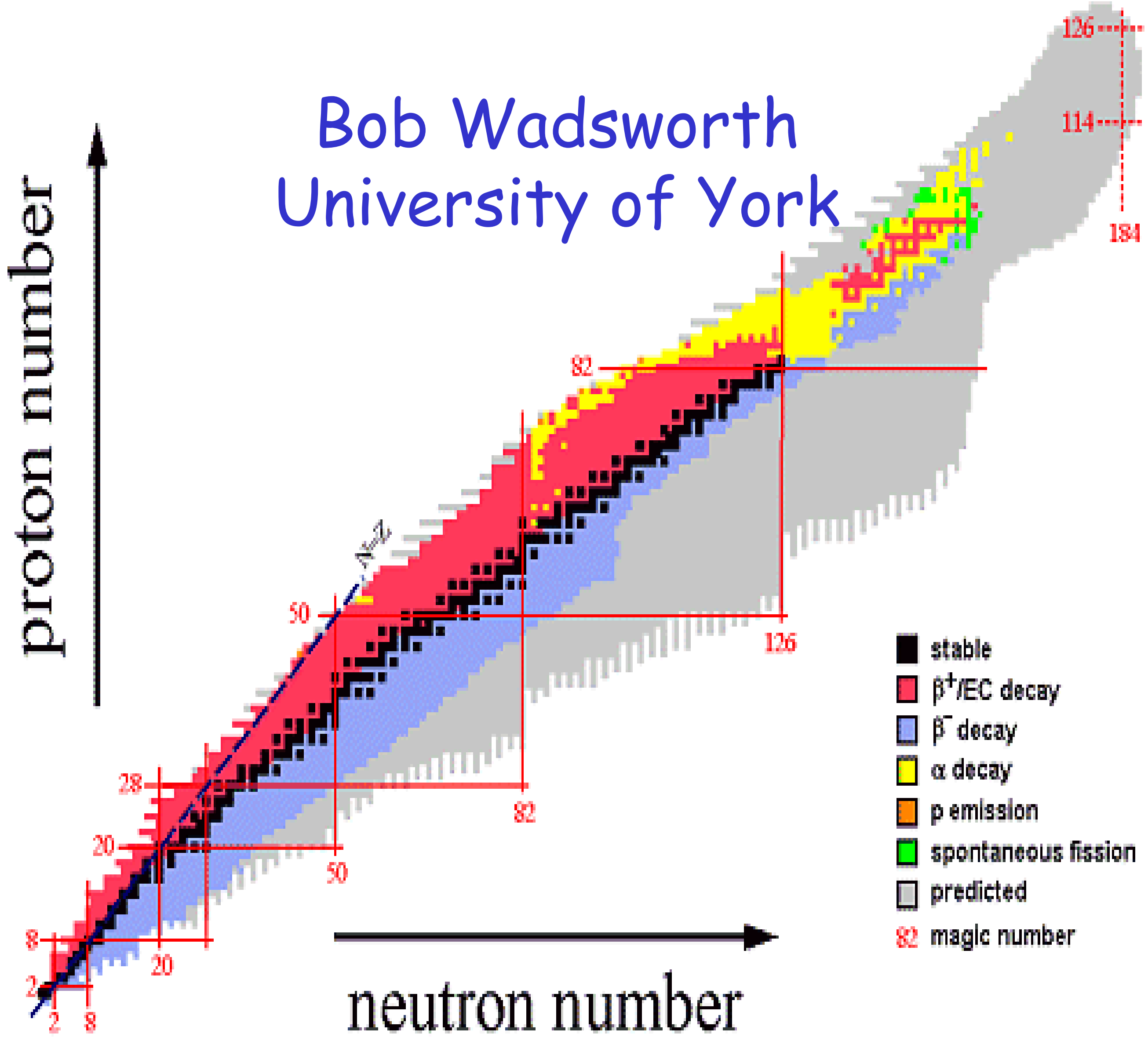
Spectroscopy near the N=Z line below ^{100}Sn

Bob Wadsworth

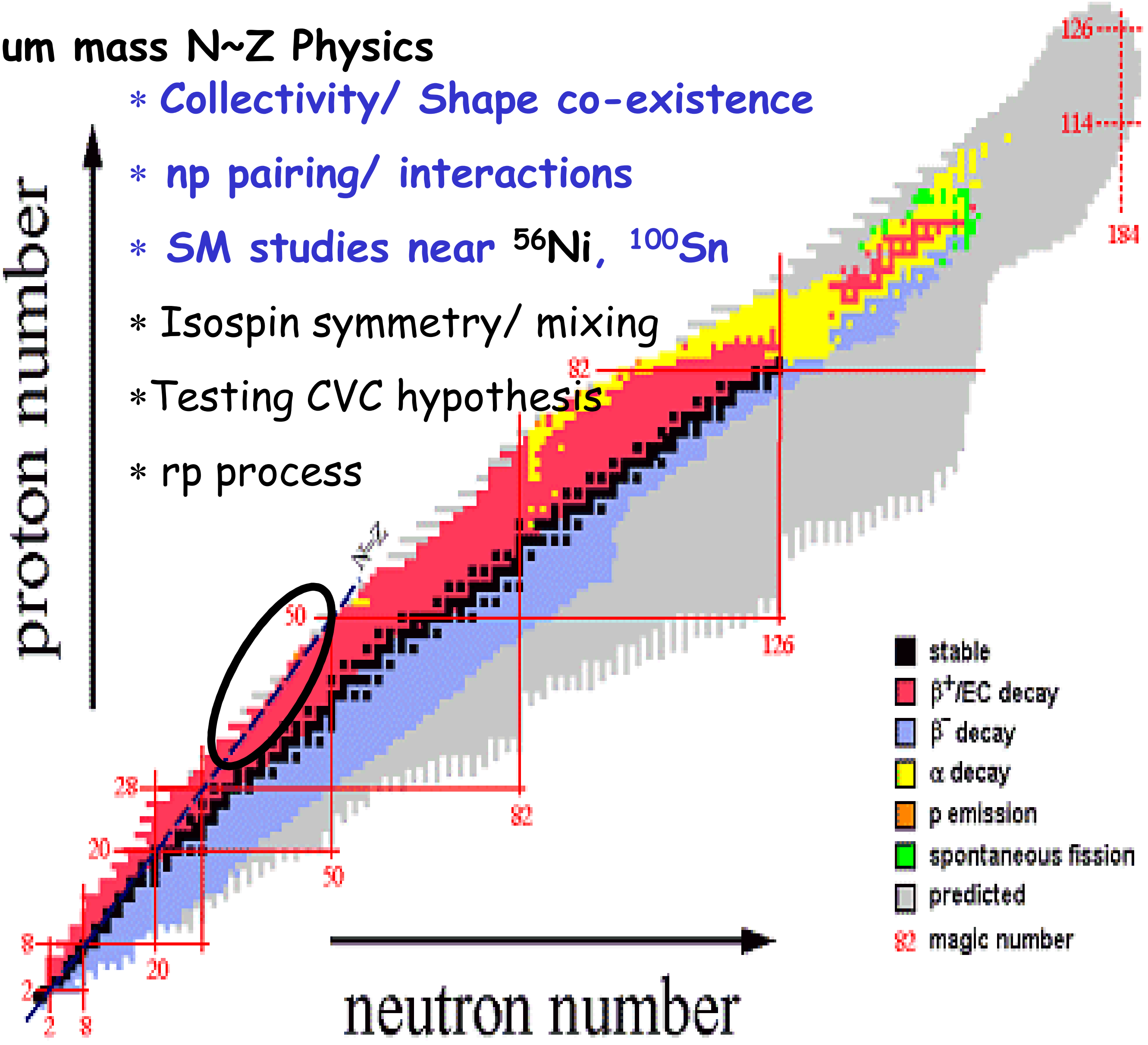
University of York



Spectroscopy near the N=Z line

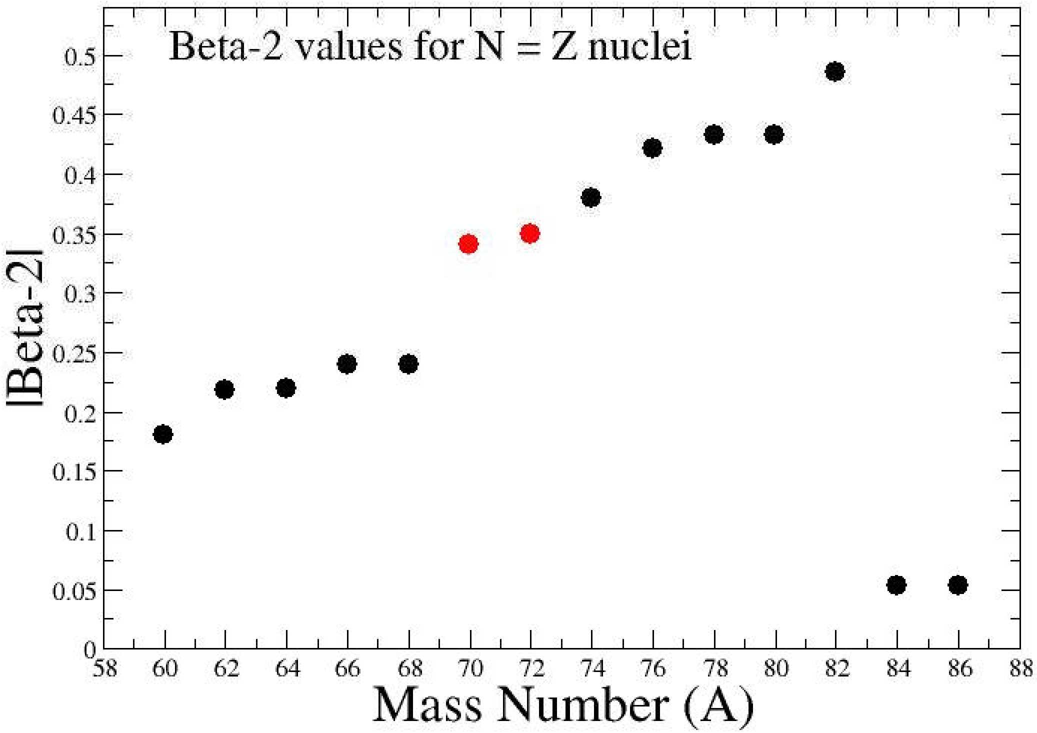
Medium mass N~Z Physics

- Collectivity/ Shape co-existence
- np pairing/ interactions
- SM studies near ^{56}Ni, ^{100}Sn
- Isospin symmetry/ mixing
- Testing CVC hypothesis
- rp process



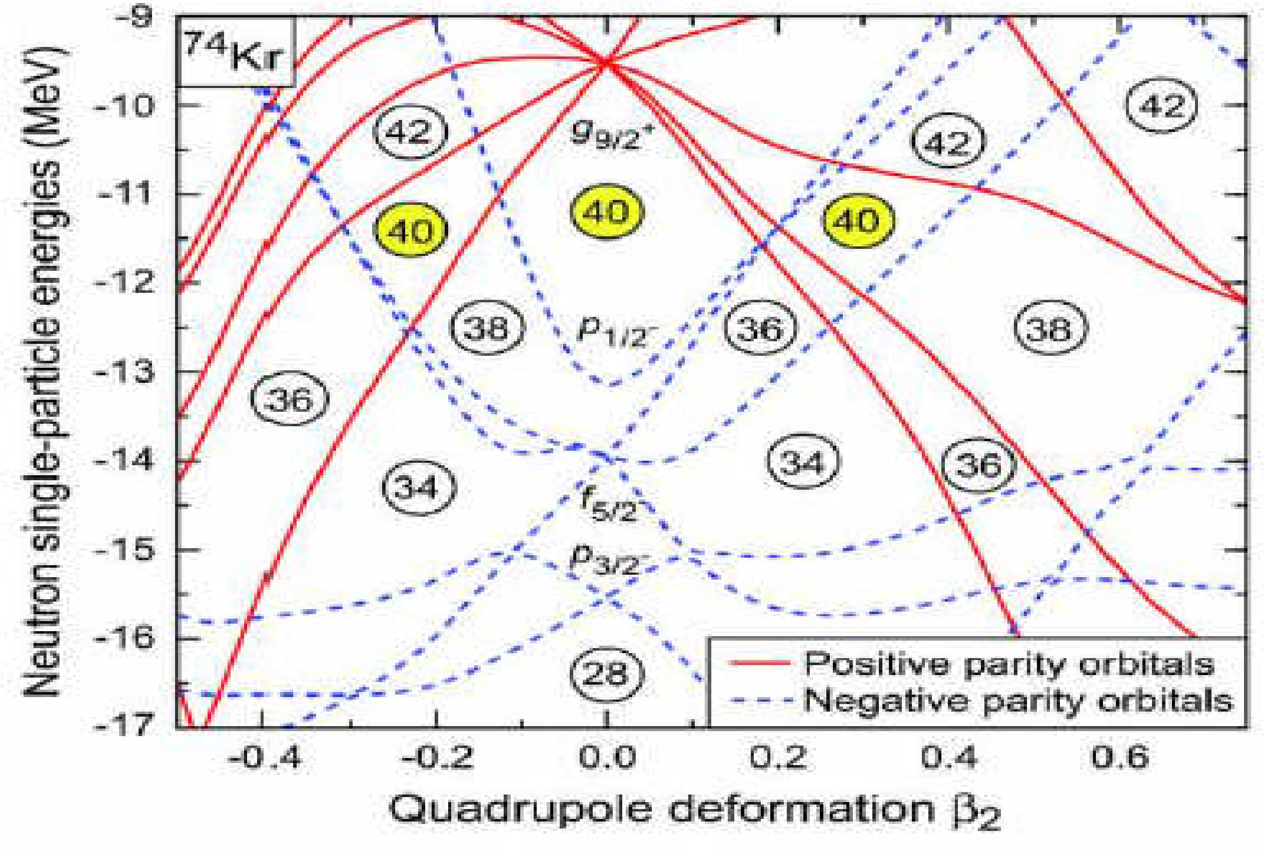
Collectivity along the N=Z line

Finite-range droplet macroscopic model + folded-Yukawa single-particle microscopic model



