SUM-135_ON.SPE - 8
Later, but with the laser on
Counts / channel
Spectrum D:\IS378-jul00\SUM-135_OFF.SPE - 8
Laser off
Counts / channel
Energy (keV)


Spectrum D:\IS378-AUG02\143_1.SPE
Counts / channel
Energy (keV)
Sn-135 August 2002
with the converter

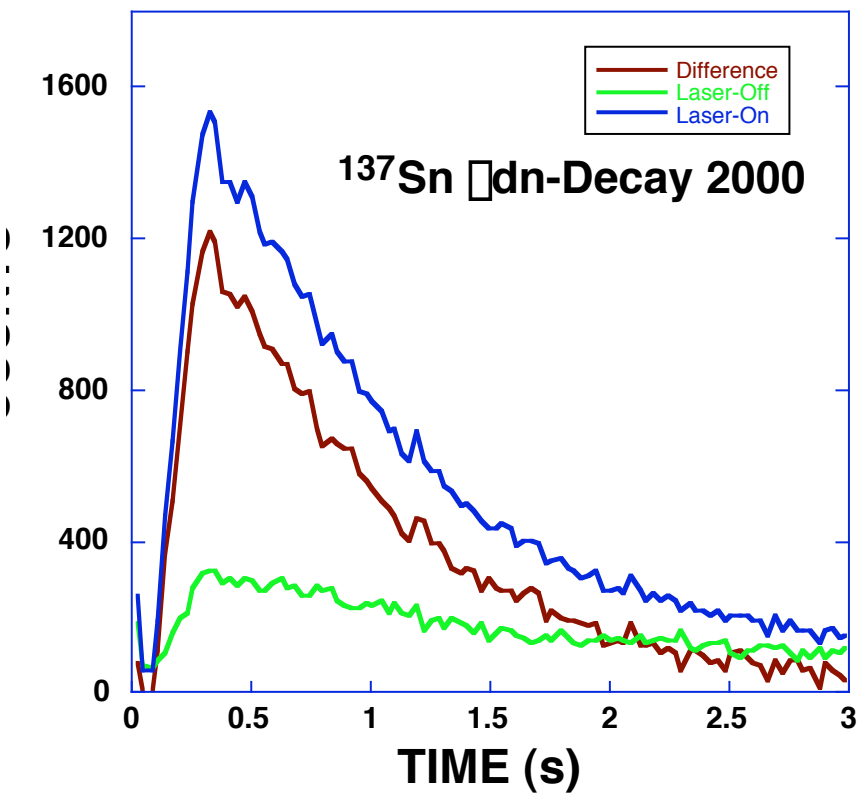
The big difference between 2000 and 2002 was the use of the neutron converter which significantly lowered the spallation production of $^{135}Cs^{m}$. Thus, we could keep the beam gate open for much longer periods of time and collect much more ^{135}Sn.

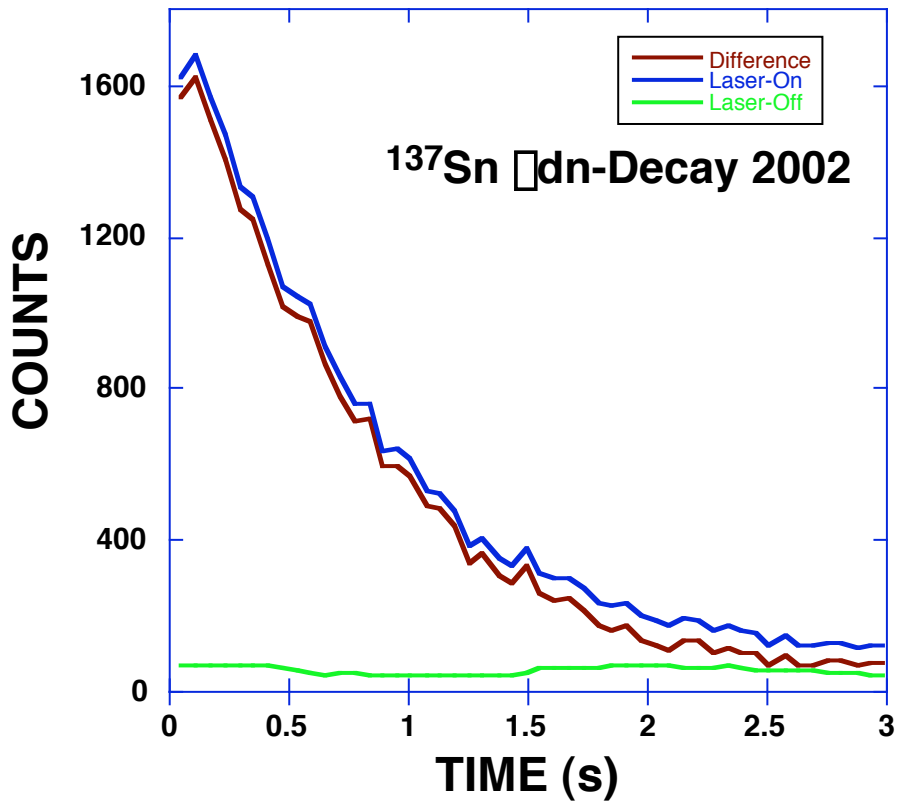
Theoreticians had complained that the level scheme of ^{135}Sb was not very detailed. Our new level scheme will be much more detailed and should provide information about other low-energy levels that are important to the testing of the model.

I. Dillmann et al.

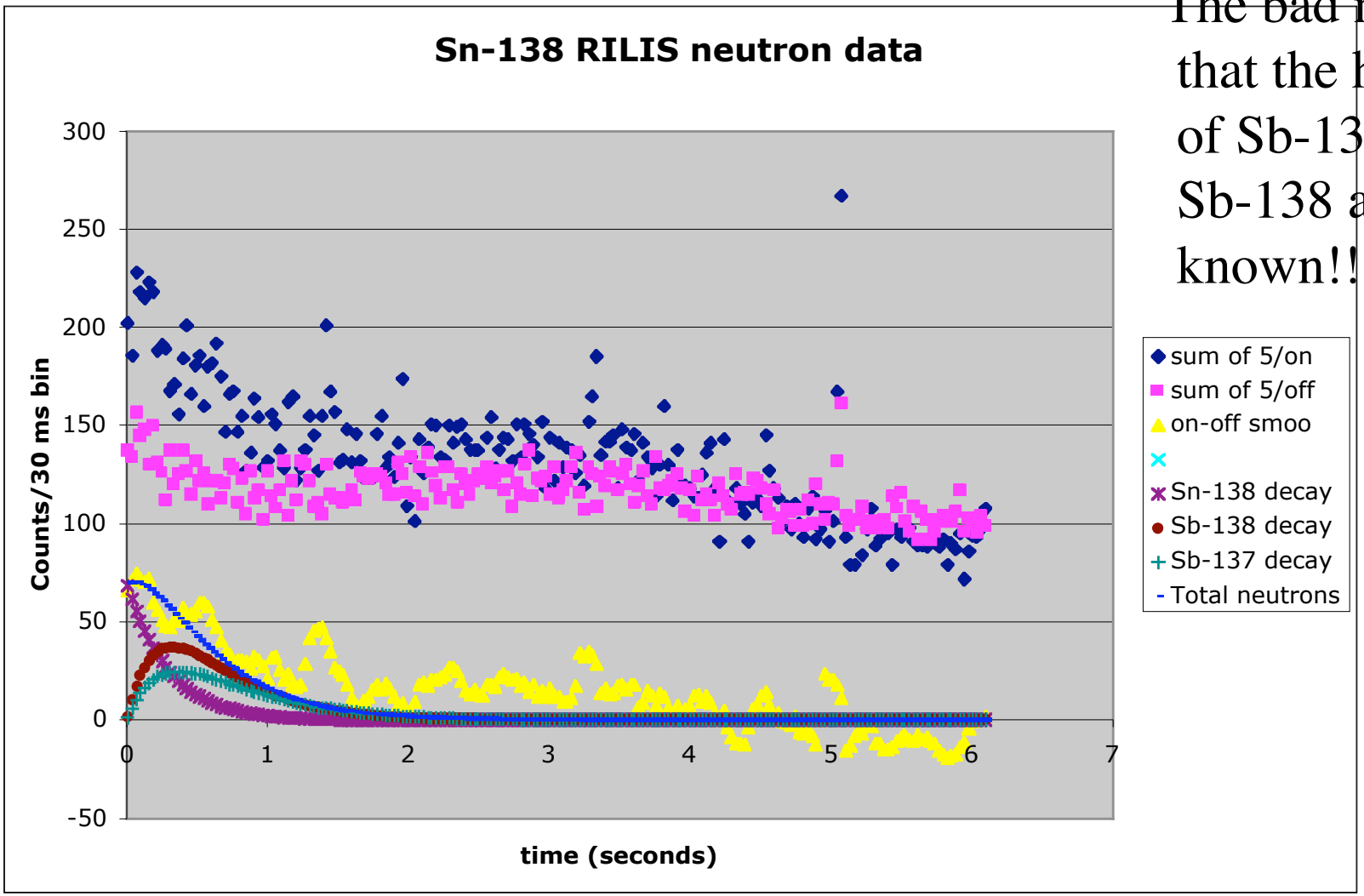


Institut für Kernchemie JOHANNES GUTENBERG UNIVERSITÄT MAINZ





We now have excellent data for the delayed-neutron time curve for the decay of a relatively pure source of Sn-137. The weakness in our analysis that I will discuss later comes from the absence of good data for the growth and decay of the daughter Sb-137.



The bad news is that the half-lives of Sb-137 and Sb-138 are not known!!!!!

The good news is that we ARE able to see ^{138}Sn decay. But, the background is large. The laser-on--laser off difference is about less than 20%.

Values in blue are from 2000, green 2000, improved in 2002, red, new in 2002.

A	133	134	135	136	137	138	139	140
T_{meas} (s)	1.44	1.12	530(20)	275(25)	**185(35)**	**200(80)**		
Pn(%)	2.9(2)	13(1)	21(5)	30(5)	**50(20)**	**50(20)**		
Q_M (MeV)	8.0	7.1	9.4	8.2	10.5	8.4	10.9	9.5
Q_{Audi}	7.6	7.2	8.6	8.0	9.7	8.9	10.7	9.8
$T_{M(GT)}$ (ms)	10.3 s	3.5 s	3000	950	800	480	390	120
T_{Hilf} (ms)			731	189	110	49	28	16
T_{Groote} (ms)			312	493	327	116	77	37
T_{ff+GT} (ms)	[1996]		300	209	186	162	62	57
T_{ff+GT} (ms)	[this work]		400	600	120	200	80	100

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

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. [ii]

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[i] P. Moeller, J. R. Nix, and K.-L. Kratz, Atomic and Nuclear Data Tables **66** (1997) 131.
[ii] A. Staudt *et al.*, Atomic Data and Nuclear Data Tables, **44**, (1990) 79.

	Counts/PSB pulse in the neutron detector					nuclei produced
	Laser on	Laser off	**net**	60% det	85% trans	Pn corr.
Sn-136	875.3	4.9	**870.4**	1451	1707	**3000**
Sn-137	39.0	6.8	**32.1**	54	63	**100**
Sn-138	9.6	8.4	**1.2**	2	2	**2**

The background at A = 138 is NOT large, the production is just quite small.

