Alpha-decay in the neighborhood of ^{100}Sn, an overview on recent results

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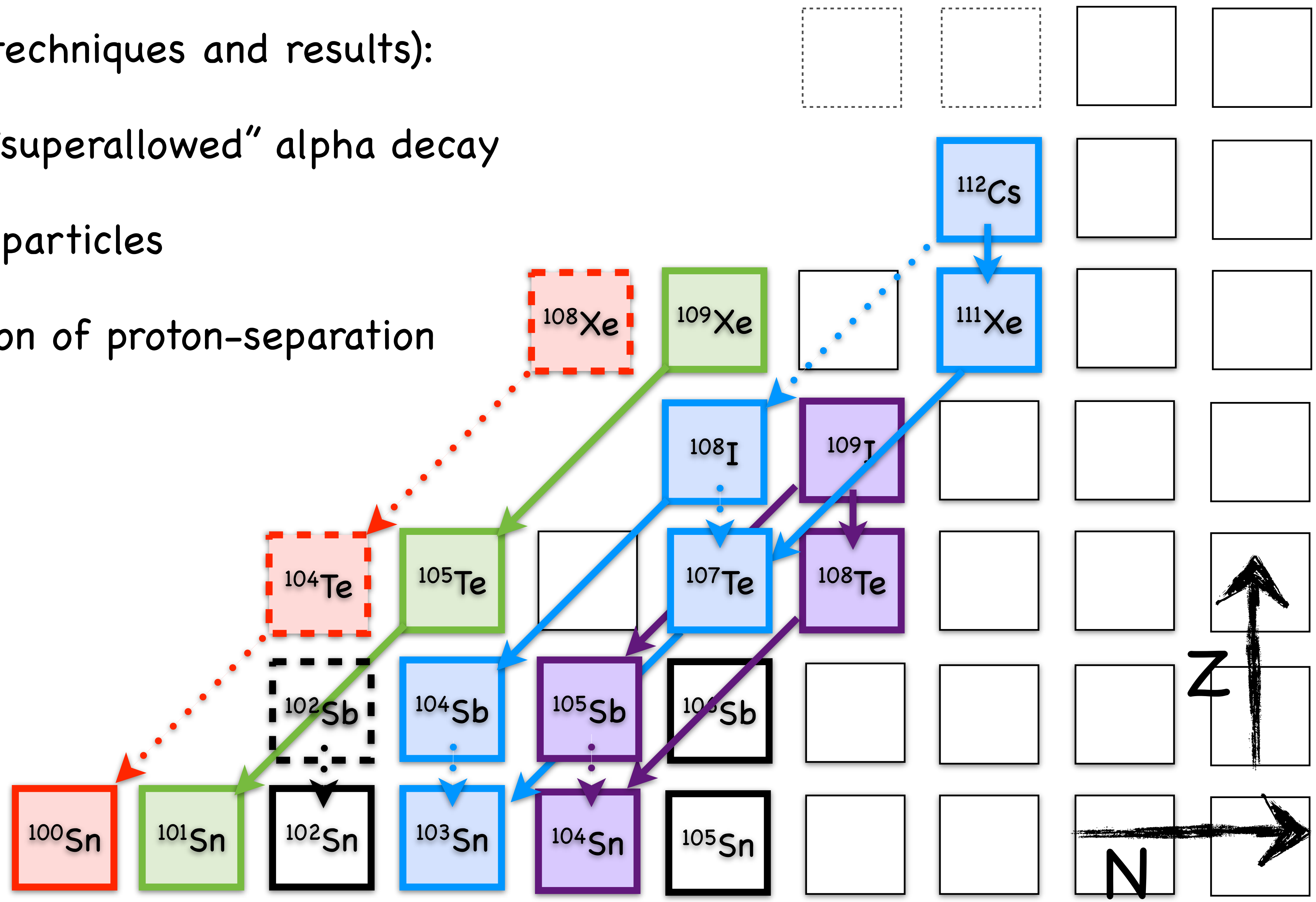
IFD-UW

Nuclear Physics Seminar, October 13th, 2011

overview

- Introduction
- Experiments (techniques and results):
  - search for “superallowed” alpha decay
  - single level particles
  - determination of proton-separation energies



- Summary and conclusions

alpha and proton decay of exotic nuclei

- Experimental determination of the limits of bound nuclei:
  - test of theoretical predictions for the nuclear binding energy at extreme N/Z values (unbound versus nucleon emission)

- Measurement of alpha or proton decay energy:
  - determine the mass excess of nuclei at or beyond the drip-lines
  - measure separation energies for short-lived nuclei with high precision (~10 keV) and from just a few ions

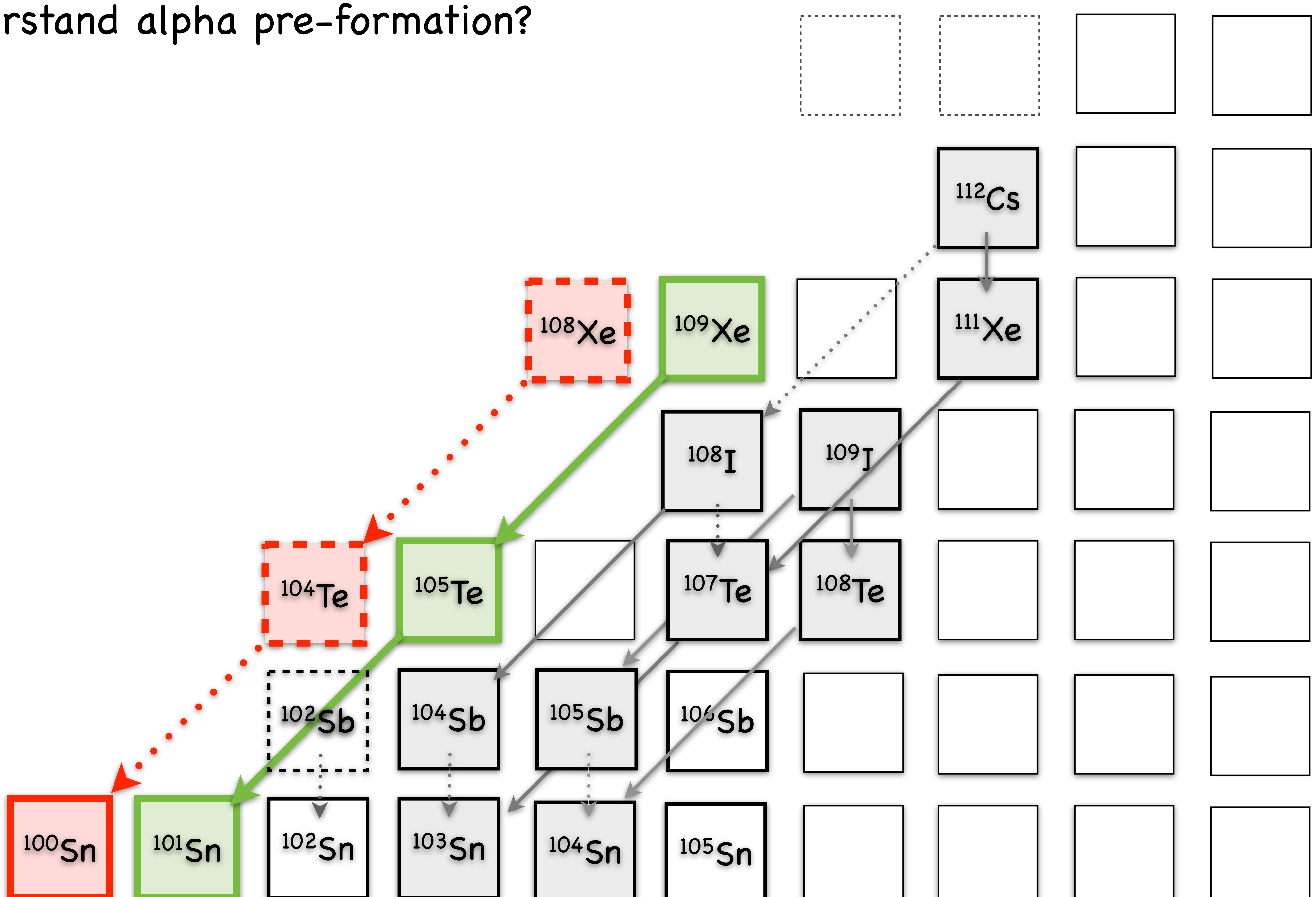
- Probe wave functions of nuclear levels involved and study of shell effects

- Experimental determination of mass excess: astrophysically relevant

alpha and proton decay island near ^{100}Sn

- Enhanced alpha decay (N~Z):

  "Superallowed" alpha-decay [Mac Farlane and Siivola, PRL 14 (1965) 114]
  -> do we understand alpha pre-formation?



alpha and proton decay island near ^{100}Sn

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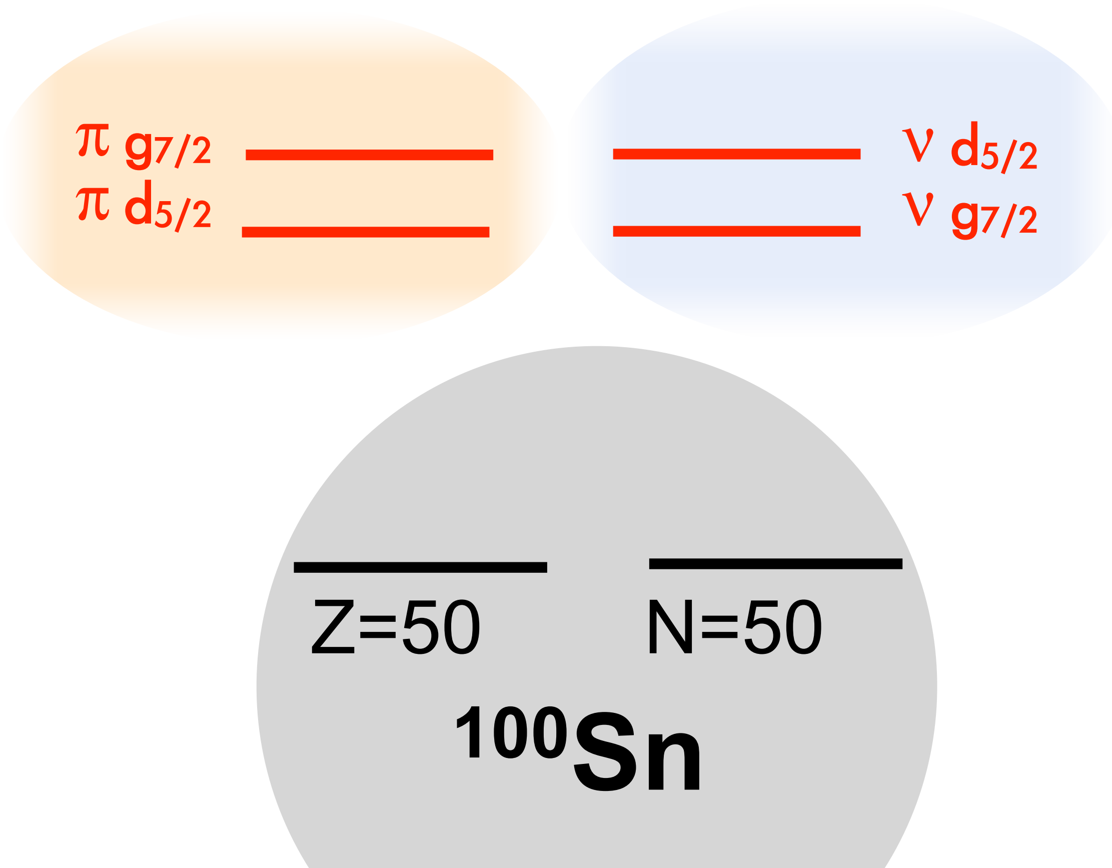
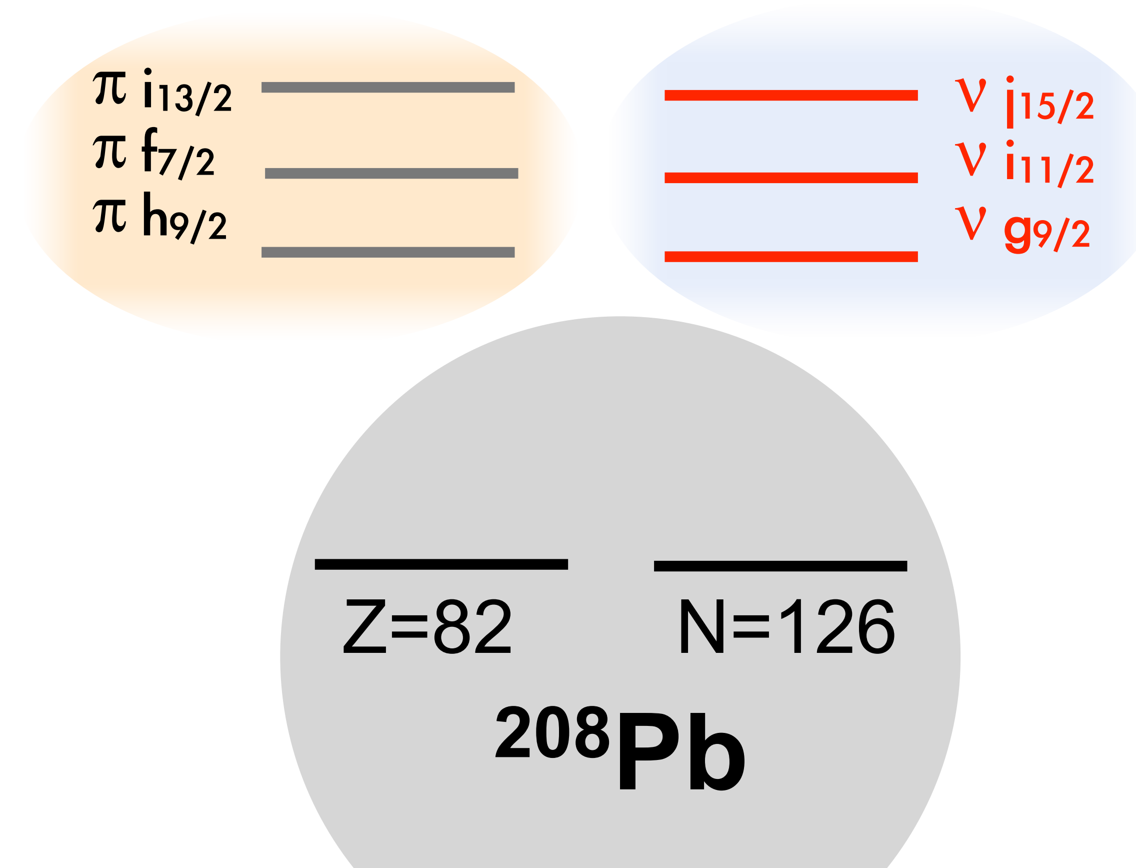
^{104}Te = ^{100}Sn + α
α made of π and ν
in the **same parity** orbitals



superallowed α-decay

^{212}Po = ^{208}Pb + α
α made of π and ν
in **opposite parity** orbitals



present α-decay reference

alpha and proton decay island near ^{100}Sn

- Enhanced alpha decay (N~Z):

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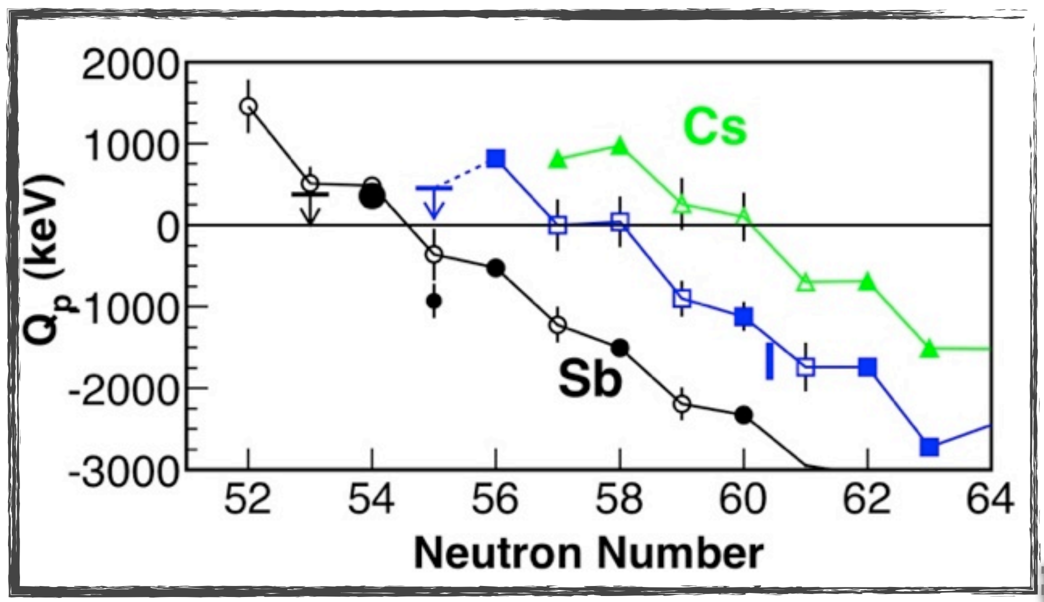
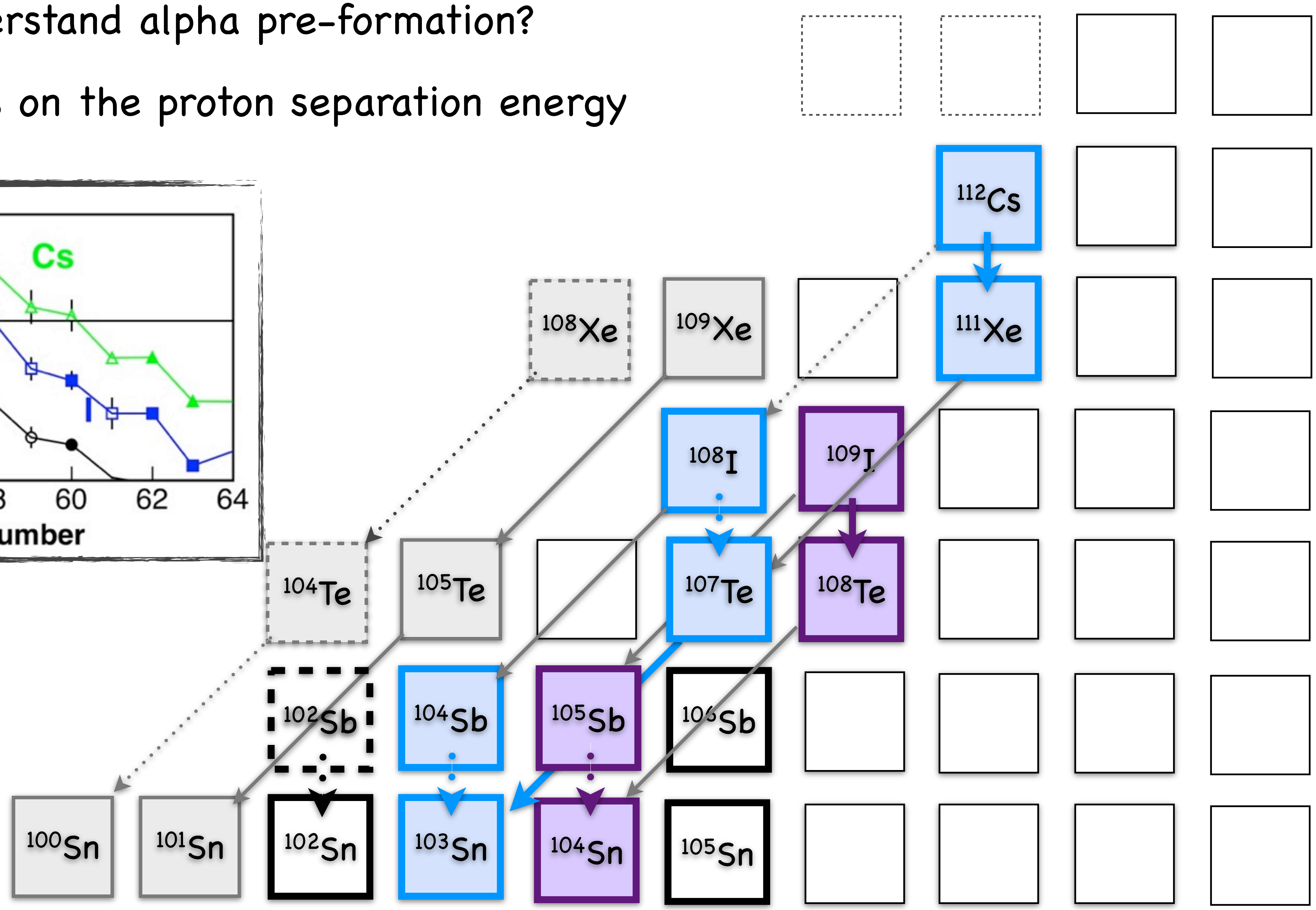
- Odd-even effects on the proton separation energy