Moller, Nix, Myers, Swiatecki
Atomic and Nuclear data tables, 59, 185 (1995)

Collectivity along the N=Z line



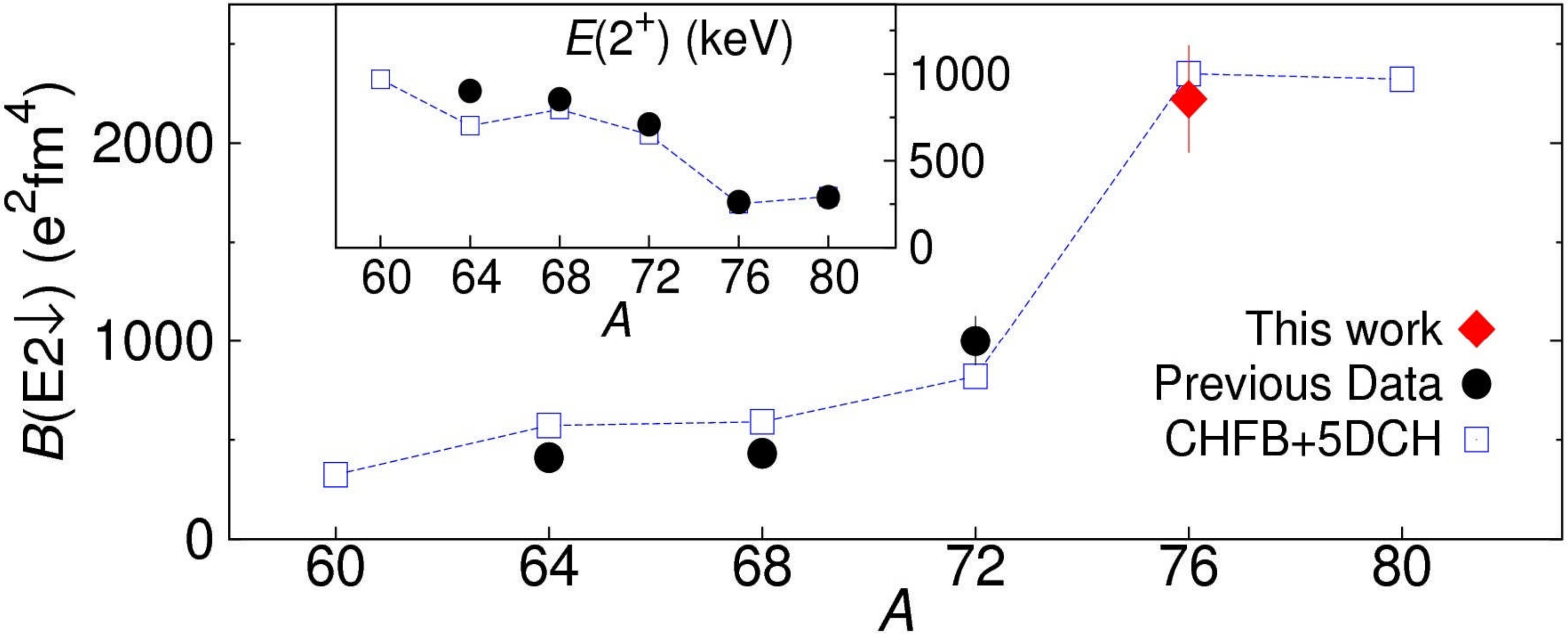
- Nuclear deformation and collectivity in the mass 70-80 is region is largely driven by proton, neutron occupancy of the $g_{9/2}$ orbit.
- Large shell-gaps at prolate, spherical and oblate shapes results in the potential for shape co-existence for many nuclei in the mid-mass region

Collectivity along the N=Z line

A Lemasson et al., PRC 85, 041303(R) (2012)

Constrained HF Bogoliubov theory with mapping to the 5D collective Hamiltonian

J P Delaroche et al., PRC 81, 014303 (2010)

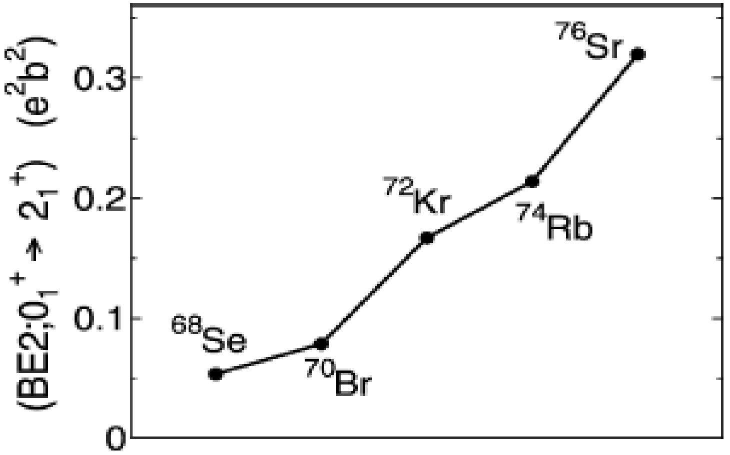


Transition strengths difficult to measure:

- ^{68}Se, ^{72}Kr Relativistic Coulex,
- ^{64}Ge Plunger lifetime expt following nucleon removal
- ^{76}Sr Doppler shift lineshape measurements + charge exchange reaction (#)

Collectivity along the N=Z line

Shell model using a truncated $f_{5/2}, p_{1/2}, g_{9/2}, d_{5/2}$ model space



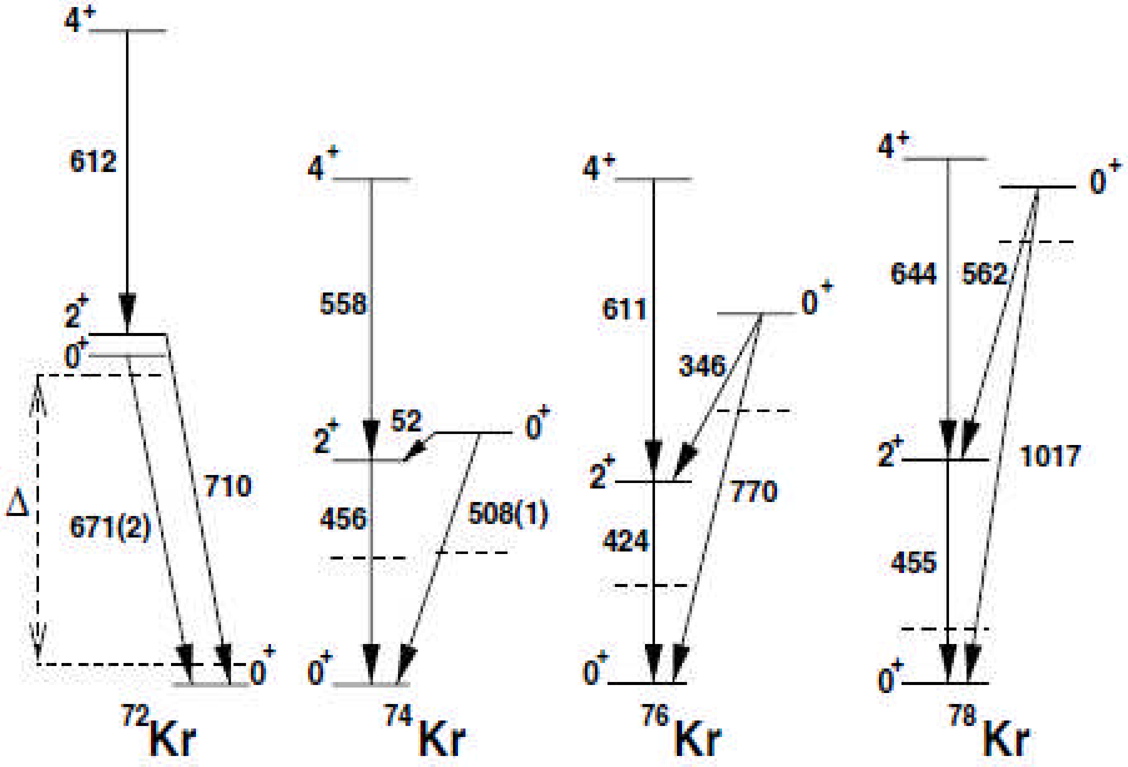
M Hasagawa, K Kaneko, T Mizusaki, Y Sun, PLB 656, 51 (2007)

Sharp increase in B(E2) values beyond ^{70}Br is attributed to a sudden jump of protons and neutrons into the upper *gd* shell.

Separator + recoil-β-tagging (or PPAC/ Ion Chamber) + Differential Plunger
Need a good efficient γ ray array

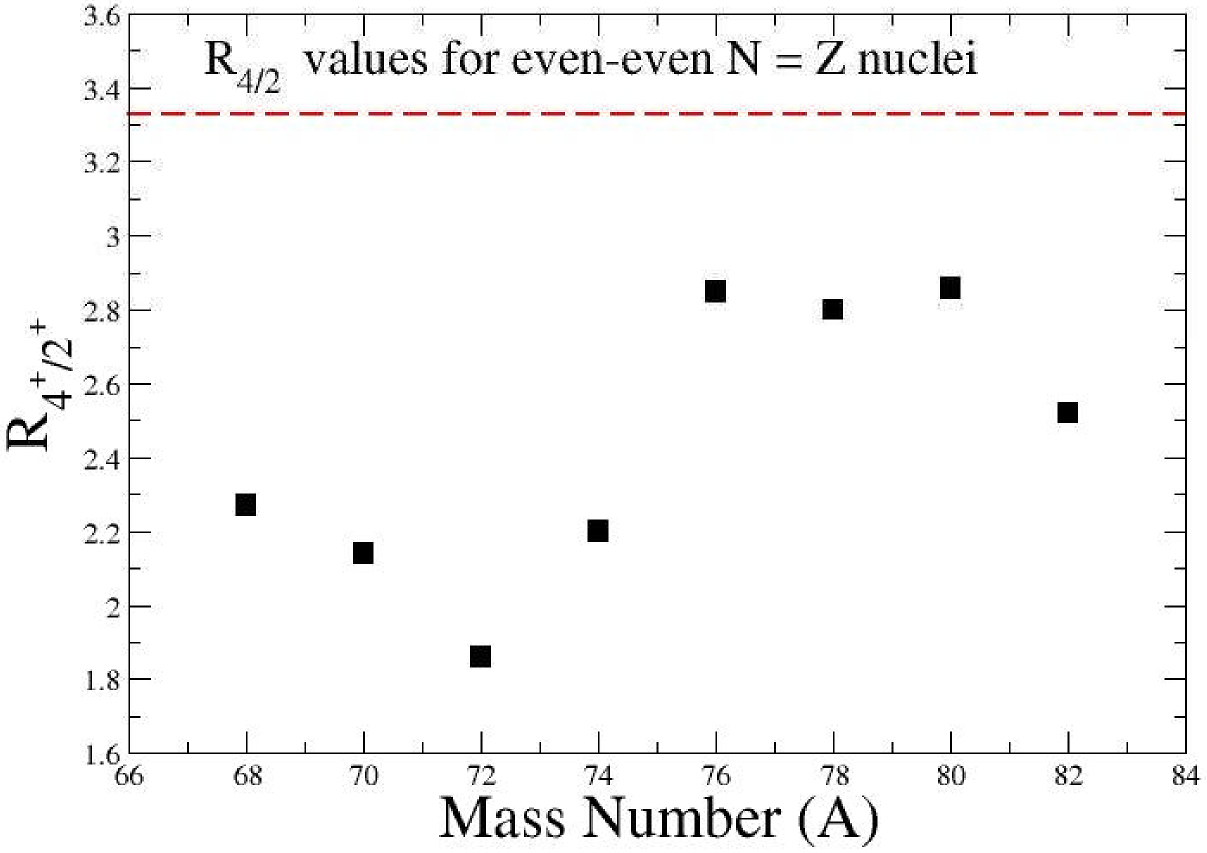
Shape co-existence along the N=Z line

Even-A Kr isotopes are known to exhibit shape co-existence, with excited 0^+ states already identified: E Bouchez et al., PRL 90, 083502 (2003)