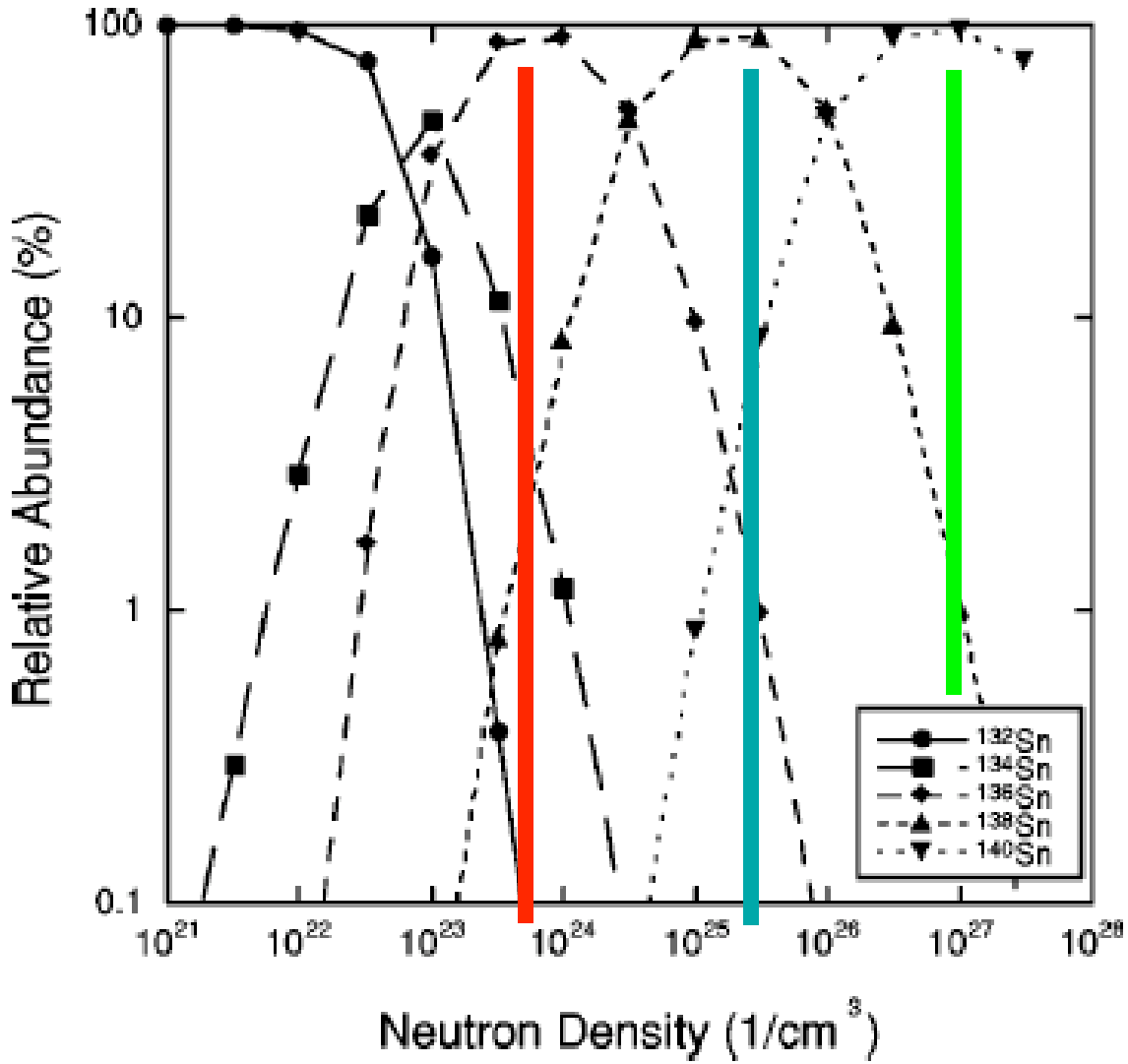


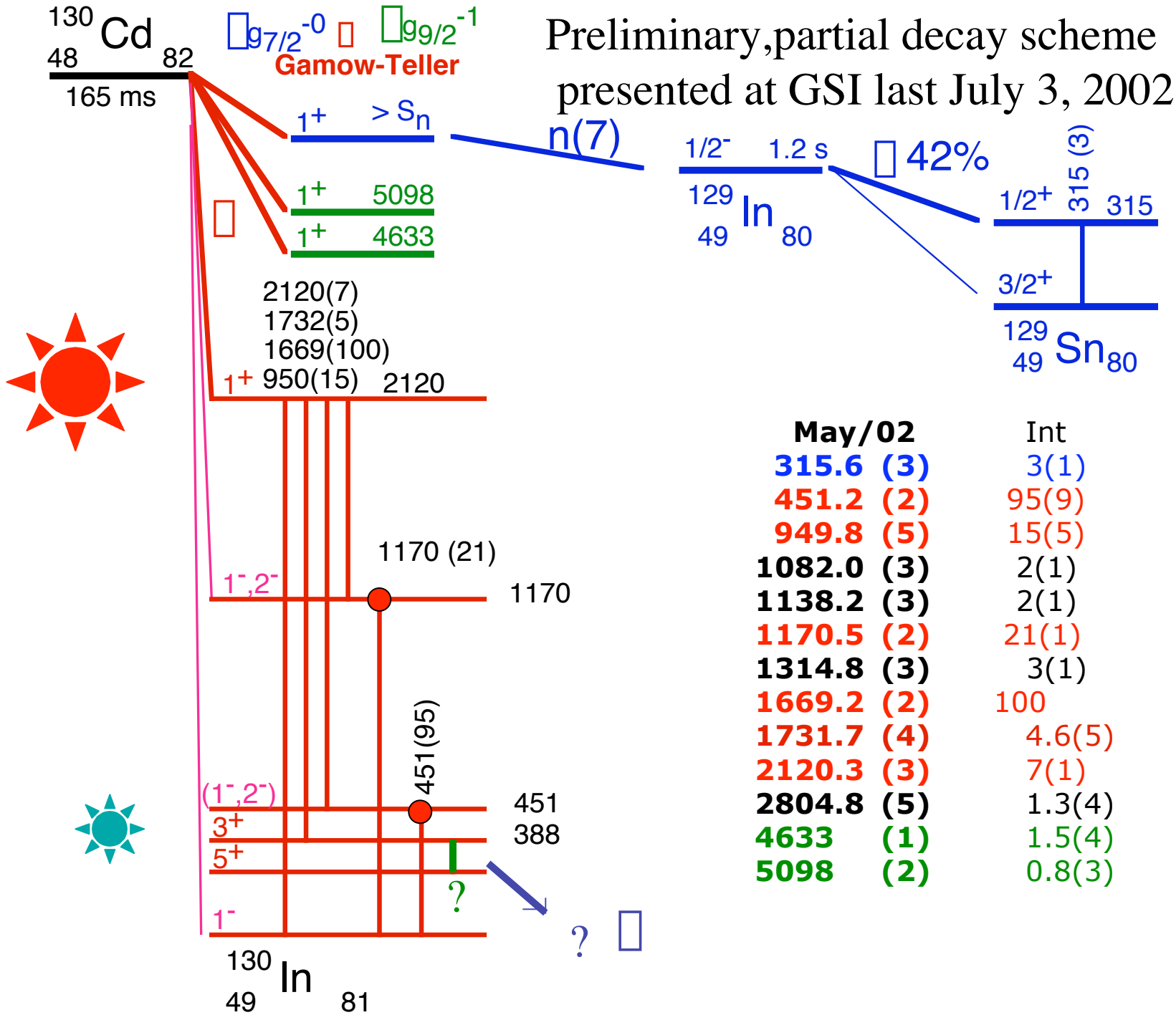
FIG. 11. Relative isotopic *r*-process abundances of Sn isotopes under freeze-out conditions ($T_9 = 1.35$) as a function of neutron density. For details, see text.

The A = 130 peak, Sn-136.

The A = 190 peak, Sn-138.

Th and U nuclides, Sn-140.

Preliminary,partial decay scheme presented at GSI last July 3, 2002.



May/02		Int
315.6	(3)	3(1)
451.2	(2)	95(9)
949.8	(5)	15(5)
1082.0	(3)	2(1)
1138.2	(3)	2(1)
1170.5	(2)	21(1)
1314.8	(3)	3(1)
1669.2	(2)	100
1731.7	(4)	4.6(5)
2120.3	(3)	7(1)
2804.8	(5)	1.3(4)
4633	(1)	1.5(4)
5098	(2)	0.8(3)

The two main features in the In-130 level scheme as known at that time were the low energy for the 1+ level shown at 2120 keV, but expected near 1400 keV, and the possible 3+ level at 388 keV. At that point we had not yet identified the 388-keV transition as a part of a large peak at 390 keV coming from In-130 decay.

In a subsequent experiment at GSI, the isomeric transition in In-130 was observed, as was a suspected transition in In-128.

With the positions of both the 1+ and 3+ levels established, it is then possible to follow the evolution of that energy difference as neutrons are added to the nucleus approaching N = 82.

The transitions underlined in green were observed in MSU1015.

Probing neutron-rich In and Cd nuclei with isomer spectroscopy

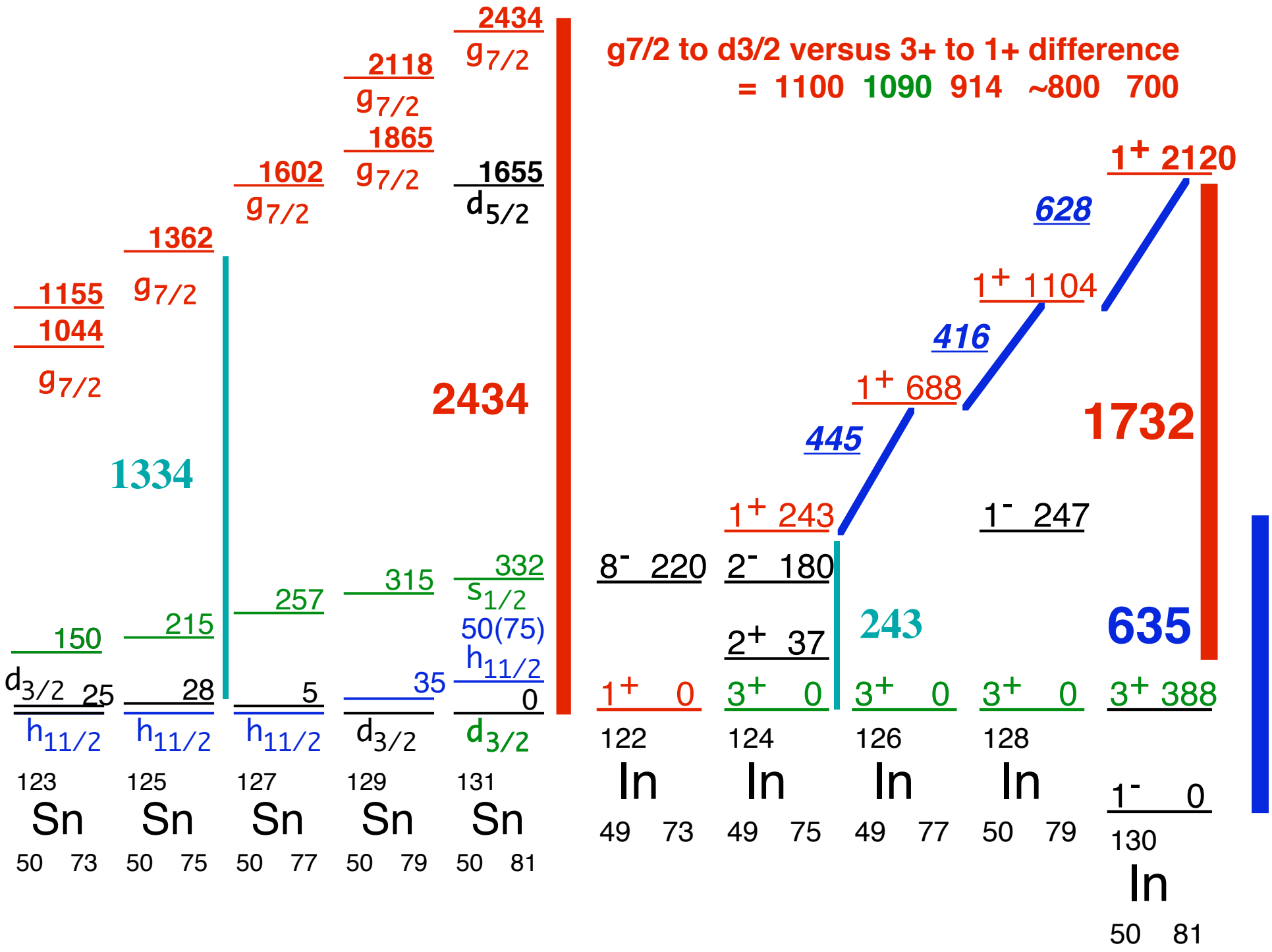
M. Hellström[a,b], M.N. Mineva[b], A. Blazhev[a,c], H.J. Boardman[d], J. Ekman[b], J. Gerl[a], K. Gladnishki[c,e], H. Grawe[a], R. Page[d], Zs. Podolyák[e] and D. Rudolph[b] for the GSI-FRS-Isomer collaboration

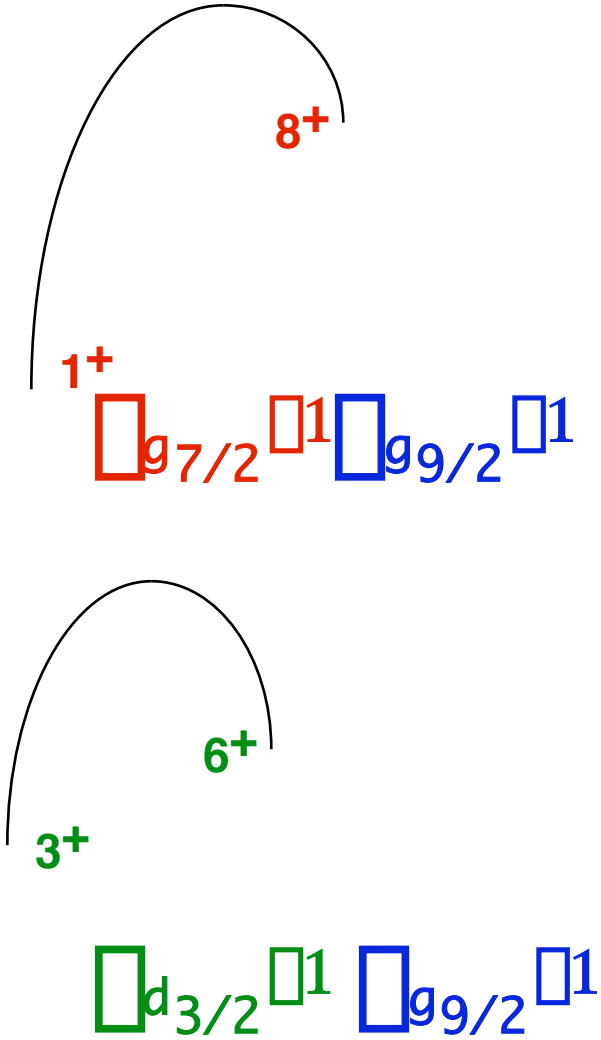
Table 1: Properties of isomers observed in the present study.

Isotope	I^π	Observed delayed γ-rays* [keV]	Half-life*,† (μs) This work	Half-life*,† (μs) Previous
^{125}Cd	$(29/2^+)$	486, 665, **720, 743**	14(2)	
^{127}Cd	?	**820**	1 - 10	
^{126}In	(1^-)	201, **244**, 614, 865	29(2)	
^{127}In	?	**221, 233**	<0.5 and 13(1)	
^{128}In	(1^-)	**248**, 323	175(90)	>10 [4]
^{129}In	$(17/2^-)$	**332, 358**, 994, 1352	11(1)	2.0(5) [5]
^{130}In	?	**389**	1 - 10	
^{129}Sn	$19/2^+$	**382**, 570, 1136, 1324	3.9(1)	3.6(2) [5]
^{130}Sn	10^+	97, **391**	1.5(1)	1.61(15) [6]

* Values are preliminary and may change as the analysis progresses.

