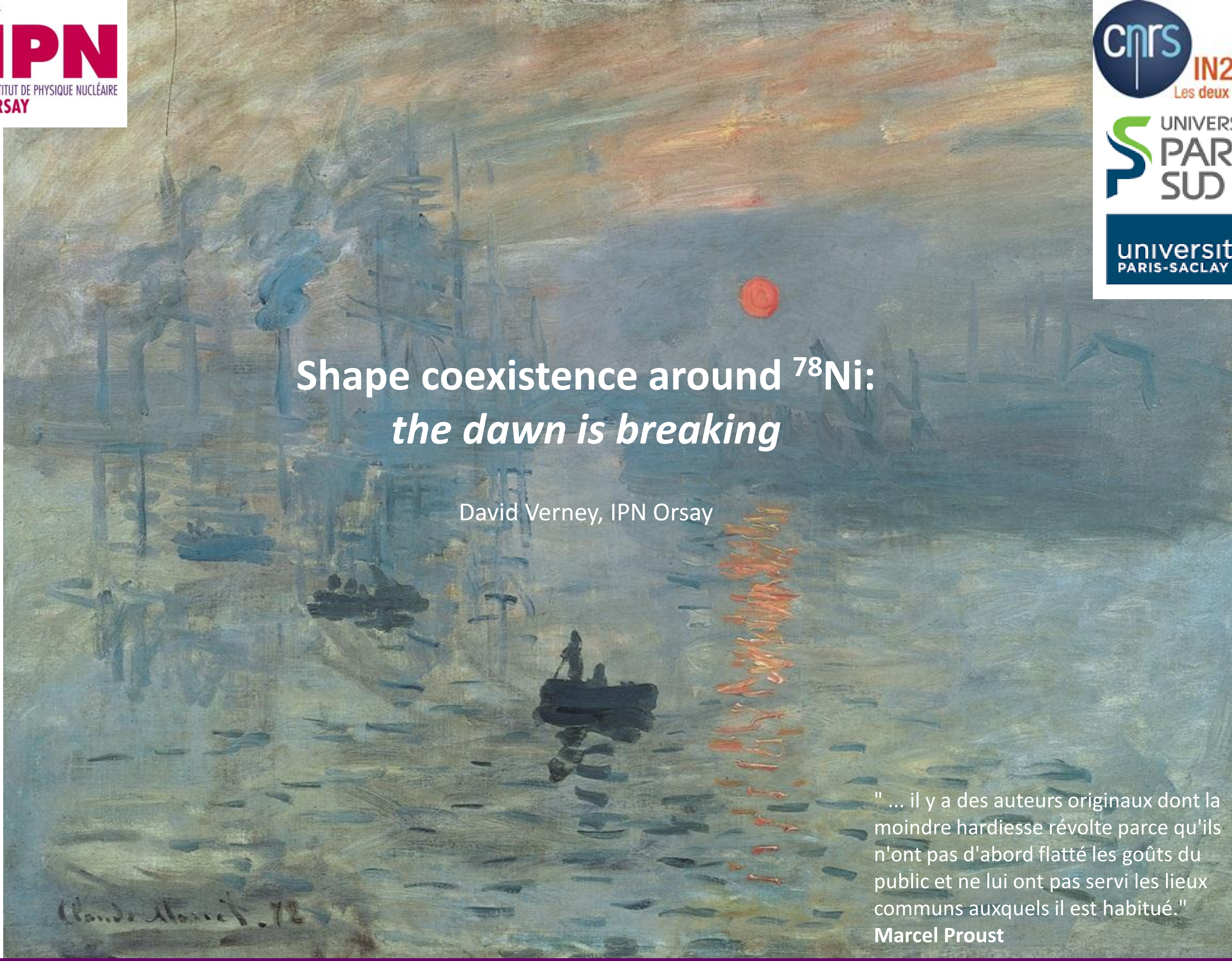


Shape coexistence around ^{78}Ni: *the dawn is breaking*

David Verney, IPN Orsay

" ... il y a des auteurs originaux dont la moindre hardiesse révolte parce qu'ils n'ont pas d'abord flatté les goûts du public et ne lui ont pas servi les lieux communs auxquels il est habitué."
Marcel Proust

More than 3 decades of ^{78}Ni-region investigation

Age of the pioneers: late 70's-mid 80's

TRISTAN(Brookhaven)/ OSIRIS(Studsvik)

"Is the region above ^{78}Ni doubly magic ?"
r-process consequences
Fogelberg, J.C. Hill, J.A. Winger and others

dormancy

Second golden age : ca 2004

Yrast (LNL,Euroball) /Coulomb exc. (ISOLDE,ORNL) /Masses (JYFL,ISOLDE) /transfer (ORNL,ISOLDE) /Radioactivity(ORNL,Orsay)

"Is N=50 a good magic number?"
r-process + structure consequences

very busy decade

The final cut ? : ca 2014

RIBF/RIKEN

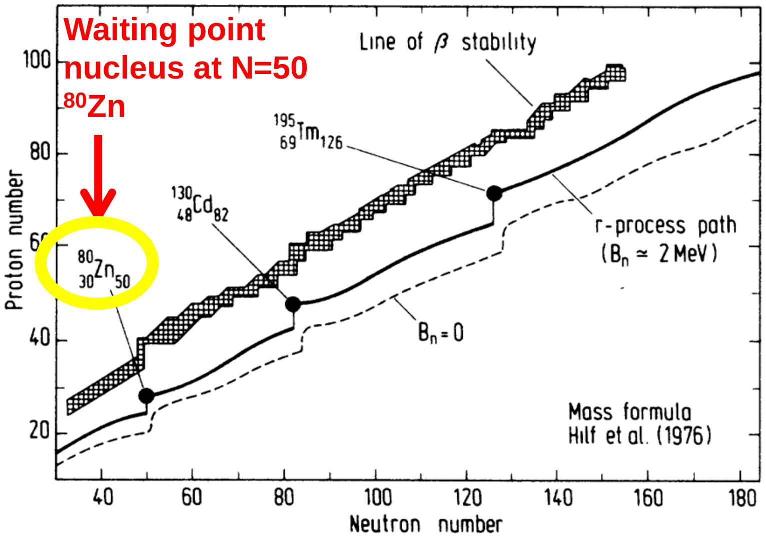
direct study of ^{78}Ni

towards an even busier decade

Third golden age : >2016

A new dawn for shape coexistence studies near N=50 towards ^{78}Ni

formed above 0.6 MeV. Considering ^{80}Zn as a doubly magic $^{78}_{28}$Ni$_{50}$ core plus a proton pair, the observation of shape coexistence seems to imply a rather rapid weakening of the shell strength above ^{78}Ni. With regard to *r*-



Gamow-Teller decay of ^{80}Zn: Shell structure and astrophysical implications

By Kratz et al. PRC 38 (1988)

Age of the pioneers: late 70's-early 80's

Omnipresence of positive parity (intruder) states

- First hinted at from transfer reaction data [e.g. Detorie et al PRC18 (1978)]
- First systematics proposed by Hoff & Fogelberg NPA **368** (1981) from β-decay
- emphasized in Meyer et al. PRC **25** (1982)

thereafter the subject somewhat fell into oblivion

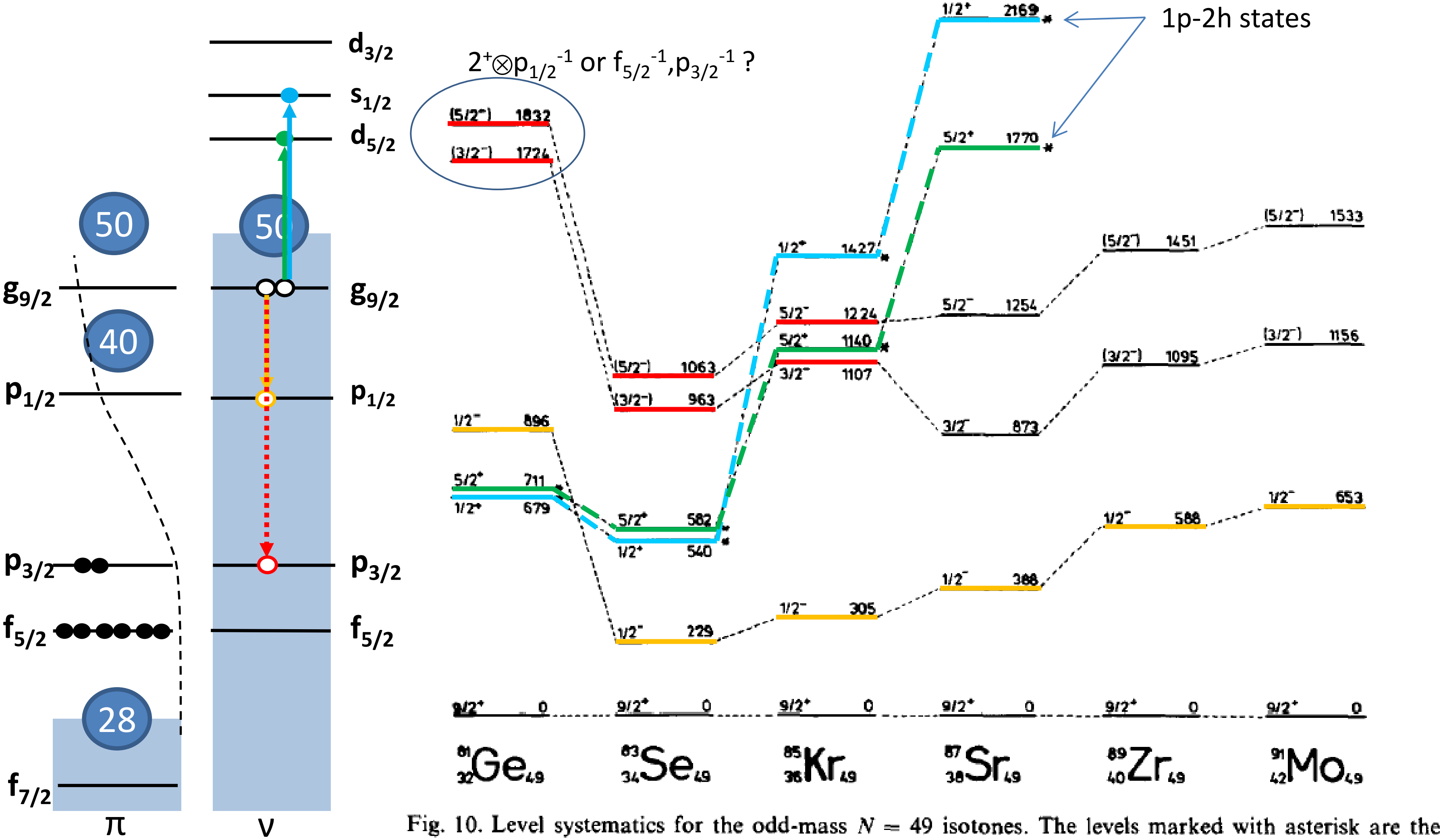
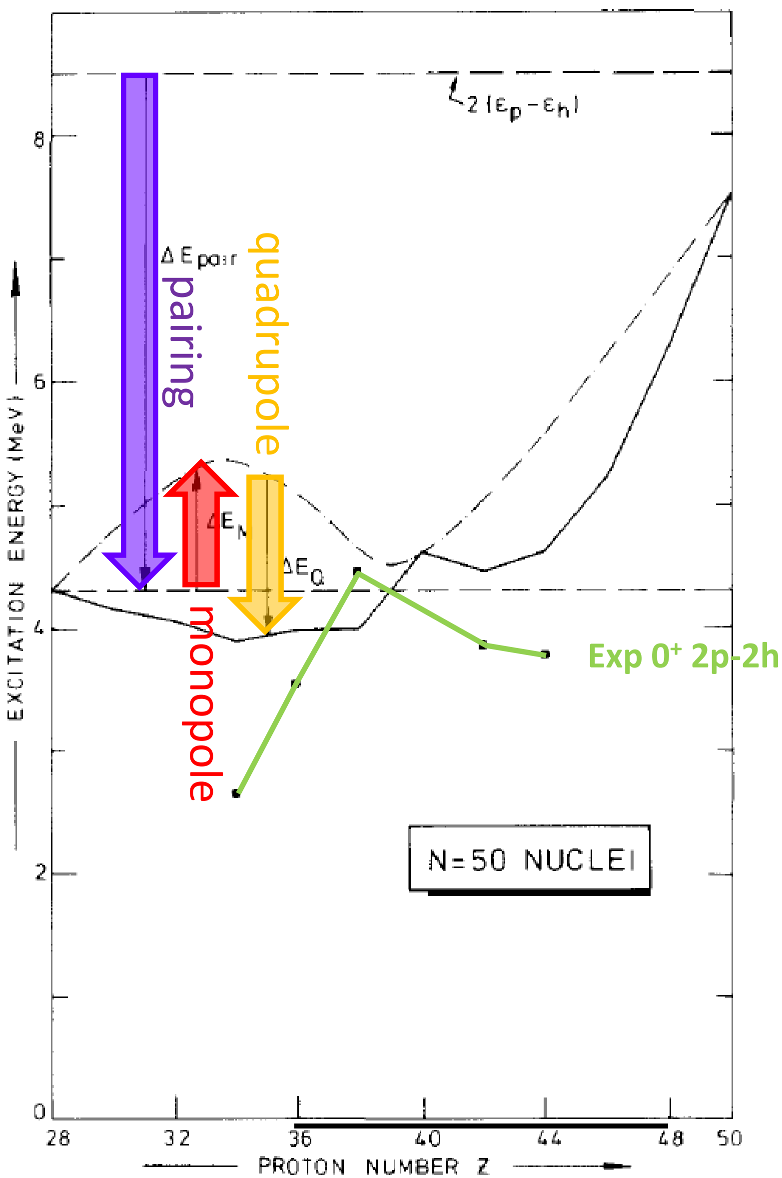
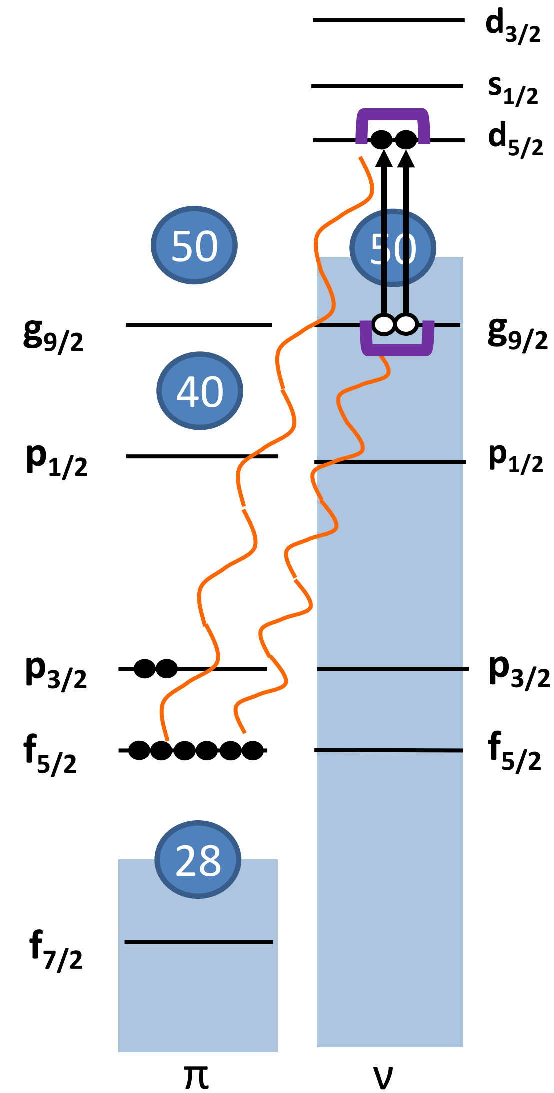