alpha and proton decay island near ^{100}Sn

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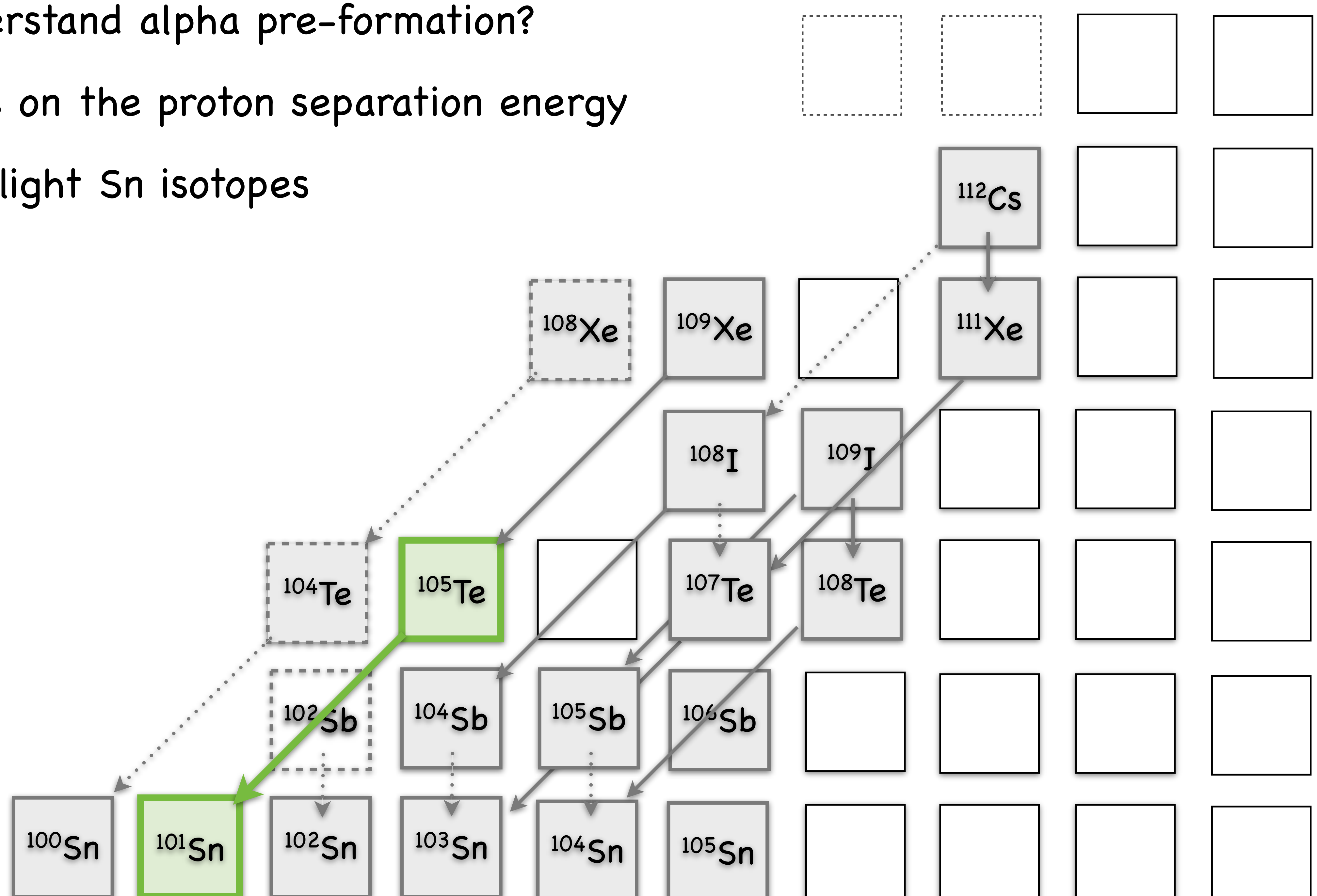
- Excited states in light Sn isotopes



alpha and proton decay island near ^{100}Sn

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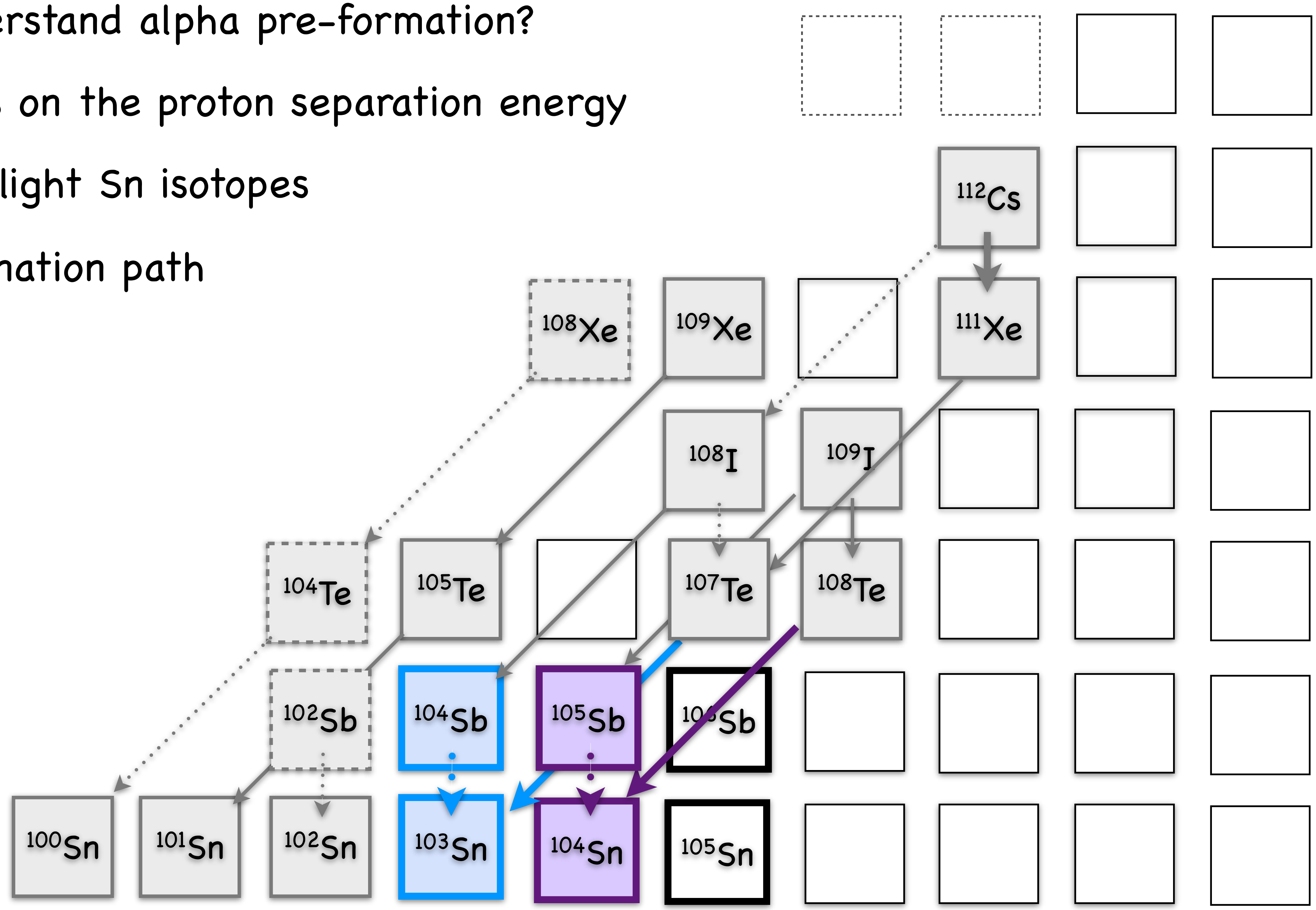
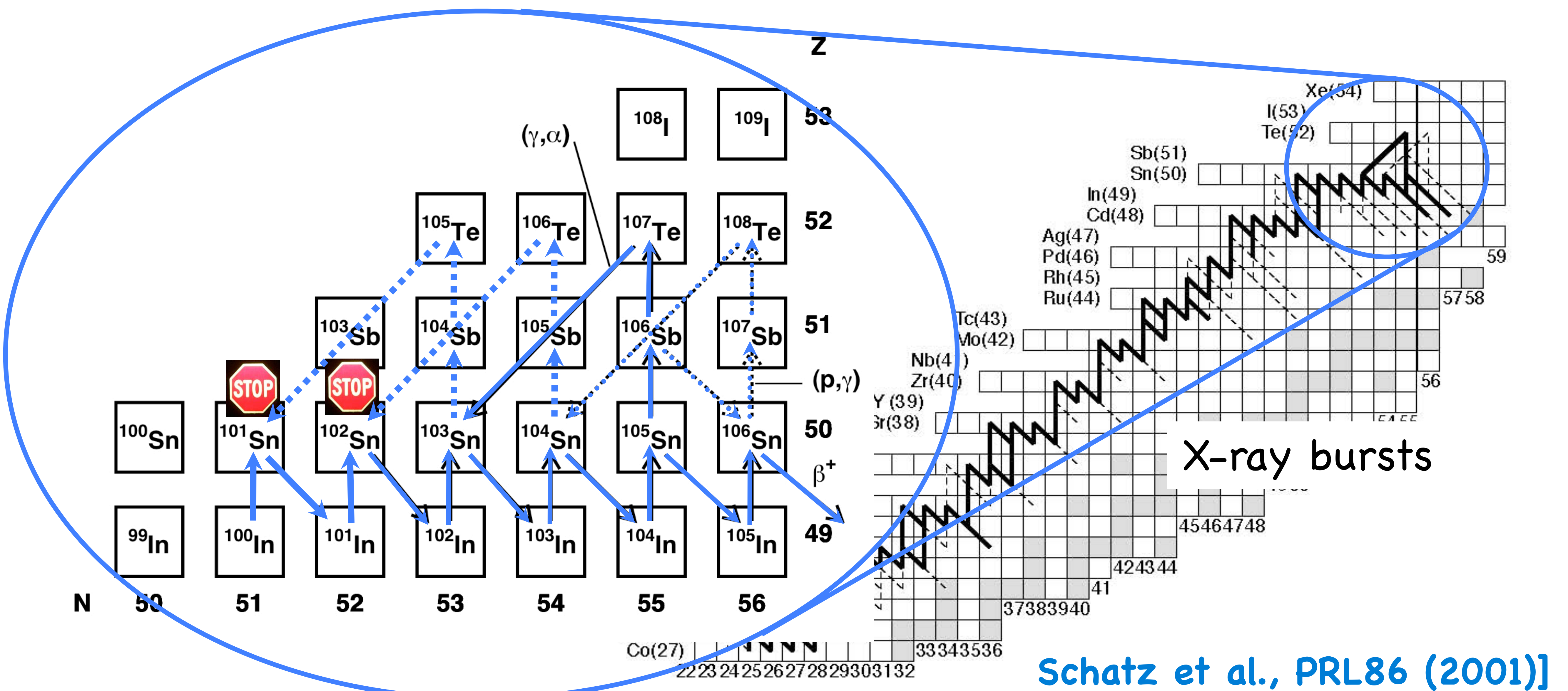
- Odd-even effects on the proton separation energy
- Excited states in light Sn isotopes
- rp-process termination path



alpha and proton decay island near ^{100}Sn

- Astrophysical interest: rp-process termination path
  - -> predicted termination region with cycle around n-deficient Sn-Sb-Te isotopes
    - ⇒ Effectively converts ^{1}H into ^{4}He
    - ⇒ Critically depends on Q_p and Q_α !



Schatz et al., PRL86 (2001)]

alpha decay of ^{105}Te

^{105}Te produced directly -> ^{50}Cr(^{58}Ni,3n)^{105}Te

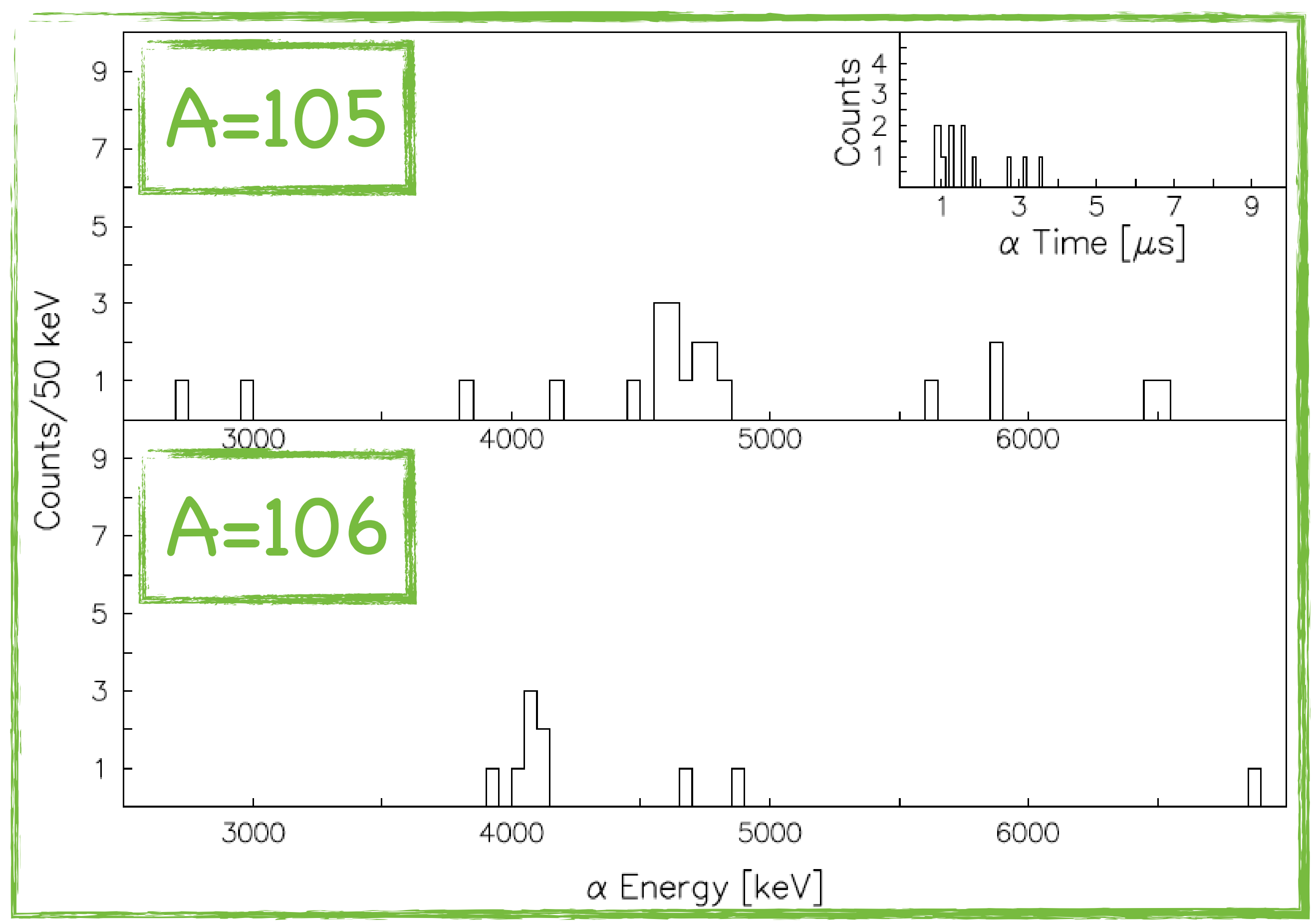
- FMA at Argonne
- DSSD detector + fast recovery electronics after implantation
- 0.6 μs < decay times < 8 μs detected

σ ~ 10 nbarn

E_α = 4720(50) keV

Q_α = 4900(50) keV

$$T_{1/2} = 0.70^{+0.25}_{-0.17} \quad \mu s$$



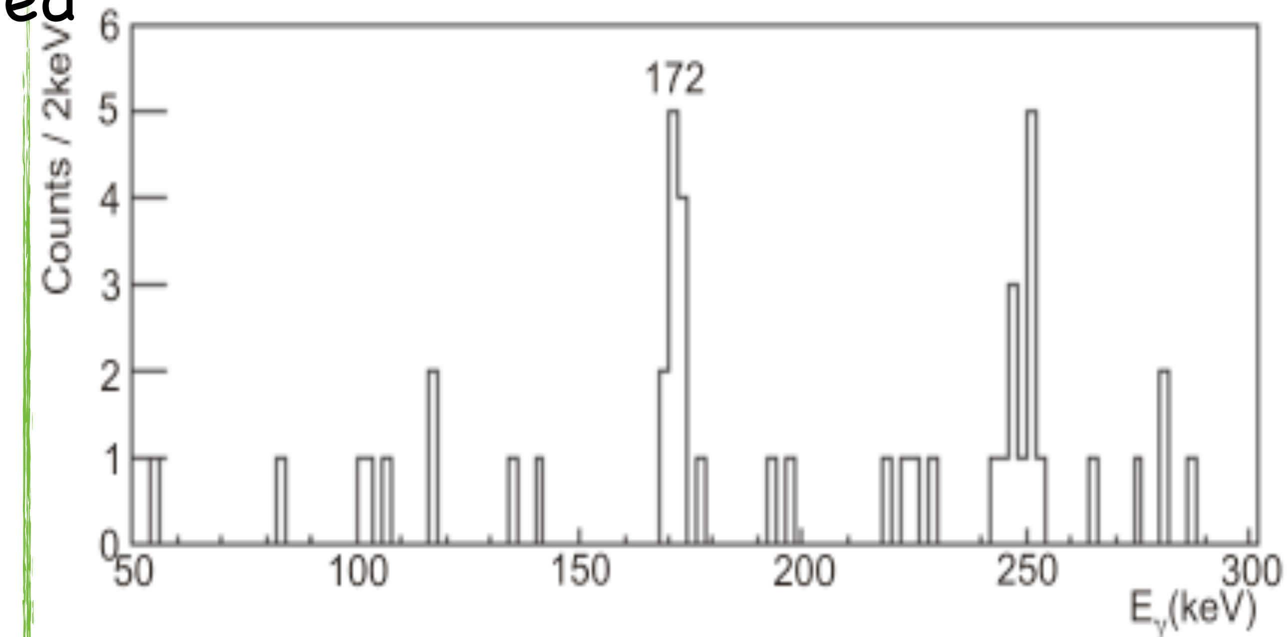
Seweryniak et al., PRC73(2006) 061301(R)

excited state in ^{101}Sn

^{101}Sn produced directly -> $^{46}Ti(^{58}Ni,3n)^{101}Sn$

- HPGe @ target (Gammasphere)
- FMA at Argonne
- DSSD detector @ focal plane
- RDT method: prompt γ rays emitted in the production of ^{101}Sn correlated with βp following decay of ^{101}Sn