† From fitting decay time distributions of the γ-rays indicated in bold type.


g7/2 to d3/2 versus 3+ to 1+ difference
= 1100 1090 914 ~800 700
2434
g7/2
2118
g7/2
1865
g7/2
1655
d5/2
1602
g7/2
1362
g7/2
1155
1044
g7/2
2434
1334
332
s1/2
315
257
215
150
50(75)
h11/2
35
28
25
5
0
d3/2
h11/2
h11/2
h11/2
d3/2
d3/2
123 Sn 50 73
125 Sn 50 75
127 Sn 50 77
129 Sn 50 79
131 Sn 50 81
1+ 2120
628
1+ 1104
416
1+ 688
445
1+ 243
1732
1- 247
8- 220
2- 180
2+ 37
243
635
1+ 0
3+ 0
3+ 0
3+ 0
3+ 388
122 In 49 73
124 In 49 75
126 In 49 77
128 In 50 79
1- 0
130 In 50 81



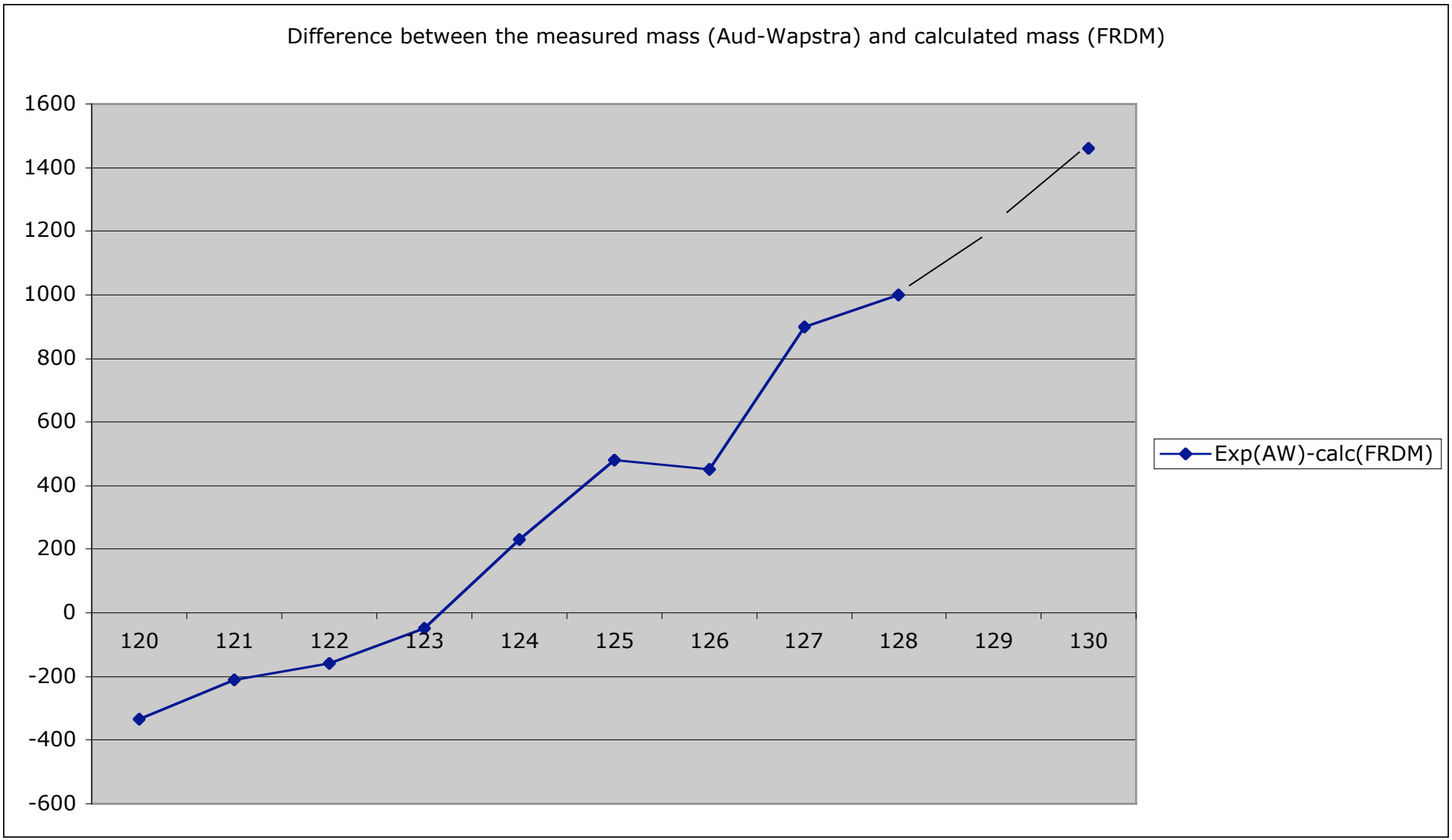
Alex Brown's OXBASH separation for the 1^+ and 3+ is only 910 keV, which is about half of the observed 1732-keV difference.

As beta decay to this 1^+ level is the main driving force for r-process waiting-pont nuclides, this high energy for the 1^+ level implies **LONGER** half-lives for N = 82 r-process isotones.

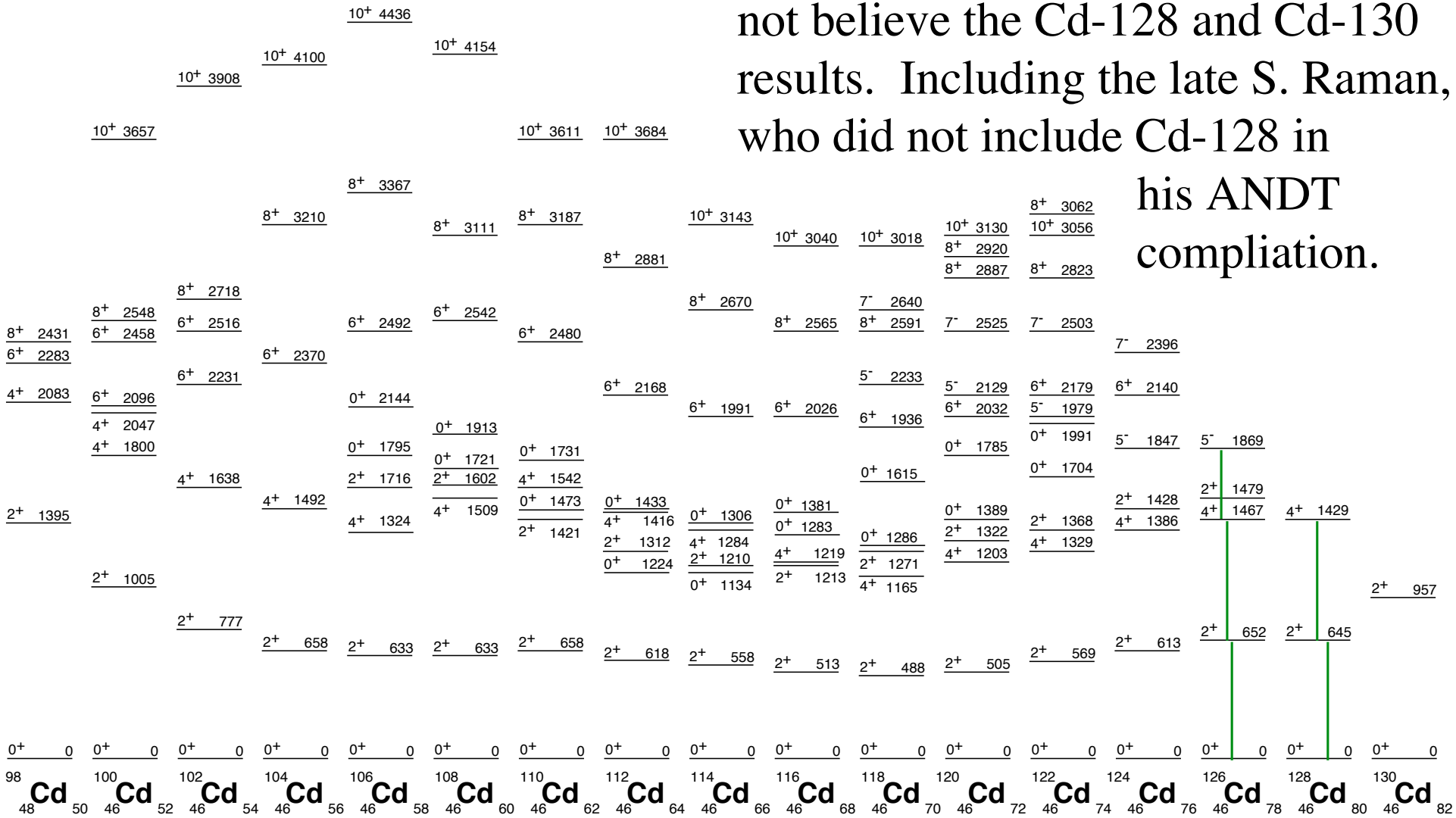
As E-beta for Cd-130 decay is about 6 MeV, a 15% lower energy would means a half-life that is twice as long.

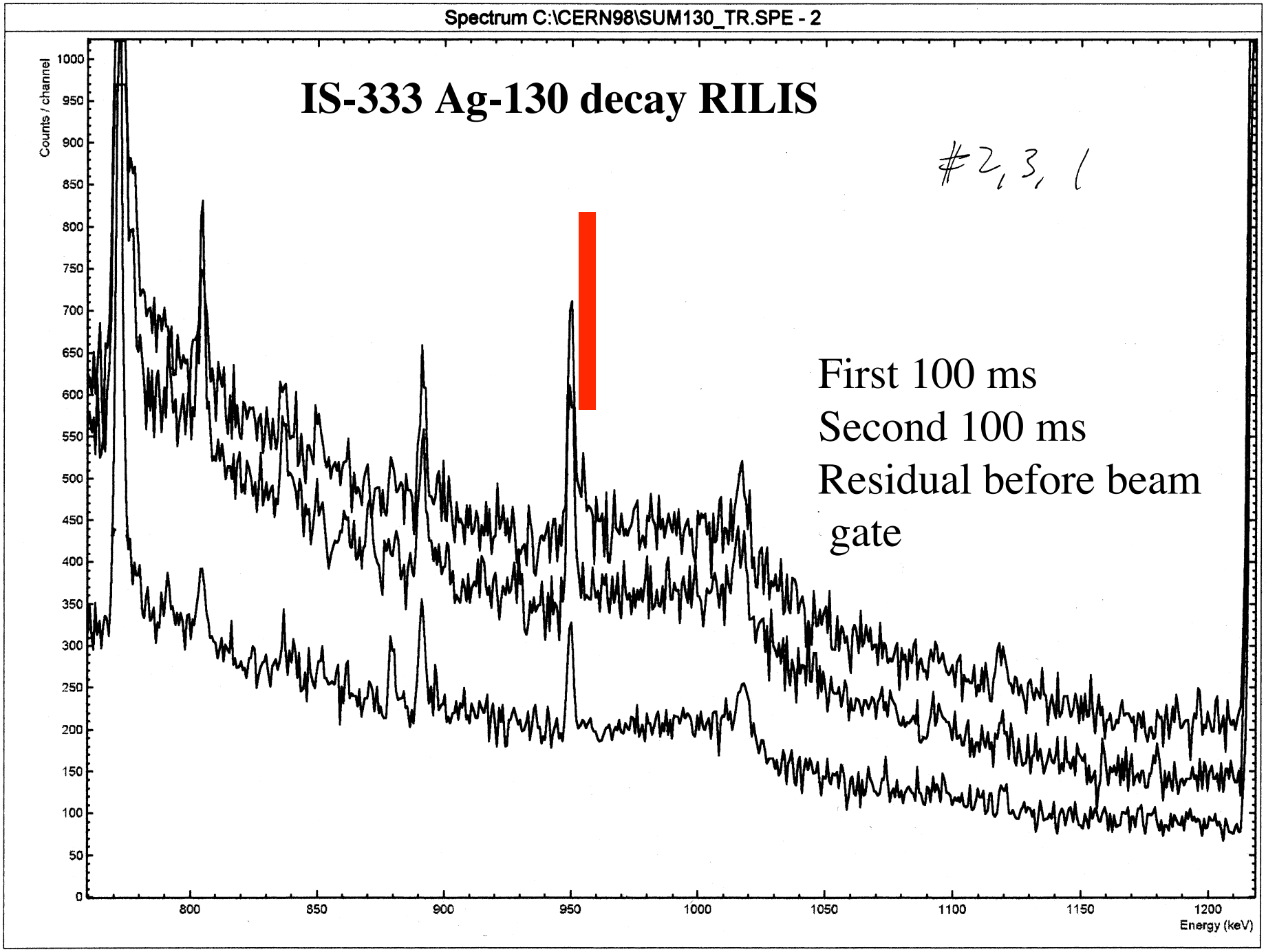
What saves the day here is that, along with the higher energy for the 1^+ level, the Q_{β} also turns out to be about 1 MeV higher than expected by many mass models. Two wrongs can, sometimes, still get it right.

