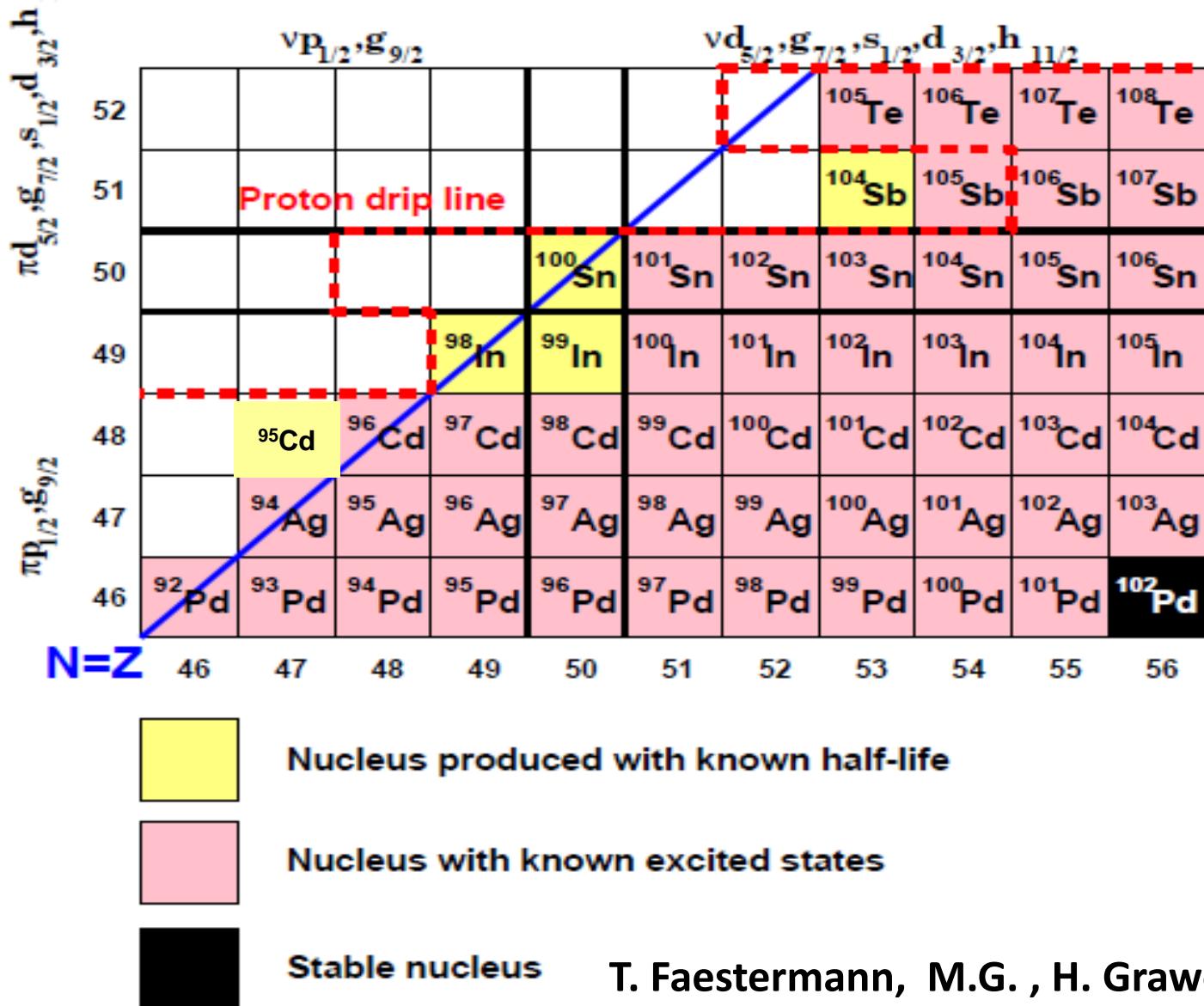


Recent results in the region of ^{100}Sn

M.Góriska

GSI Darmstadt



H. Baba*5, B. Blank*7, A. Blazhev*8, P. Boutachkov*9, F. Brown*10, I. Čeliković,*1,*2,
G. de France*1, P. Davis*17, P. Doornenbal*5, T. Faestermann*3, Y. Fang*11, R. Gernhäuser*3,
N. Goel*9, M. G.*9, H. Grawe*9, S. Ilieva*12, T. Isobe*5, A. Jungclaus*13, G. D. Kim*14,
Y.-K. Kim*14, I. Kojouharov*9, R. Krücken*4, N. Kurz*9, M. Lewitowicz*1, Z. Liu*20, G. Lorusso*5,
D. Lubos*3, K. Moschner*8, S. Nishimura*5, I. Nishizuka*15, F. Nowacki*21, J. Park*4, Z.
Patel*16, M. Rajabali*4, S. Rice*16, H. Sakurai*6, H. Schaffner*9, K. Sieja*21, L. Sinclair*17,
P. A. Söderström*5, K. Steiger*3, T. Sumikama*15, Z. Wang*4, R. Wadsworth*17,
H. Watanabe*18, P.J. Woods*20, J. Wu*19, and Z. Xu*6

*1 GANIL,

*2 Institute "Vinča", University of Belgrade

*3 TechnischeUniversitätMünchen

*4 TRIUMF

*5 RIKEN NishinaCenter

*6 University of Tokyo

*7 CENBG

*8 University of Cologne

*9 GSI Darmstadt

*10 Brighton University

*11 Osaka University

*12 TU Darmstadt

*13 IEM CSIC, Madrid

*14 Institute for Basic Science

*15 Tohoku University

*16 Surrey University

*17 York University

*18 Beihang University

*19 Peking University

*20 University of Edinburg

*21 IPHC, Université de Strasbourg

Experimental conditions and techniques for spectroscopy

➤ Fusion symmetric reaction

EXOGAM, EUROBALL, GASP, AGATA.. + Ancillaries
- in-beam, seniority/core excited isomers

MSEP at GSI, IGISOL, LISOL

- β decay
- spin-gap isomers

Argonne, OakRidge

- α -decay

➤ Fragmentation, Spallation

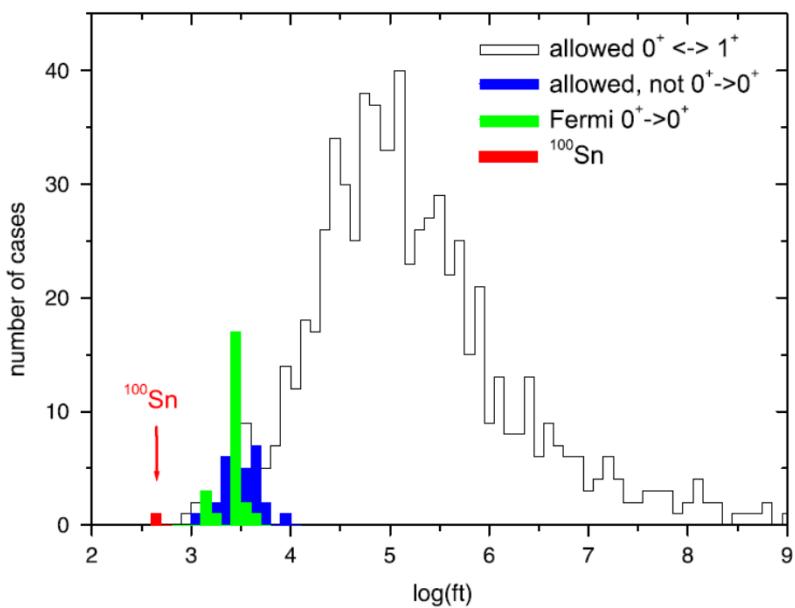
GSI, RIBF, NSCL, GANIL, REX-ISOLDE
- Coulex
- Transfer
- Isomers

Shell structure around ^{100}Sn / ^{56}Ni

$L=2 (=|l_p - l_h|)$ softness
E2 polarisation, isomers

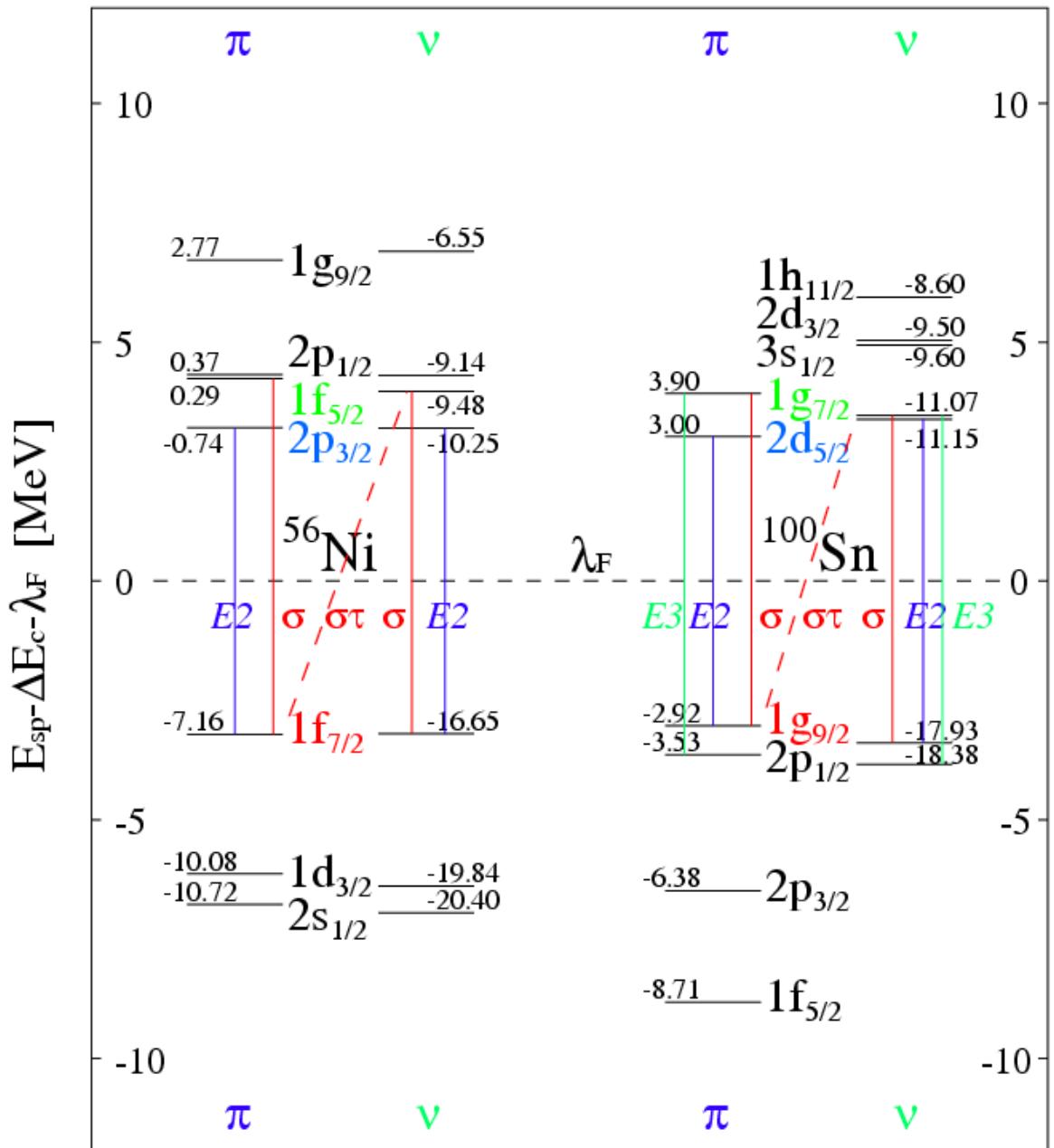
$\sigma/M1$ and σ/GT transitions

$L=3 (=|l_p \pm l_h|)$ E3 collectivity



C.B. Hinke et al., Nature 486, 341(2012)

H. Grawe et al., Phys. Scr. T56, 71(95)
H. Grawe, M. Lewitowicz NPA693, 116(01)

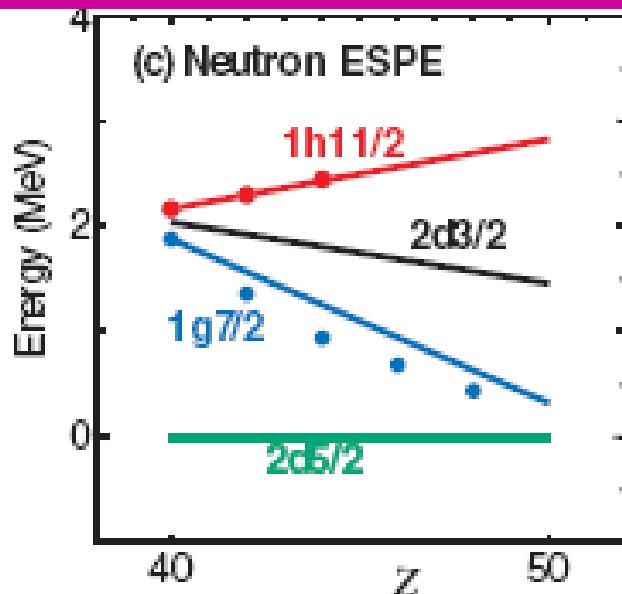


^{100}Sn ESPE evolution

Tensor interaction monopole

$$\nu h_{11/2} - \pi g_{9/2}, \nu g_{7/2} - \pi g_{9/2}$$

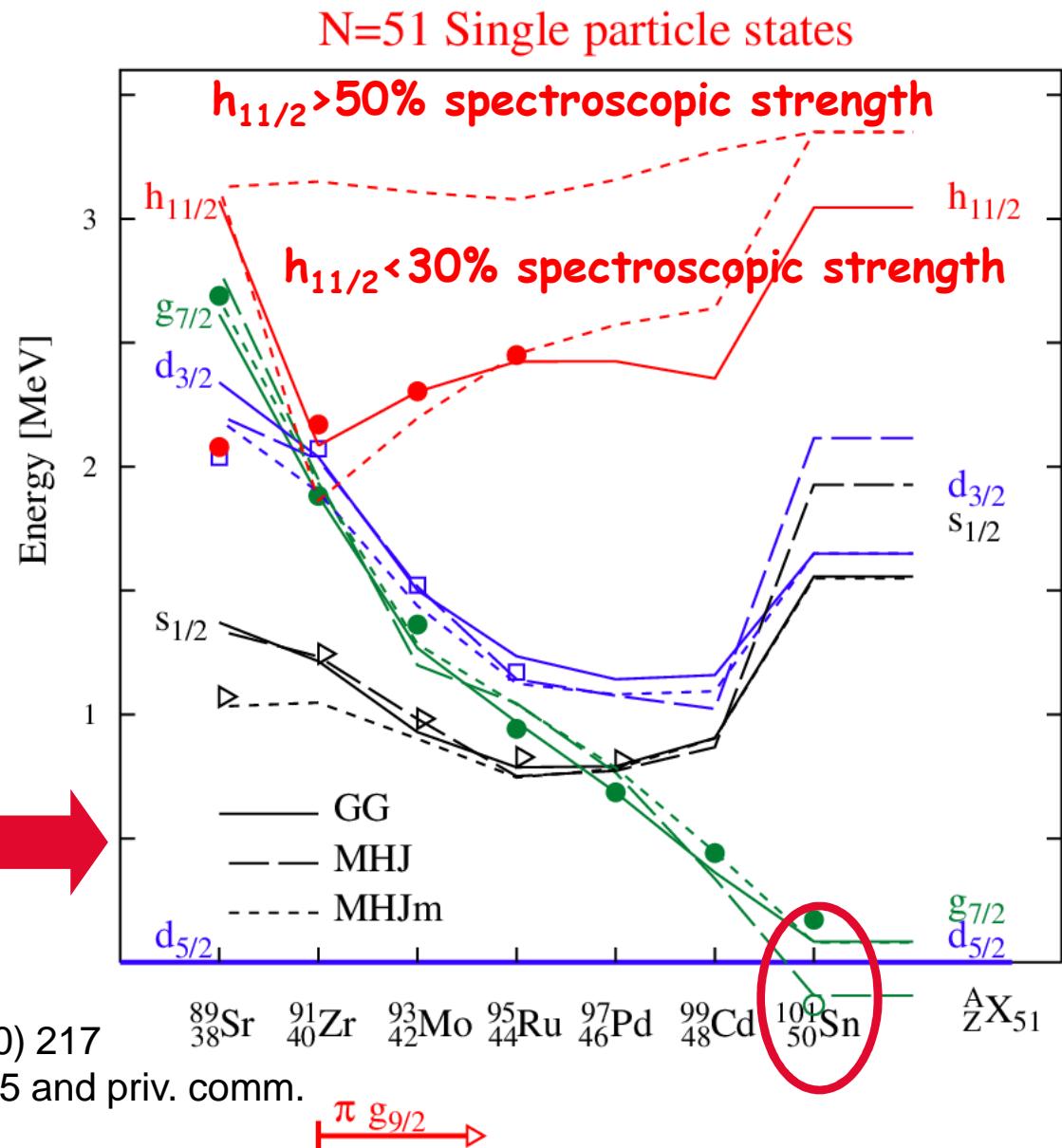
T. Otsuka et al., PRL 95,
232502 (2005)



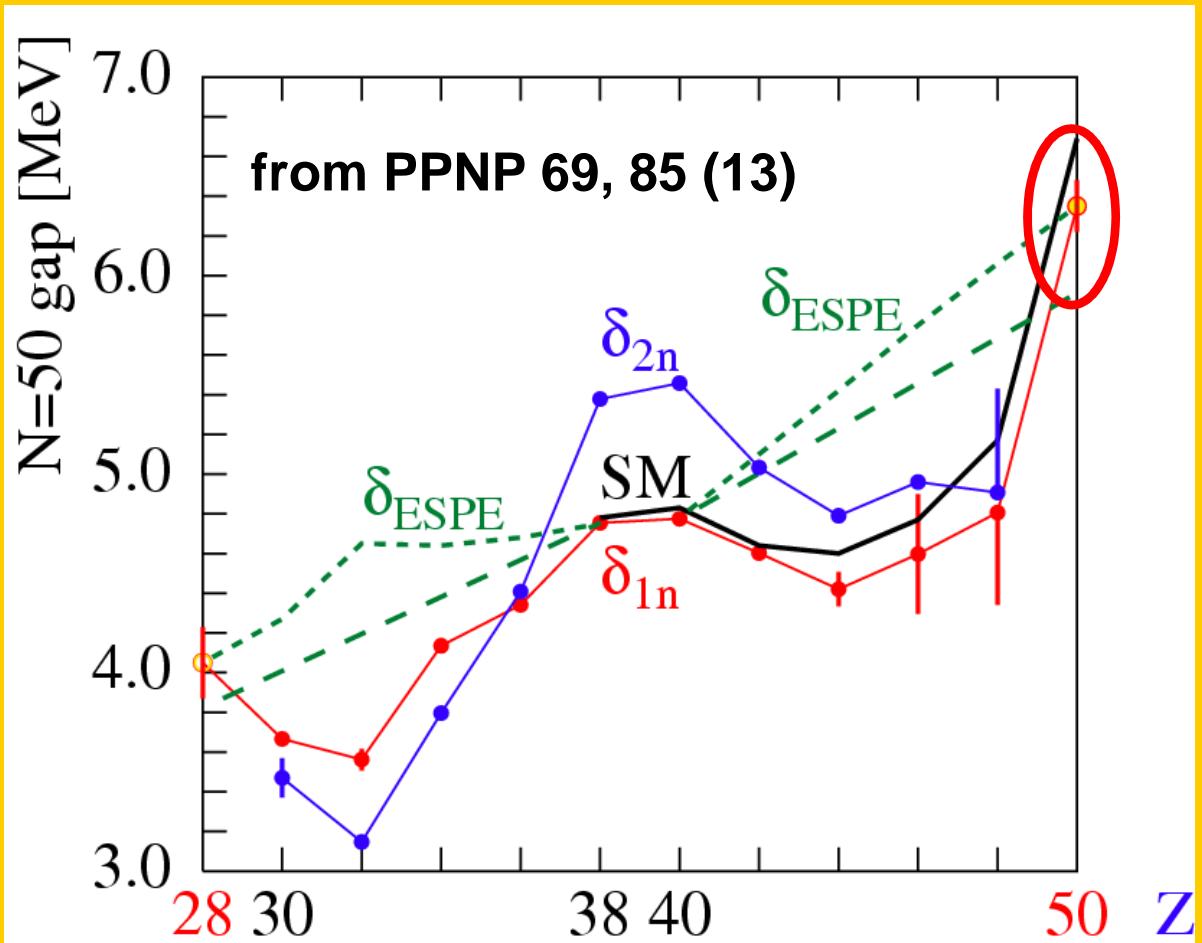
$\pi\nu$ interaction tuned for the model space ^{88}Sr , $\pi(p_{1/2}, g_{9/2})$
 $\nu(d_{5/2}, g_{7/2}, d_{3/2}, s_{1/2}, h_{11/2})$ gives the correct description of the evolution of SPEs

M. Górska et al., Proc. ENPE99, AIP CP495 (2000) 217

M. Hjorth-Jensen et al., Phys. Rep. 261 (1995) 125 and priv. comm.



Shell gap along N=50



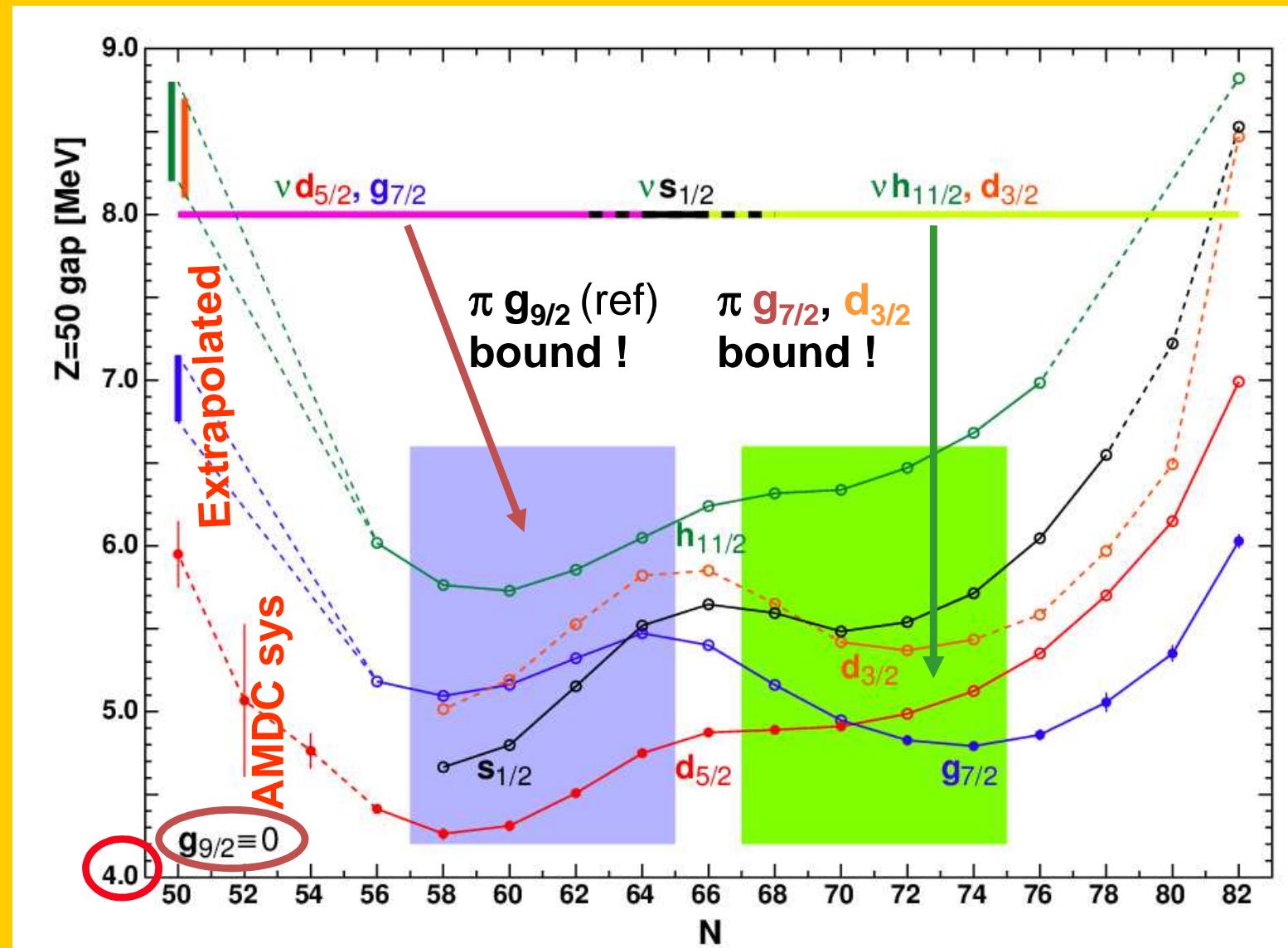
^{100}Sn :
6.35(13) MeV for $d_{5/2}$ g.s.
→ robust shell gaps !

