New perspectives north to ^{78}Ni

D. Verney, IPN Orsay

► N=50 shell gap evolution: salient features from experimental data

►► deeper into nuclear structure close to ^{78}Ni :
valence space, single particle state effective sequence

►► what we think we have understood, what remains to be understood

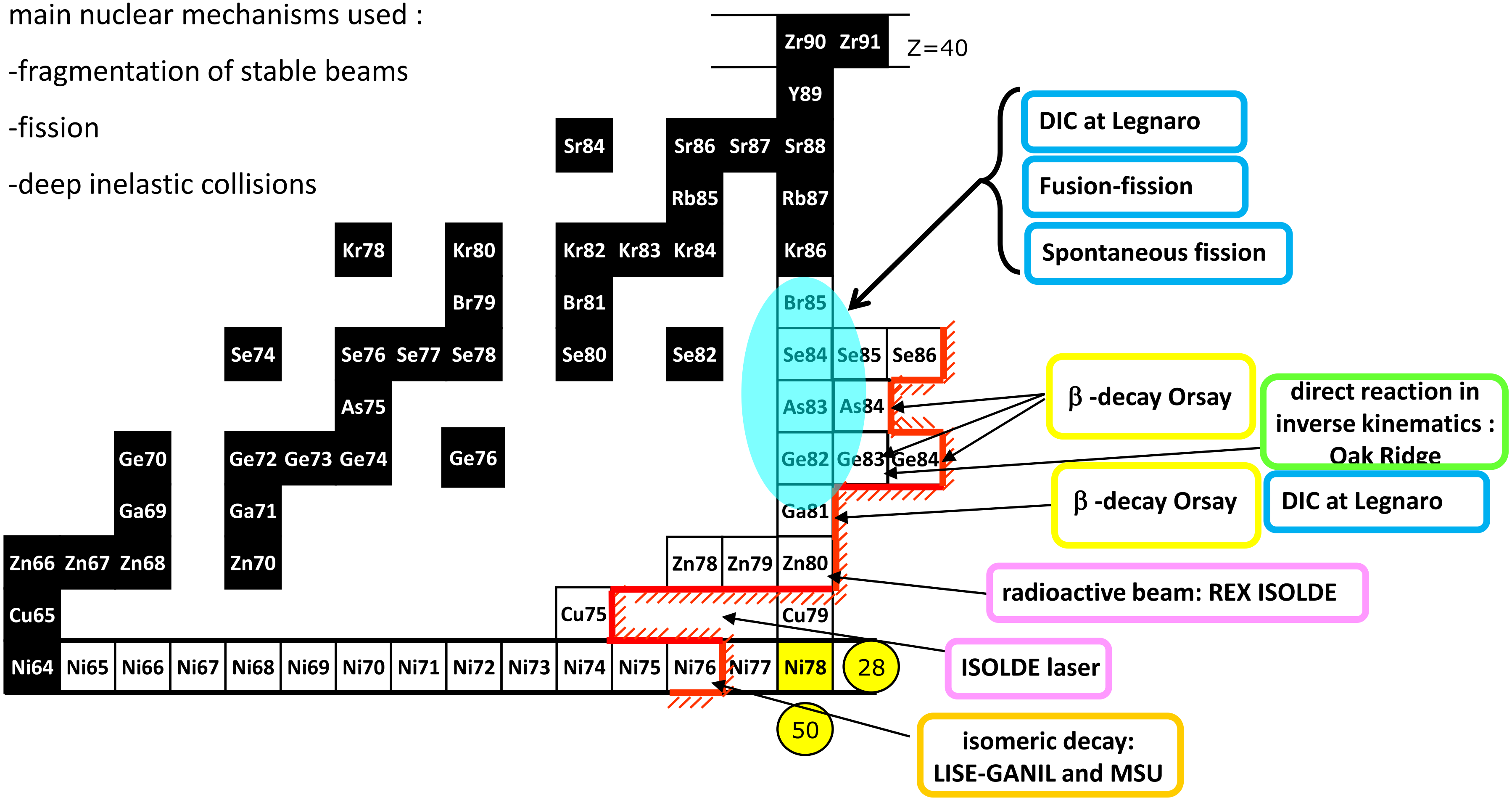
► What has been done, what will be (hopefully) done in near future,

► what can we expect on the longer range term ? (with SPES, SPIRAL2) main nuclear mechanisms used :

-fragmentation of stable beams

-fission

-deep inelastic collisions



probably yes…

• from B(E2) measurement in ^{80}Zn (REX-ISOLDE)
J. Van de Walle et al. PRC 79, 014309 (2009)

«No direct evidence is found for an enhanced Z = 28 core polarization, but the larger proton effective charge needed in the SMI calculations to describe N = 50 isotopes with Z < 40 indicate a larger proton core polarization for these isotopes. No evidence is found for breaking of the N = 50 shell gap. »

• from Yrast structure studies from DIC experiments (Legnaro) down to ^{82}Ge
Y. H. Zhang et al. PRC 70, 024301 (2004) and subsequent studies E. Sahin et al.

« The generally good agreement obtained between calculated and measured level energies in all the cases considered is taken as an argument for the proper description of such semi magic nuclei within the shell-model framework and therefore of the persistence of the N=50 closed shell down to Z=32. »

• from β-decay studies down to ^{81}Ga (Orsay)
O. Perru et al. Eur. Phys. J. A 28, 307 (2006)
D. Verney et al. PRC 76, 054312 (2007)

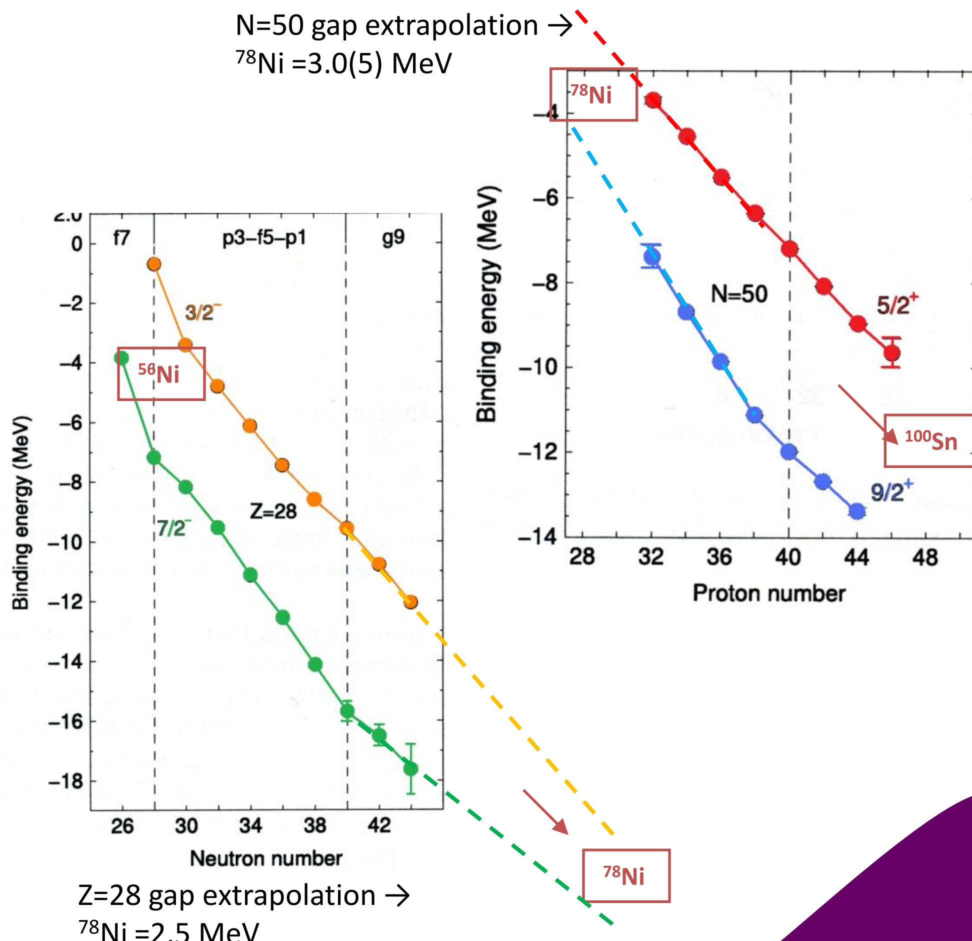
• from mass measurements down to ^{80}Zn (IGISOL Jyvaskyla)
J. Hakala et al. PRL 101, 052502 (2008)

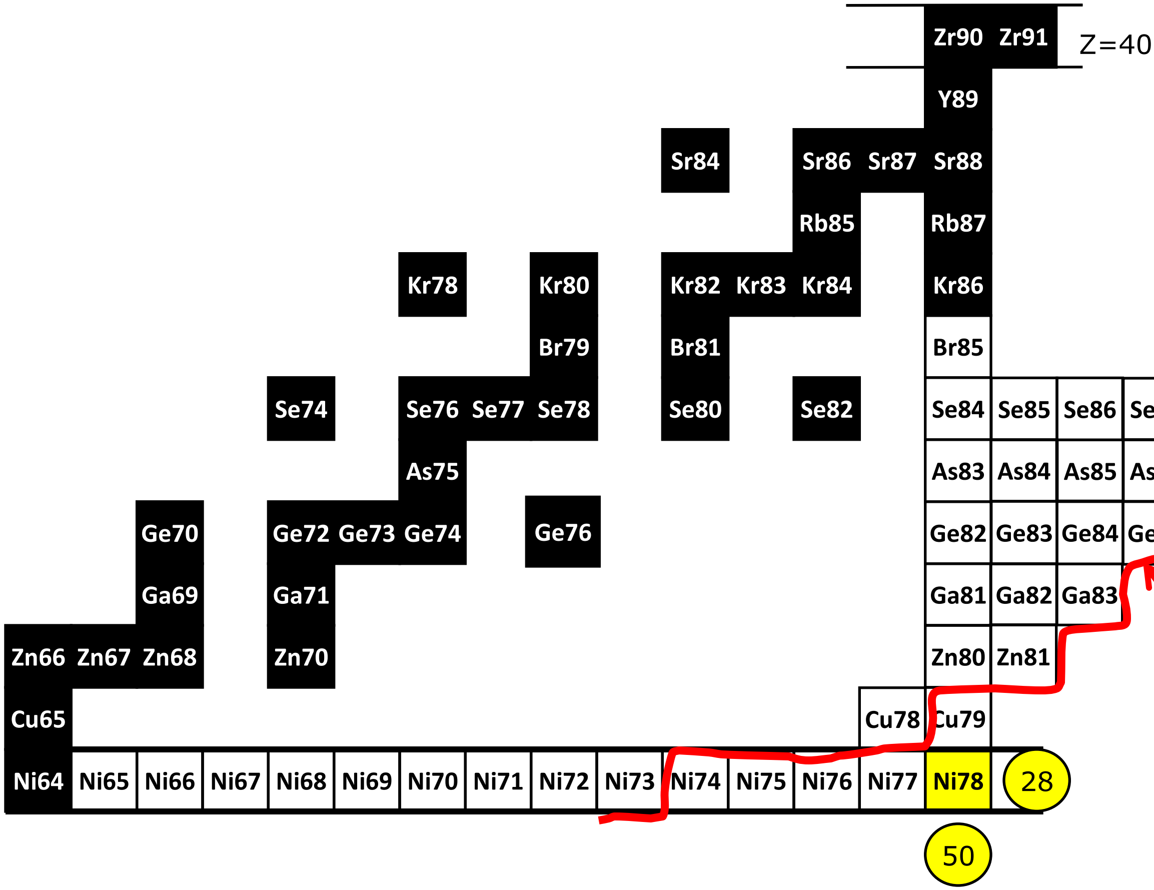
« The data indicates the persistence of this gap towards Ni (Z =28) with an observed minimum at Z=32. »

maybe not…

O. Sorlin, M. Porquet Prog. Part. Nucl. Phys. 61 (2008) 602

from binding energies of the states below and above Z=28 and N=50





present limit of
high precision mass measurements

from AME 2010
G. Audi private communication

Mass measurements (IGISOL Jyvaskyla) Hakala et al PRL101 052502 (2008)

$\Delta = S_{2n}(52) - S_{2n}(50)$

(this quantity is the one traditionnally used to extract shell gaps from mass measurements)

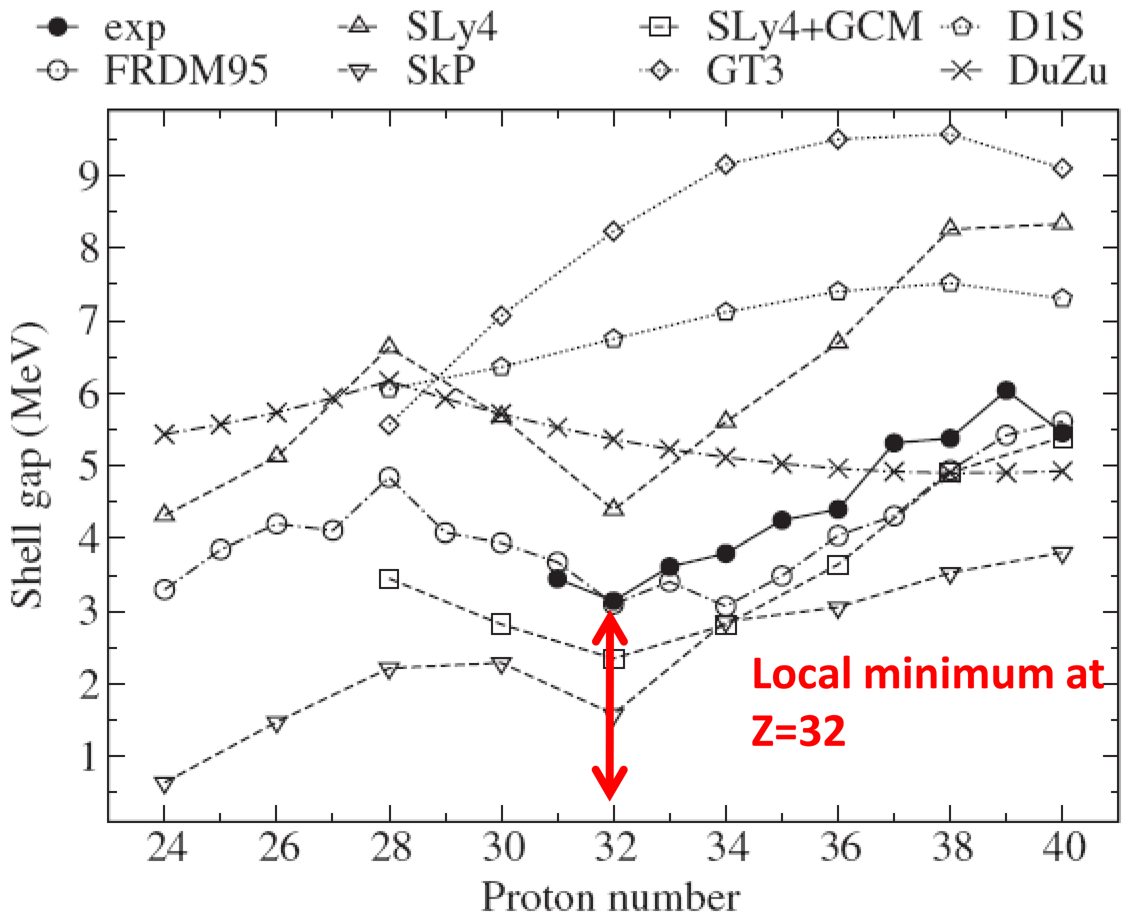
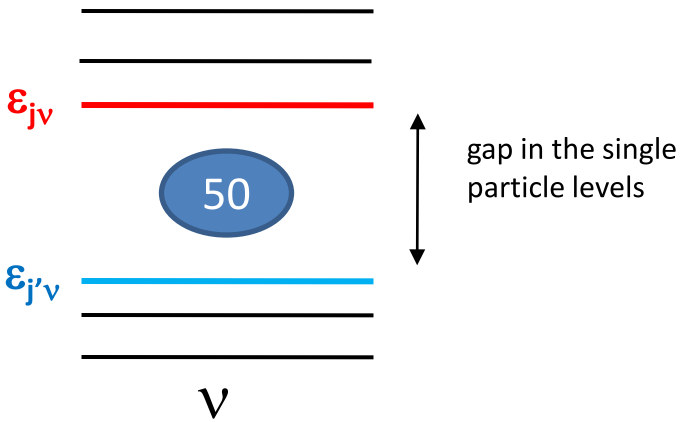


FIG. 4. Evolution of the $N = 50$ shell gap and comparison to theoretical models.



K. Heyde et al. / 0^+ intruder states 193

NPA466 (1987) 189

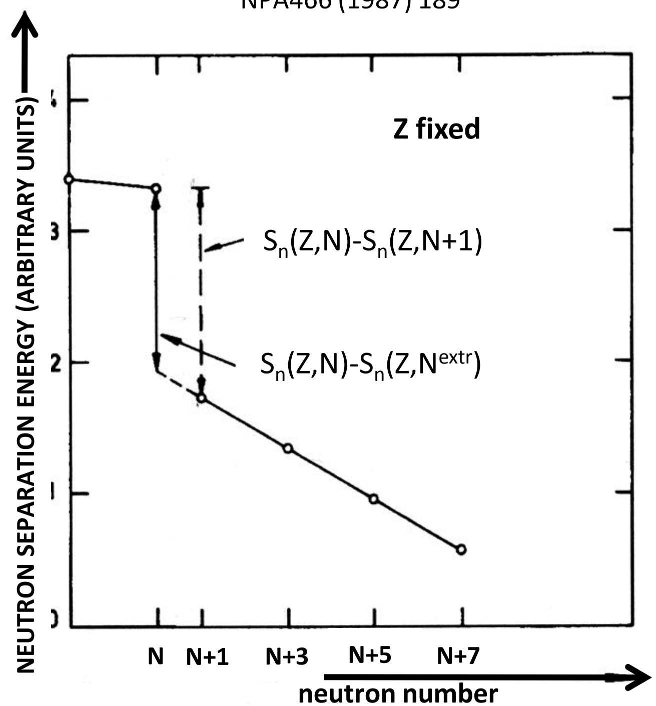


Fig. 3. Outline of a graphical method in order to obtain the unperturbed particle-hole energy in a given closed shell nucleus $A(Z, N)$, where $Z(N)$ denote the proton (neutron) number of the shell closure, starting from empirical proton separation energies S_p. The dashed line denotes the standard prescription, the full line the new prescription. Z^{extr} denotes the extrapolated value for the proton separation energy from above the shell closure.