-> excited state in ^{101}Sn at 172 keV identified

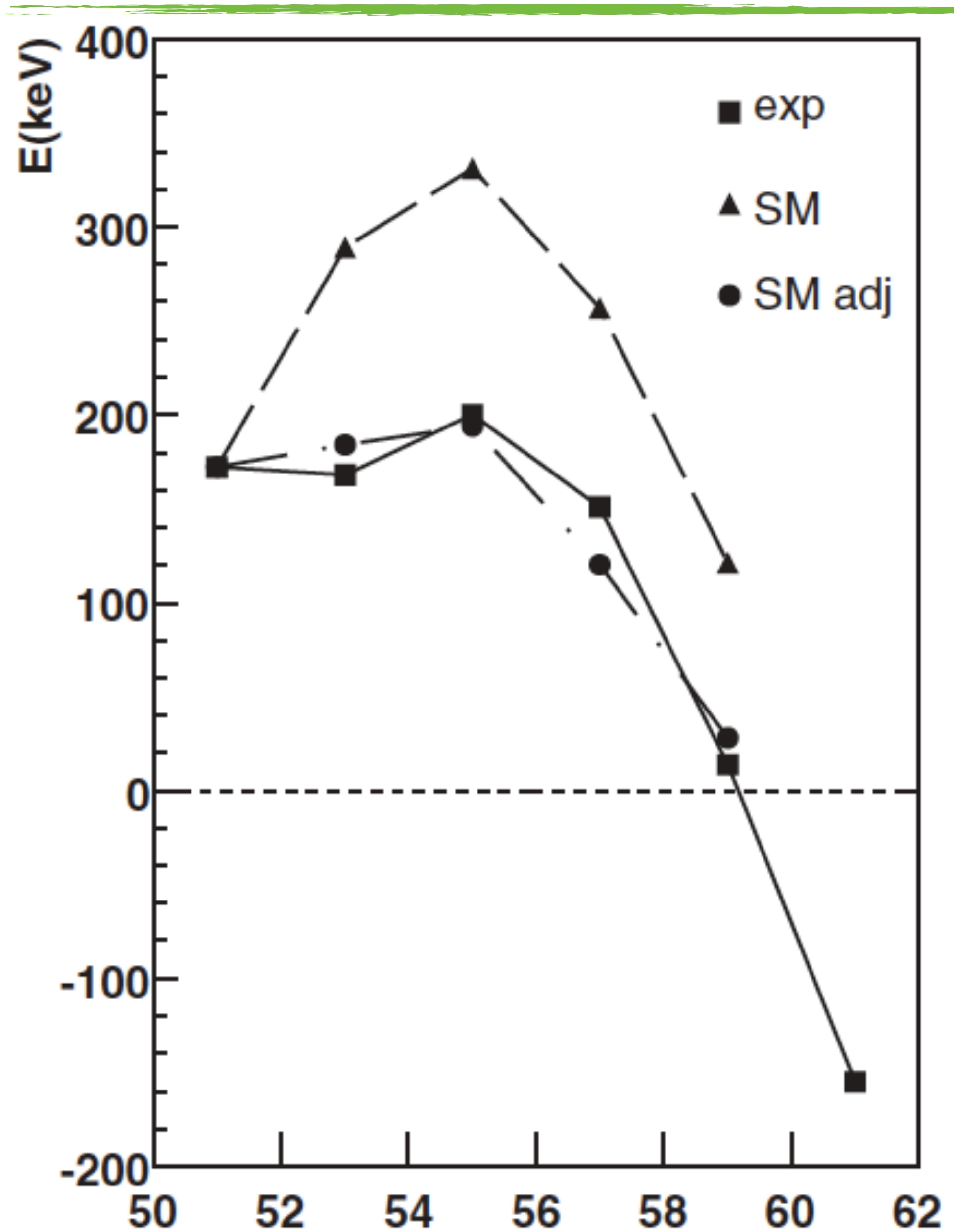


Seweryniak *et al.*, PRL **99** (2007)

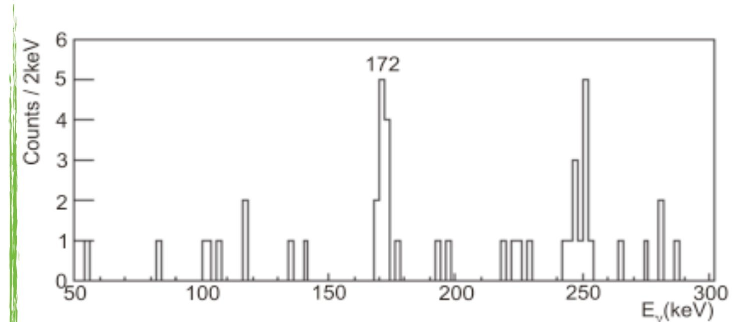
excited state in ^{101}Sn

-> excited state in ^{101}Sn at 172 keV identified:

interpreted as the $g_{7/2}$->$d_{5/2}$ single-neutron states transition



Seweryniak et al. PRL 99 (2007)



Seweryniak *et al*., PRL **99** (2007)

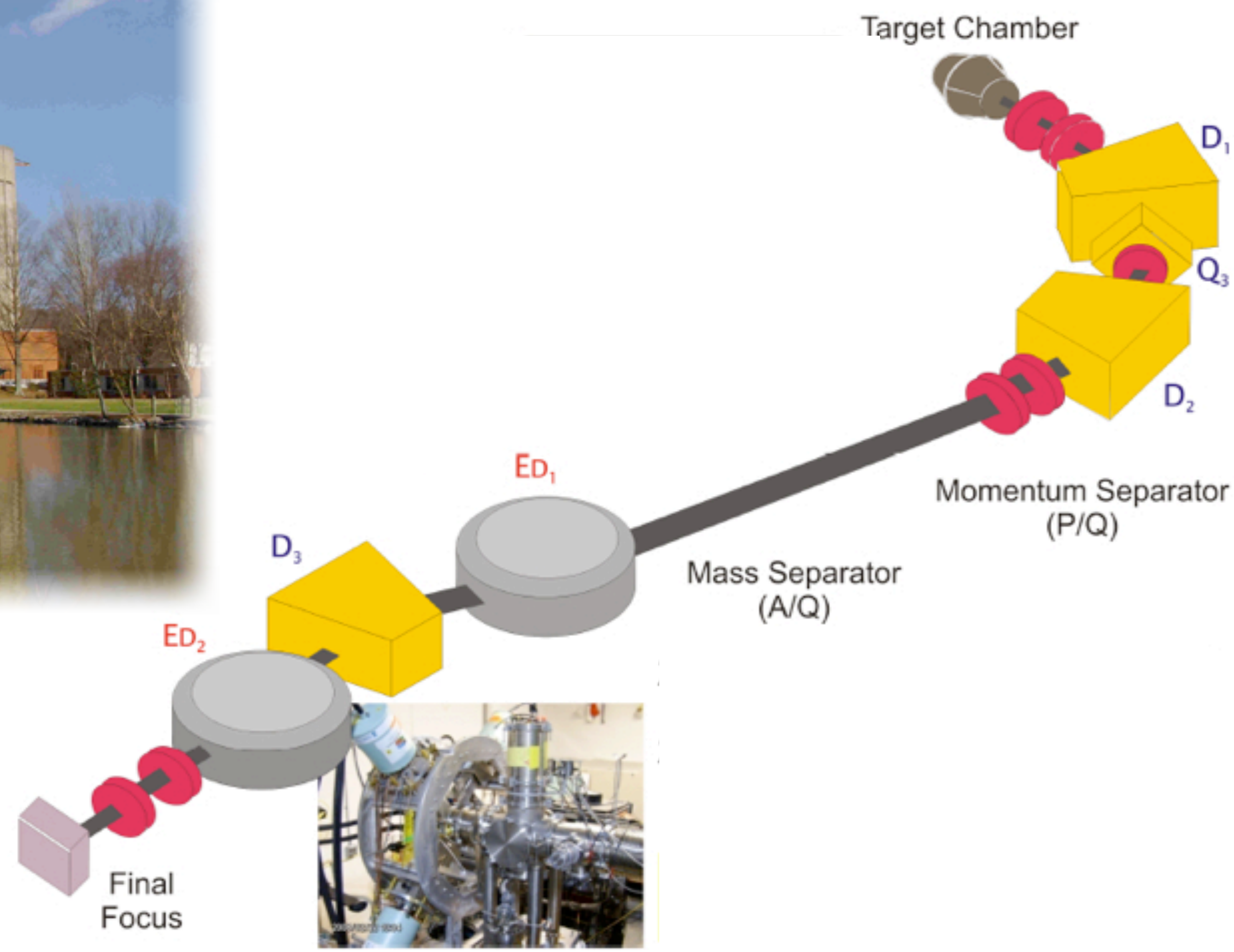
SM matrix elements:
M. Hjorth-Jensen et al., Phys. Rep 261 (1995) 125

SM adj: $(g_{7/2})^2_{0+}$ reduced by ≈30%

alpha decay of ^{109}Xe and ^{105}Te

^{105}Te produced as alpha-decay daughter of ^{109}Xe

- ^{54}Fe+^{58}Ni -> ^{112}Xe*(3n)^{109}Xe
- Recoil Mass Spectrometer at the HRIBF, ORNL

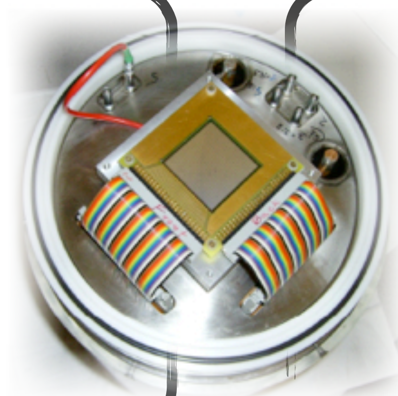


Experimental methods

$^{109}Xe \rightarrow ^{105}Te \rightarrow ^{101}Sn$
Exp I

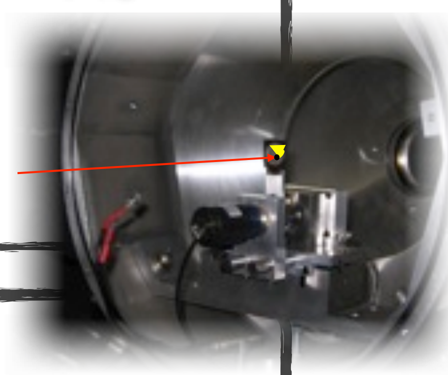
$^{54}Fe + ^{58}Ni \rightarrow ^{112}Xe^*(3n)^{109}Xe$
~8 part. nA
standard target

DSSD (40x40, 65 μm)
+ veto detectors

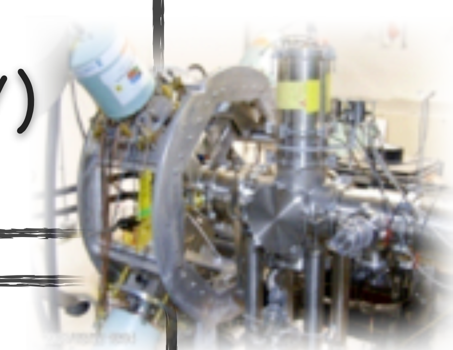


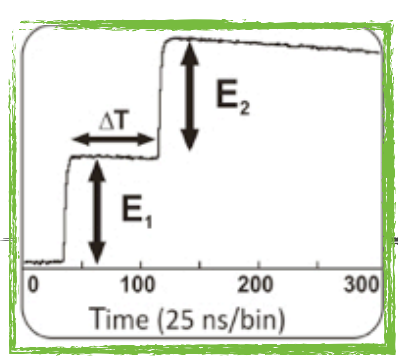
$^{109}Xe \rightarrow ^{105}Te \rightarrow ^{101}Sn$
Exp II

$^{54}Fe + ^{58}Ni \rightarrow ^{112}Xe^*(3n)^{109}Xe$
~50 part. nA
rotating target



DSSD (40x40, 65 μm)
+ veto detectors
+ HPGe (11.2% @ 123 keV)





Digital DAQ: alpha catcher mode

The alpha catcher

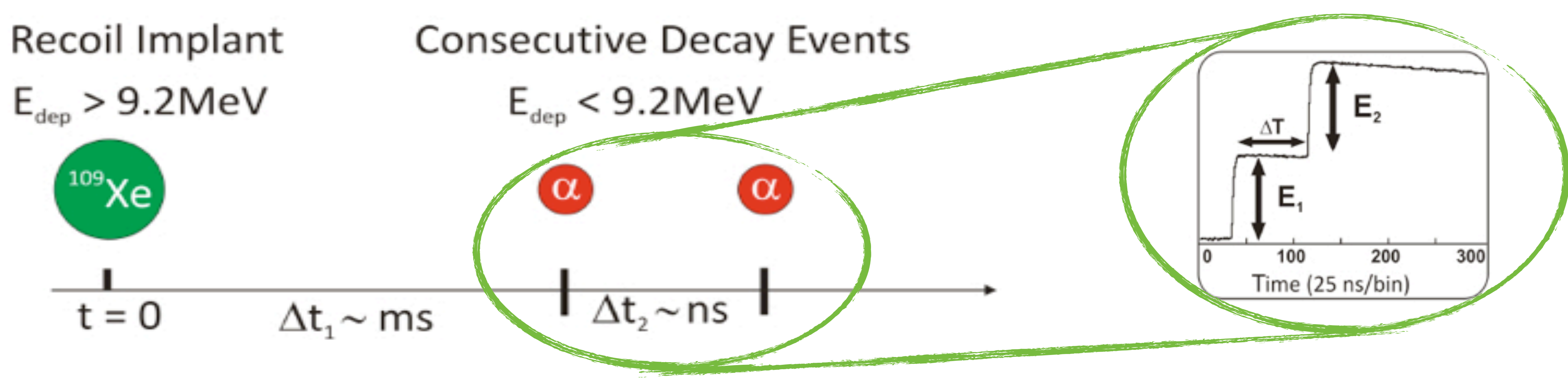
Expected half-lives

$$^{109}Xe \xrightarrow{\sim\ ms} {}^{105}Te \xrightarrow{\sim\ \mu s} {}^{101}Sn$$

New experimental method

DSP-based data acquisition system:

- → recording pulse shapes (traces) for single α and pile-up α-α decay events
- → method very selective
- → very sensitive (ΔT between two pile-up traces covers wide range)
- → very small dead time (~10-15% at ~2 kHz ions and ~150 Hz traces)