- Exp. gaps from separation energies S_{1n}, S_{2n}
- ESPE from exp. multiplets corrected for π occupation
- - - theoretical monopole
T. Otsuka et al.,
PRL104,012501 (10)
- SM in valence space, no corex

^{78}Ni :
4.05(18) MeV for $d_{5/2}$ g.s.
4.7 from LSSM and $d_{5/2}$ g.s.
K. Sieja, F. Nowacki, PRC 85,051301(R) (12)

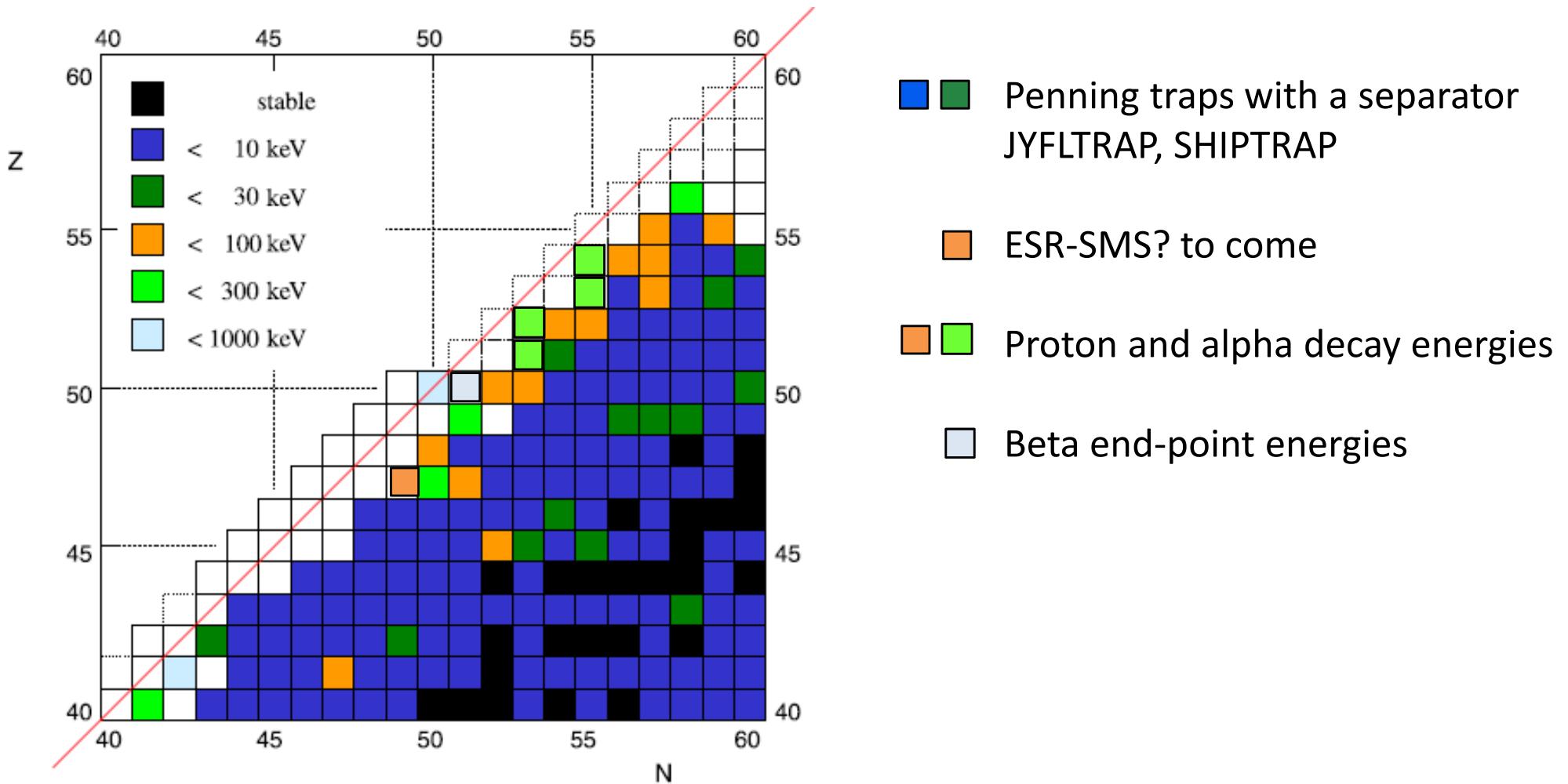
Experimental proton Z=50 shell gap and Z=51 single particle level evolution along the $^{100-132}\text{Sn}$ isotopic chain

Reference: $\pi g_{9/2}$



courtesy: H. Grawe

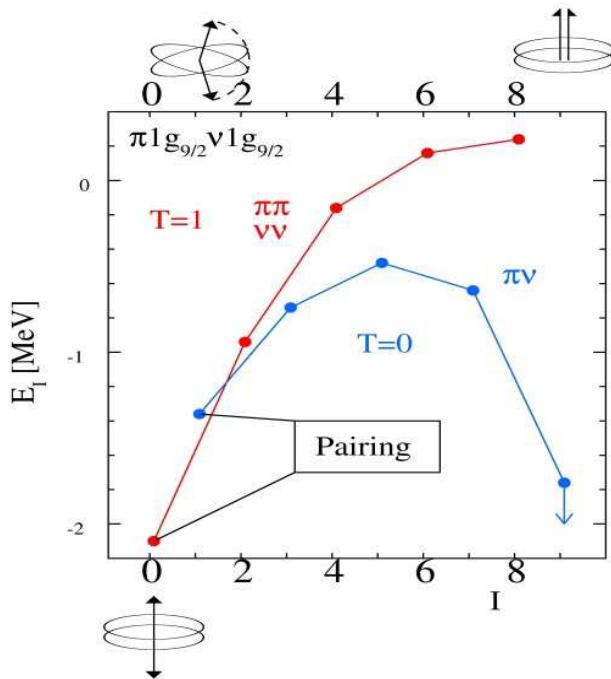
Precision of known Masses



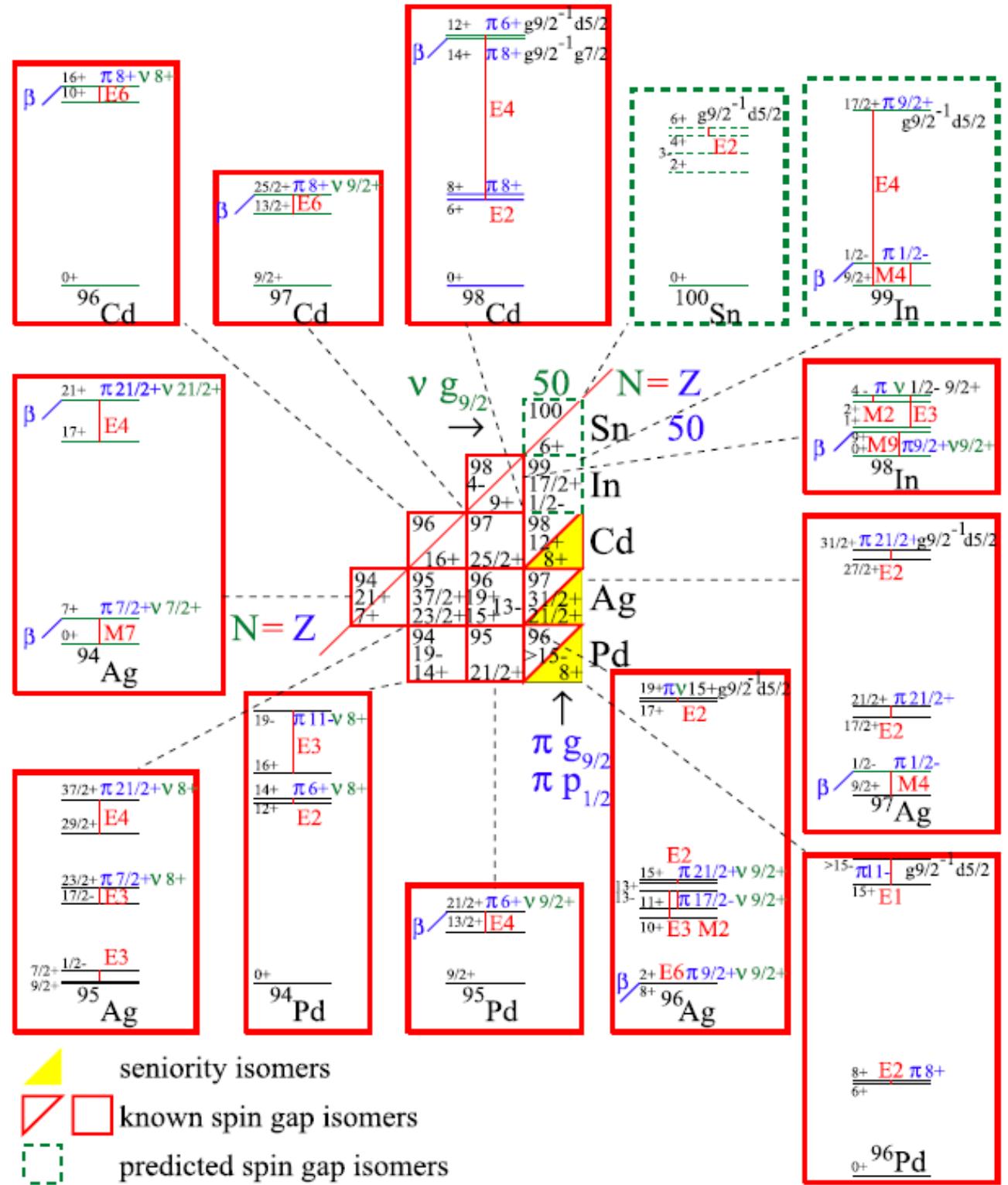
Spin gap isomers below $N = Z = 50$

with RISING and
GSI - ISOL

- proton - neutron
hole-hole interaction
in $p\ n\ g_{9/2}^{-n}$

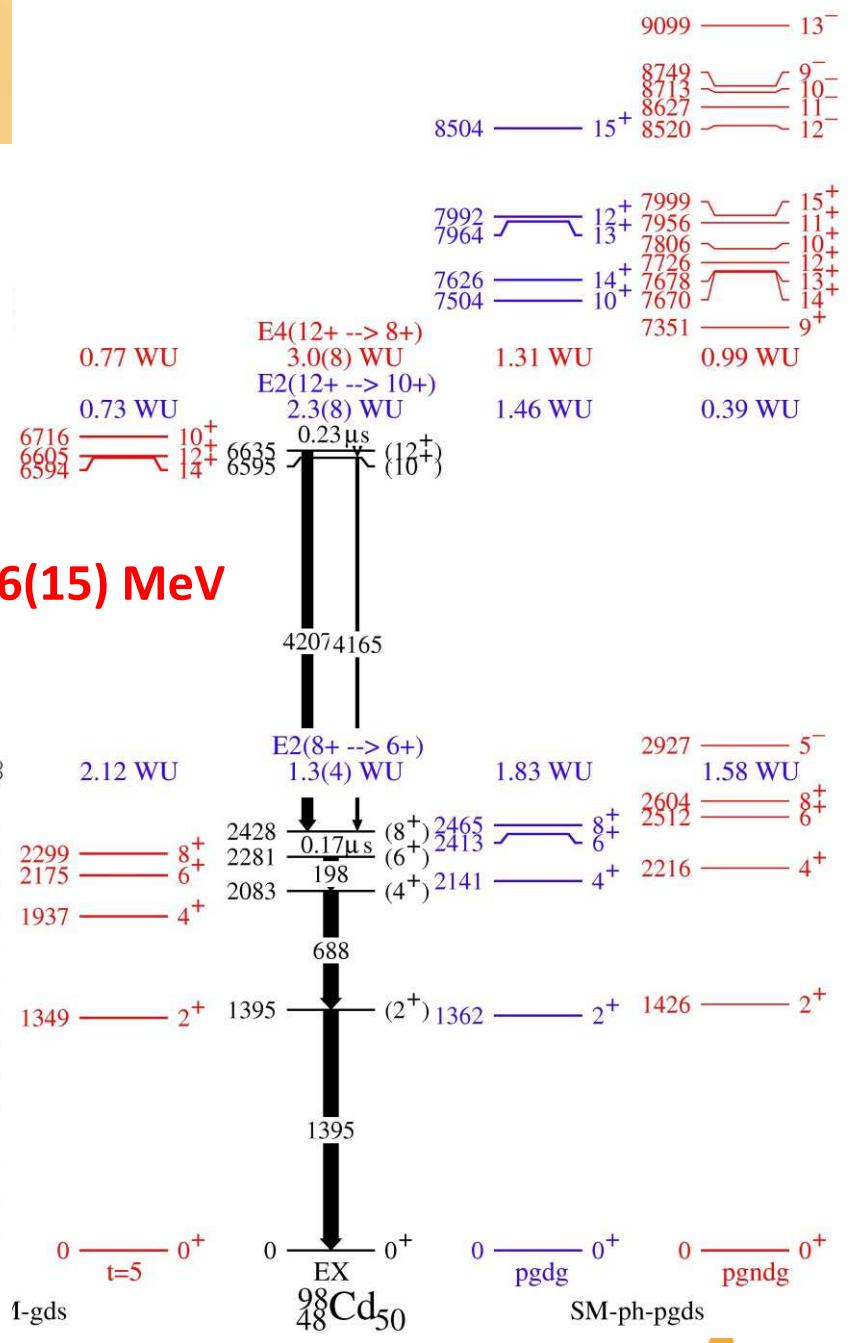
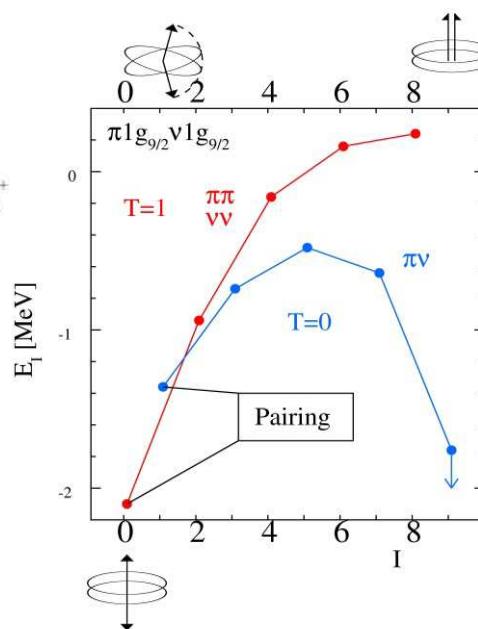
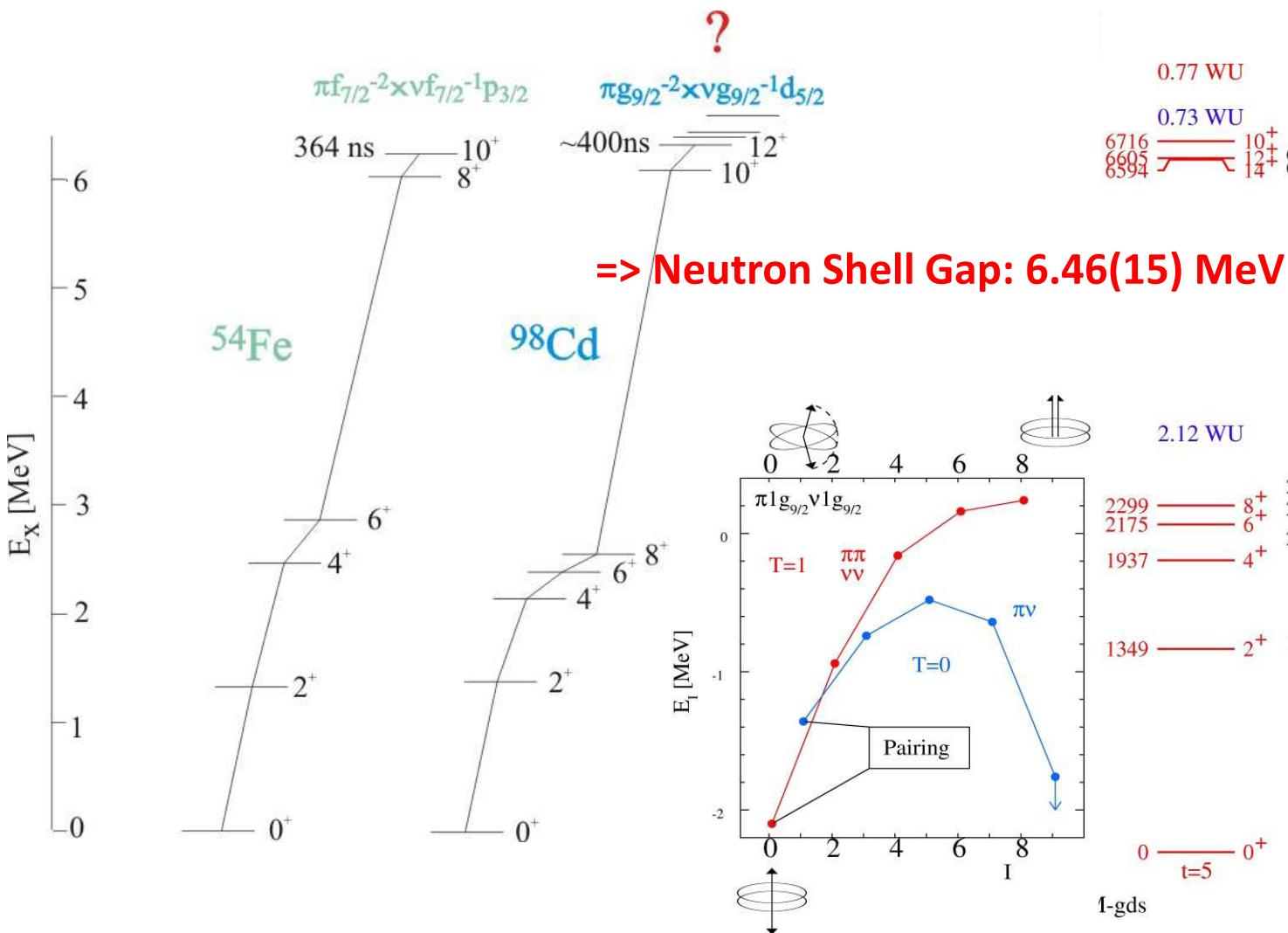


- core excitation
in large-scale SM



Core excited isomers

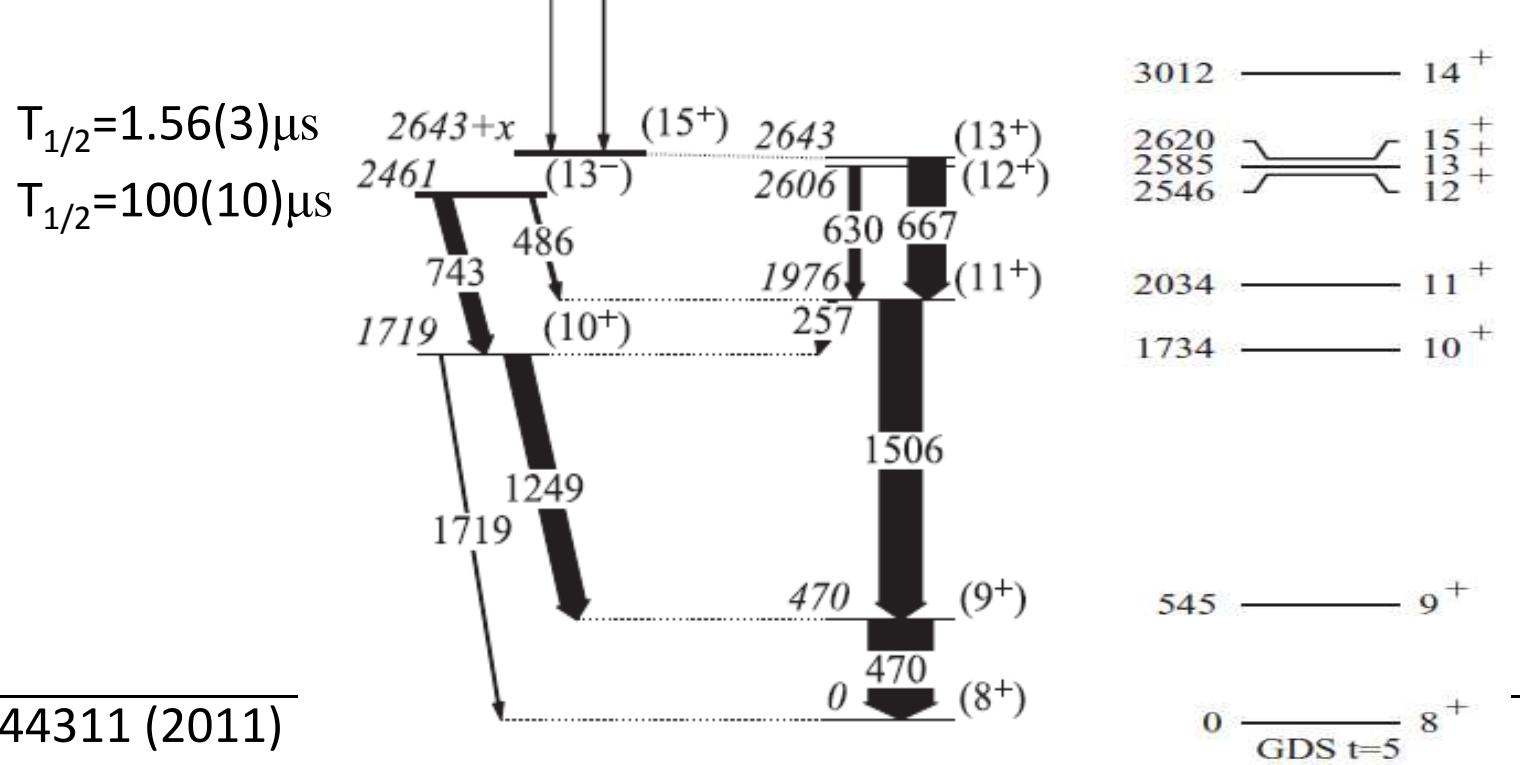
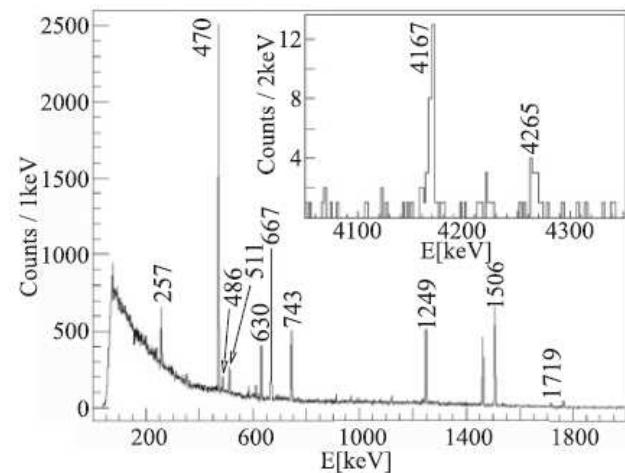
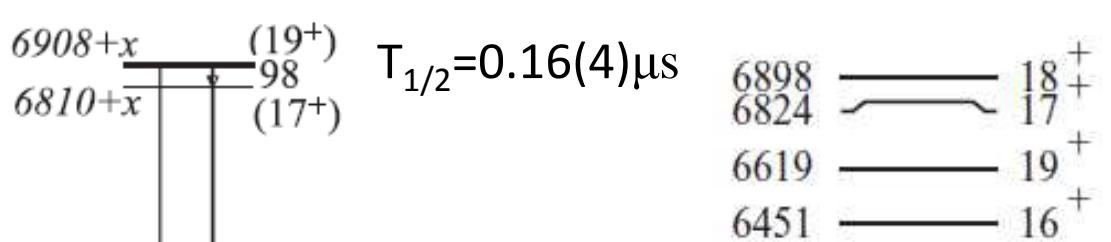
ν shell gap size extracted from ^{98}Cd analog of ^{54}Fe



