Nuclear Structure in Exotic Nuclei : From ^{100}Sn to ^{78}Ni

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TOPICS:

Techniques:

- in-beam
- ISOL
- in-flight separation

N≃Z (^{100}Sn):

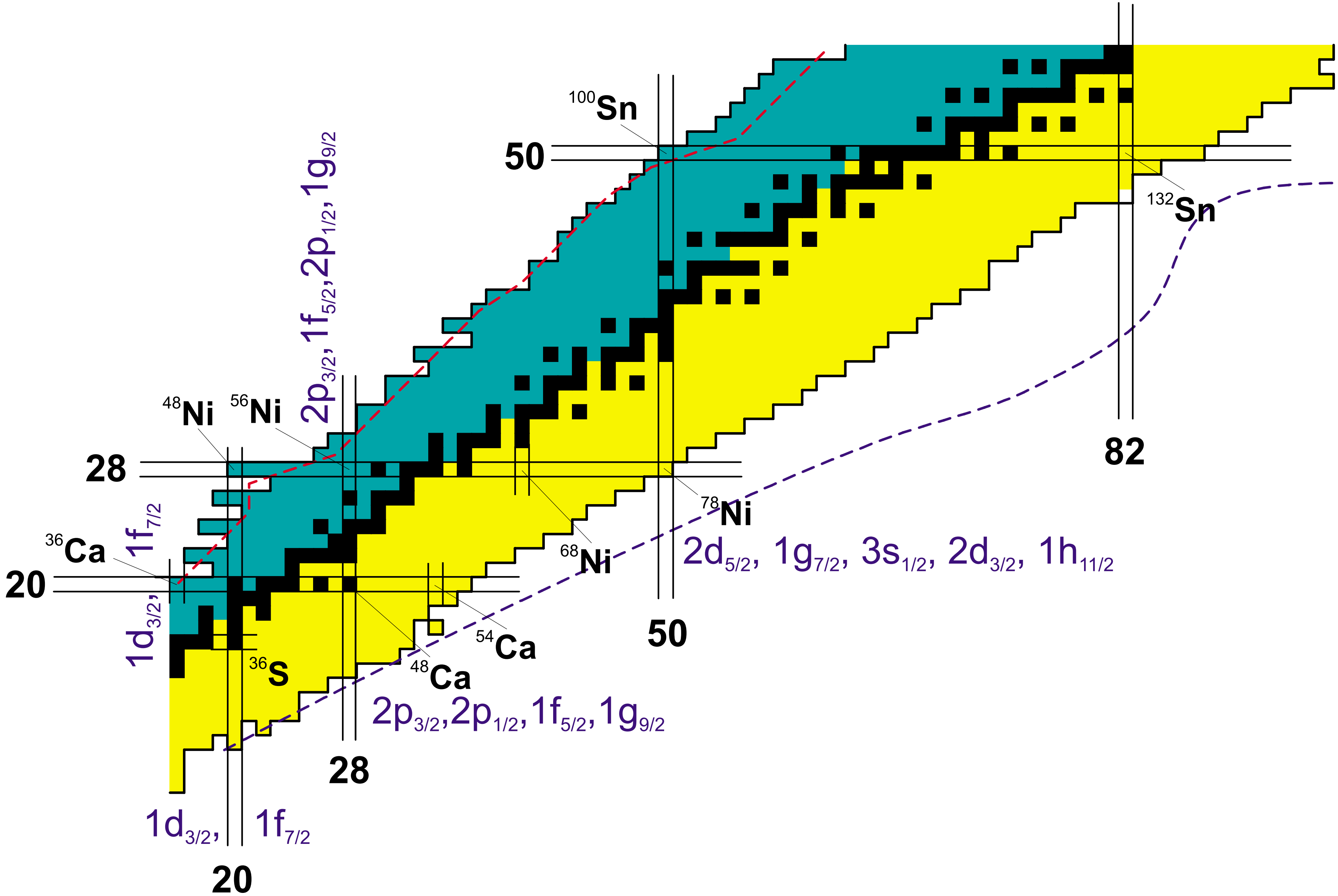
- single particle energies
- core excitation $L = 2, (3, \sigma, \sigma\tau)$
- $\pi\nu$ interaction; seniority vs. spin-gap isomers
- empirical vs. large-scale shell model

N≫Z ($^{68-78}$Ni):

- monopole interaction
- $\sigma\tau$ vs. $(\sigma \times \vec{r})\tau$ driven shell structure
- N=40 and 50 shell evolution

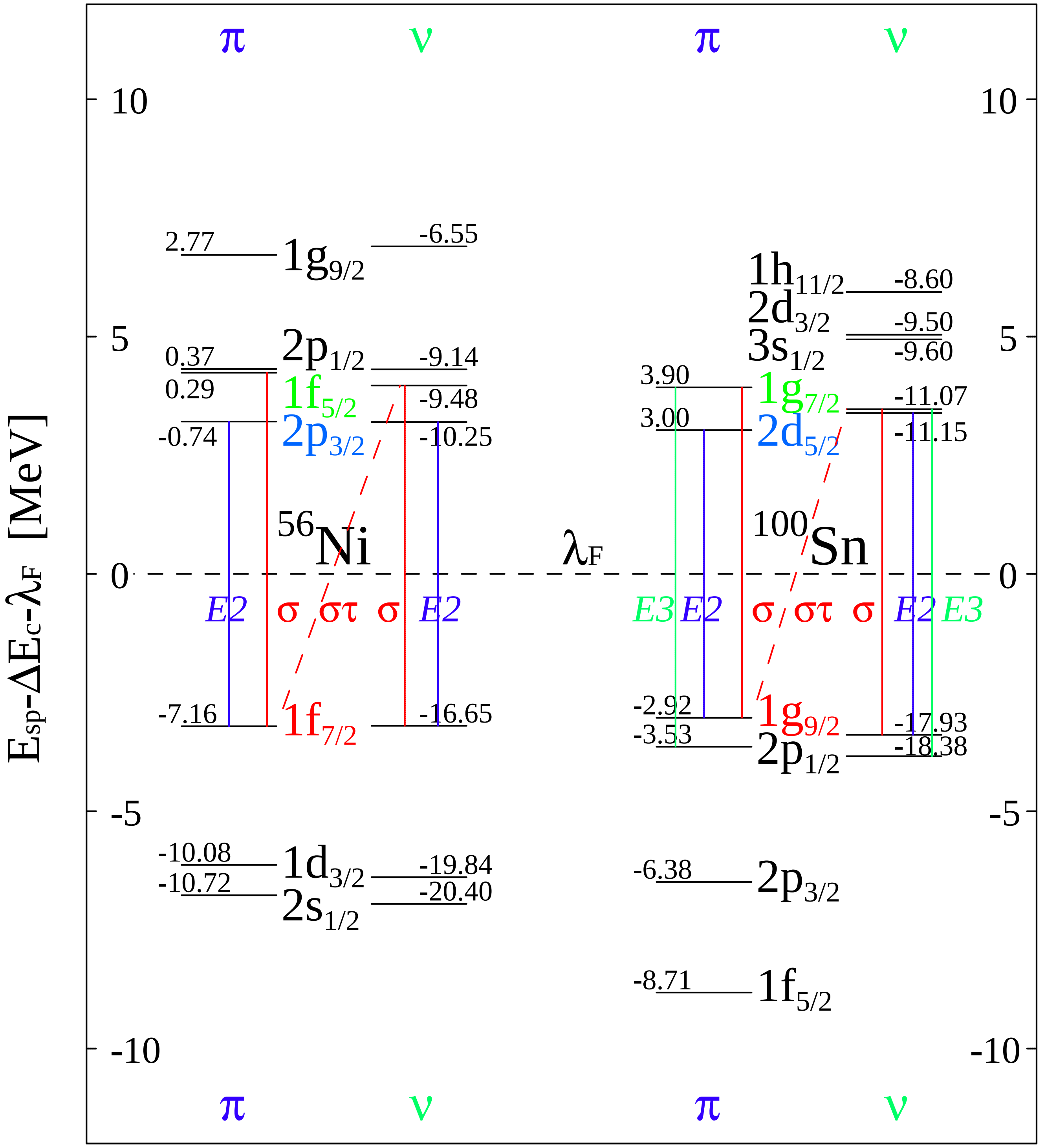
New shells @ N ≫ Z :

- harmonic oscillator vs. spin-orbit shell
- N=6, 16(14), 34(32) examples
- T=1 monopole



100Sn
132Sn
82
50
50
28
28
20
20
48Ni
56Ni
78Ni
68Ni
36Ca
48Ca
54Ca
36S
2p3/2, 1f5/2, 2p1/2, 1g9/2
1d3/2,
1f7/2
1d3/2,
1f7/2
2p3/2,2p1/2,1f5/2,1g9/2
2d5/2, 1g7/2, 3s1/2, 2d3/2, 1h11/2

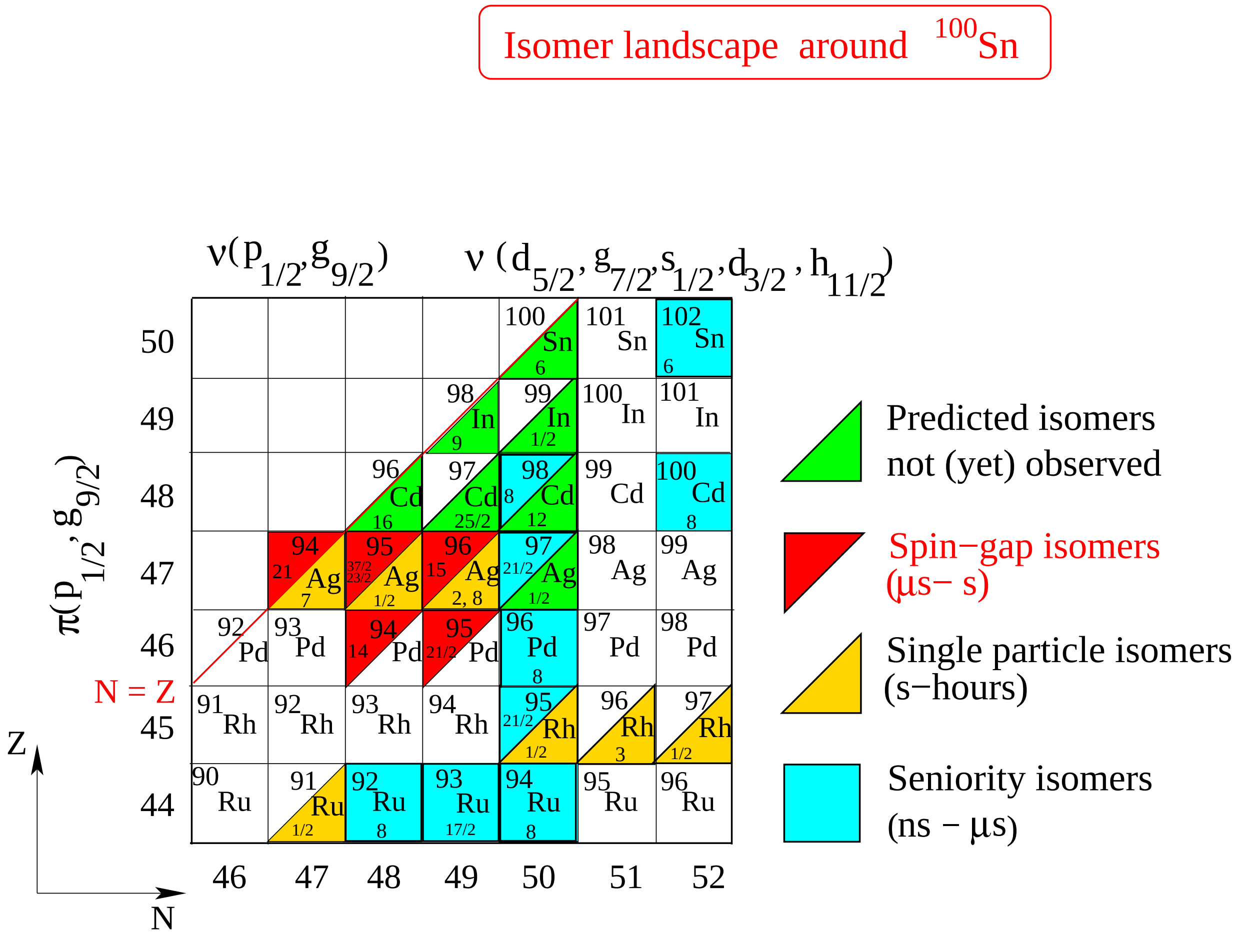
Shell structure in N = Z doubly magic $^{56}_{28}Ni_{28}$ and $^{100}_{50}Sn_{50}$