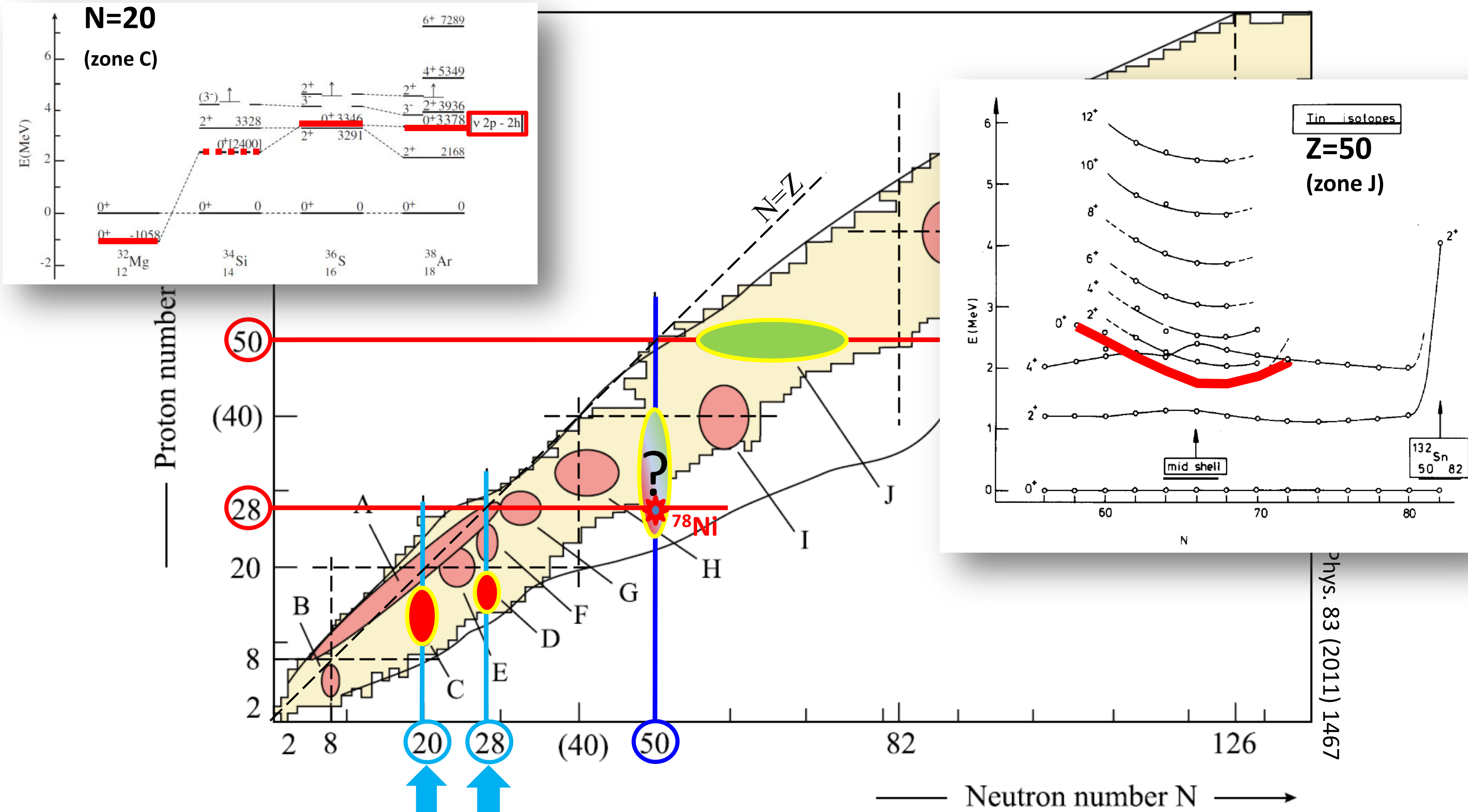
Fig. 10. Level systematics for the odd-mass $N = 49$ isotones. The levels marked with asterisk are the $\frac{1}{2}^+$, $\frac{5}{2}^+$ intruder states.

Age of the pioneers: late 70's-early 80's

Wood et al. Phys. Rep. 215 (1992)







historical case N=20 (^{32}Mg region)
Klapisch PRL 31 118 (1973)
Thibault PRC 12 644 (1975)
Détraz PRC 19 164 (1979)

N=28 (^{42}Si region)
Bastin PRL 99 022503 (2007)
GANIL

More than 3 decades of ^{78}Ni-region investigation

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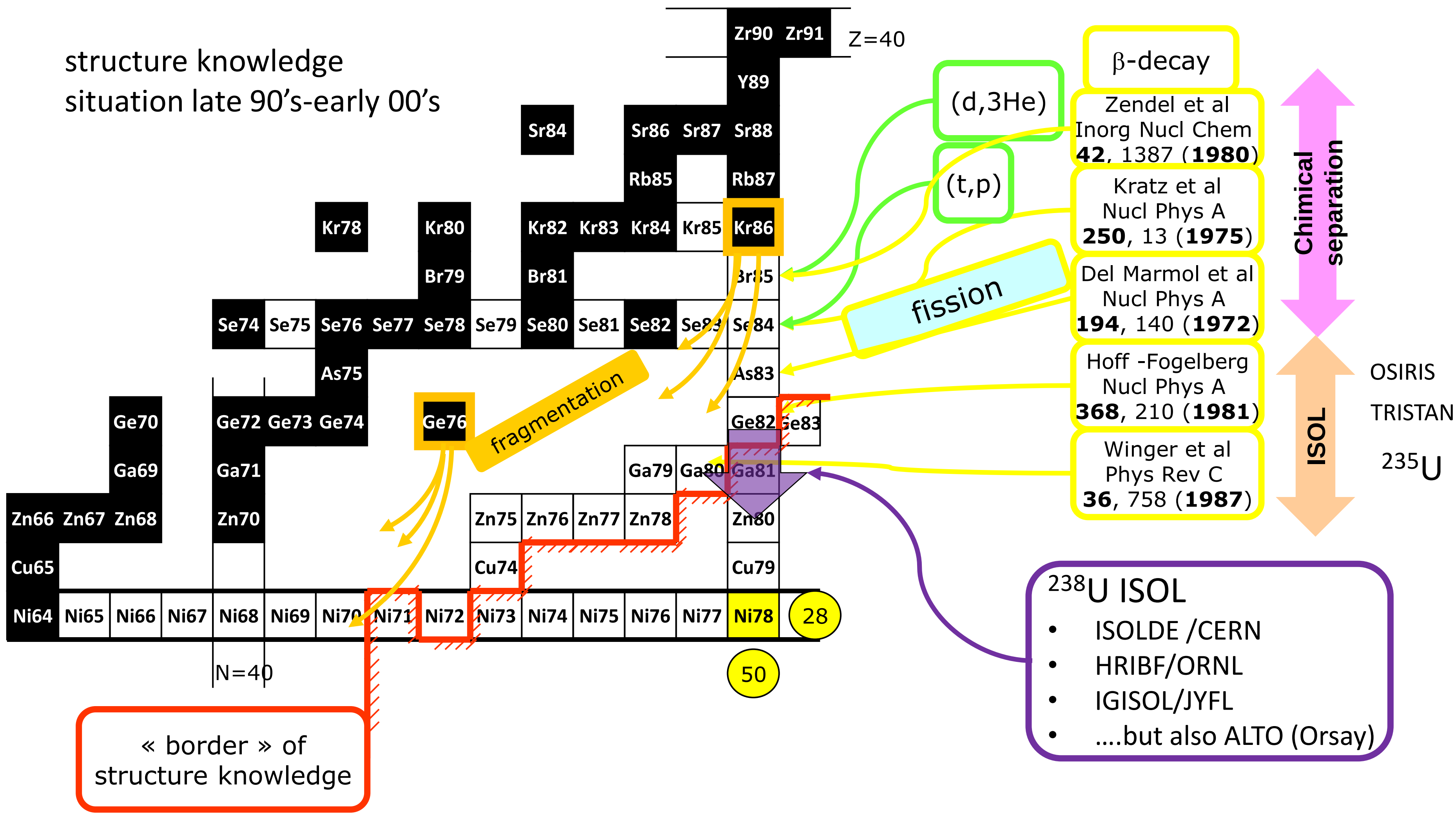
/transfer (ORNL,ISOLDE)
/Radioactivity(ORNL,Orsay)

"Is N=50 a good magic number?"
r-process + structure consequences

are the necessary ingredients
for the occurrence of shape
coexistence in the N=50 region
towards ^{78}Ni
there?