96Ag

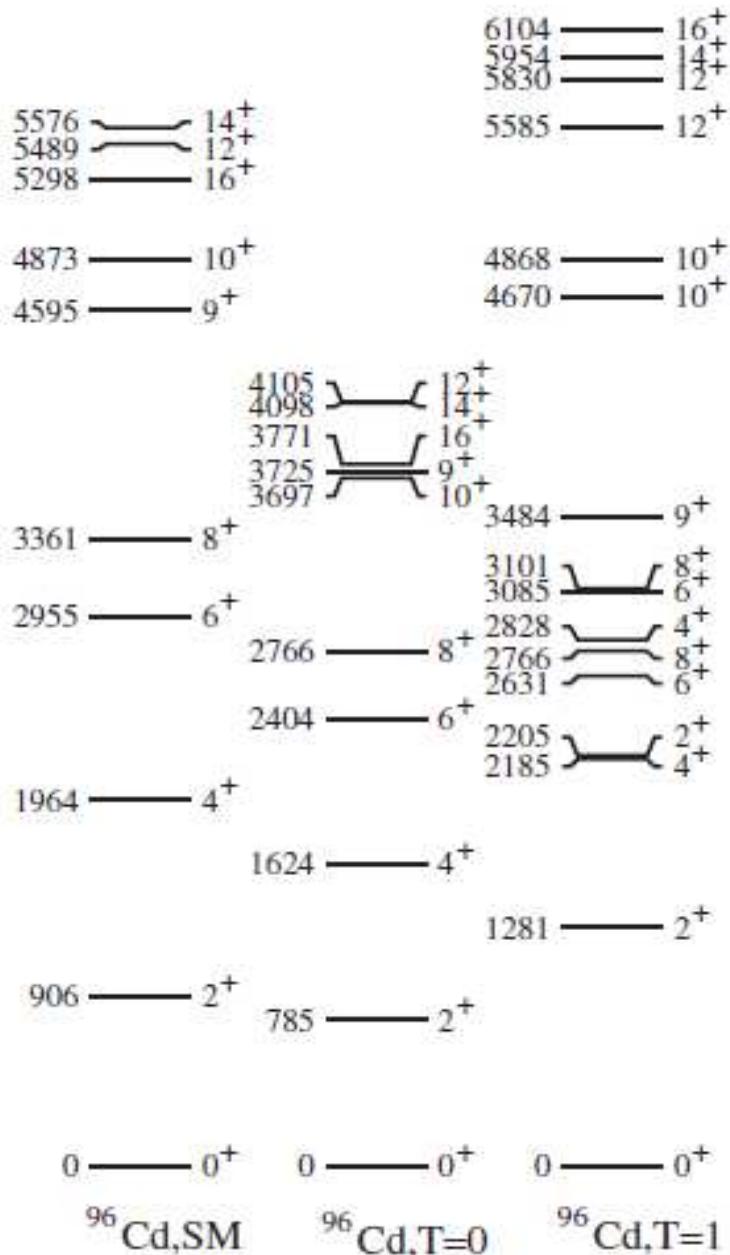
P. Boutachkov et al.,

=> Neutron Shell Gap: 6.7(15) MeV



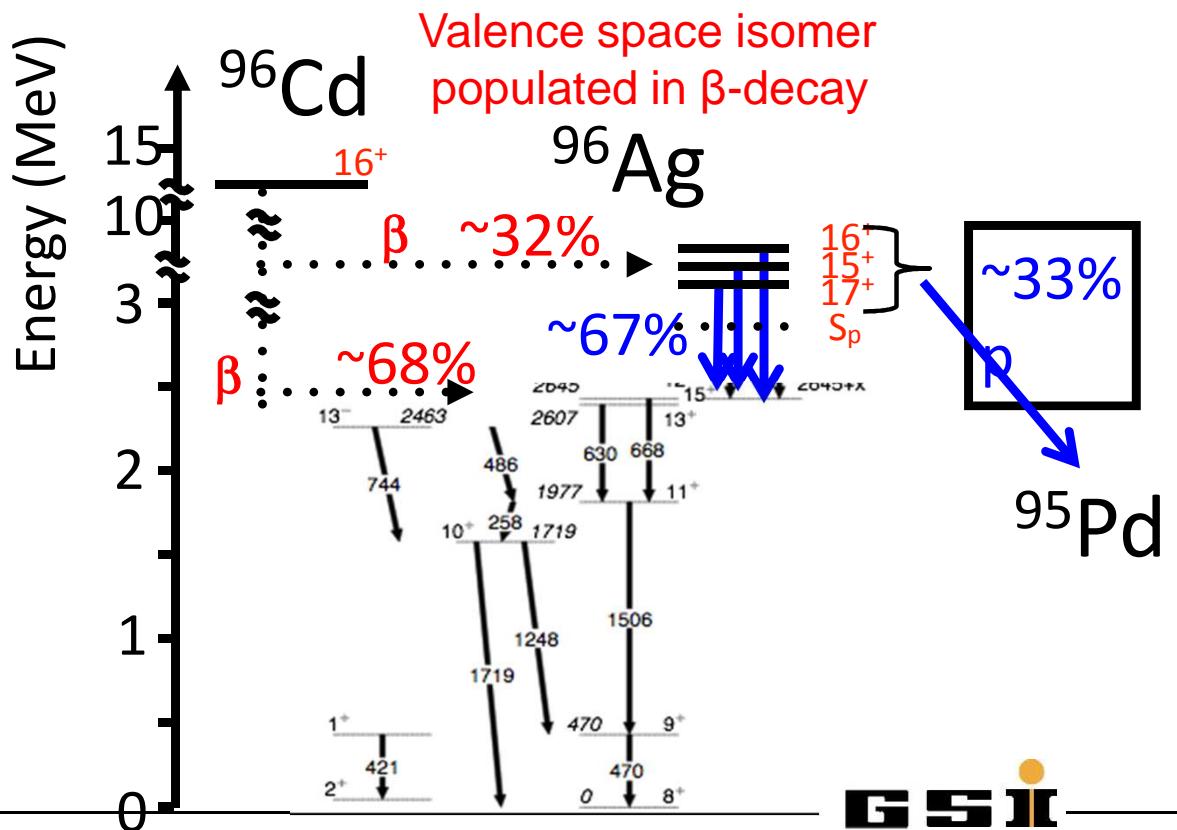
^{96}Cd : Isoscalar $\nu\pi$ interaction at high spin

B. S. Nara Singh, et al., PRL 107, 172502 (2011)



LSSM calcs - $\nu\pi(\text{gds})$ model space + ^{80}Zr core

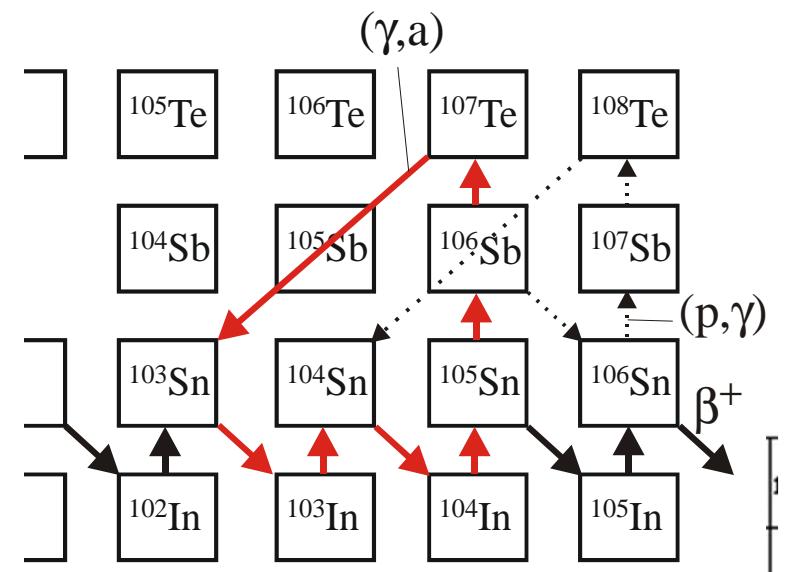
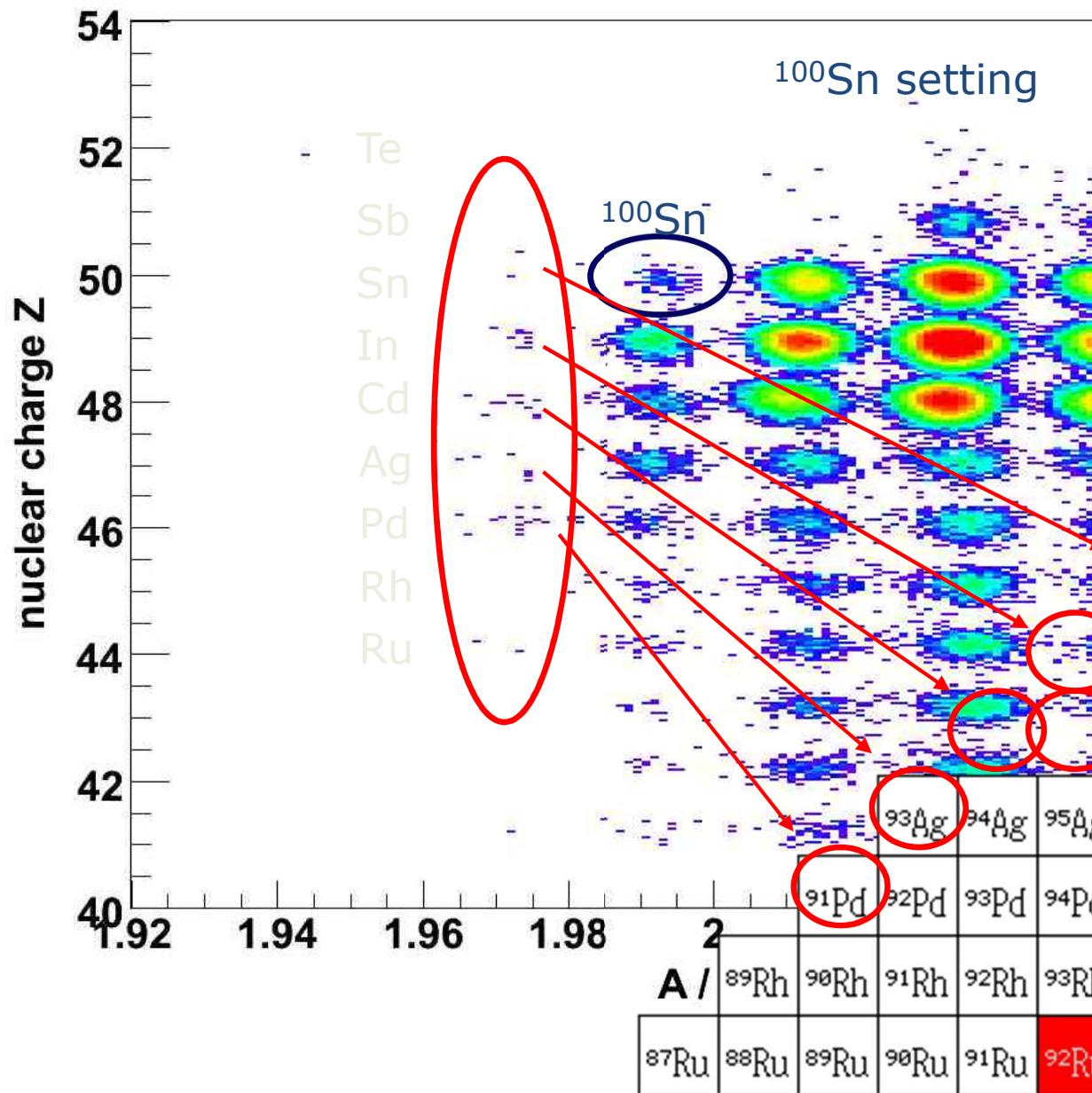
- ⇒ predict 16^+ state β -decays to 3 resonance states above the p thres that have significant core excited wavefn components + direct pop. of 15^+ isomer in ^{96}Ag .
- ⇒ Using simple WKB estimates, $15^+, 16^+, 17^+$ states were estimated to have large proton decay branches



Probing the proton dripline-Where does the rp-process end?

C.B. Hinke et al., Nature 486, 341(2012)

Faesterman et al, PPNP 69, 85 (13)



H. Schatz et al. PRL 86, 2001

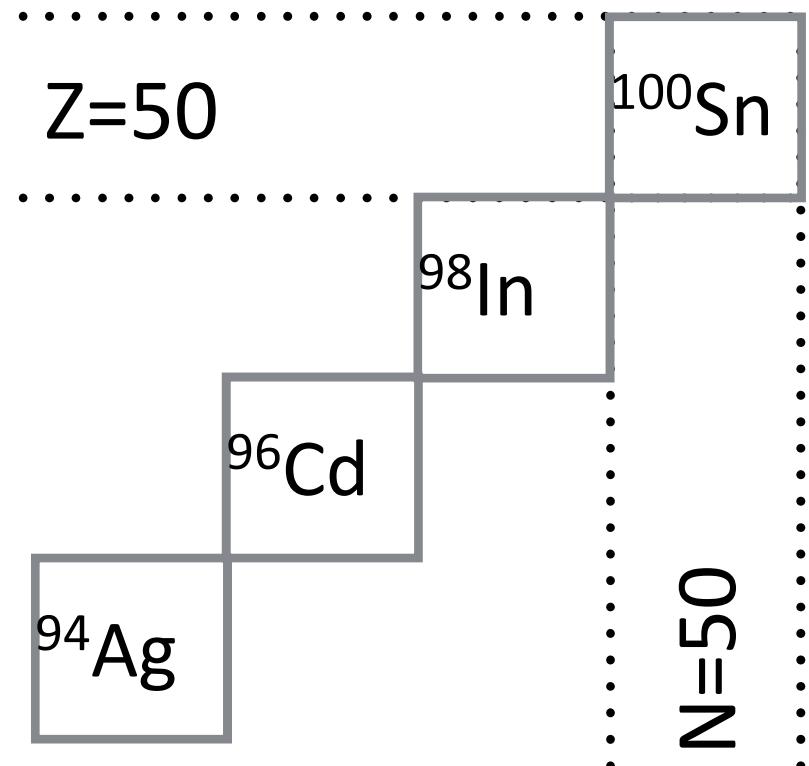
RIBF83 Experiment:

P Boutachkov, A Blazhev, R.Wadsworth
Isomer studies of ^{98}In , ^{96}Cd , ^{94}Ag

1 GSI

2 University of Cologne

3 University of York



RIBF009 Experiment:

M. Lewitowicz*¹, R. Gernhäuser*³,
R. Krücken*⁴, S. Nishimura*⁵, I. Čeliković,*

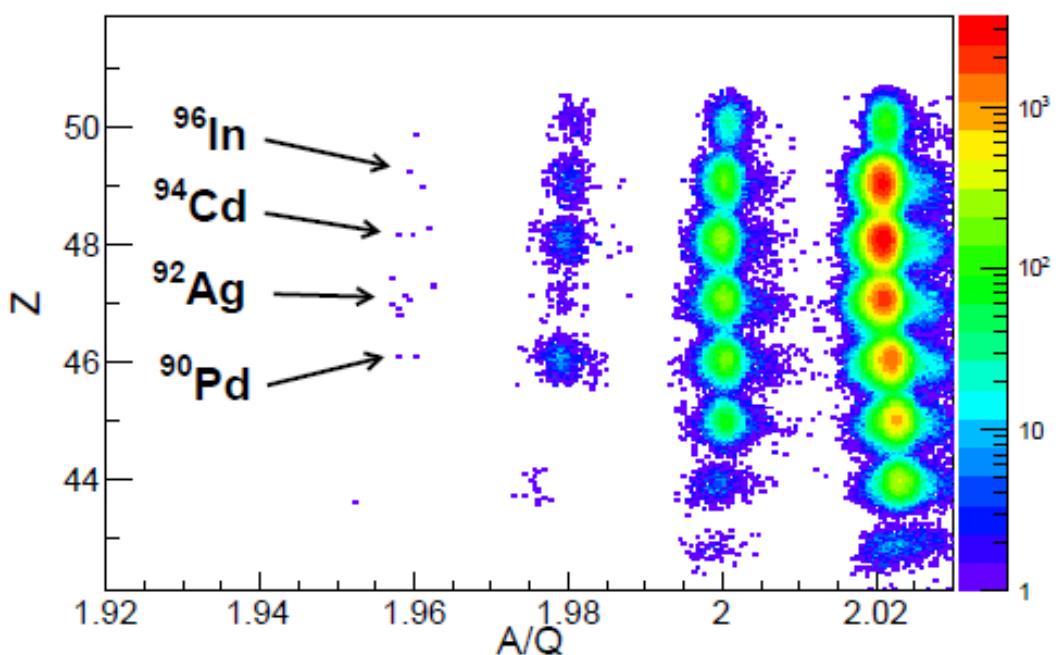
*¹ GANIL,

*² University of Belgrade

*³ Technische Universität München

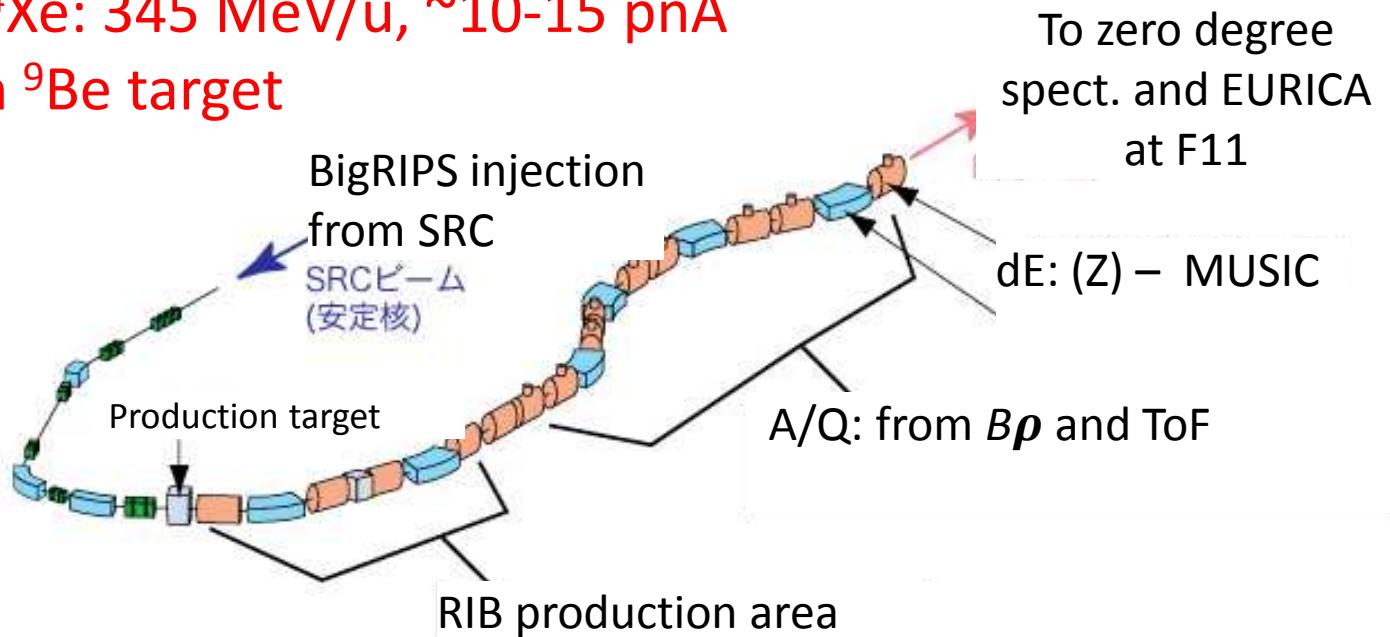
*⁴ TRIUMF

*⁵ RIKEN Nishina Center

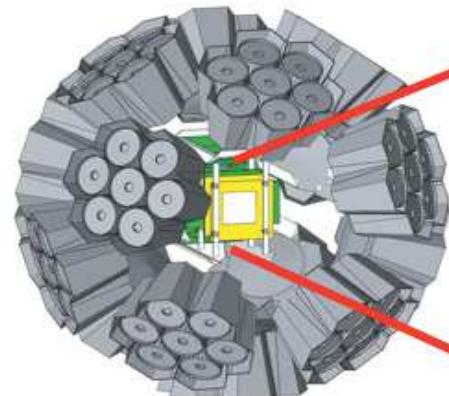


Radioactive Ion Beam Factory - RIKEN

^{124}Xe : 345 MeV/u, ~10-15 pnA
on ^9Be target

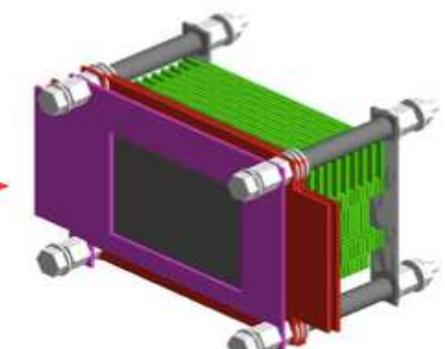
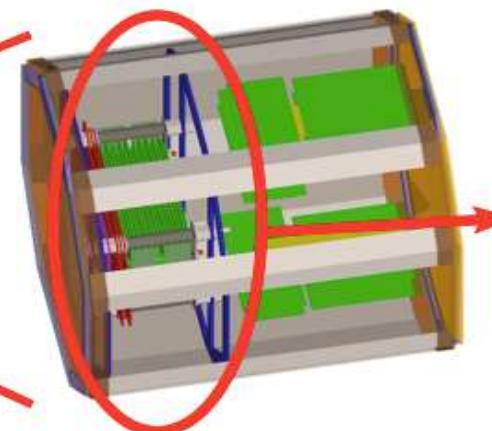