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

oσ /M1 and στ /GT transitions

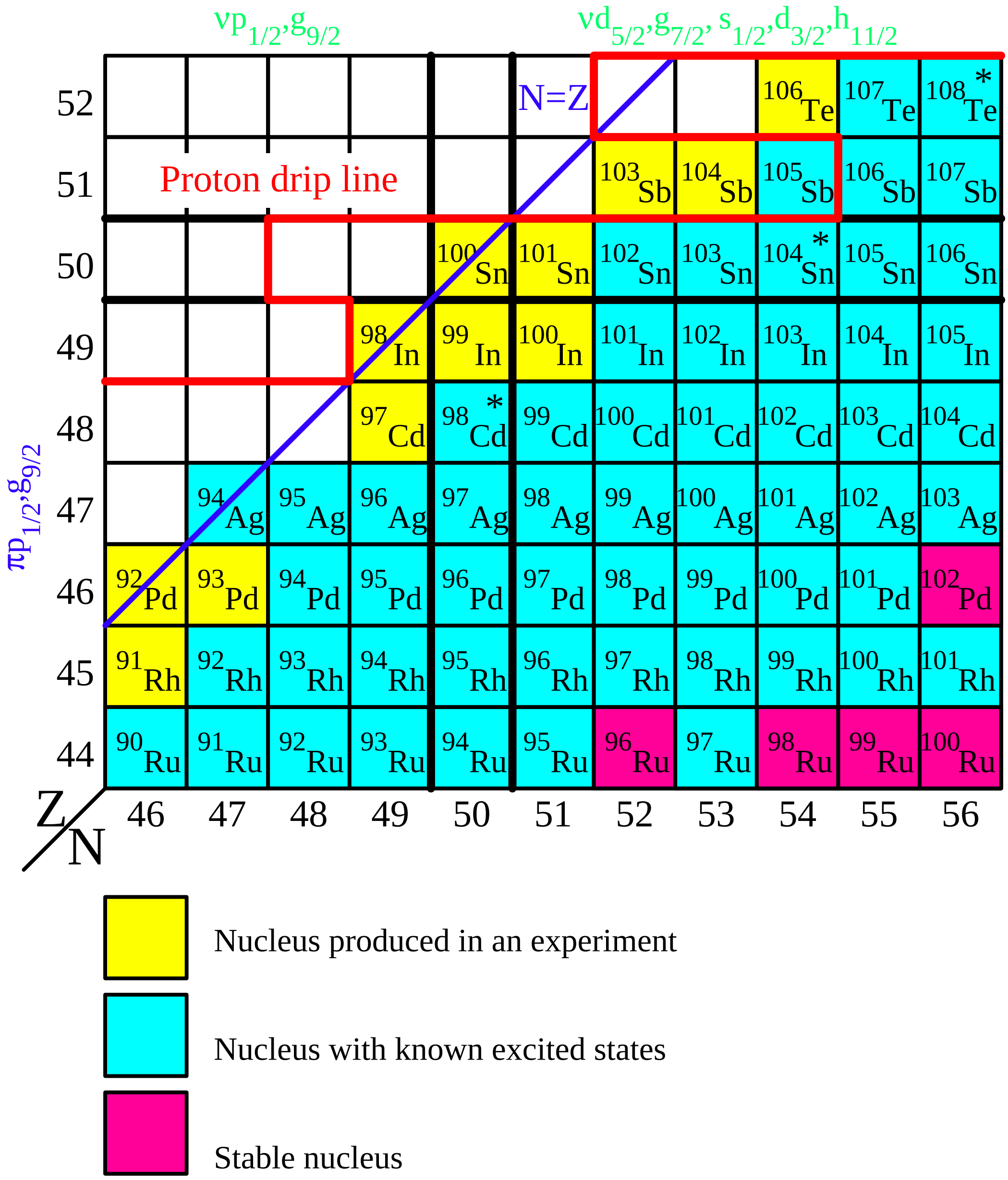
o L=3 (=|l_p± l_h|) E3 collectivity



Isomer landscape around ^{100}Sn
$\nu(p_{1/2}, g_{9/2})$
$\nu(d_{5/2}, g_{7/2}, s_{1/2}, d_{3/2}, h_{11/2})$
$\pi(p_{1/2}, g_{9/2})$
N = Z
Z
N
Predicted isomers not (yet) observed
Spin−gap isomers (μs− s)
Single particle isomers (s−hours)
Seniority isomers (ns − μs)

Experimental approach to ^{100}Sn

- o in-beam, fusion-evaporation
- o ISOL mass separation, fusion-evaporation
- o in-flight A,Z separation, fragmentation



Shell model ^{100}Sn
np - nh in gds space

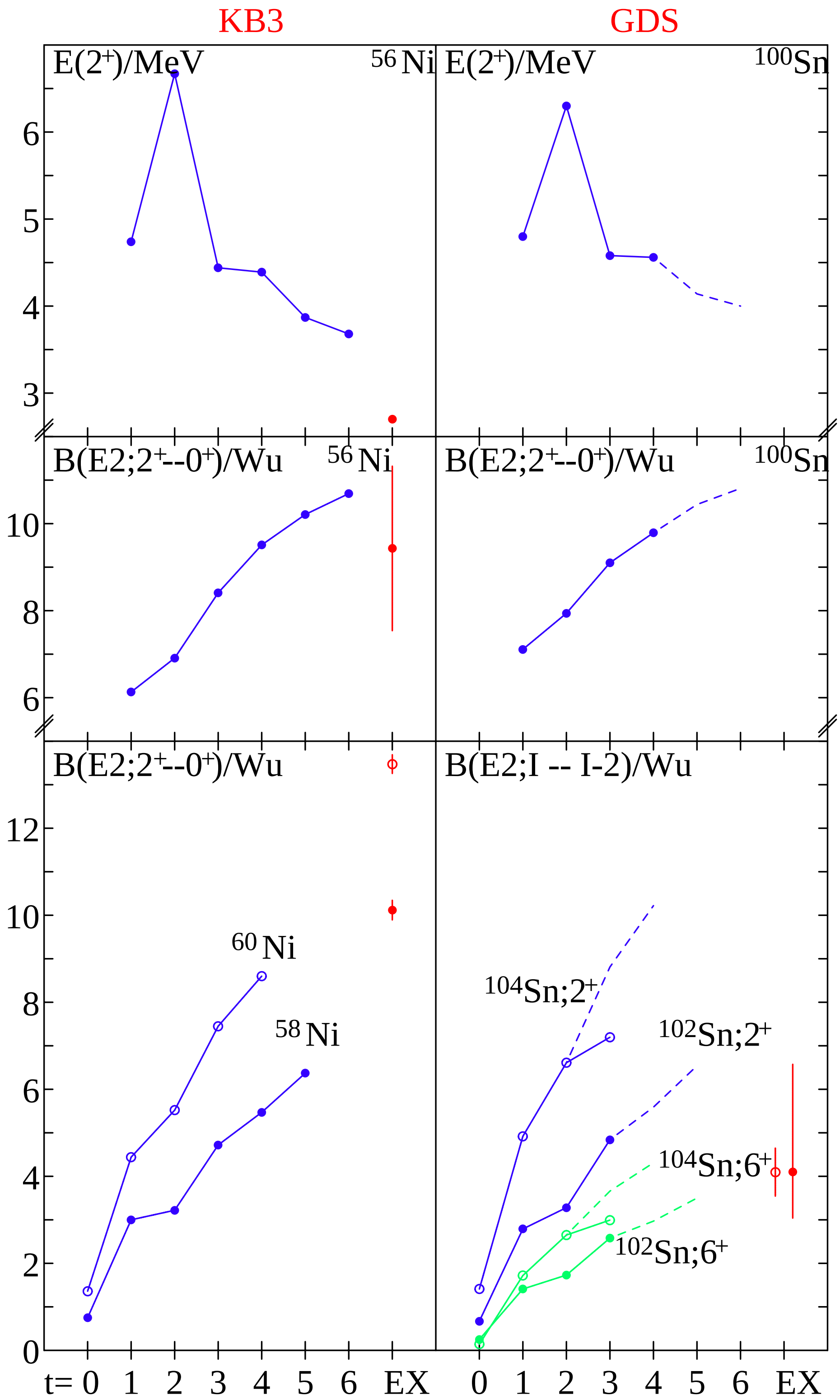
F. Nowacki, NPA704,223c(02)

$$^{98}\mathbf{Cd}\quad \mathbf{B(E2;}8^+ \rightarrow 6^+\mathbf{)} \;=\; \mathbf{37}\; e^2fm^4 \quad \mathbf{0p-0h}$$
$$=\; \mathbf{57}\; e^2fm^4 \quad \mathbf{4p-4h}$$
$$=\; \mathbf{14}\binom{7}{4}\; e^2fm^4 \quad \mathbf{Exp}^a$$
$$=\; \mathbf{30(4)}\; e^2fm^4 \quad \mathbf{Exp}^b$$
$$\rightarrow \delta e_\pi \sim 0.1e$$

$$^{102}\mathbf{Sn}\quad \mathbf{B(E2;}6^+ \rightarrow 4^+\mathbf{)} \;=\; \mathbf{7.2}\; e^2fm^4 \quad \mathbf{0p-0h}$$
$$=\; \mathbf{73}\; e^2fm^4 \quad \mathbf{3p-3h}$$
$$=\; \mathbf{116}\binom{70}{30}\; e^2fm^4 \quad \mathbf{Exp}^c$$
$$\rightarrow \delta e_\nu \sim 0.6e$$

Large Isovector Effect !