Shape co-existence along the N=Z line

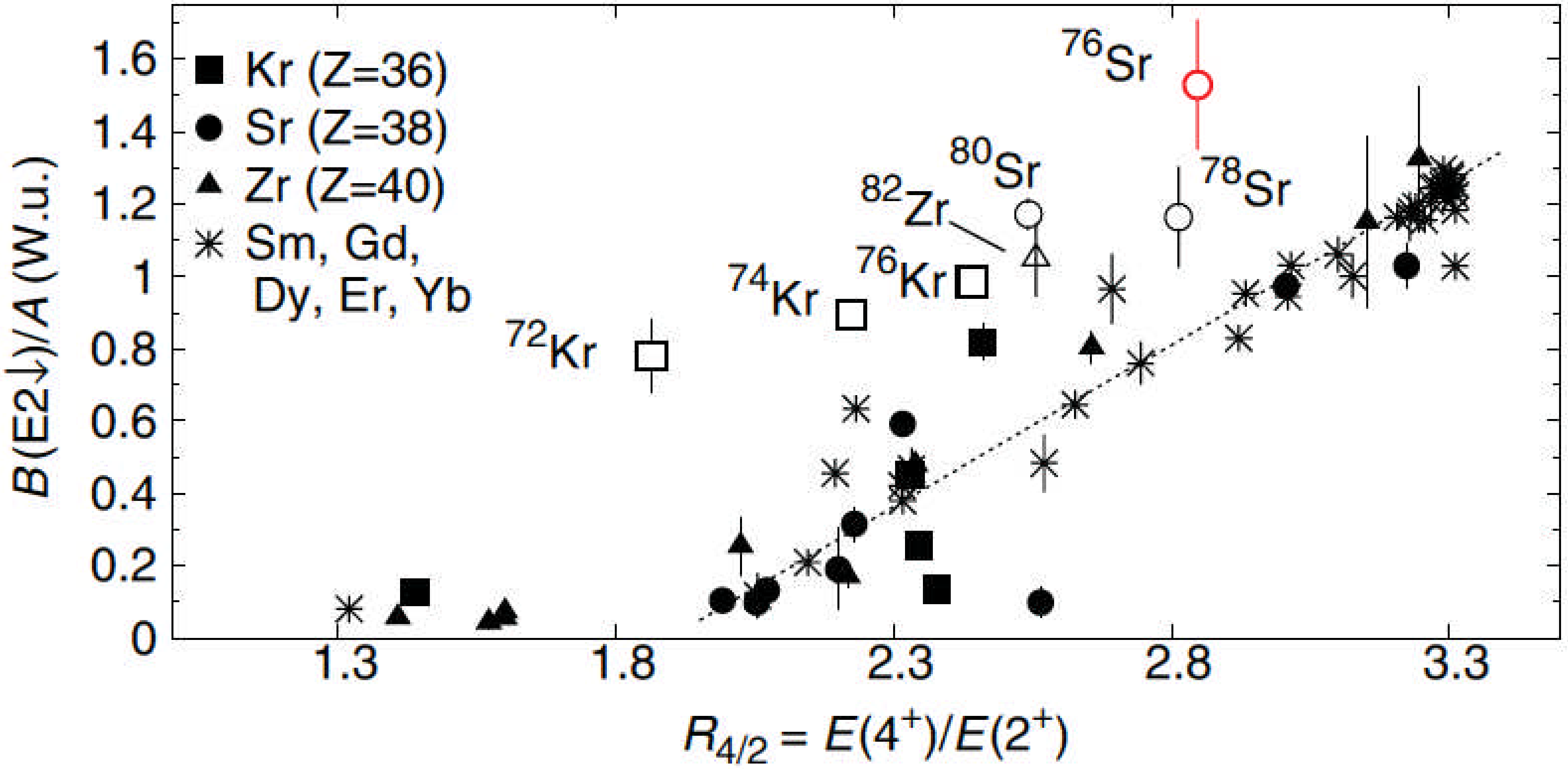
$$R_{4/2} = E_{4+}/E_{2+}$$



Why are the $R_{4/2}$ values well below the rotational limit for A~80 nuclei?

Shape co-existence along the N=Z line

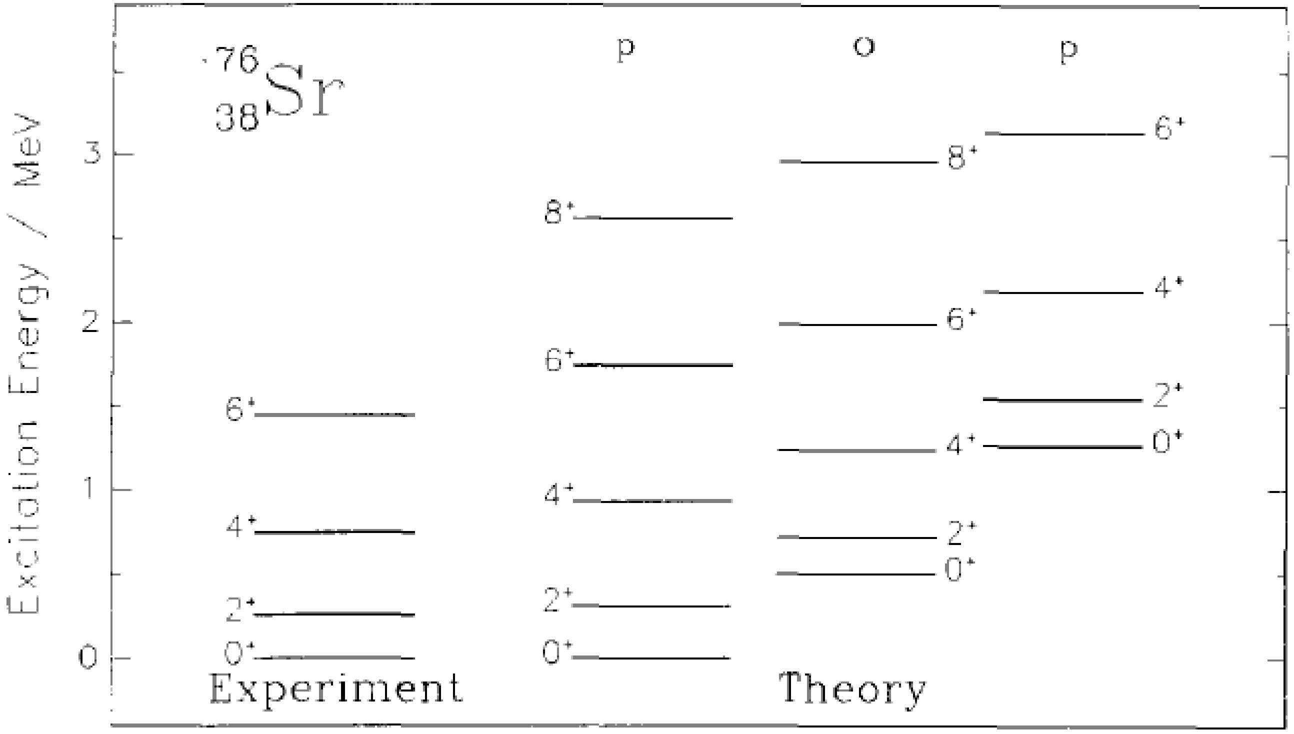
A Lemasson et al., PRC 85, 041303(R) (2012)



- ∗ Clear correlation between B(E2)/A and $R_{4/2}$ values for vibrational to rotational nuclei:
- ∗ Deviations (OPEN SYMBOLS) occur in nuclei where shape co-existence is known or expected

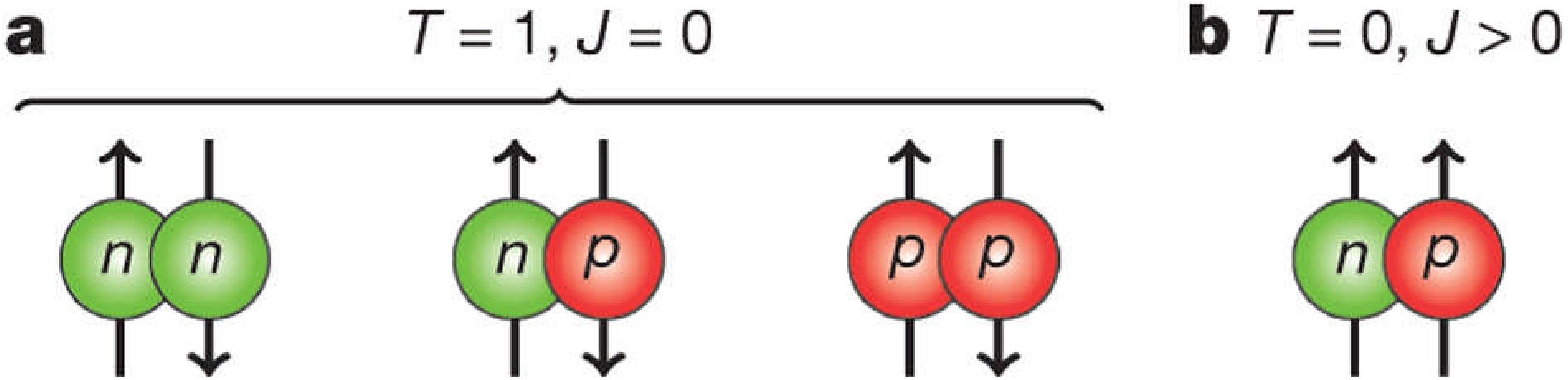
Shape co-existence along the N=Z line

0^+_2 in ^{76}Sr at ~0.5 MeV: A. Petrovici *et al., Nucl. Phys. A605, 290 (1996).*



Nuclei such as ^{76}Sr, ^{78}Y, ^{80}Zr, ^{82}Nb, ^{84}Mo etc only have data on yrast states $\Rightarrow$ clearly need information on non-yrast states to test the hypothesis that shape co-existence may be responsible for low $R_{4/2}$ values.

Neutron-proton pairing in N=Z nuclei



- Studies of Binding energies in e-e and o-o nuclei indicate that T=1 *np* pairing is dominant, with no evidence for a T=0 (deuteron-like) pair condensate.

P. Vogel, Nucl. Phys. A662 (2000) 148,
A.O. Macchiavelli et al PRC 61 (2000) 014303R

- Comparison of data with mean-field calculations for A=68-80 nuclei suggests the presence of a strong isovector (T=1) *np* pair field at low spin, but no evidence for T=0 pairing.

A Afanasjev, S Frauendorf, Phys. Rev. C 71, 064318 (2005)

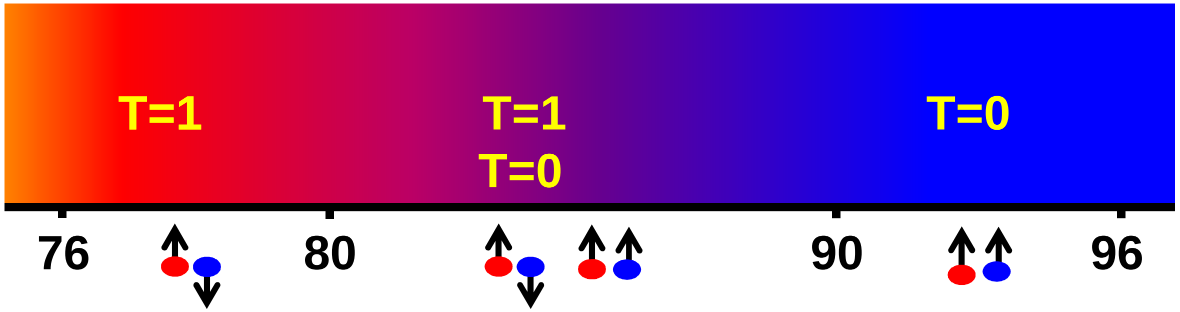
- Odd-odd nuclei such as ^{66}As,^{70}Br,^{74}Rb have T = 1, 0^+ grd states, but no low-lying [J=1,T=0] state, implying T=0 pairing mode is weak in this mid-mass region.

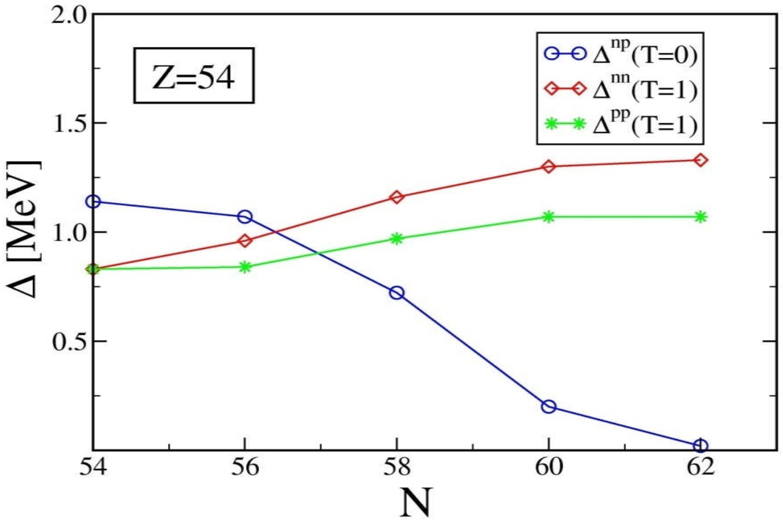
- Does T=0 pairing/ interaction play a role at low or high spin in heavier N=Z nuclei?

A.L. Goodman PRC 58 R3051 (1998) and PRC 60, 014311 (1999)
W Satula, R Wyss PLB 393, 1 (1997) and PRL 86, 4488 (2001)
J Engel et al., PLB 389, 211 (1996) + ... Etc.