12 EB clusters,
 $\epsilon_\gamma \sim 8\%$ @1.3 MeV



1 Si-DSSD 0.3 mm, 60x40 x-y strips for X-Y posn. +
3 Si-DSSD, 1mm thick, 60 by 40 x-y strips for implantation

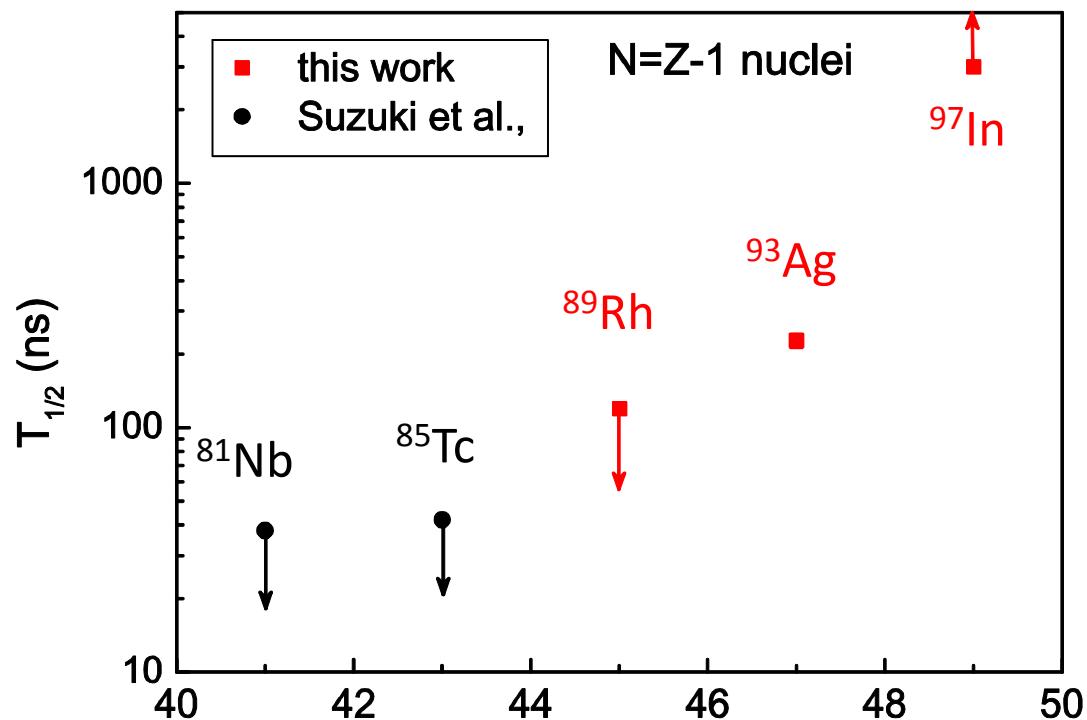
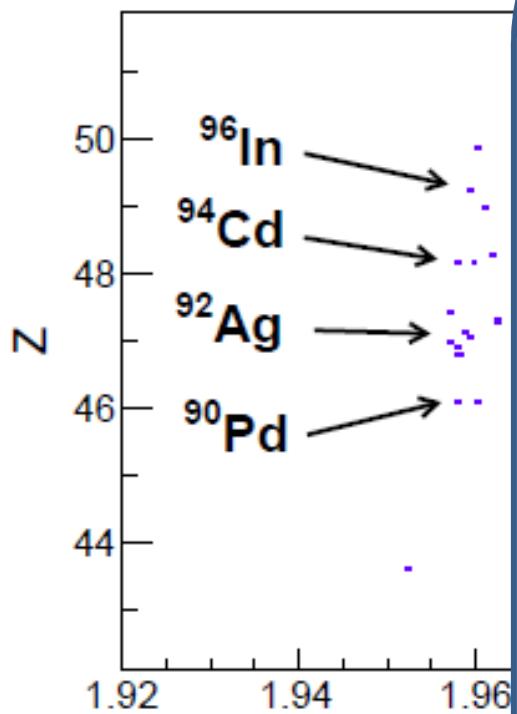
Modified SIMBA: Silicon IMplantation Beta Absorber



20 Si-DSSD, 1mm thick,
7x1 strips for β calorimetry to ~ 10 MeV

Systematics of N=Z-1 proton emitters from $\pi g_{9/2}$

I. Čeliković, M Lewitowicz, et al., Phys.Rev.Lett. 116, 162501 (2016)

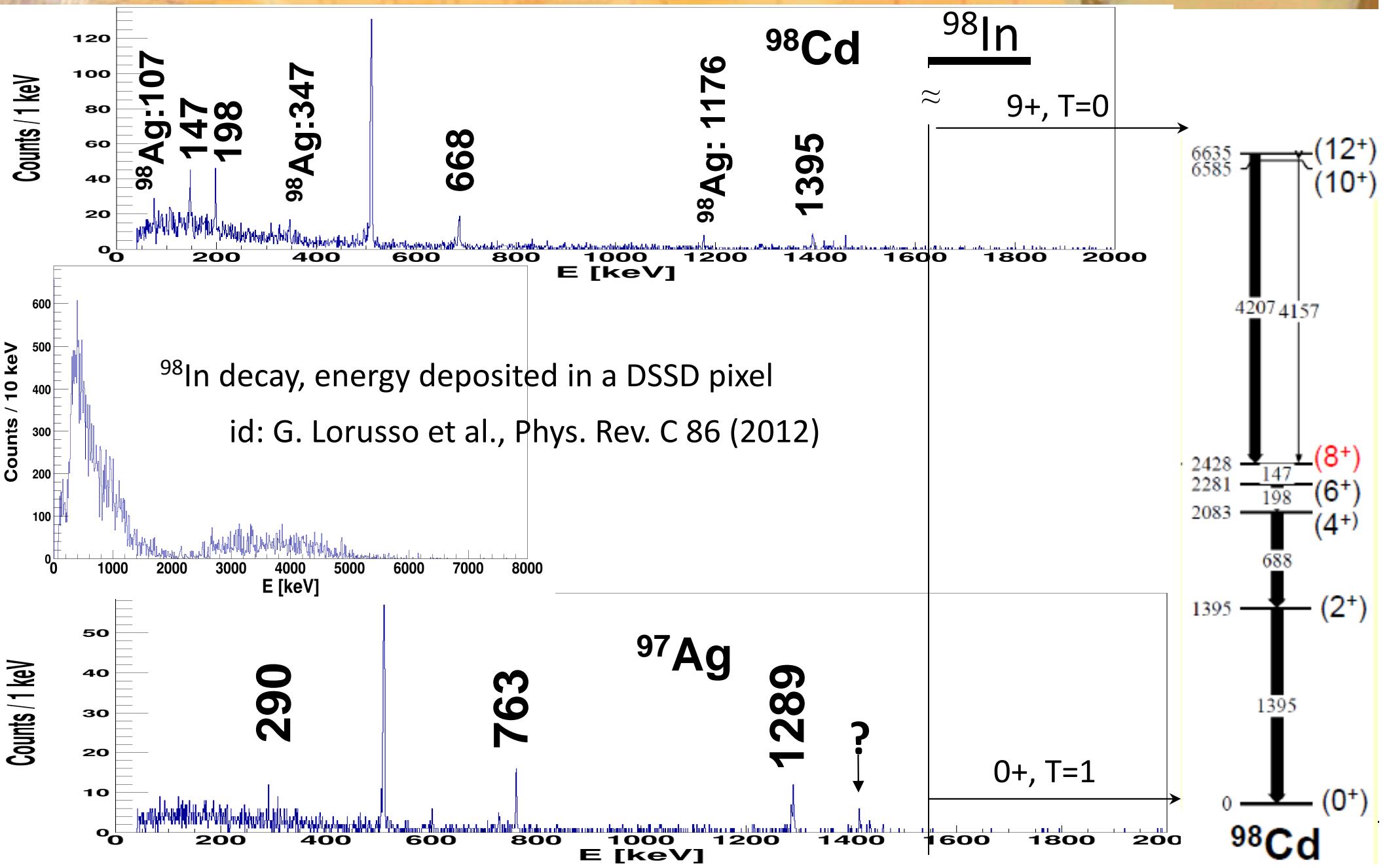


- Half-lives of N=Z-1 nuclei are increasing towards $Z=50$
- Systematics shows stabilising effect of the $Z=50$ shell closure

$$T_{1/2}(\text{In}) > 3 \mu\text{s}$$

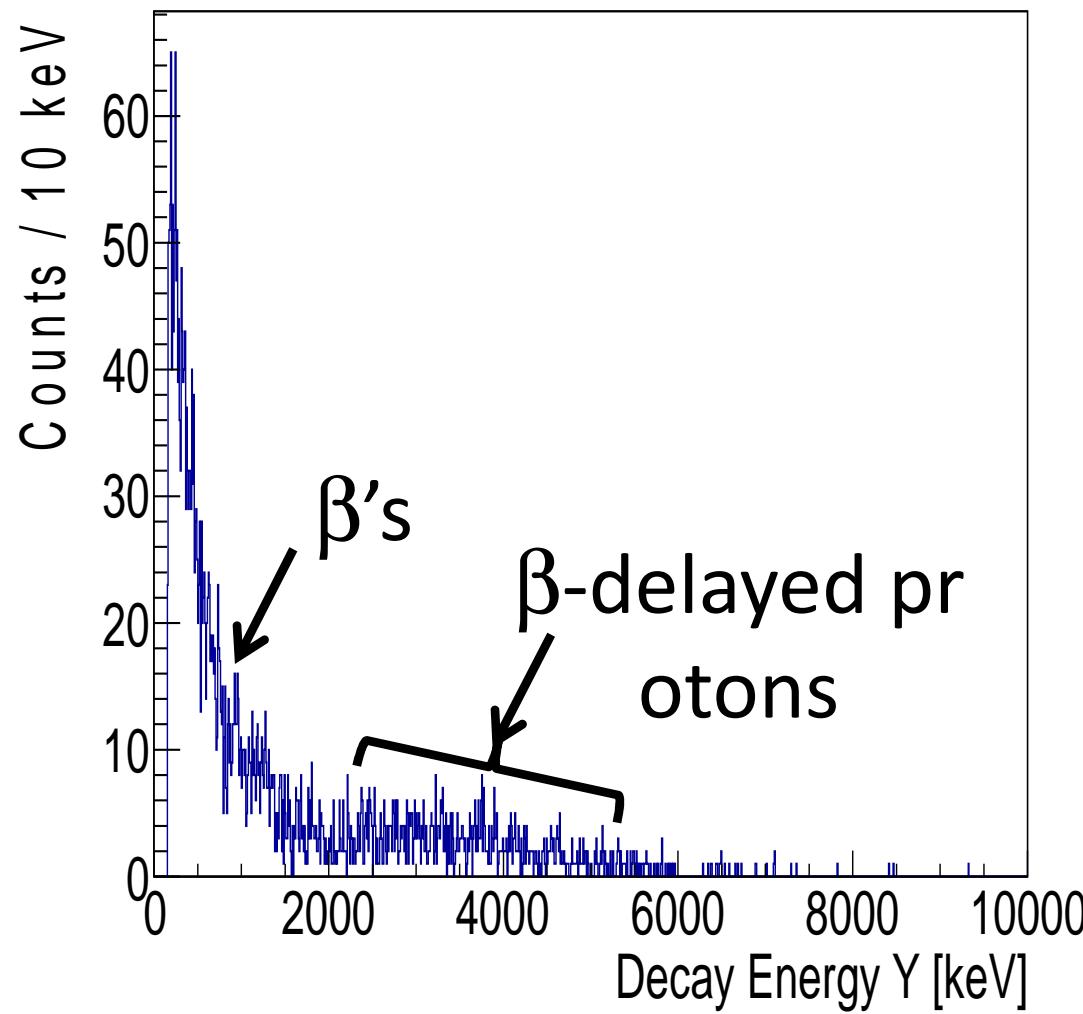
^{98}In $\beta/\beta\text{p}$ - decay

P Boutachkov et al.,

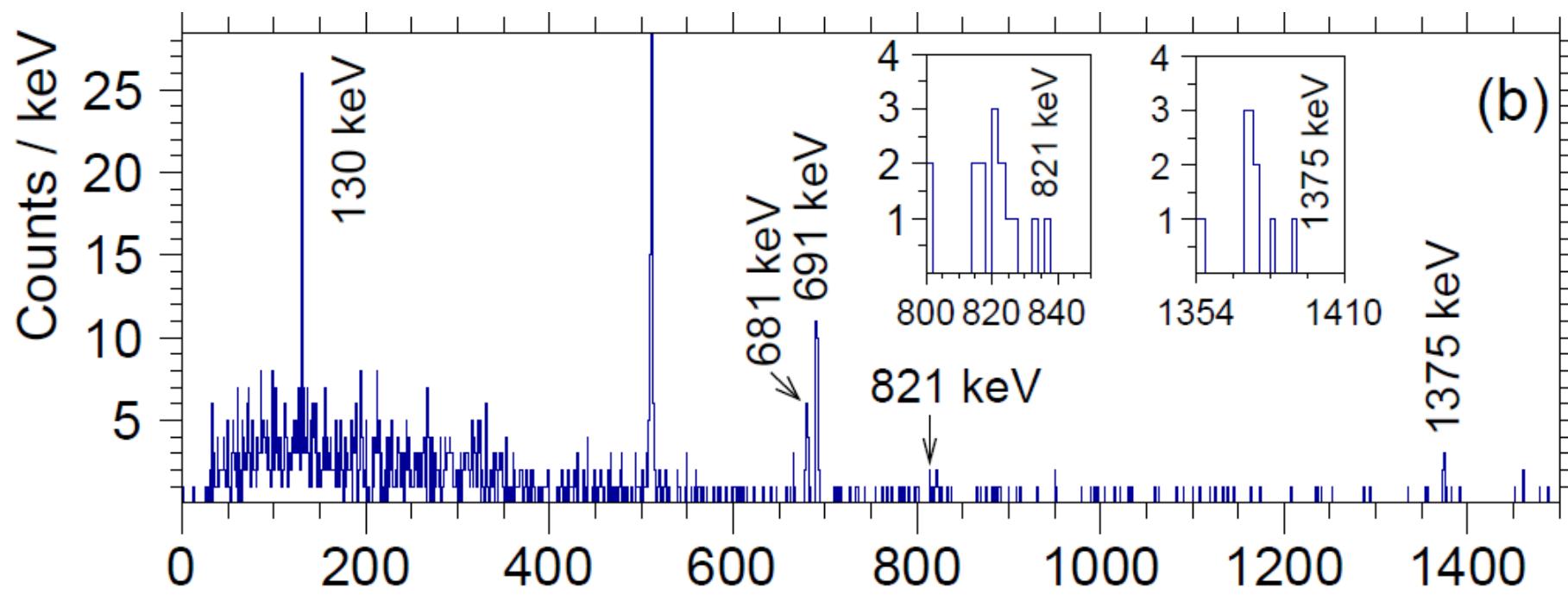
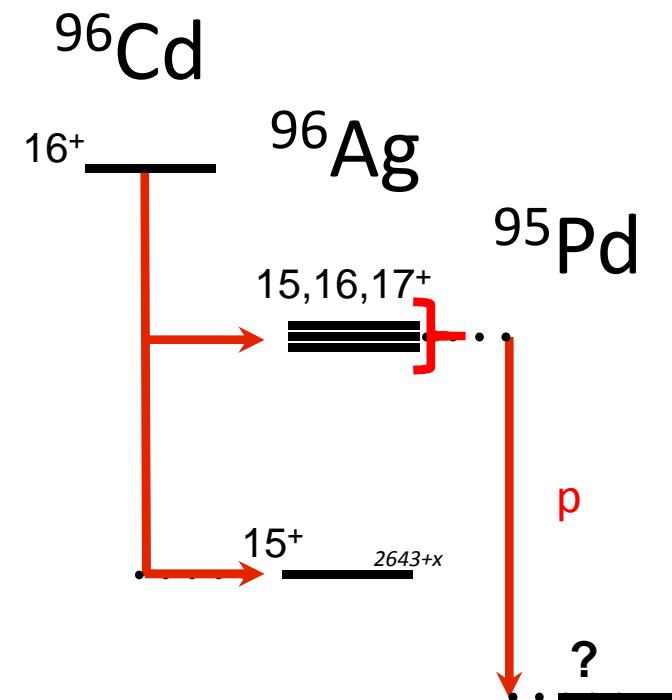
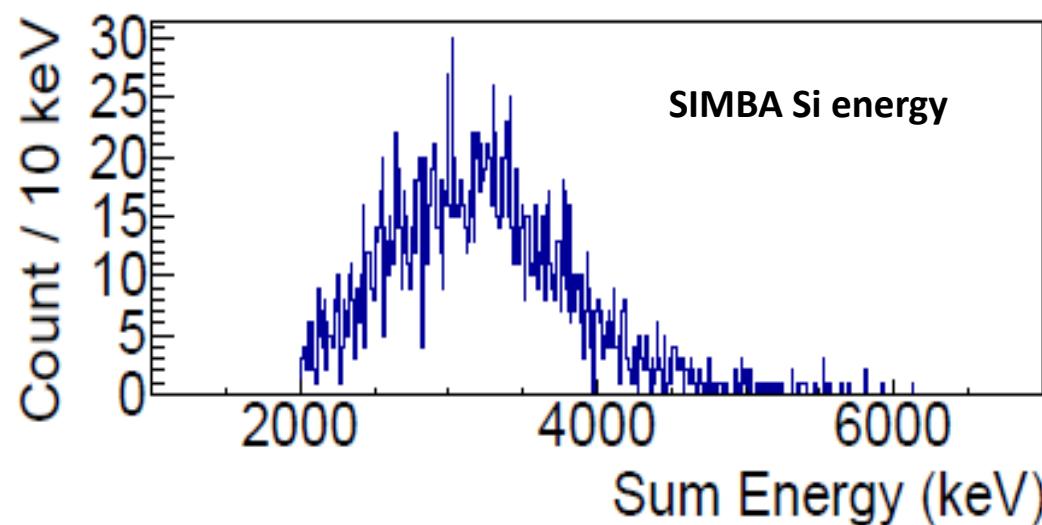


Results: ^{96}Cd 16^+ isomer decay

SIMBA spectrum following ^{96}Cd ion implants



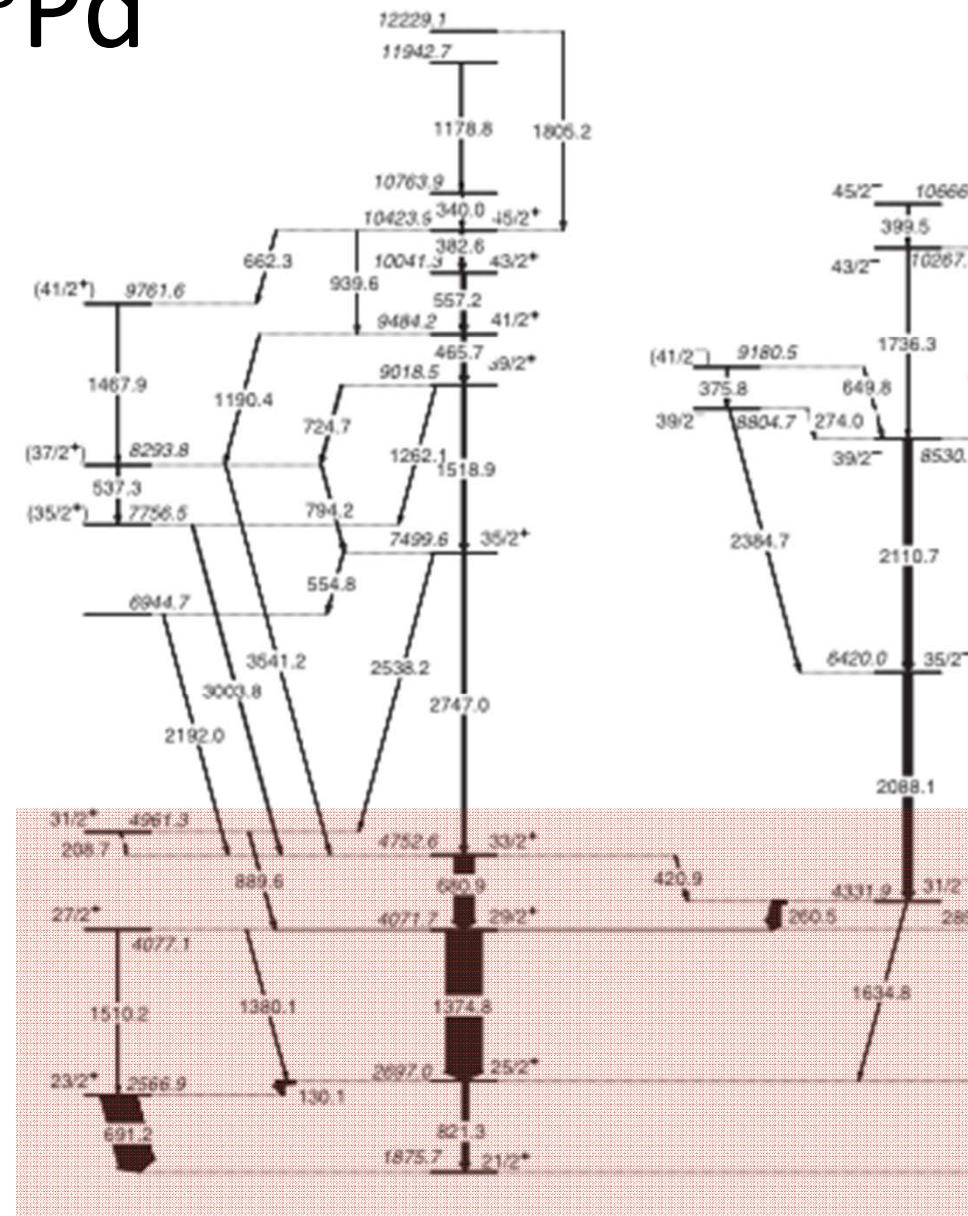
^{96}Cd ions + β -del. protons



$E\gamma$ from : Marginean, R., et al.: *PRC* 86, 034339 (2012)