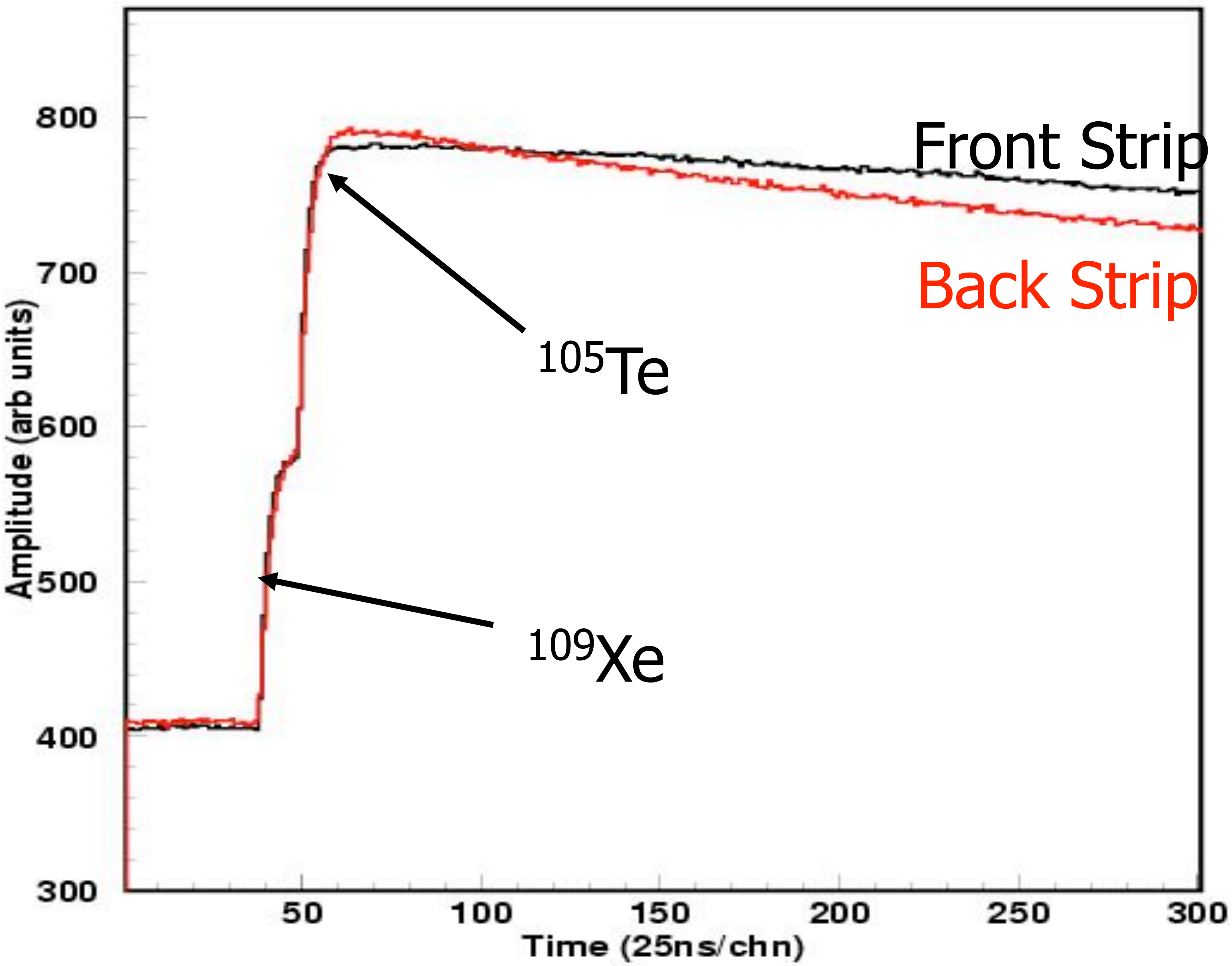


PSA 100% @ 150 ns

R. Grzywacz et al., NIMB 261 (2007)

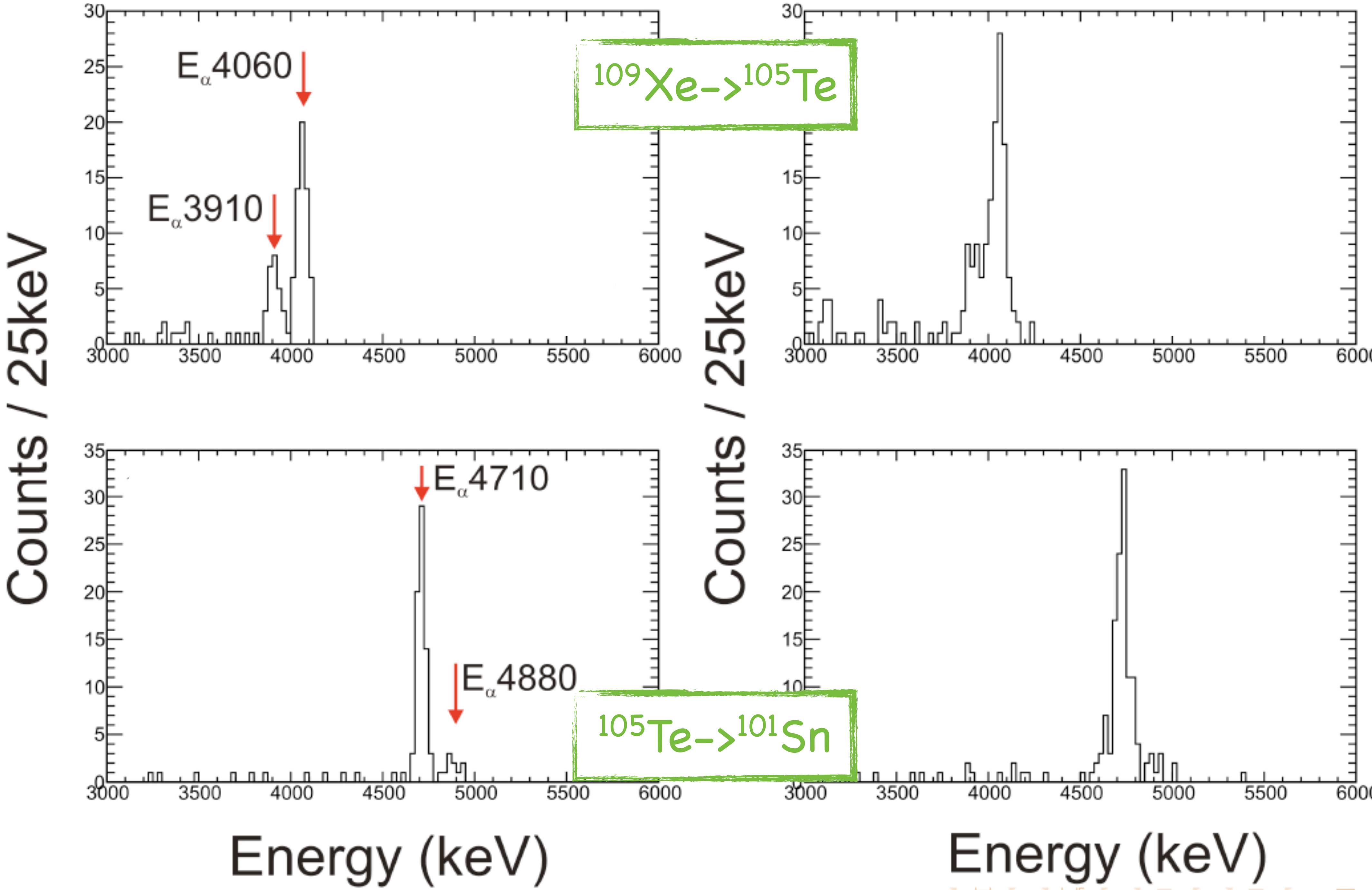
alpha decay of ^{109}Xe and ^{105}Te: results

$^{109}Xe \rightarrow ^{105}Te \rightarrow ^{101}Sn$ -> example of $\alpha-\alpha$ pile-up traces



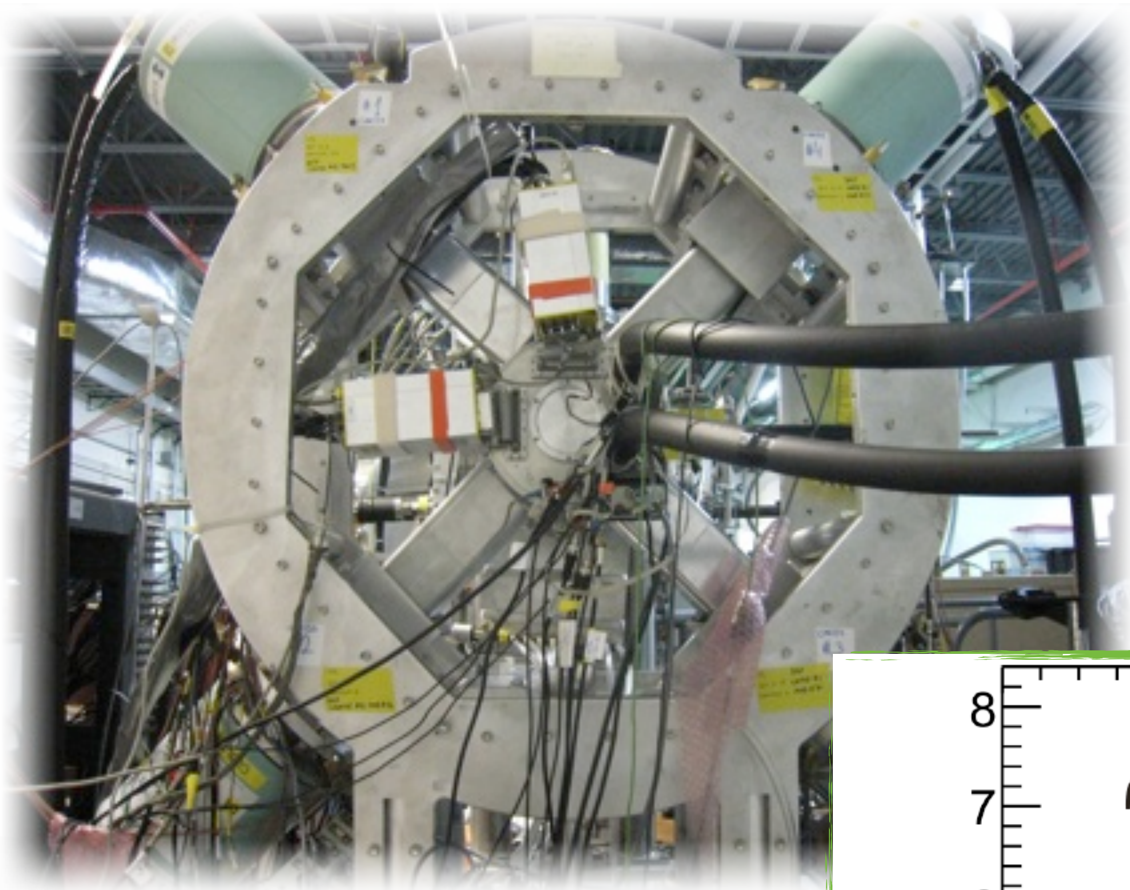
alpha decay of ^{109}Xe and ^{105}Te: results

Exp I: no γ **Exp II: with γ**

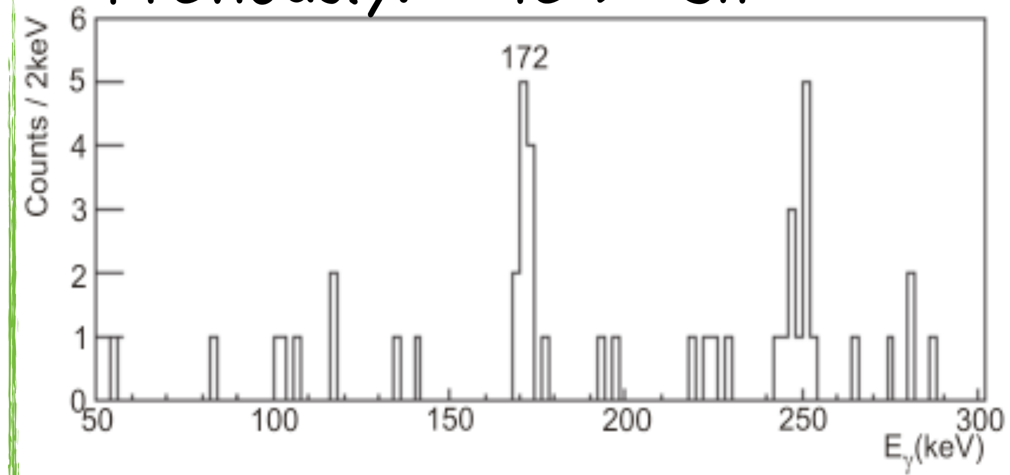


S.N. Liddick et al., Phys. Rev. Lett. 97 (2006) 082501 I.G. Darby et al. Phys. Rev. Lett 105 (2010) 162502

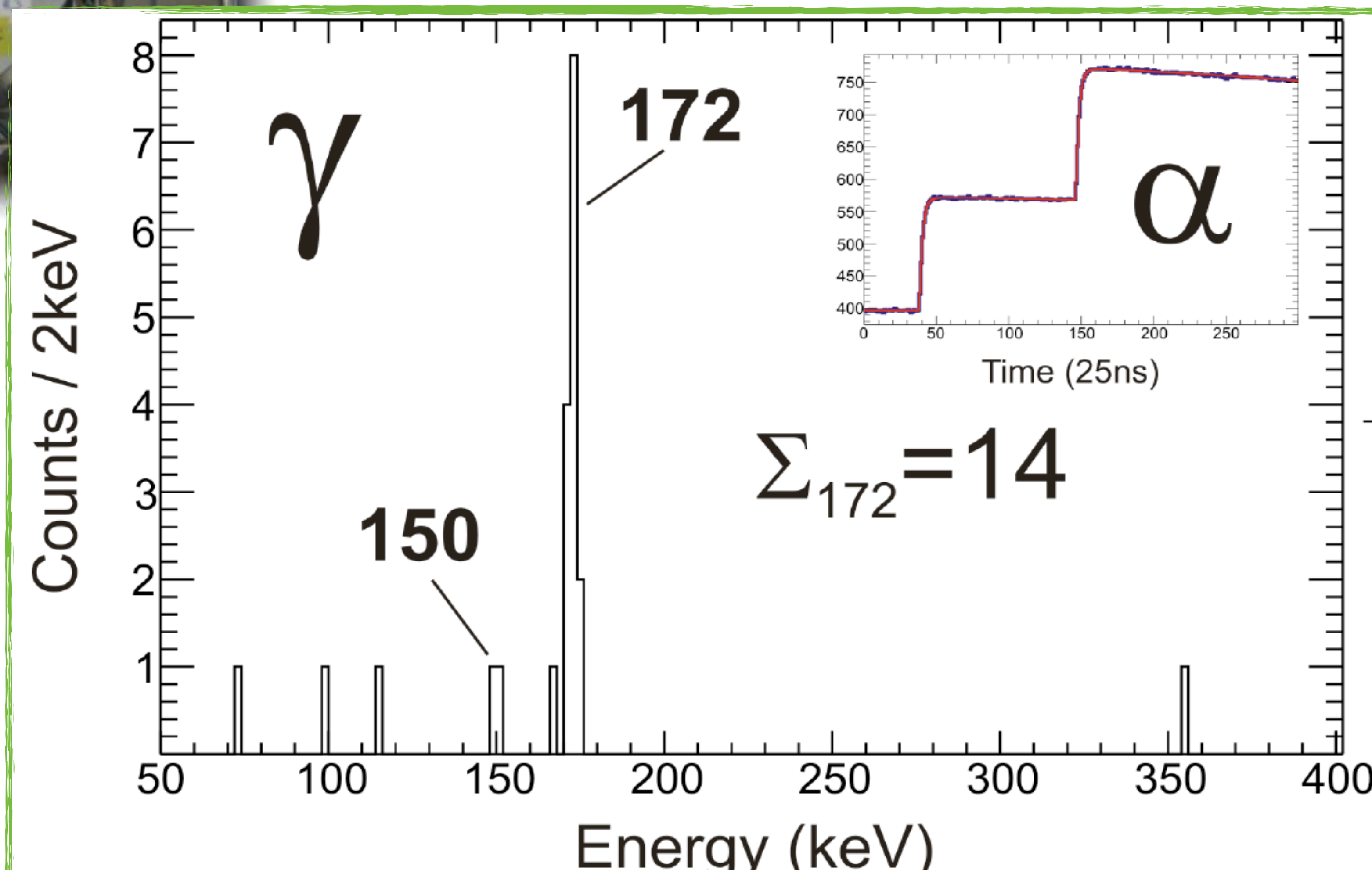
results: the 172 keV gamma transition!



Previously: $^{105}Te \rightarrow ^{101}Sn$

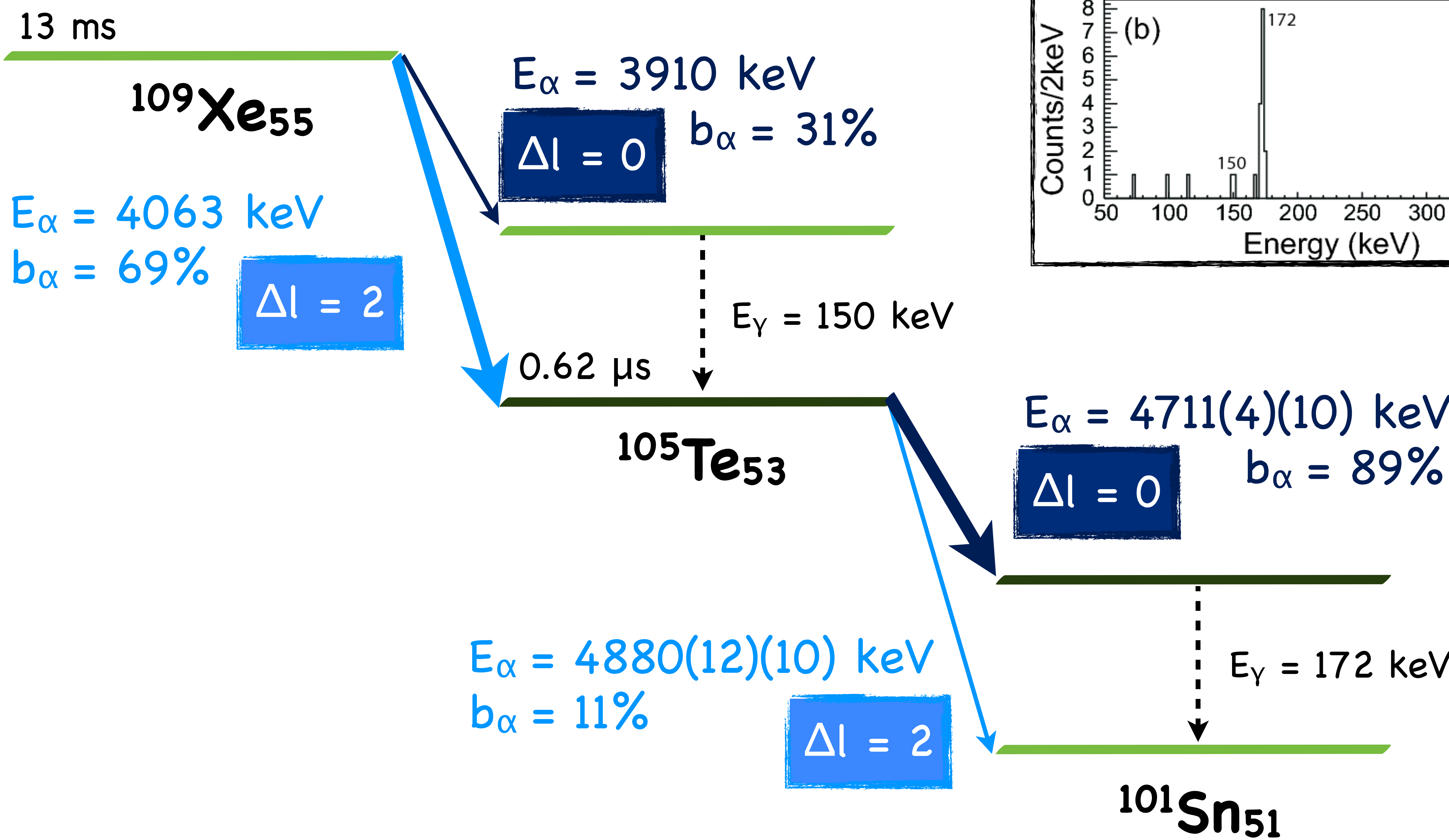


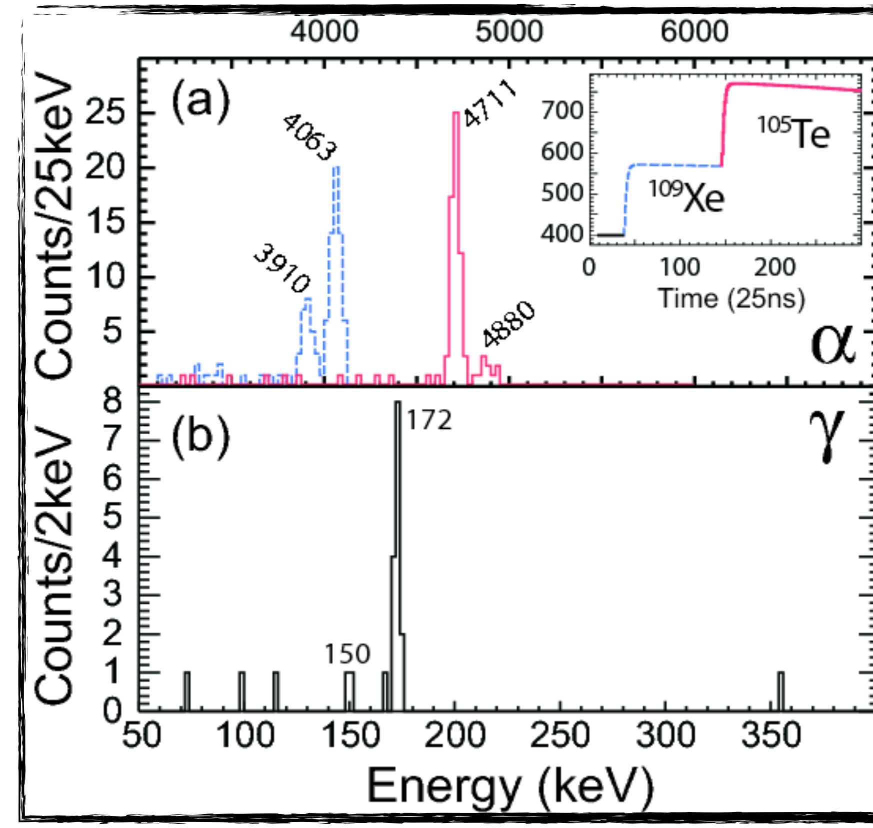
Seweryniak *et al.*, PRL **99** (2007)