More than 3 decades of ^{78}Ni-region investigation

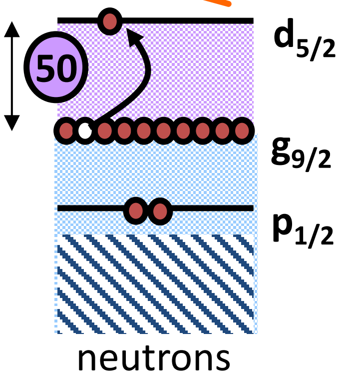


At the beginning, no (serious) evidence was found for shell quenching down to Z=30 in the low-energy/low-spin data :

- **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)

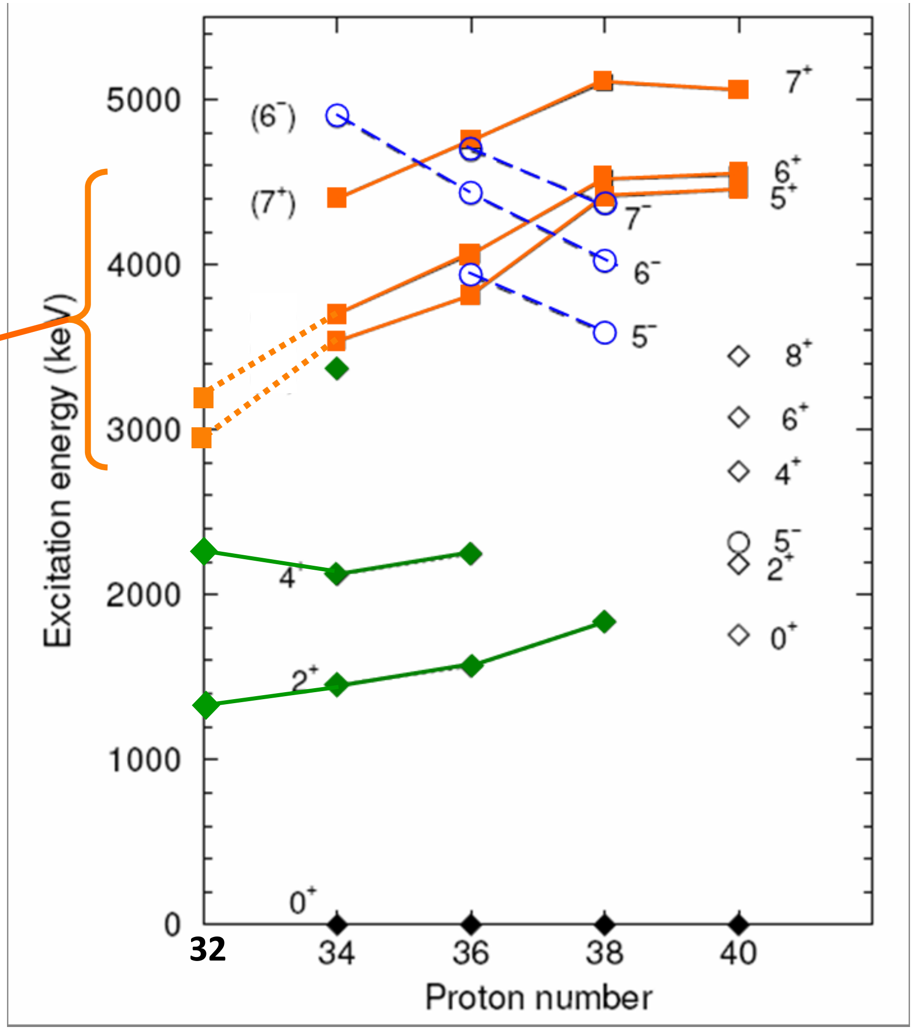
- **from B(E2) measurement in ^{80}Zn (REX-ISOLDE)**
  J. Van de Walle et al. PRC 79, 014309 (2009)

«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. »



But : Yrast spectroscopy

Zr: H.Fann et. al
Phys. Lett. B 44, 19 (1973)
Sr: P.C.Li et. al.
Nucl. Phys. A 462, 26 (1987)
Kr: G.Winter et. al.
Phys. Rev. C48, 1010 (1993)
Se: Prevost et. al.
Eur. Phys. J. A 22,391-395 (2004)
Ge: T.Rzaca-Urban et. al.
PRC 76, 027302 (2007)



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

N=50 gap extrapolation
→ ^{78}Ni =3.0(5) MeV

High-precision mass spectrometry (IGISOL Jyvaskyla) Hakala et al PRL101 052502 (2008)

later on : up to ^{82}Zn ISOLTRAP [Wolf et al. PRL 110, 041101 (2013)]

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

(Quantity usually used to extract shell gaps from mass data)

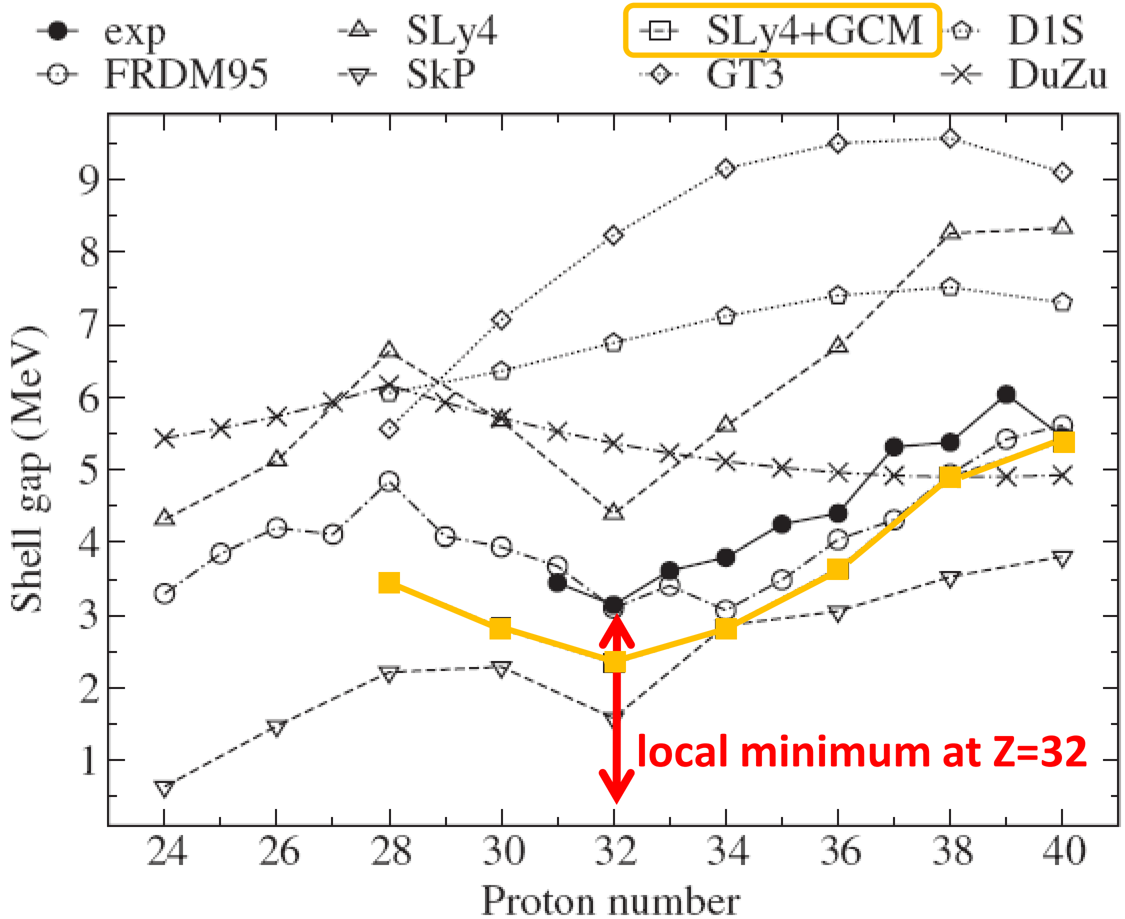


FIG. 4. Evolution of the $N = 50$ shell gap and comparison to theoretical models.

The question of the size of the gap at N=50: what masses say

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

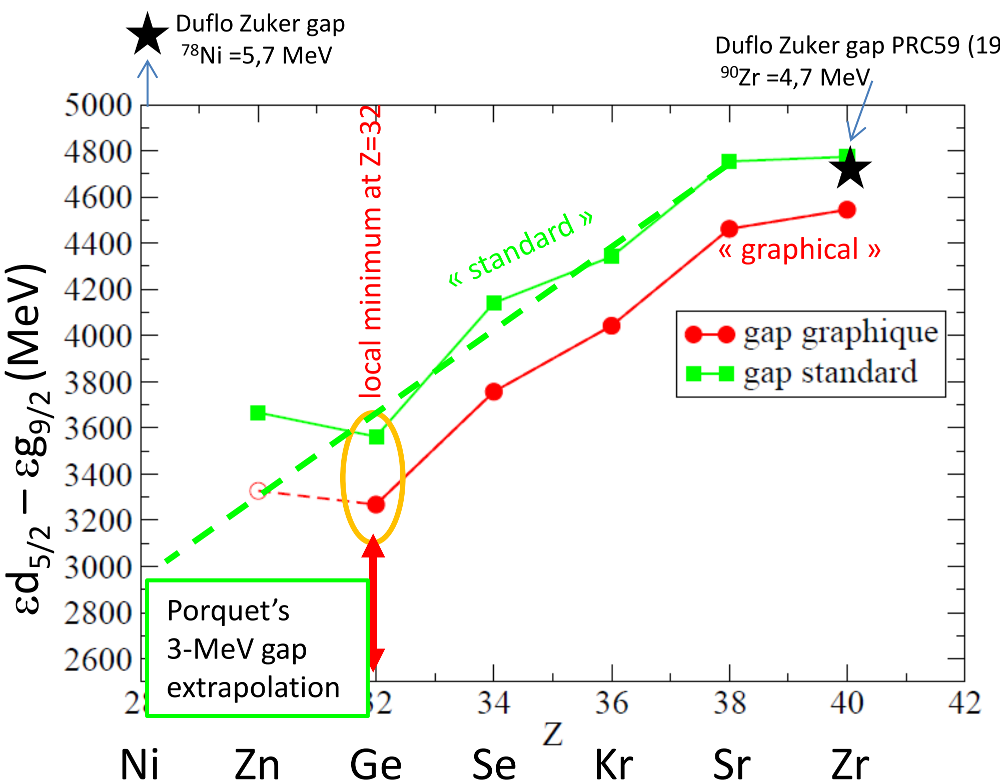
using data taken from AME
[including ISOLTRAP and IGISOLTRAP data]

« standard »

$$\text{gap neutron} : \Delta_n = 2BE(Z,N) - BE(Z,N+1) - BE(Z,N-1)$$
$$= S_n(Z,N) - S_n(Z,N+1)$$

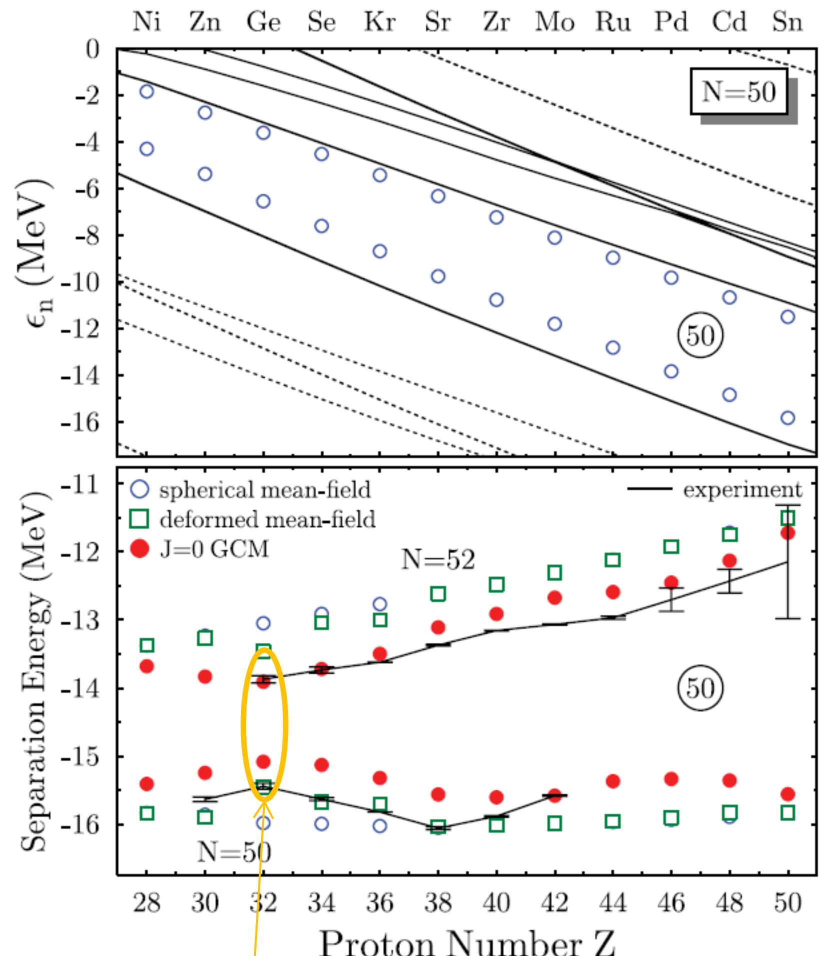
« graphical » K. Heyde et al. Phys. Let. B176 (1986) NPA466 189(1987)