Courtesy: B. Wadsworth

⁹⁵Pd



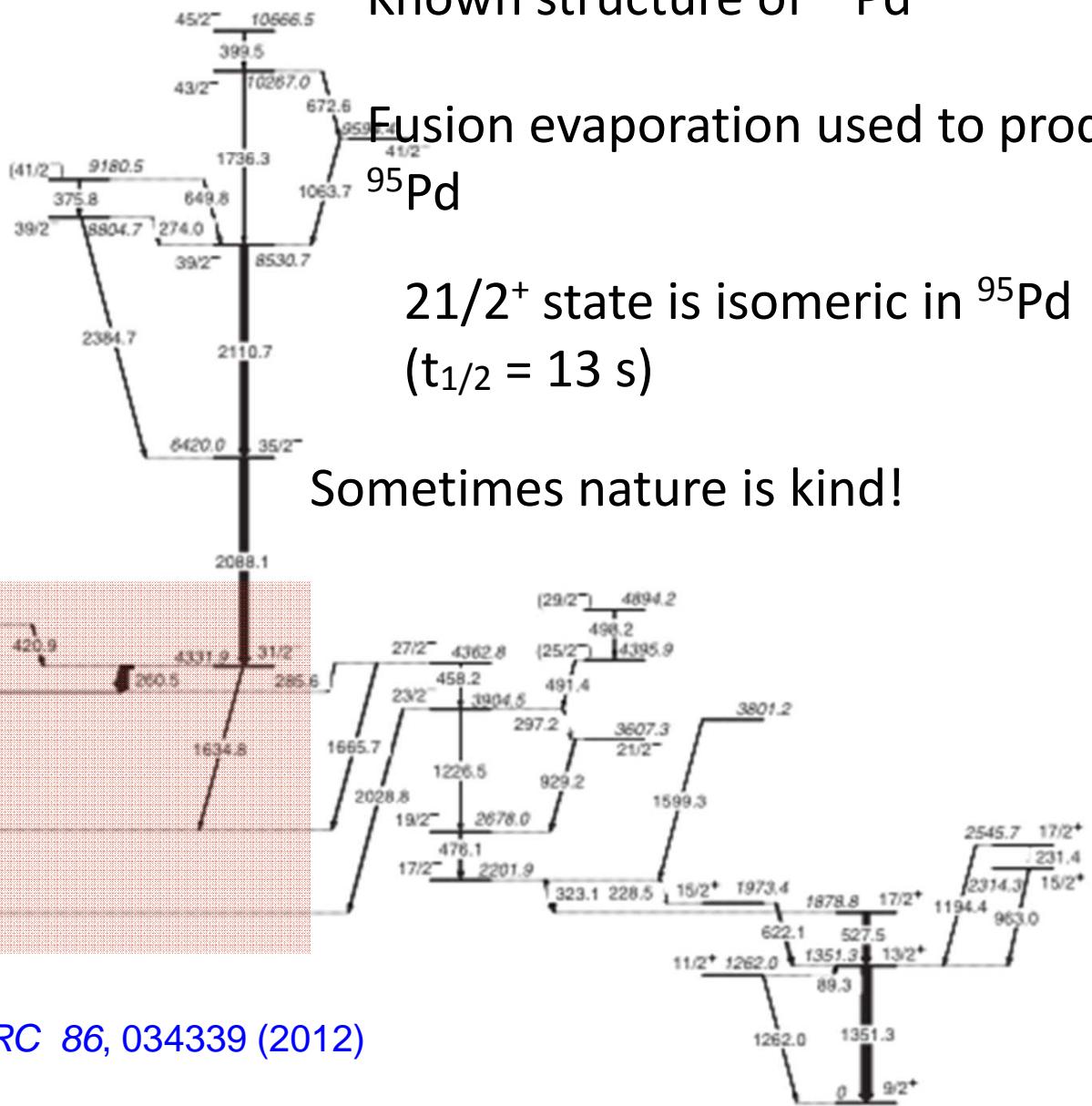
Level scheme: Marginean, R., et al.: PRC 86, 034339 (2012)

Known structure of ⁹⁵Pd

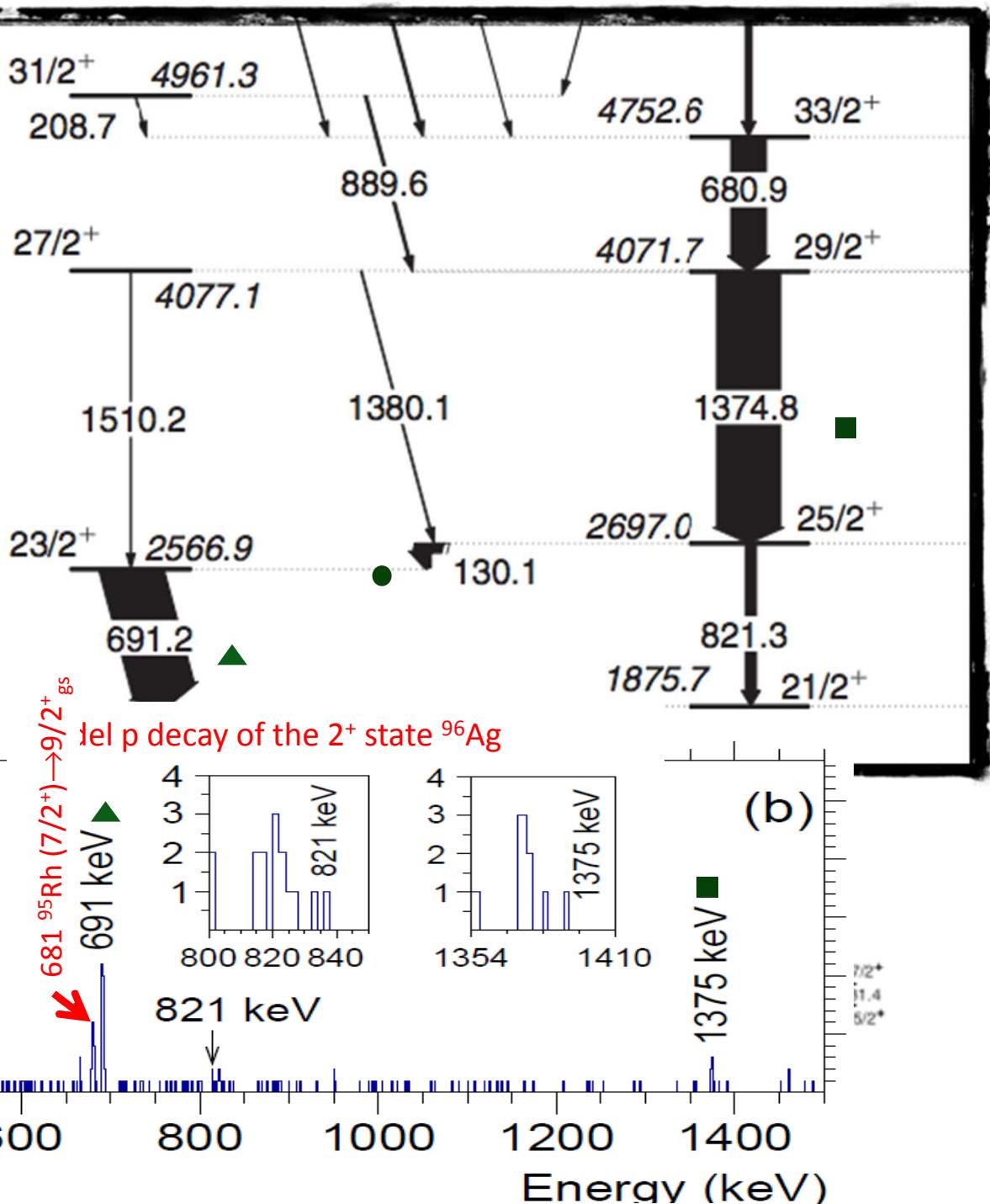
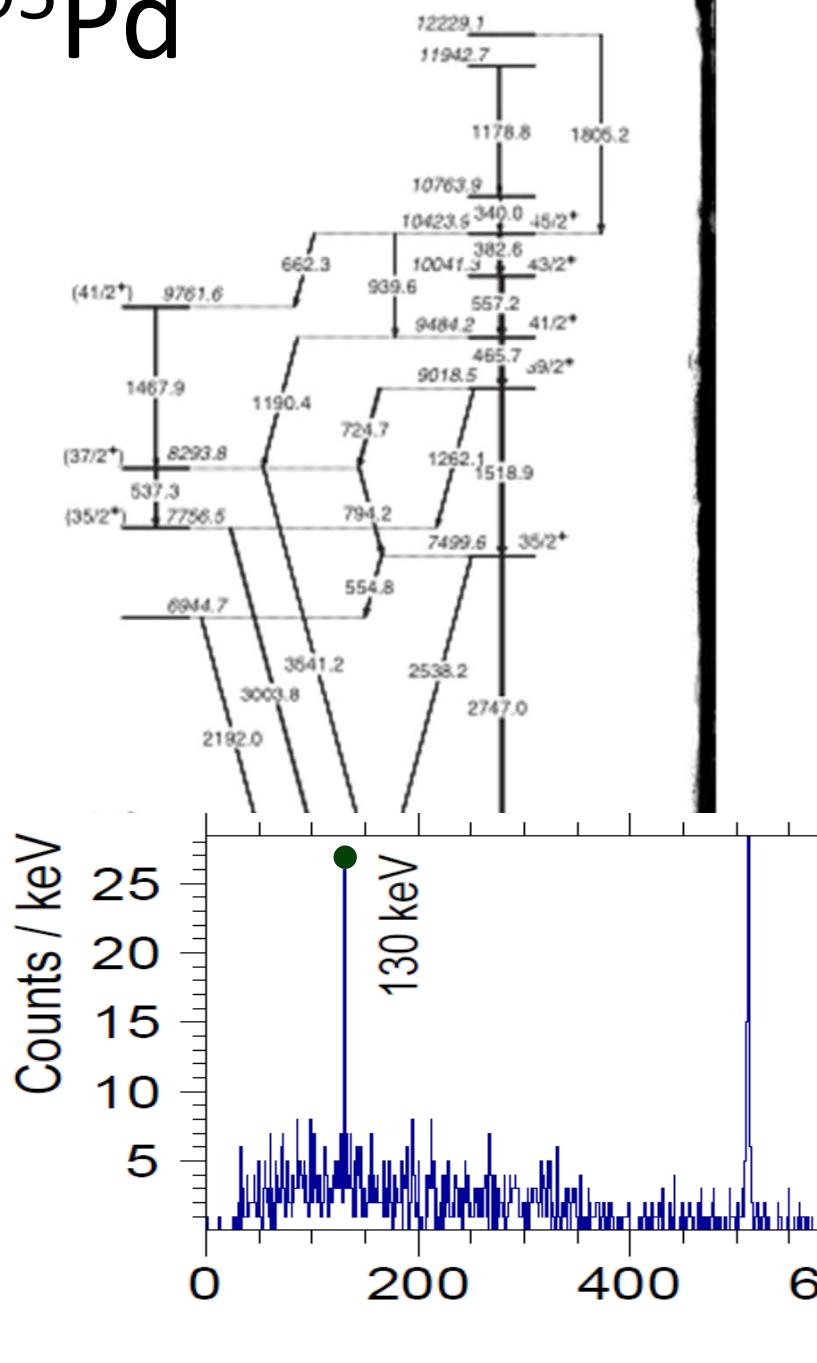
Fusion evaporation used to produce
⁹⁵Pd

21/2⁺ state is isomeric in ⁹⁵Pd
($t_{1/2} = 13$ s)

Sometimes nature is kind!



⁹⁵Pd



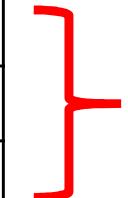
681 grows with $\frac{1}{2}$ life consistent with the 6.9 sec decay $\frac{1}{2}$ life of the 2⁺ state in ⁹⁶Ag

^{96}Cd 16^+ isomer decay

LSSM (*gds* space)/ WKB ($\ell = 0, 2, 4$ barrier penetration) calcs have been made by H. Grawe/ T. Faestermann to investigate the population and decay of the $15^+, 16^+, 17^+$ resonance states in ^{96}Ag .
Calculations still being checked, but prelim conclusions are:

- 1) Resonance population intensity is confirmed at $\sim 30\%$
- 2) Population $15^+ / 17^+$ states favoured mainly for decay energy reasons.

E_{res} (MeV)	I^π	I_β (%)
9.34	16^+	6.0
9.11	15^+	9.7
8.82	17^+	14.5

 $\sim 30\%$

- 3) p-emission is strongest for $\ell = 2$ decays. Indications that β -p decay comes mainly from core excited configurations.
- 4) $29/2^+, 25/2^+$ states favoured by decay energy, Q_p , and WKB barrier penetration

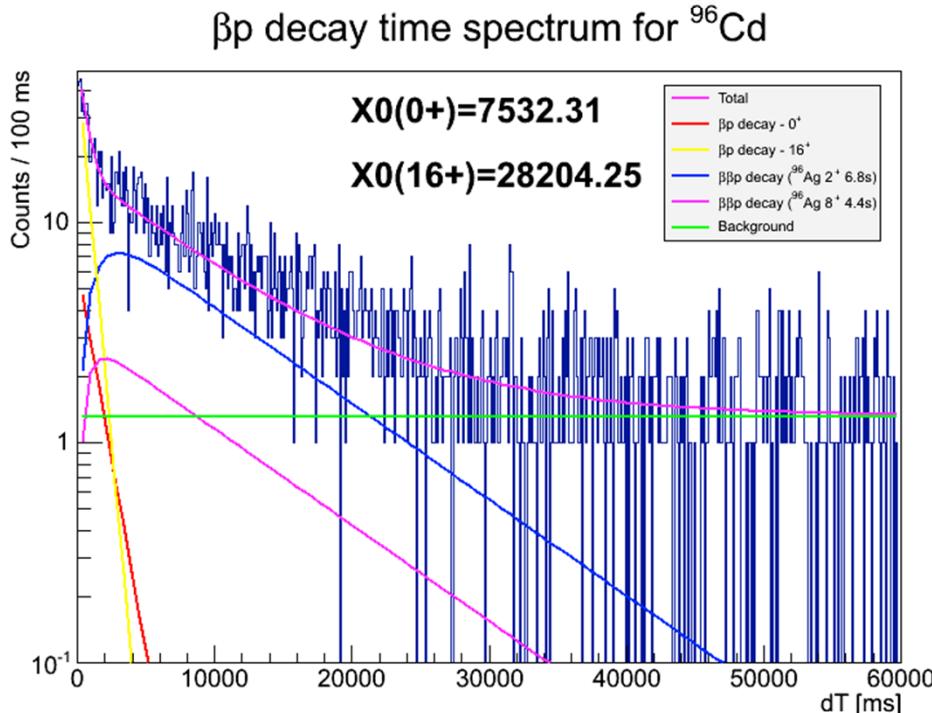
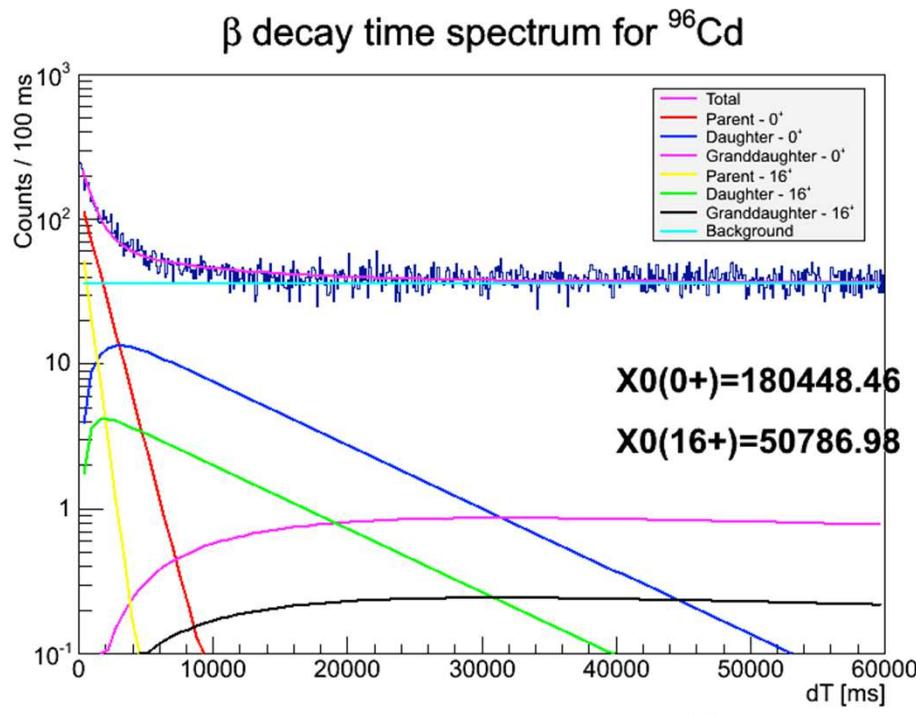
$\Rightarrow \ell = 2$ favoured over $\ell = 4$ by the lower centrifugal barrier

$\Rightarrow \ell = 2$ favoured over $\ell = 0$ because of low Spec. Factors

Calcs consistent with exptl obs. – i.e: no substantial evidence of decays from $27/2^+, 31/2^+$ or $33/2^+$ states

β -delayed proton - branching ratios

Fitting: two exponentials for ${}^{96}\text{Cd}$, background (daughter+time-random)

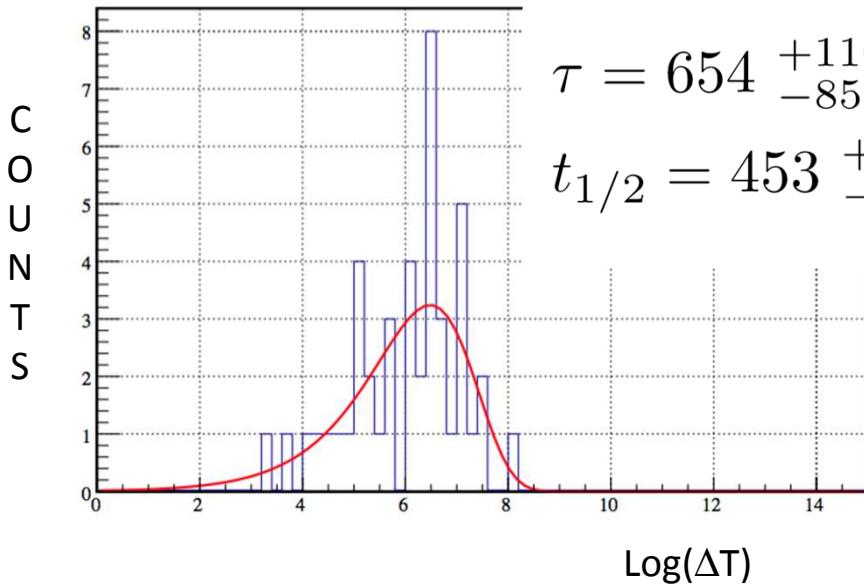


Proton-Beta branching ratio extracted:

16⁺ isomer: 11(3)%
 Ground state: 1.5(5)% cf 5(4)%*

* G. Lorusso et al, PRC 86, 014313 (2012)

Lifetimes



$$\tau = 654^{+116}_{-85} \text{ ms}$$

$$t_{1/2} = 453^{+80}_{-59} \text{ ms}$$

Schmidt method:

K. H. Schmidt , Z. Phys A316, 19 (1984)

16⁺ isomer:

Sum of 470, 668 and 1506 keV γ 's
in ⁹⁶Ag

Prev. result:

$$\tau_{1/2} = 290^{+110-100} \text{ ms ,}$$

Nara Singh et al PRL 107,

172502

$$\tau = 1397(130) \text{ ms}$$

$$t_{1/2} = 968(90) \text{ ms}$$

Ground state:
From fit of β -decay data with gs lifetime
as free parameter

Prev. results:

$$\tau_{1/2} = 1030^{+240-210} \text{ ms ,}$$

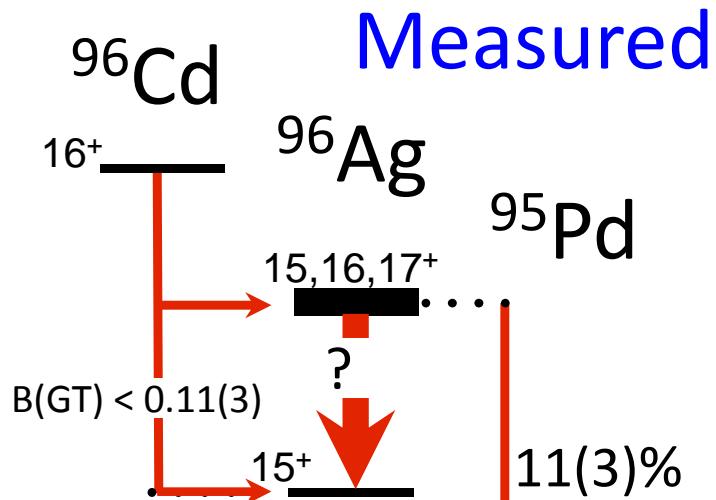
D Bazin et al PRL 101, 252501

$$\tau_{1/2} = 670^{+/-150} \text{ ms ,}$$

Nara Singh et al PRL107, 172502

^{96}Cd B(GT) + β del p values

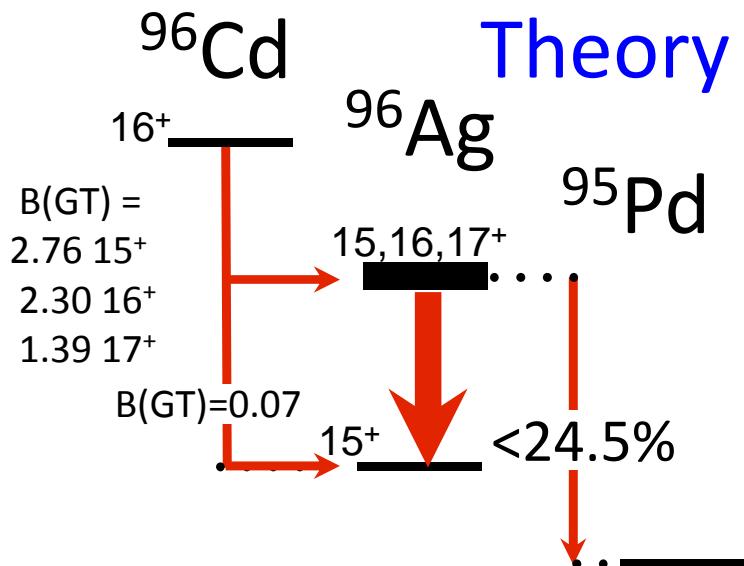
P. Davis, B. Wadsworth



Pandemonium effect: Unable to extract the exclusive B(GT) strengths

$$B(\text{GT}) = \frac{3860(18)}{f} \frac{I\beta}{\tau_{1/2}}$$

See Nara Singh et al., PRL 107, 172502 for details
p- β branching: 16^+ isomer: $11(3)\%$
 Ground state: $1.5(5)\%$
 cf $5(4)\%$, G. Lorusso et al, PRC 86, 014313 (2012)