I.G. Darby et al. Phys. Rev. Lett 105 (2010) 162502

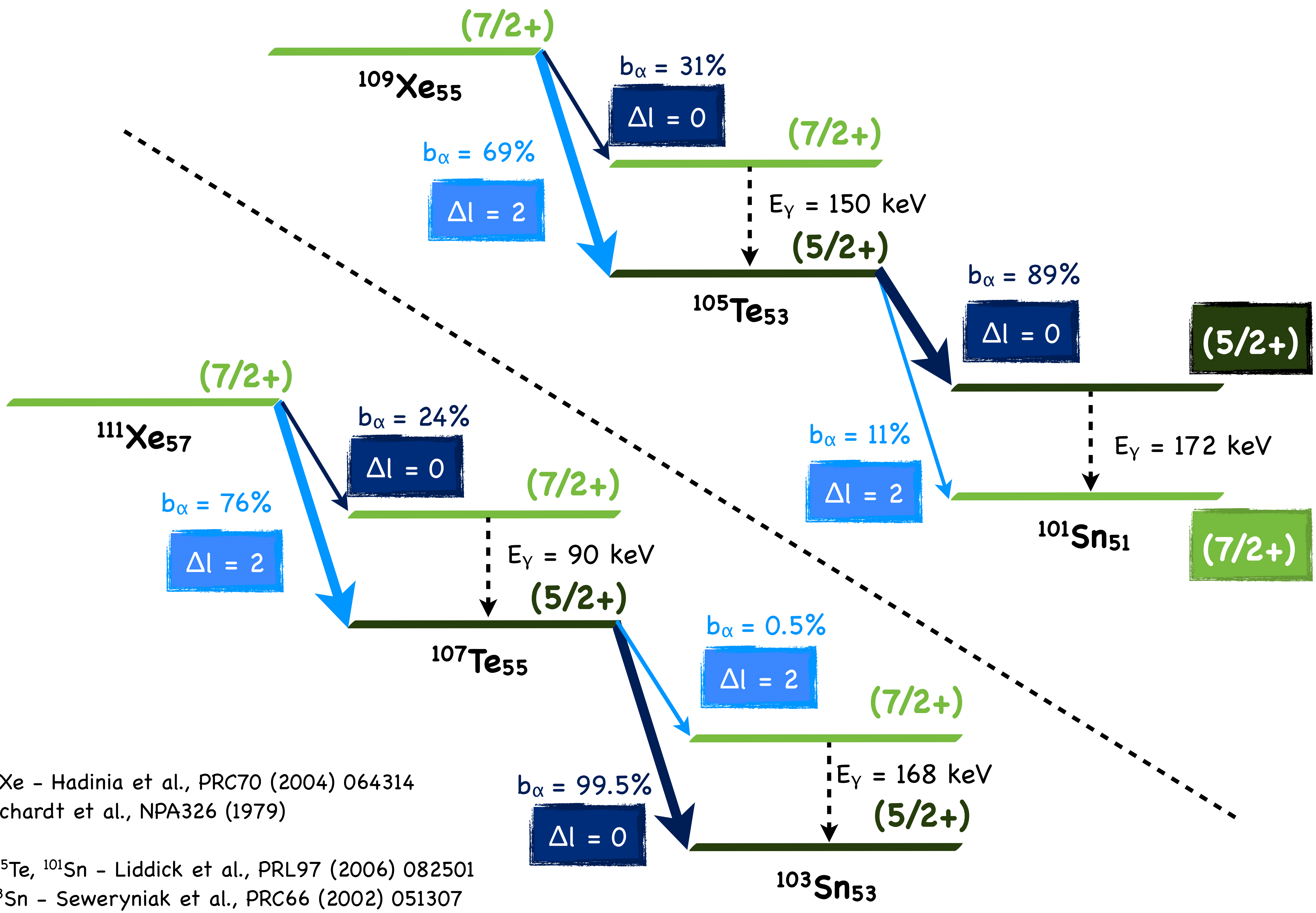
results: main decay path ^{105}Te->^{101}Sn*





I.G. Darby et al, Phys. Rev. Lett. **105**, 2010

results: ground state spin-switch between ^{103}Sn and ^{101}Sn



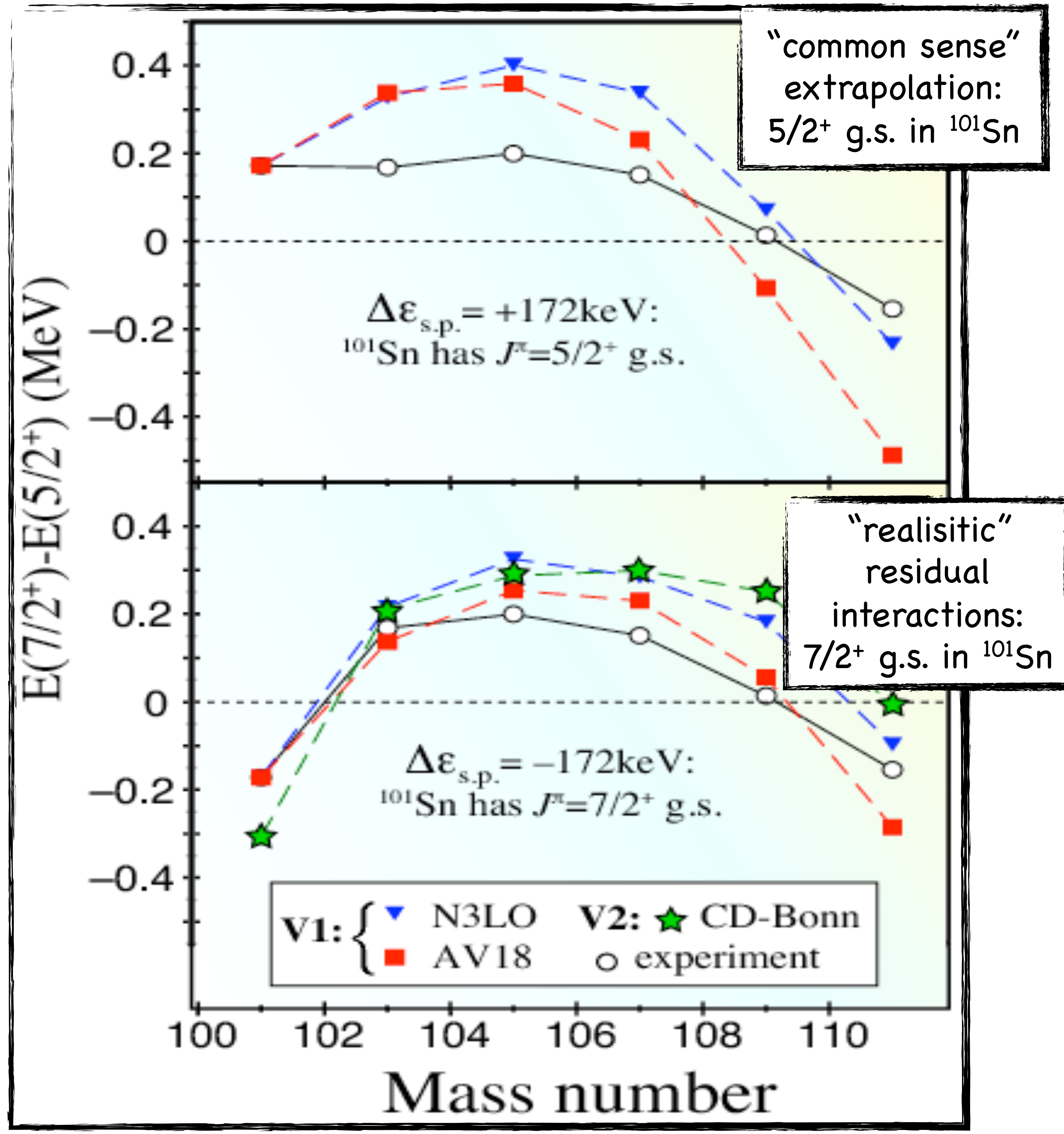
^{107}Te, ^{111}Xe - Hadinia et al., PRC70 (2004) 064314
^{111}Xe- Schardt et al., NPA326 (1979)

^{109}Xe, ^{105}Te, ^{101}Sn - Liddick et al., PRL97 (2006) 082501
^{107}Te, ^{103}Sn - Seweryniak et al., PRC66 (2002) 051307
^{103}Sn - Fahlander et al., PRC63 (2001) 021307(R)

results: shell-model interpretation

Two-level model:

- truncated configuration space ($g_{7/2}$ and $d_{5/2}$): very small splitting between $g_{7/2}$ and $d_{5/2}$ states (almost degenerate) + large energy separation from higher-lying orbitals
- pairing interaction between the $g_{7/2}$ neutrons is particularly strong
- matrix elements computed from N3LO and AV18 potentials



M. Hjorth-Jensen et al, Phys. Rep. **261**, 1995

I.G. Darby et al, Phys. Rev. Lett. **105**, 2010

results: shell-model interpretation

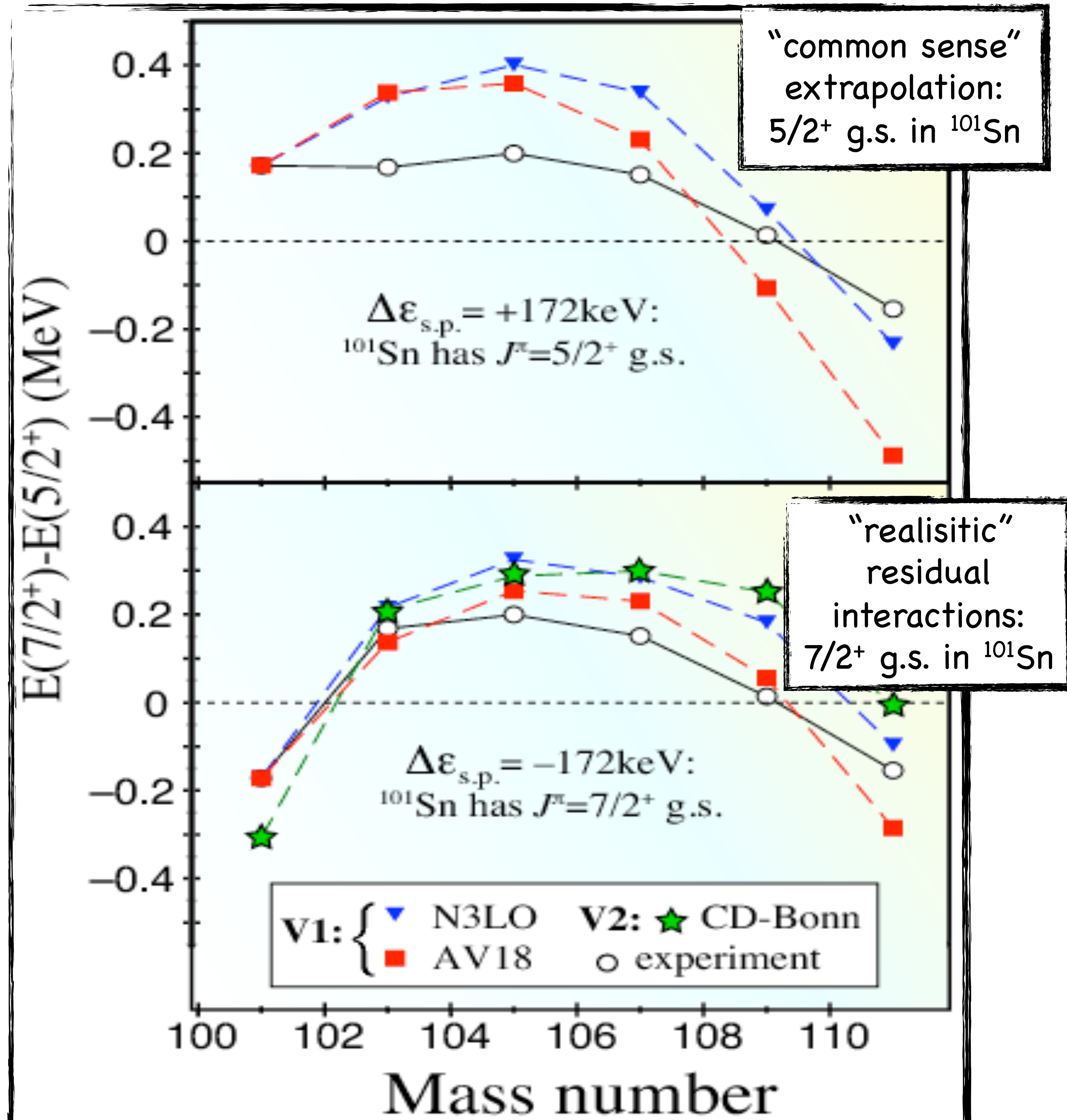
Calculation variant V1:

- ^{100}Sn core
- valence nucleons in $d_{5/2}$, $g_{7/2}$, $d_{3/2}$, $s_{1/2}$ and $h_{11/2}$ shells
- res. interaction based on AV18 or N3LO potential
- neutron $d_{5/2}$ - $g_{7/2}$ splitting $|\Delta\varepsilon_{SP}|\approx172$ keV

Calculation variant V2:

- ^{88}Sr core
- valence protons in $p_{1/2}$ and $g_{9/2}$ shells and neutrons in $d_{5/2}$, $g_{7/2}$, $d_{3/2}$, $s_{1/2}$ and $h_{11/2}$ shells
- res. interaction derived from CD-Bonn potential

No free parameters

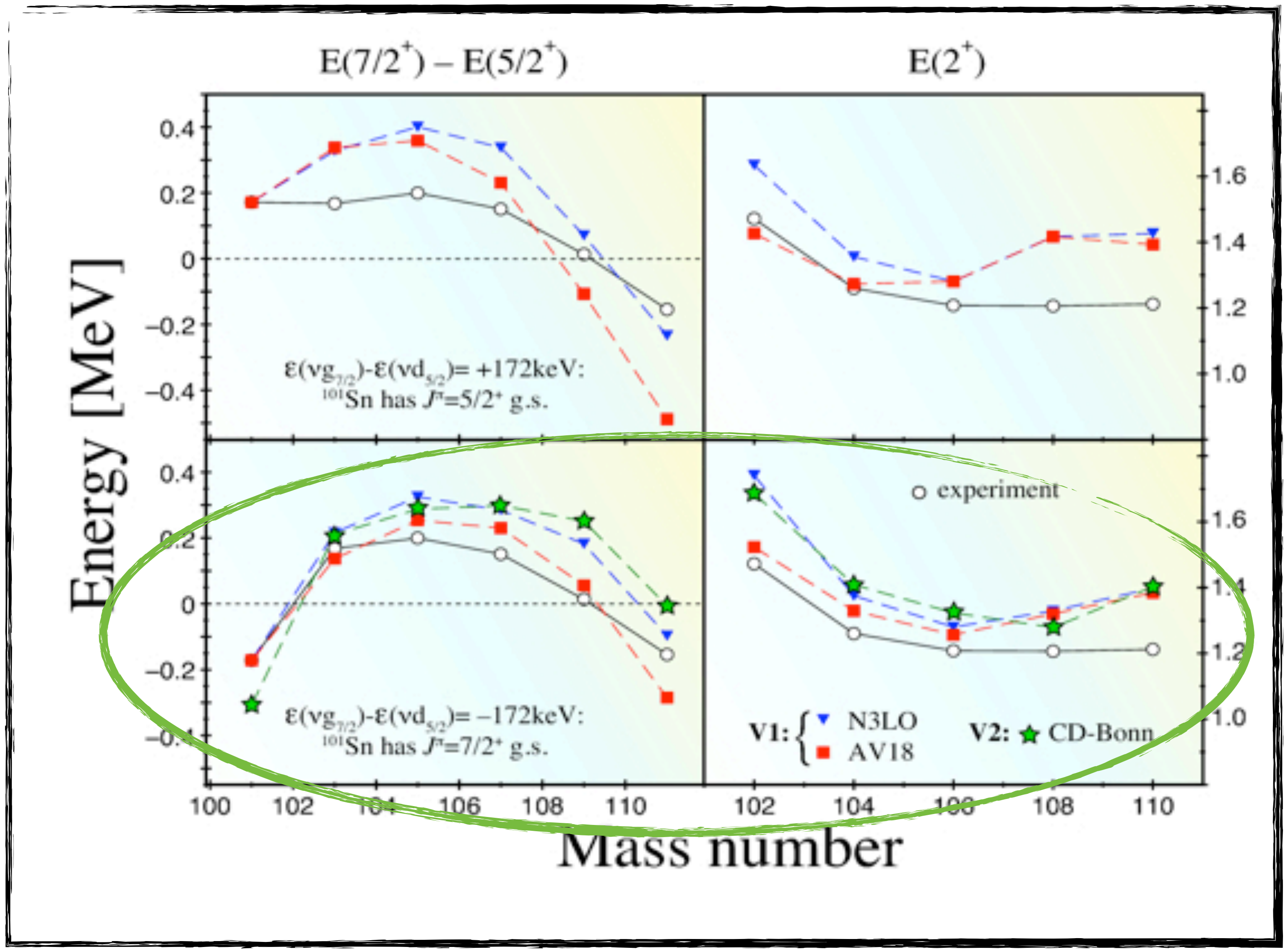


Very robust calculations:
regardless of the g.s. assumed for ^{101}Sn, the g.s. of the heavier odd-A Sn isotopes always turns out to be $5/2^+$

M. Hjorth-Jensen et al, Phys. Rep. **261**, 1995

I.G. Darby et al, Phys. Rev. Lett. **105**, 2010

results: shell-model interpretation



well reproduced by V1 and V2

- E(7/2+)-E(5/2+) parabolic trend
- crossing between 5/2+ and 7/2+ g.s. between ^{109}Sn and ^{111}Sn
- energy of lowest 2+ seniority-two state in even-A Sn isotopes

AV18 for $^{105/107}$Te (52 protons+53(55) neutrons)

-> predicts robustly $5/2^+$ g.s. and $7/2^+$ excited state (regardless of the choice of the level ordering)

-> no indication of a change in the structure of Te isotopes

==> the $5/2^+$ and $7/2^+$ level inversion is very unlikely to occur between ^{109}Xe and ^{105}Te.