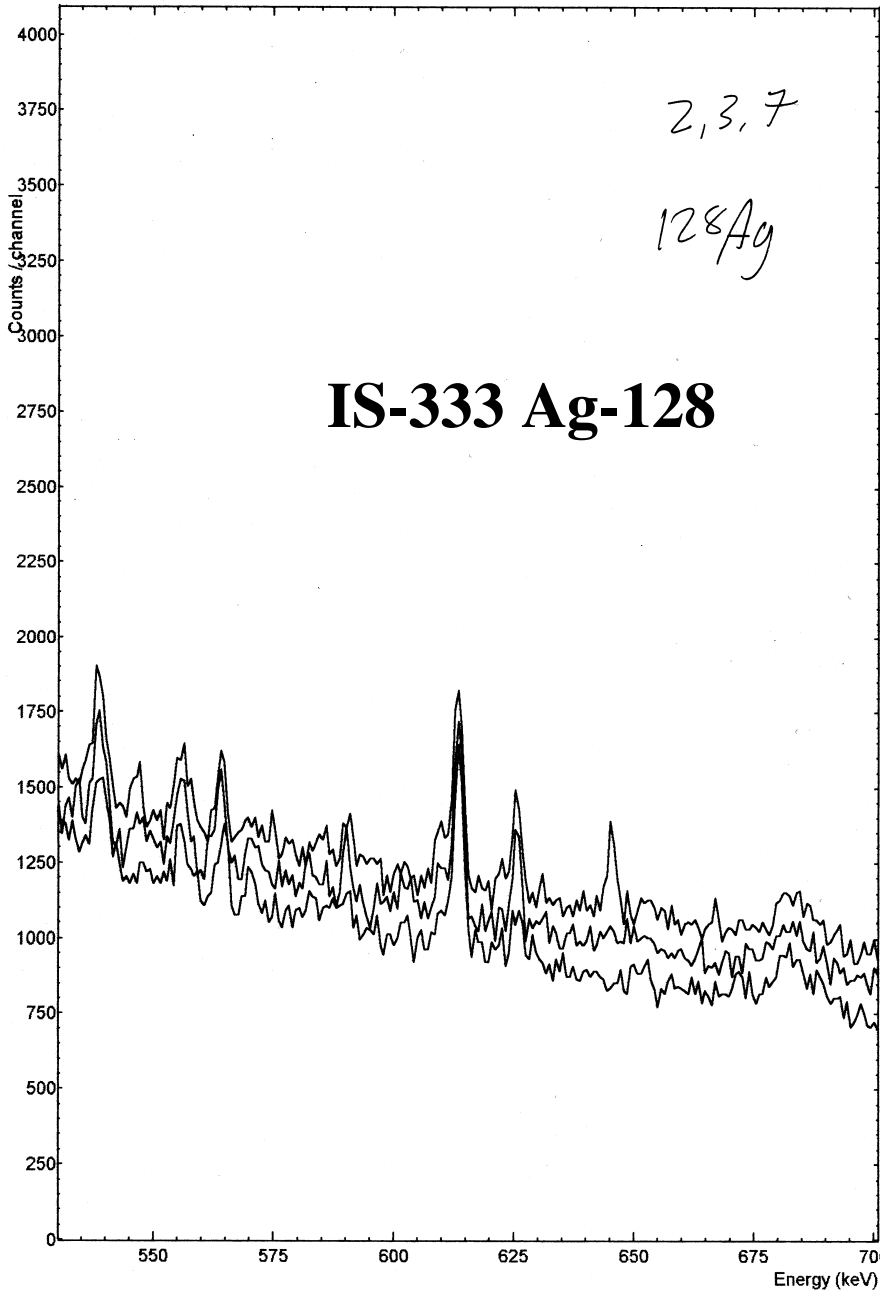
This graph incorporates the new mass for Cd-130 (Dillmann et al.) and shows the strong drift of the higher observed masses (lower binding energy) for the heavier Cd nuclides, consistent with a weakened interaction. Note that it starts above Cd-124 (N = 76 N/Z = 1.58).

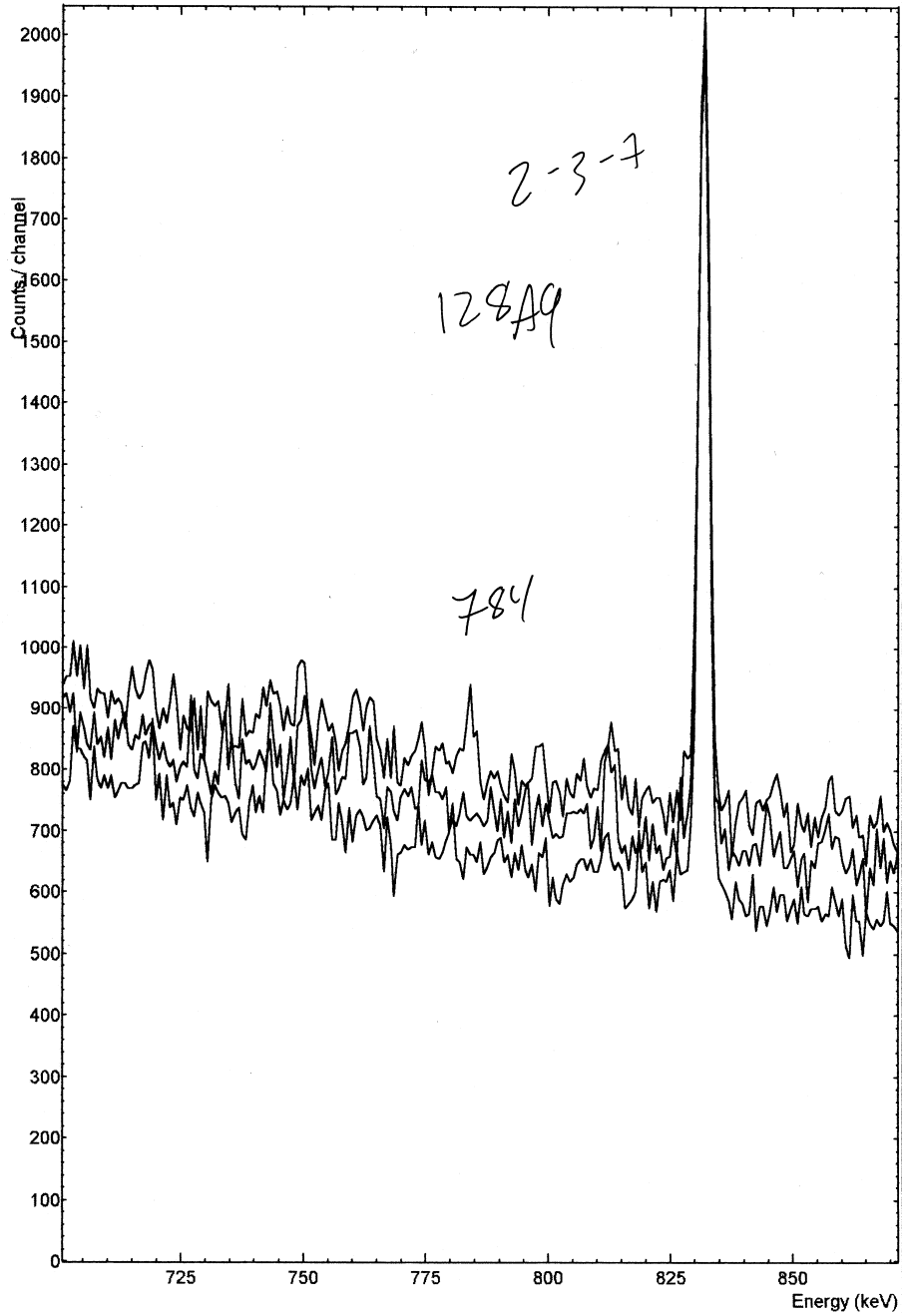


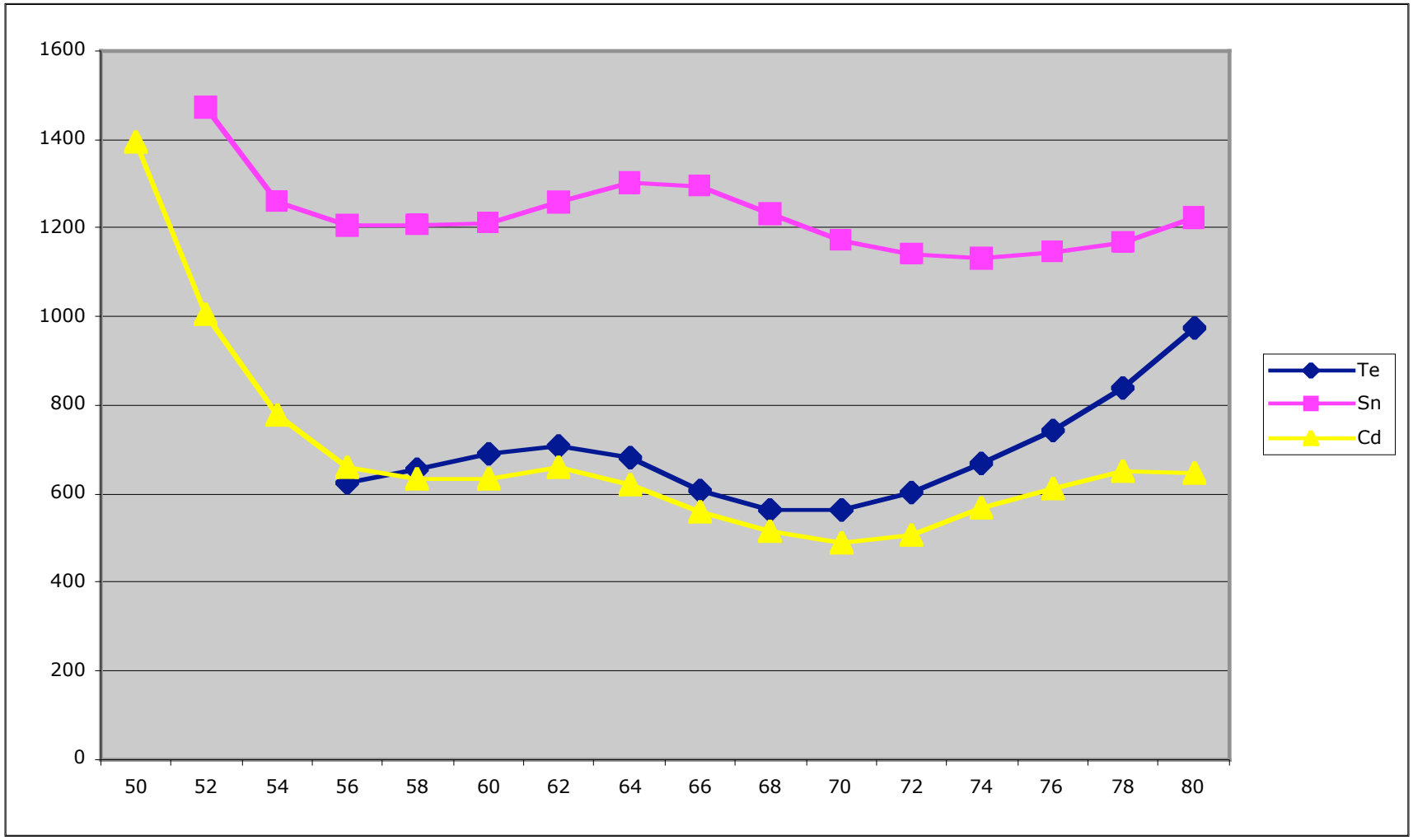
There are people out there who do not believe the Cd-128 and Cd-130 results. Including the late S. Raman, who did not include Cd-128 in his ANDT compliation.




Spectrum C:\CERN98\SUM130_TR.SPE - 2
IS-333 Ag-130 decay RILIS
#2, 3, 1
First 100 ms
Second 100 ms
Residual before beam gate
Counts / channel
Energy (keV)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
800
850
900
950
1000
1050
1100
1150
1200


2,3,7
128Ag
IS-333 Ag-128
Counts / channel
Energy (keV)


2-3-7
128Ag
784
Counts / channel
Energy (keV)



One of the reasons for disbelieving the rather sparse data for the levels in Cd-128 is their anomalous behavior as N = 82 is approached.

Given the skepticism about the structure for Cd-128 that has been presented, and to also provide some more insight into structure of neutron-rich nuclides, I will show some data from another source.