$$\epsilon_{j_\nu} - \epsilon_{j'_\nu} = S_n(Z,N) - S_n(Z,N^{\text{extr.}})$$



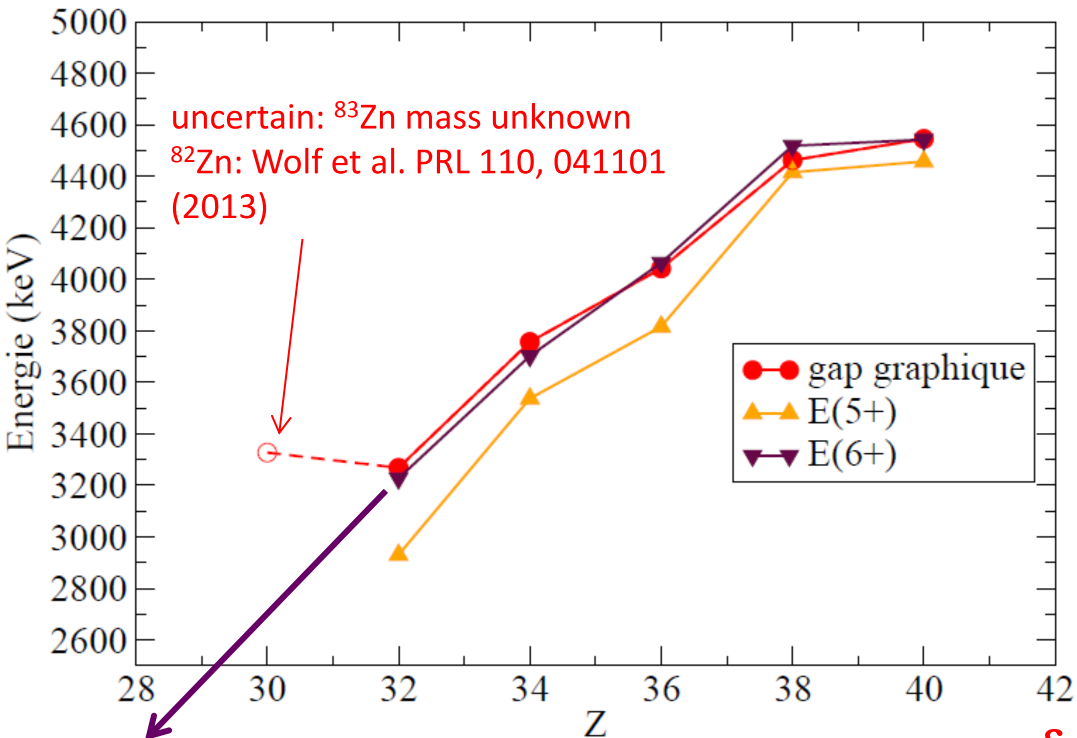
collective origin

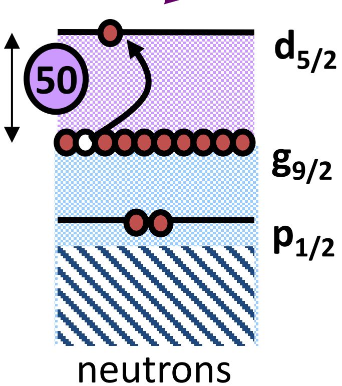
First theoretical treatment : beyond mean field
Bender et al. Phys. Rev. C **78**, 054312 (2008)

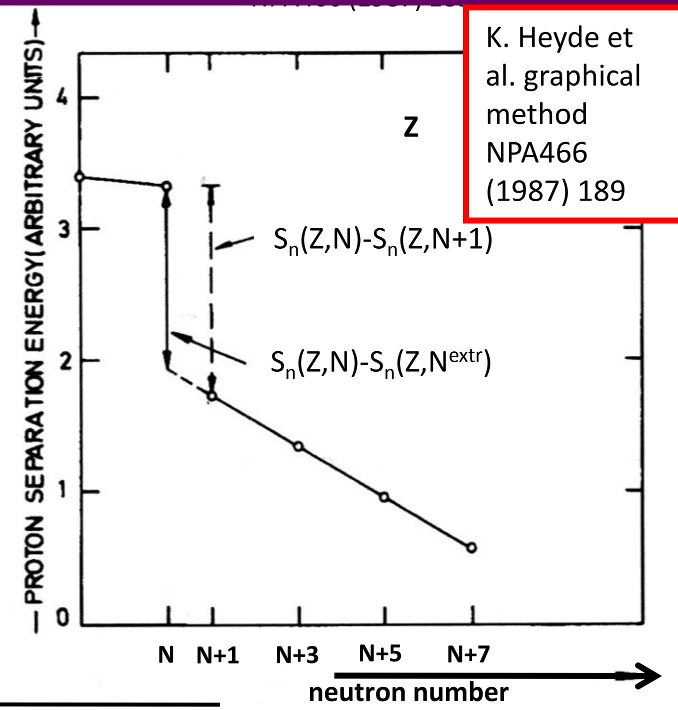


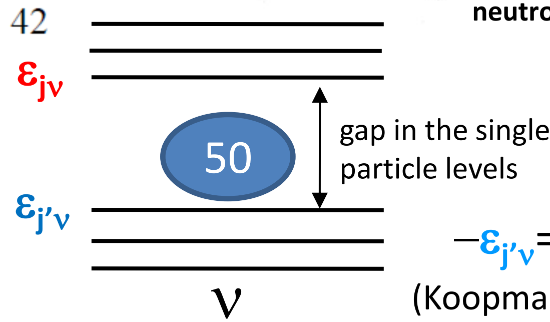
maximum influence of beyond mean-field correlations

The question of the size of the gap at N=50: back to core-breaking states









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

(Koopmans theorem)

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

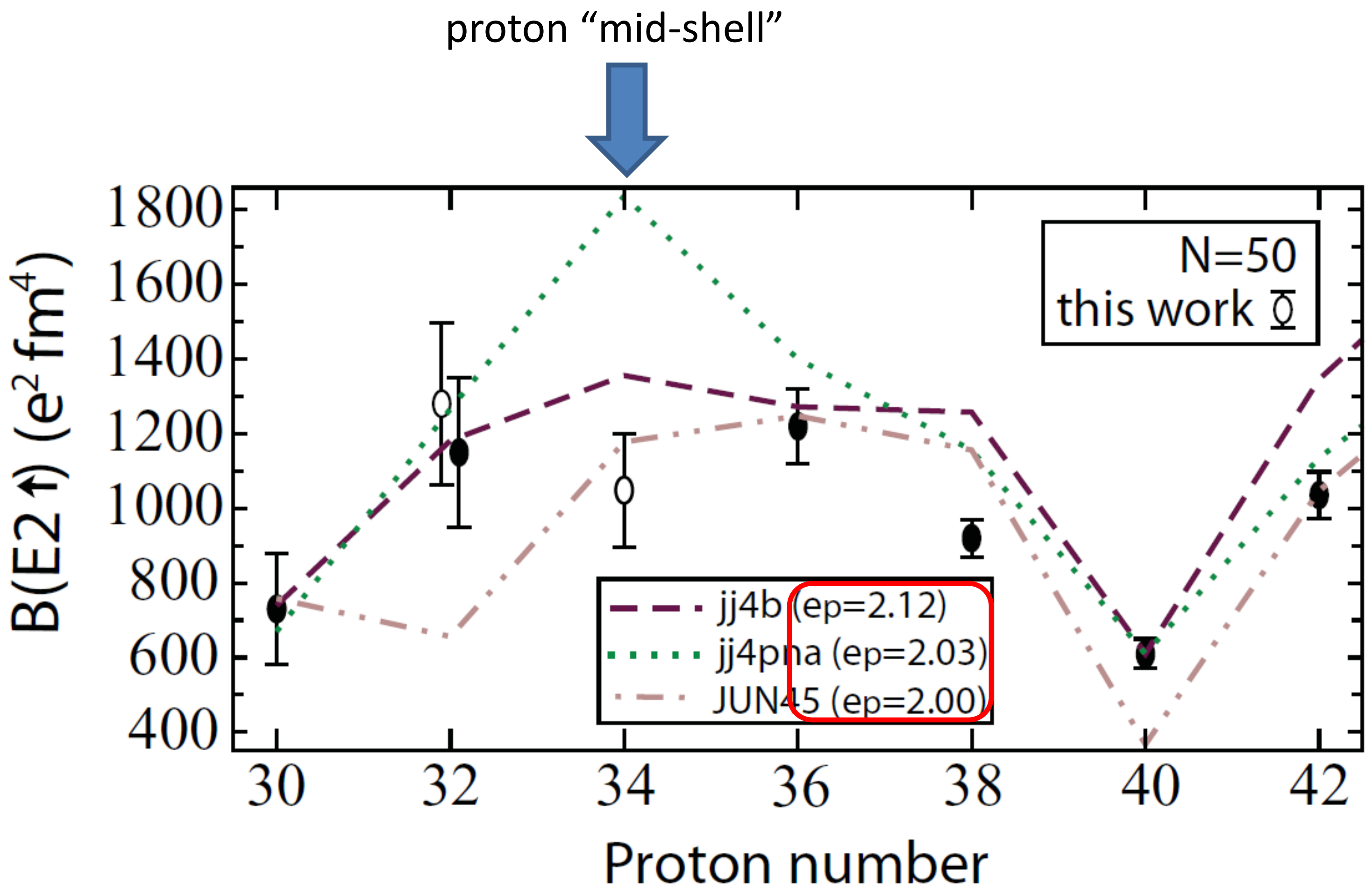
for the evaluation of $\varepsilon_{j\nu}$

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

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

What coulex says ?