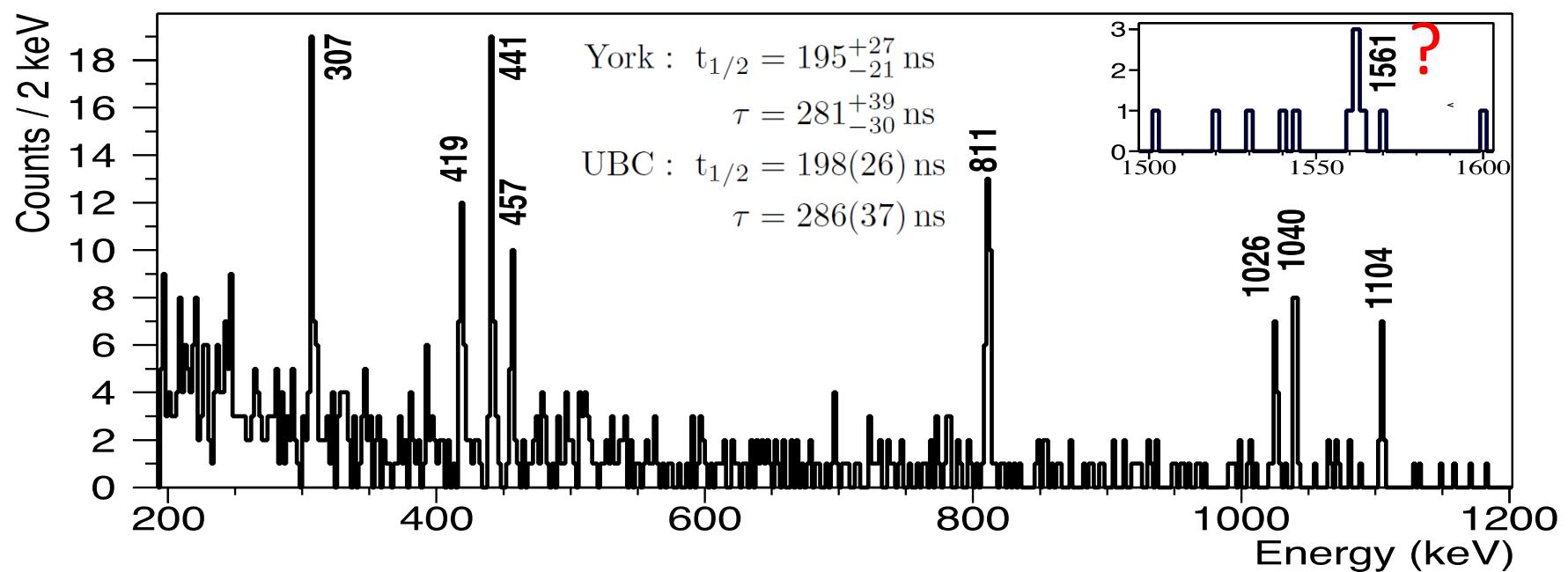
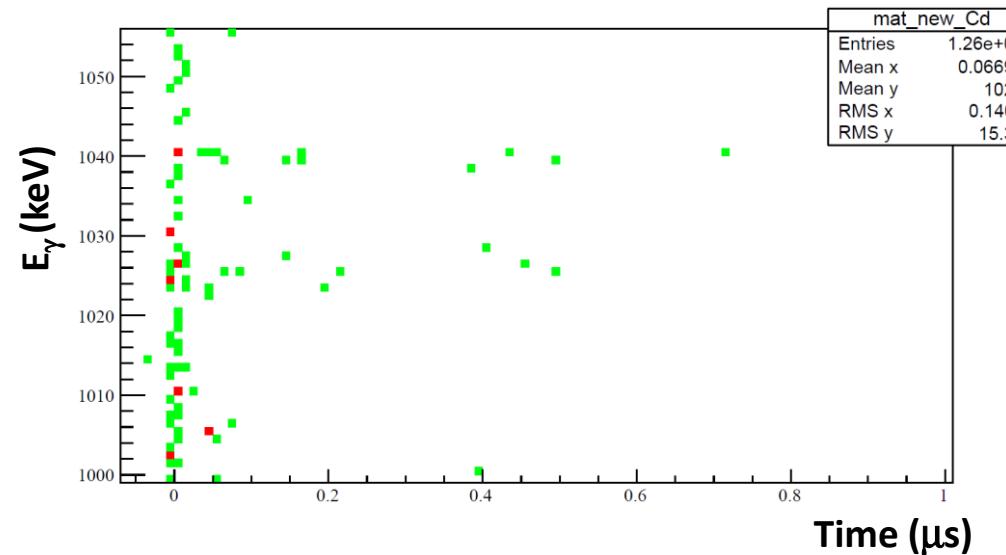
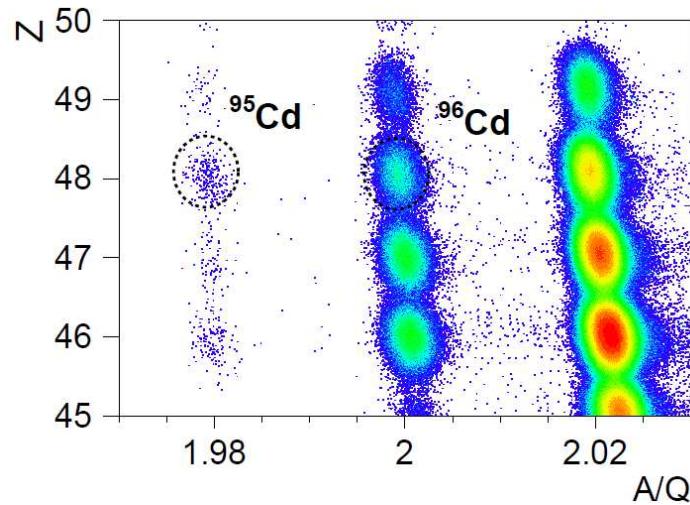
Lifetimes:

16⁺ isomer:

- p-emission is strongest for $\ell = 2$ decays.
- Indications that β -p decay comes mainly from core excited configurations.

cf $\tau_{1/2} = 1030+240-210$ ms, D Bazin et al PRL 101, 252501
 $\tau_{1/2} = 670+/-150$ ms, Nara Singh et al PRL107, 172502

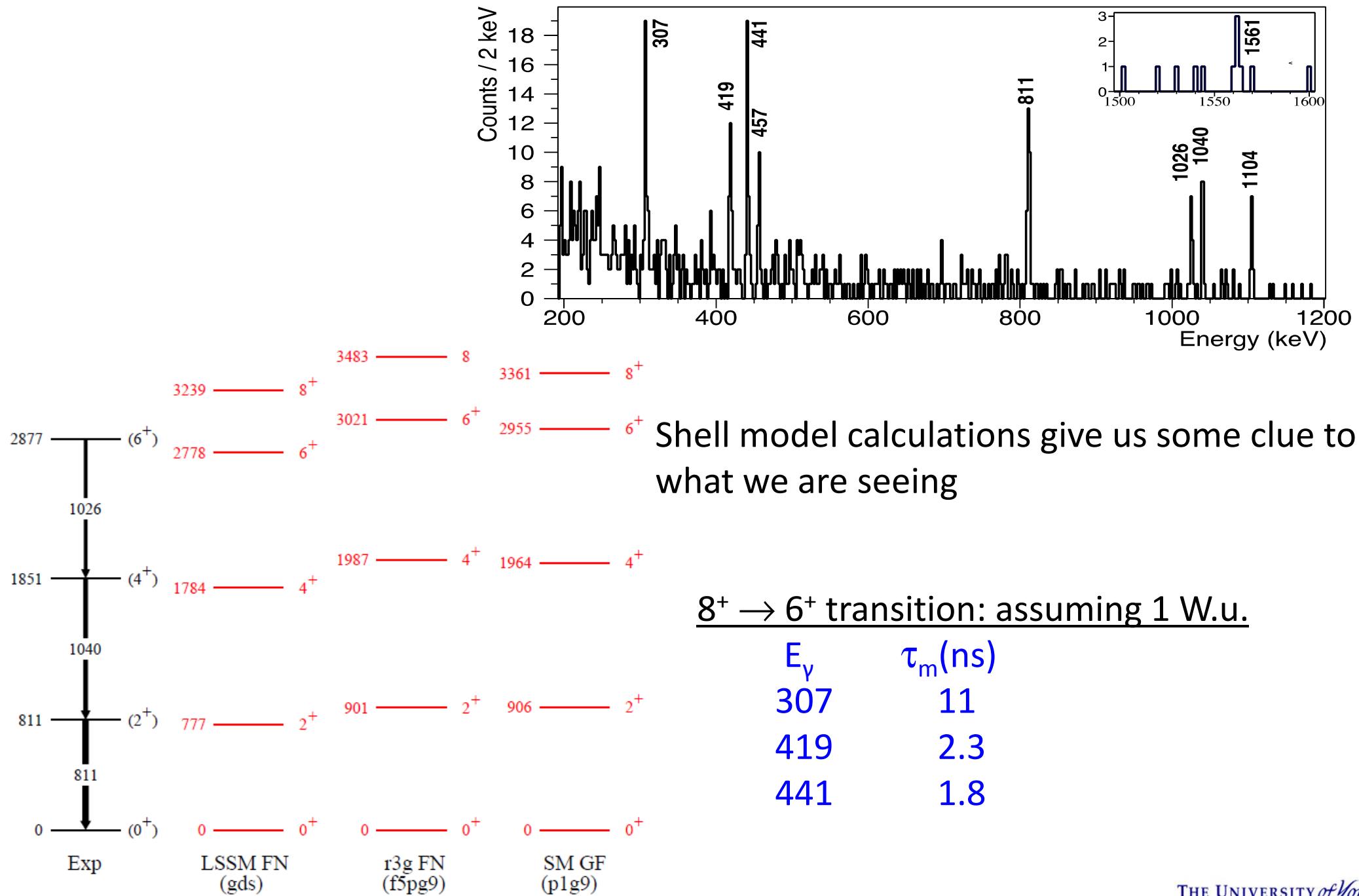
Gamma decaying isomer in ^{96}Cd : RIBF9,83



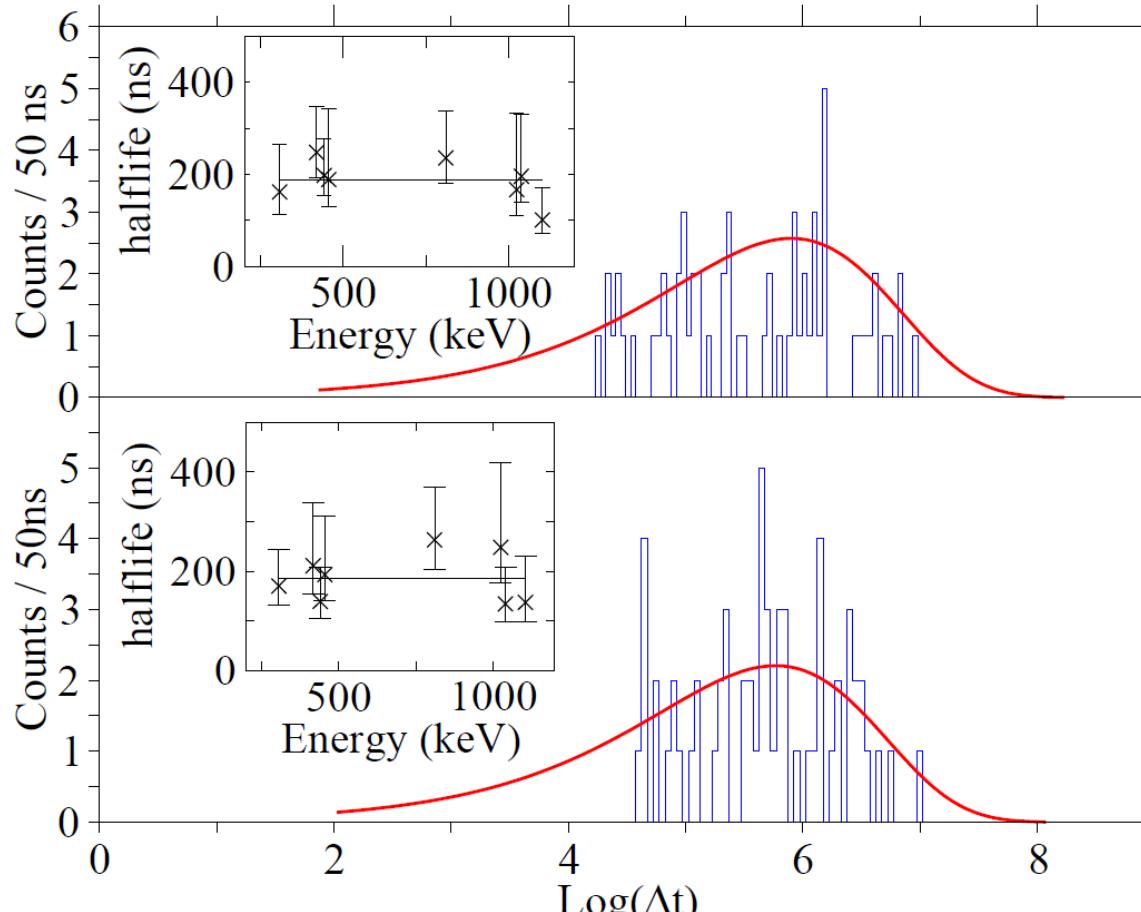
γ rays within ~ 50 - 900 ns of the ion being implanted
 Sum of RIBF9 and RIBF83 expt data

Courtesy B. Wadsworth

Gamma decaying isomer in ^{96}Cd



Lifetime of γ decaying isomer



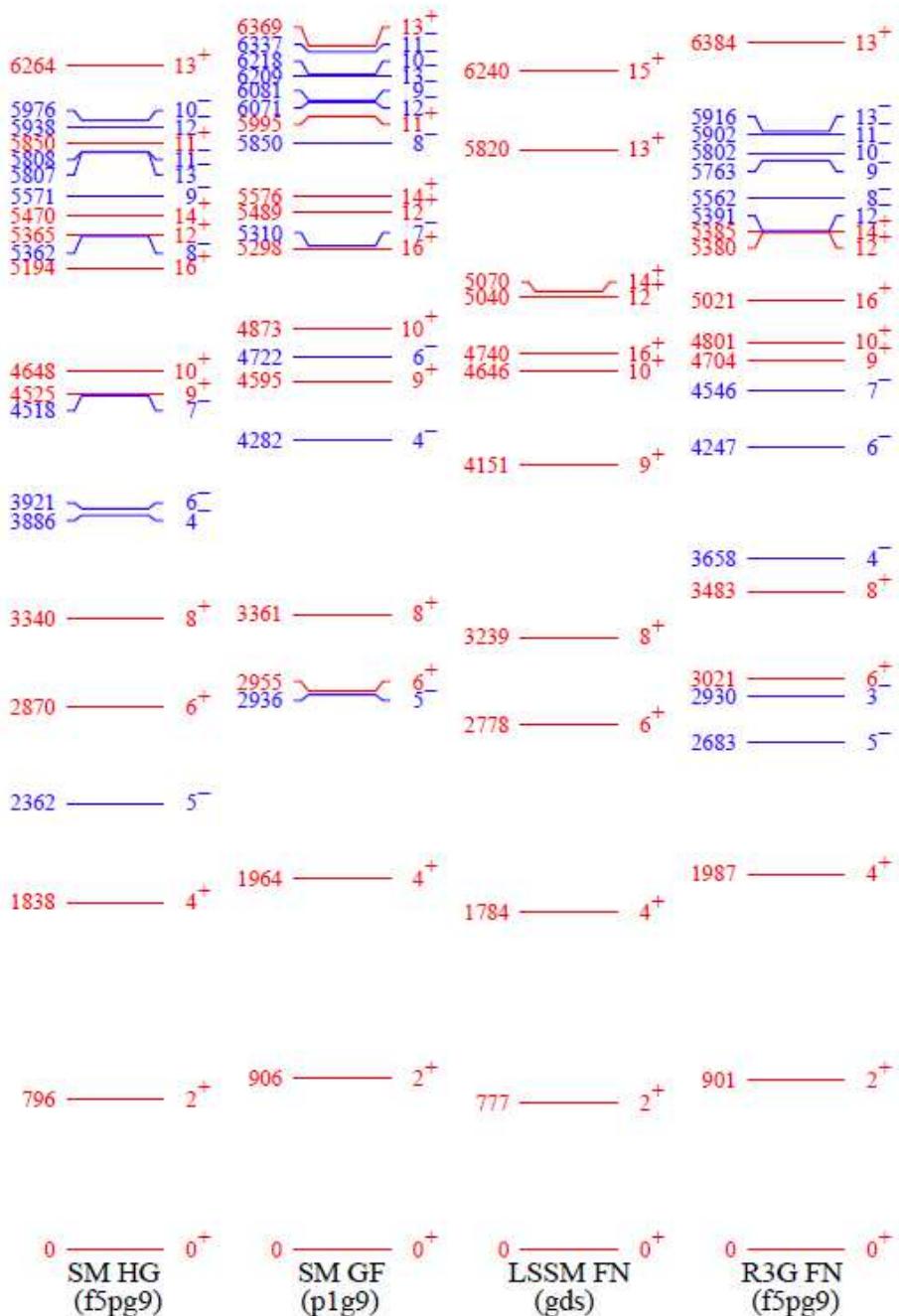
Δt = time diff. between γ and ^{96}Cd implant

York : $t_{1/2} = 195^{+27}_{-21}$ ns
(RIBF83)
 $\tau = 281^{+39}_{-30}$ ns

UBC : $t_{1/2} = 198(26)$ ns
(RIBF9)
 $\tau = 286(37)$ ns

K H Schmidt (Z. Phys A. 316, 19 (1984)): - sum events in the 8 γ transitions.

Nature of ^{96}Cd γ decaying isomer?



- 14^+ - probably not as all 8 γ 's have coincs with 1 or more of the others
- Negative parity state, 12^- or 13^-

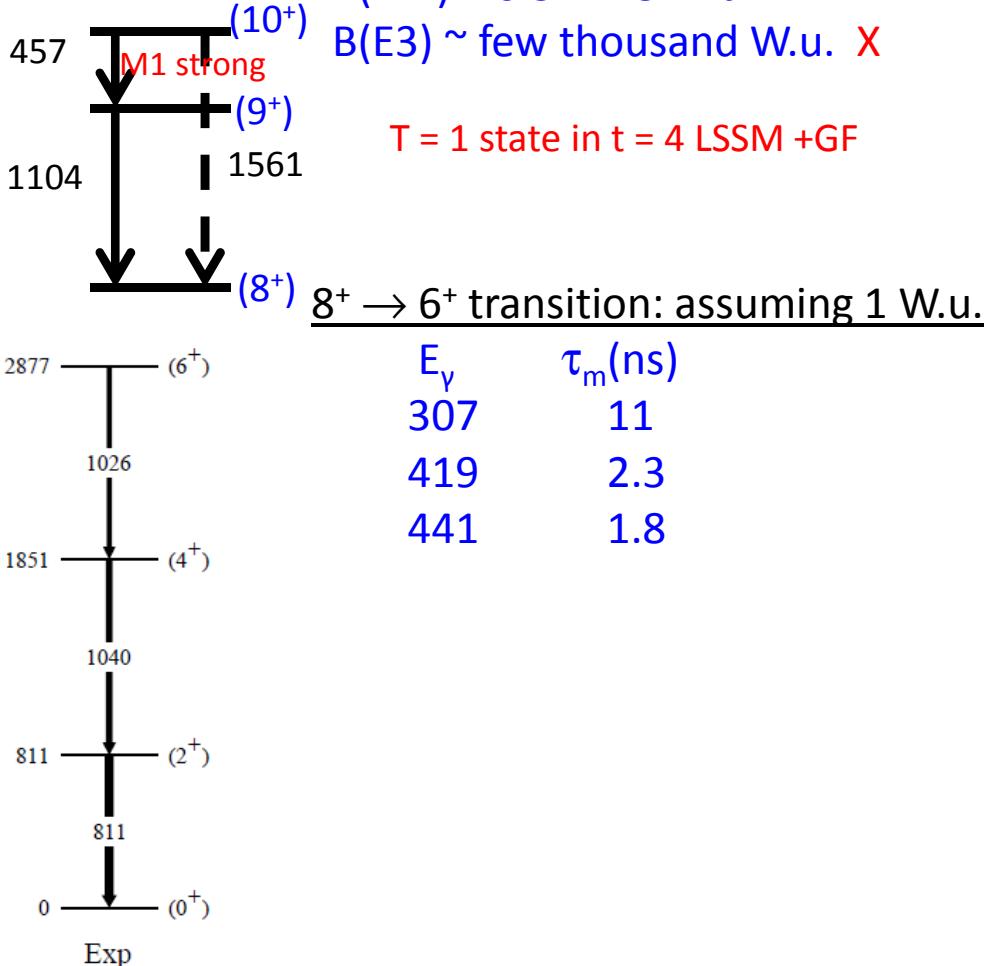
For 307, 419, 441 keV trans.