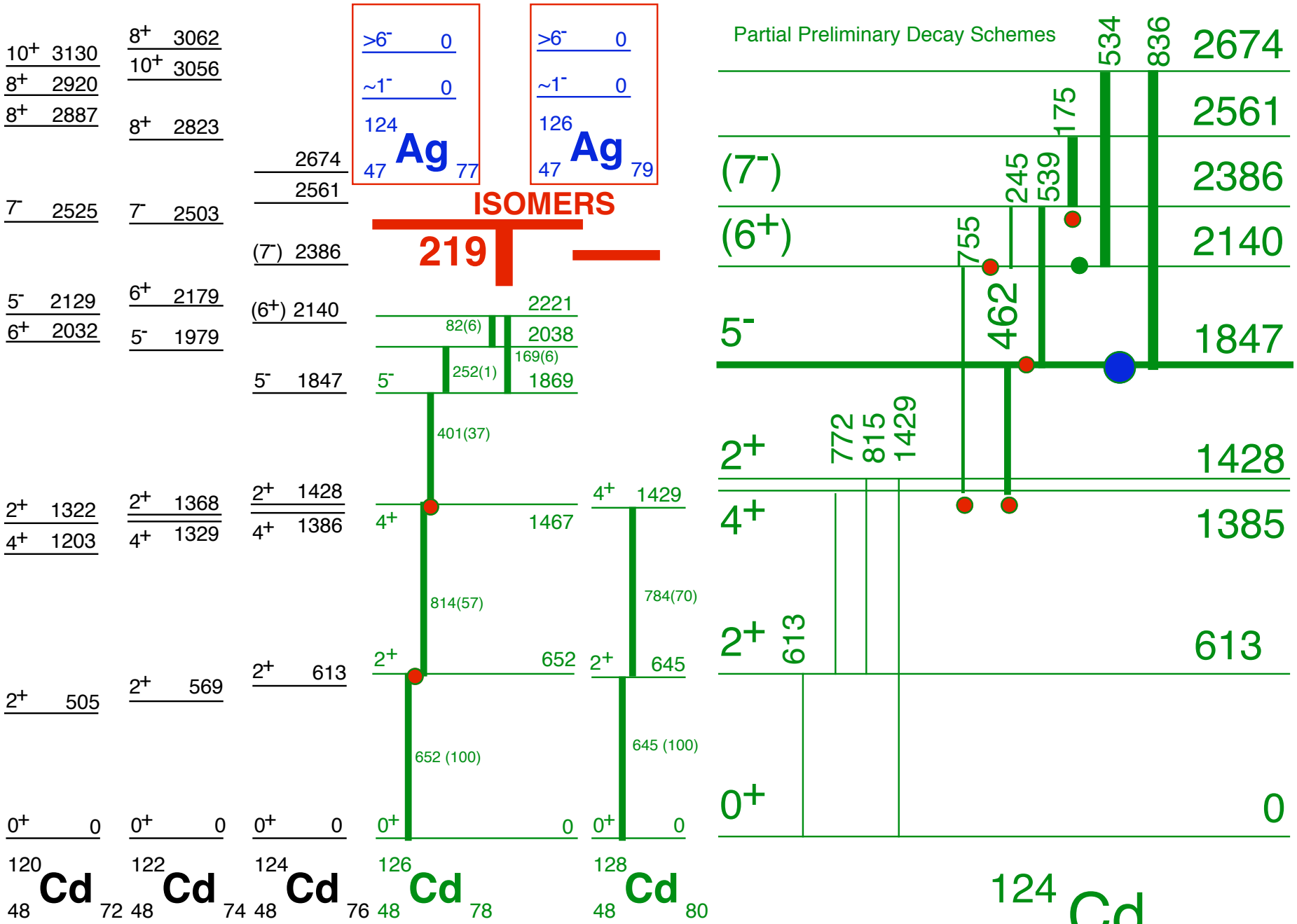
Data from the fantastic beta-gamma counting system at MSU built by the Mantica group and used for experiment MSU 1015 (2003).

Session DF - Nuclear Structure: 94 $\leq$ A < 160.
ORAL session, Friday afternoon, October 31
Canyon B, TM

[DF.006] Level structures of ^120Pd, ^126Cd, and ^128Cd from beta decay and isomeric decay

W. B. Walters, N. Hoteling, J. Rikovska, J. Shergur (University of Maryland), P. F. Mantica, B. E. Tomlin, B. A. Brown, A. D. Davies, A. Estrada, P. Hosmer, S. N. Liddick, T. J. Mertzimekis, F. Montes, A. C. Morton, W. F. Mueller, M. Ouellette, E. Pellegrini, P. Santi, H. Schatz, A. Stolz (NSCL, Michigan State University), D. Seweryniak (Argonne National Laboratory)

Nuclides in the 114<A<129 mass region were studied at the NSCL following fragmentation of a 120-MeV/A ^136Xe beam. Time-correlated gamma-ray singles and coincidence spectra following both beta decay and isomeric gamma decay were collected as a function of Z and A for the implanted fragments using the MSU beta counting system and 12 SeGA Ge detectors. The first 2^+ level in ^120Pd was identified at 438 keV following beta decay of ^120Rh. Previously reported gamma rays were observed within 20 microseconds of implantation of ^128Cd and ^126Cd fragments. In addition, a new gamma ray was observed at 219 keV in the decay of the ^126Cd isomer. The structures of the even-even Pd and Cd nuclides will be discussed in the framework of both the Interacting Boson Model and the Shell Model. This work was supported by the U. S. NSF and U. S. DOE.


Partial Preliminary Decay Schemes
ISOMERS
219
>6- 0
~1- 0
124 47 Ag 77
>6- 0
~1- 0
126 47 Ag 79
10+ 3130
8+ 2920
8+ 2887
8+ 3062
10+ 3056
8+ 2823
2674
2561
7- 2525
7- 2503
(7-) 2386
5- 2129
6+ 2179
(6+) 2140
6+ 2032
5- 1979
5- 1847
2+ 1322
2+ 1368
2+ 1428
4+ 1203
4+ 1329
4+ 1386
2+ 505
2+ 569
2+ 613
0+ 0
0+ 0
0+ 0
82(6)
252(1)
169(6)
401(37)
814(57)
652 (100)
784(70)
645 (100)
2221
2038
1869
1467
652
0
4+ 1429
2+ 645
0+ 0
120 48 Cd 72
122 48 Cd 74
124 48 Cd 76
126 48 Cd 78
128 48 Cd 80
462/613 = 0.46 center
462/613 = 0.72 edge
401/650 = 0.52 center
401/650 = 0.74 edge
534
836
2674
175
2561
245
539
(7-)
2386
755
(6+)
2140
462
5-
1847
772
815
1429
2+
1428
4+
1385
613
2+
613
0+
0
124 48 Cd 76

$\square g_{9/2}^{-5}$ ↑ $\square h_{11/2}^{+1}$ ↑ $\square h_{11/2}^{+6}$ ↓↑ $\square g_{7/2}^{+8}$ 8^- $\square p_{1/2}$ $\square d_{3/2}^{+1}$ 1^-.....

$\square$ = -57 $^{120}_{45}$Rh$_{75}$

$Q_\square$ = ~ 11.1 MeV

t = ????? s

t_{calc} = 130 ms

S_n = ~6.7 MeV

P_n = ~ 3%

9^- 3600 2^-

$\square g_{7/2}^{-1} \rightarrow \square g_{9/2} + \square^\square + \square$

G-T allowed branch

log ft = 4.2

log f = 5.03

log t = - 0.83 t = 148 ms

$\square g_{9/2}^{-4}$ $\square h_{11/2}^{+1}$ ↑ $\square h_{11/2}^{+6}$ $\square g_{7/2}^{+7}$ ↑

$\square g_{9/2}^{-3}$ $\square p_{1/2}$ $\square d_{3/2}^{+1}$ $\square g_{7/2}^{+7}$

8^+ 2000

6^+ 1800

4^+ 1000???

2^+ 400 or 450????

0^+ 0

$^{120}_{46}$Pd $\square$ = -68 ^{74}

$\square g_{9/2}^{-4}$ $\square h_{11/2}^{+1}$ ↑ $\square h_{11/2}^{+5}$ ↑

$\square h_{11/2} \rightarrow \square g_{9/2} + \square^\square + \square$

first forbidden branch

log ft = 5.5

log f = 5.41

log t = 0.09 t = 1.2 s

120(10) ms

NEW DATA

(4^+) 1056

618

(2^+) 912

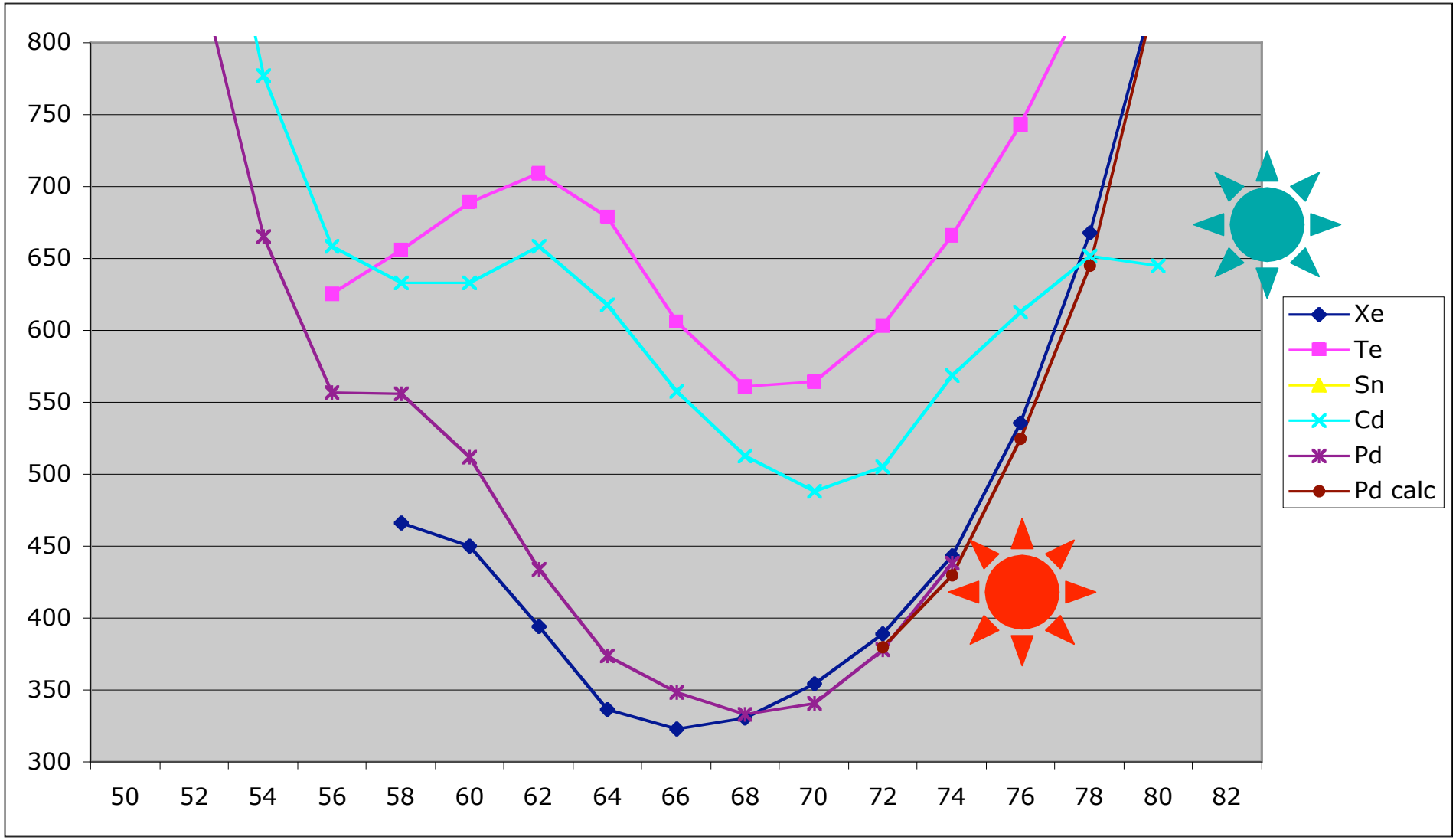
912

2^+ 438

438

0^+ 0

$^{120}_{46}$Pd $\square$ = -68 ^{74}



IBM-2 calculations of even–even Pd nuclei

Ka-Hae Kim [a], Adrian Gelberg [a,b], Takahiro Mizusaki [a], Takaharu Otsuka [a], Peter von Brentano [b]

[a] *Department of Physics, University of Tokyo, Hongo, Tokyo 113, Japan*
[b] *Institut für Kernphysik der Universität zu Köln, 50937 Cologne, Germany*

Received 1 March 1996

Nuclear Physics A 604 (1996) 163–182

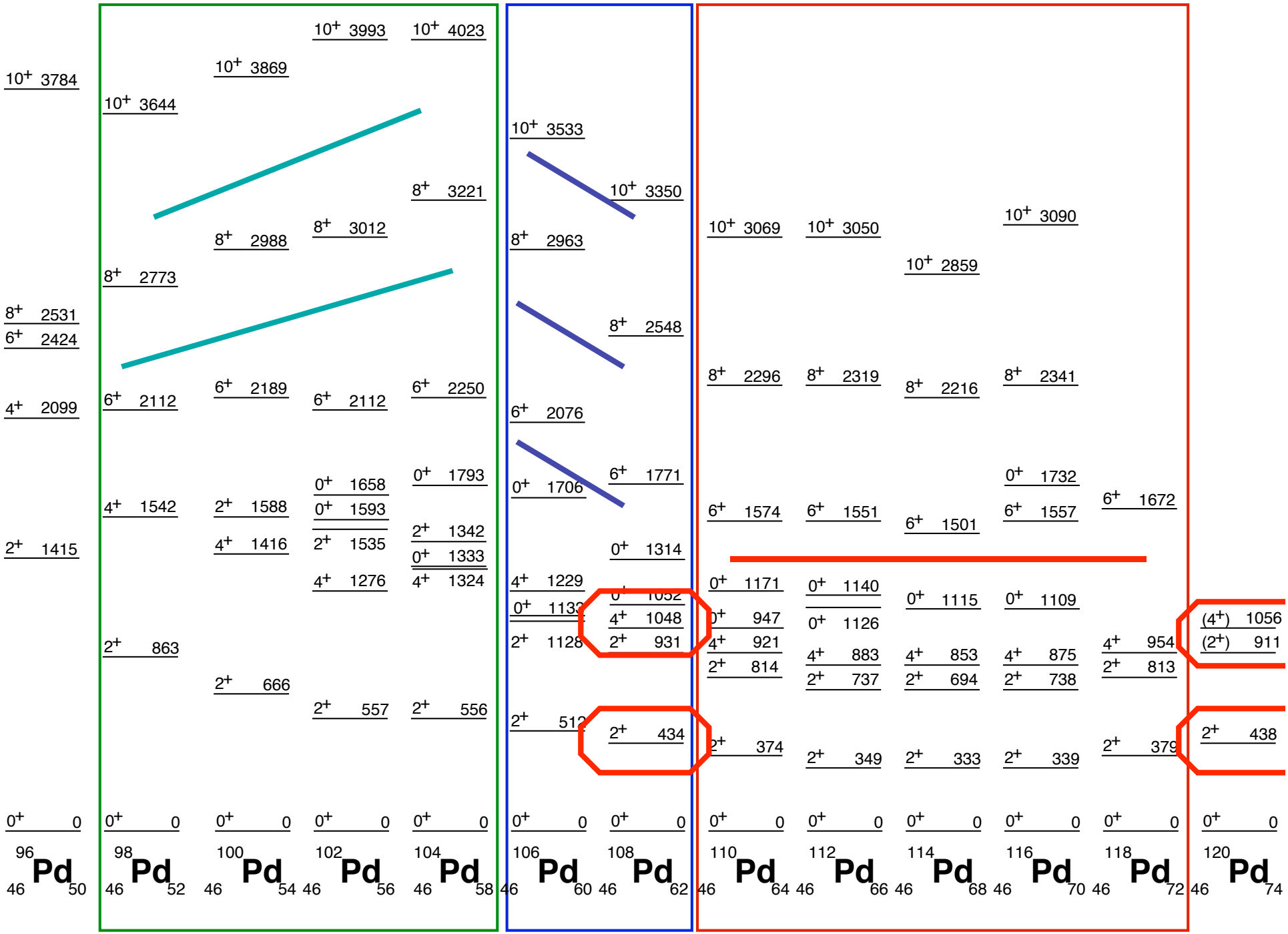
The new data from MSU experiment 1015 in which the decay of Rh-120 to Pd-120 was sought provided not only the new data for the 2+ and 4+ energies in Pd-120, but confirmation of the low 2+ energy in Cd-128.