Koopmans theorem :

$-\varepsilon_{j'\nu} = S_n(Z,N)$

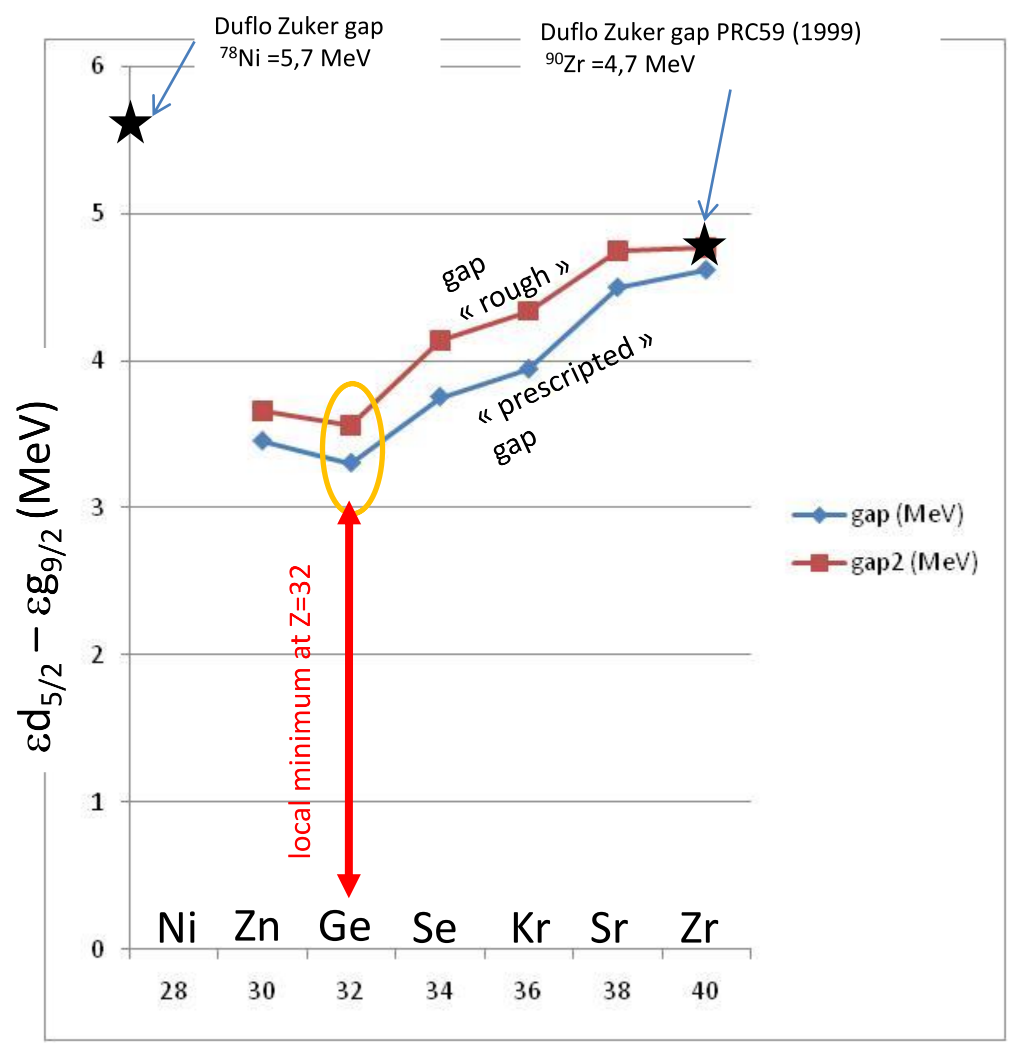
but $S_n(Z,N+1)$ is not a good prescription for

for the evaluation of $\varepsilon_{j\nu}$

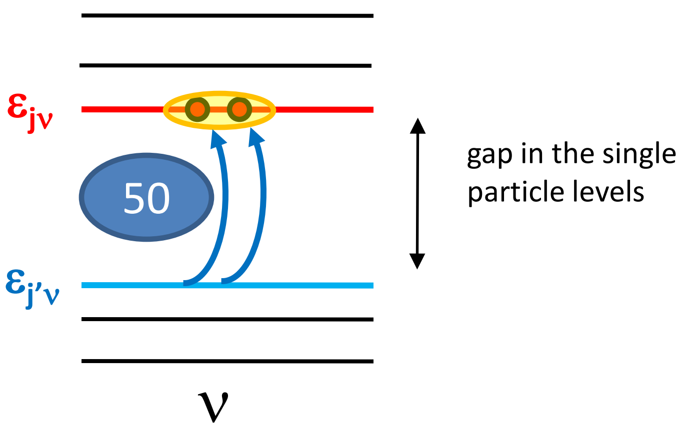
one has to estimate $\varepsilon_{j'\nu}$ and $\varepsilon_{j\nu}$ in the **same** nucleus

then the good prescription becomes : $\varepsilon_{j\nu} - \varepsilon_{j'\nu} = S_n(Z,N) - S_n(Z,N^{extr})$

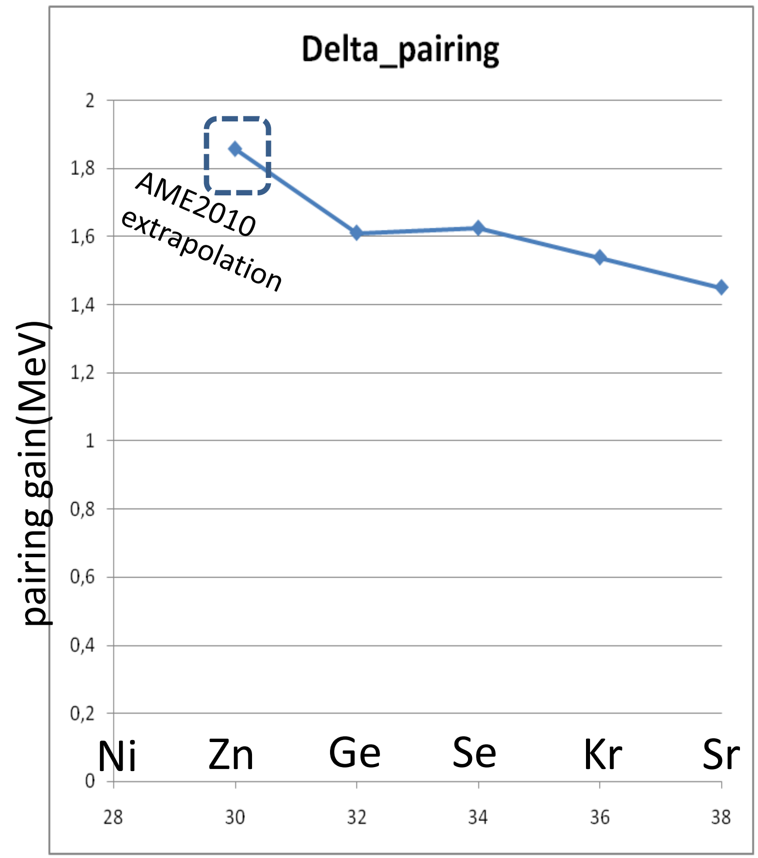
using data taken from mass evaluation 2010 (with kind authorization by G. Audi)

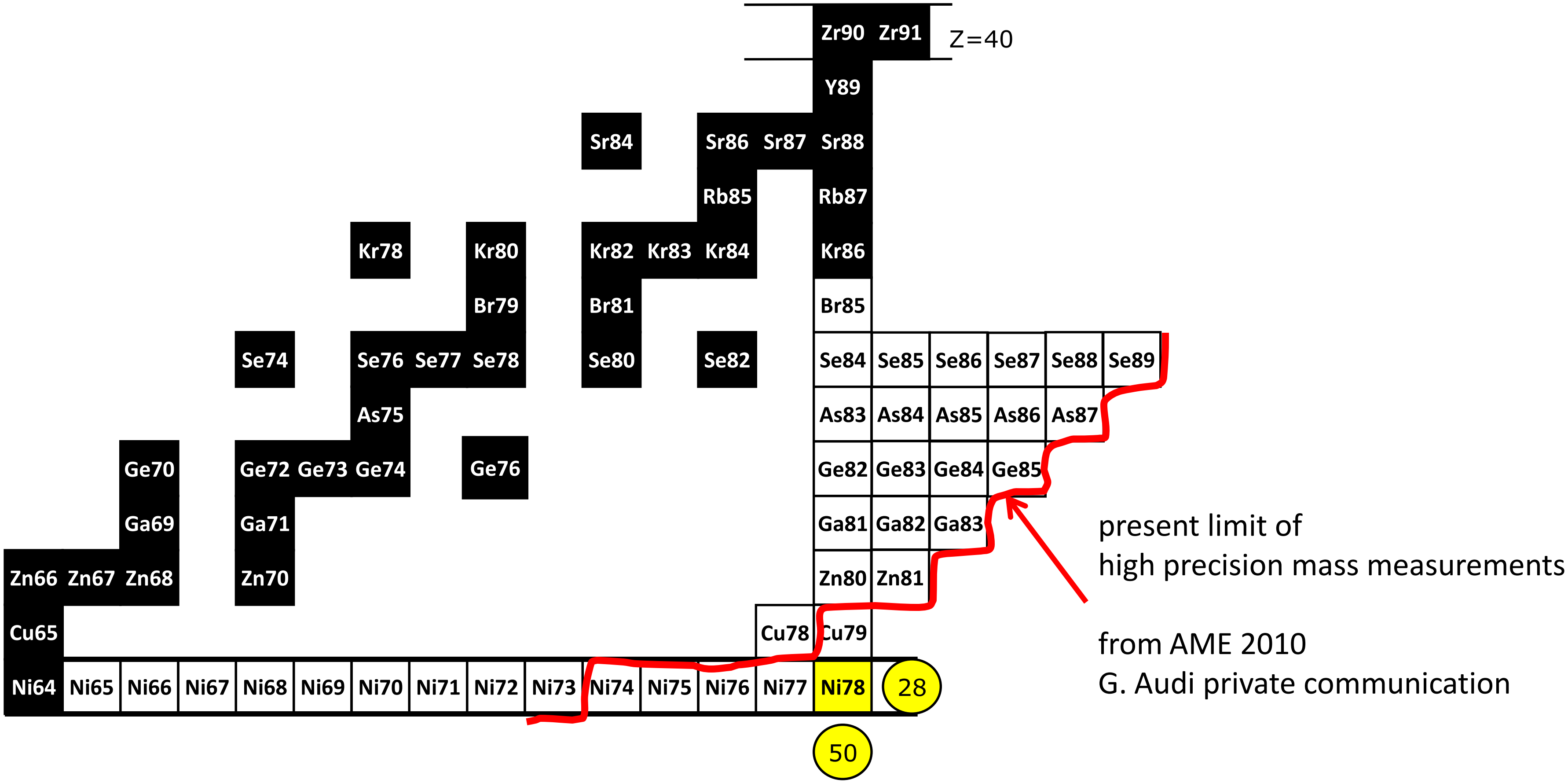


using data taken from mass evaluation 2010 (with kind authorization by G. Audi)



neutron pairing gain = $2S_n(Z,N+1) - S_{2n}(Z,N+2)$





conclusion from mass data

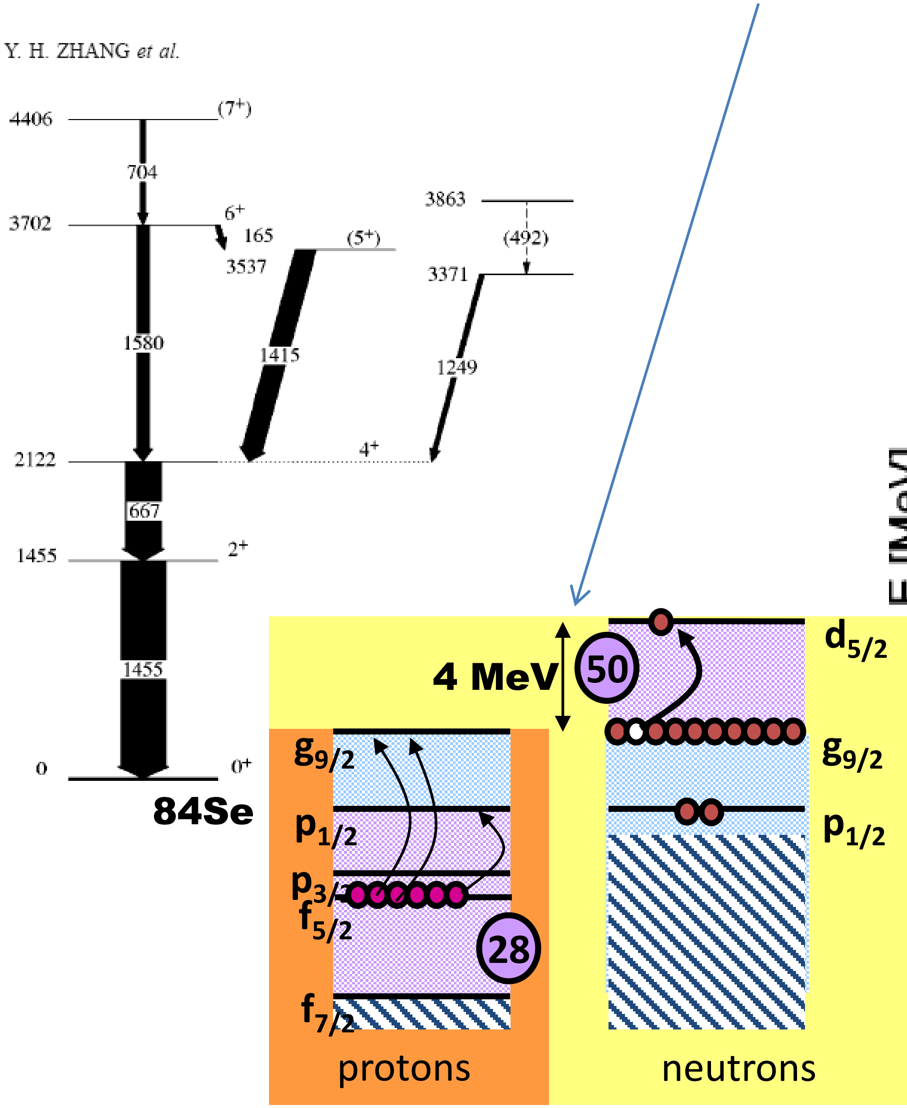
▶ a local minimum in the shell gap at Z=32

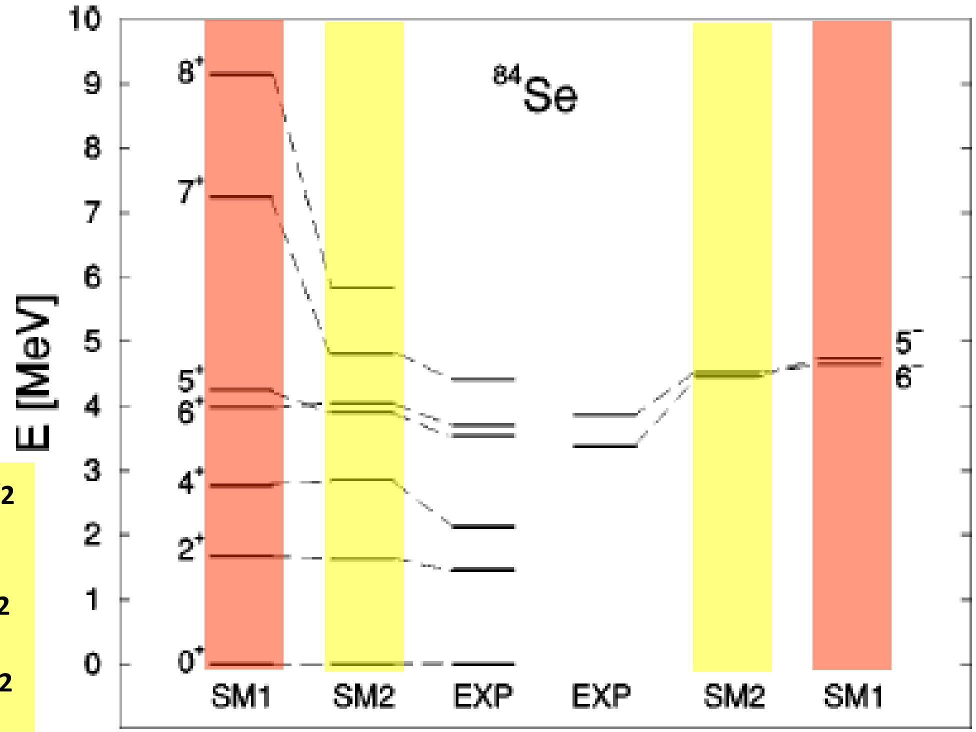
▶ N=50 appears to become somewhat "porous" relative to pair promotions (towards ^{78}Ni)

- what will be the result on structure?
- what is the microscopic mechanism at play which could explain this local minimum ?