Neutron-proton pairing in N=Z nuclei

A. L. Goodman , PRC 60, 014311 (1999) –
studies of ground states of e-e N = Z, A = 76-96 nuclei

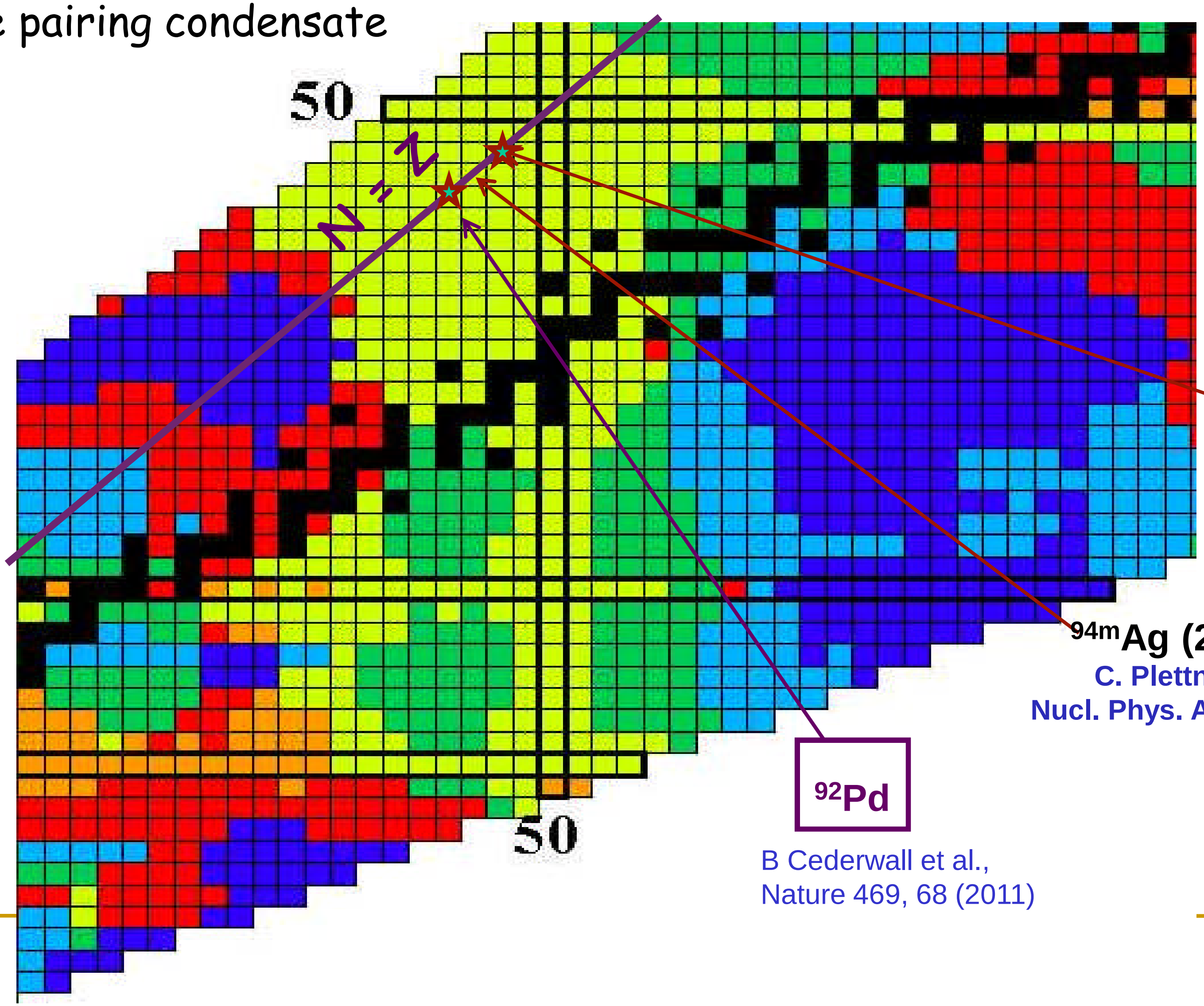




Calculation by W. Satula, R. Wyss, Phys. Rev. Lett. Vol. 86, 4488 (2001)

Evidence for isoscalar np interaction

As yet there is no data that definitively supports the presence of np T=0 BCS type pairing condensate



^{96m}Cd (16^+)

B S Nara Singh et al., PRL 107, 172501 (2011)

^{94m}Ag (21^+)

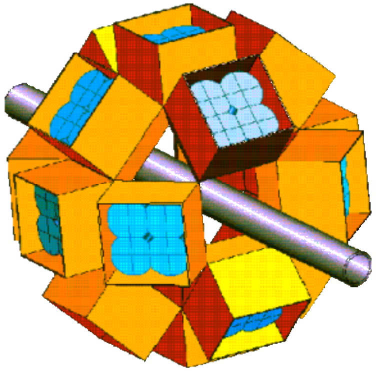
C. Plettner et al. Nucl. Phys. A733, 20 (2004)

^{92}Pd

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

Evidence for isoscalar np interaction

Excited states in ^{92}Pd populated via fusion-evaporation at the Coulomb barrier (GANIL).



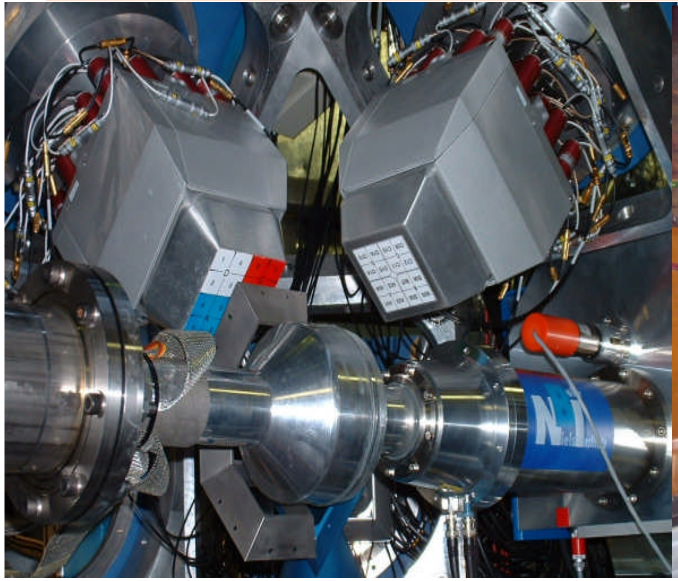
$$^{36}\mathrm{Ar} + {}^{58}\mathrm{Ni} \rightarrow {}^{94}\mathrm{Pd}^{*} \rightarrow {}^{92}\mathrm{Pd} + 2n$$

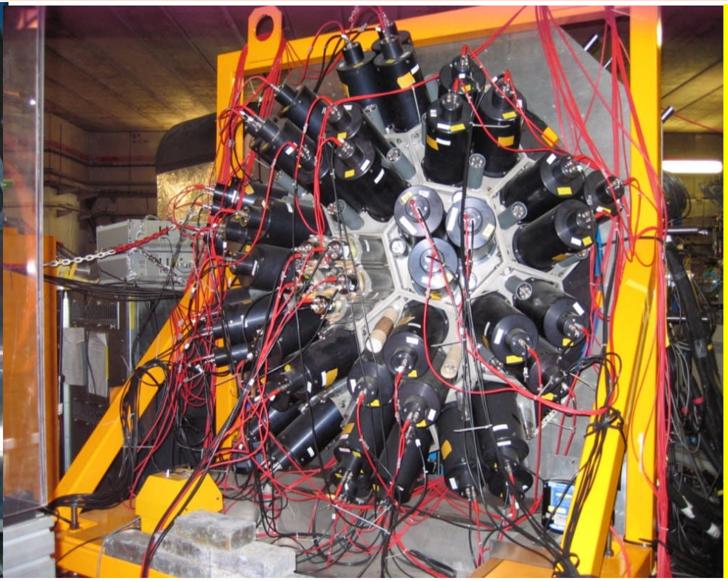
E_{beam} = 111 MeV I_{beam} = 5-10 pnA, 14 days

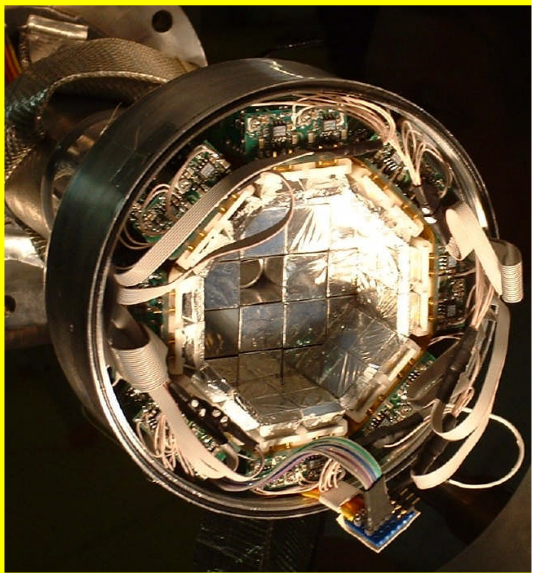
Detector systems:

EXOGAM	**NEUTRON WALL**	**DIAMANT CsI(Tl) array**
ε ~ 0.11	ε(n) ~ 0.25 ε(”clean” 2n) ~ 0.03	ε(p) ~ 0.50 ε(α) ~ 0.40

ε(any charged particle) ~ 0.66 ➔ veto efficiency for particle mult. >1 = 88%

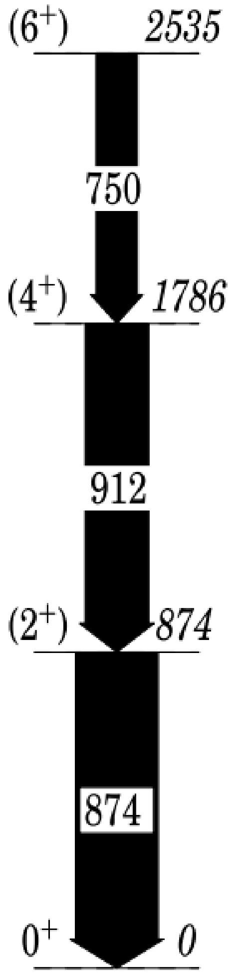


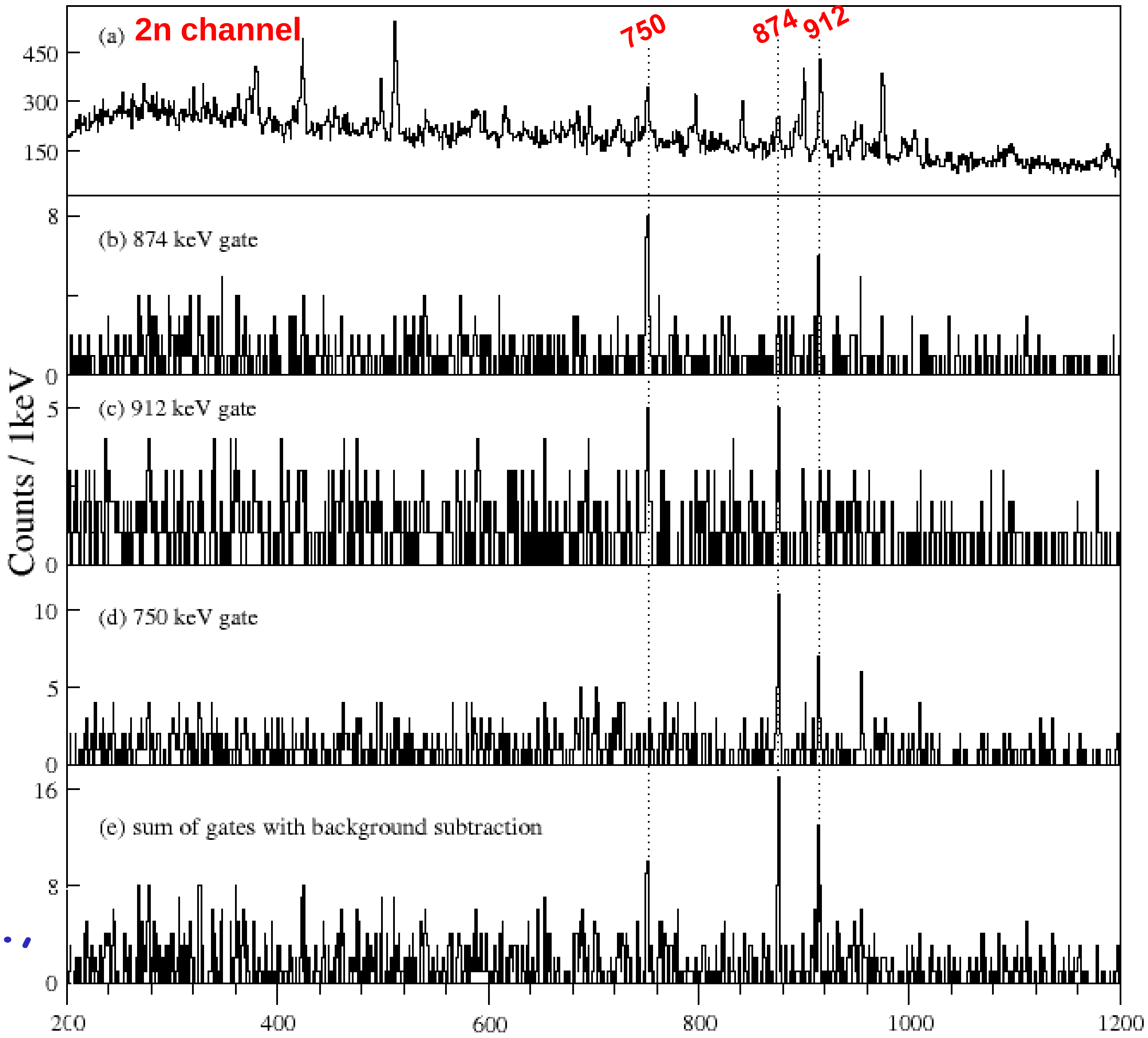




^{92}Pd level scheme

H Al-Azri (York PhD student)