J. Van de Walle et al. PRL **99,** 142501 (2007) REX-ISOLDE
A. Gade et al. Phys. Rev. C **81**, 064326 (2010) MSU

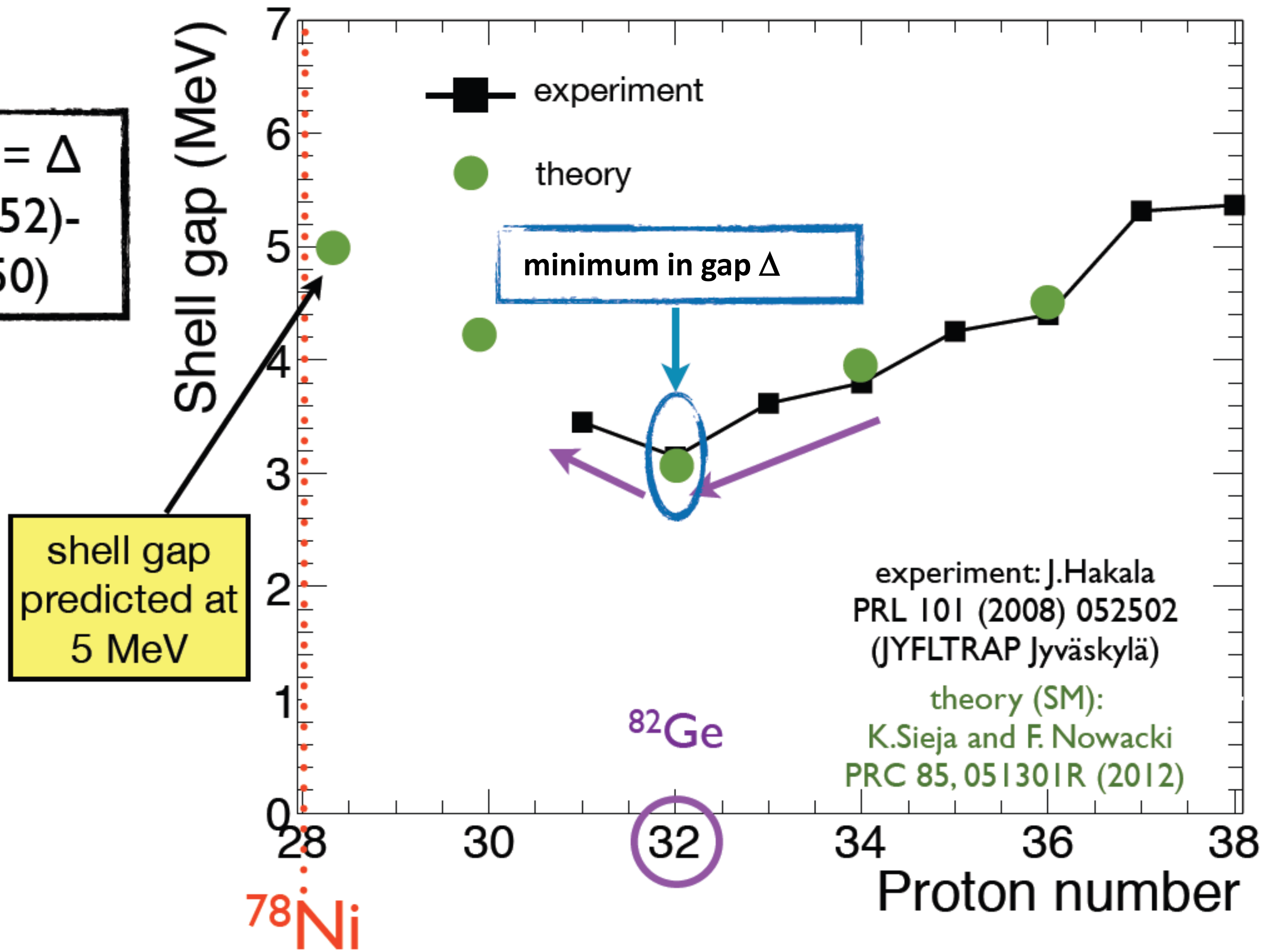


The question of the size of the gap at N=50: back to core-breaking states

K. Sieja and F. Nowacki, Phys. Rev. C 85, 051301R (2012)

pf-shell orbitals for protons
f5/2, p, g9/2, d5/2 orbitals for neutrons

Shell gap = Δ = $S_{2n}(N=52)$ - $S_{2n}(N=50)$



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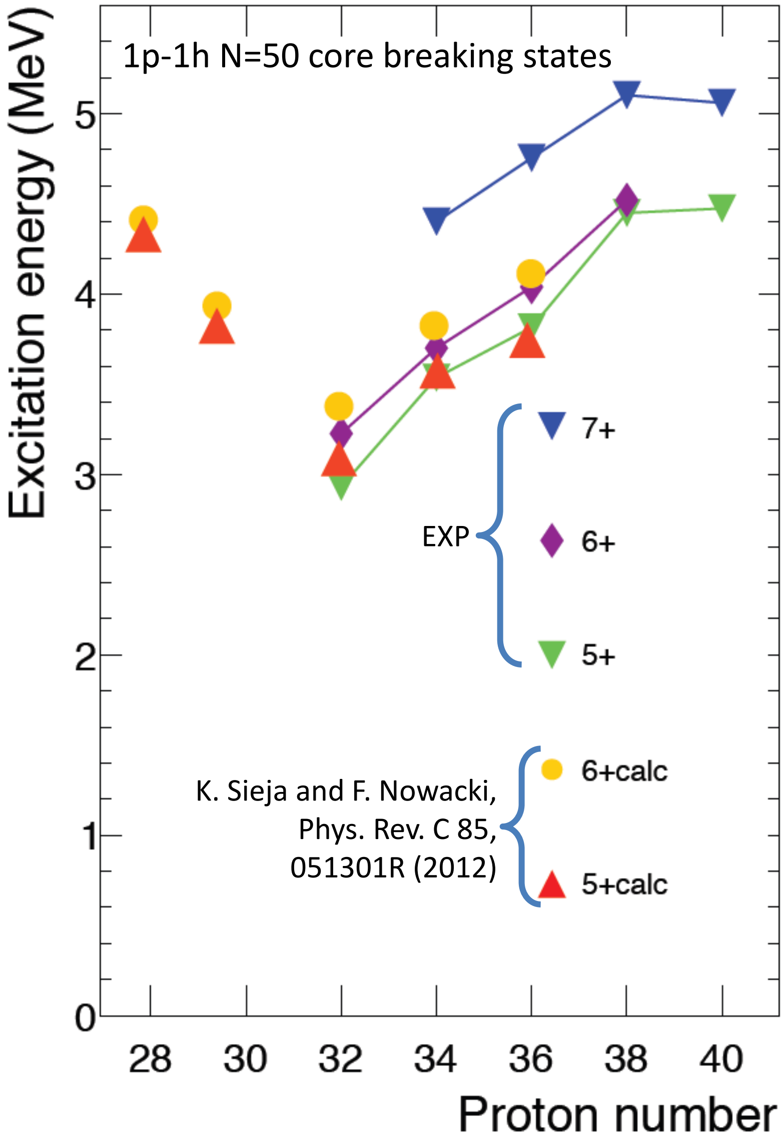
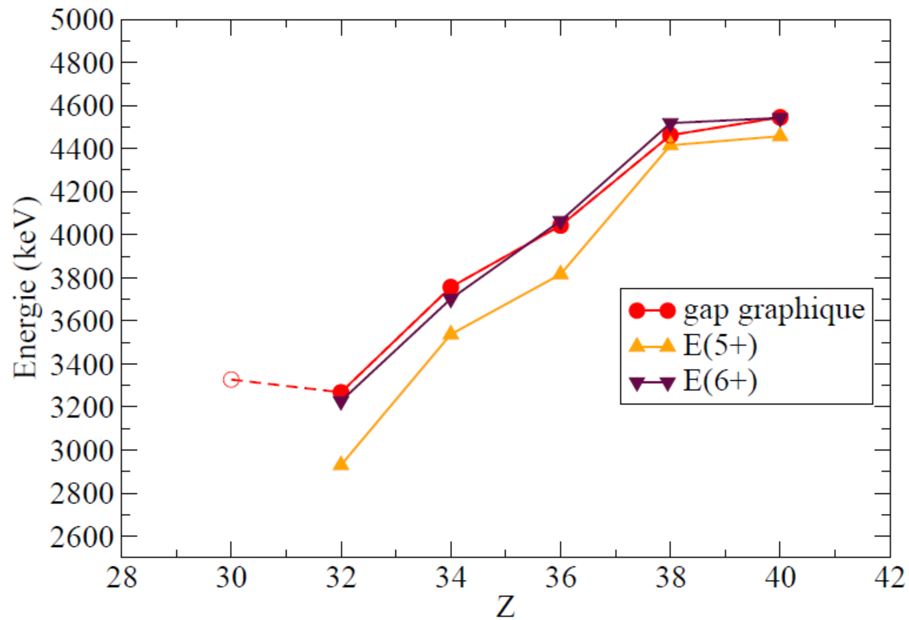
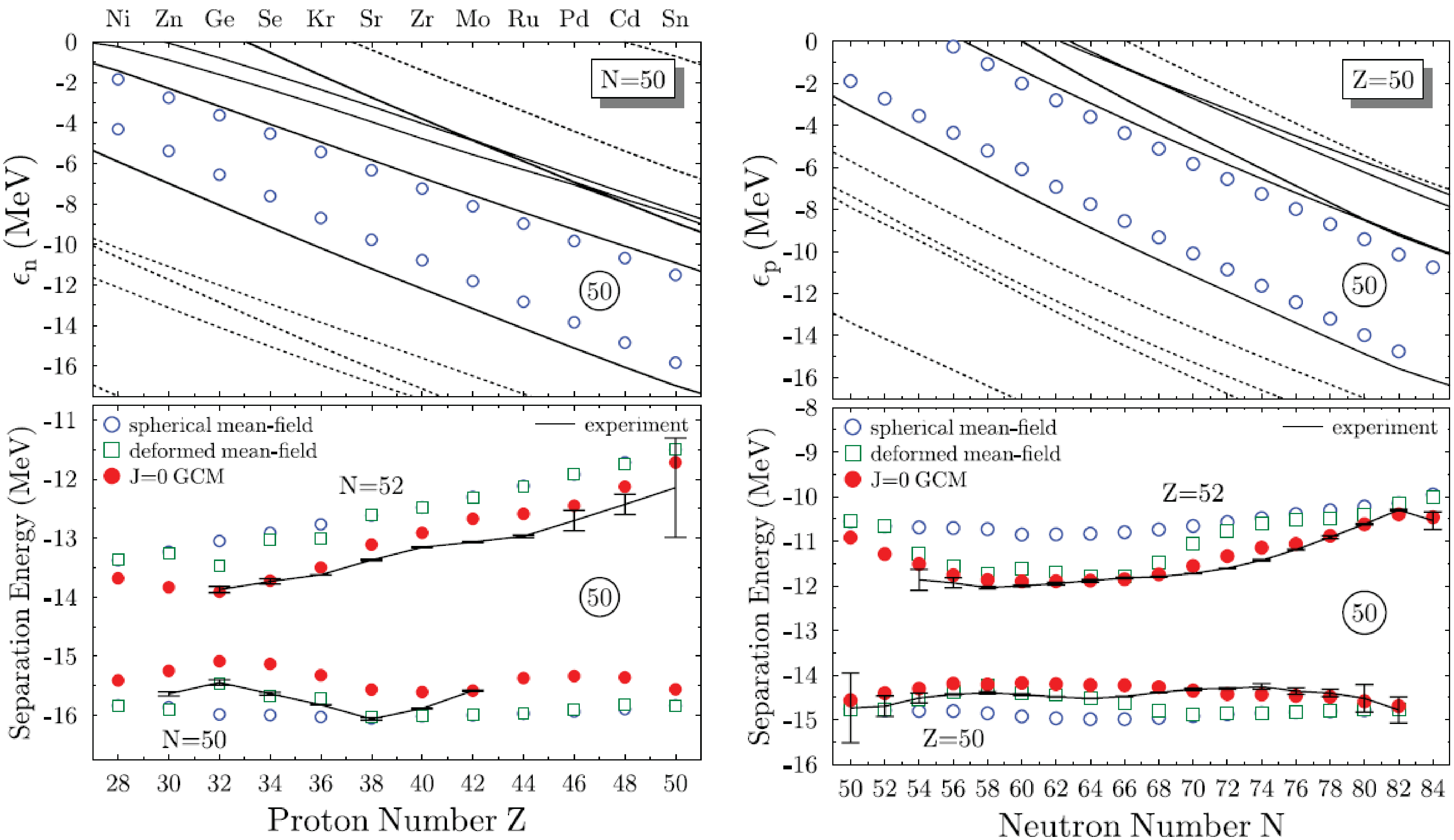




Fusion-fission experiment within AGATA@GANIL campaign (spokespersons G. Duchêne and G. De Angelis) run in 2015 search for core-breaking Yrast states in ^{80}Zn
→ unsufficient statistics

N=50 vs Z=50 situations



figures taken from
Bender et al. Phys. Rev. C **78**, 054312 (2008)

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r-process + structure consequences

very busy decade

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RIBF/RIKEN

direct study of ^{78}Ni

towards an even busier decade

Third golden age : >2016

A new dawn for shape coexistence studies near N=50 towards ^{78}Ni

What we have learned from the "second golden age"

- experimental data: spectroscopy and masses

→ the N=50 spherical gap decreases from Z=40 to Z=32

→ increases again (or is stabilized) at Z=30

- maximum beyond mean field correlations at Z=32
  (not proton mid shell)

- SM description of N=50 isotones

→ cross neutron shell excitations are mandatory, max influence : Z=32

first hints

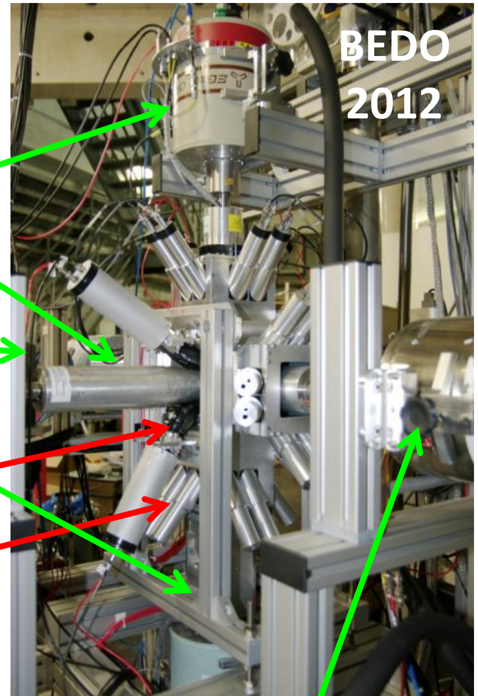
5 HPGe detectors
Source-cap distance = 5 cm
$\varepsilon_{\gamma\,(1\,\mathrm{MeV})} \approx$ 4-5 %

2 tapered EUROGAM1
(French-UK
gamma Loan Pool)