The gap used in the calculation has ~ the good size

Y.H. Zhang et al. PRC 70 (2004) 024301
Medium/high spin states fed in DIC at Legnaro



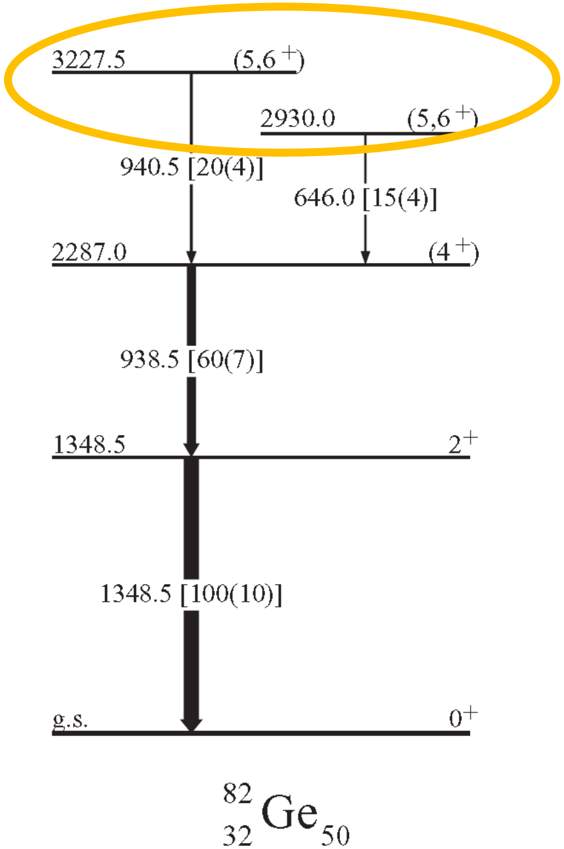


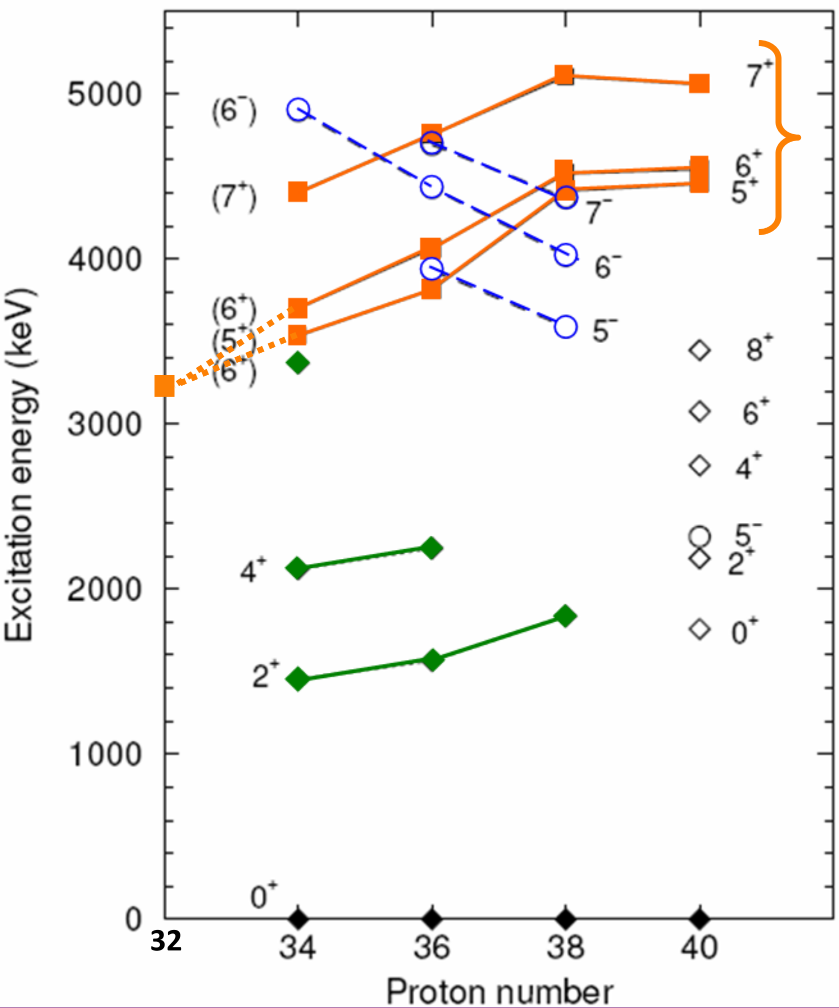
SM calculation proton valence space

SM calculation proton valence space + neutron 1ph

2 levels added : one of the two “must be” 1p-1h across N=50

T. Rza¸ca-Urban et al. PRC 76 (2007) 027302
Medium/high spin states fed in 248Cm spontaneous fission

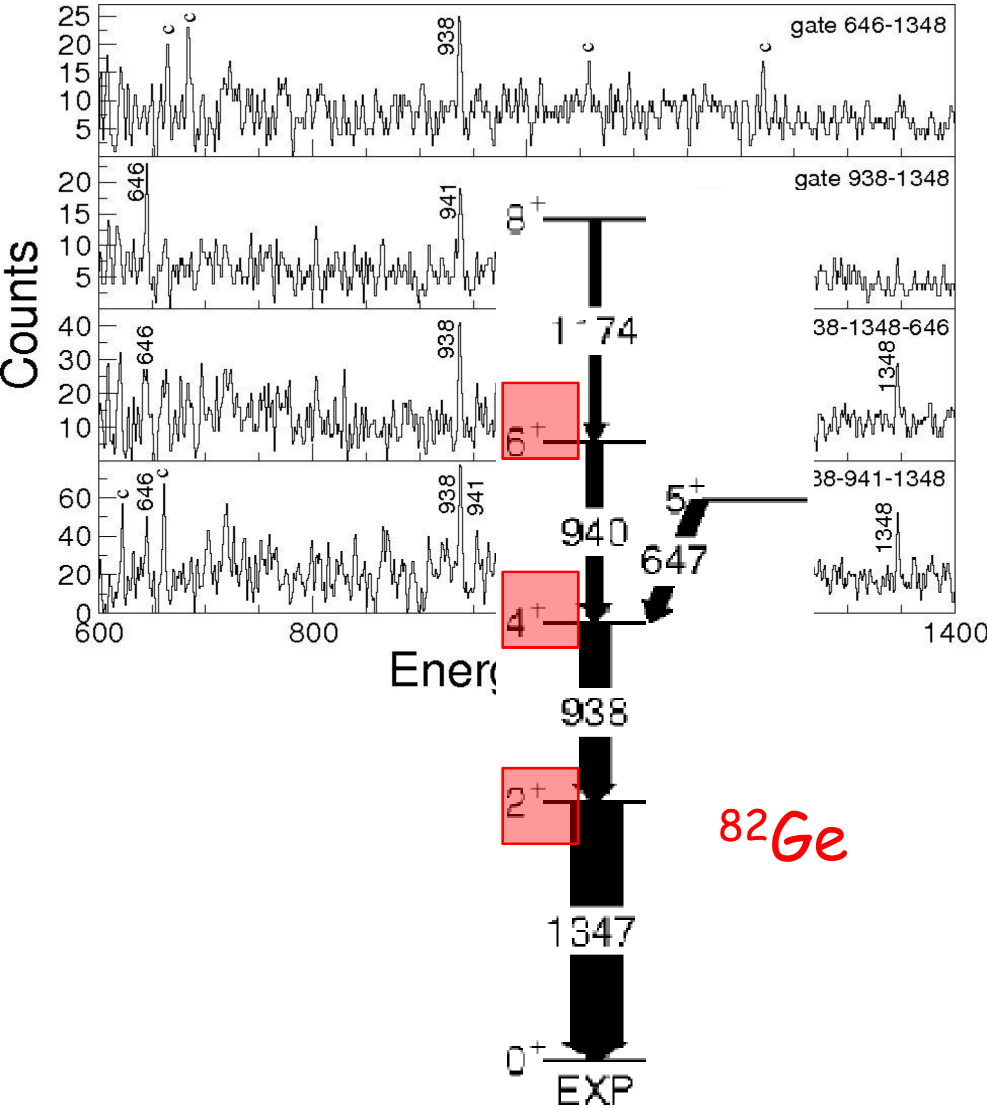


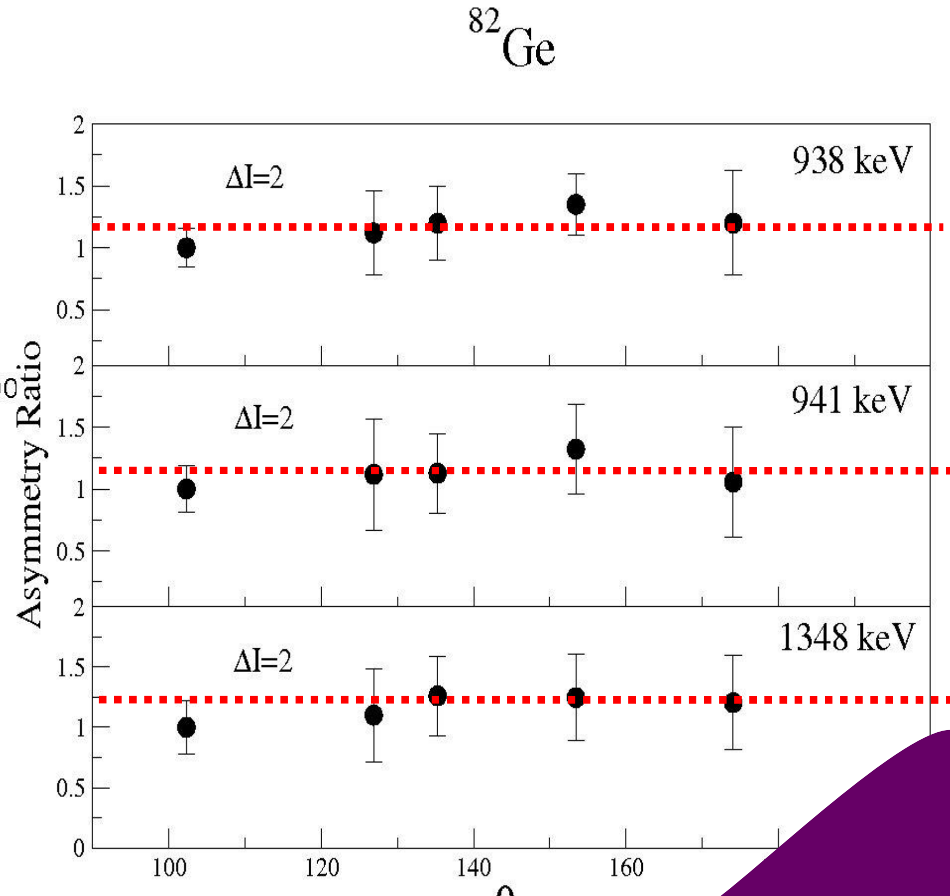


E. Sahin courtesy, submitted to PLB

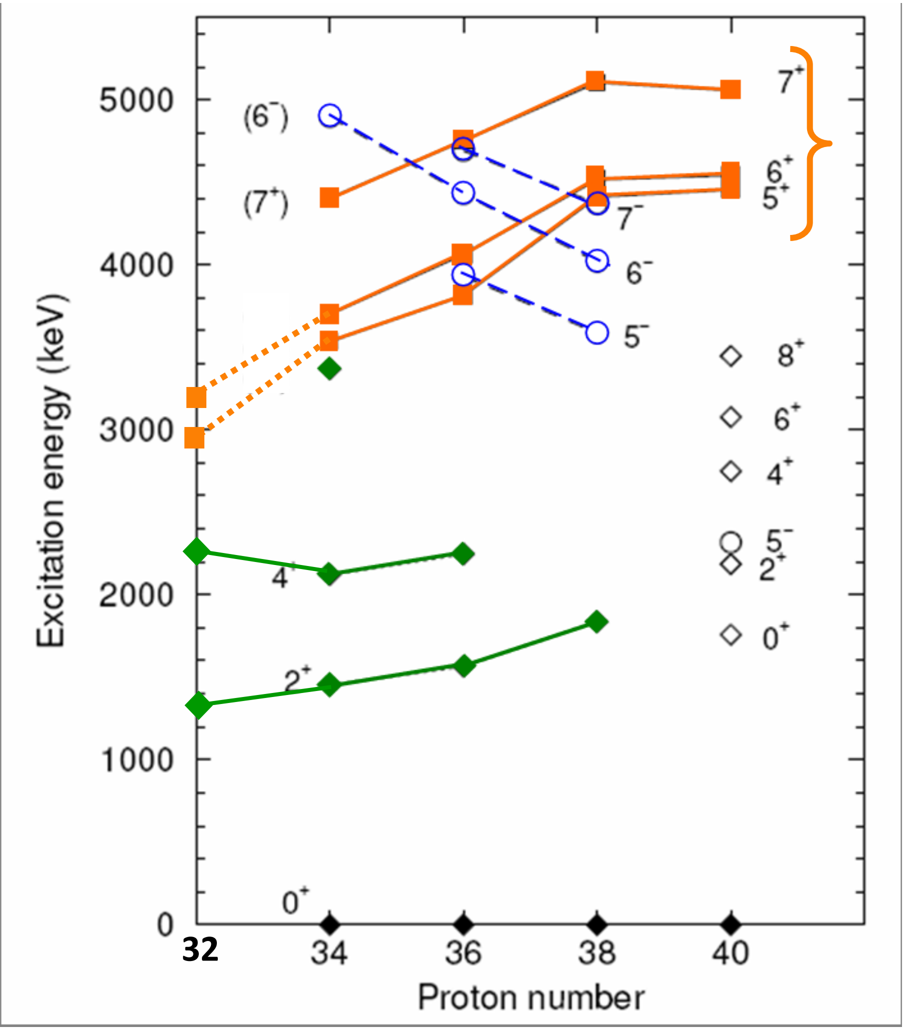
GASP experiment, performed in June 2009
$^{82}Se + ^{238}U$ @ 515 MeV
60 mg/cm^2 thick uranium target
γγγ triple coincidences were acquired in the GASP array

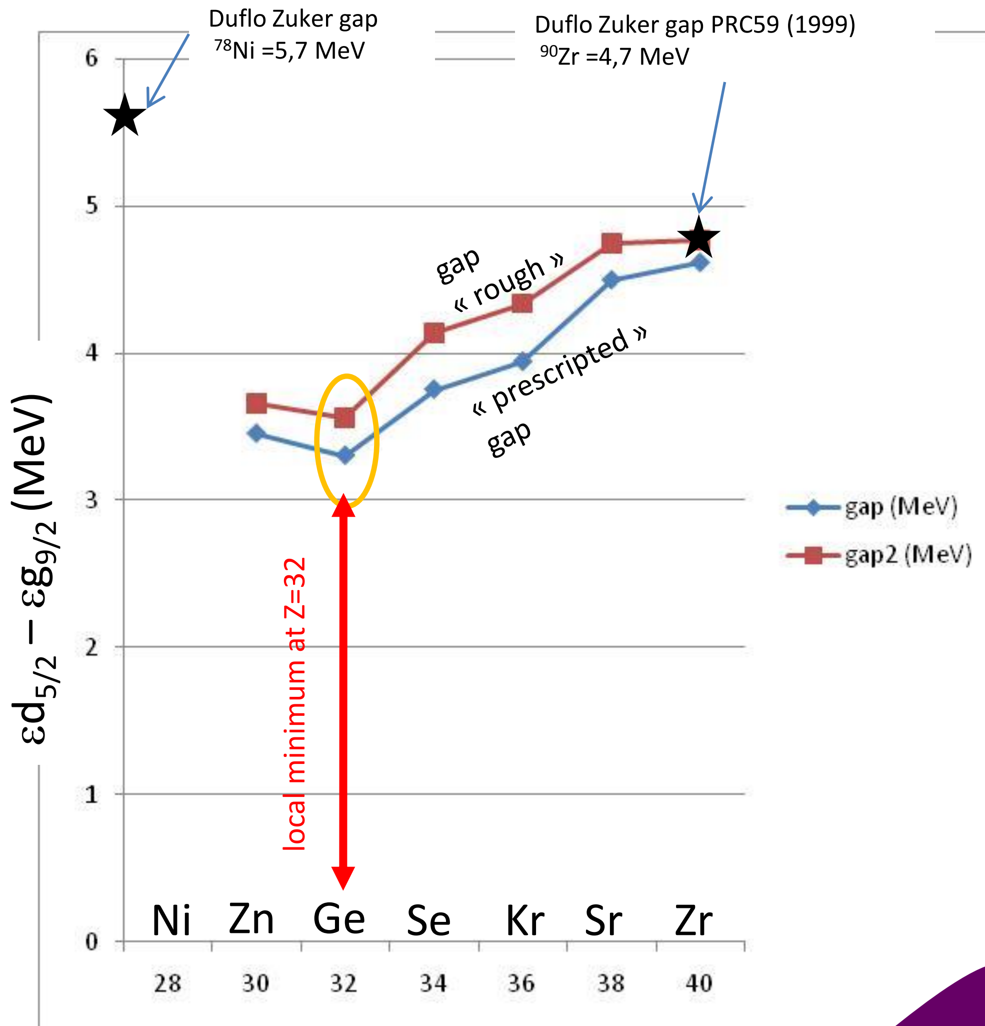
Multipolarity assignments from Asymmetry Ratio method



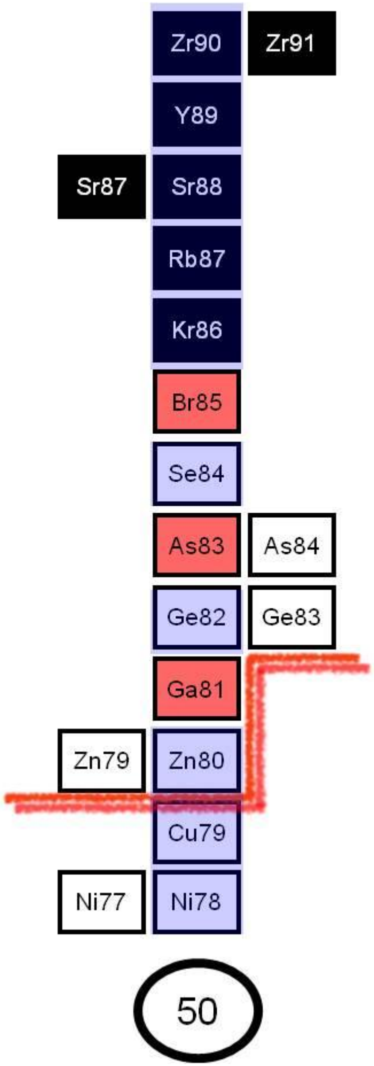


N=50 gap minimum at Z=32: could provide a simple explanation to the Yrast structure behavior