Hence, the Cd data remain "ugly" in the sense that the 2+ energies do not rise toward the n = 82 closed shell.

In contrast, the new data for Pd-120 are found almost exactly where 1996 IBM-d calculations had predicted.

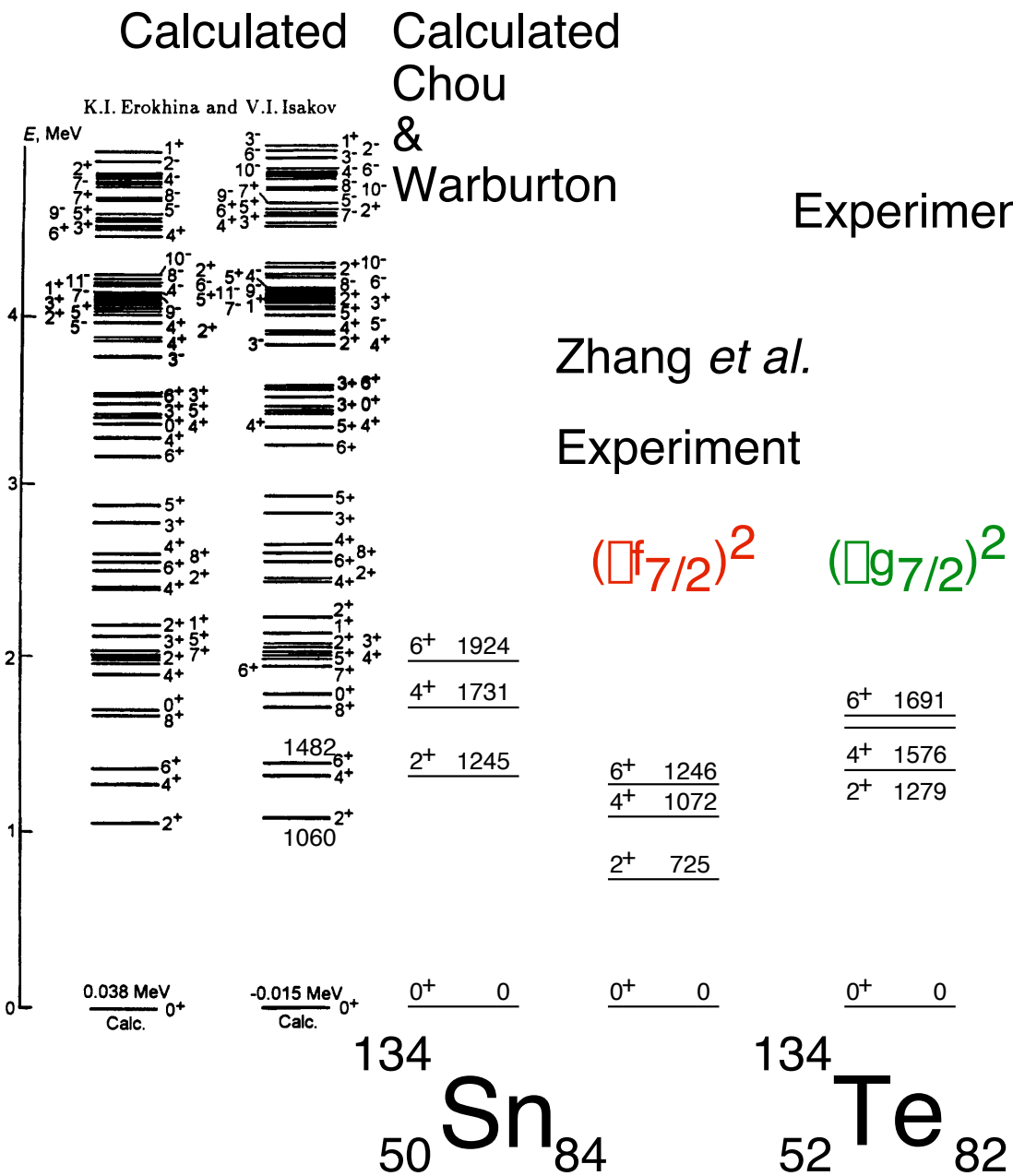
On the next slide are shown the degree to which the rather complete structures of the even-even Pd nuclides tend to mirror each other around a 2+ minimum at Pd-114(N = 68).

The levels of the Pd nuclides have been broken down into a "shell -model region caused by the N = 56 subshell, a transition region, and a symmetric collective region centered at N = 68.


10+ 3784
4+ 2099
2+ 1415
0+ 0
96 46 Pd 50
10+ 3644
8+ 2773
8+ 2531
6+ 2424
6+ 2112
4+ 1542
2+ 863
0+ 0
98 46 Pd 52
10+ 3869
8+ 2988
6+ 2189
2+ 1588
4+ 1416
2+ 666
0+ 0
100 46 Pd 54
10+ 3993
8+ 3012
6+ 2112
0+ 1658
0+ 1593
2+ 1535
4+ 1276
2+ 557
0+ 0
102 46 Pd 56
10+ 4023
8+ 3221
6+ 2250
0+ 1793
2+ 1342
0+ 1333
4+ 1324
2+ 556
0+ 0
104 46 Pd 58
10+ 3533
8+ 2963
6+ 2076
0+ 1706
4+ 1229
0+ 1133
2+ 1128
2+ 512
0+ 0
106 46 Pd 60
10+ 3350
8+ 2548
6+ 1771
0+ 1314
4+ 1048
2+ 931
2+ 434
0+ 0
108 46 Pd 62
10+ 3069
8+ 2296
6+ 1574
0+ 1171
0+ 947
4+ 921
2+ 814
2+ 374
0+ 0
110 46 Pd 64
10+ 3050
8+ 2319
6+ 1551
0+ 1140
0+ 1126
4+ 883
2+ 737
2+ 349
0+ 0
112 46 Pd 66
10+ 2859
8+ 2216
6+ 1501
0+ 1115
4+ 853
2+ 694
2+ 333
0+ 0
114 46 Pd 68
10+ 3090
8+ 2341
6+ 1557
0+ 1732
0+ 1109
4+ 875
2+ 738
2+ 339
0+ 0
116 46 Pd 70
6+ 1672
4+ 954
2+ 813
2+ 379
0+ 0
118 46 Pd 72
(4+) 1056
(2+) 911
2+ 438
0+ 0
120 46 Pd 74

I would like to conclude with a short summary of what I believe is the “case” for the weakening of the nucleon-nucleon interaction for nuclides with high N/Z where higher N/Z means over 1.6.

I would argue that the first sign of something new were the data for Sn-134, 1997, but it has been the recent new data for B(E2) values in Sn and Te found here at Oak Ridge that have made such talk more respectable.



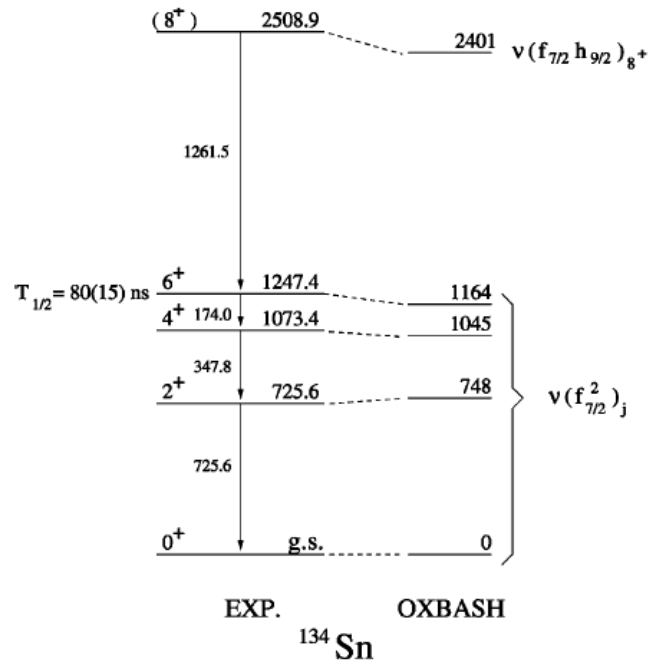


Fig. 3. The partial level scheme of ^{134}Sn obtained in the present work. The right-hand side of the figure shows calculations performed with the code OXBASH [14]

The caption does not point out that the OXBASH interactions were multiplied by 0.6!!!!!!!

Experimental and Calculated levels for ^{134}Sn.

PHYSICAL REVIEW C **66**, 054313 (2002)

Anomalous behavior of 2^+ excitations around ^{132}Sn

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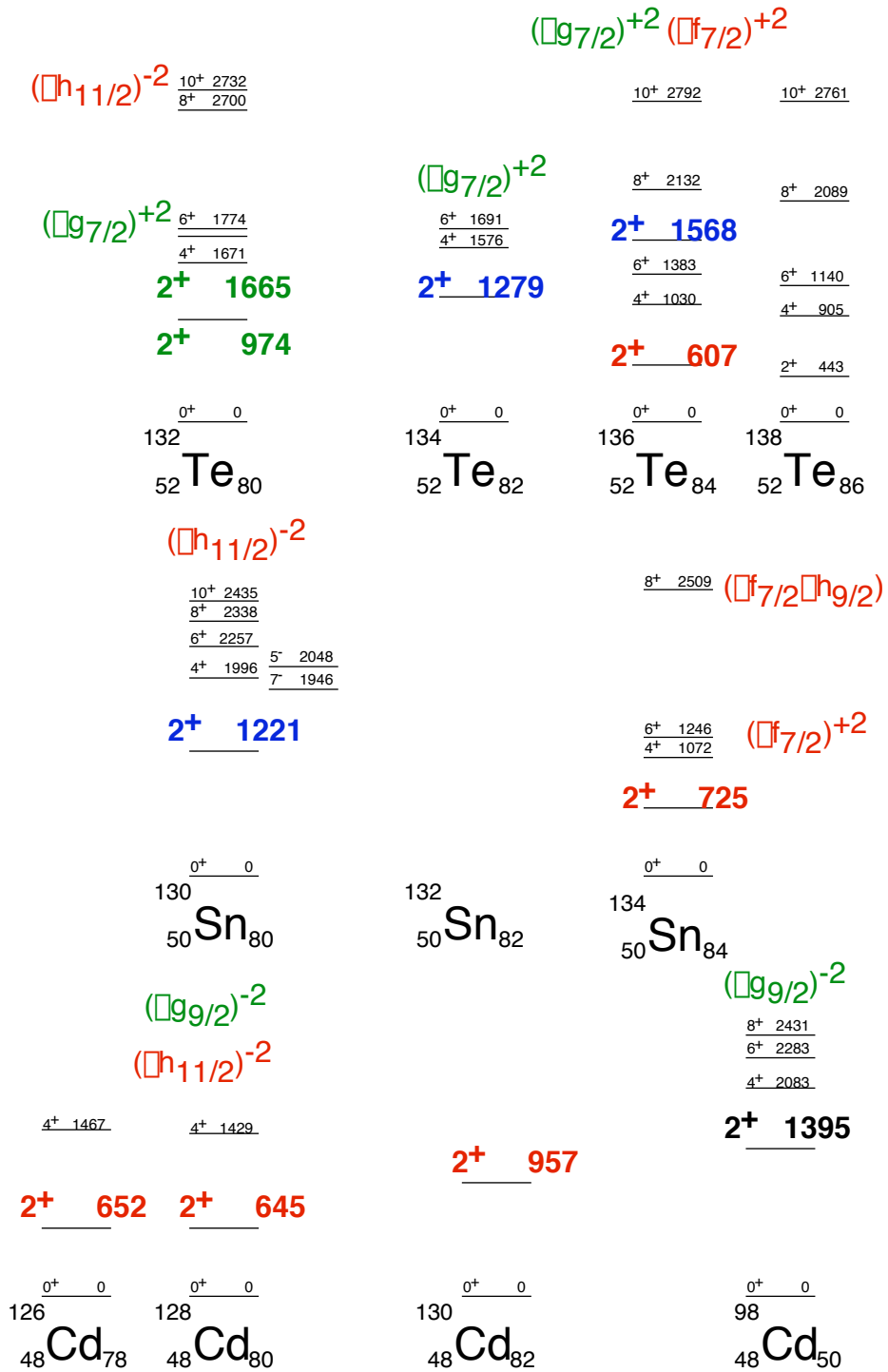
[4]*Department of Physics and Astronomy, University of North Carolina, CB 3255, Phillips Hall, Chapel Hill, North Carolina 27599*
[5]*Institute of Theoretical Physics, University of Warsaw, ulnica Hoża 69, PL-00-681 Warsaw, Poland*
[6]*Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Science, Sofia-1784, Bulgaria*
(Received 21 August 2002; published 27 November 2002)