M. Hjorth-Jensen et al, Phys. Rep. **261**, 1995

I.G. Darby et al, Phys. Rev. Lett. **105**, 2010

alpha decay chain ^{108}Xe -> ^{104}Te -> ^{100}Sn

Production of ^{100}Sn in the superallowed α decay of ^{104}Te:

^{108}Xe

$T_{1/2}$ (th) ~ 100-150 μs

Q_α (th) = 4.44-4.65(15) MeV

^{104}Te

$T_{1/2}$ (th) ~ 5 - 50 ns

Q_α (th) = 5.05-5.42(7) MeV

Q_α (extr)> 5.0-5.2 MeV

^{100}Sn

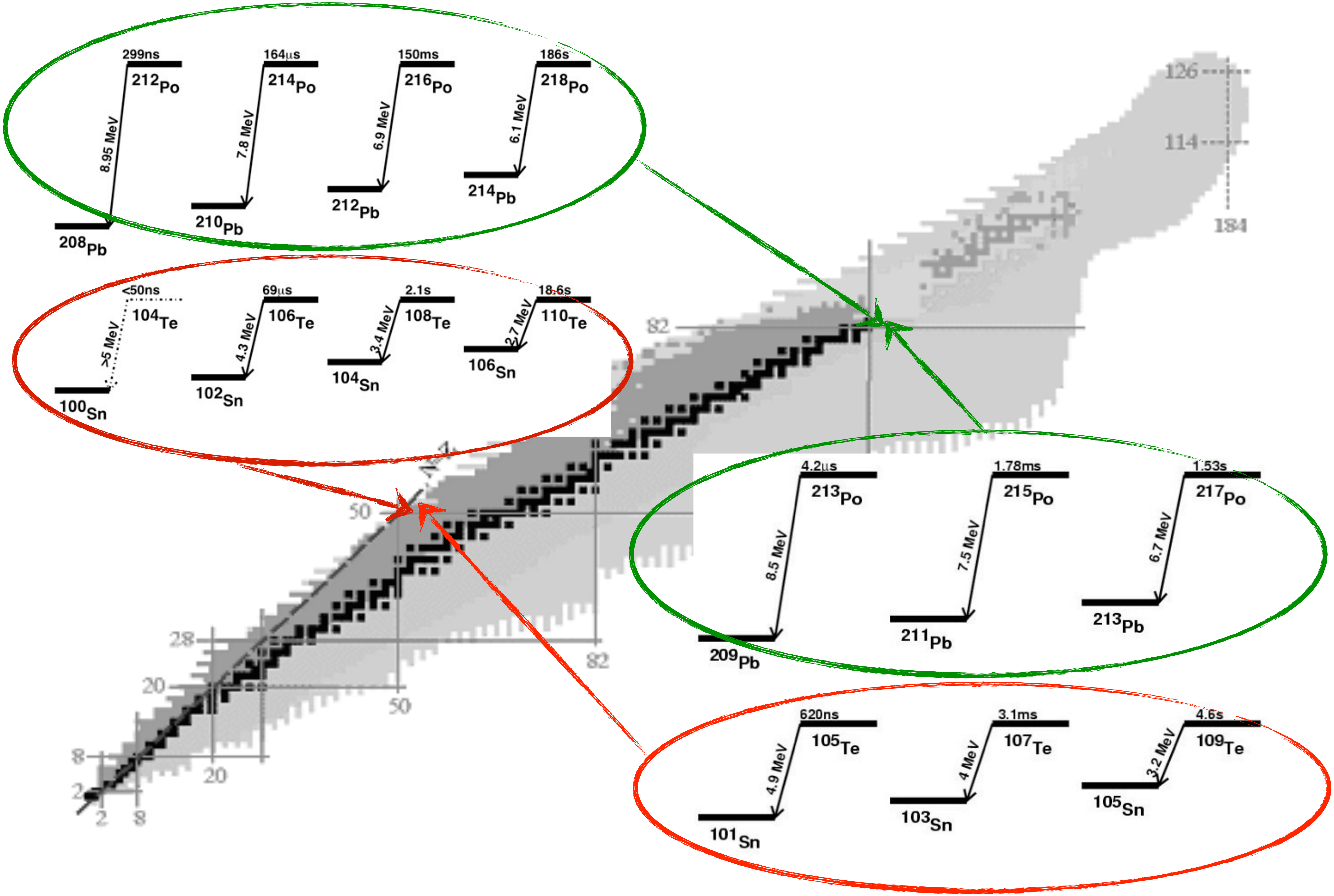
Theory:

Xu and Ren, PRC74, 2006;
Mohr, EPJA31, 2007

Extrapolated limits:

Liddick et al., PRL97, 2006;
Seweryniak et al., PRC73, 2006

magicity of ^{100}Sn



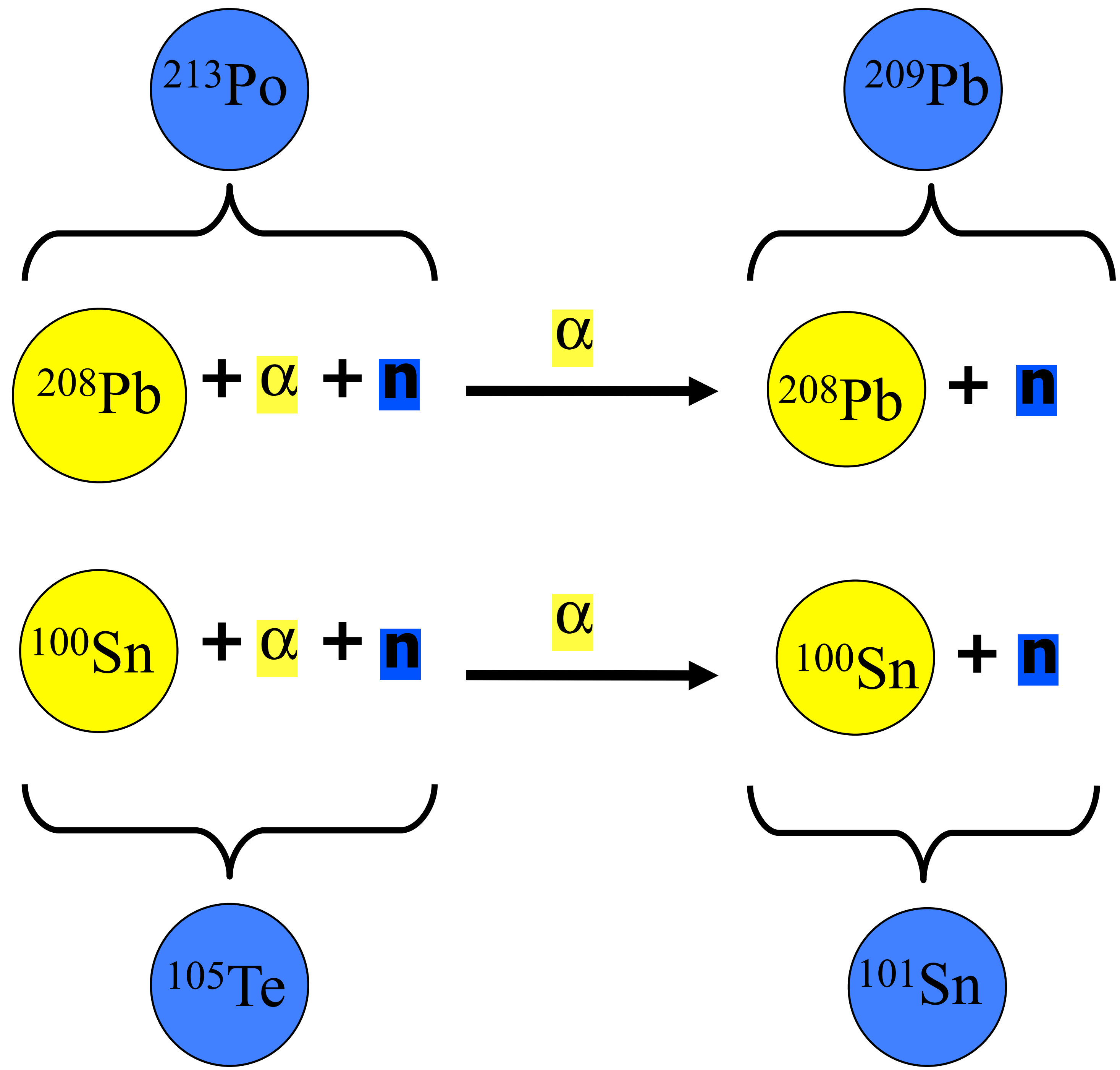
"superallowed" alpha decay?

Reduced decay width

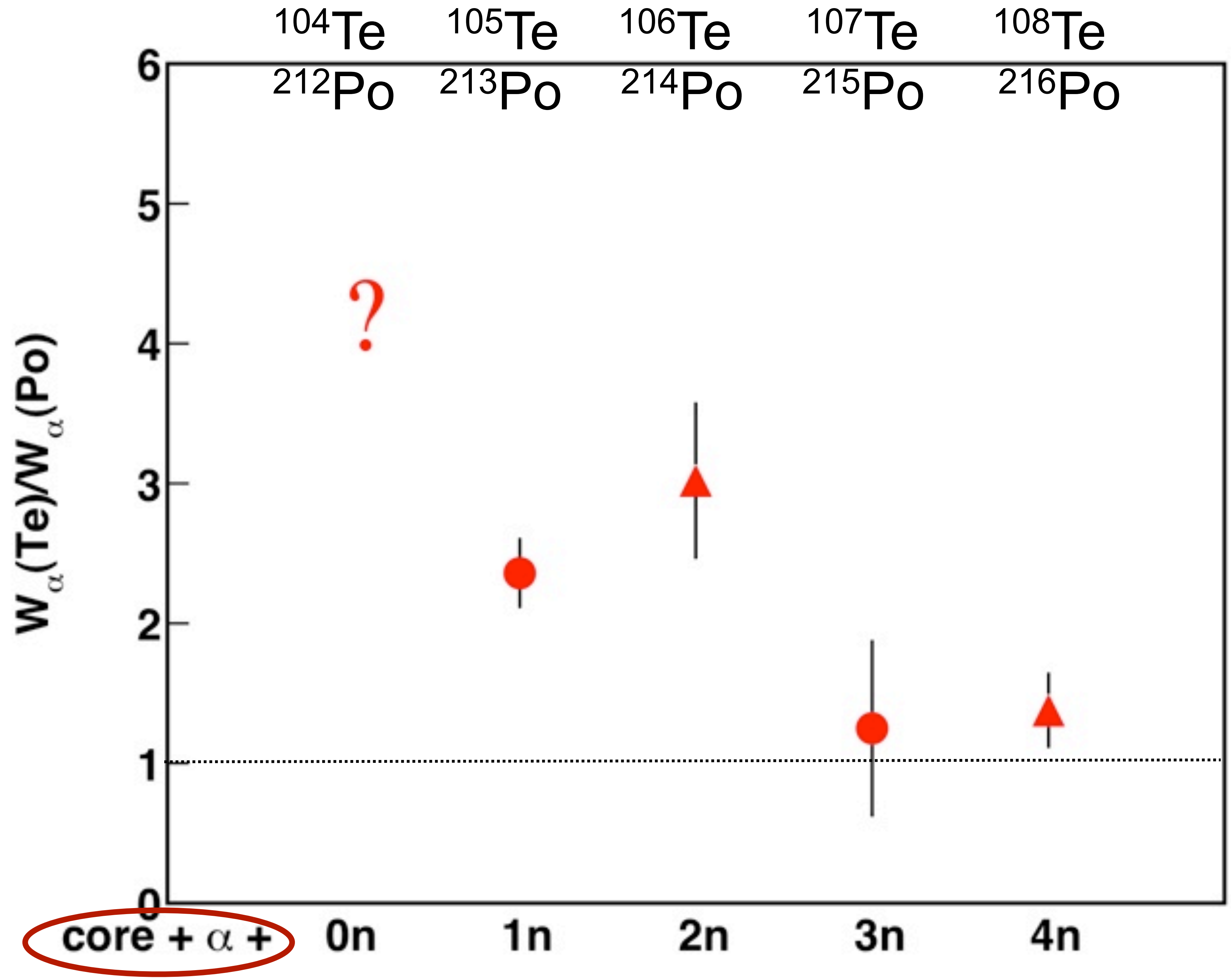
$$\delta^2 = \frac{\lambda_\alpha h}{P}$$

Reduced decay width relative to ^{212}Po:

$$W_\alpha = \frac{\delta^2}{\delta^2(^{212}Po)}$$



Re-normalized alpha-decay widths (ℓ=0 transitions)



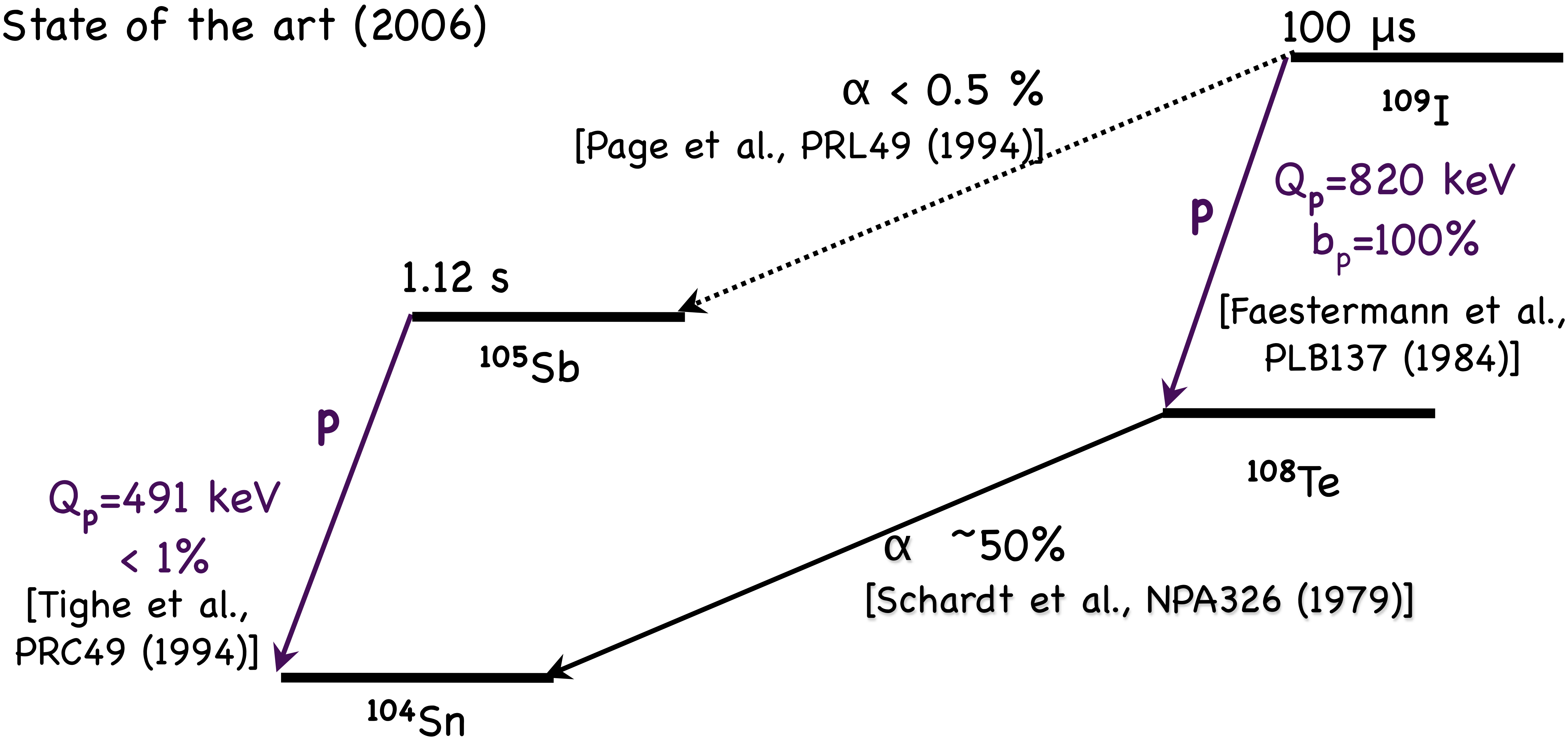
Superallowed alpha decay? We clearly see an enhancement,

but is it already superallowed in ^{105,106}Te?

$\Rightarrow$ Need to measure ^{104}Te $\rightarrow$ ^{100}Sn

alpha decay of ^{109}I -> S_p in ^{105}Sb

State of the art (2006)

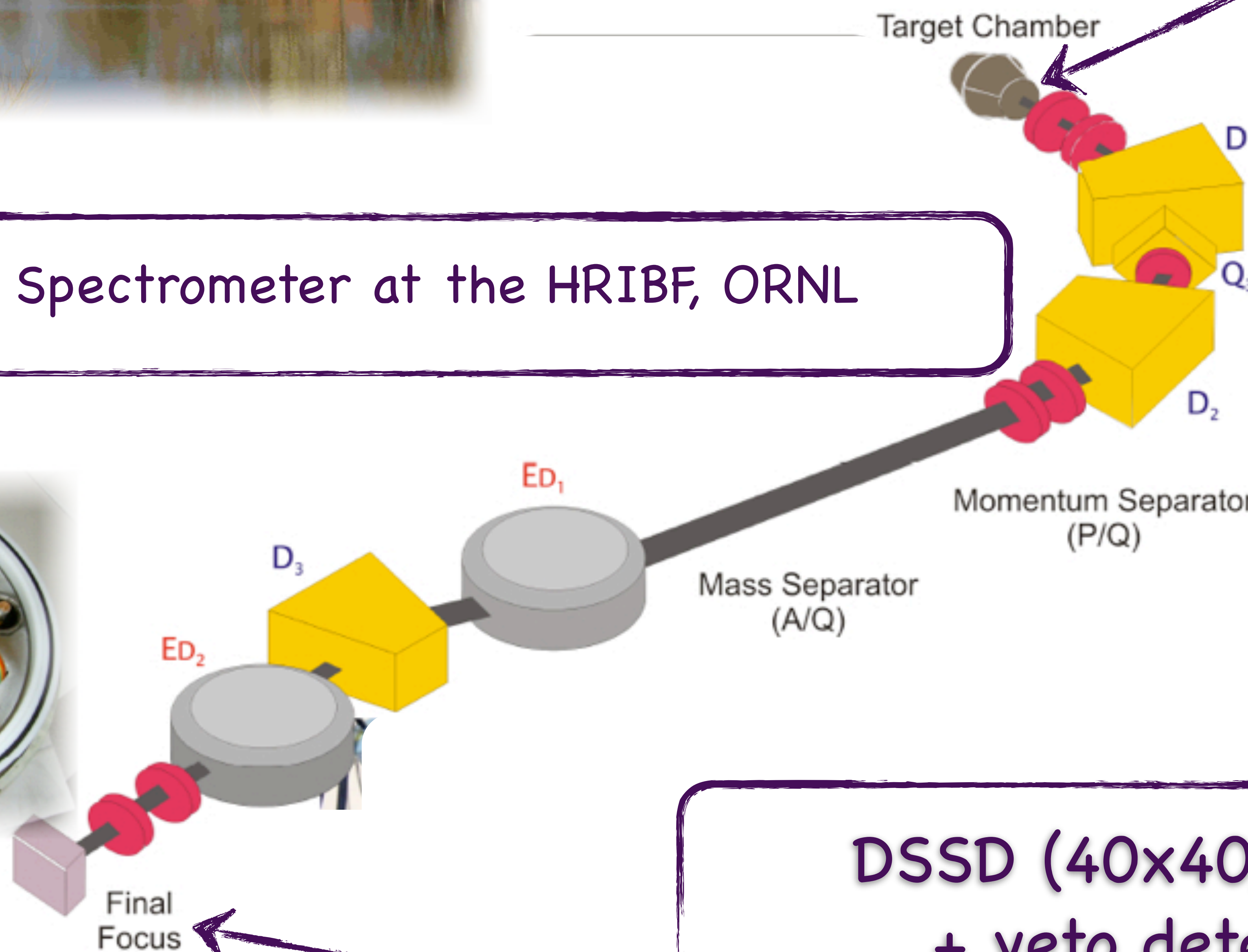


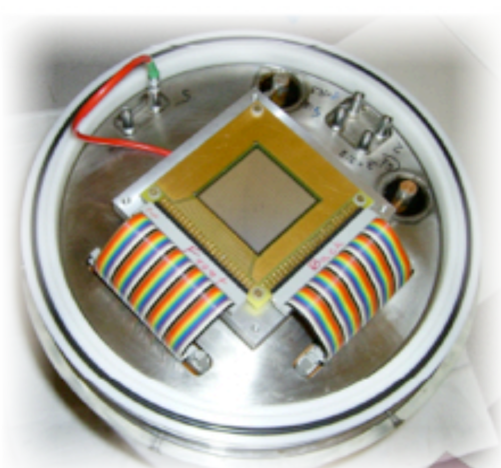
All other attempts to measure ^{105}Sb proton decay failed:
Munich set-up: Gillitzer et al., ZPA326 (1987)
SHIP: Berthes, GSI Report GSI-87-12, 1987
GSI-FRS: Friese et al, Proc. Hirschegg, 1996
GSI-ISOL: Liu et al., PRC72 (2005)