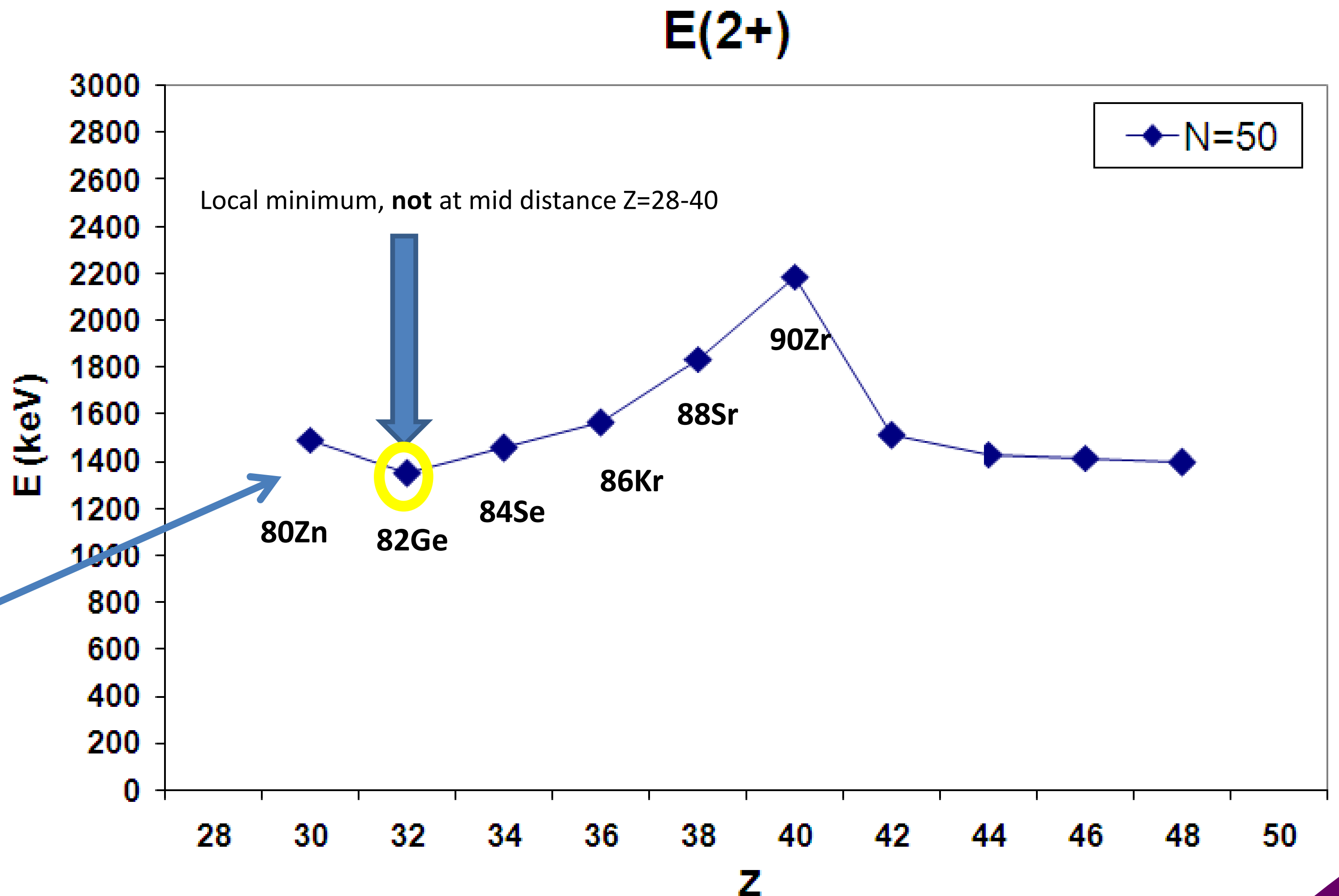
one issue which could be addressed with SPES: Yrast structure in ^{80}Zn



Estimated beam intensities with BEST Cyclotron@SPES
Protons on direct target: E_p=40MeV, Current on target 200 μA
UCx target; other targets shown in "Comments"
September 2010 – Ref.: F. Gramegna 4/10

Element	A	Z	N	T1/2 s	RIBs at 260KeV 1+	Re-accelerated RIBs C.B. eff=3-4 % Linac tr.=50% particles/s	q+	Max E/A	Comments * target different from UCx. To be developed @SPES SIS= surface ion source LIS= laser ion source FEBIAD= plasma source x = easy, xxxx= difficult
Ga	77	31	46	1.32E+01	2,56E+08	5,12E+06	13	11	
Ga	78	31	47	5.09E+00	1,63E+08	3,26E+06	13	11	
Ga	79	31	48	2.85E+00	8,28E+07	1,66E+06	13	10,5	
Ga	80	31	49	1.70E+00	3,05E+07	6,10E+05	13	10,5	
Ga	81	31	50	1.22E+00	1,13E+07	2,27E+05	13	10,5	
Ga	82	31	51	5.99E-01	3,29E+06	6,58E+04	13	10,5	
Ga	83	31	52	3.10E-01	6,06E+05	1,21E+04	13	10,5	
Ga	84	31	53	8.50E-02	4,02E+04				
Ga	85	31	54	7.00E-02	3,62E+03				
Ge	75	32	43	4.97E+03	7,01E+07	1,40E+06	13	10,7	LIS source xxx
Ge	77	32	45	4.07E+04	4,73E+08	9,46E+06	13	10,7	
Ge	78	32	46	5.28E+03	7,31E+08	1,46E+07	13	10,7	
Ge	79	32	47	1.90E+01	1,38E+08	2,76E+06	13	10,7	
Ge	80	32	48	2.95E+01	1,62E+08	3,23E+06	13	10,3	
Ge	81	32	49	7.60E+00	3,21E+07	6,41E+05	13	10,3	
Ge	82	32	50	4.60E+00	1,16E+07	2,32E+05	13	10,3	
Ge	83	32	51	1.85E+00	2,47E+08	4,94E+06	13	10,3	
Ge	84	32	52	9.47E-01	6,61E+05	1,32E+04	13	10,3	
Ge	85	32	53	5.35E-01	1,11E+05	2,22E+03	13	10,3	
Ge	86	32	54	1.23E-01	5,18E+03				
Ge	87	32	55	1.30E-01	3,71E+02				
As	76	33	43	9.31E+04	1,17E+07	2,34E+05	14	12	FEBIAD source
As	77	33	44	1.40E+05	5,67E+07	1,13E+06	14	12	
As	78	33	45	5.44E+03	1,73E+08	3,46E+06	14	12	
As	79	33	46	5.41E+02	2,75E+08	5,50E+06	14	12	
As	80	33	47	1.52E+01	7,68E+07	1,54E+06	14	12	
As	81	33	48	3.33E+01	1,63E+08	3,26E+06	14	12	
As	82	33	49	1.91E+01	1,07E+08	2,13E+06	14	11	
As	83	33	50	1.34E+01	6,33E+07	1,27E+06	14	11	
As	84	33	51	4.50E+00	1,86E+07	3,72E+05	14	11	
As	85	33	52	2.02E+00	5,83E+06	1,17E+05	14	11	
As	86	33	53	9.45E-01	1,54E+06	3,08E+04	14	11	
As	87	33	54	4.80E-01	2,07E+05	4,14E+03	14	11	
As	88	33	55	2.33E-01	3,53E+04				
As	89	33	56	8.30E-02	3,27E+03				
Se	79	34	45	3.57E+13	1,64E+07	3,28E+05	14	11,5	FEBIAD source
Se	81	34	47	1.11E+03	1,29E+08	2,58E+06	14	11,5	
Se	82	34	48	3.41E+27	3,73E+08	7,46E+06	14	11,5	
Se	83	34	49	1.34E+03	4,07E+08	8,14E+06	14	11,5	
Se	84	34	50	1.86E+02	1,45E+08	2,90E+06	14	11,5	
Se	85	34	51	3.17E+01	2,16E+07	4,32E+05	14	11	
Se	86	34	52	1.53E+01	6,67E+06	1,33E+05	14	11	
Se	87	34	53	5.29E+00	1,15E+06	2,30E+04	14	11	
Se	88	34	54	1.53E+00	1,36E+05	2,71E+03	14	11	
Se	89	34	55	4.10E-01	1,51E+04				
Se	90	34	56	1.82E-01	1,84E+03				
Se	91	34	57	2.70E-01	4,81E+02				
Br	82	35	47	1.27E+05	9,95E+07	1,99E+06	15	12,3	FEBIAD source
Br	83	35	48	8.64E+03	3,20E+08	6,40E+06	15	12,3	

and also the peculiar evolution of the E(2+) of the even-even N=50 isotones



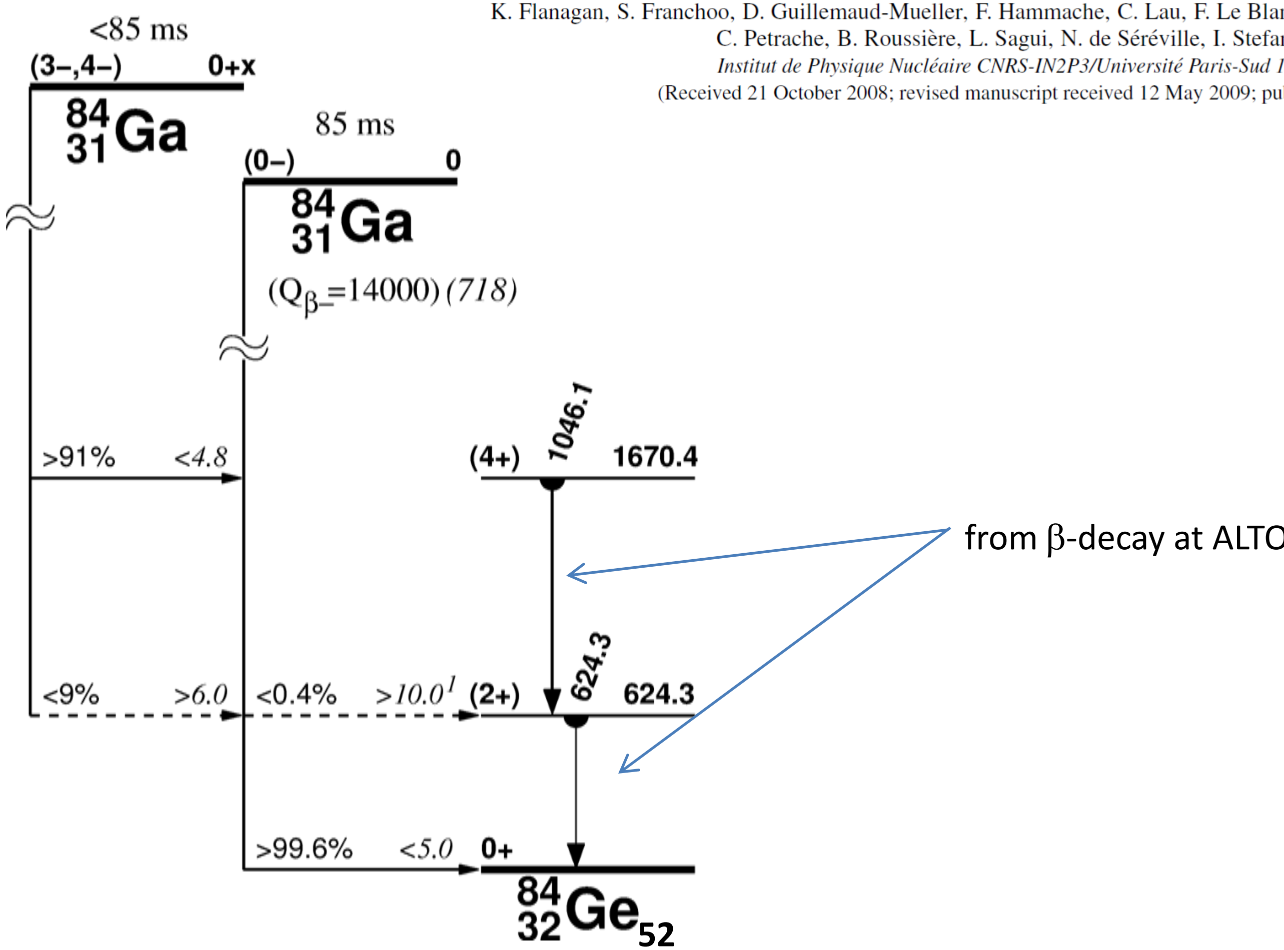
J. Van de Walle et al.
PRL **99, 142501 (2007)**
REX-ISOLDE

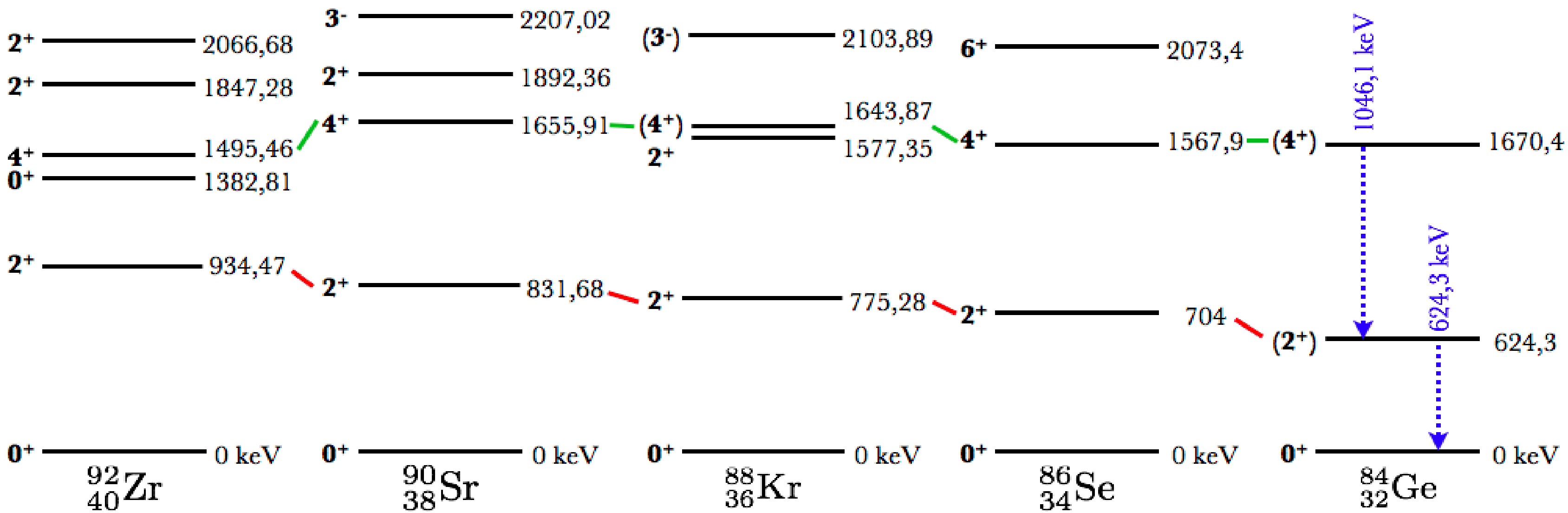
experiment at ALTO

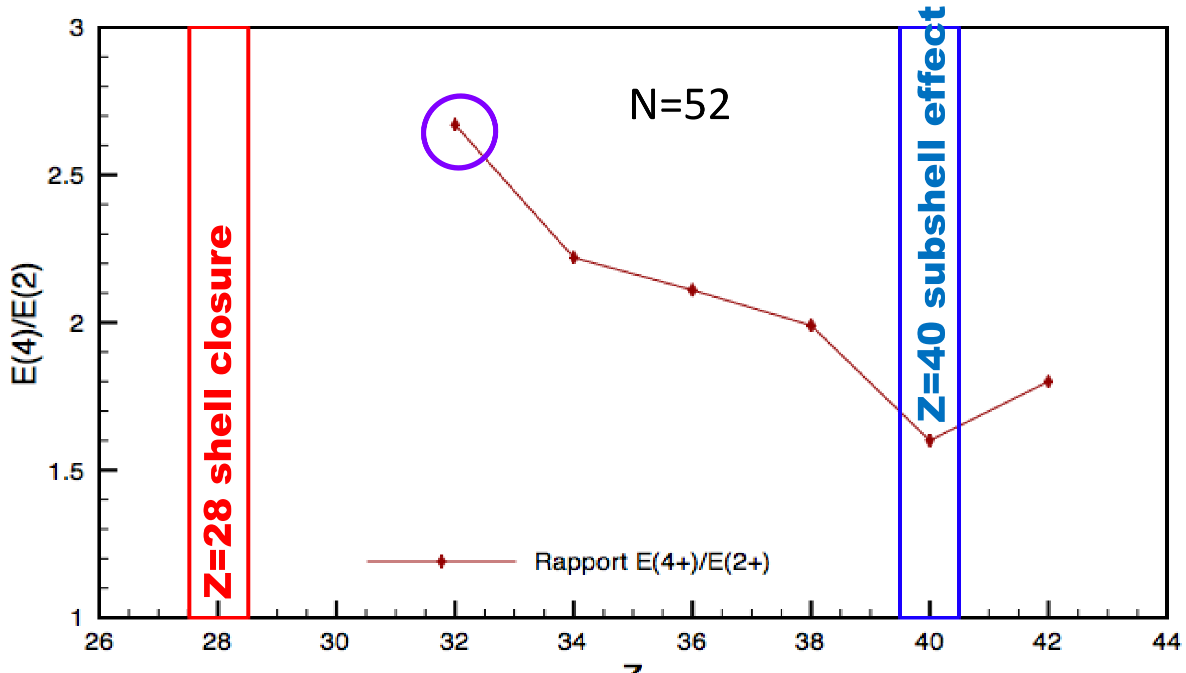
PHYSICAL REVIEW C **80**, 044308 (2009)