$B(E1) \sim \text{few} \times 10^{-8} \text{ W.u. OK}$

$B(M2) \sim 0.5 - 2.5 \text{ W.u. X}$

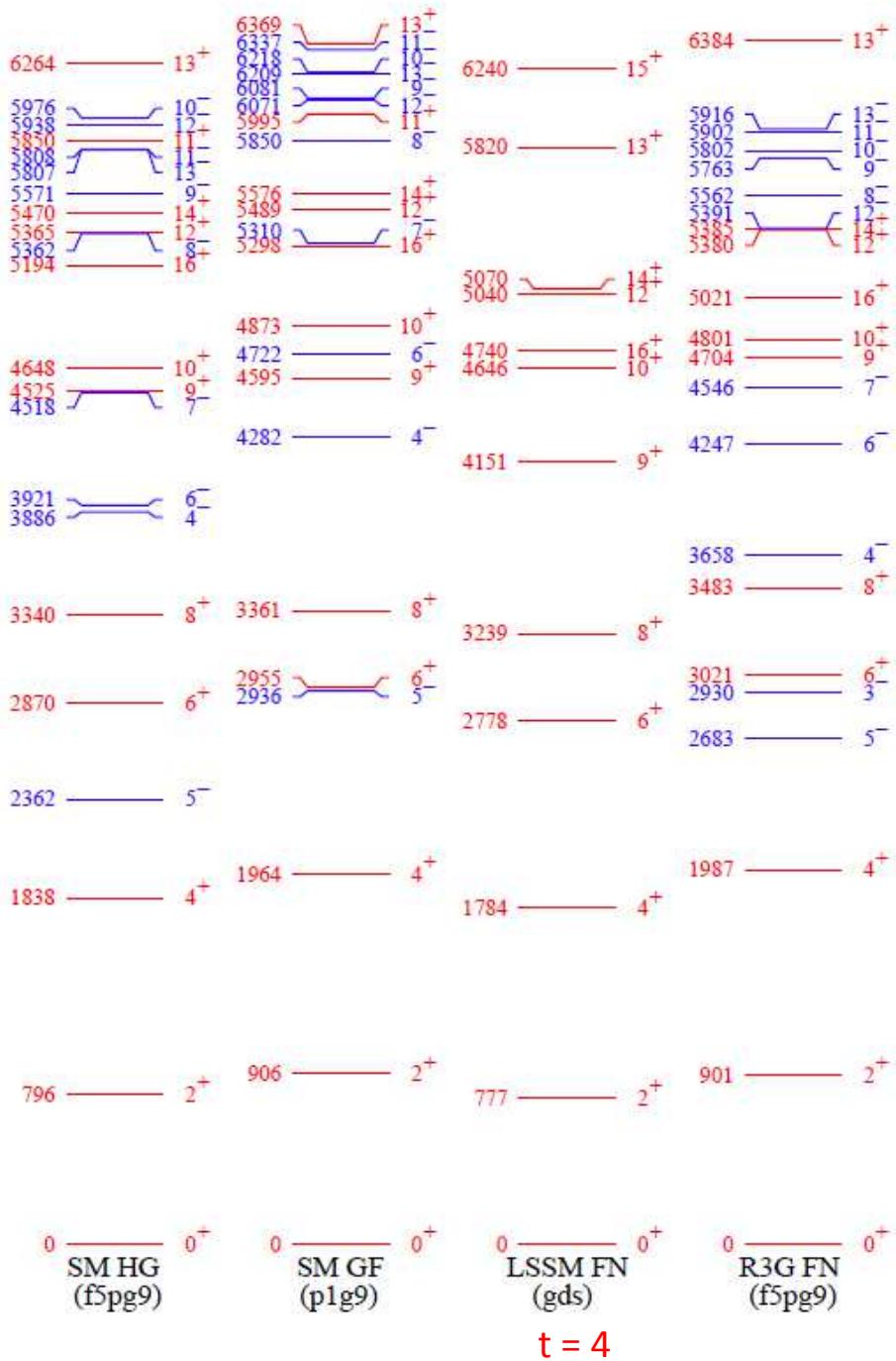
$B(E3) \sim \text{few thousand W.u. X}$

T = 1 state in t = 4 LSSM +GF

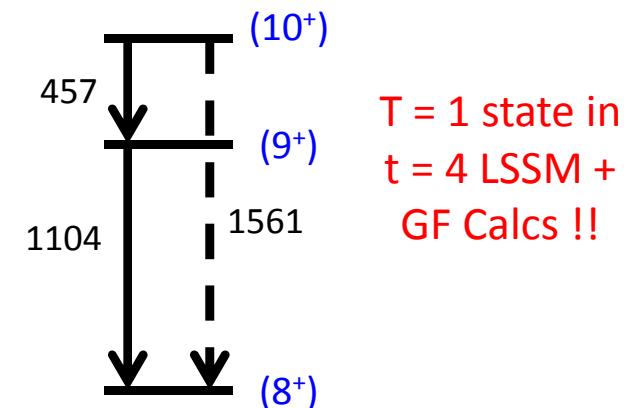


Courtesy B. Wadsworth

Other comparisons



10⁺ predicted to be 1.3 – 1.6 MeV above the 8⁺



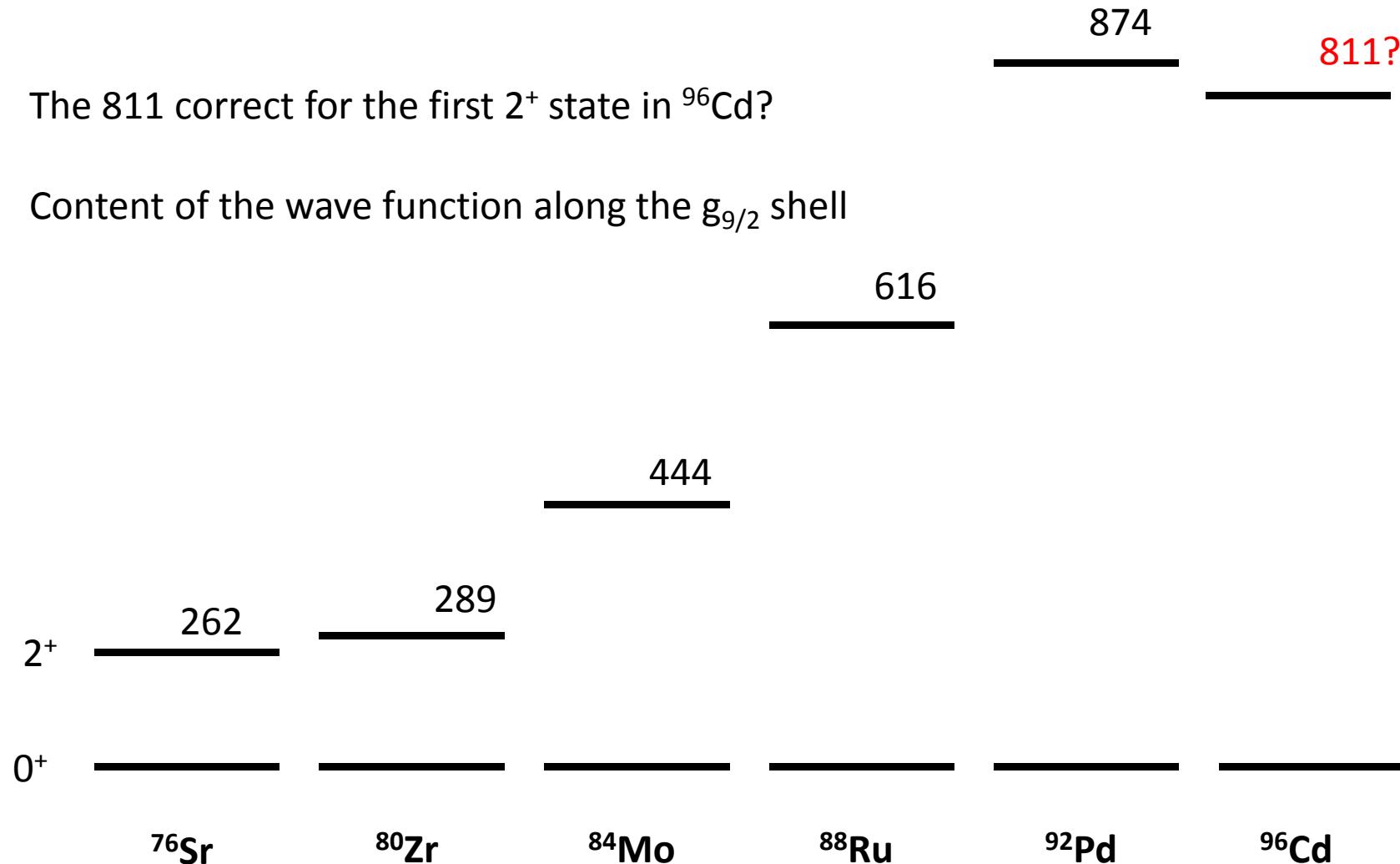
Strong M1 pred. for 10 → 9 in GF space, BR(M1/E2) = 77/23 % for 457/1561

In a pair approx the T=1 9⁺ state →
Energetically favoured coupling of a
9⁺,T=0 pair to a 0⁺, T=1, pair,
which are the lowest states in ⁹⁸In.....

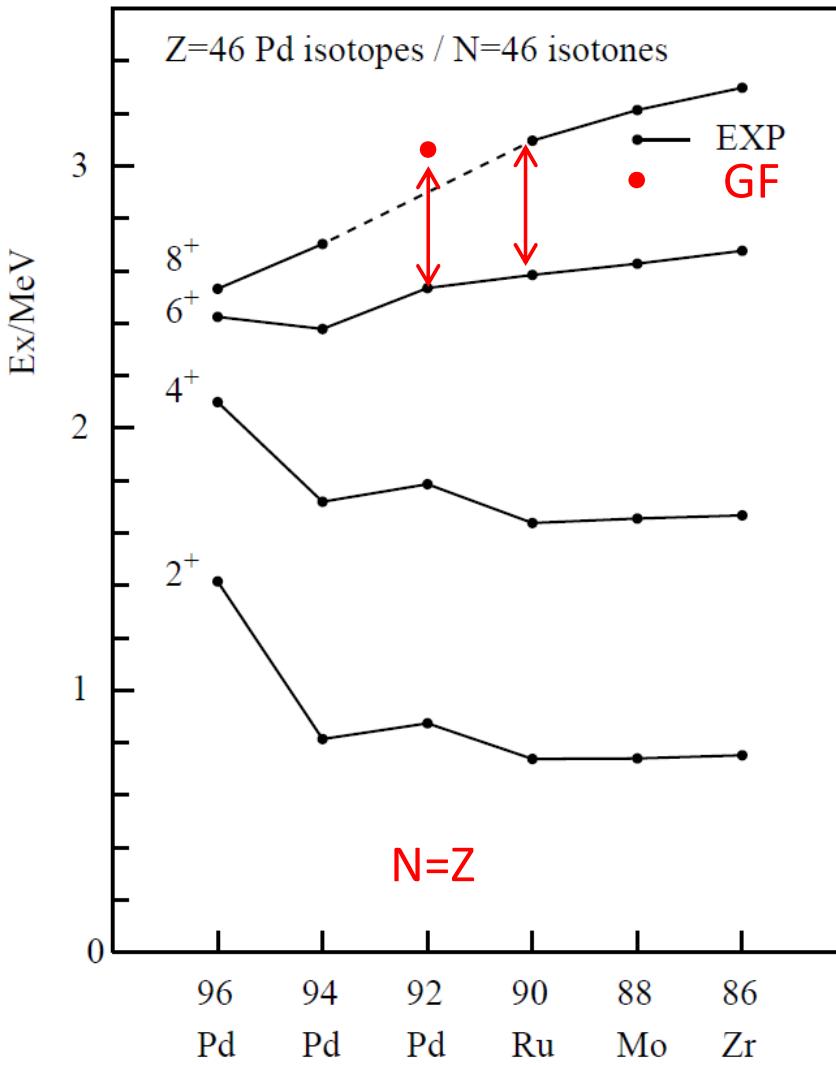
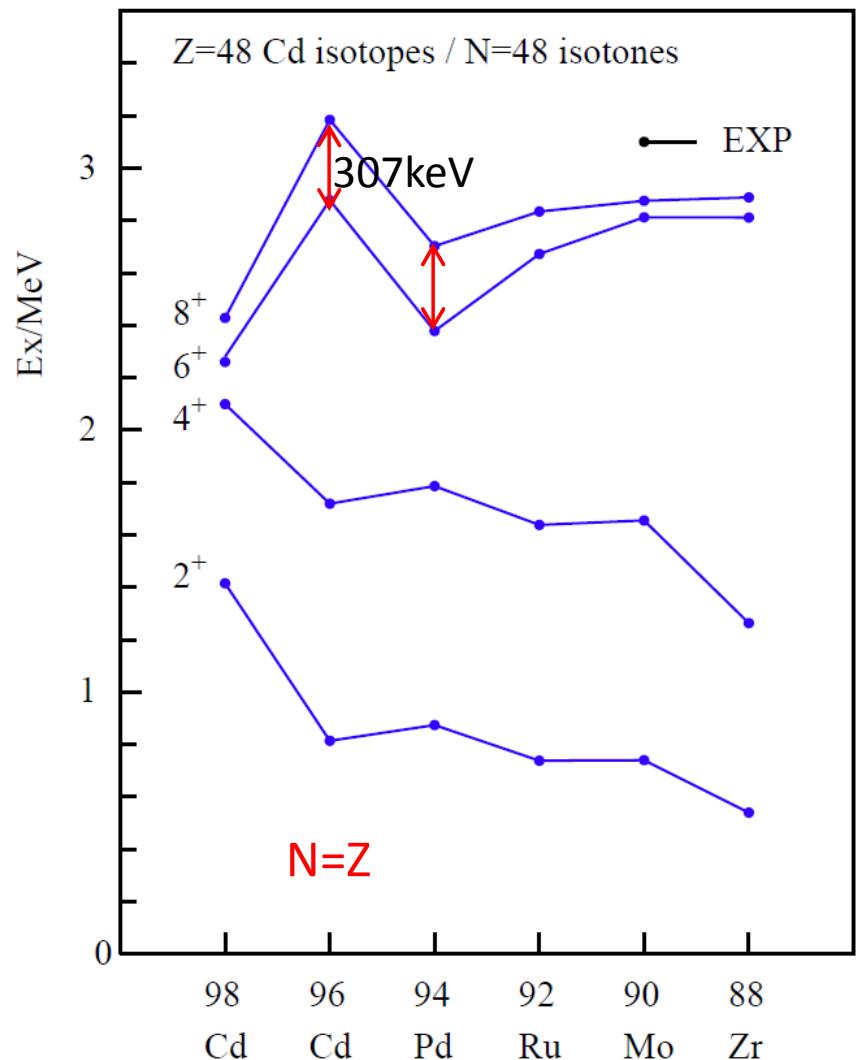
Further SM calculations underway!!
H. Grawe/ F Nowacki

2+ systematics for N=Z nuclei

- The 811 correct for the first 2⁺ state in ⁹⁶Cd?
- Content of the wave function along the g_{9/2} shell



Energy systematics $2^+ - 8^+$



92Pd:B. Cederwall, et al., Nature 469(2011)68

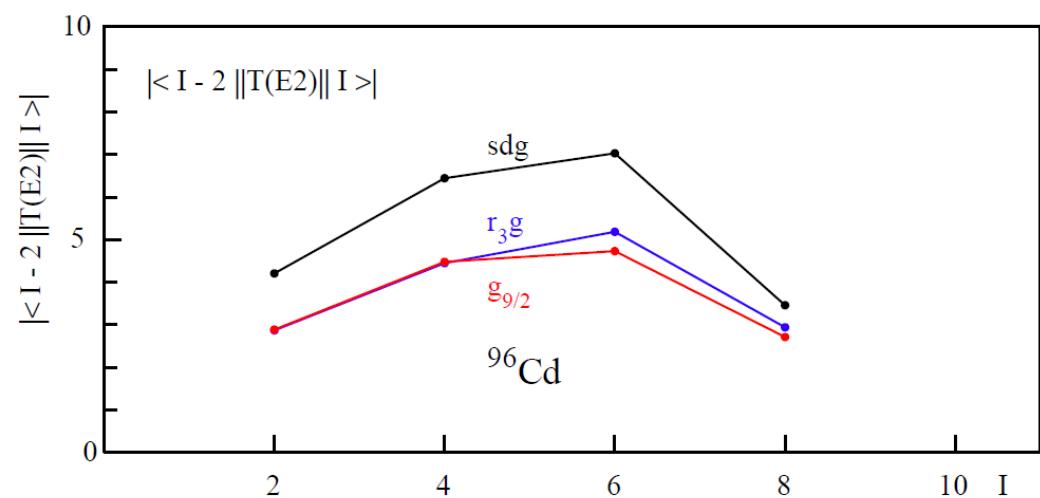
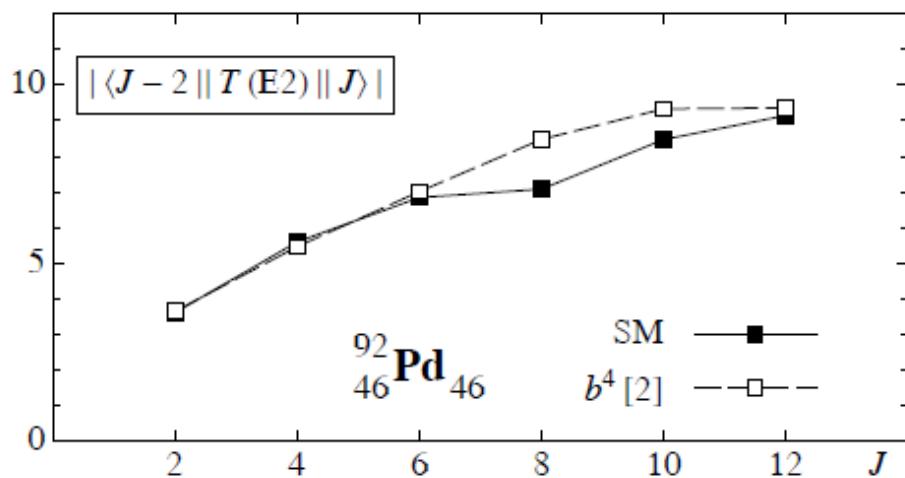
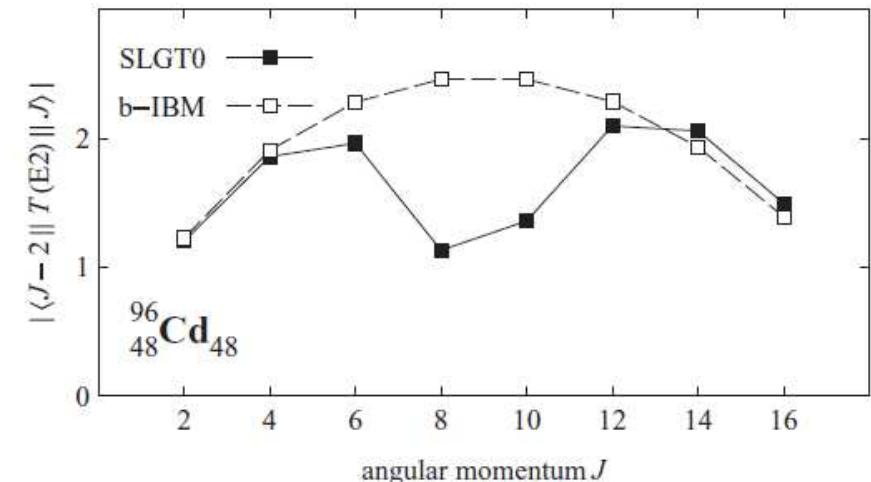
Courtesy: H. Grawe



IBM vs SM

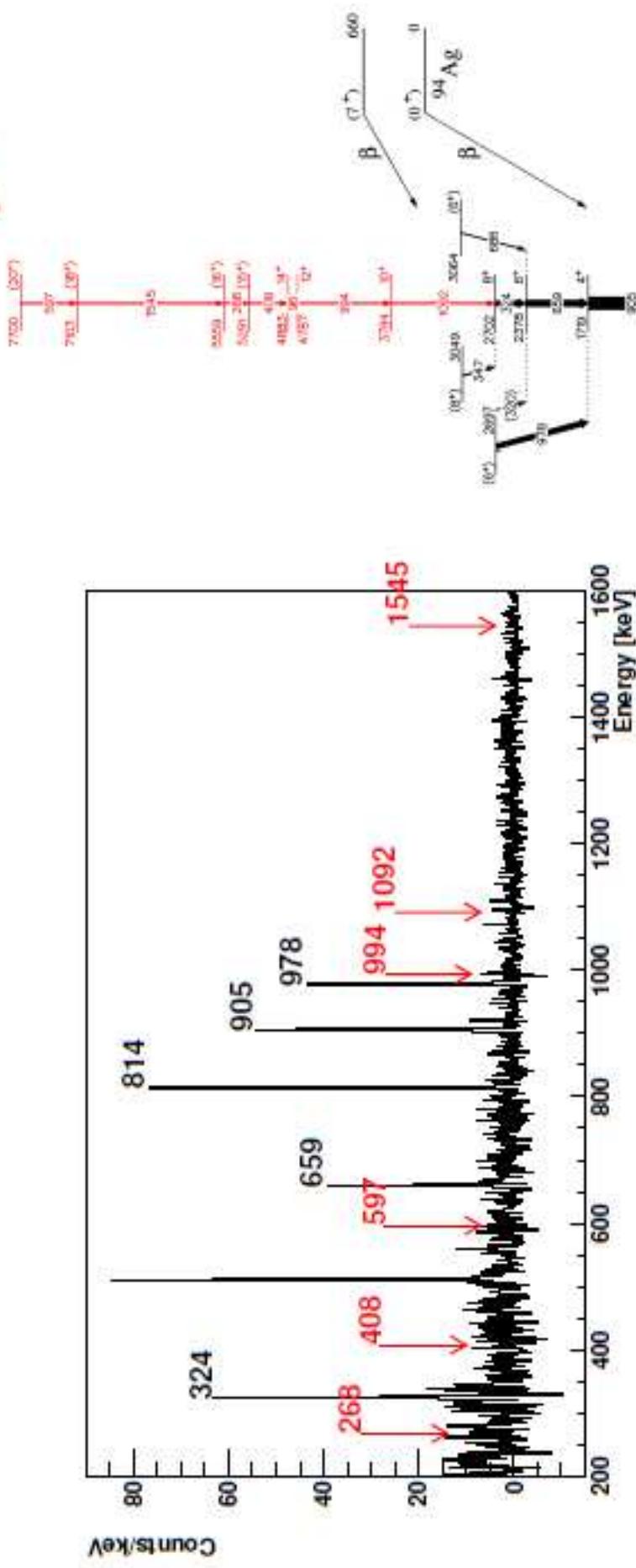
P. VAN ISACKER, International Journal of Modern Physics E, Vol. 22, No. 11 (2013) 1330028

- The low spin states are dominated by Boson T=0,J=9+ coupling
- sudden drop is observed for 8+ in ^{96}Cd as a seniority remnant
“It seems as if the two B pairs do not like to couple to a total angular momentum which equals their individual spins.”
- the deviations of E2 matrix elements between B-pairs and SM are much smaller for ^{92}Pd
- SM results for ^{96}Cd depends strongly on the model space



A.P. Zuker,¹ A. Poves,^{2,3} F. Nowacki,¹ and S. M. Lenzi⁴
PHYSICAL REVIEW C **92**, 024320 (2015)

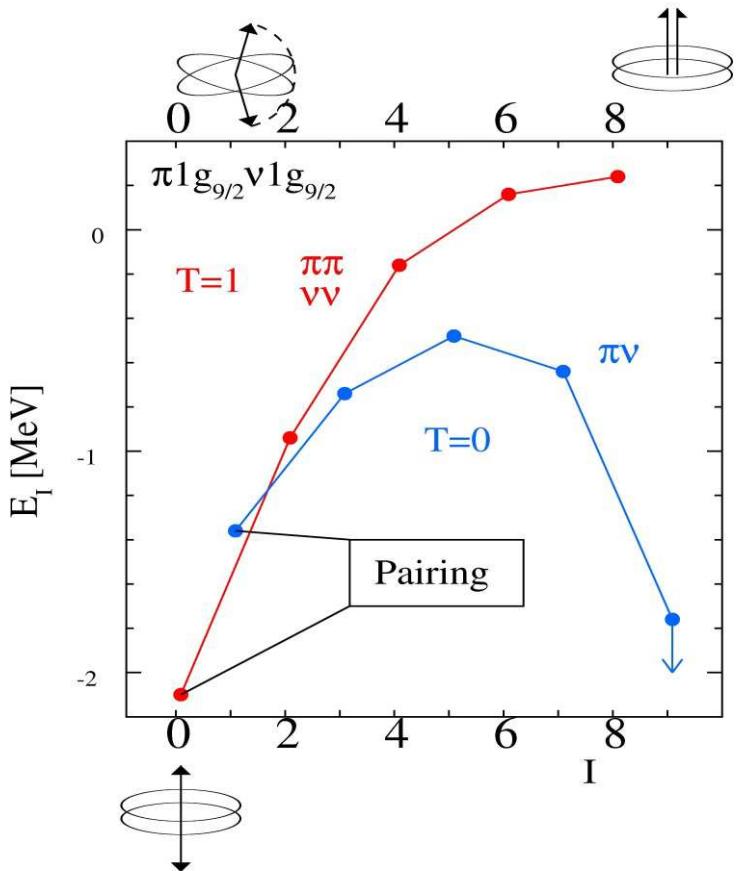
^{94}Ag : Evidence for the 21^+ decay?