alpha decay of ^{109}I -> S_p in ^{105}Sb

$^{54}Fe+^{58}Ni \rightarrow ^{112}Xe^{*}(p2n)^{109}I$

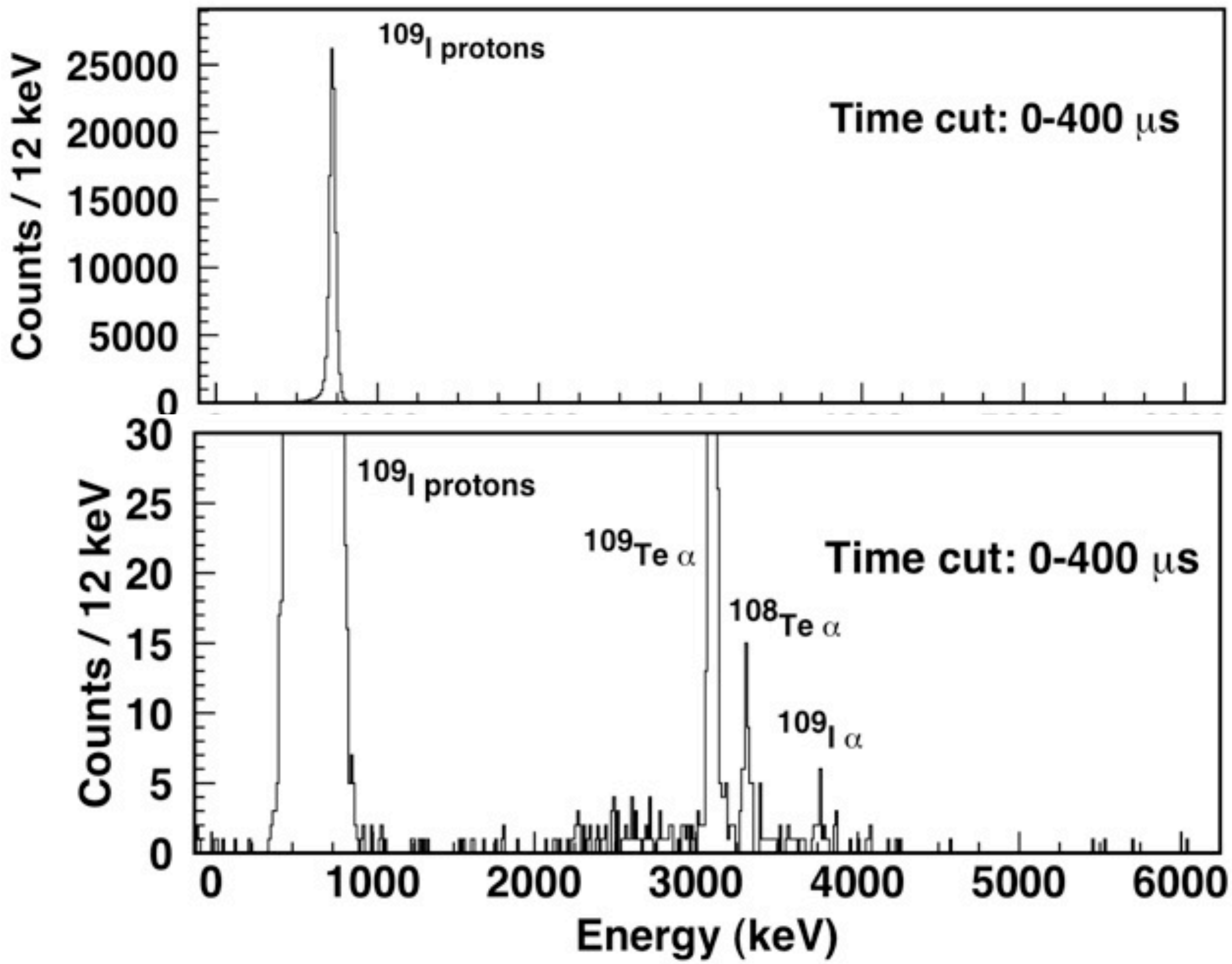
Recoil Mass Spectrometer at the HRIBF, ORNL





DSSD (40x40, 65 μm)
+ veto detectors

alpha decay of ^{109}I: results



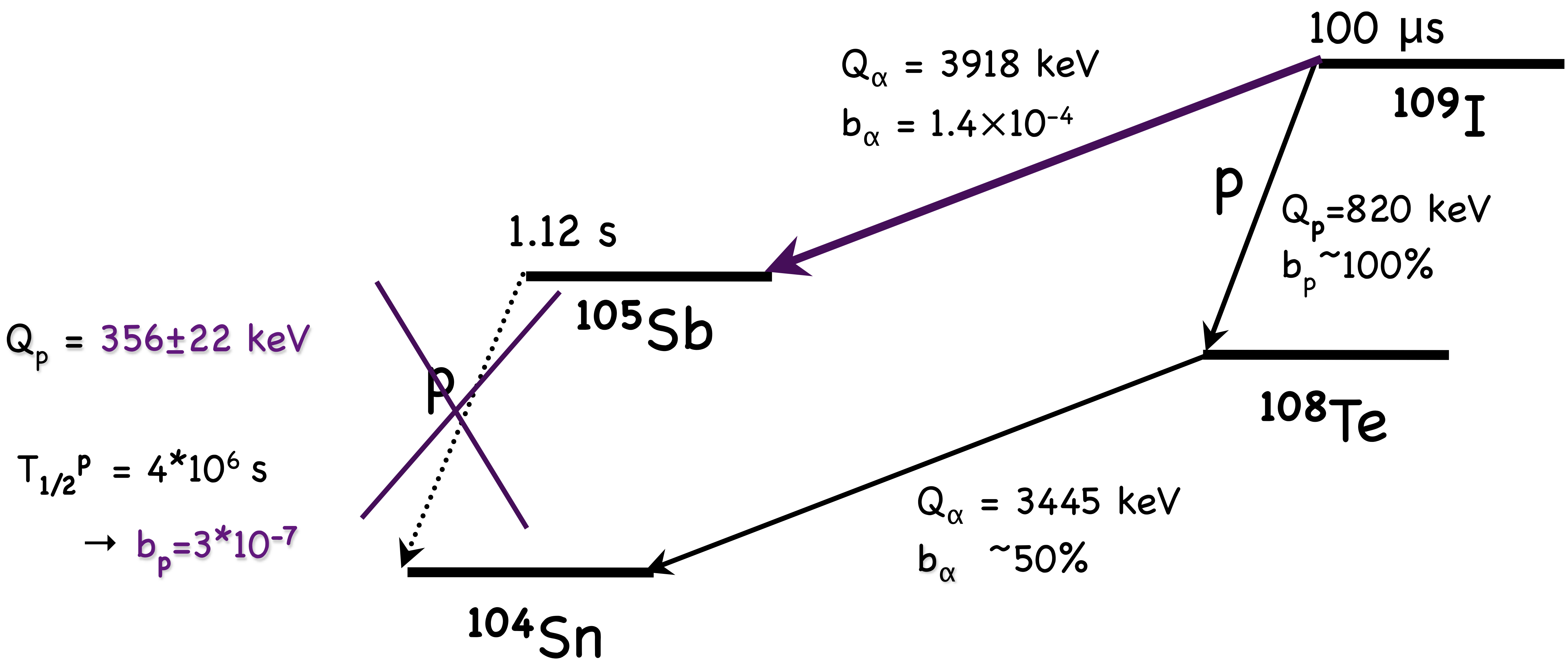
implanted 153 000 ^{109}I ions at RMS at HRIBF

$$E_\alpha(^{109}\mathrm{I}) = 3774 \pm 20 \text{ keV} \Rightarrow Q_\alpha(^{109}\mathrm{I}) = 3918 \pm 21 \text{ keV}$$

$$b_\alpha = (1.4 \pm 0.4)*10^{-4} \rightarrow T_{1/2}^{\alpha} \sim 1.5 \text{ s}$$

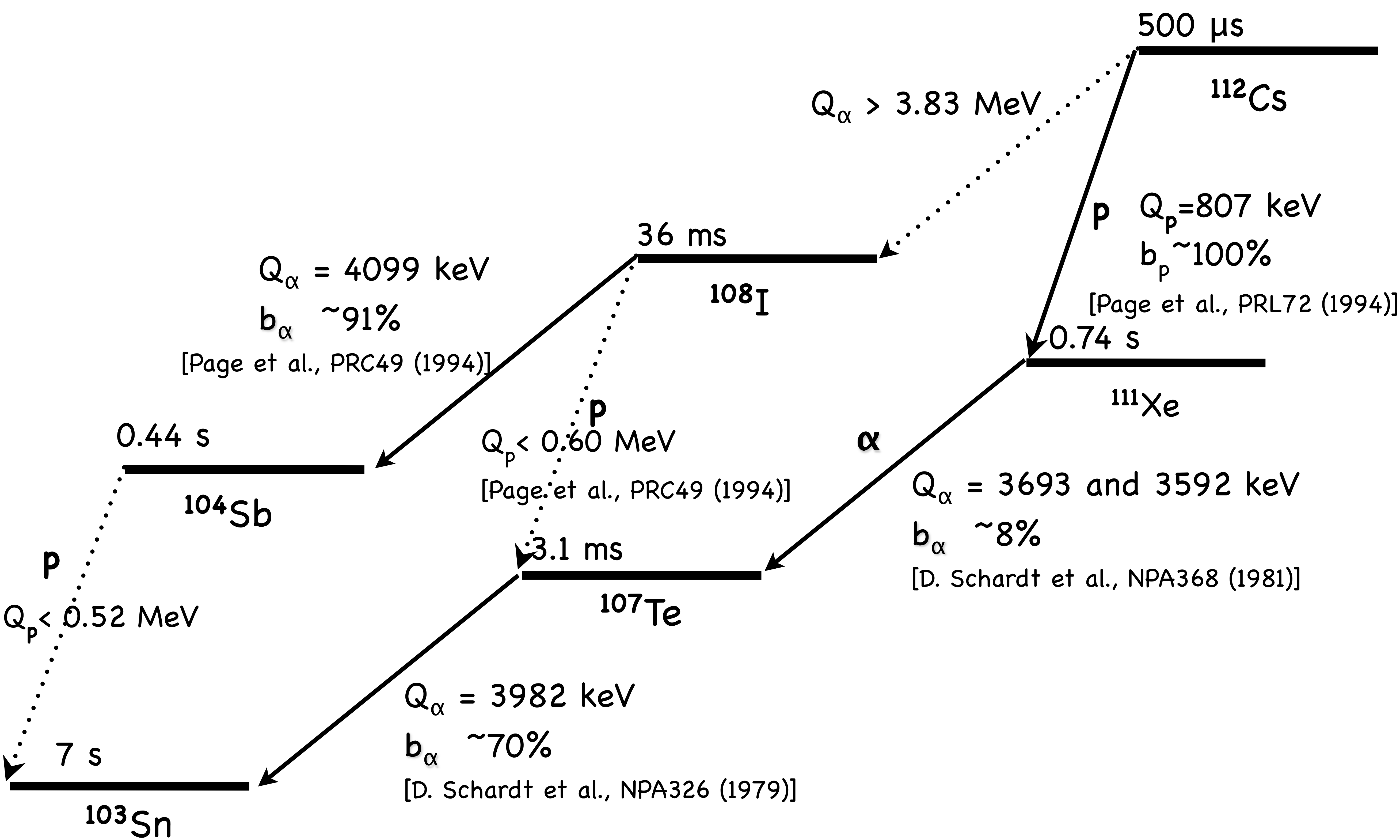
CM et al., PRL98 (2007)

alpha decay of ^{109}I -> Q_p-value of ^{105}Sb



⇒ Practically **impossible** to observe g.s. proton emission from ^{105}Sb

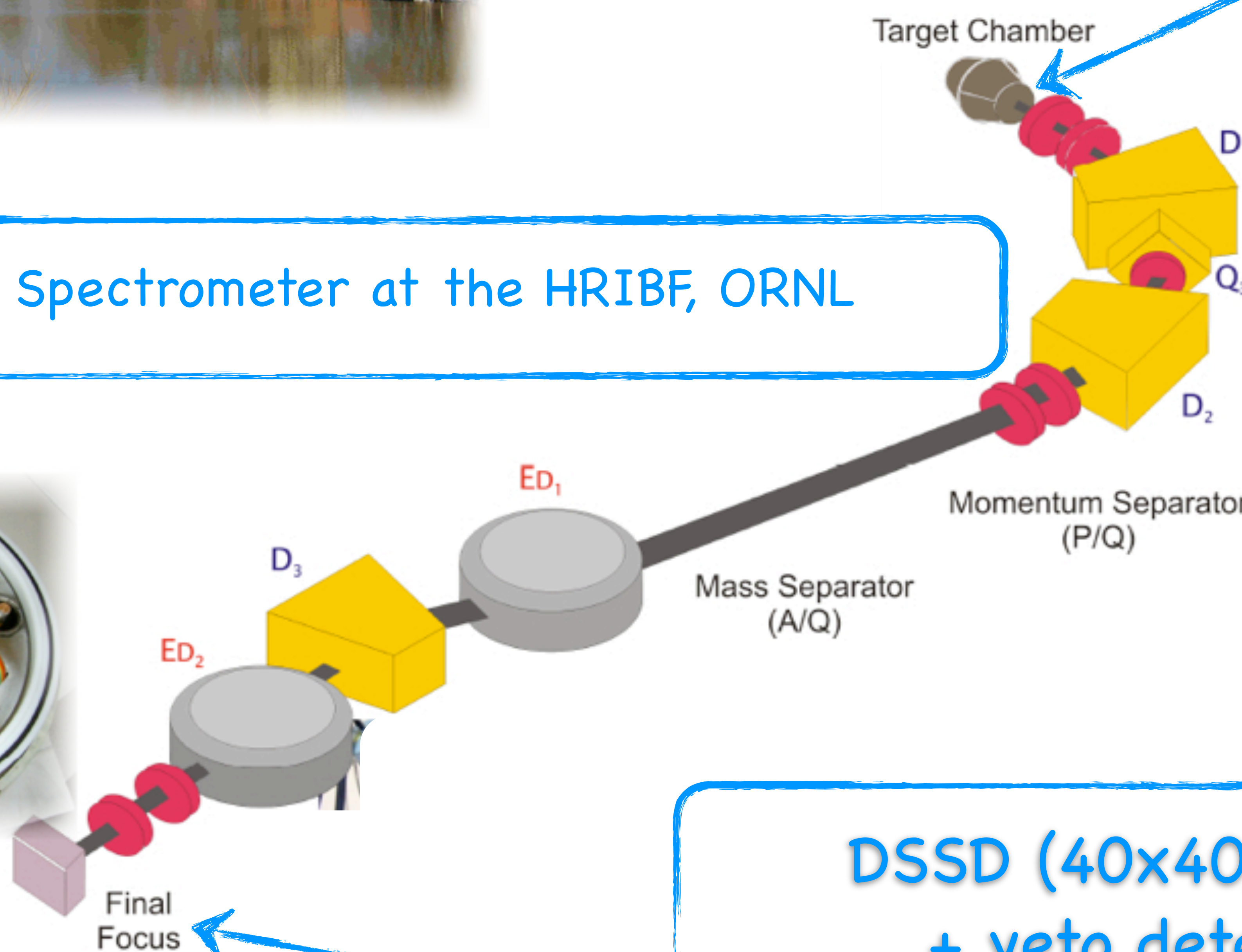
alpha decay of ^{112}Cs -> S_p in ^{104}Sb

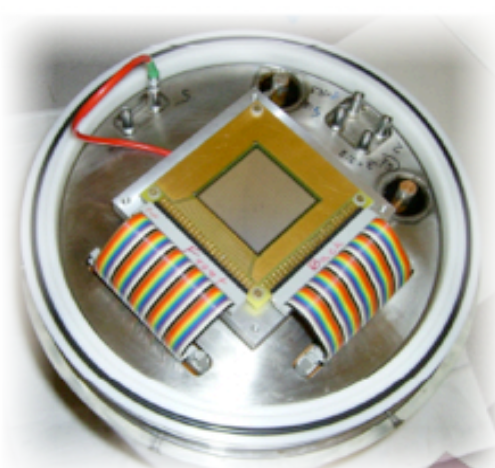


alpha decay of ^{112}Cs -> S_p in ^{104}Sb

$^{58}Ni + ^{58}Ni \rightarrow ^{116}Ba^{*}(p3n)^{112}Cs$

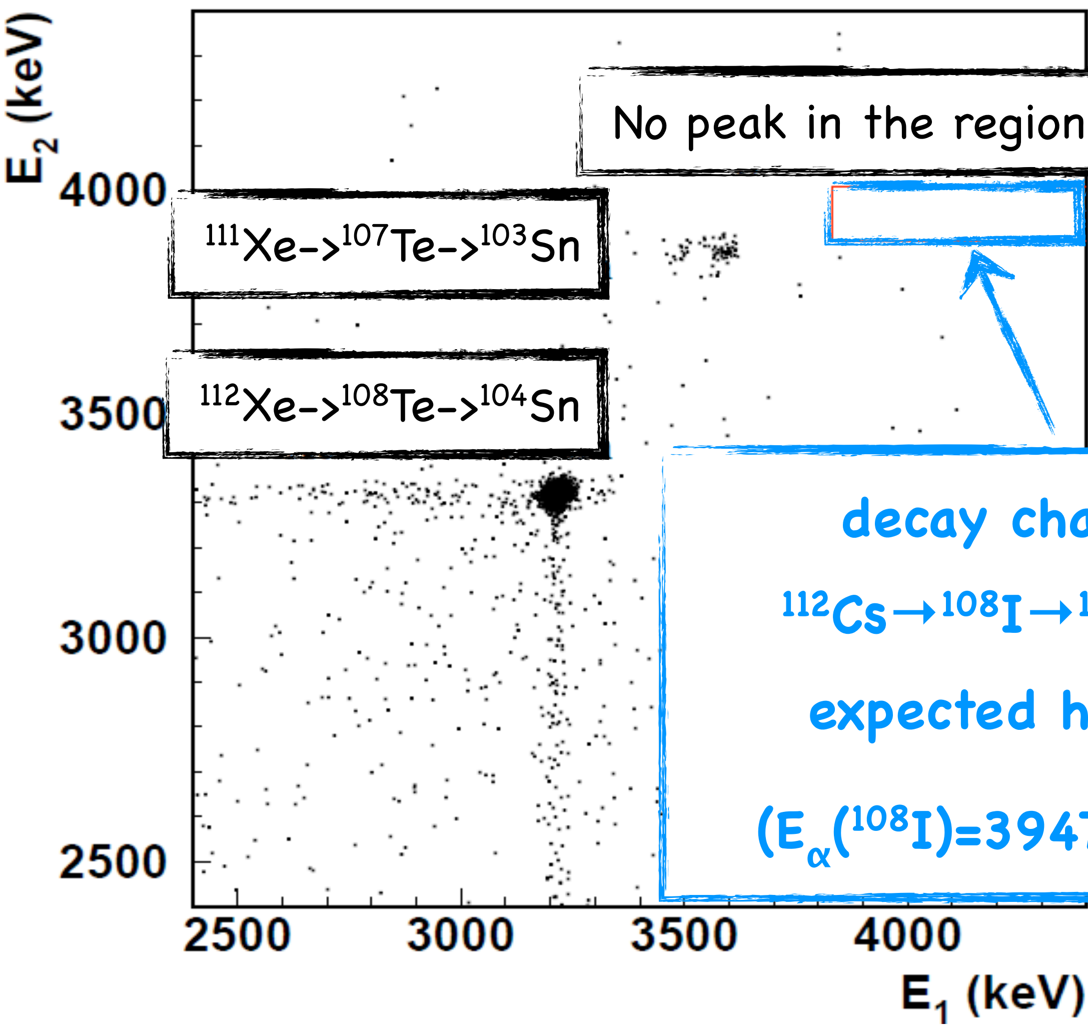
Recoil Mass Spectrometer at the HRIBF, ORNL