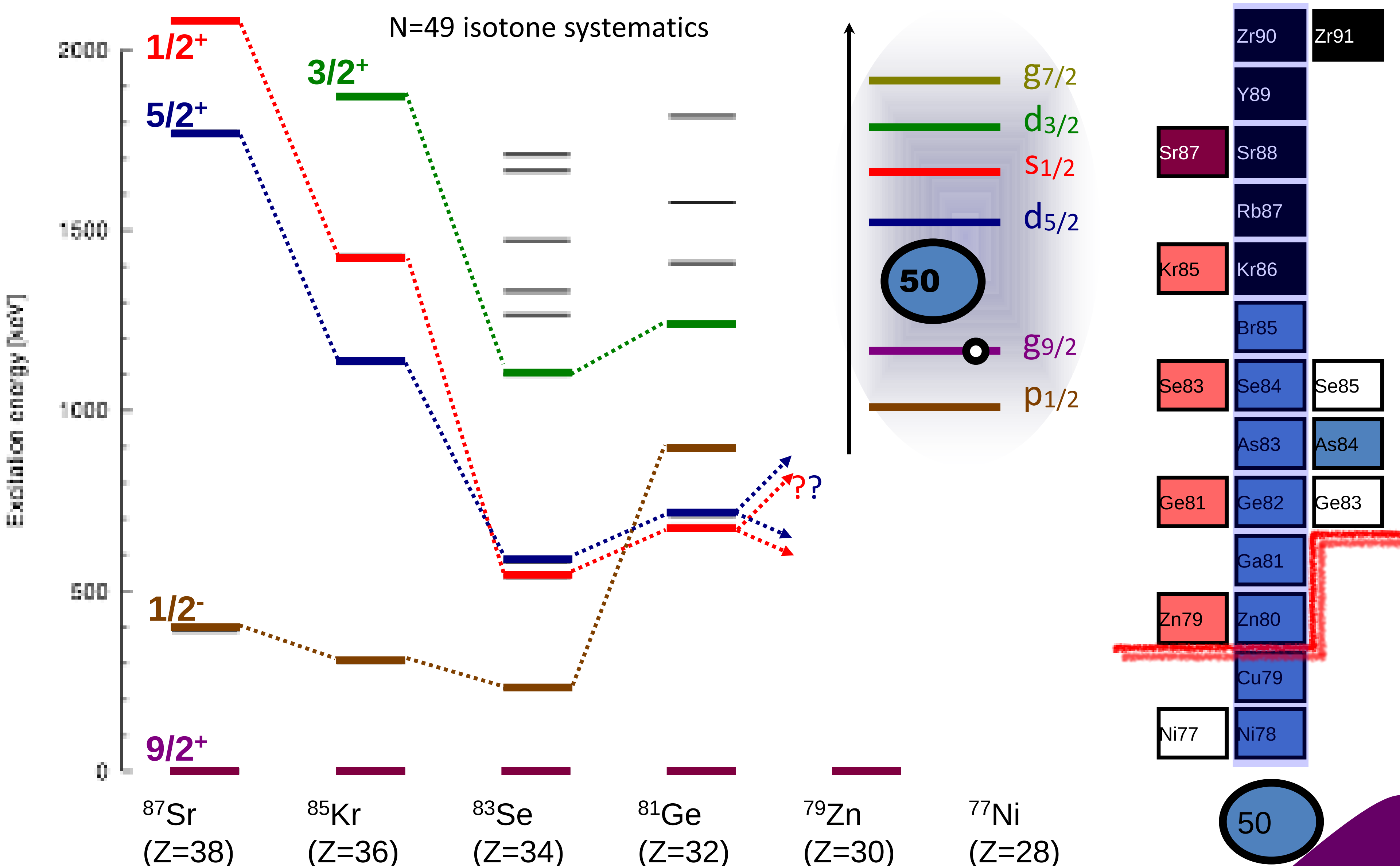
Experimental study of ^{84}Ga β decay: Evidence for a rapid onset of collectivity in the vicinity of ^{78}Ni

M. Lebois, D. Verney,* F. Ibrahim, S. Essabaa, F. Azaiez, M. Cheikh Mhamed, E. Cottereau, P. V. Cuong,† M. Ferraton, K. Flanagan, S. Franchoo, D. Guillemaud-Mueller, F. Hammache, C. Lau, F. Le Blanc, J.-F. Le Du, J. Libert, B. Mouginot, C. Petrache, B. Roussière, L. Sagui, N. de Séréville, I. Stefan, and B. Tastet
Institut de Physique Nucléaire CNRS-IN2P3/Université Paris-Sud 11, Orsay, France
(Received 21 October 2008; revised manuscript received 12 May 2009; published 9 October 2009)

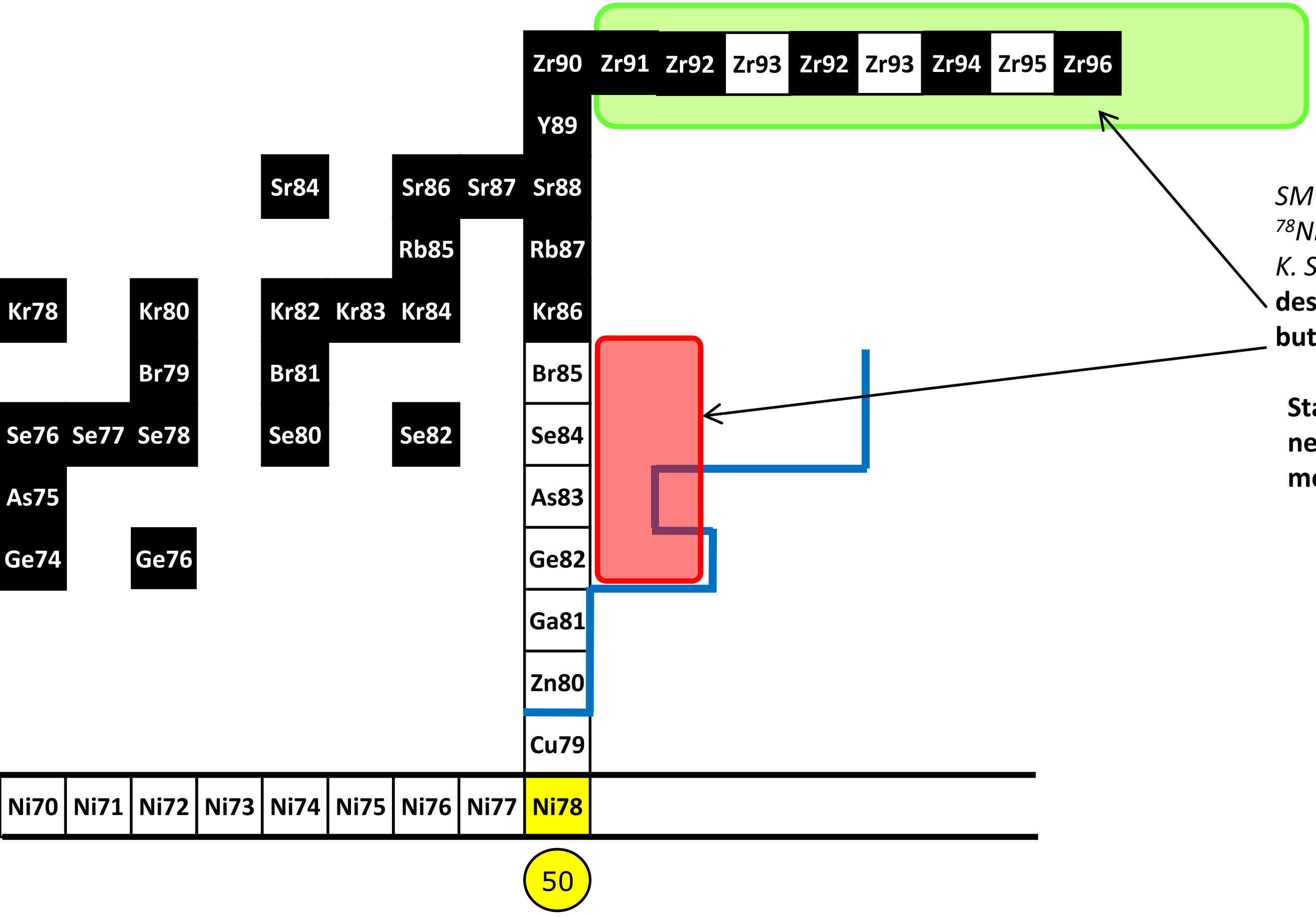



2+ 2066,68
2+ 1847,28
4+ 1495,46
0+ 1382,81
2+ 934,47
0+ 0 keV
$^{92}_{40}$Zr
3- 2207,02
2+ 1892,36
4+ 1655,91
2+ 831,68
0+ 0 keV
$^{90}_{38}$Sr
(3-) 2103,89
(4+) 1643,87
2+ 1577,35
2+ 775,28
0+ 0 keV
$^{88}_{36}$Kr
6+ 2073,4
4+ 1567,9
2+ 704
0+ 0 keV
$^{86}_{34}$Se
(4+) 1670,4
(2+) 624,3
0+ 0 keV
1046,1 keV
624,3 keV
$^{84}_{32}$Ge


N=52
Z=28 shell closure
Z=40 subshell effect
Rapport E(4+)/E(2+)
E(4)/E(2)
Z
3
2.5
2
1.5
1
26
28
30
32
34
36
38
40
42
44



R.A.Meyer et al., PRC 25 (1982) 682



SM calculations in valence space above ^{78}*Ni*

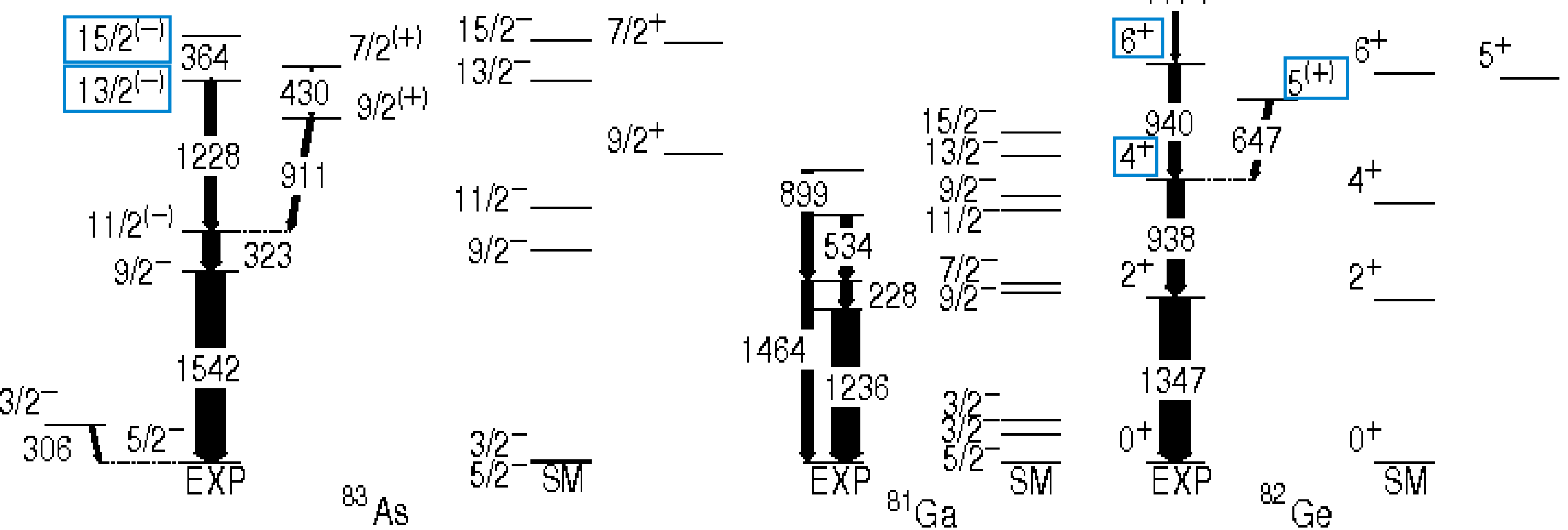
K. Sieja et al. PRC ***79****, 064310 (2009)*

description of Zr chain OK,
but lower in the shell : failure

Starting from realistic NN interaction necessary modifications: monopole, pairing terms

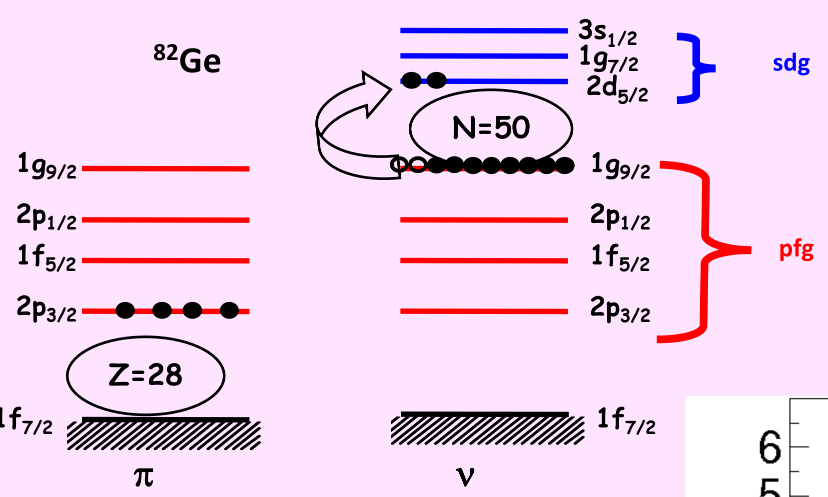
PRISMA CLARA
+ GASP performed in June 2009
$^{82}Se+^{238}U$ @ 515 MeV
60 mg/cm^2 thick uranium target
γγγ triple coincidences were acquired in the GASP array

Excitations across the N=50 Energy Gap



Up to 2p-2h excitations

E. Sahin courtesy
E. Sahin et al. to be published in PLB



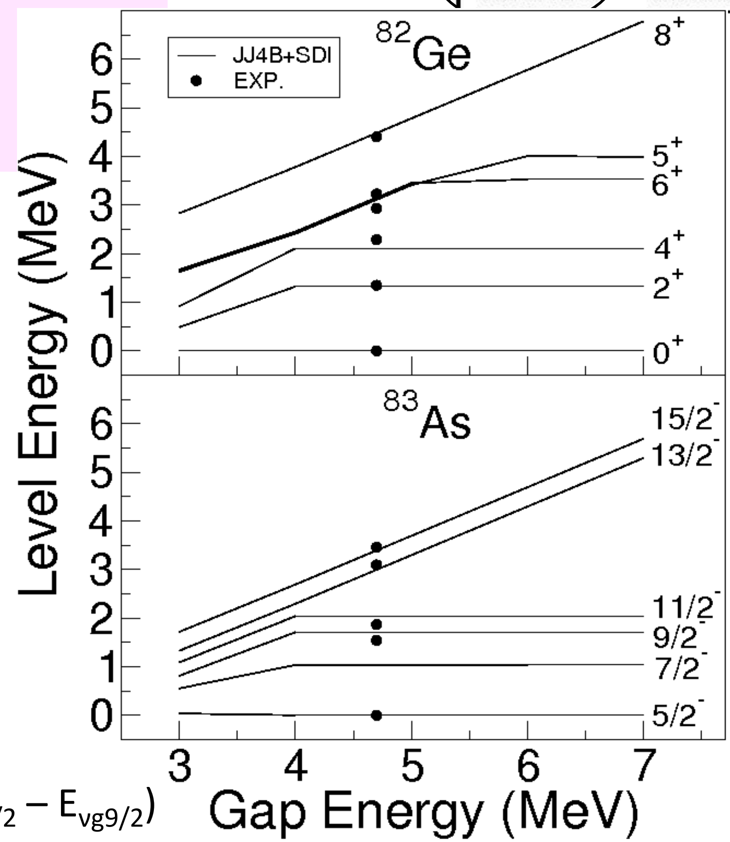
JJ4B B.A. Brown and A.F. Lisetskiy

(first used with success in Verney et al. PRC76, 054312 (2007) : ^{81}Ga, more recently in A. Gade et al. PRC **81**, 064326 (2010) ^{82}Ge and ^{84}Se)

+ SDI

Model Space	Single-Particle Energy			
pfg	$E(1f_{5/2})$	$E(2p_{3/2})$	$E(2p_{1/2})$	$E(1g_{9/2})$
	-9.28590	-9.65660	-8.26950	-5.89440
sdg	$E(2d_{5/2})$	$E(3s_{1/2})$	$E(1g_{7/2})$	
	-1.19440	-0.16800	0.2700	

2 neutrons in the $1g_{9/2}$ orbital have been allowed to cross the N=50 shell gap