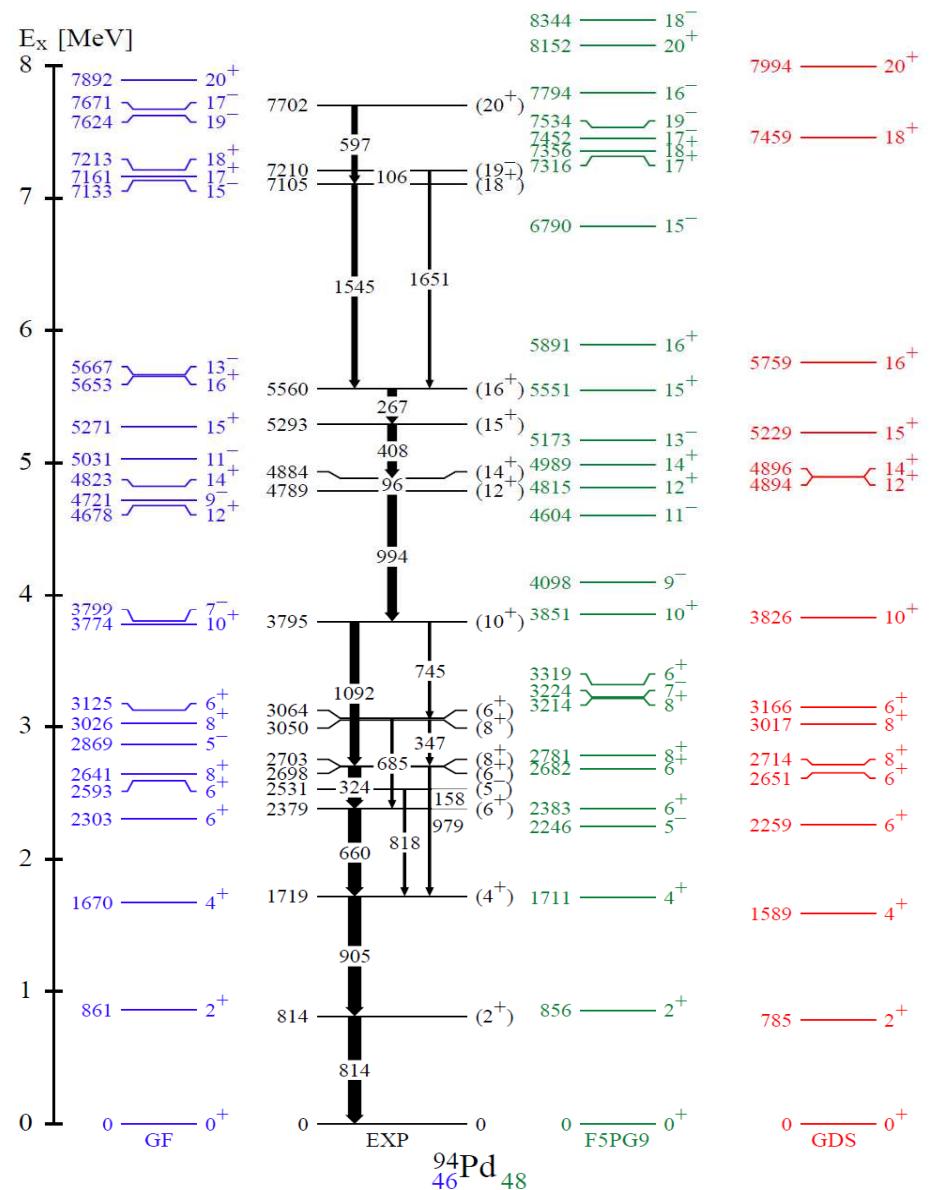
- None of the transitions fed exclusively through 21^+ decay observed
- High-spin isomeric ratios of other species in setting suggest
 - **60 implanted ^{94}Ag nuclei in 21^+ state**
 - ↳ Intensity per γ line following the decay ≈ 5 counts
 - ↳ Direct proton spectroscopy not feasible (Branchings: 1p: 4%, 2p: 0.5%)
- Based on C. Plettner et al., Nuclear Physics A 733 (2004) 20–36



$^{94}\text{Pd}/^{94}\text{Ag}$

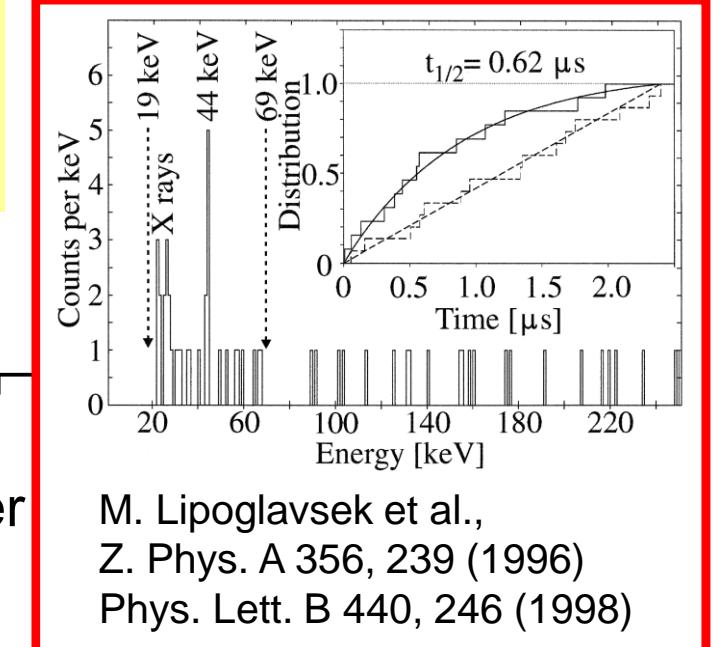
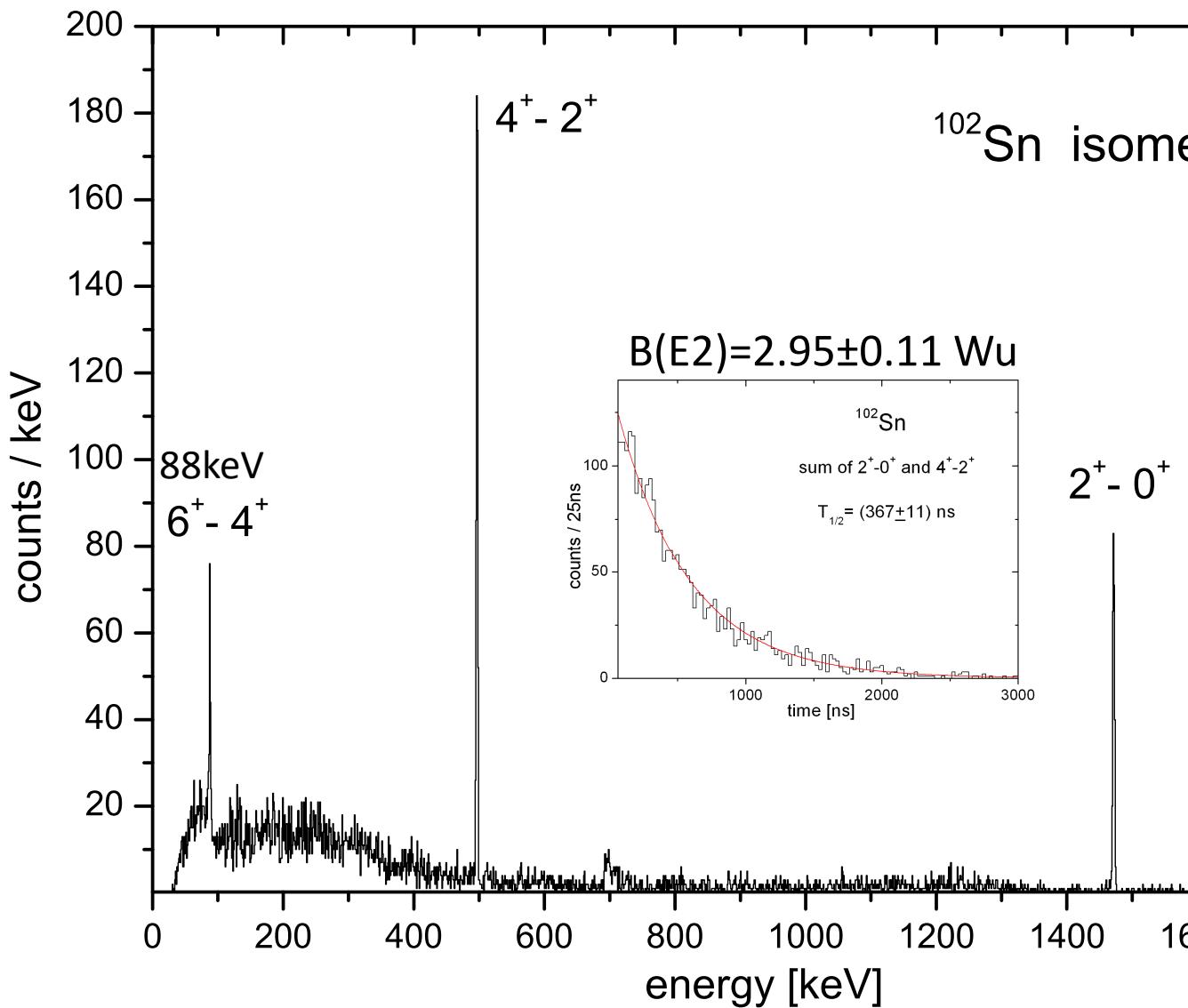


- M. Górska *et al.*, Z. Phys. A **353**, 233 (1995).
 R. Grzywacz *et al.*, Phys. Rev. C **55**, 1126 (1997)
 M. La Commara *et al.*, Nucl. Phys. A **708**, 167 (2002)
 C. Plettner *et al.*, Nucl. Phys. A **733**, 20 (2004).
 T. S. Brock *et al.*, Phys. Rev. C **82**, 061309 (2010)



$(vd_{5/2}g_{7/2})^2$ 6^+ isomer in ^{102}Sn
to be published

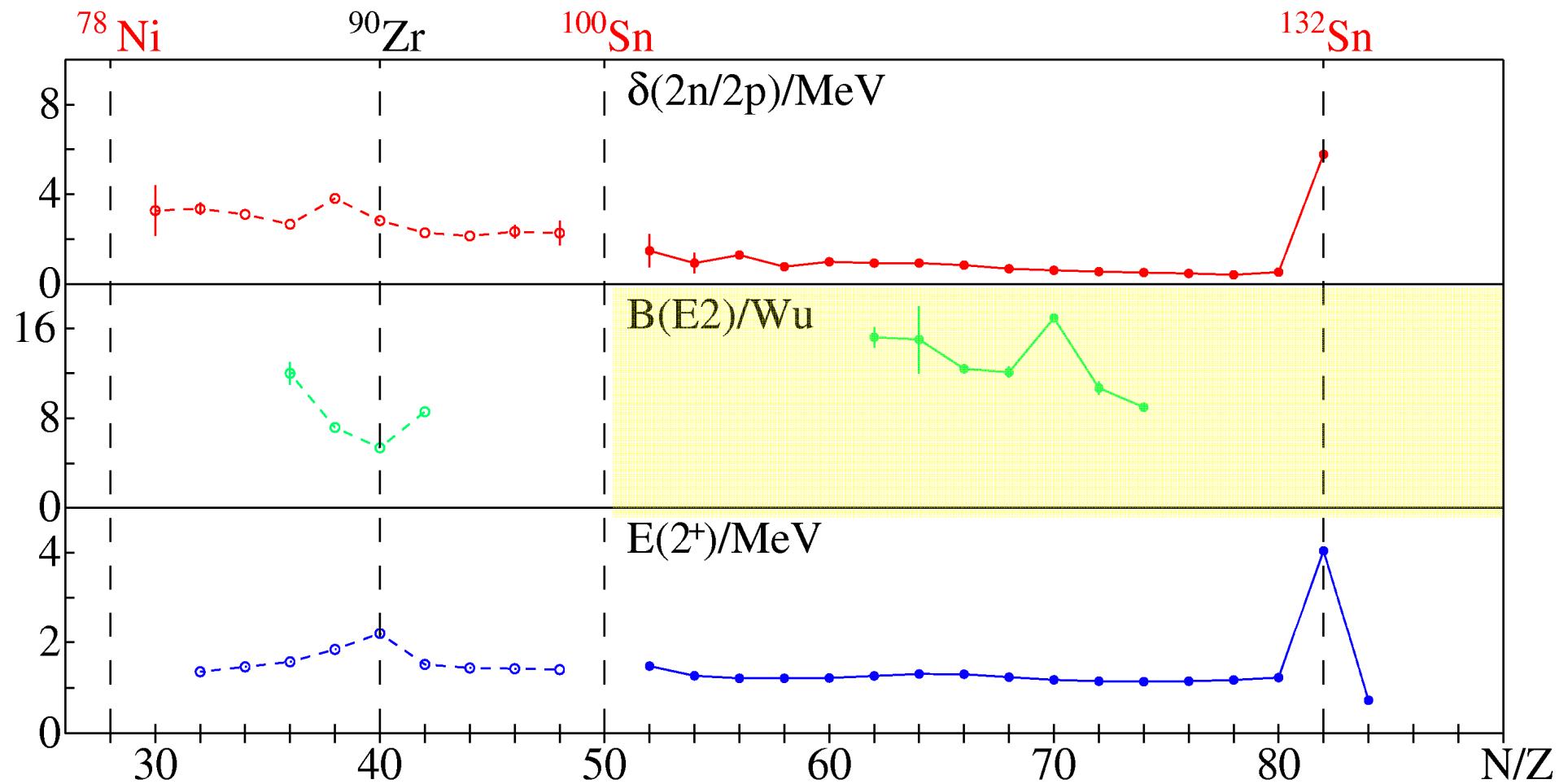
Purity of configuration compared to the 2^+



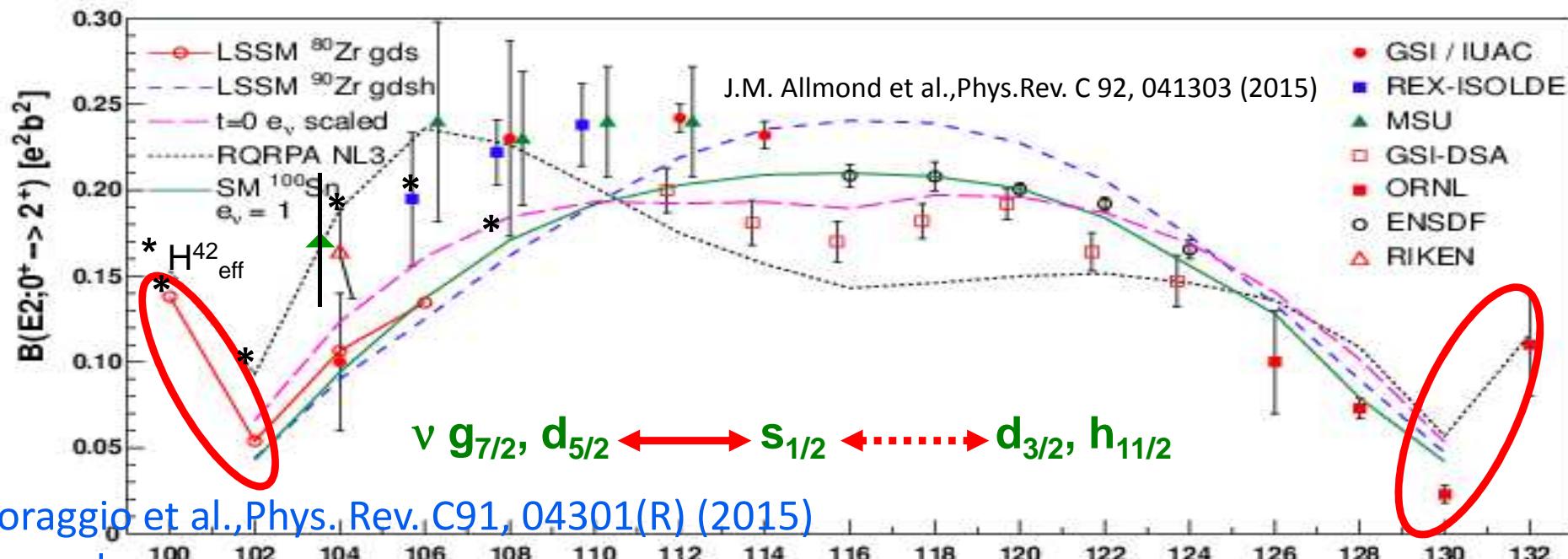
LSSM F. Nowacki:
gds space
1.5, 0.5
 $B(E2) = 1.87$ W.u.
1.17, 0.8
 $B(E2) = 2.85$ W.u.

A. Bohr and B. R. Mottelson,
Nuclear Structure, Vol. 2(1975)

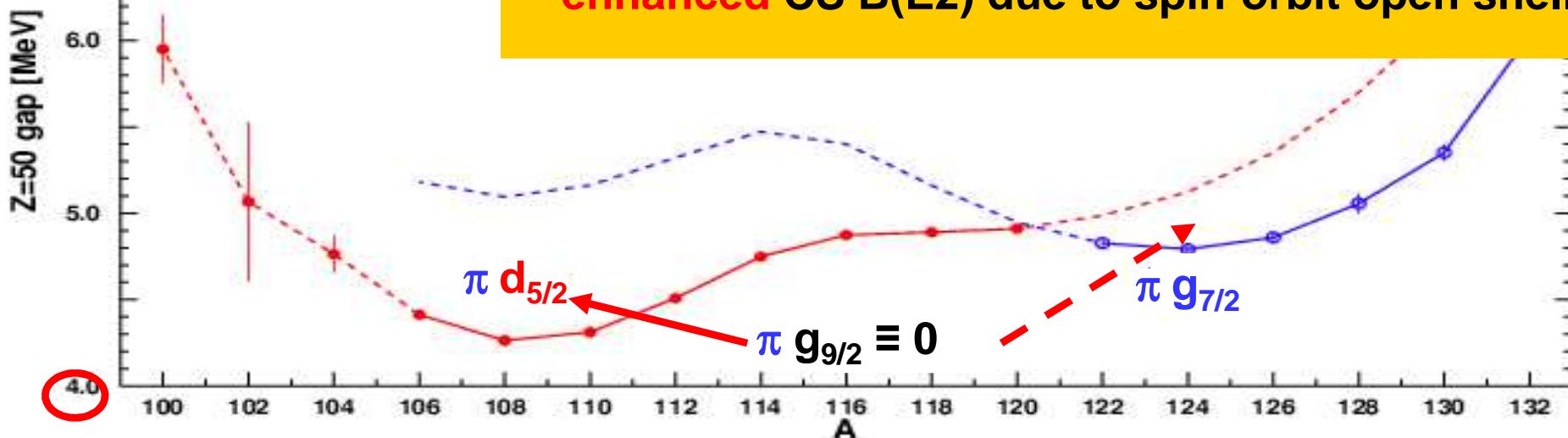
$B(E2:2^+ \rightarrow 0^+)$ in Z=50 chain: Status 2006



Proton core excitation: $B(E2; 0^+ \rightarrow 2^+)$ and $Z=50$ shell gap

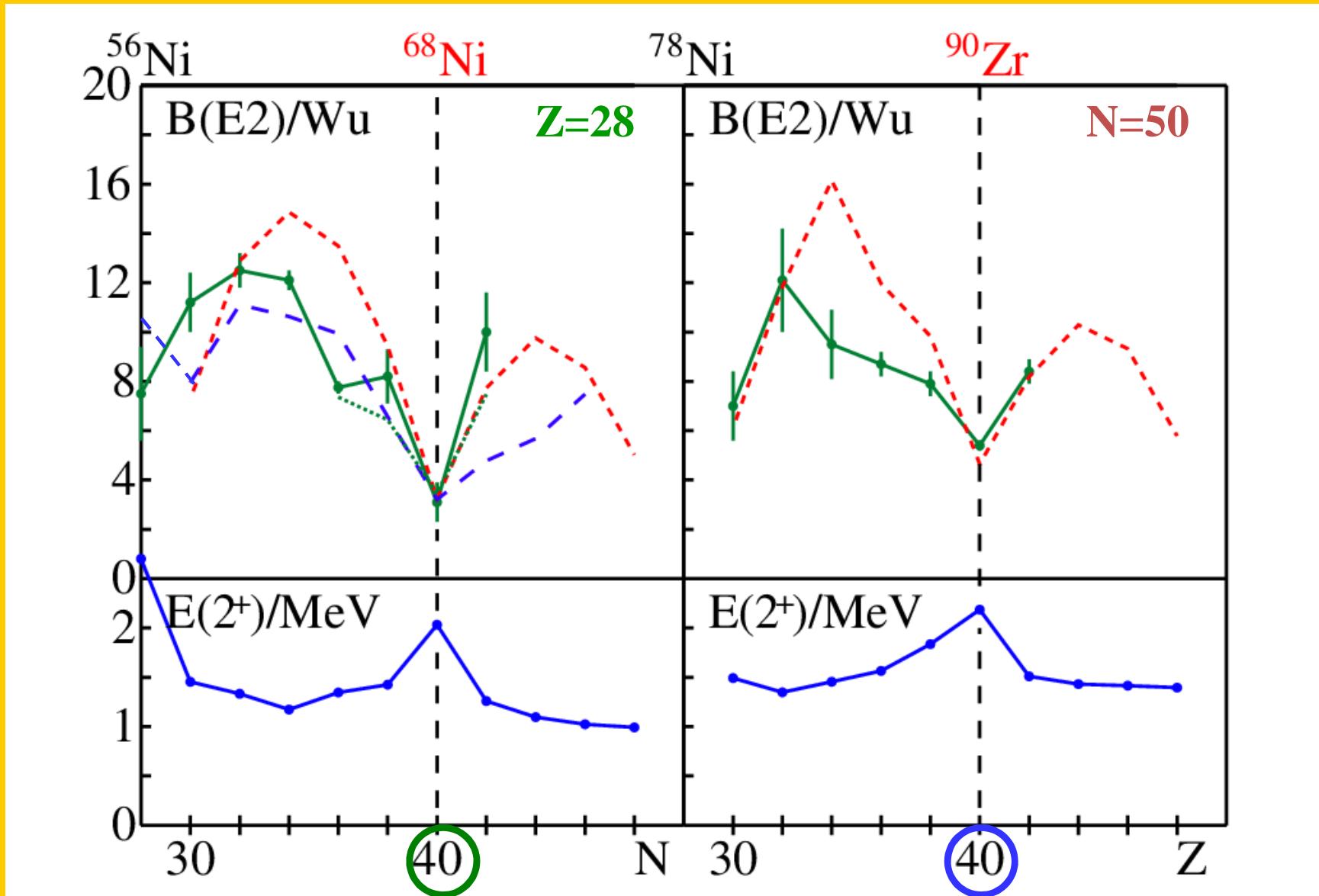


- lower bump enhanced due to stretched π ph and ν pp excitation within $\pi = +$ orbitals
- flat top due to hindered E2 involving $\nu s_{1/2}, h_{11/2}$
- enhanced CS $B(E2)$ due to spin-orbit open shell



Probing shell structure with $E(2^+)$ and $B(E2; 2^+ \rightarrow 0^+)$

$N, Z = 40$ $fpg_{9/2}$ shell in $Z=28$ (Ni) isotopes and $N=50$ isotones
Experiment vs. SM and LSSM



Summary

- Identification of N=Z-2 proton emitters
- Spectroscopy of N=Z nuclei below ^{100}Sn
- ^{98}In spectroscopy
- ^{96}Cd 16+ β decay and β delayed p decay branch
- Core excitation components in the 16+ wf
- Evidence for new γ -decaying isomer in ^{96}Cd with half-live(s) of ~ 200 ns
- tentative identification of 2⁺ 4⁺ 6⁺ and 8⁺ states and pn pairing
- Sn chain B(E2)/ effective charges

Gaps and single particle/hole energies for N>>Z CS nuclei