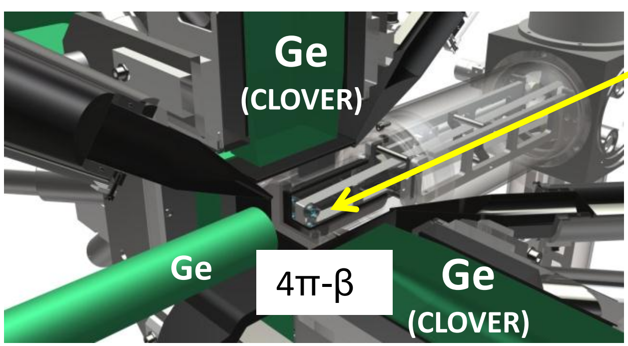
2 CLOVERS

$4\pi\ \beta$ (plastic) detector
ε_β = 55 %

BGO guard
detectors belt

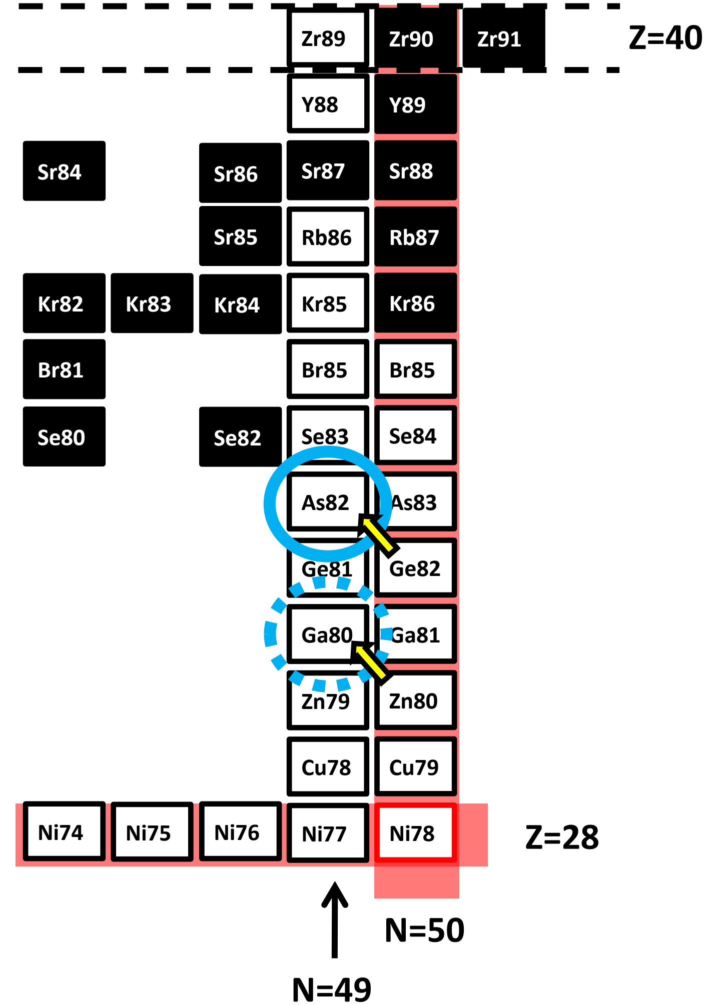


1 coaxial (large volume)



collection point

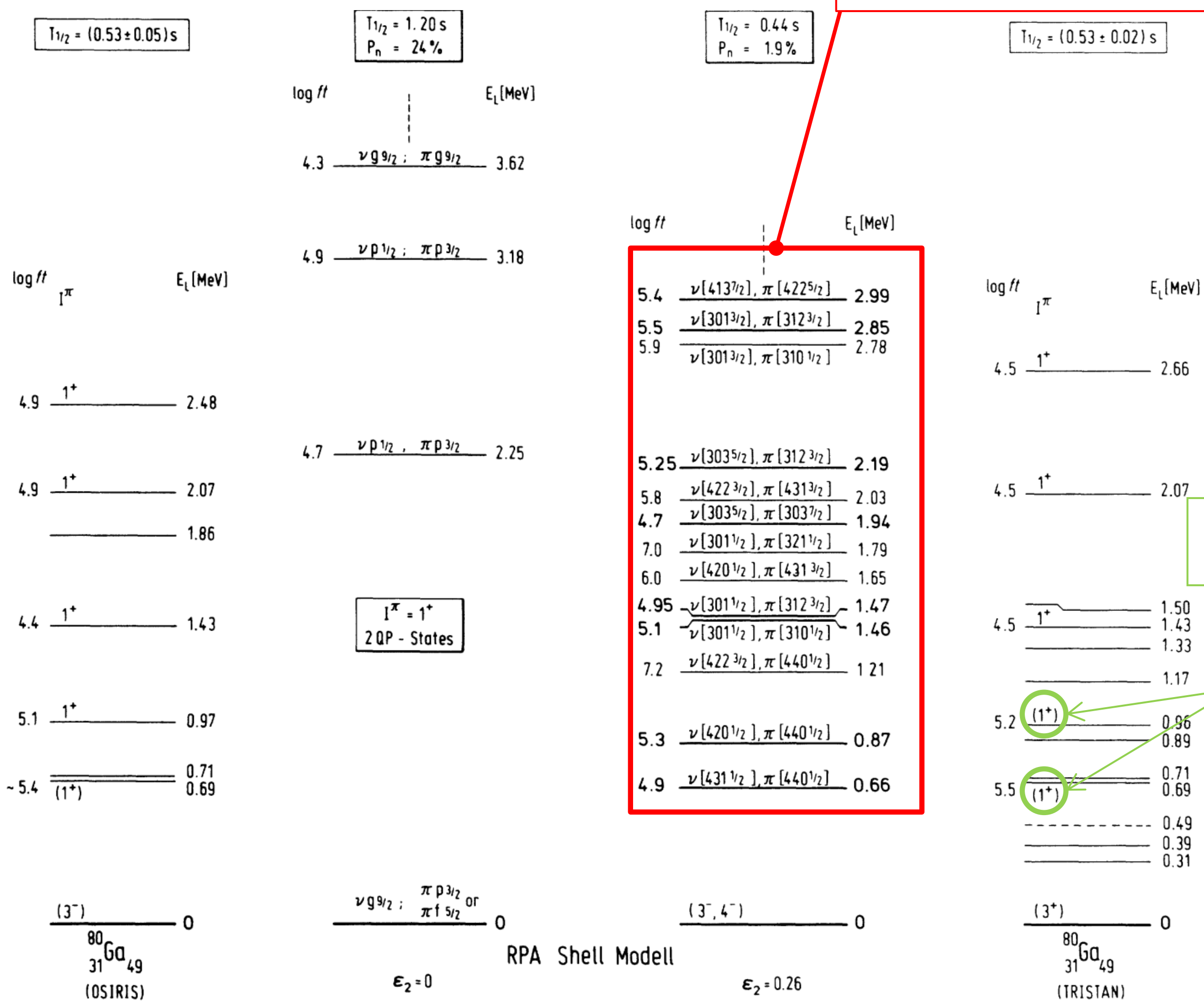
BEDO (BEta Decay studies at Orsay)
commissioning experiment (2012)
Etilé et al. PRC **91** 064317 (2015)



Gamow-Teller decay of ^{80}Zn: Shell structure and astrophysical implications By Kratz et al. PRC 38 (1988)

« formed above 0.6 MeV. Considering ^{80}Zn as a doubly magic $^{78}_{28}Ni_{50}$ core plus a proton pair, the observation of shape coexistence seems to imply a rather rapid weakening of the shell strength above ^{78}Ni. With regard to *r*- »

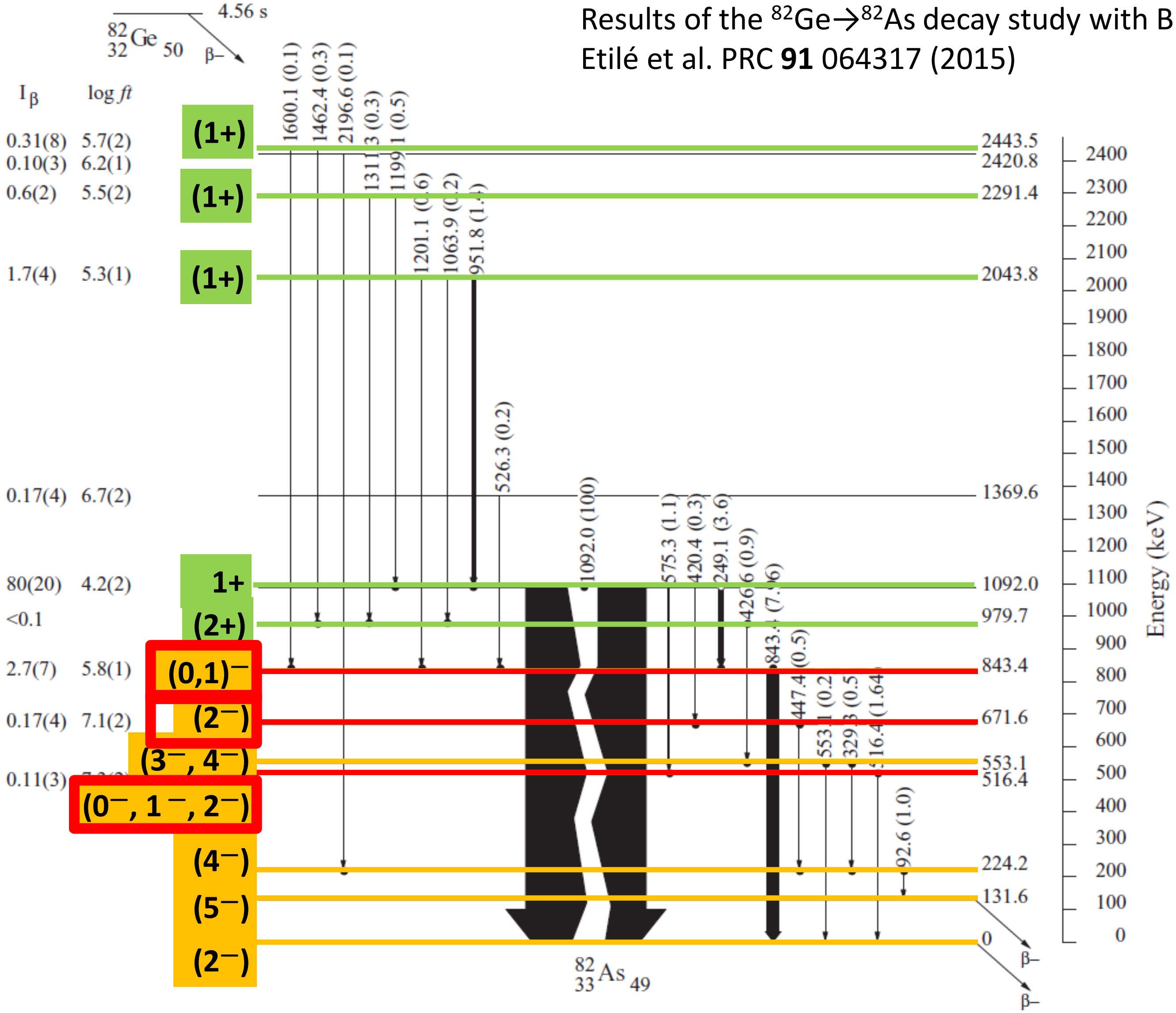
RPA calculations, with significant quadrupole deformation (ε_2=0.26) produce naturally an enormous amount of 1+ states (2QP states, Nilsson labeled), which was found satisfying (!)



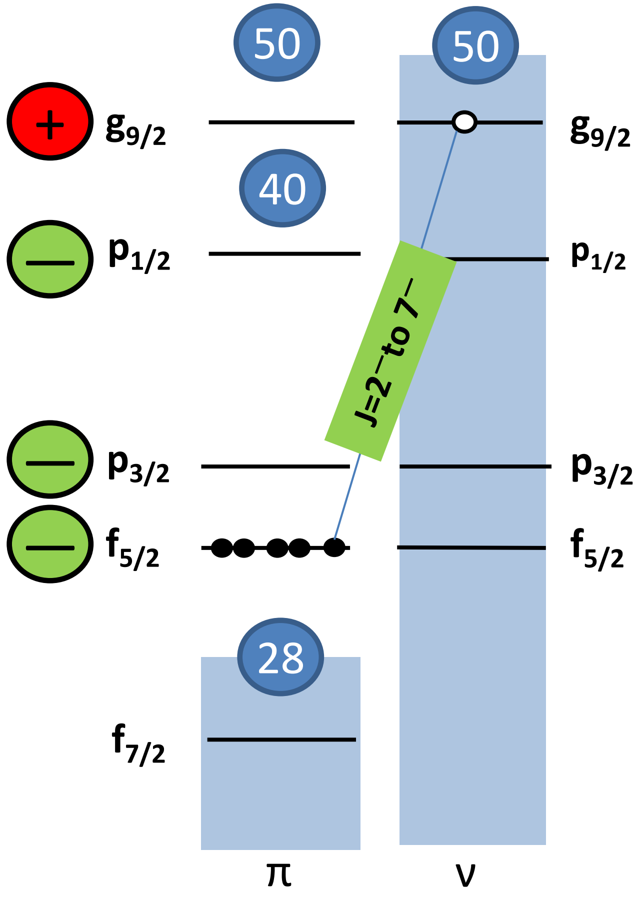
Winger et al. PRC 36 (1987) [TRISTAN]