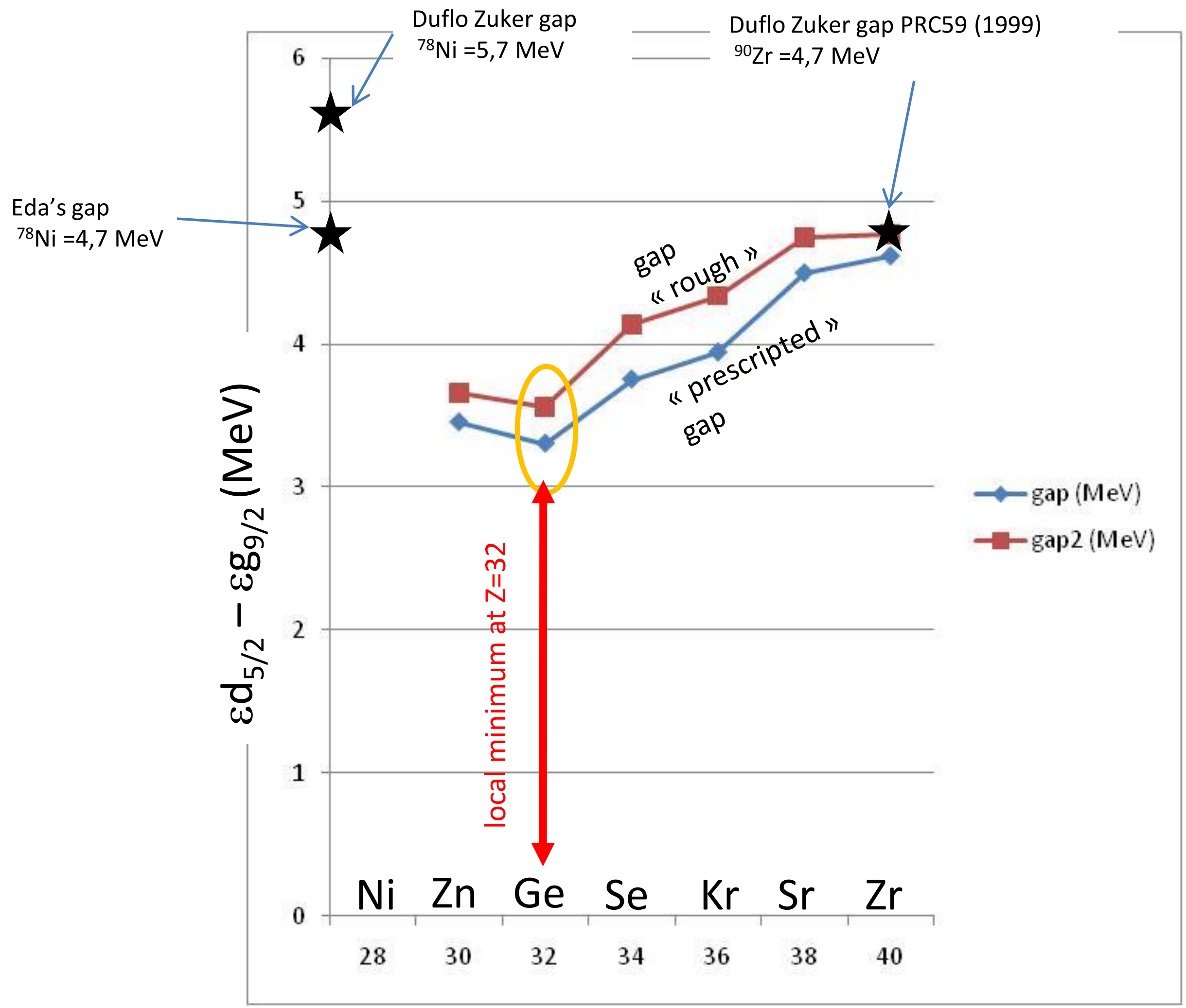


$(E_{\nu d5/2} - E_{\nu g9/2})$

E. Sahin courtesy

E. Sahin et al. to be published in PLB

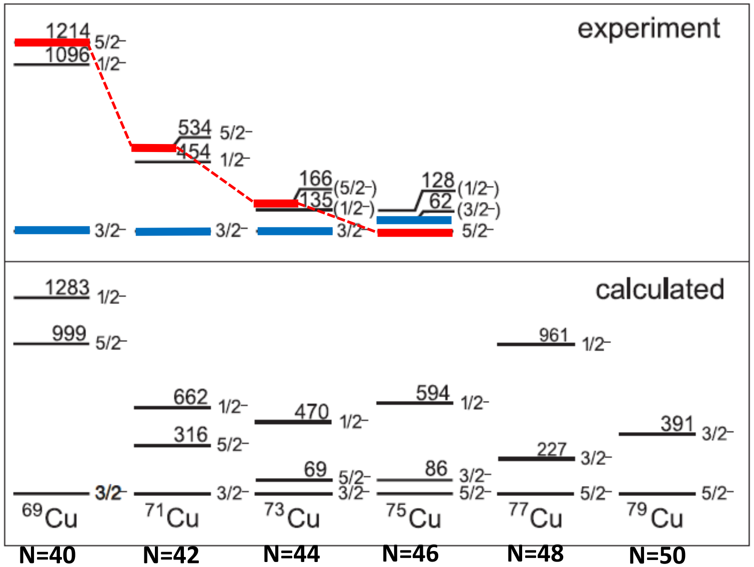
$(E_{\nu d5/2} - E_{\nu g9/2})$=4,7 MeV


Duflo Zuker gap
78Ni =5,7 MeV
Duflo Zuker gap PRC59 (1999)
90Zr =4,7 MeV
Eda's gap
78Ni =4,7 MeV
6
5
4
3
2
1
0
εd5/2 – εg9/2 (MeV)
gap
« rough »
« prescripted »
gap
local minimum at Z=32
gap (MeV)
gap2 (MeV)
Ni
Zn
Ge
Se
Kr
Sr
Zr
28
30
32
34
36
38
40

some monopole effect at play…
maybe, but what single particles ?

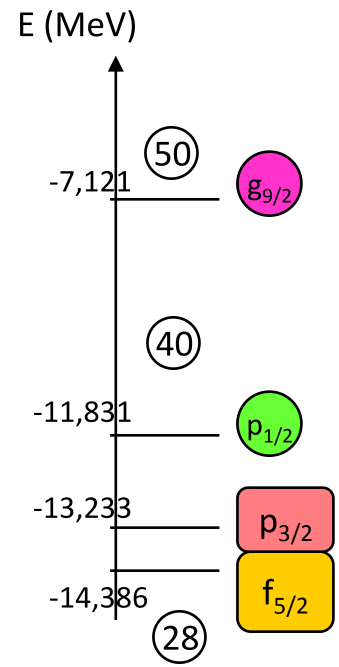
single particle sequence : PROTONS

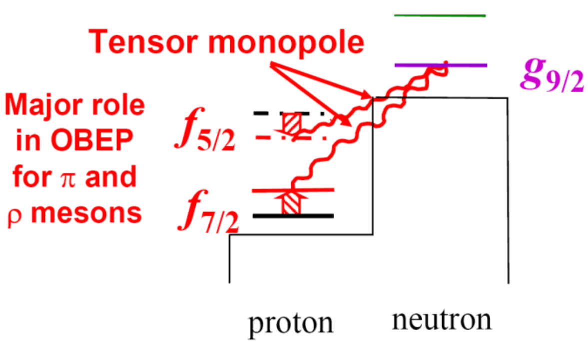
PRL **103,** 142501 (2009) K. Flanagan et al.

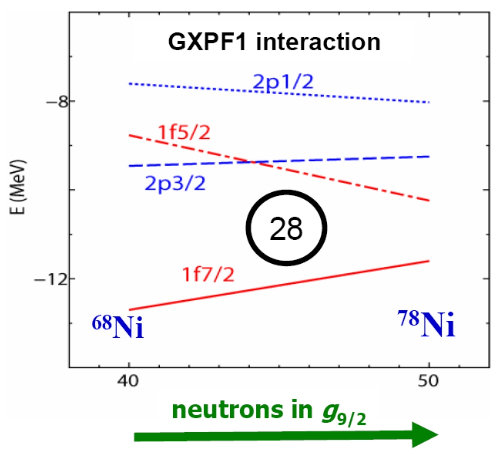


► well understood as due to the tensor term of the monopole part of the p-n interaction (cf *T. Otsuka et al. PRL95, 232502 (2005)*

Proton single particles at N=50





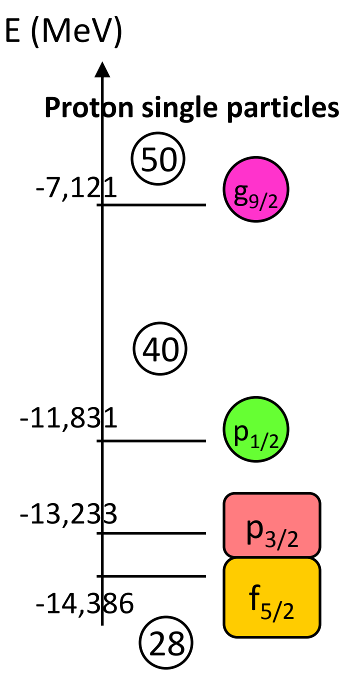


►already hinted at in the 80’s !!
(from shell model, empirical interaction)
Ji and Wildenthal Phys. Rev. C 38, 2849 (1988)

single particle sequence : PROTONS

A. Pfeiffer et al. NPA 455 (1986) 381

STUDY OF THE ($\vec{d}$, ^{3}He) REACTION ON ^{84}Kr AND ^{86}Kr AND THE LOWEST MOMENTS OF THE PROTON STRENGTH DISTRIBUTIONS IN THE Zr REGION



From Ji et Wildenthal Phys. Rev. C ***38****, 2849 (1988)*

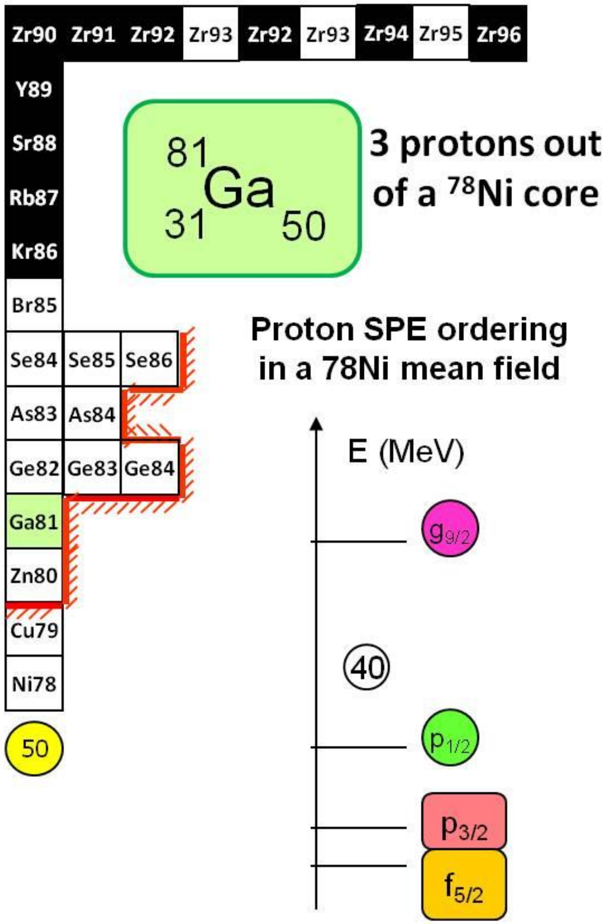
Single particle properties of individual nuclei

	$1f_{7/2}$	$1f_{5/2}$	$2p_{3/2}$	$2p_{1/2}$	$1g_{9/2}$	$\lvert\lambda\rvert$	Δ	$\Gamma^{\downarrow}(1f_{7/2}^{-1})$	Refs.
^{84}Kr	16.76	9.93	8.88	6.84	6.19	8.76	2.16	4.0	[13], this work
	1.00	0.66	0.61	0.17	0.00				
^{86}Kr	17.84	11.60	10.33	8.79	7.01	10.16	1.30	4.1	[12,14], this work
	1.00	0.80	0.61	0.10	0.00				
^{86}Sr		8.93	8.76	6.98	5.56	7.47	1.63		[16,15]
		0.73	0.90	0.37	0.09				
^{88}Sr		10.43	9.80	7.98	6.17	8.94	0.70		[17,15]
		0.98	0.88	0.09	0.07				
^{90}Zr	16.16	9.77	9.02	7.17	5.51	7.07	1.21	5.9	[19,20,6]
	1.00	0.95	0.92	0.55	0.10				
^{92}Zr	16.66	11.00	9.67	7.55	6.31	7.73	0.97	6.1	[19,20,6]
	1.00	1.00	0.94	0.41	0.08				
^{94}Zr		11.25	10.82	8.92	7.08	8.64	1.04		[19,20]
		0.97	0.91	0.64	0.06				
^{96}Zr	18.61	12.20	12.47	10.75	7.95	9.72	1.05	7.0	[21,19,20,26]
	1.00	0.99	0.83	0.87	0.03				
^{92}Mo	15.01	8.92	7.94	6.12	4.94	5.88	1.72	6.8	[18,25]
	1.00	0.94	0.87	0.58	0.25				
^{94}Mo			8.64	7.55	5.84	6.62	1.93		[18,22,25]
			0.87	0.71	0.31				
^{96}Mo		11.02	9.70	7.98	6.48	7.78	1.92		[18,22,23,25]
		0.97	0.86	0.53	0.24				
^{98}Mo		11.03	10.71	9.46	7.07	8.65	1.75		[24,23,25]
		0.93	0.94	0.67	0.19				
^{100}Mo			10.98	8.95	8.10	9.30	2.25		[22,23]
			0.76	0.48	0.20				

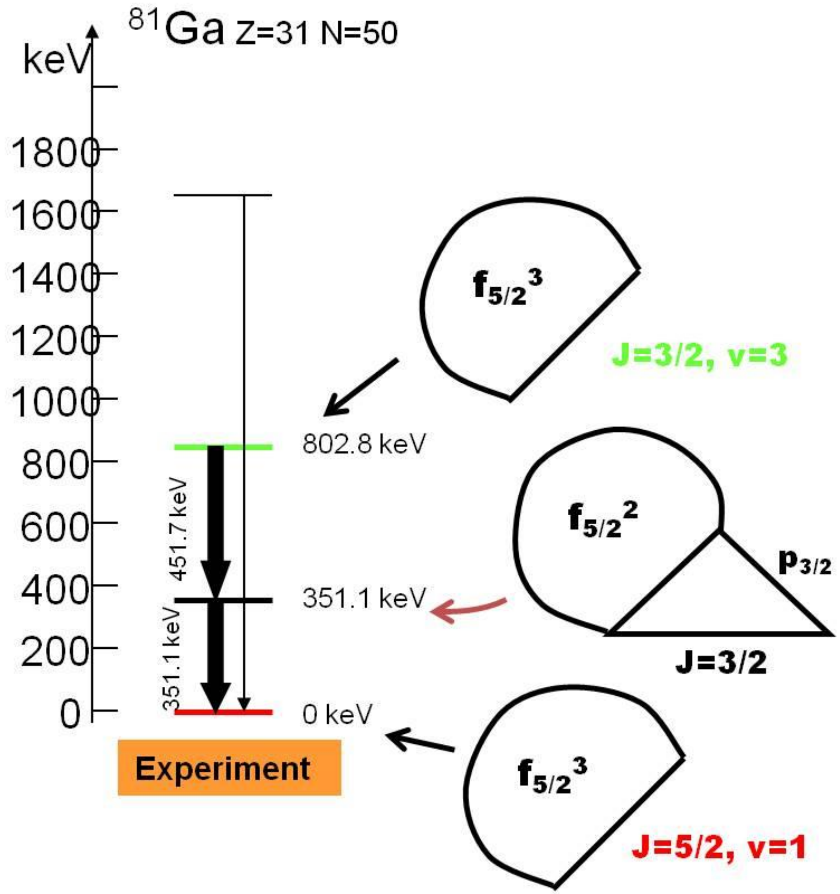
First line: Single particle energies $|E_{lj}|$, Fermi energy λ, gap parameter Δ, spreading widths $\Gamma^{\downarrow}(1f_{7/2}^{-1})$; all quantities in MeV.

Second line: Proton occupation probabilities $v_{lj}^2 = \langle p_{lj} \rangle / (2j+1)$.

single particle sequence : PROTONS



► evident from the study of ^{81}Ga
*D. Verney et al. PRC **76**, 054312 (2007)*

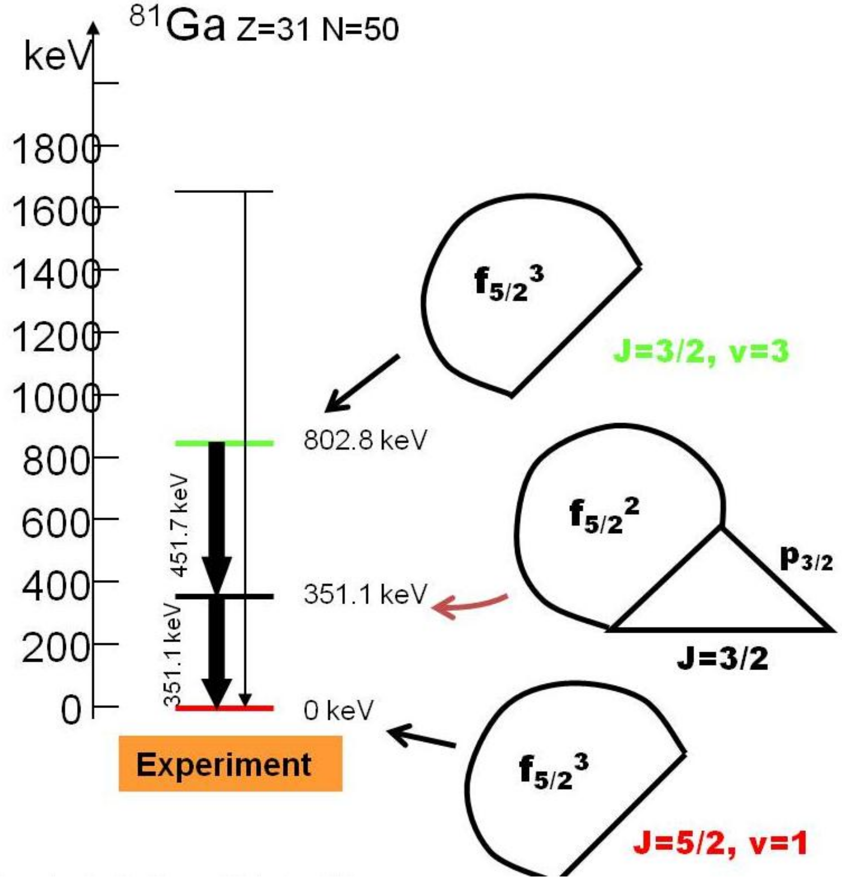


► confirmed once again:
*A. Gade et al. PRC **81**, 064326 (2010)*
82Ge and 84Se studied using intermediate-energy Coulomb excitation on a 197Au target and inelastic scattering on 9Be