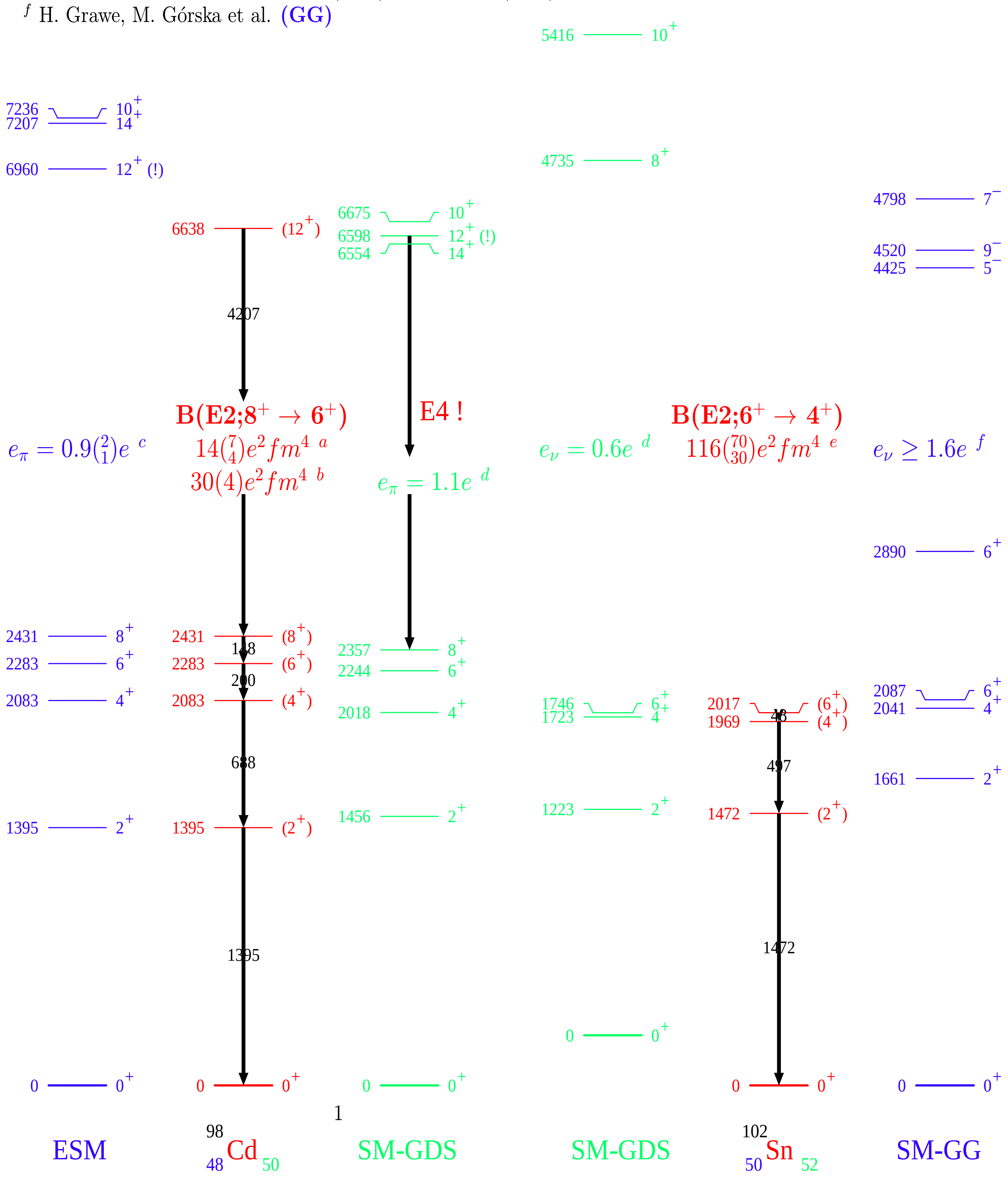
[a] M. Górska et al., PRL 79, 2415 (1997)
[b] R. Grzywacz, ENAM98, AIP Conf. Proc. 455, 430 (1998)
[c] M. Lipoglavšek et al., PL 440B, 246 (1998)



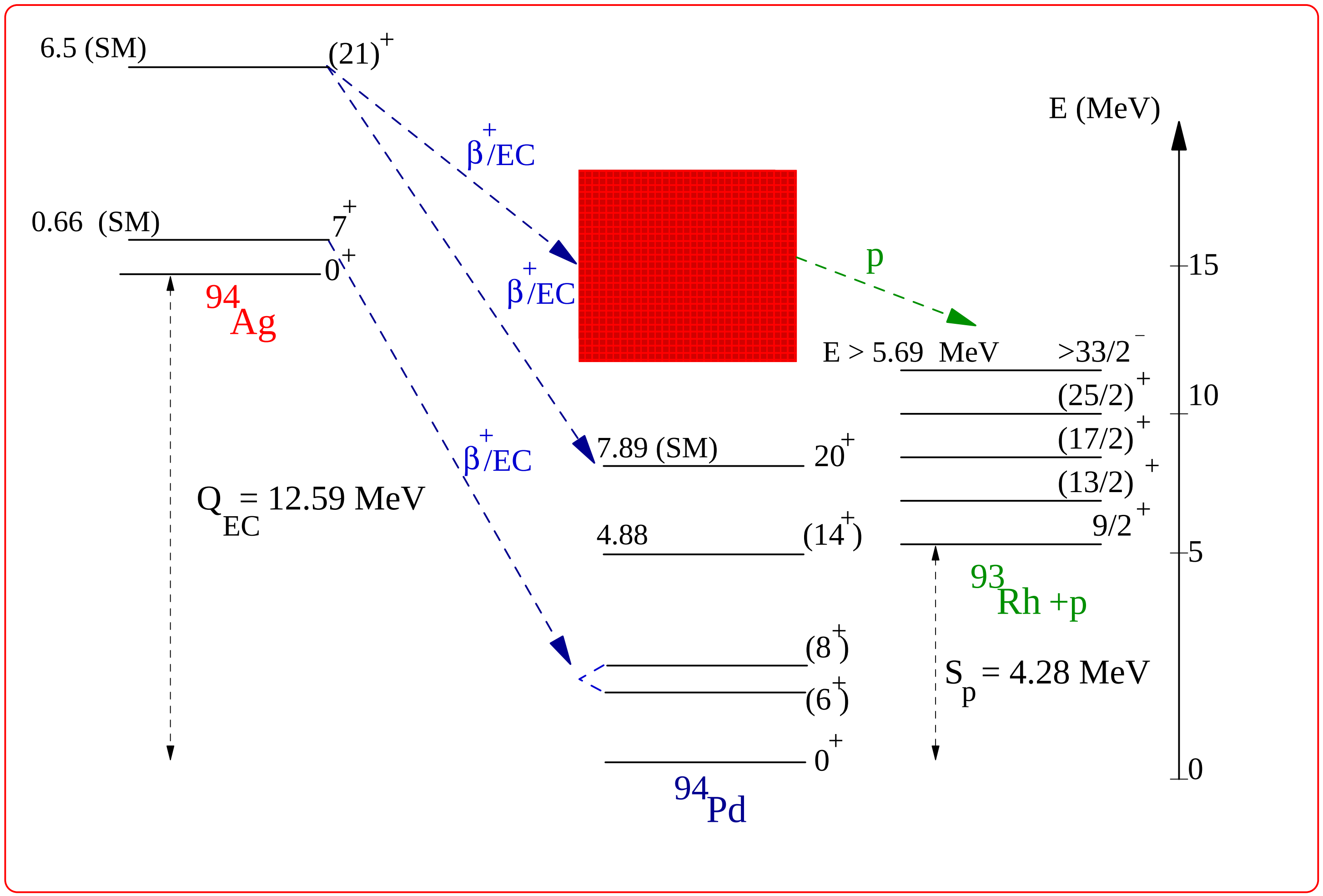
F. Nowacki, NPA704,223c(02)