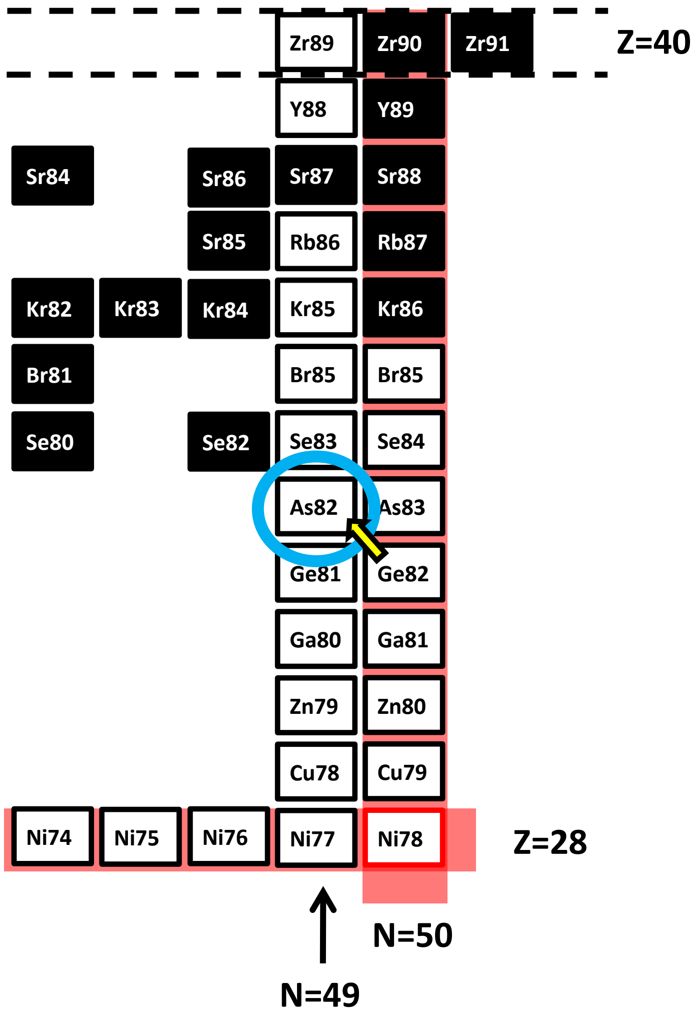
in a similar study Winger et al removed the parenthesis only at higher energies

Results of the $^{82}Ge \rightarrow ^{82}As$ decay study with BEDO
Etilé et al. PRC **91** 064317 (2015)

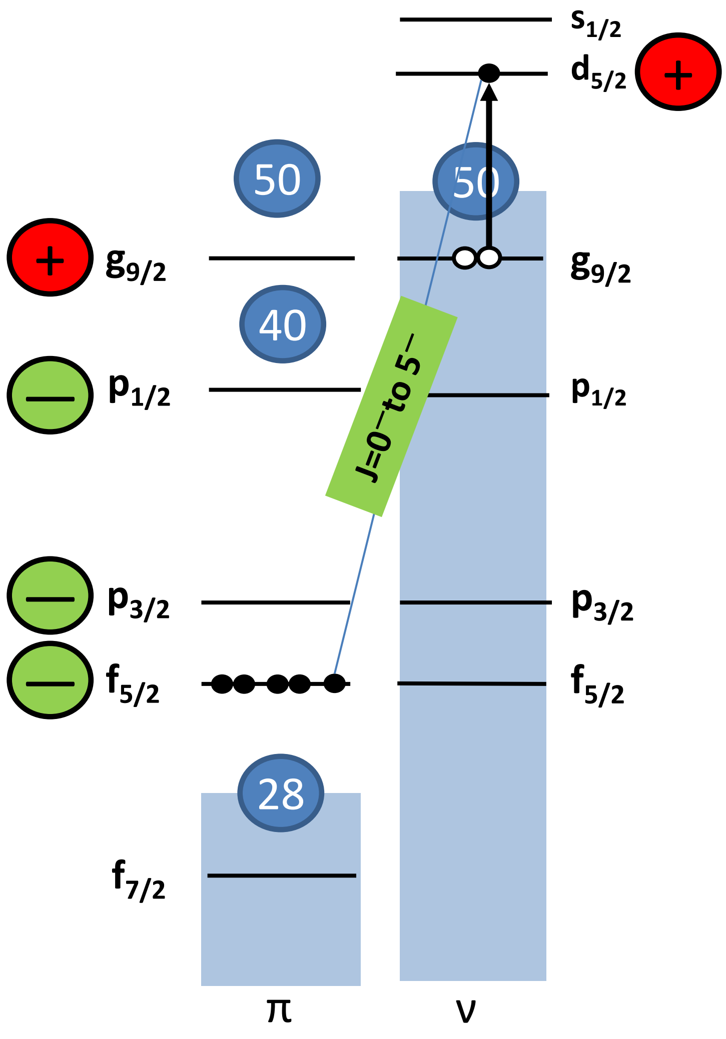


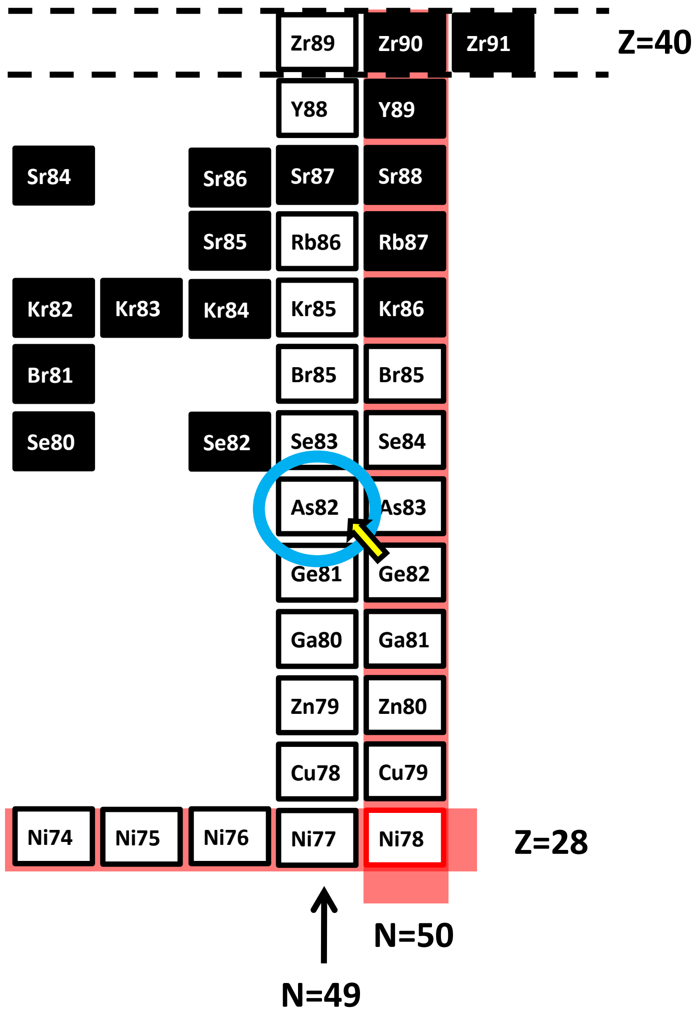
the question of the low-energy low-spin (J<2) states in ^{82}As





first hints


s1/2
d5/2
+
50
50
+
g9/2
g9/2
40
p1/2
p1/2
J=0⁻ to 5⁻
p3/2
p3/2
f5/2
f5/2
28
f7/2
π
ν


Zr89
Zr90
Zr91
Z=40
Y88
Y89
Sr84
Sr86
Sr87
Sr88
Sr85
Rb86
Rb87
Kr82
Kr83
Kr84
Kr85
Kr86
Br81
Br85
Br85
Se80
Se82
Se83
Se84
As82
As83
Ge81
Ge82
Ga80
Ga81
Zn79
Zn80
Cu78
Cu79
Ni74
Ni75
Ni76
Ni77
Ni78
Z=28
N=50
N=49

zeroth order couplings from neighboring N=49 odd-nuclei spectroscopy

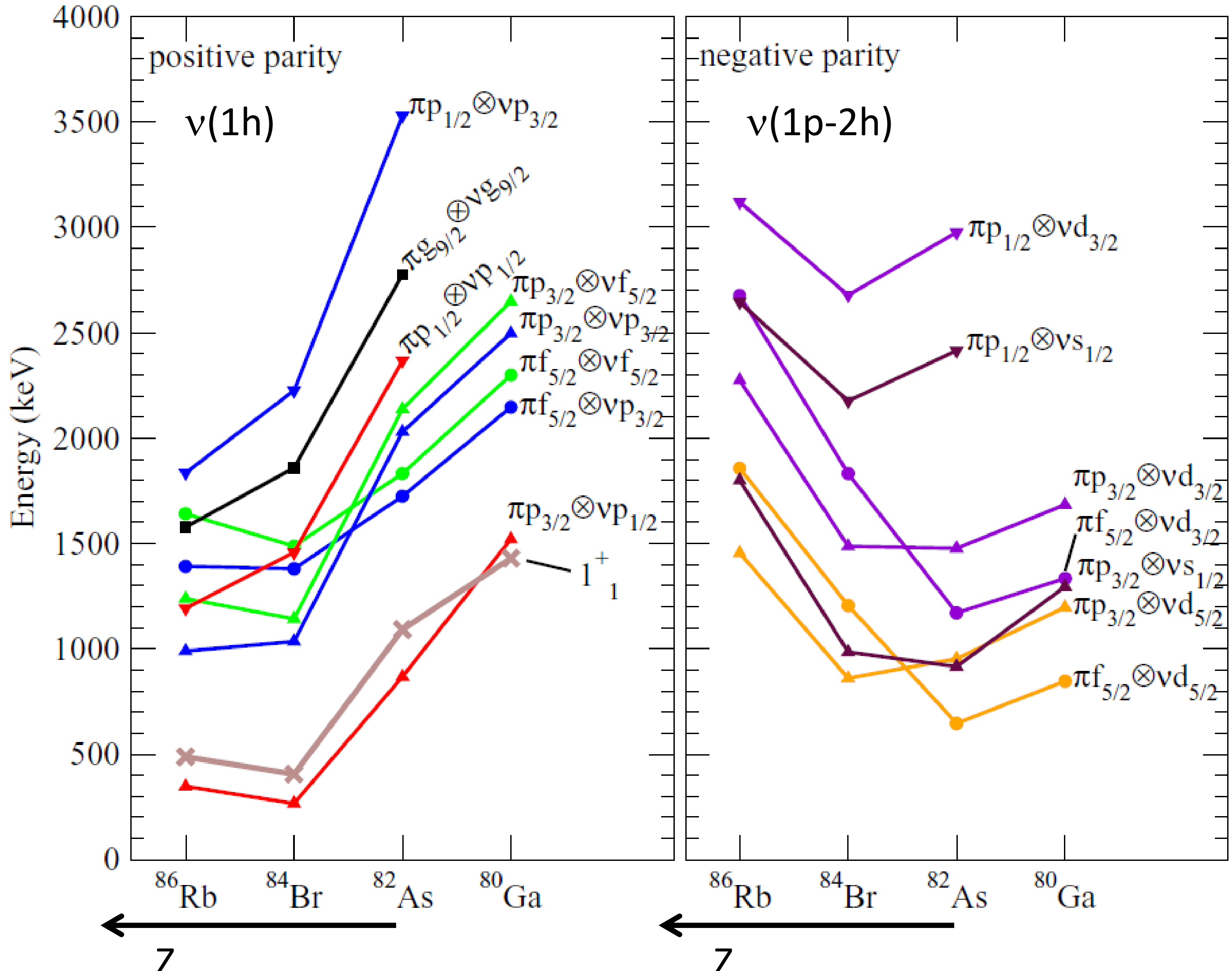
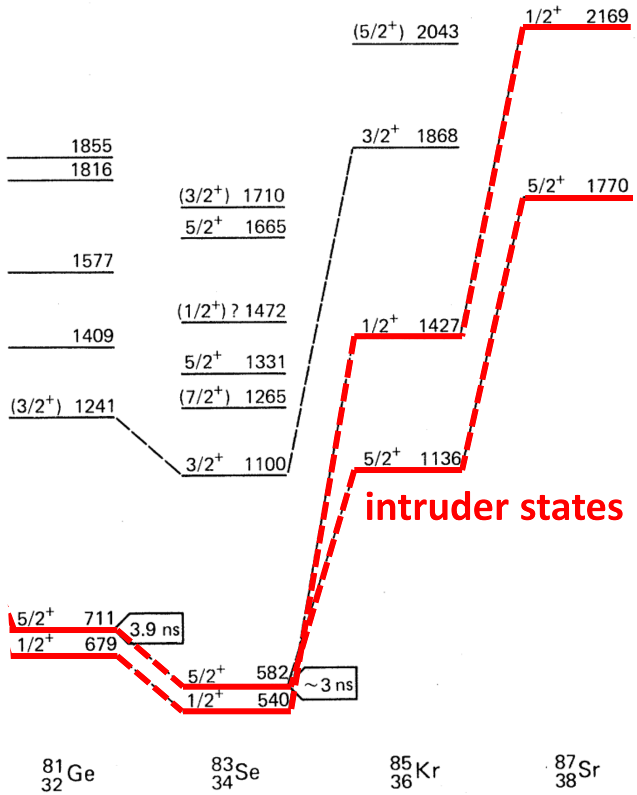


Fig. from Etilé et al. PRC **91** 064317 (2015)