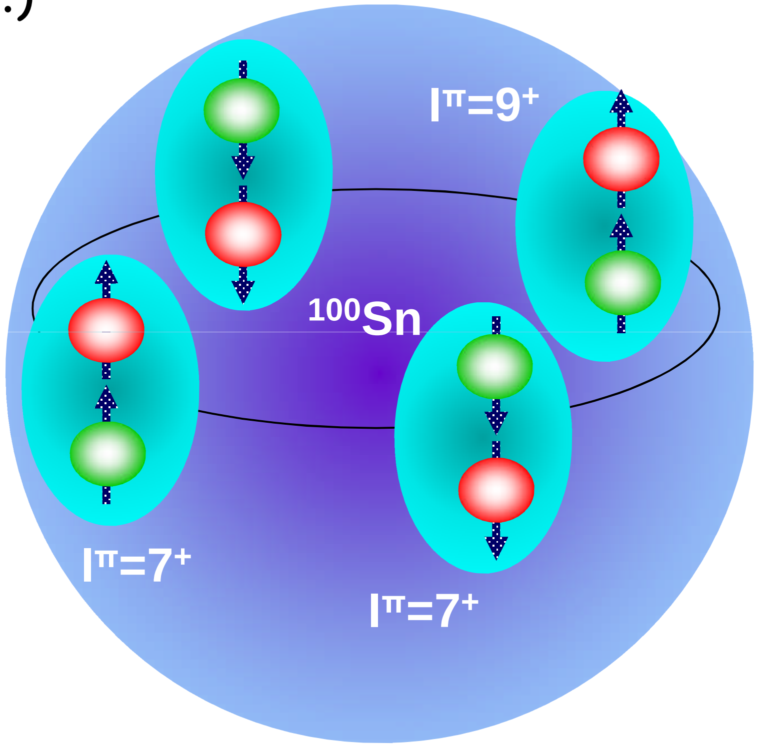




B Cederwall et al., Nature 469, 68 (2011)

Evidence for isoscalar np interaction

Shell Model Calculations in $p_{1/2},g_{9/2}$ space predict strong np interactions
➔ Spin-aligned T=0 np coupling scheme for N=Z nuclei below ^{100}Sn
(J. Blomqvist et al.)



$^{92}Pd_{gs}$

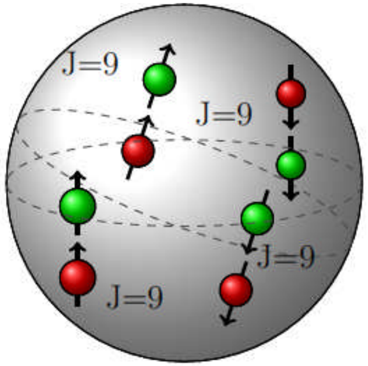
- 4-deuteron hole-like pairs coupled to J=9, each with a different angular momentum projection M = +9, -9, +7, -7 to satisfy the Pauli Principle.

Aligned np coupling: $\Psi_{G.S.}=[(\{\nu g_{9/2}^{-1} \times \pi g_{9/2}^{-1}\}_{9+})^2]_{0+} \times [(\{\nu g_{9/2}^{-1} \times \pi g_{9/2}^{-1}\}_{7+})^2]_{0+}$

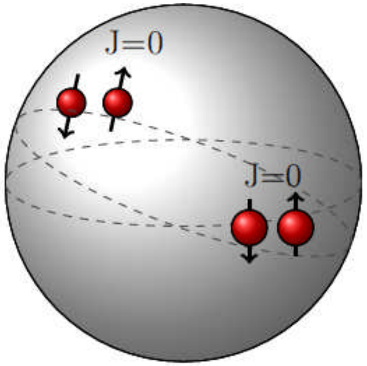
- Similar results confirmed for ^{96}Cd – S Zerguine and P Van Isacker, PRC 83, 064311 (2011)

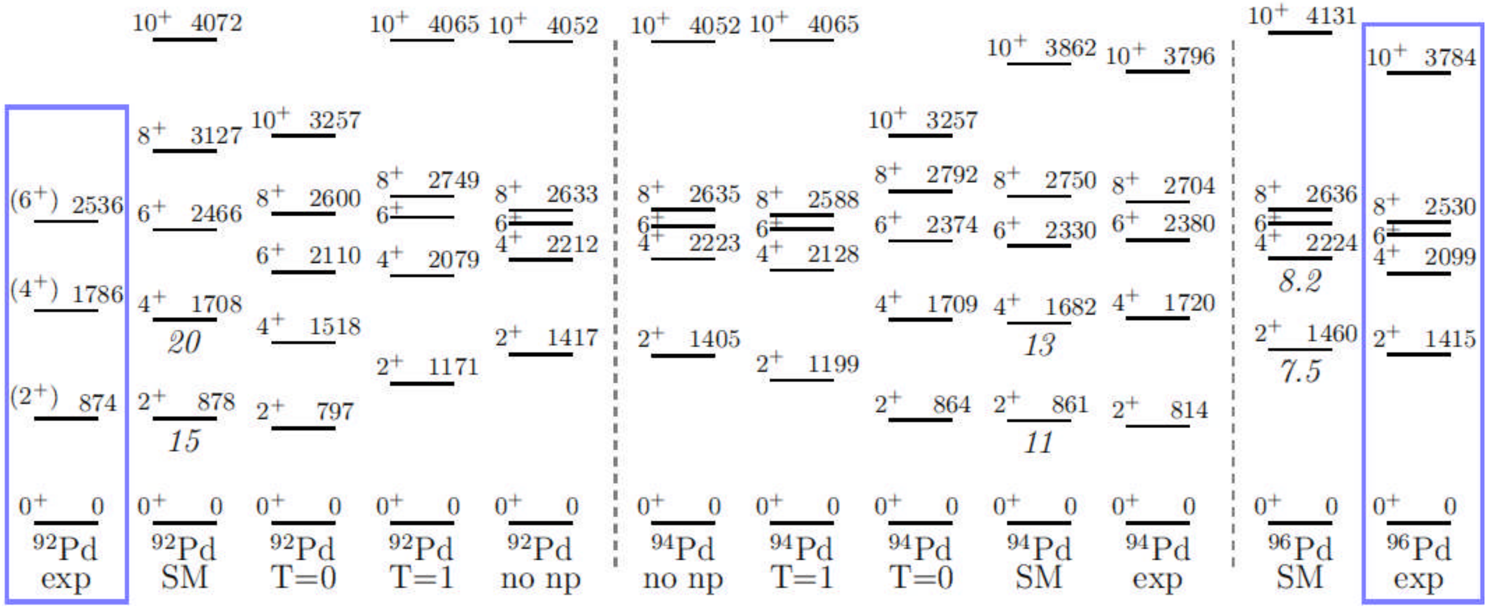
Evidence for isoscalar np interaction

Effect of isoscalar np interaction at N=Z



Shell model calculations by **J. Blomqvist et al.**

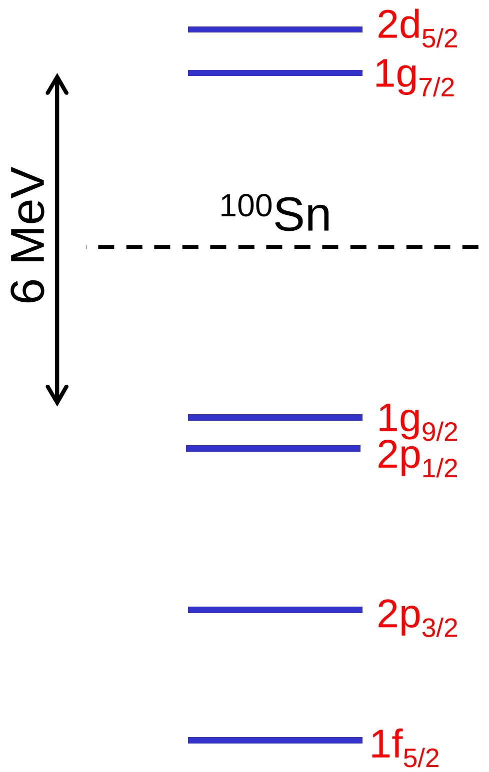


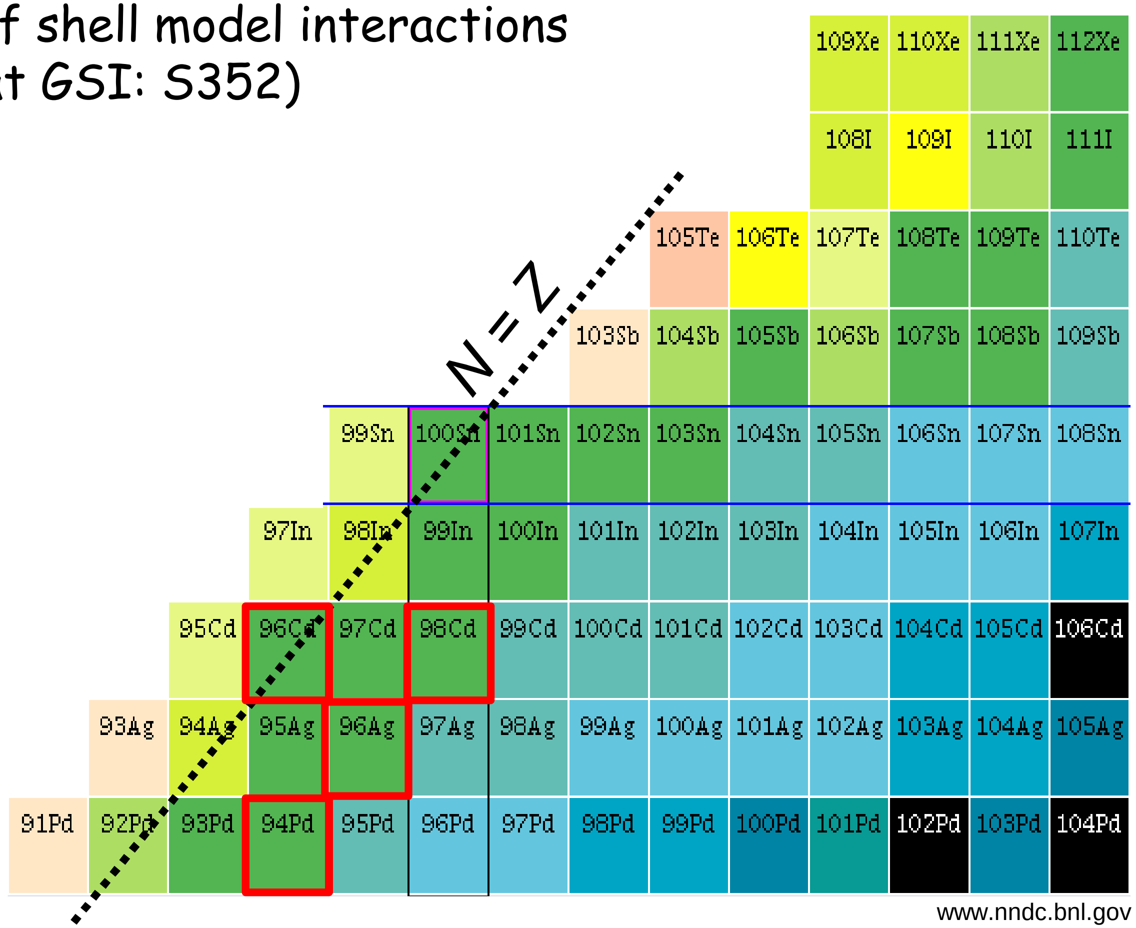


Calculations done in several model spaces,:i.e., 0g9/2, 0g9/2-1p1/2 and 0g9/2-1p1/2-0f5/2-1p3/2 which all give similar results . Int. parameters determined to reproduce exp energies in ^{94,95}*Pd,* ^{93,94}*Rh*

Isomers in N ≅ Z nuclei below ^{100}Sn

Provide excellent tests of shell model interactions
and model spaces (Expt at GSI: S352)





										109Xe	110Xe	111Xe	112Xe
										108I	109I	110I	111I
								105Te	106Te	107Te	108Te	109Te	110Te
							103Sb	104Sb	105Sb	106Sb	107Sb	108Sb	109Sb
				99Sn	100Sn	101Sn	102Sn	103Sn	104Sn	105Sn	106Sn	107Sn	108Sn
			97In	98In	99In	100In	101In	102In	103In	104In	105In	106In	107In
		95Cd	96Cd	97Cd	98Cd	99Cd	100Cd	101Cd	102Cd	103Cd	104Cd	105Cd	106Cd
	93Ag	94Ag	95Ag	96Ag	97Ag	98Ag	99Ag	100Ag	101Ag	102Ag	103Ag	104Ag	105Ag
91Pd	92Pd	93Pd	94Pd	95Pd	96Pd	97Pd	98Pd	99Pd	100Pd	101Pd	102Pd	103Pd	104Pd