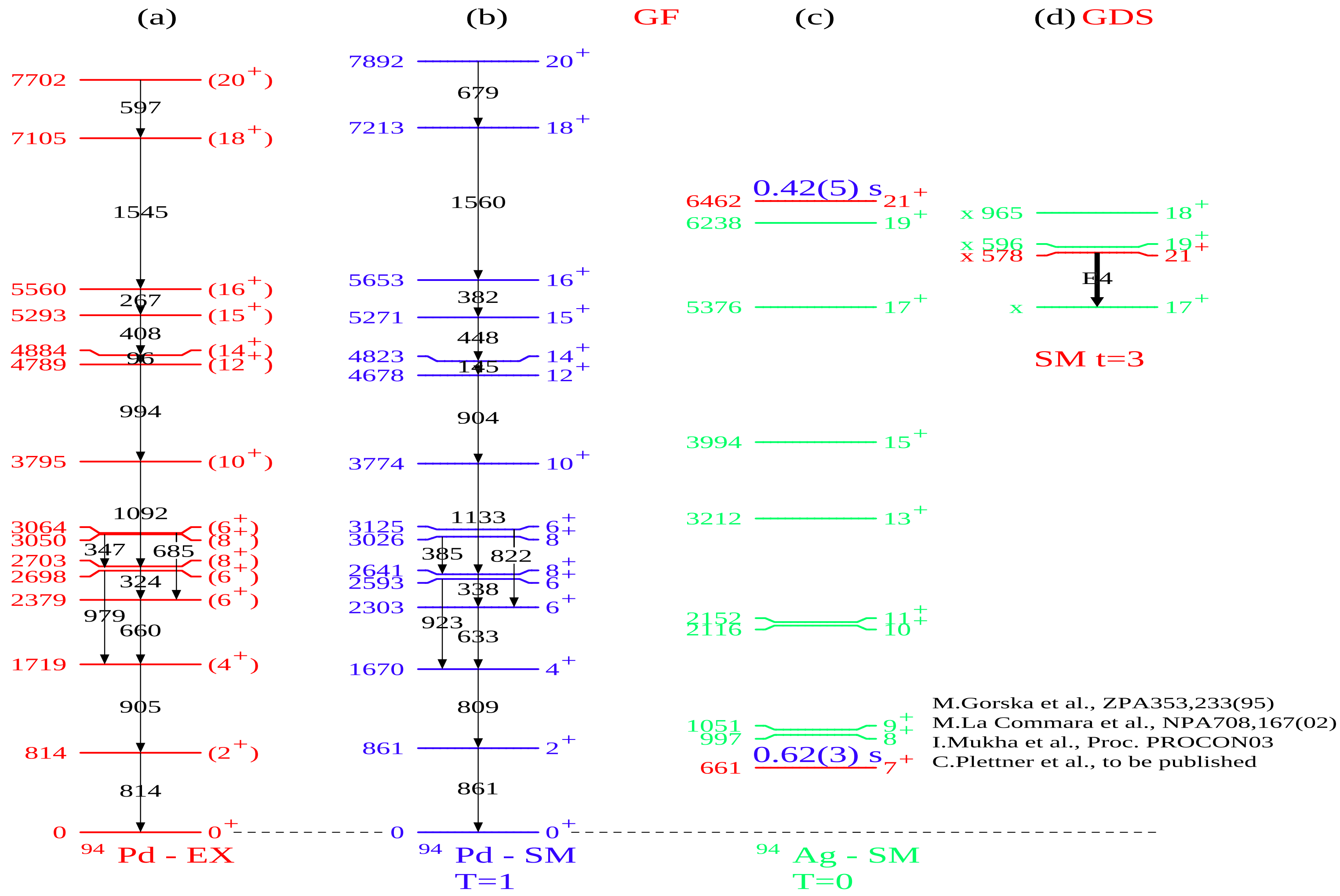
^{100}Sn core excitation

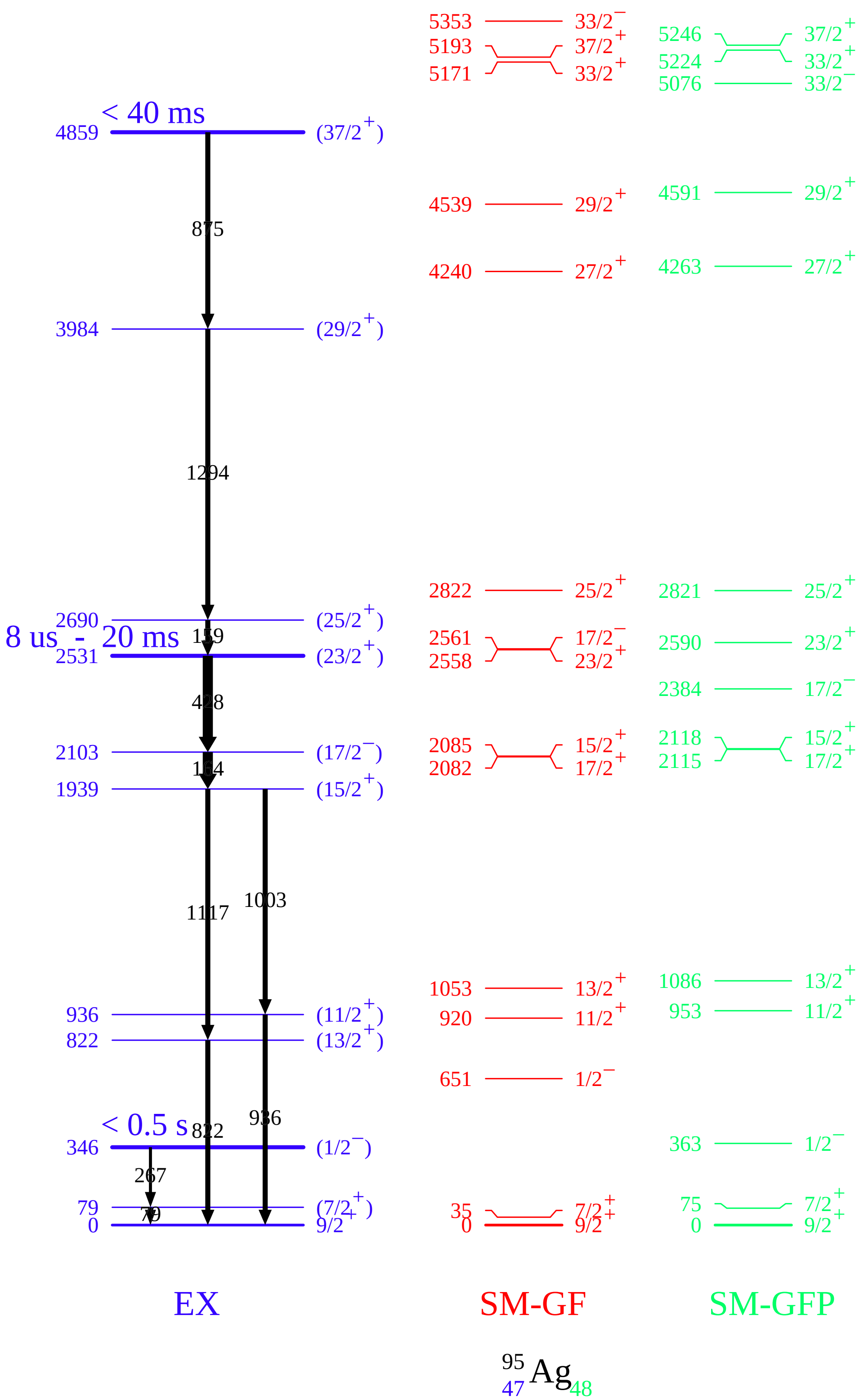
[a] M. Górska et al., PRL 79,2415(1997)
[b] R. Grzywacz, ENAM98, AIP CP 455,430(1998)
[c] H. Grawe et al., NS98, AIP CP 481,177(1999) **(ESM)**
[d] F. Nowacki, NPA704,223c(2002) **(GDS)**
[e] M. Lipoglavšek et al., ZPA356,239(1996); PLB440,246(1998)
[f] H. Grawe, M. Górska et al. **(GG)**



The decay modes of ^{94}Ag

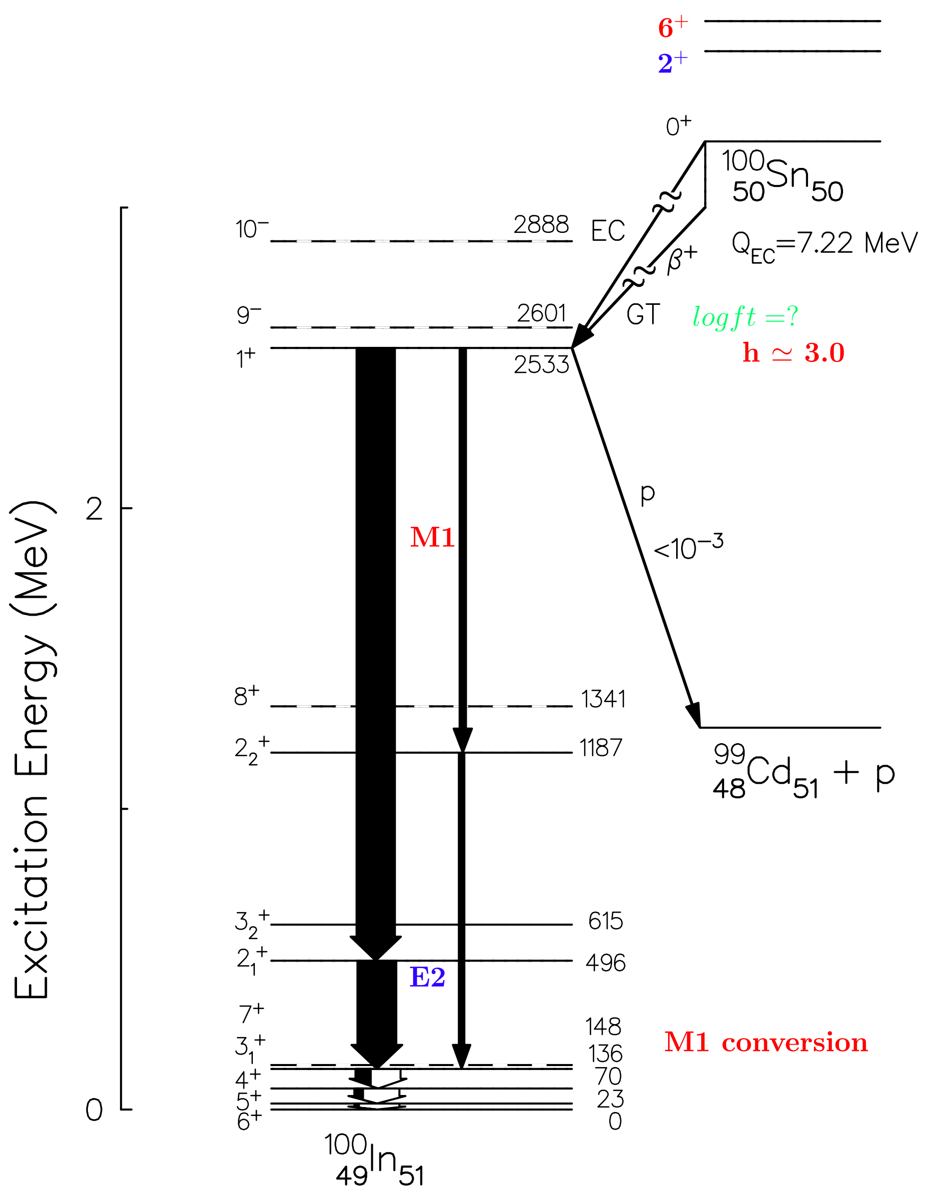



(a)
(b)
GF
(c)
(d) GDS
7702 (20+)
597
7105 (18+)
1545
5560 (16+)
267
5293 (15+)
408
4884 (14+)
96
4789 (12+)
994
3795 (10+)
1092
3064 (6+)
3050 (8+)
347
685
2703 (8+)
2698 (6+)
324
2379 (6+)
979
660
1719 (4+)
905
814 (2+)
814
0 0+
94 Pd - EX
7892 20+
679
7213 18+
1560
5653 16+
382
5271 15+
448
4823 14+
145
4678 12+
904
3774 10+
1133
3125 6+
3026 8+
385
822
2641 8+
2593 6+
338
2303 6+
923
633
1670 4+
809
861 2+
861
0 0+
94 Pd - SM
T=1
0.42(5) s
6462 21+
6238 19+
5376 17+
3994 15+
3212 13+
2152 11+
2116 10+
1051 9+
997 8+
0.62(3) s
661 7+
94 Ag - SM
T=0
x 965 18+
x 596 19+
x 578 21+
E4
x 17+
SM t=3
M.Gorska et al., ZPA353,233(95)
M.La Commara et al., NPA708,167(02)
I.Mukha et al., Proc. PROCON03
C.Plettner et al., to be published