DSSD (40x40, 65 μm)
+ veto detectors

alpha decay of ^{112}Cs: results -> alpha-alpha correlations



decay chain

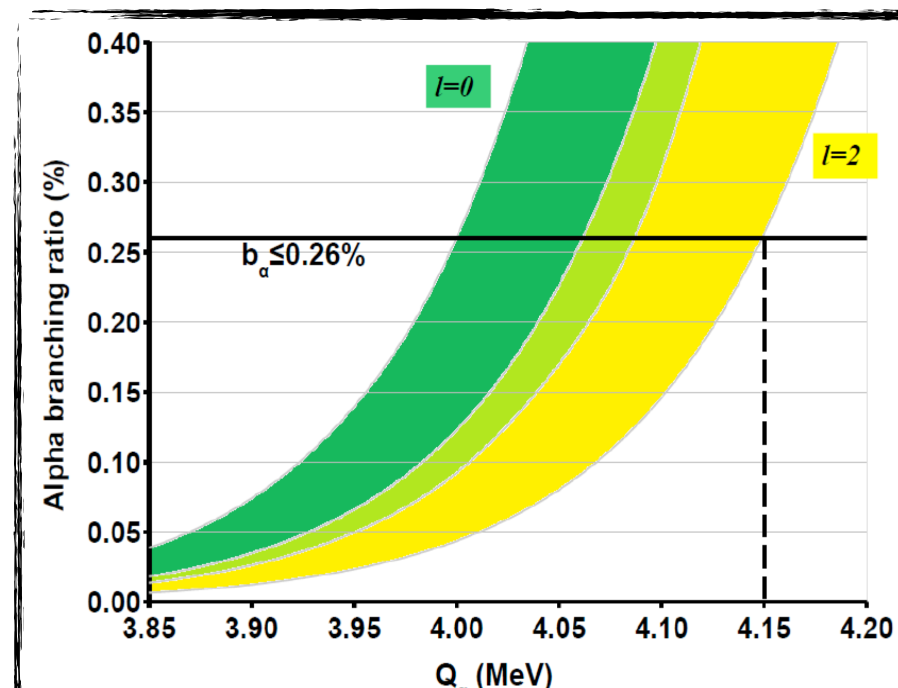
$^{112}Cs \rightarrow ^{108}I \rightarrow ^{104}Sb$

expected here

$(E_{\alpha}(^{108}I)=3947keV)$

Alpha decay of ^{112}Cs not observed

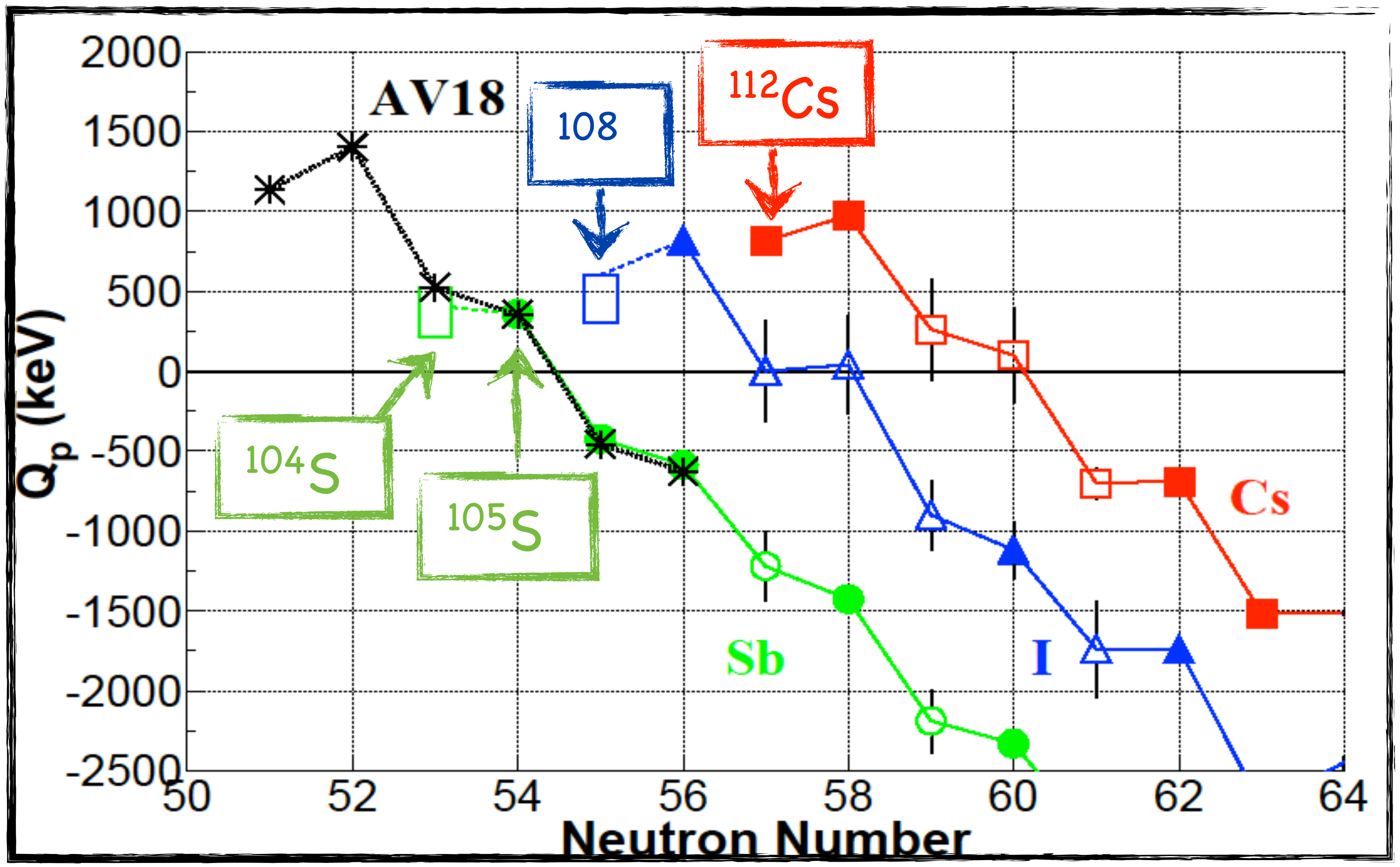
alpha branching ratio < 0.26%



	Q_p (MeV)	Q_{α} (MeV)
^{104}Sb	0.15-0.52	
^{108}I	0.24-0.60	
^{112}Cs		3.83-4.21

L. Cartegni et al., submitted to PRC

^{109}I and ^{112}Cs results: odd-even effects on S_p energy

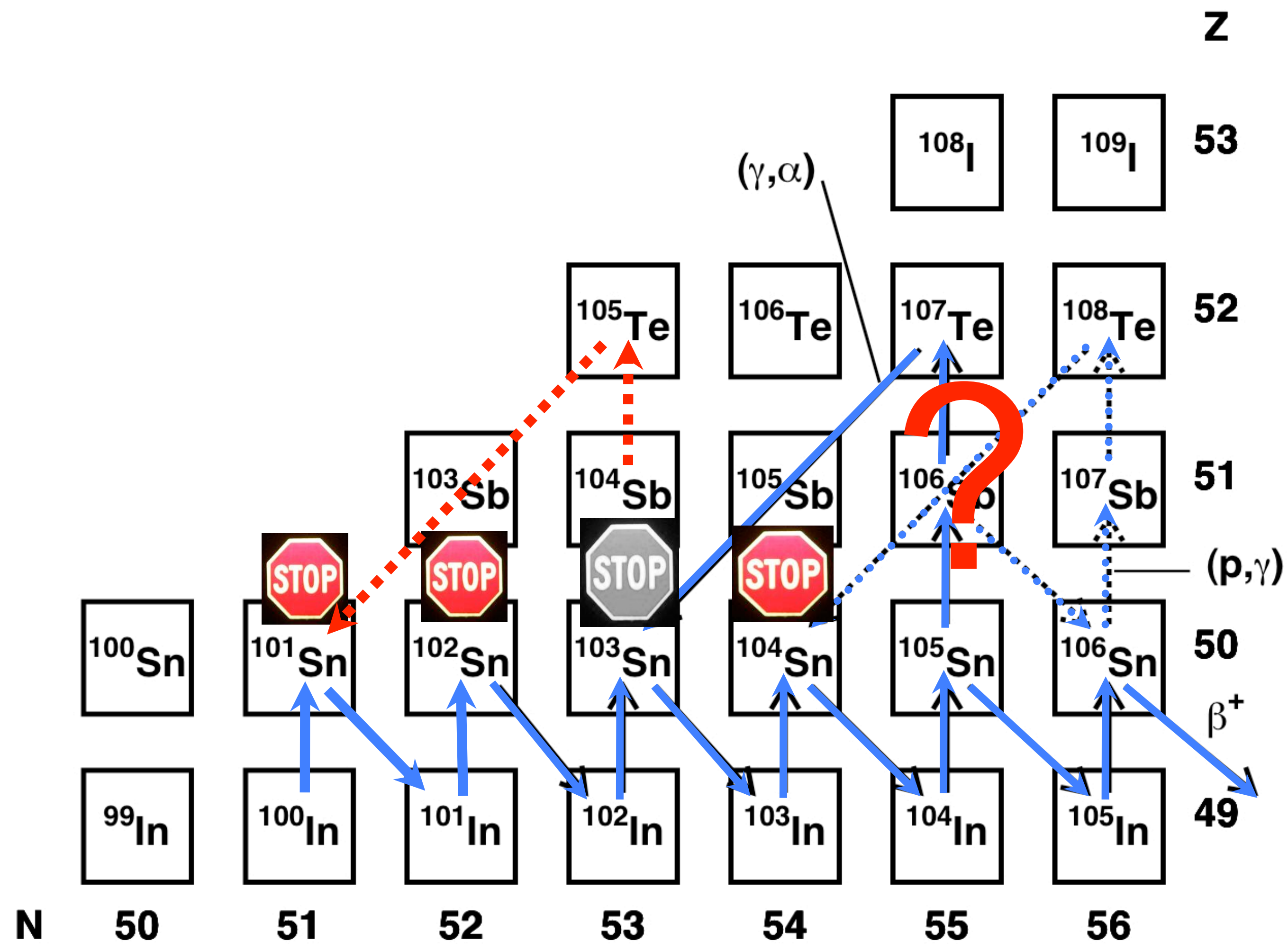


- strong staggering of the S_p values for odd-Z isotopes near ^{100}Sn
- calculations with AV18 possible for Z=51 Sb isotopes:
  binding energies calculated for Sn and Sb isotopes and S_p values normalized to the measured Sp(^{105}Sb)
  ==> ^{103}Sb will be very unstable ($T_{1/2}$~ps) but thanks to the odd-even effects, ^{102}Sb may be a "longer-lived" proton emitter ($T_{1/2}$~ns)

L. Cartegni et al., submitted to PRC
CM et al., PRL98 (2007)

AV18: I.G. Darby et al, PRL**105**, 2010;
M. Hjorth-Jensen et al, Phys. Rep. **261**, 1995

^{109}I and ^{112}Cs results: rp-process termination



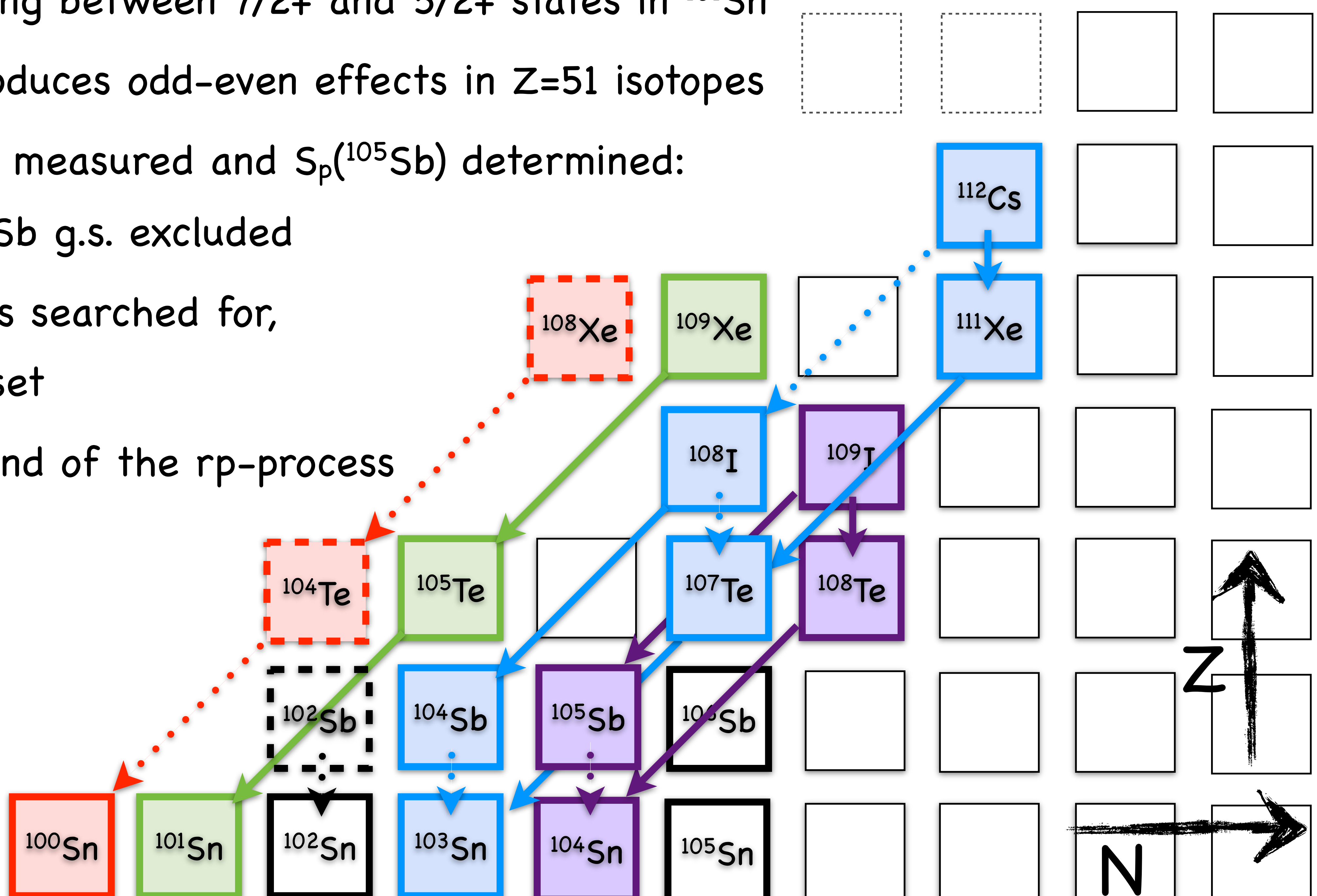
New Q_p values:

- ^{105}Sb excludes formation of Sn-Sb-Te cycle at ^{104}Sn and corresponding enhancement in energy production and X-ray luminosity during the tail end of an X-ray burst
- ^{104}Sb excludes the formation of the cycle already at ^{103}Sn
- ^{106}Sb suggests that very little cycling happens at rp-process end [Elomaa et al., PRL 102 (2009)]

=> the rp-process simply dies out

summary

- Fine structure in the alpha decay of ^{105}Te observed (α and γ)
- Observed ordering of 5/2$^+$ and 7/2$^+$ levels explained by theory (AV18,N3LO...): due to unusually strong pairing interaction between $g_{7/2}$ neutrons and unusually small energy splitting between 7/2+ and 5/2+ states in ^{101}Sn
- The same SM reproduces odd-even effects in Z=51 isotopes
- Alpha decay of ^{109}I measured and S_p(^{105}Sb) determined: proton decay of ^{105}Sb g.s. excluded
- Alpha decay of ^{112}Cs searched for, limits on Sp(^{104})Sb set
- No cycling at the end of the rp-process



outlook

- Keep searching for the decay chain (^{112}Ba ->) ^{108}Xe -> ^{104}Te -> ^{100}Sn
- Keep searching for the alpha decay branch in the decay of ^{112}Cs

References

PHYSICAL REVIEW C 73, 061301(R) (2006)

α decay of ^{105}Te

D. Seweryniak,[1] K. Starosta,[2] C. N. Davids,[1] S. Gros,[1] A. A. Hecht,[3] N. Hoteling,[3] T. L. Khoo,[1] K. Lagergren,[4] G. Lotay,[5] D. Peterson,[1] A. Robinson,[1] C. Vaman,[2] W. B. Walters,[3] P. J. Woods,[4] and S. Zhu[1]
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PRL 97, 082501 (2006) PHYSICAL REVIEW LETTERS week ending 25 AUGUST 2006

Discovery of ^{109}Xe and ^{105}Te: Superallowed α Decay near Doubly Magic ^{100}Sn

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PRL 99, 022504 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

Single-Neutron States in ^{101}Sn

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Orbital Dependent Nucleonic Pairing in the Lightest Known Isotopes of Tin

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α Decay of ^{109}I and Its Implications for the Proton Decay of ^{105}Sb and the Astrophysical Rapid Proton-Capture Process

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Experimental study of the decays of ^{112}Cs and ^{111}Xe

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THANK YOU!