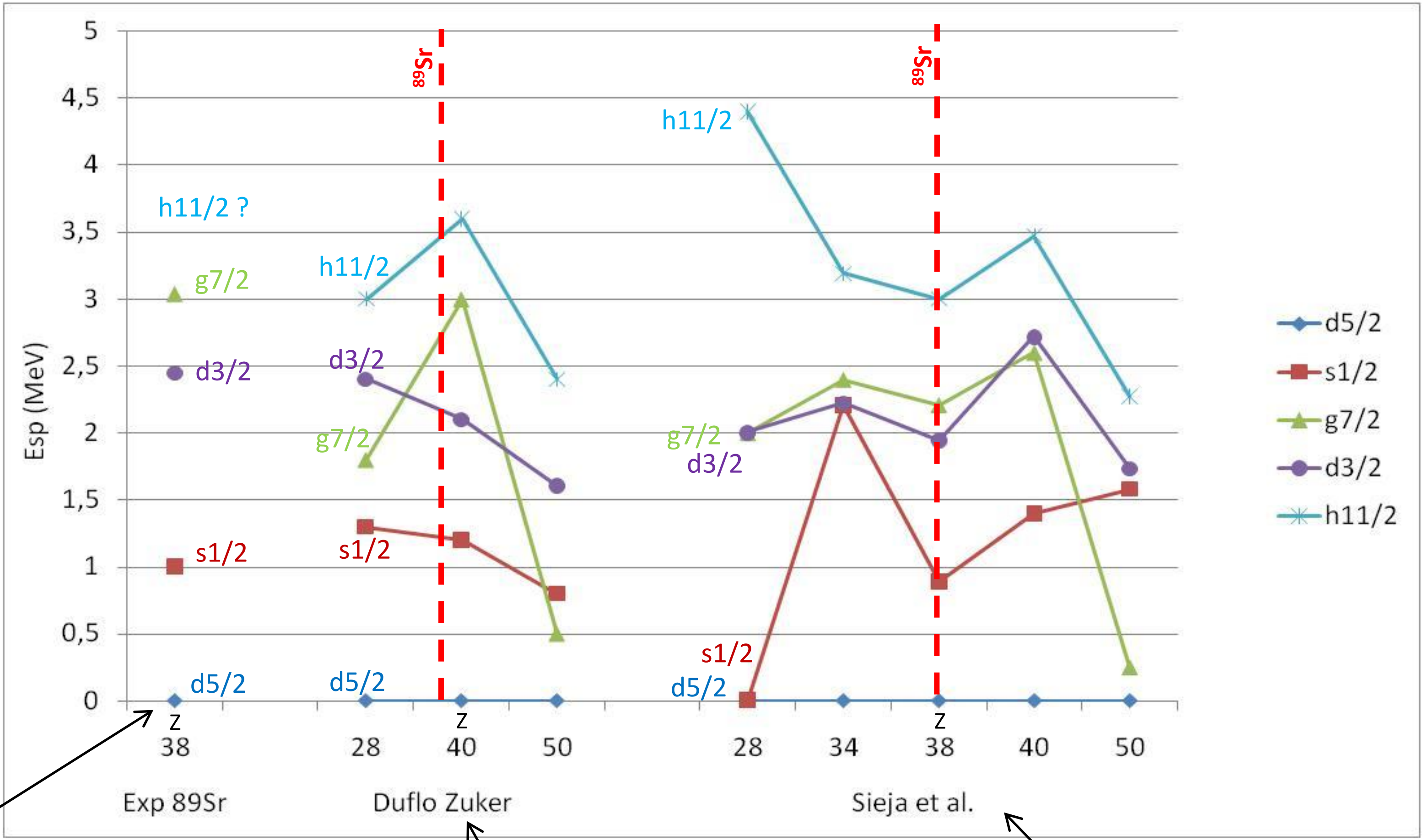
A closed subject ? no !

► short term perspectives :
e.g. GSI PRESPEC Campaign LoI :N.Pietralla et al.
"Relativistic Coulomb M1 excitation of neutron-rich ^{85}Br"

► mid term perspectives :
direct reaction at new RIB facilities e.g. the ^{81}Ga case
^{82}Ge(d,3He)



single particle sequence : NEUTRONS



From T.A. Hughes

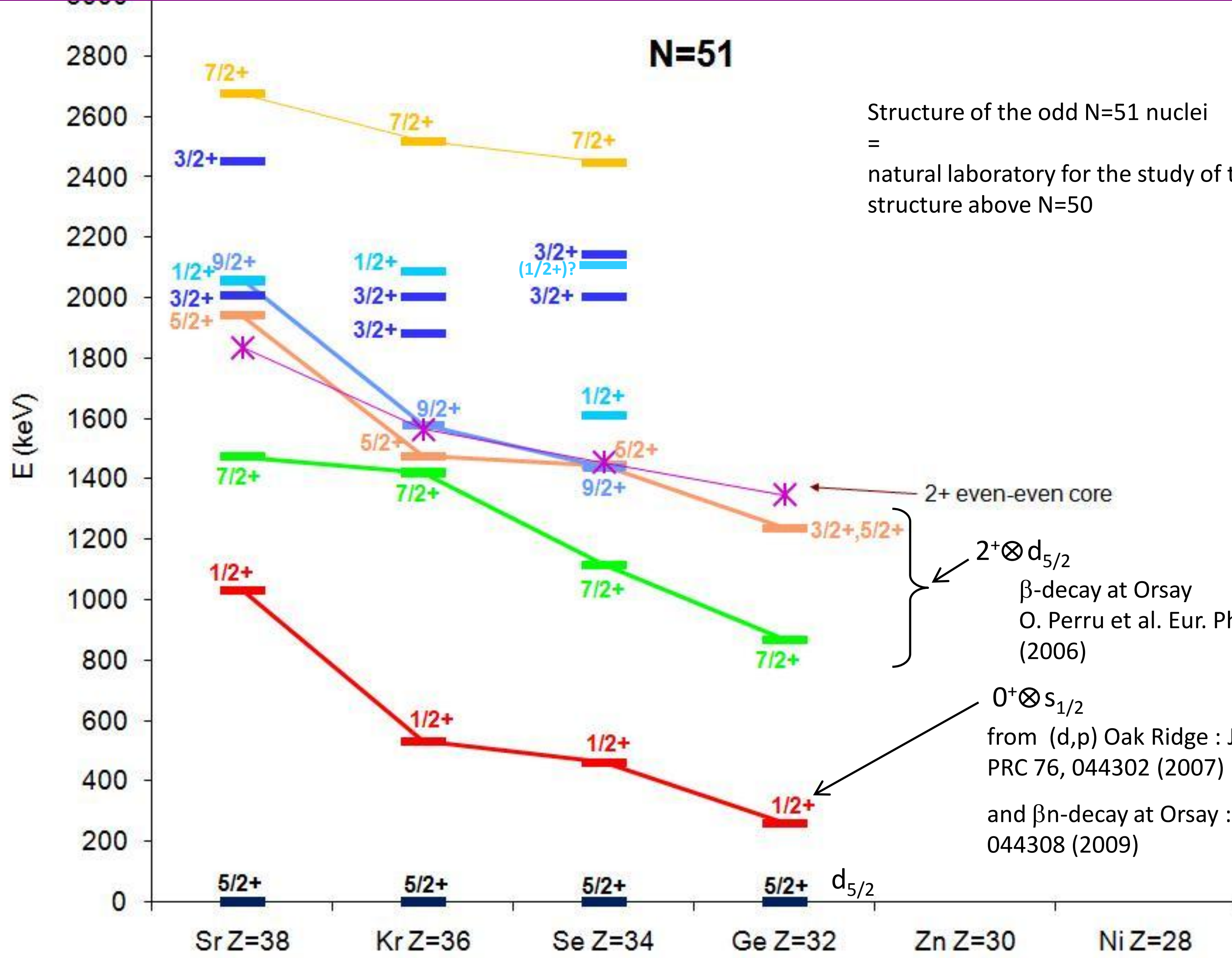
Phys. Rev. ***181****, 1586 (1969)*

but in fact the problem of the position of h11/2 remains unsolved → need for the observation of negative parity Yrast states in N=51

From Duflo Zuker

PRC ***59****, R2347 (1999)*

SM calculations in valence space above ^{78}Ni
K. Sieja et al. PRC ***79****, 064310 (2009)*



Structure of the odd N=51 nuclei

=

natural laboratory for the study of the neutron structure above N=50

$2^+ \otimes d_{5/2}$

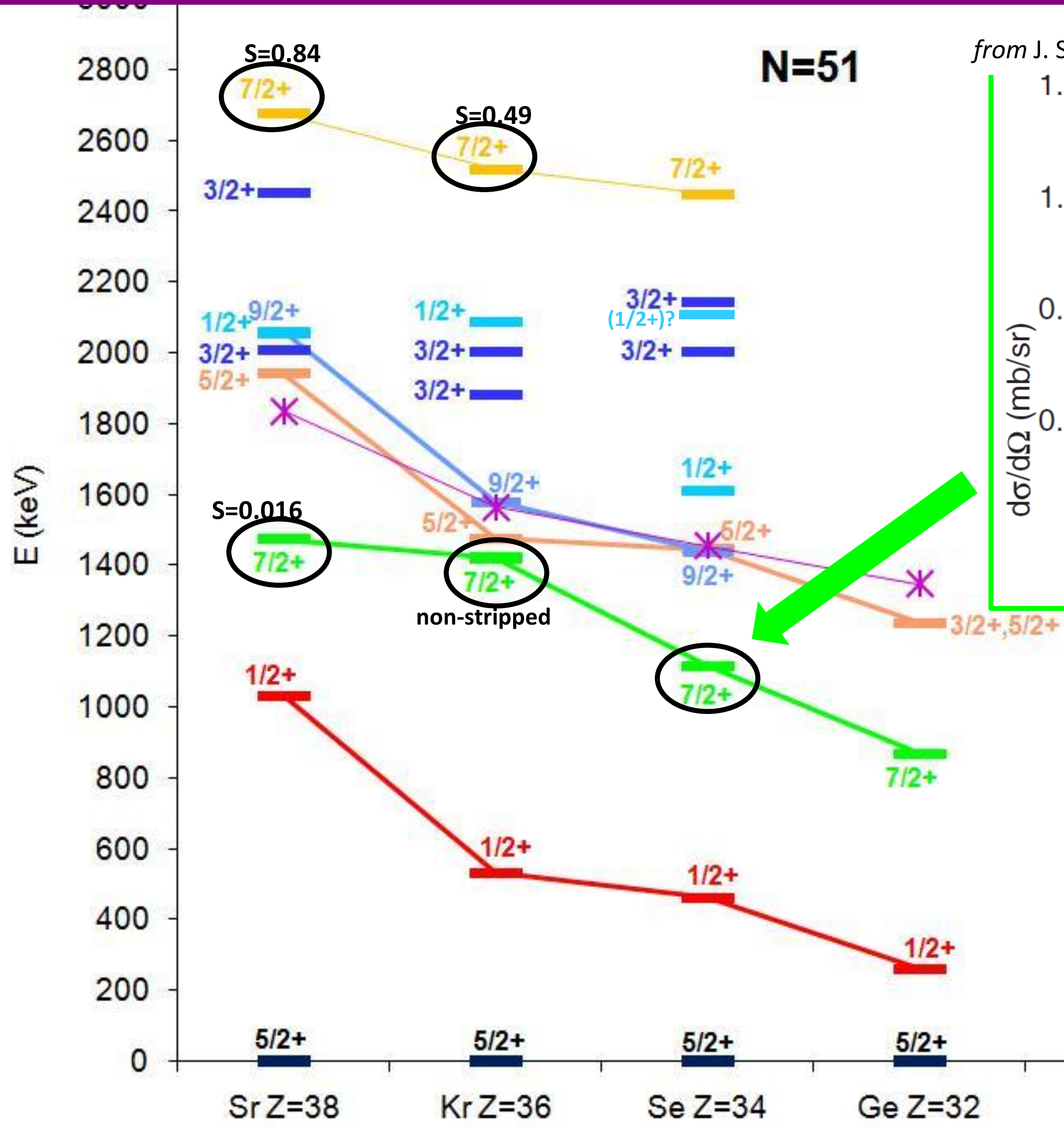
β-decay at Orsay

O. Perru et al. Eur. Phys. J. A 28, 307 (2006)

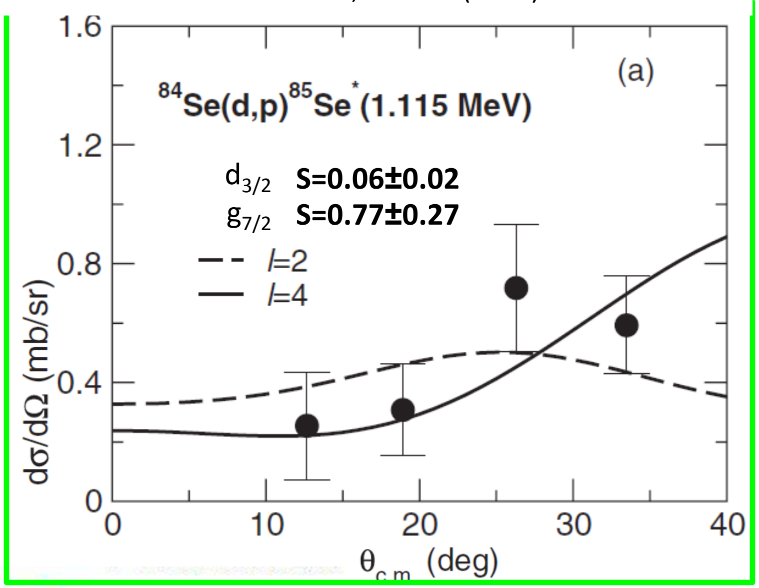
$0^+ \otimes s_{1/2}$

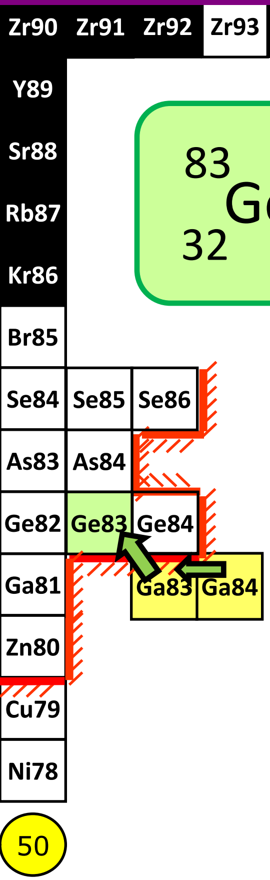
from (d,p) Oak Ridge : J. S. Thomas et al. PRC 76, 044302 (2007)

and βn-decay at Orsay : M. Lebois PRC 80, 044308 (2009)



from J. S. Thomas et al. PRC 76, 044302 (2007)