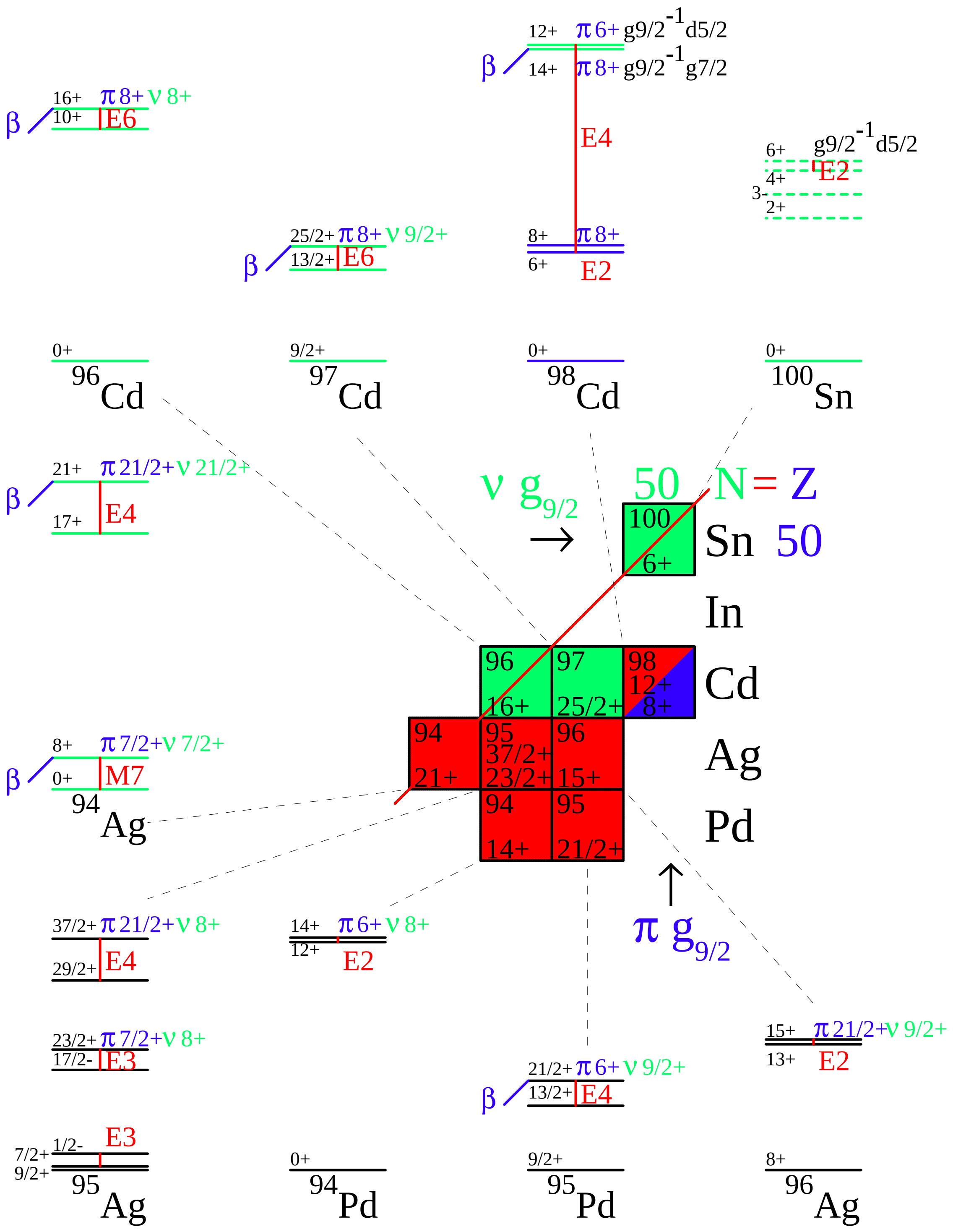


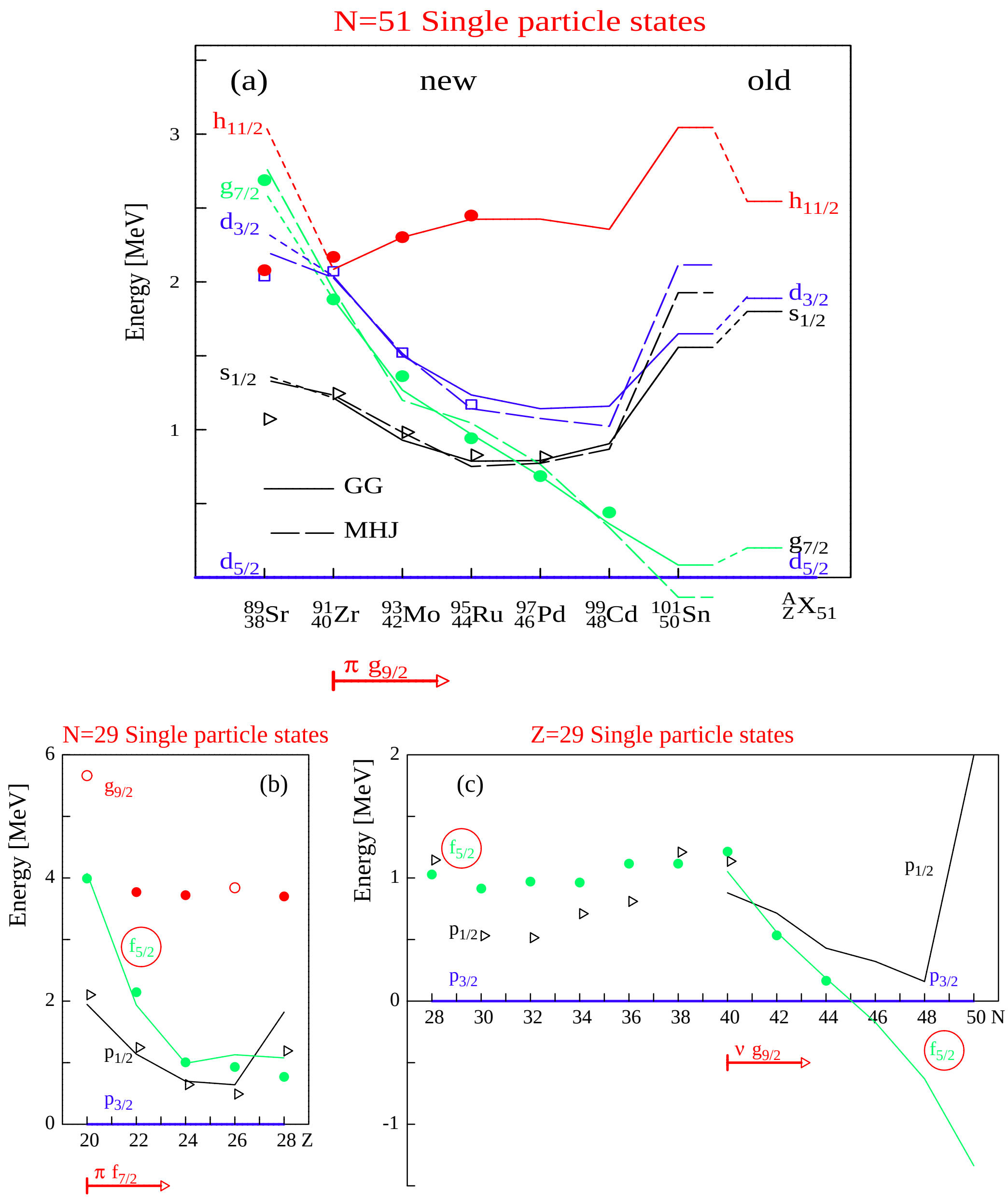
< 40 ms
4859 (37/2+)
875
3984 (29/2+)
1294
2690 (25/2+)
8 us - 20 ms
159
2531 (23/2+)
428
2103 (17/2−)
164
1939 (15/2+)
1117
1003
936 (11/2+)
822 (13/2+)
< 0.5 s
822
936
346 (1/2−)
267
79 (7/2+)
79
0 9/2+
5353 33/2−
5193 37/2+
5171 33/2+
4539 29/2+
4240 27/2+
2822 25/2+
2561 17/2−
2558 23/2+
2085 15/2+
2082 17/2+
1053 13/2+
920 11/2+
651 1/2−
35 7/2+
0 9/2+
5246 37/2+
5224 33/2+
5076 33/2−
4591 29/2+
4263 27/2+
2821 25/2+
2590 23/2+
2384 17/2−
2118 15/2+
2115 17/2+
1086 13/2+
953 11/2+
363 1/2−
75 7/2+
0 9/2+
EX
SM-GF
SM-GFP
95 47 Ag 48

^{100}Sn β^+/EC decay



Spin gap isomers below N=Z=50





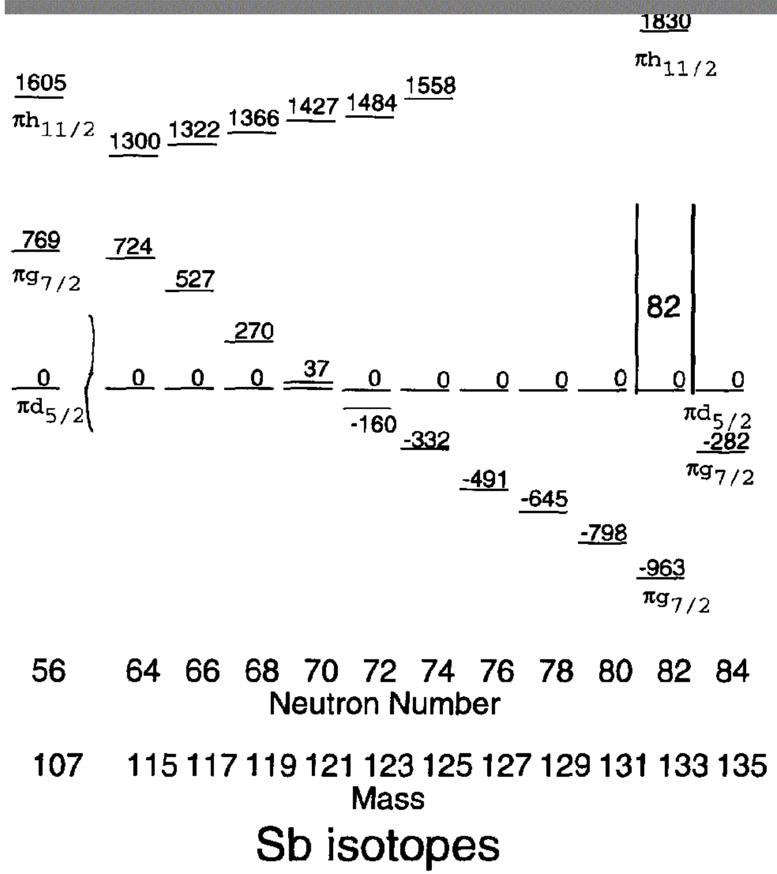
Monopole strong for :

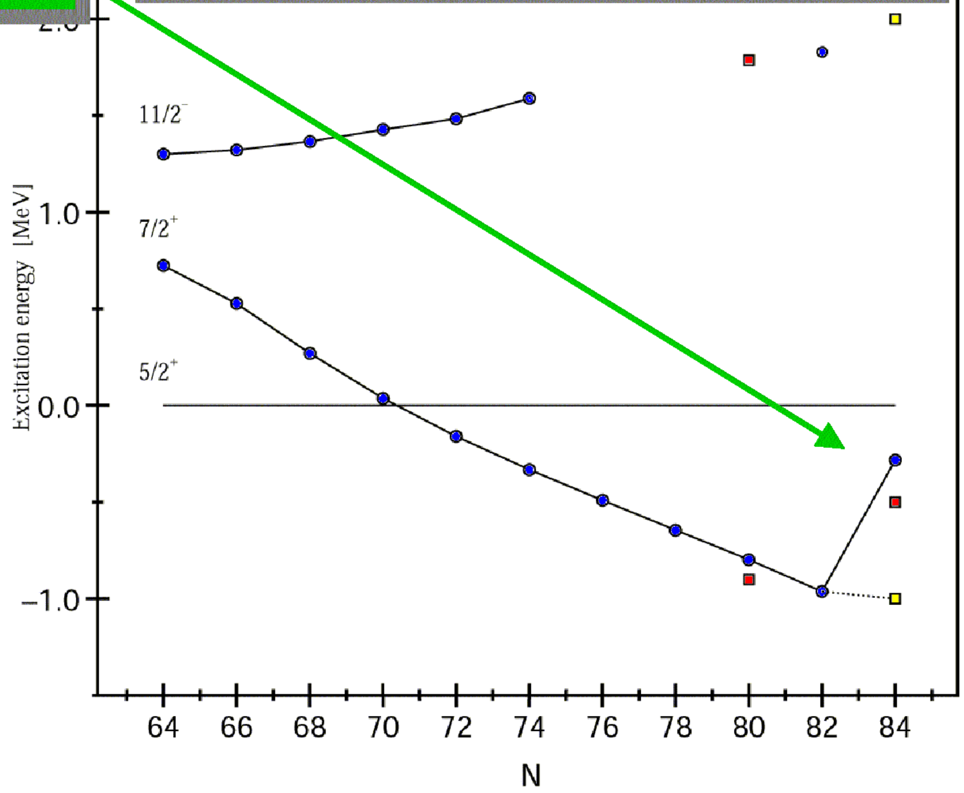
→ $\pi\,\nu$ (T=0) proton-neutron interaction

→ S = 0 spin-flip

→ $n_1 = n_2$ radial overlap

Energy of the level reproduced by Shell Model without quenching





A. Covello et al., LNL may 2002

The knowledge of s.p. structure is of fundamental importance

MONOPOLE SHIFT – REALISTIC INTERACTION

Monopole:

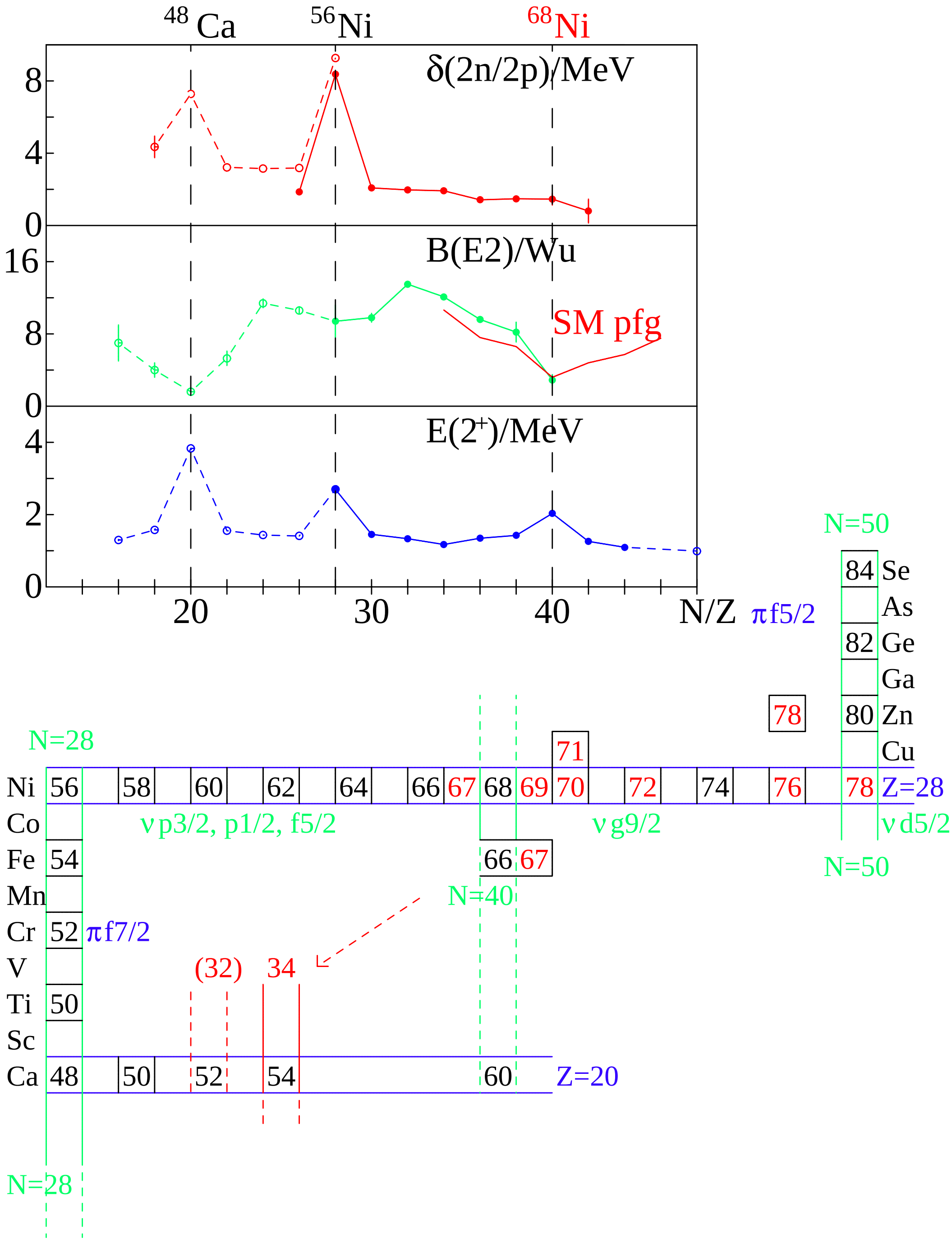
$$V^m_{jj'} = \Sigma_J (2J+1)\langle jj'|V|jj'\rangle_J / \Sigma_J (2J+1)$$

Relative orbital monopole shift:

$$\Delta(j'_1, j'_2) = V^m_{jj'_1} \cdot (2j+1-\delta_{jj'_1}) - V^m_{jj'_2} \cdot (2j+1-\delta_{jj'_2})$$

Multiplet $j, j'_{1,2}$	S,T/$\pi\nu$	V^m (MeV)	$\Delta(j'_1, j'_2)$ (MeV)	Interaction
$\pi f_{7/2} \nu f_{5/2}$	S=0,$\pi\nu$	-1.046	4.258	FPD6
$\pi f_{7/2} \nu p_{3/2}$	S=1,$\pi\nu$	-0.513		NPA523(91)325
$f_{7/2} f_{5/2}$	S=0,T=1	-0.082		
$f_{7/2} p_{3/2}$	S=1,T=1	+0.174		
$f^2_{7/2}$	S=1,T=1	-0.208		
$\pi f_{7/2} \nu f_{5/2}$	S=0,$\pi\nu$	-1.134	4.352	KB
$\pi f_{7/2} \nu p_{3/2}$	S=1,$\pi\nu$	-0.590		NPA114(68)241
$f_{7/2} f_{5/2}$	S=0,T=1	-0.464		
$f_{7/2} p_{3/2}$	S=1,T=1	-0.251		
$f^2_{7/2}$	S=1,T=1	-0.301		
$\nu g_{9/2} \pi f_{5/2}$	S=0,$\pi\nu$	-1.034	5.310	S3V68
$\nu g_{9/2} \pi p_{3/2}$	S=1,$\pi\nu$	-0.503		J.Phys.G18
$g_{9/2} f_{5/2}$	S=0,T=1	-0.504		(92)1377,1401
$g_{9/2} p_{3/2}$	S=1,T=1	-0.123		
$g^2_{9/2}$	S=1,T=1	-0.134		
$\pi g_{9/2} \nu g_{7/2}$	S=0,$\pi\nu$	-0.744	4.258	MHJ
$\pi g_{9/2} \nu d_{5/2}$	S=1,$\pi\nu$	-0.370		Phys.Rep.261
$g^2_{9/2}$	S=1,T=1	-0.098		(95)125

From N=28 to N=50



N = 50 shell gap extrapolation

Configurations: $\pi 0 f_{5/2} \nu 0 g_{9/2}$

$\pi 0 f_{5/2} \nu 1 d_{5/2}$

Assumption: $V^m_{f_{5/2} d_{5/2}} \approx 0.5 \cdot V^m_{f_{5/2} g_{9/2}}$

	Z-28	*N = 50*	*shell gap*	
	occ.	*SkP/HFB*	*EXP*	
	$\pi 0 f_{5/2}$	*(MeV)*	*(MeV)*	
Se	*6*	*2.8*	*4.13(4)*	
Ge	*4*	*2.5*	*3.8(4)*	
Zn	*2*	*2.0*	-	
Ni	*0*	*1.9*	*2.08*	*S3V68*
			2.60	*S3V*
			2.56	*"EXP"*

Z = 28 shell gap extrapolation

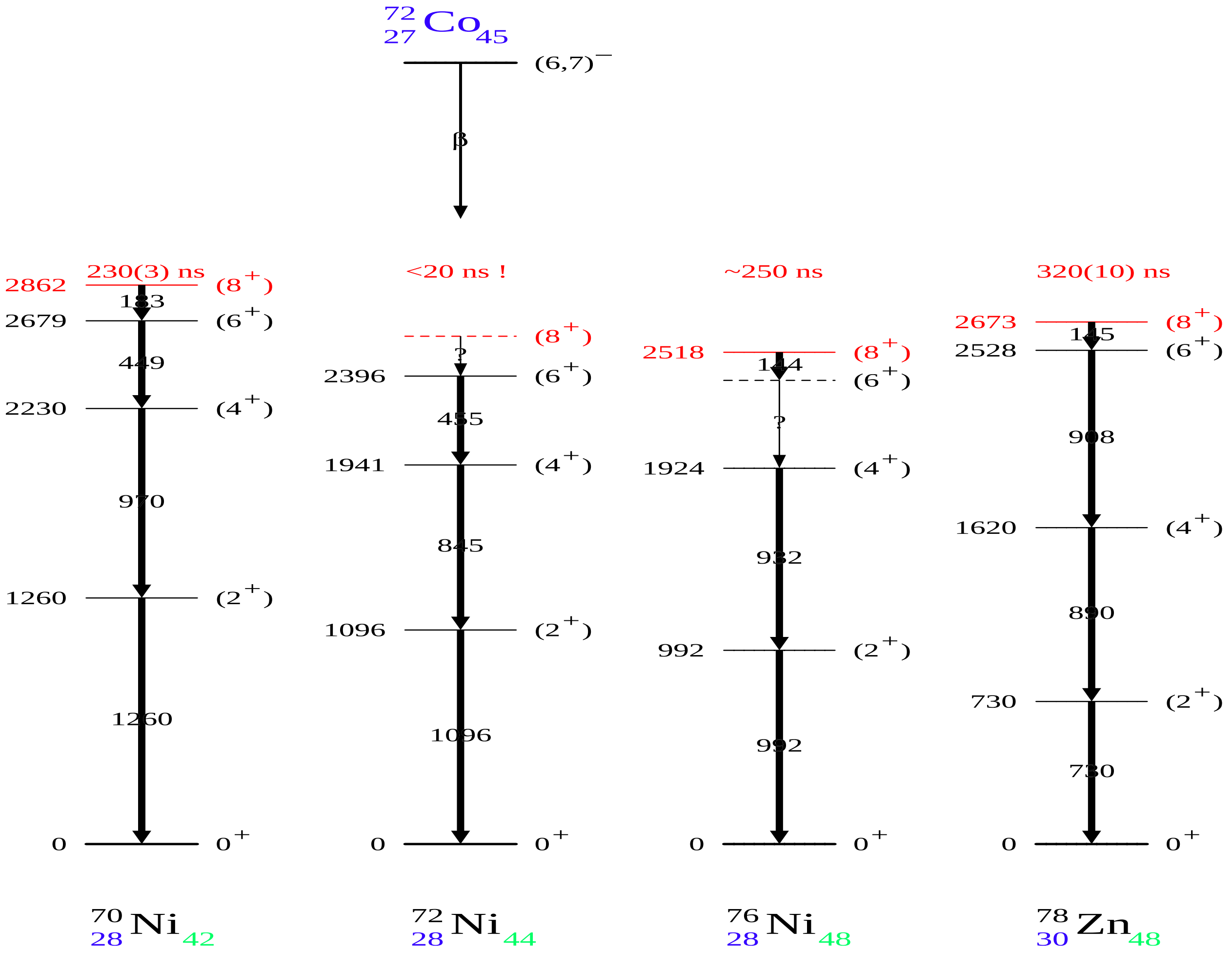
Configurations: $\pi 0 f_{5/2} \nu 0 g_{9/2}$

$\pi 0 f_{7/2} \nu 0 g_{9/2}$

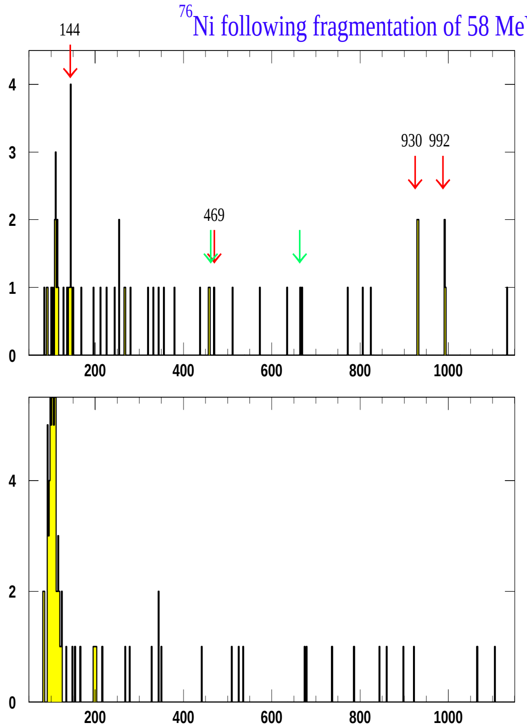
Assumption: $V^m_{f_{7/2} g_{9/2}} \approx 0.5 \cdot V^m_{f_{5/2} g_{9/2}}$