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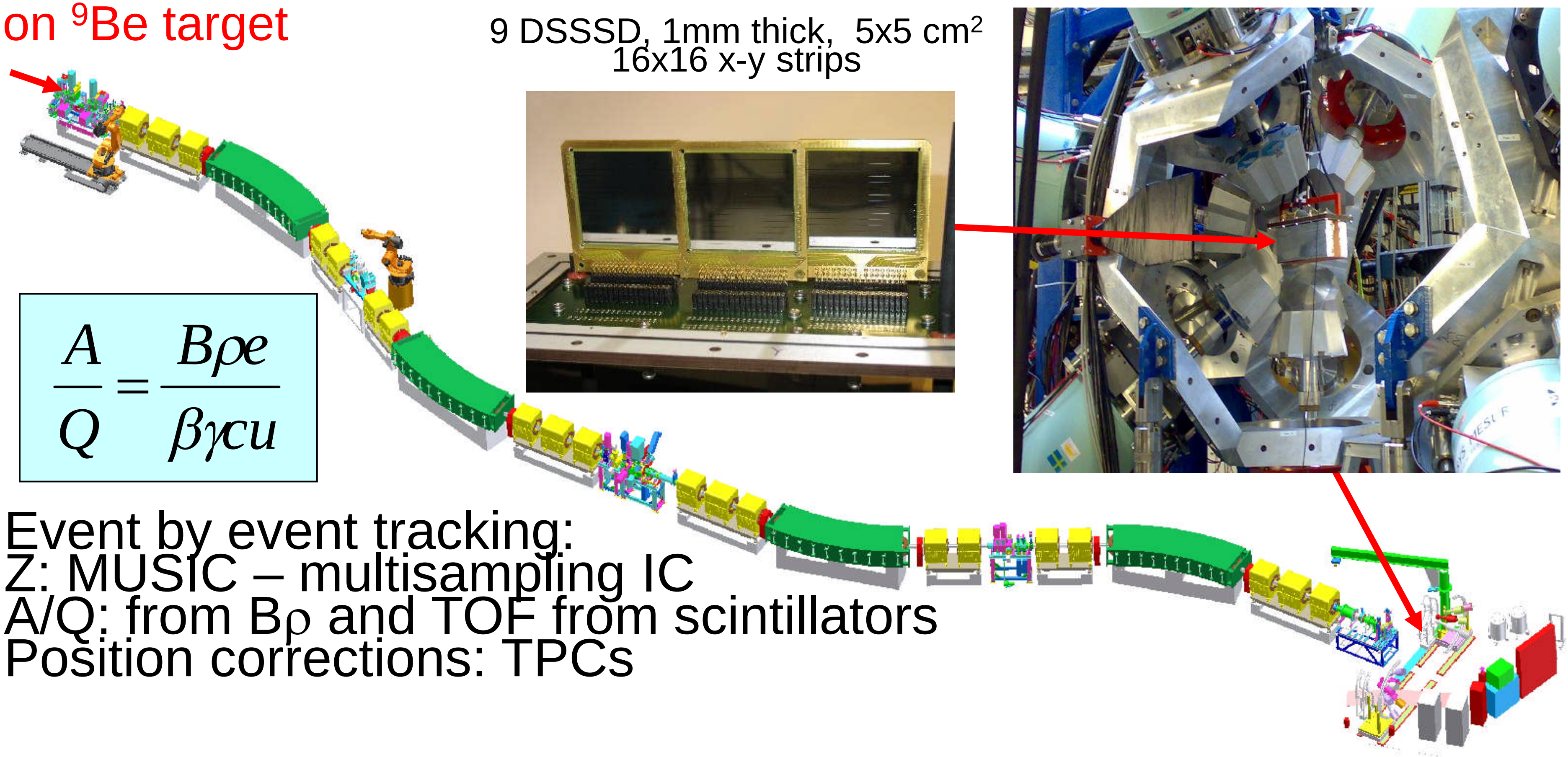
Isomers in N ≅ Z nuclei below ^{100}Sn

^{124}Xe: 850 MeV/u,~10^9 pps
on ^{9}Be target



9 DSSSD, 1mm thick, 5x5 cm^2
16x16 x-y strips

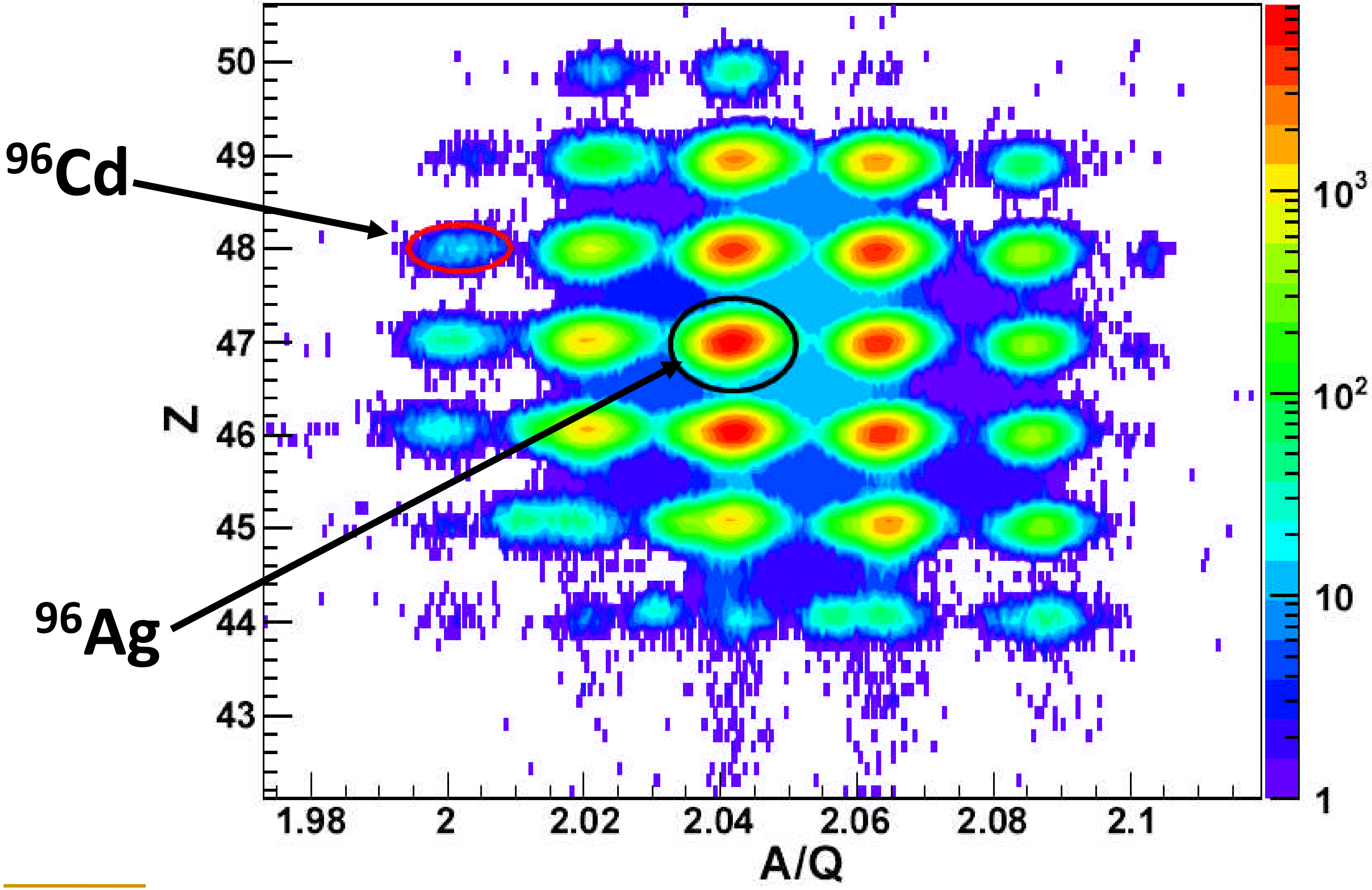
15 CLUSTERs x 7 crystals
ε_γ=11% at 1.3MeV

$$\frac{A}{Q} = \frac{B\rho e}{\beta\gamma c u}$$

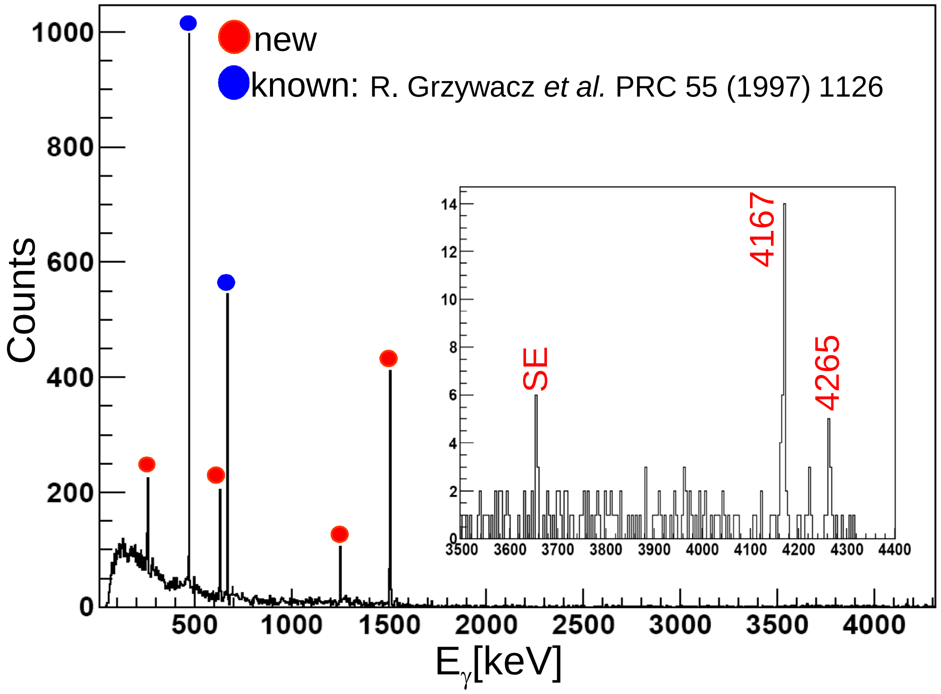
Event by event tracking:
Z: MUSIC – multisampling IC
A/Q: from Bρ and TOF from scintillators
Position corrections: TPCs

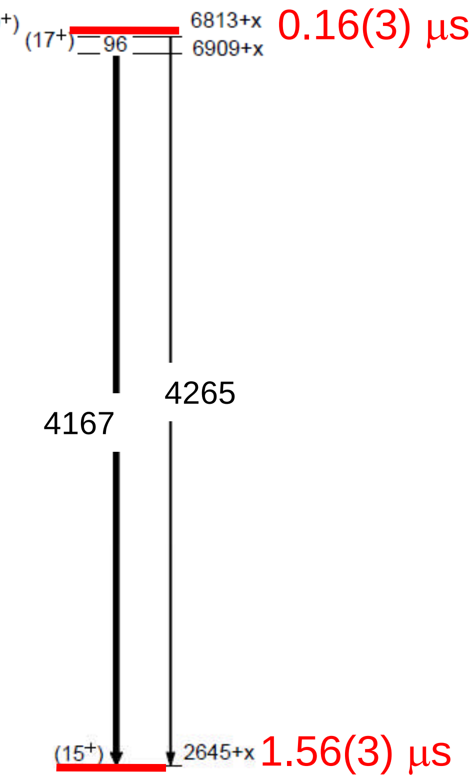
H. Geissel *et al.* NIM B70 (1992) 286
S. Pietri *et al.* Nucl. Inst. and Meth. B261(2007) 1079
R. Kumar *et al.* Nucl. Inst. and Meth. A598 (2009) 754