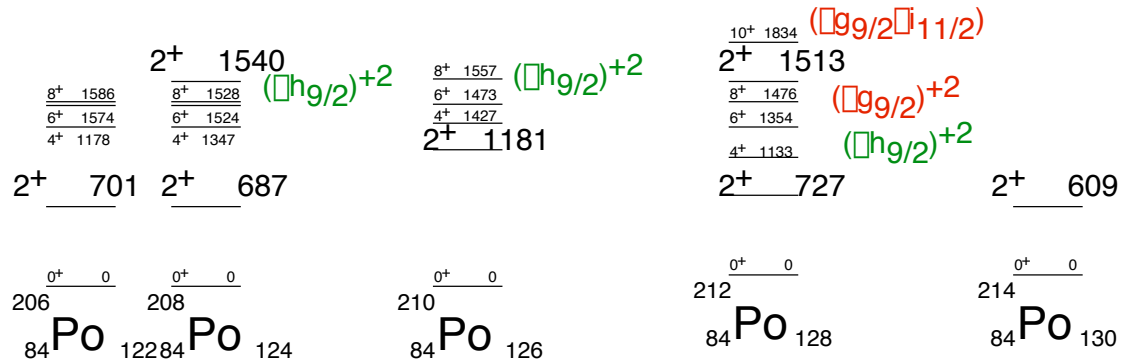
In certain neutron-rich Te isotopes, a decrease in the energy of the first excited 2^+ state is accompanied by a decrease in the $E2$ strength to that state from the ground state, contradicting simple systematics and general intuition about quadrupole collectivity. We use a separable quadrupole-plus-pairing Hamiltonian and the quasiparticle random phase approximation to calculate energies, $B(E2,0^+\rightarrow 2^+)$ strengths, and g factors for the lowest 2^+ states near ^{132}Sn ($Z\geqslant 50$). We trace the anomalous behavior in the Te isotopes to a reduced neutron pairing above the $N=82$ magic gap.

In this paper the argument is made for a reduced neutron pairing gap.

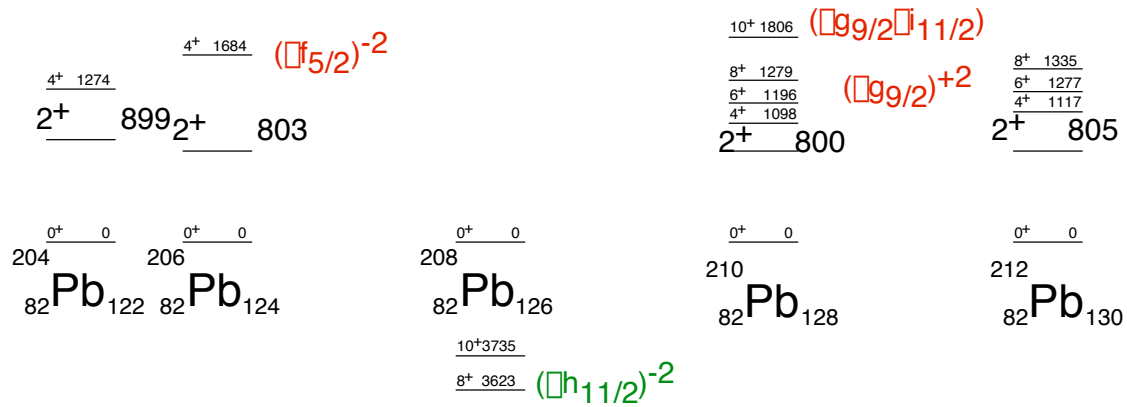
How anomalous????

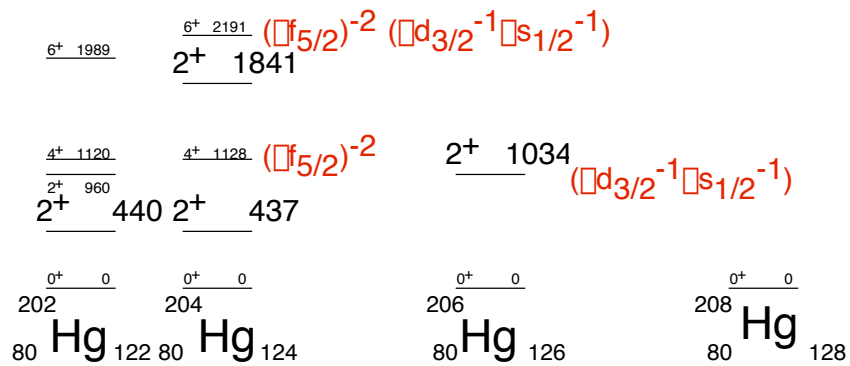


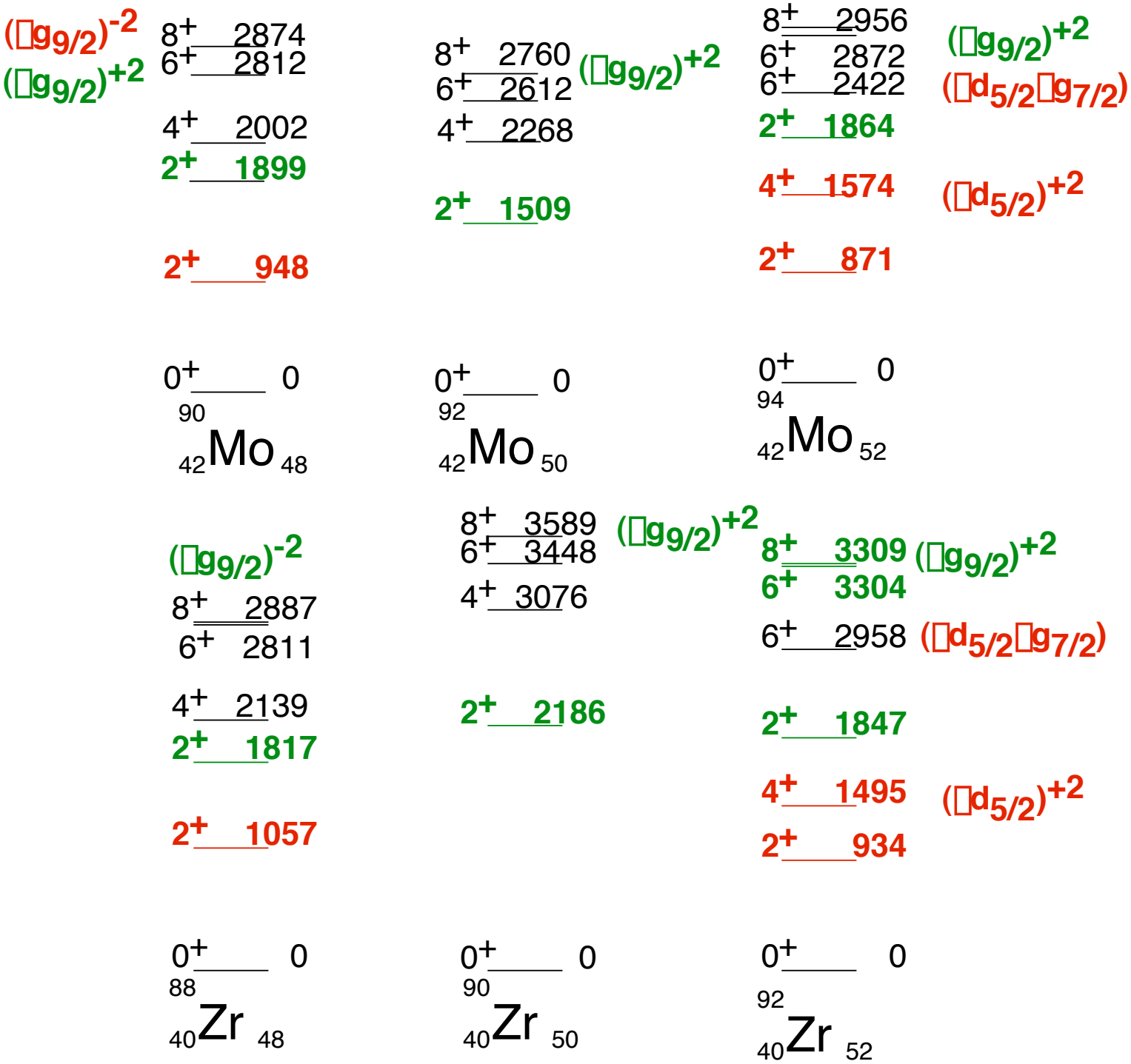
As can be seen, the 2+ levels in the Hg nuclides are also significantly lower than the adjacent closed shell nuclides.



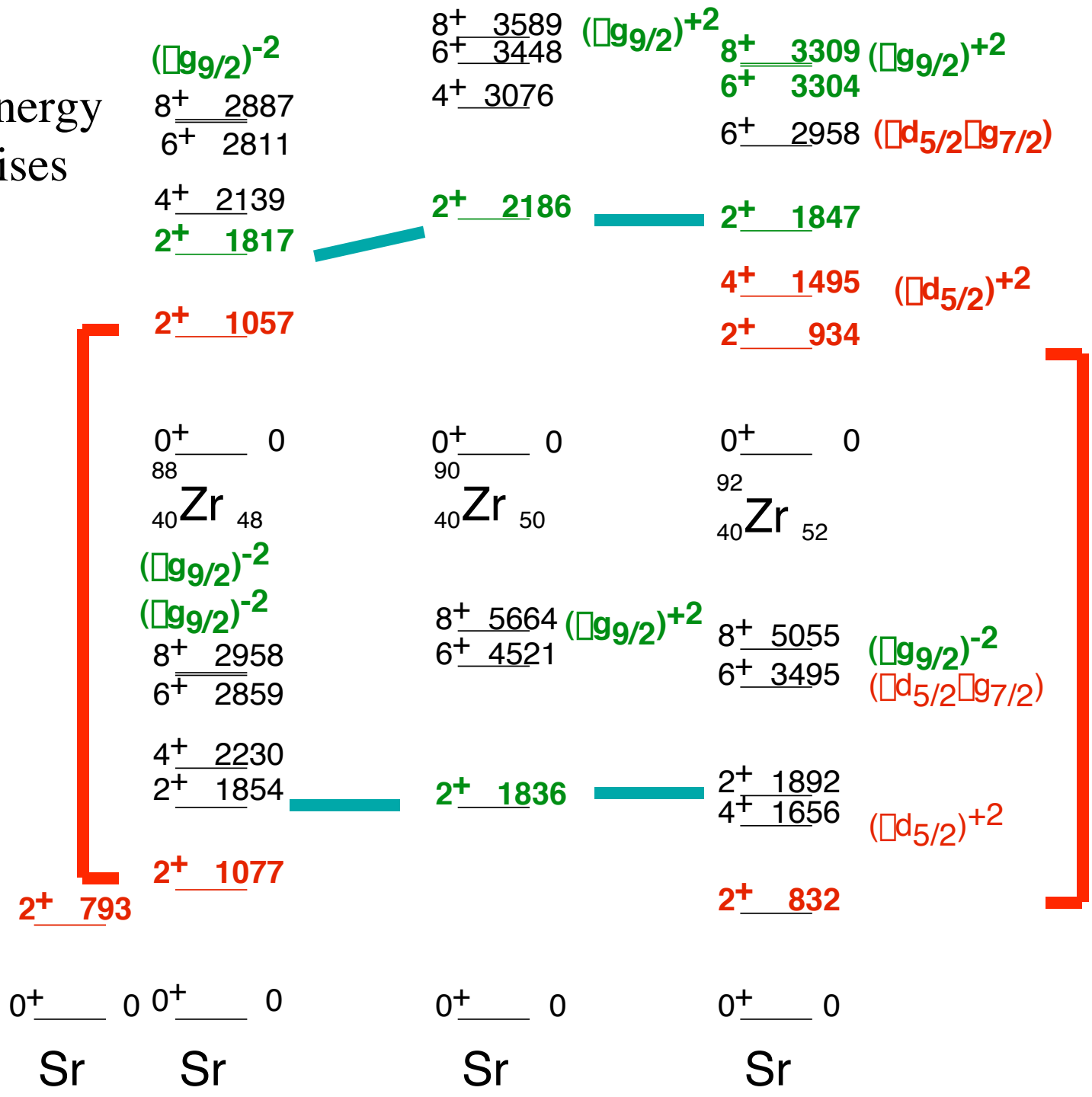
And, there is a slight drop in energy as N = 126 is approached.