N-40	**Z = 28 shell gap**	
occ.	**EXP**	
$\nu 0 g_{9/2}$	**(MeV)**	
0	**5.91(28)**	
10	**4.46**	**S3V68**
	4.39	**S3V**
	3.58	**"EXP"**

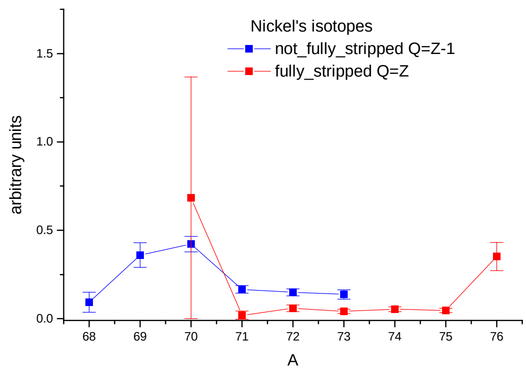
$I^{\pi}=8^{+}$ isomerism



^{76}Ni following fragmentation of 58 MeV/A ^{86}Kr at GANIL



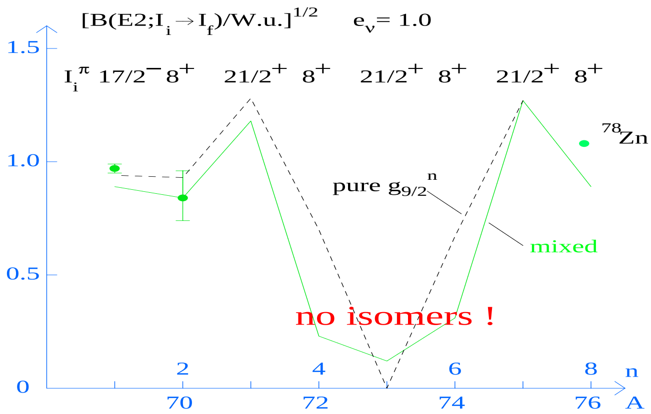
"Isomeric ratio"

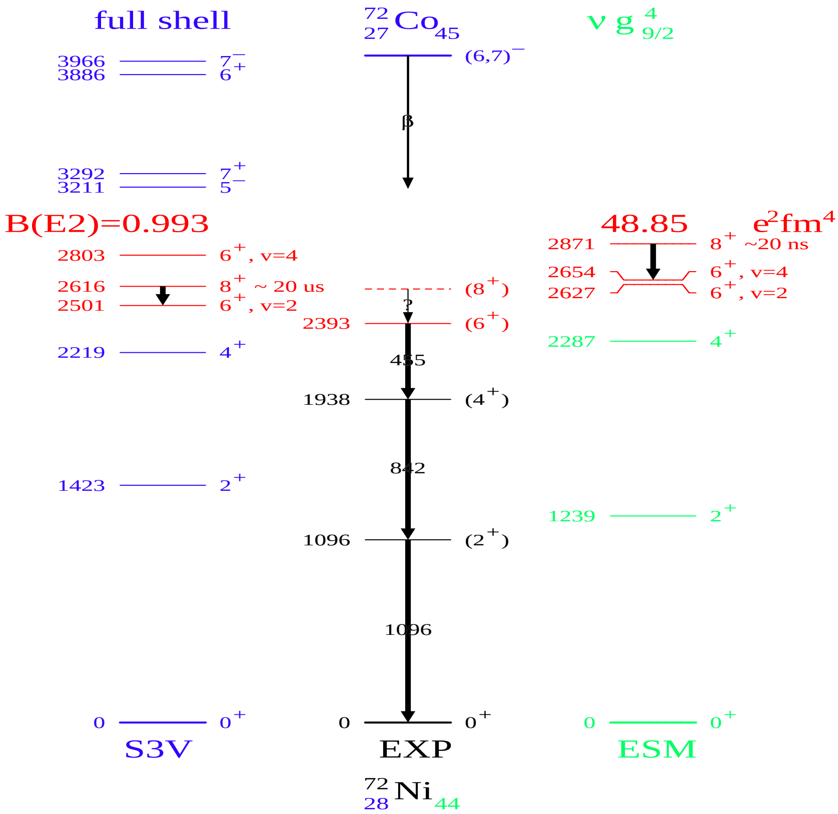


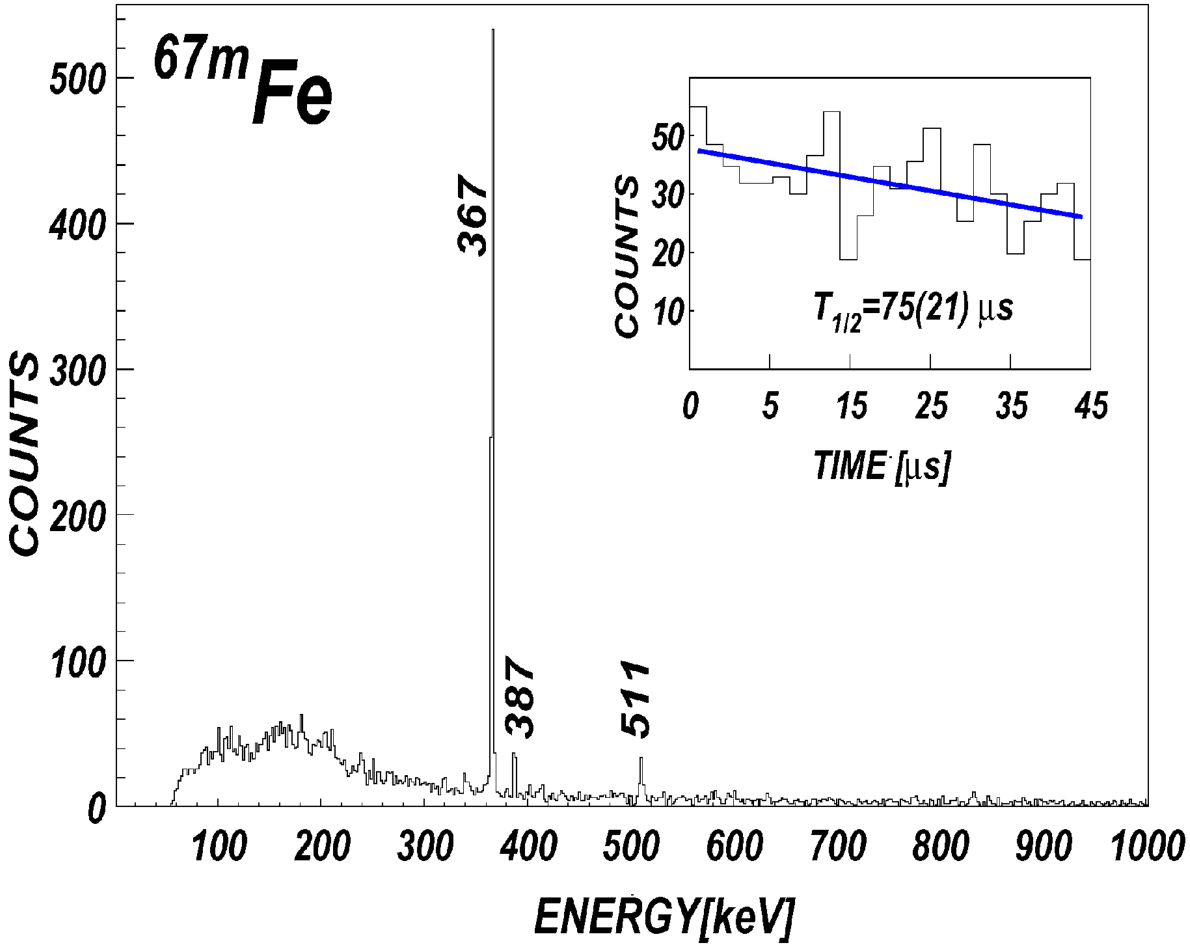
Missing $I^{\pi}=8^{+}$ isomer

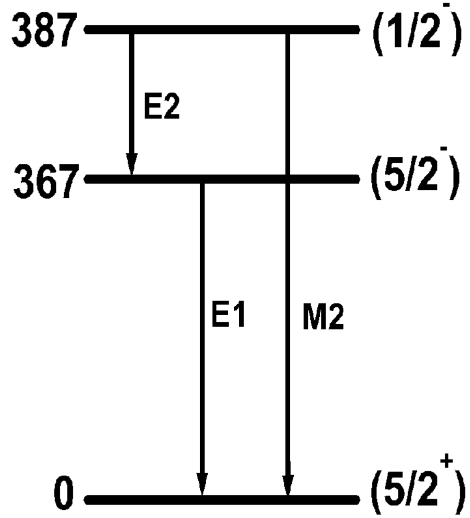
Seniority isomers

E2 transitions in N > 40 Ni isotopes






67mFe
COUNTS
ENERGY[keV]
367
387
511
COUNTS
TIME [μs]
T1/2=75(21) μs


387
367
0
(1/2-)
(5/2-)
(5/2+)
E2
E1
M2

Monopole migration

$V^m = \Sigma(2J+1)\langle jj'|V|jj'\rangle_J / \Sigma(2J+1)$

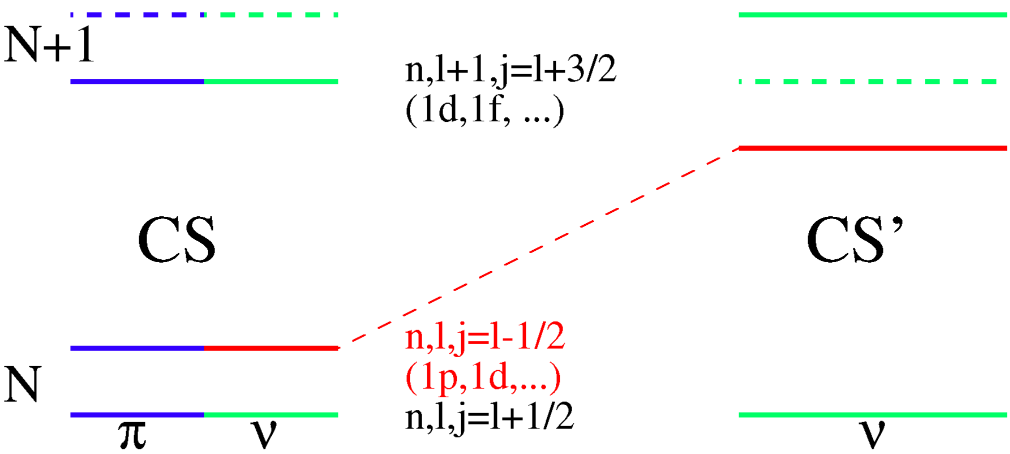
$V = -|v_{\sigma\tau}(r)|(\sigma\,\sigma)(\tau\,\tau)$