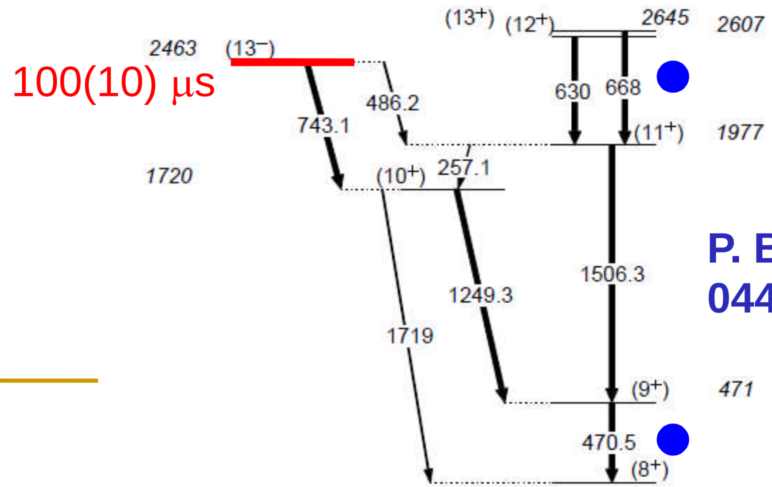
Isomers in N ≅ Z nuclei below ^{100}Sn



Isomers in ^{96}Ag



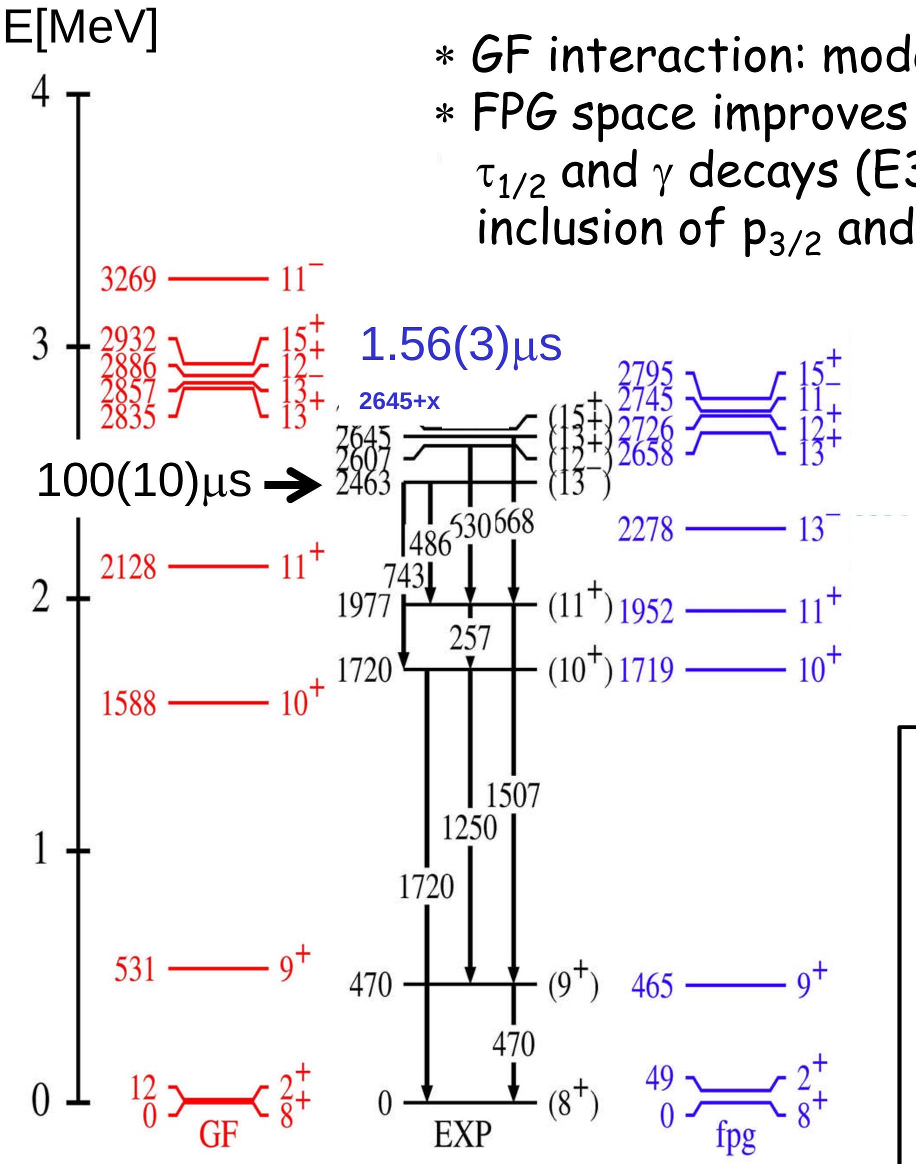




P. Boutachkov *et al.*, PRC 84, 044311 (2011)

Isomers in ^{96}Ag

- ∗ GF interaction: model space: $\pi\nu(g_{9/2}, p_{1/2})$
- ∗ FPG space improves position of 10^+, 11^+ and 13^- levels, also $\tau_{1/2}$ and γ decays (E3 and M2) of new 100μs isomer requires inclusion of $p_{3/2}$ and $f_{5/2}$ orbitals to calc B(E3), B(M2)'s



fpg: GF + SNA

$\pi\nu$ 1p-1h excitation from $f_{5/2}$ and $p_{3/2}$

TBME from OXBASH package (SNA+GF) and SPE tuned to ^{100}Sn

J^π_i	J^π_f	σL	B($\sigma\lambda$) W.u. Expt	GF	FPG
13^-	11^+	M2	$9.6(14)\times10^{-5}$		3.6×10^{-5}
		E3	0.62(9)		0.53
	10^+	E3	0.145(17)		0.057
15^+	13^+	E2[a]	2.45(6)	2.99	2.93

Electric trans calc with p/n eff. Charges of (1.5/0.5)e

a = assuming E_γ = 50 keV

Core excited isomer in ^{96}Ag

P Boutachkov et al., PRC 84, 044311 (2011**)**

GDS

LSSM calculations with
5p-5h, t=5, excitations
Antoine+Nathan codes

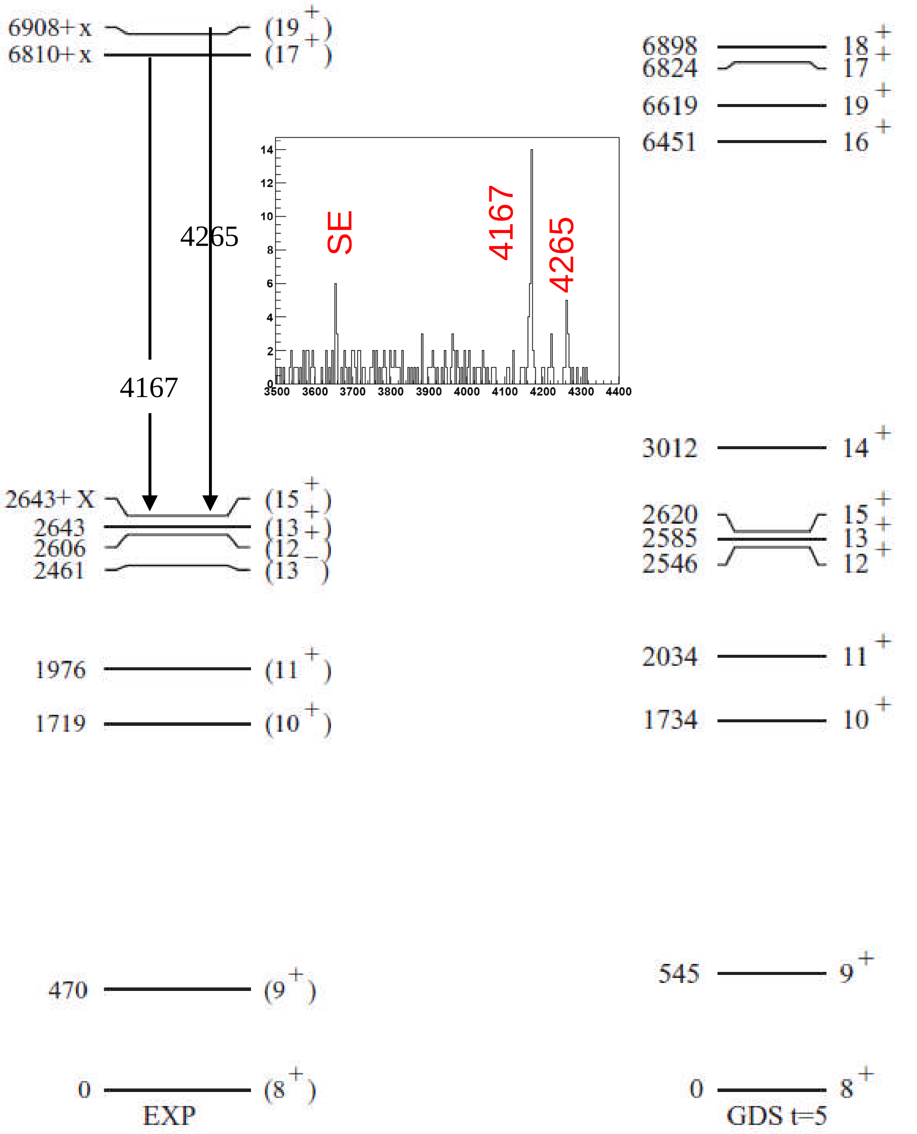
J^{π}_{i}	J^{π}_{f}	σL	B($\sigma\lambda$) W.u. Expt	GDS
19^+	17^+	E2	4.7(10)	3.6
	15^+	E4	0.9(6)	0.7

p/n eff. Charges of (1.5/0.5)e

Incorrect order of 17^+,19^+ may result from incorrect details of the interaction. Fine tuning of residual p-h interaction is needed.

Similar effect noted for 10^+, 12^+ states in ^{98}Cd

– A. Blazhev et al., Phys Conf . Series 205, 012035 (2010)



Evidence for T=0 np Int. in ^{96}Cd

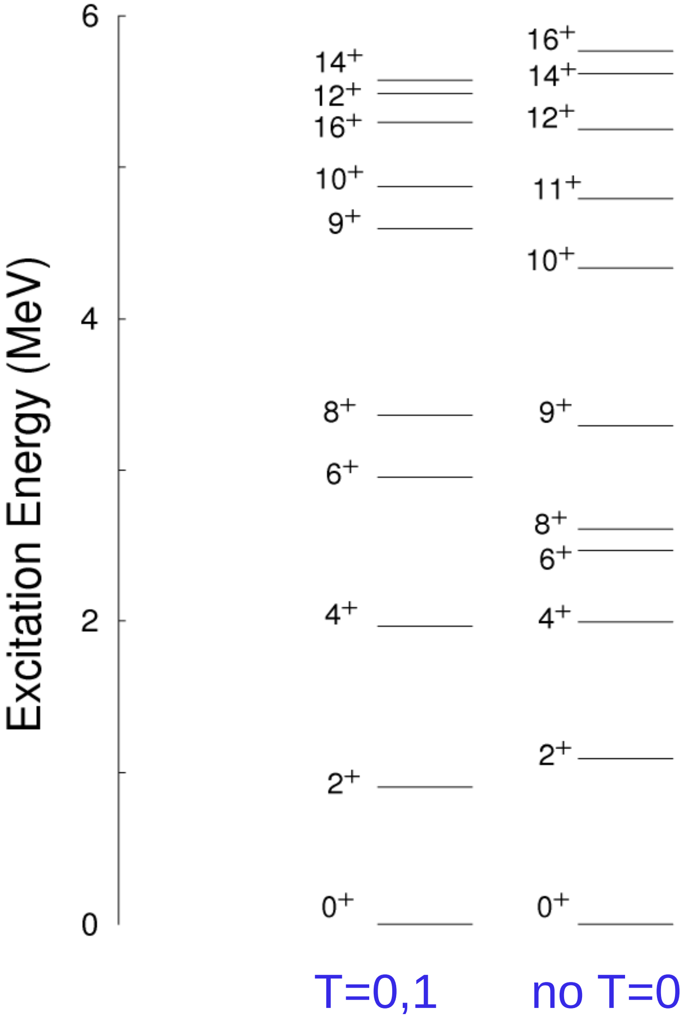
- **Long standing SM predictions of the presence of 16^+ and $25/2^+$ spin-gap isomers in ^{96,97}Cd, for example:**

K Ogawa, Phys Rev C 28, 958 (1983)

- **Spin gap isomer results from extra BE due to the large attractive n-p interaction for maximally aligned hole-hole configs.**

Existence of isomer provides evidence for the importance of the T = 0 np interaction at high-spin

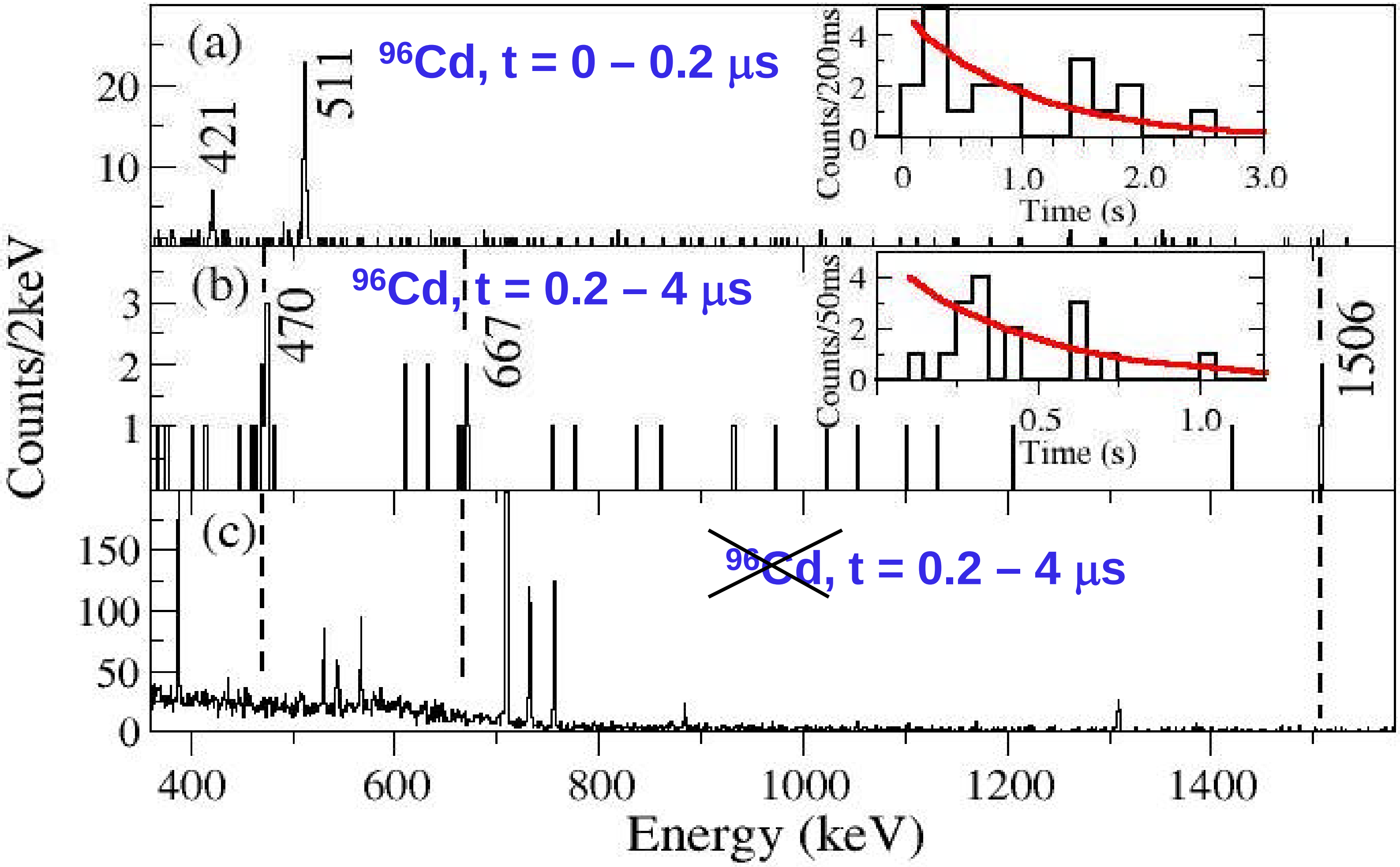
Cf ^{92}Pd results – B Cederwall et al., Nature 469, 68 (2011)