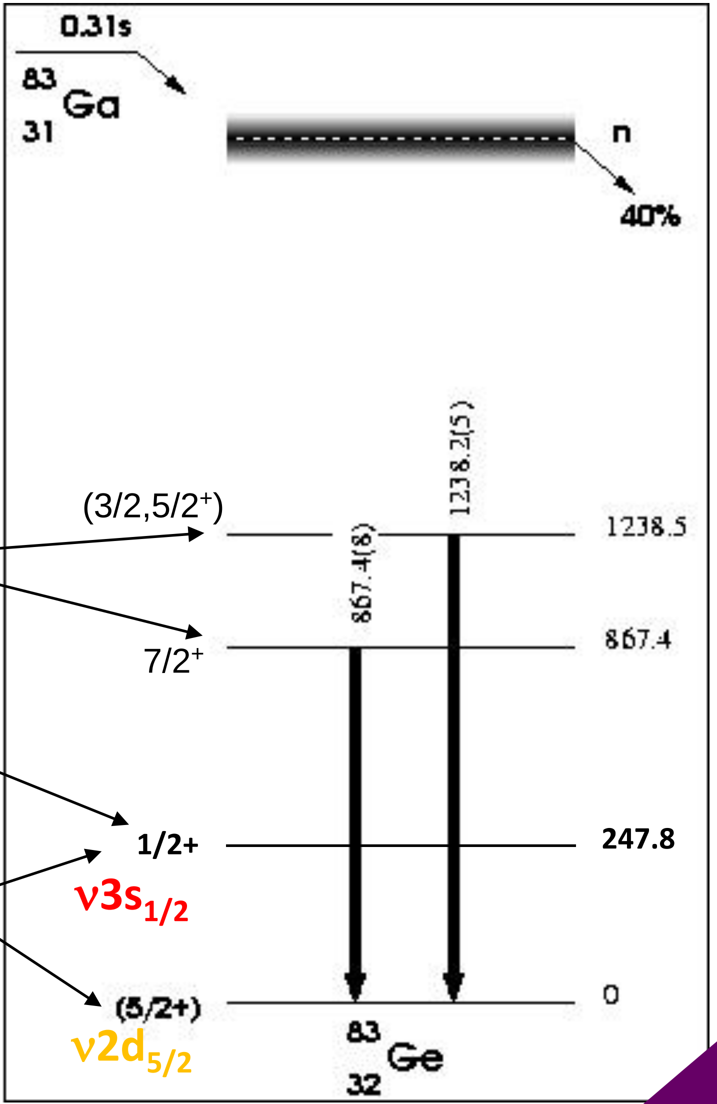
$^{83}_{32}Ge_{51}$

4 protons + 1 neutron out of a ^{78}Ni core

observed in β-decay at PARRNe
O. Perru et al.
EPJ **A** 28 (2006) 307

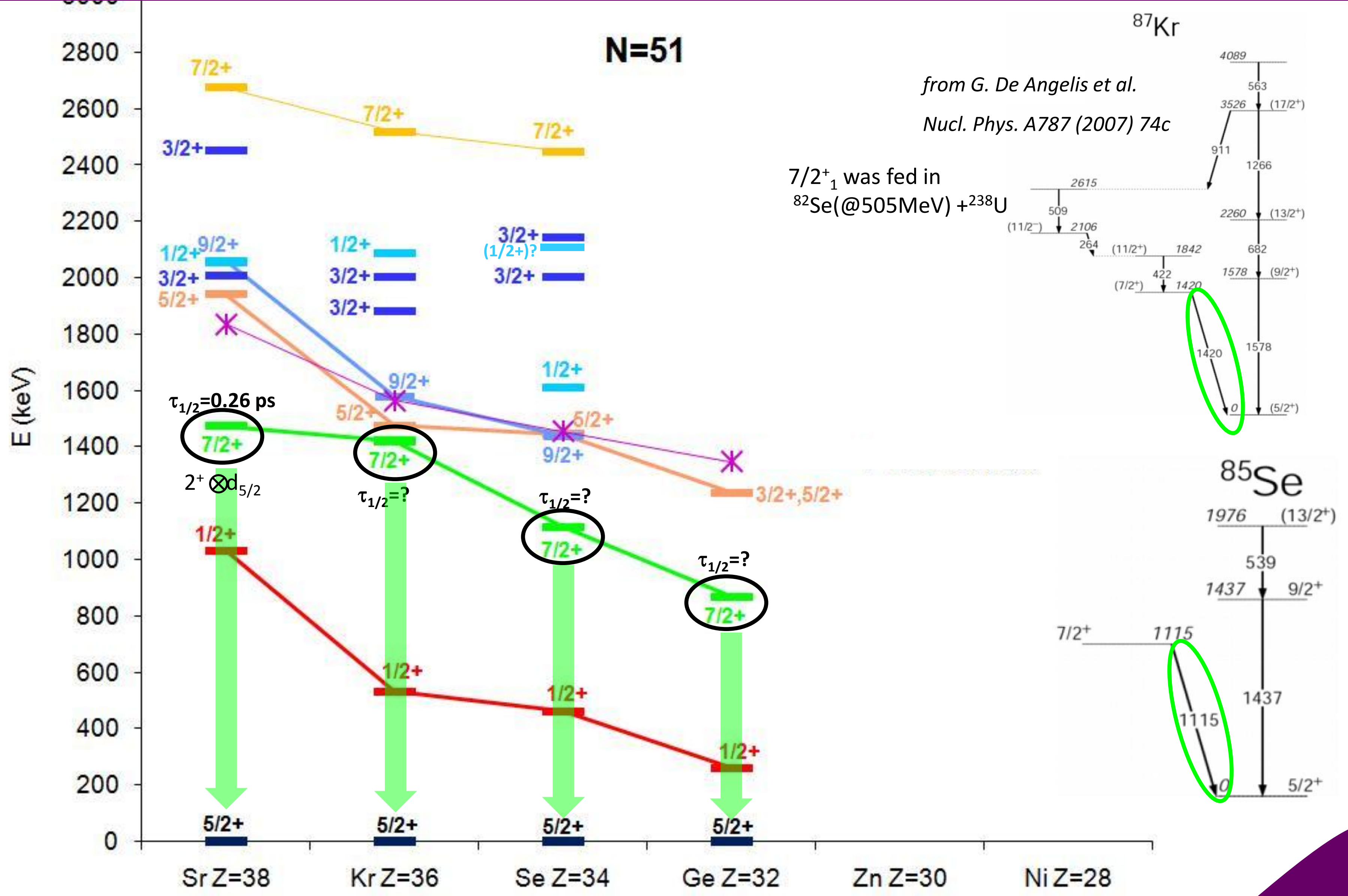
observed in βn-decay at ALTO
Lebois et al. PRC 80 (2009) 044308

observed in ^{2}H(^{82}Ge,p)^{83}Ge at Oak Ridge
Thomas et al.
PRC 71 (2005) p. 021302



β-decay at Oak Ridge J. A. Winger et al. PRC **81,** 044303 (2010) : existence of 867 keV

a good way to disentangle the situation :
lifetime measurements of the $7/2^+_1$ in the N=51 chain using the plunger technique

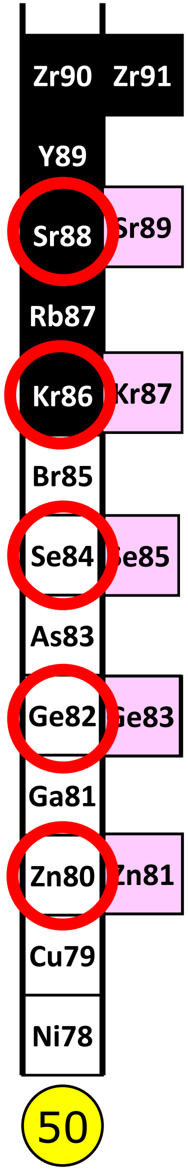


the question is : how fast is the transition in the two cases

$$\begin{cases} \left[2^+ \otimes d_{5/2}\right]7/2_1 \rightarrow \left[0^+ \otimes d_{5/2}\right]5/2_{gs} \\ \left[0^+ \otimes g_{7/2}\right]7/2_1 \rightarrow \left[0^+ \otimes d_{5/2}\right]5/2_{gs} \end{cases}$$

Core – particle (weak) coupling model

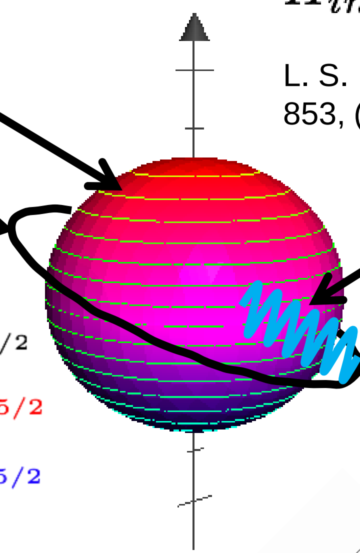
(highly empirical treatment, for a more fundamental approach see talk by Gianluca Colò on Thursday)



Even-even semi-magic core

Core excitation energies taken from experiment : E(2+), E(4+), E($0+_2$) etc

Neutron single particle



Thankappan & True
Phys. Rev. B, **137**, 793 (1965)

$$H_{int} = -\xi(\mathbf{J}_c^{(1)} \cdot \mathbf{j}_p^{(1)}) - \eta(\mathbf{Q}_c^{(2)} \cdot \mathbf{Q}_p^{(2)})$$

L. S. Kisslinger & R. A. Sorensen Rev. Mod. Phys., **35**, 853, (1963)

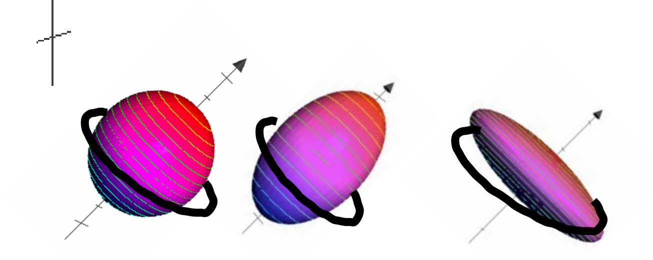
Parameters :

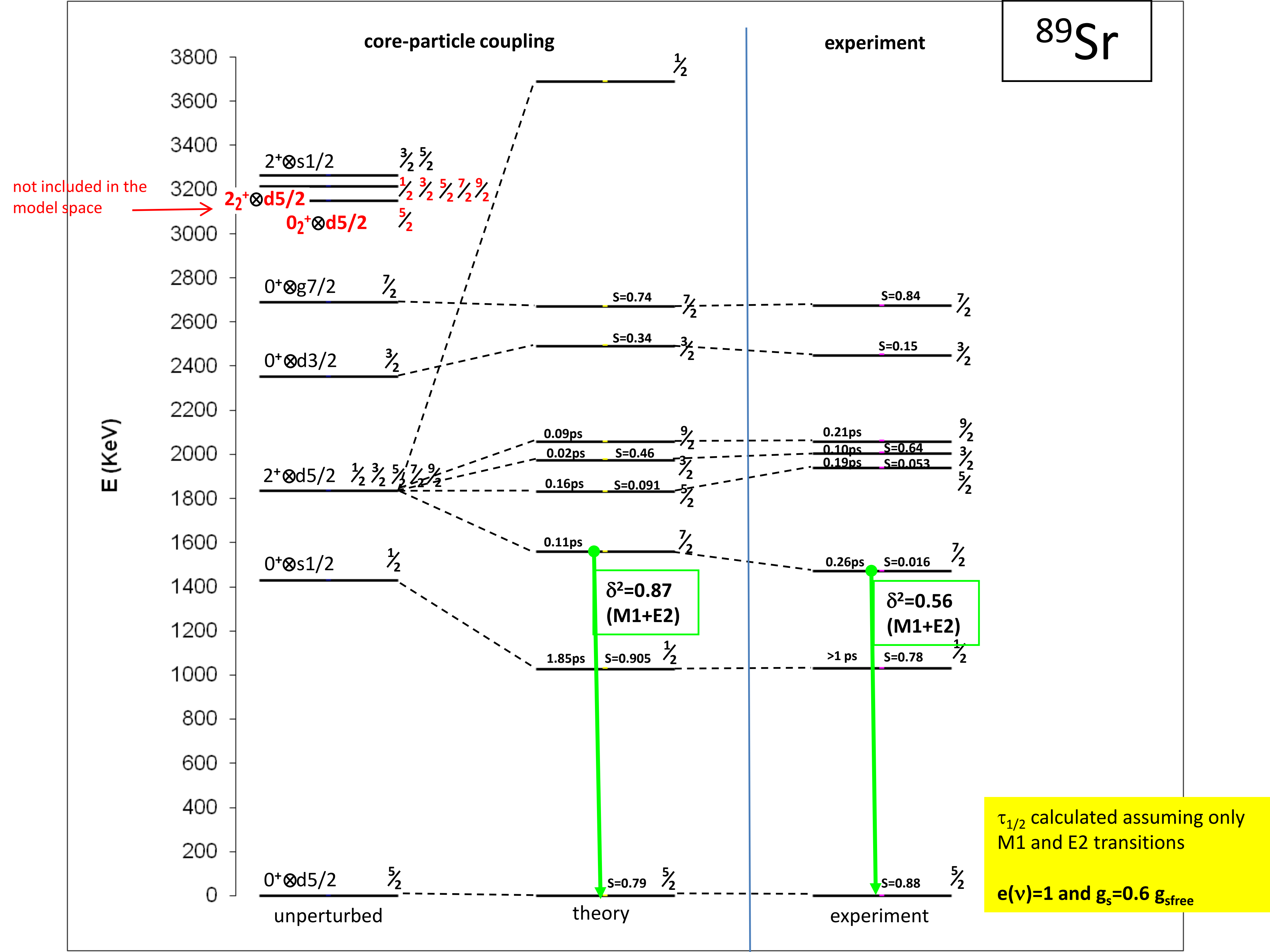
$$E_{3s_{1/2}} = \epsilon_{3s_{1/2}} - \epsilon_{2d_{5/2}}$$

$$E_{1g_{7/2}} = \epsilon_{1g_{7/2}} - \epsilon_{2d_{5/2}}$$

$$E_{2d_{3/2}} = \epsilon_{2d_{3/2}} - \epsilon_{2d_{5/2}}$$

Vector space :
$0+_1 \otimes$ 2d5/2
$2+_1 \otimes$ 2d5/2
$2+_1 \otimes$ 3s1/2
Etc…

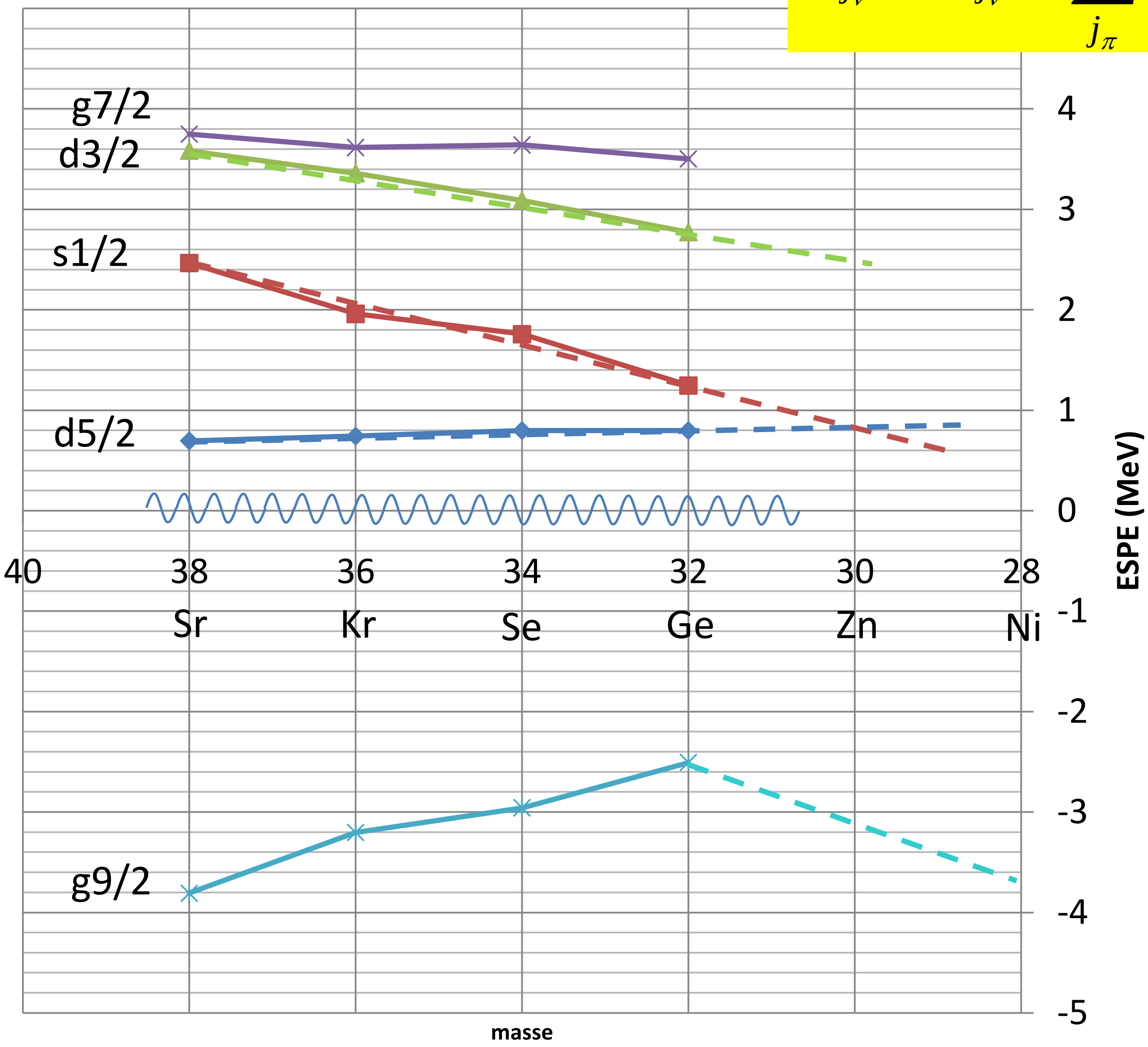




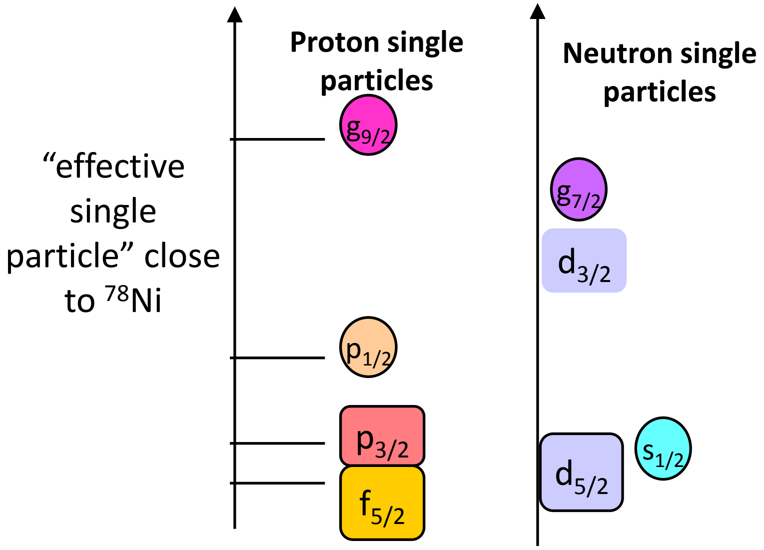
89Sr
core-particle coupling
experiment
E (KeV)
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
not included in the model space
2+⊗s1/2
2₂+⊗d5/2
0₂+⊗d5/2
0+⊗g7/2
0+⊗d3/2
2+⊗d5/2
0+⊗s1/2
0+⊗d5/2
S=0.74
S=0.34
0.09ps
0.02ps
S=0.46
0.16ps
S=0.091
0.11ps
1.85ps
S=0.905
S=0.79
S=0.84
S=0.15
0.21ps
0.10ps
S=0.64
0.19ps
S=0.053
0.26ps
S=0.016
>1 ps
S=0.78
S=0.88
δ²=0.87 (M1+E2)
δ²=0.56 (M1+E2)
unperturbed
theory
experiment
τ1/2 calculated assuming only M1 and E2 transitions
e(ν)=1 and gs=0.6 gsfree

Neutron effective single particle energy evolution
extracted from N=51 systematics, using the core-particle coupling approach

$$\tilde{\varepsilon}_{j_\nu} = \varepsilon_{j_\nu} + \sum_{j_\pi} \overline{E}(j_\nu, j_\pi)(2j_\pi + 1)\,v_{j_\pi}$$



What we think we have understood :



On proton side:

▶ Single particle sequence in ^{78}Ni mean-field ~ understood

▶ Z=28 proton gap evolution → ^{78}Ni : unknown

On neutron side:

▶ Single particle sequence in 78Ni mean-field ~ not understood

▶ N=50 neutron gap evolution → 78Ni : local minimum at Z=32 and connection to collectivity

▶ much progress is (still) expected from theoretical side (especially SM)

▶ secure experimental data are missing closer to ^{78}Ni