S=1 : ~1	T=1 : =1
S=0 : ~2	T=0 : =3

} π ν ~2

N ~ Z   HO --> SO   N >> Z

$(CS)_{ls} \rightarrow (CS')_{jj}$



Signature:

	N_m -->	N_m 2*N
-- HO (ls)-->SO (jj) shell	8	6
-- rapid change, locality	20	16(14)
-- SO splitting increased (apparent)	40	34(32)

Tensor monopole interaction

(T. Otsuka, private communication)

$$V^m = \Sigma(2J+1)\langle jj'|V|jj'\rangle_J / \Sigma(2J+1)$$

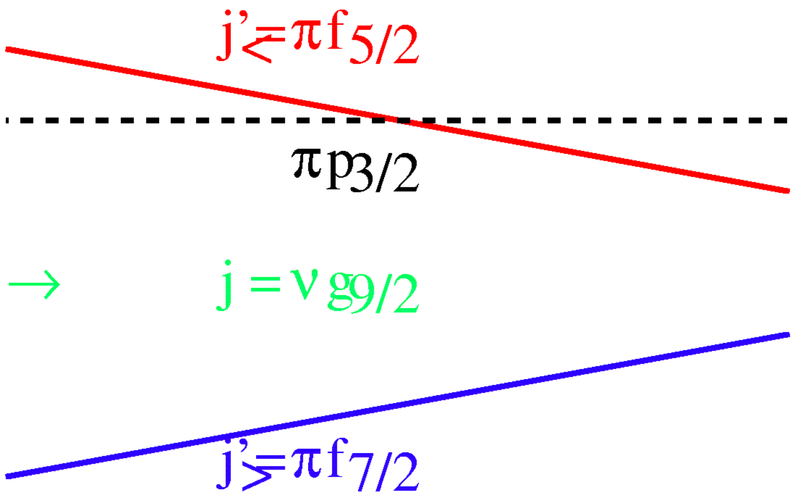
$$V = v_T(r)(\sigma\ r)(\sigma\ r)(\tau\ \tau)$$

$$\rightarrow \sim (\sigma\ Y^1)^k$$

Strong for k=2 and πν

Sum rule :

$$\Sigma(2J+1)\langle jj'_<|V|jj'_<\rangle + \Sigma(2J+1)\langle jj'_>|V|jj'_>\rangle = 0$$



(N,Z)=CS

^{68}Ni :

5.9 MeV

(N,Z)=(N,Z) + (2j+1)

^{78}Ni :

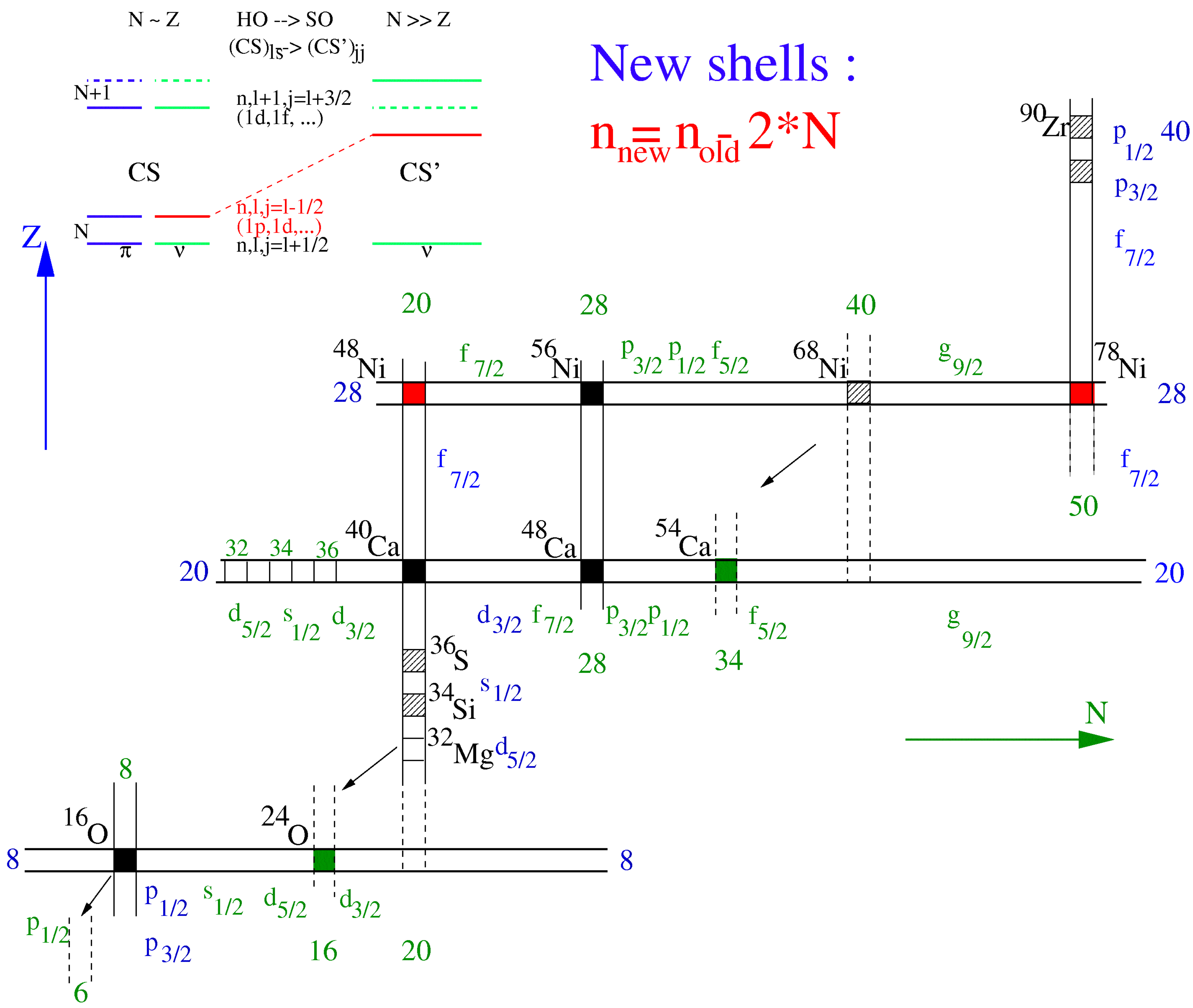
3.6-4.4 MeV

Signature:

-- rapid change, locality

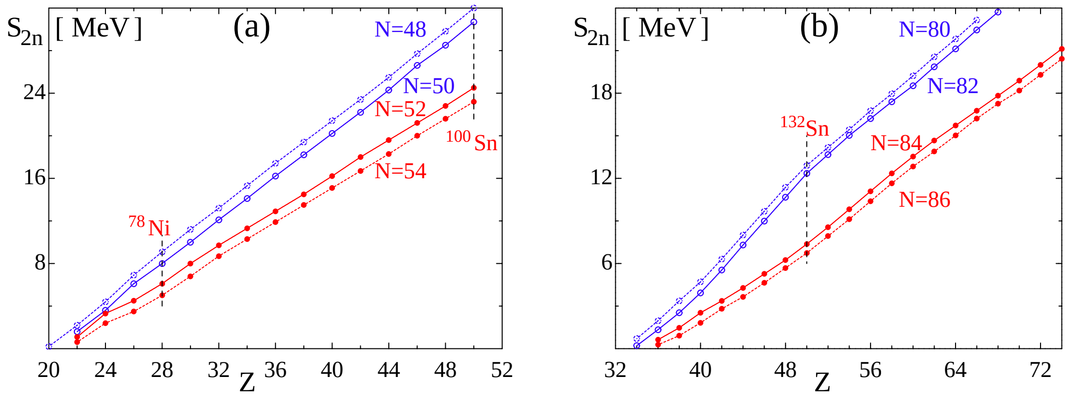
-- SO splitting reduced

(apparent)

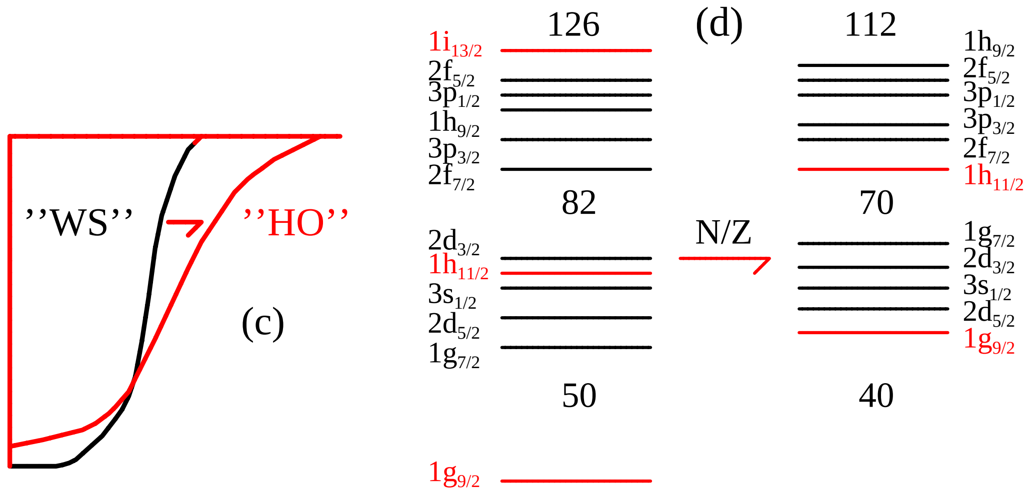


New shells :
$n_{new} = n_{old} - 2*N$
N ~ Z
HO --> SO
$(CS)_{ls}$ -> $(CS')_{jj}$
N >> Z
N+1
n,l+1,j=l+3/2
(1d,1f, ...)
CS
CS'
N
n,l,j=l-1/2
(1p,1d,...)
n,l,j=l+1/2
π
ν
ν
Z
N
^{16}O
^{24}O
^{32}Mg
^{34}Si
^{36}S
^{40}Ca
^{48}Ca
^{54}Ca
^{48}Ni
^{56}Ni
^{68}Ni
^{78}Ni
^{90}Zr
$p_{1/2}$
$p_{3/2}$
$s_{1/2}$
$d_{5/2}$
$d_{3/2}$
$f_{7/2}$
$p_{3/2}$ $p_{1/2}$ $f_{5/2}$
$g_{9/2}$
8
6
16
20
28
32
34
36
40
50

Shell quenching



New shells



Signature

-- Sequence: (1) shell quenching; (2) shell reordering

-- Woods-Saxon (WS)/Spin-orbit (SO) gap to Harmonic-oscillator (HO) gap

-- Smooth in N/Z

-- Spin-orbit splitting reduced

SUMMARY :

- **Techniques**

- *Interconnection to production mechanism*
- *Luminosity*
- *Time scale , half life*
- *Spin, excitation energy*

- **N≃Z - ^{100}Sn**

- *Equivalence ^{56}Ni - ^{100}Sn*
- *Core excitation in identical $\pi\nu$ shell*
- *Spin-gap isomers (^{98}Cd,(12^{+}); ^{94}Ag, (21^{+}), $E_x \simeq 6$ MeV)*
- *Large scale shell model*

- **N≫Z - ^{68}Ni to ^{78}Ni**

- *Monopole driven shell structure*
- *Weakness of N=40 - persistence of N=50 shell*
- *Disappearance of seniority isomers*

- **New shells @ N≫Z**

- *New shells N=6,16(14),34(32) symmetric in isospin*
- *T=1 monopole important in j=1/2 shell*

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