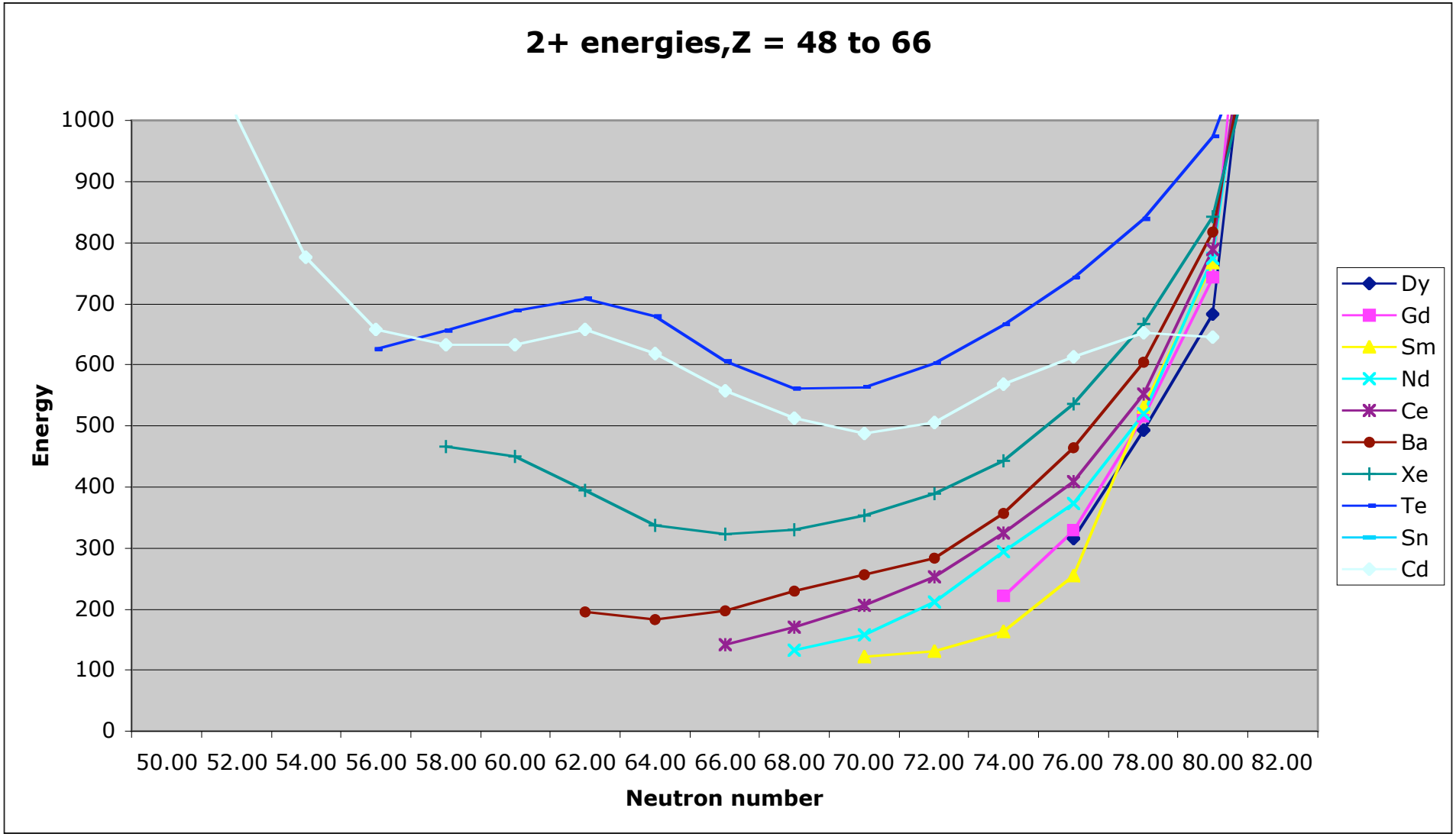



(νg9/2)-2
(νg9/2)+2
8+ 2874
6+ 2812
4+ 2002
2+ 1899
2+ 948
0+ 0
90
42Mo 48
8+ 2760
6+ 2612
(νg9/2)+2
4+ 2268
2+ 1509
0+ 0
92
42Mo 50
8+ 2956
6+ 2872
6+ 2422
(νg9/2)+2
(νd5/2νg7/2)
2+ 1864
4+ 1574
(νd5/2)+2
2+ 871
0+ 0
94
42Mo 52
(νg9/2)-2
8+ 2887
6+ 2811
4+ 2139
2+ 1817
2+ 1057
0+ 0
88
40Zr 48
8+ 3589
6+ 3448
(νg9/2)+2
4+ 3076
2+ 2186
0+ 0
90
40Zr 50
8+ 3309
(νg9/2)+2
6+ 3304
6+ 2958
(νd5/2νg7/2)
2+ 1847
4+ 1495
(νd5/2)+2
2+ 934
0+ 0
92
40Zr 52

Here, the 2+ energy in Sr clearly rises as N = 50 is approached.



The question was raised as to how 2+ energies vary as the N = 82 shell is approached. Below is the chart showing how strange the behavior of the 2+ energies in Cd are!!!



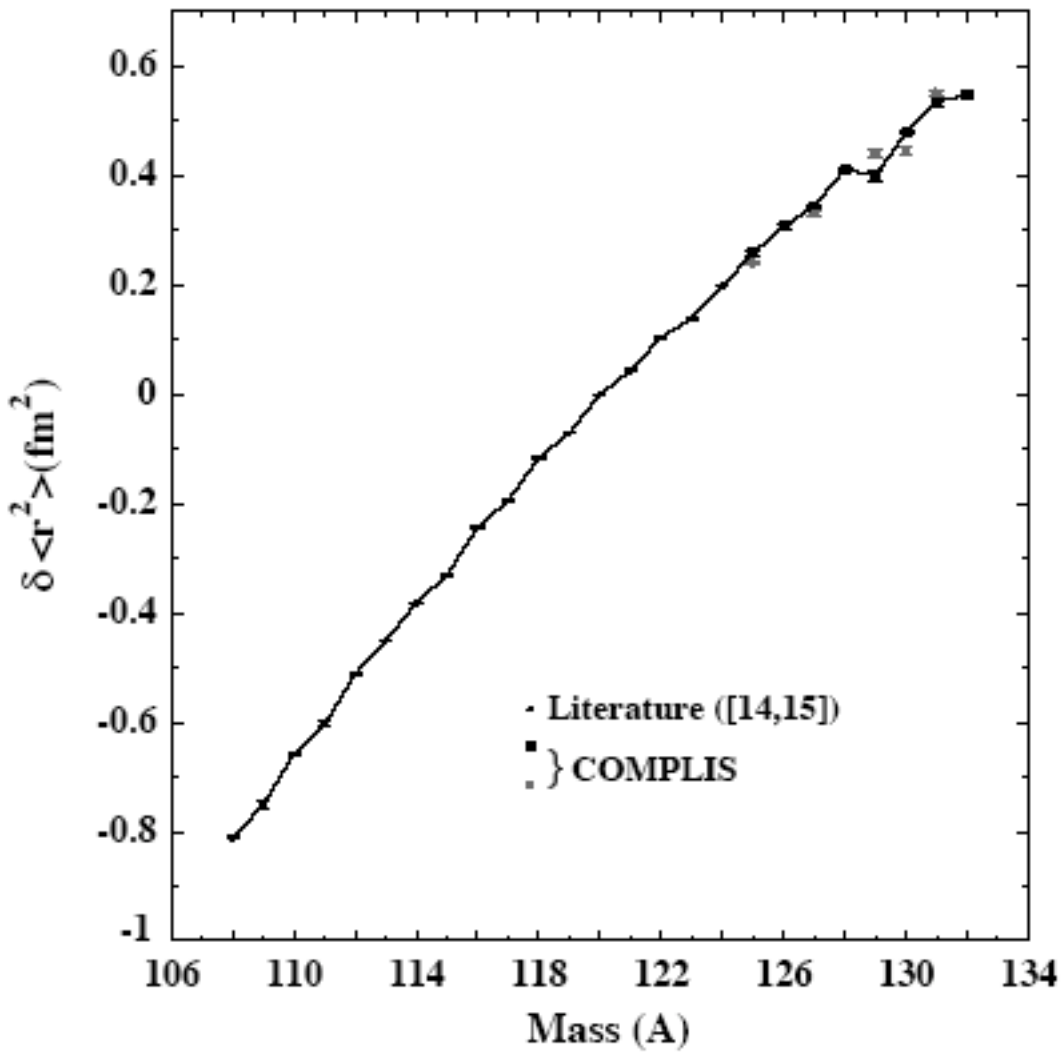
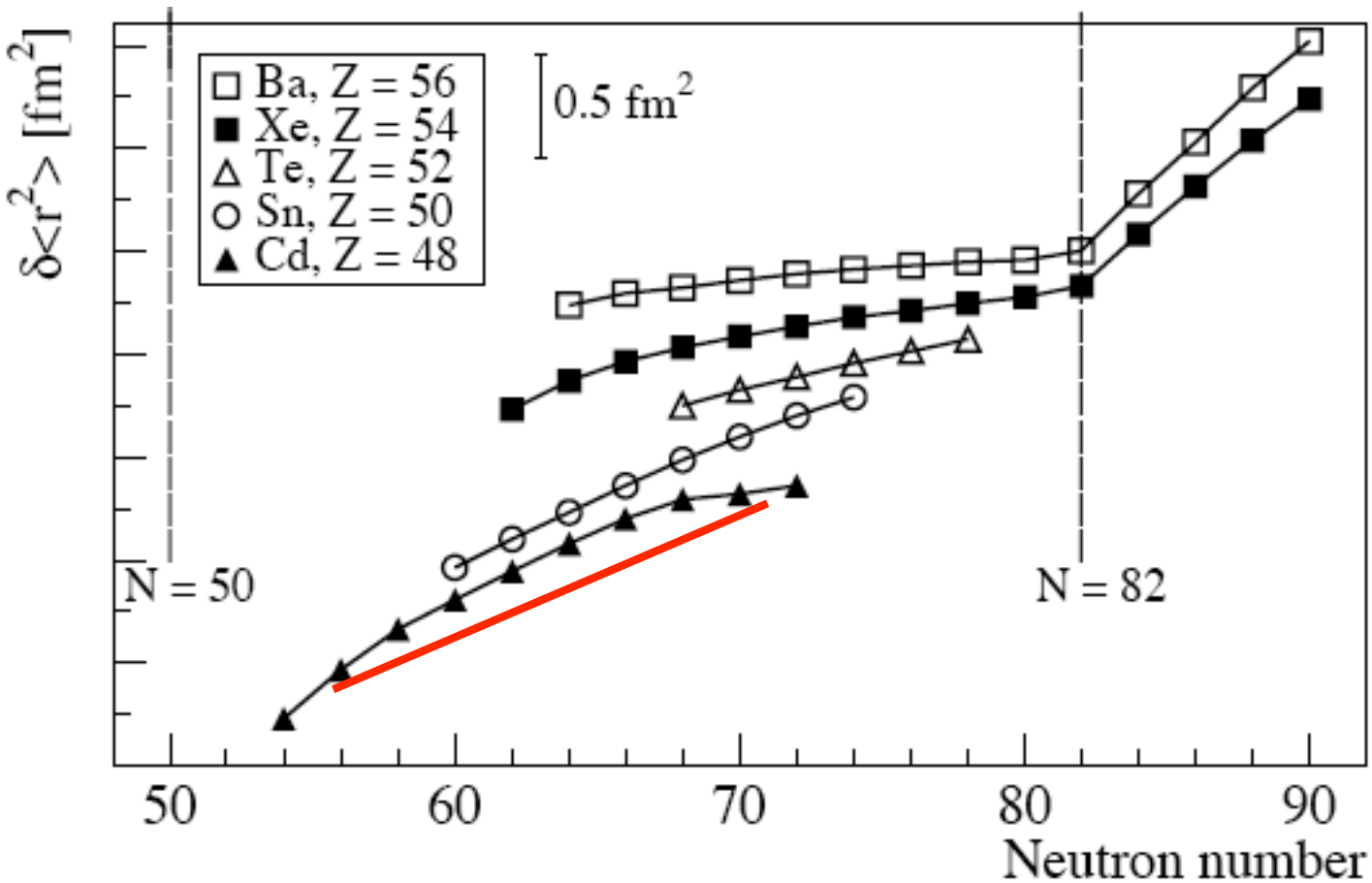


Fig. 3. Charge radius change in the tin isotopes. The line relies all the ground-states nuclei.



I am not certain as to how to interpret these Cd radii. These data go out to Cd-120. It certainly looks inviting to take advantage of the good Cd RILIS yields to extend these out, at least to Cd-126.

They might be showing larger radii owing to the intruder admixtures.

It is possible to interpret the lowered 2+ energies in the even-even Cd nuclides (lowered relative to the isotonic Te nuclides) as arising from a lowered proton pairing, or, perhaps the proton pairing is normal, and it is just a consequence of the lowered neutron pairing noted in the previous paper!!!!

And, there are also the lowered total binding energies for all of the Cd nuclides, relative to the FRDM masses. Perhaps FRDM is not the best comparison, but those values are used extensively for calculations where no data are available.

And, the absence of isomerism in Cd-130 and the suggested lower energy for the 2+ energy in Cd-130. A reliable determination for the 2+ energy in Cd-130 and B(E2) values for the heavy Cd nuclides may be better measures for proton pairing in these nuclides.

Then, there is the position of the 1+ level in In-130.

The remedy in OXBASH is a significant lowering of the pn interaction strength…..same as for Sn-134.

In other words, much of the new data for neutron-rich Cd and In nuclides could be accommodated by lowered interaction strengths for these very neutron-rich nuclides.

Where does RILIS go? Remember, RILIS gives **chemical selectivity**, but it can't beat diffusion…..as for Ni nuclides.

Each time we have started a new element, 2 or three new isotopes have been found.

At ISOLDE, Cd-133 is in sight, In-136 and In-137 are possible hopefully we will get better data for Ag-130, both neutron and gamma ray data. From In-136 and In-137, we could get structure in Sn-136, for example.

We are approved for antimony and should get Sb-137 and Sb-138 with neutrons. Cs-138 will overwhelm the gamma rays.

And, there was the Mn-66 study that revealed the low 2+ energy in Fe-66 that provided strong evidence for deformation in Ca-48 to Ni-78 region. There is much more spectroscopy that could be done with Mn.

If TRIUMF initiates a RILIS program, with their larger beam currents, they might be able to move to more out one two additional neutrons.

Thank you for your attention.