SM Calculations by H Grawe
GF int., $g_{9/2}$, $p_{1/2}$ model space

Gross and Frenkel, Nucl. Phys. A 267, 85 (1976)

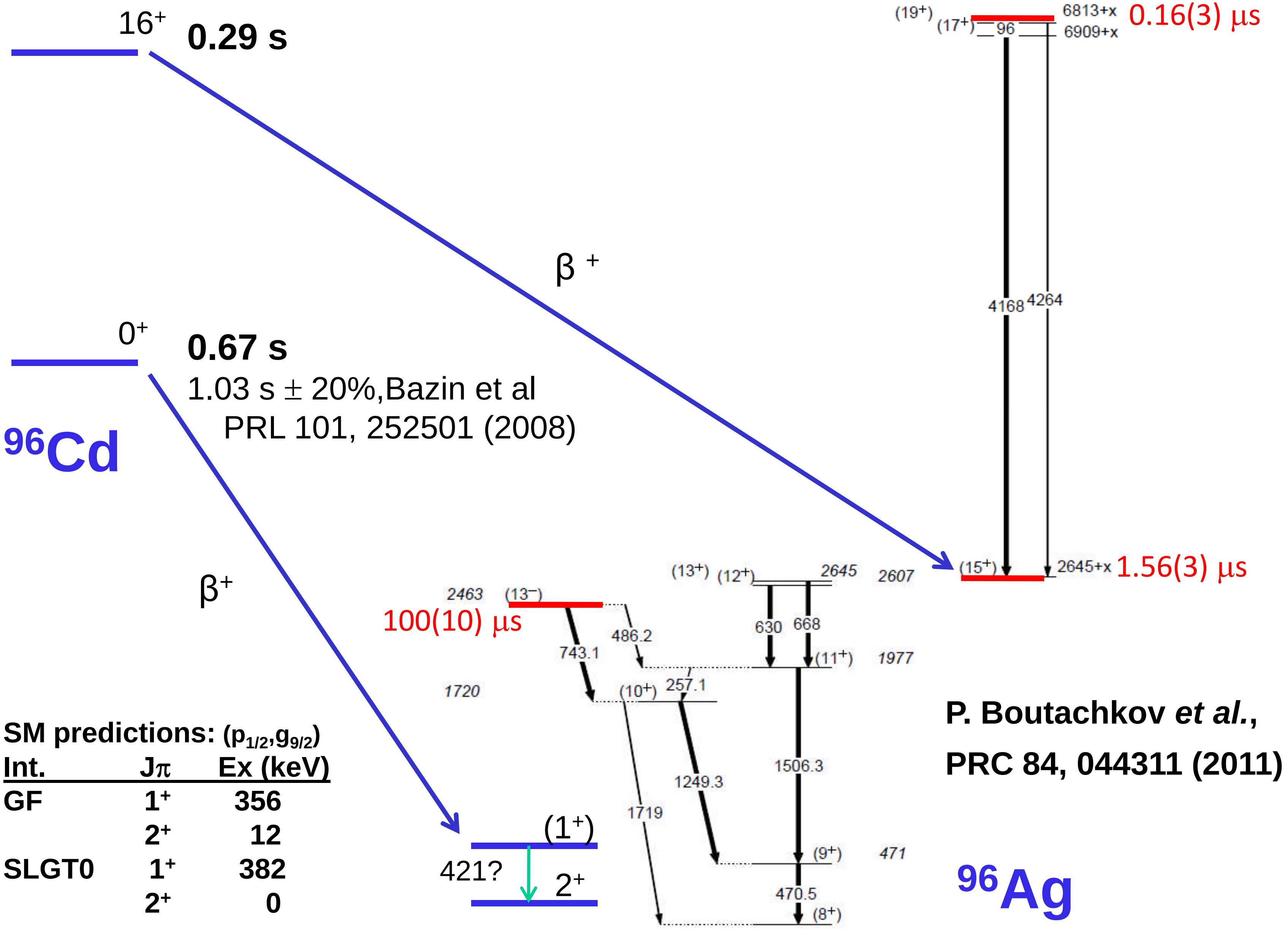
Spin-gap isomer ^{96}Cd



$T_{1/2}$ (421) = 0.67 ± 0.15 sec, **$T_{1/2}$ (470, 1506, 667) = $0.29^{+0.11}_{-0.10}$ sec**

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

Spin-gap isomer ^{96}Cd



0.29 s

0.67 s

1.03 s ± 20%,Bazin et al
PRL 101, 252501 (2008)

^{96}Cd

^{96}Ag

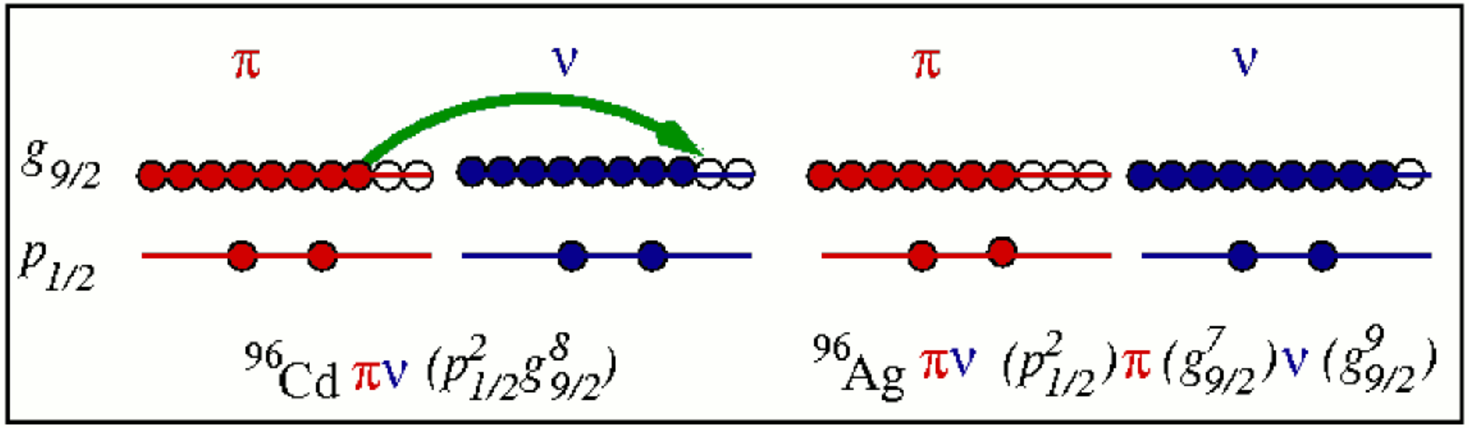
P. Boutachkov *et al.*,
PRC 84, 044311 (2011)

SM predictions: ($p_{1/2}$,$g_{9/2}$)

Int.	Jπ	Ex (keV)
GF	1^+	356
	2^+	12
SLGT0	1^+	382
	2^+	0

THE UNIVERSITY *of York*

Spin-gap isomer ^{96}Cd



^{96}Ag, 15$^+$ state: 100% of GT strength in $p_{1/2}$, $g_{9/2}$ model space

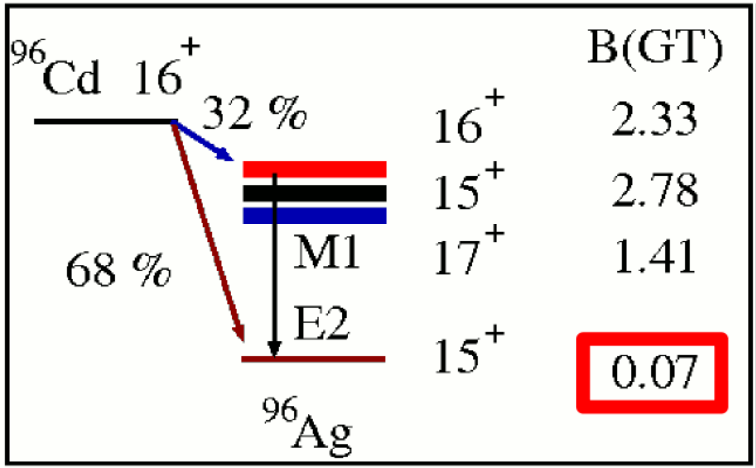
B_{GF} = 0.14 with quenching factor of 0.6 (Herndl and Brown NPA627, 35 (1997))

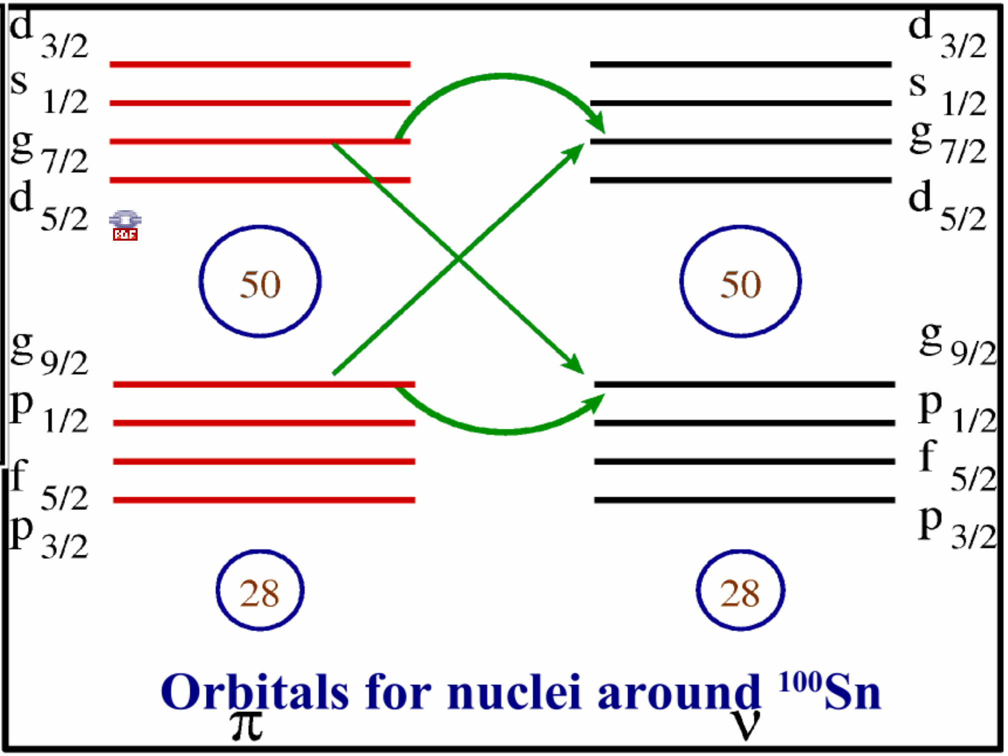
$B_{exp} = [3860(18) * I_\beta] / (f\ T_{1/2}) = 0.19^{+0.08}_{-0.07}$

with $T_{1/2}$ = 0.29 secs

Spin-gap isomer ^{96}Cd – LSSM Calcs with Core excitations

GT strength is fragmented, due to the mixed nature of the states





Quenching factor 0.75

High statistics are needed to obtain the B(GT) distribution

Summary

- *Mapping of collectivity along the N=Z line is underway, but still lots to do:*
  ⇒ lifetime measurements/ mapping B(E2) values
  ⇒ role of shape co-existence in the mid-mass A~ 66-84 region.

- *Evidence that isoscalar np coupling is important at both low and high spin for N=Z nuclei close to ^{100}Sn. But no direct evidence yet of T=0 np (BCS type) pair condensate.*
  ⇒ Need to measure lifetimes of low-lying states in A~90 N=Z nuclei and
  ⇒ extend/ identify yrast bands in nuclei such as ^{92}Pd/ ^{96}Cd as well as investigate T=0,1 states in ^{90}Rh, ^{94}Ag, ^{98}In etc.

- *Several isomers/ γ rays observed in N~Z mass 90 nuclei in recent years, including core-excited states –*
  ⇒ these data provide stringent tests of model spaces and shell model interactions, but
  ⇒ more data required to help tune the interactions used in SM calculations

Significant interest to try and extend studies to N < Z nuclei to investigate isomers/ isospin symmetry/ effects of weak binding in the mass 60-100 region.