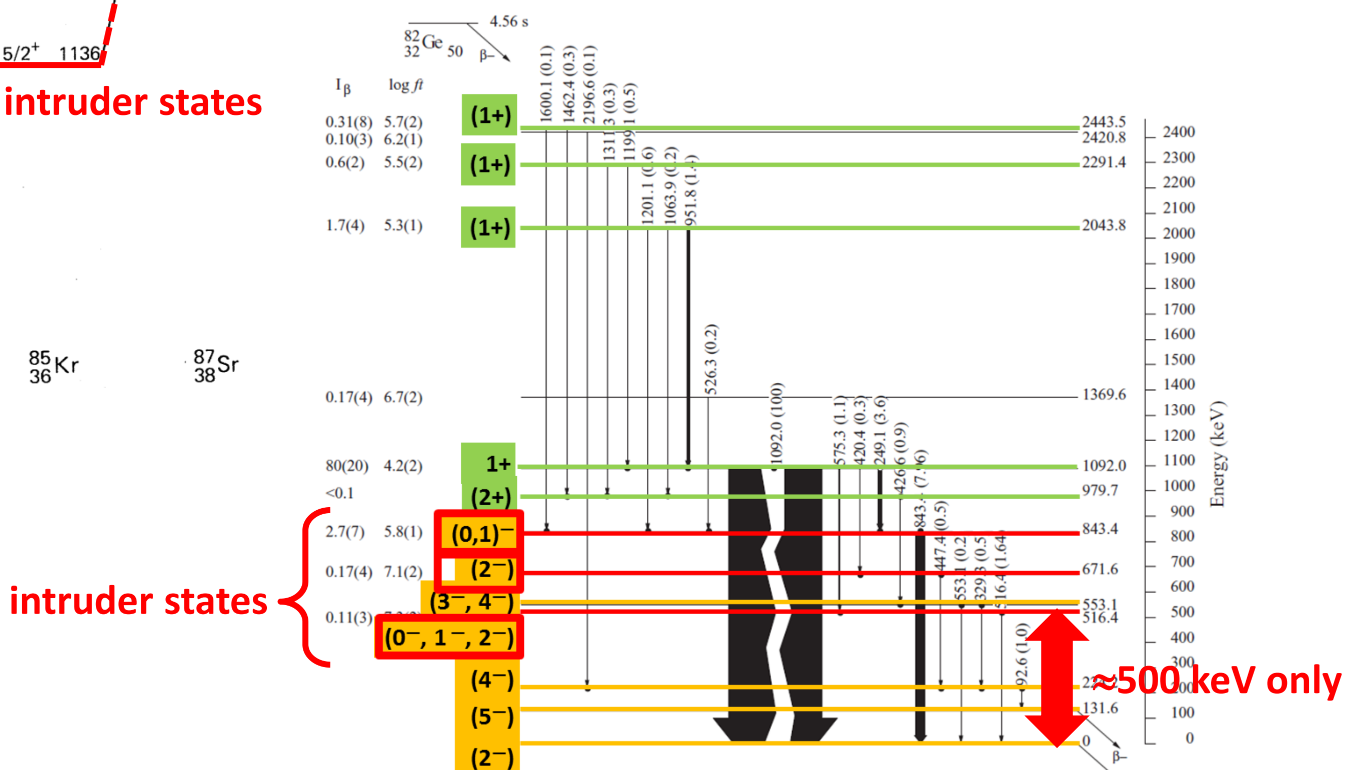
Intruder states at N≈50



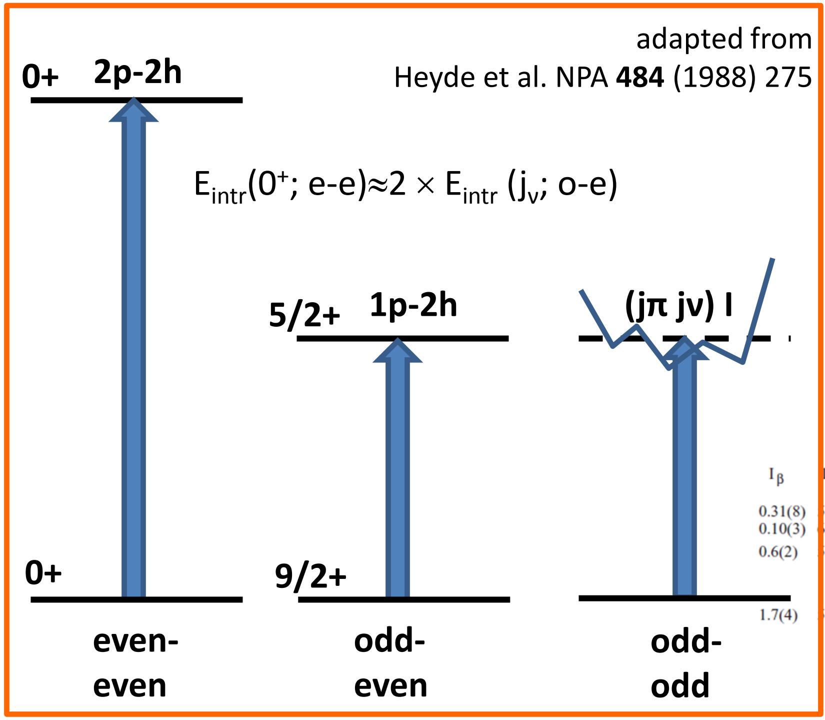
N=49

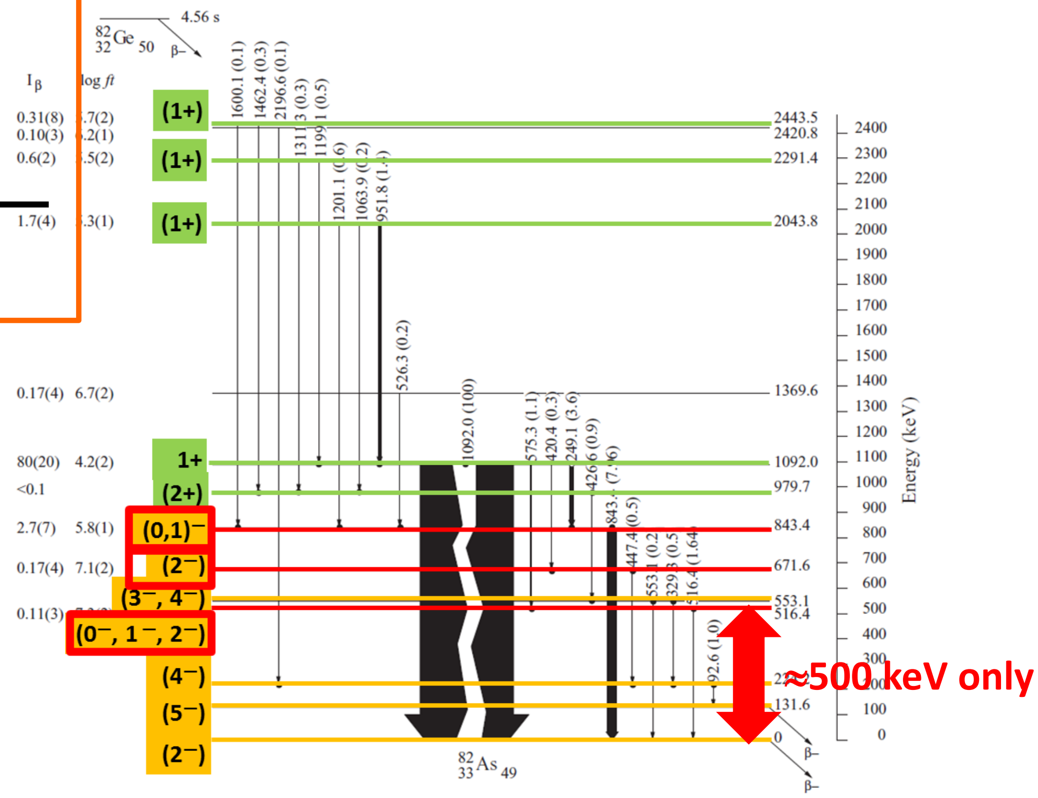
Meyer et al. PRC **25** 682 (1982)
pioneering interpretation of the positive parity states in the odd N=49 isotones

the “Kratz conjecture” was indeed correct
(not from the good arguments though)

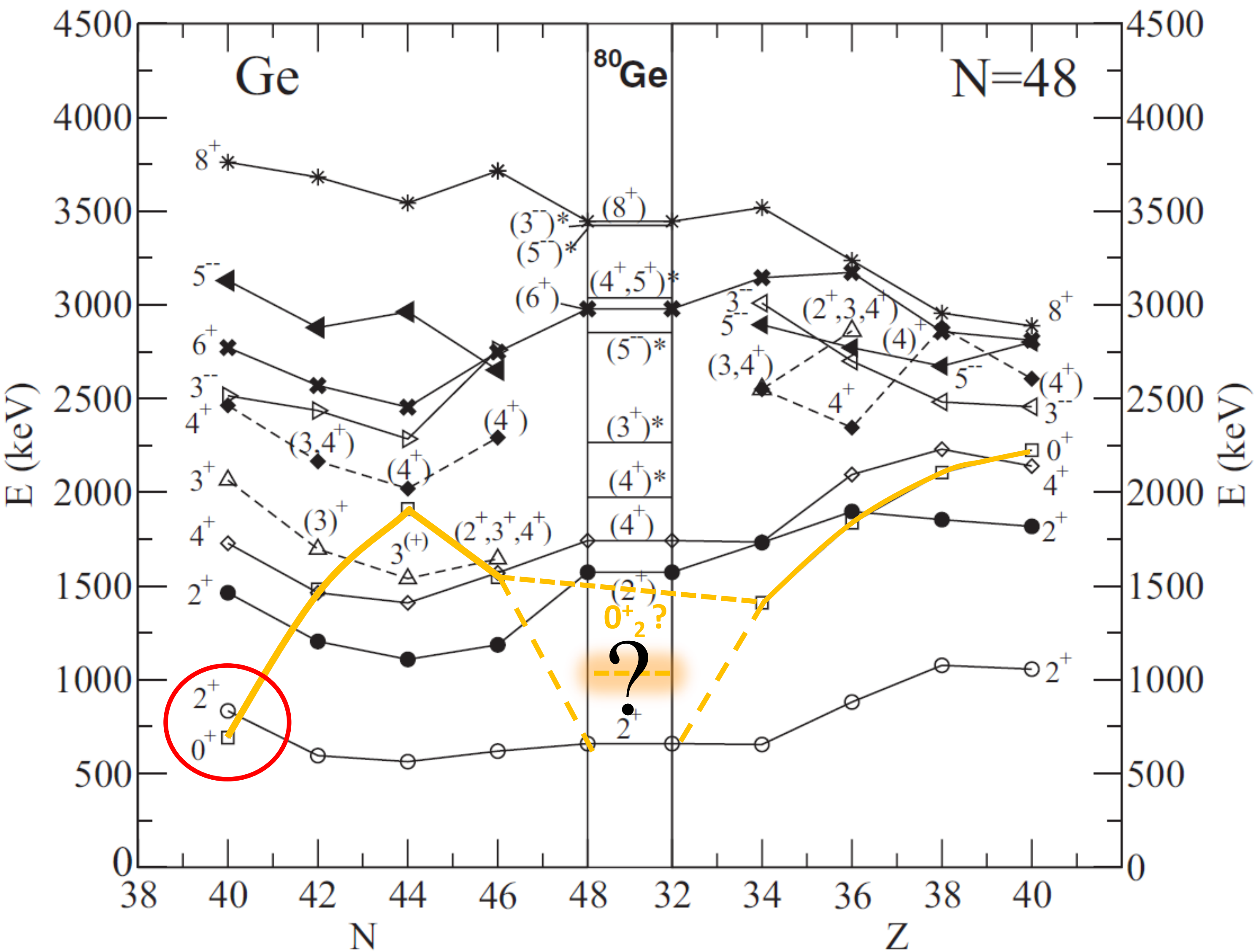


^{82}As Z=33, N=49


adapted from
Heyde et al. NPA 484 (1988) 275
0+ 2p-2h
E_intr(0+; e-e)≈2 × E_intr (jν; o-e)
5/2+ 1p-2h
(jπ jν) I
0+
9/2+
even-even
odd-even
odd-odd


82 32 Ge 50
4.56 s
β–
Iβ
log ft
(1+)
(1+)
(1+)
1+
(2+)
(0,1)⁻
(2⁻)
(3⁻, 4⁻)
(0⁻, 1⁻, 2⁻)
(4⁻)
(5⁻)
(2⁻)
2443.5
2420.8
2291.4
2043.8
1369.6
1092.0
979.7
843.4
671.6
553.1
516.4
131.6
0
82 33 As 49
Energy (keV)
≈500 keV only

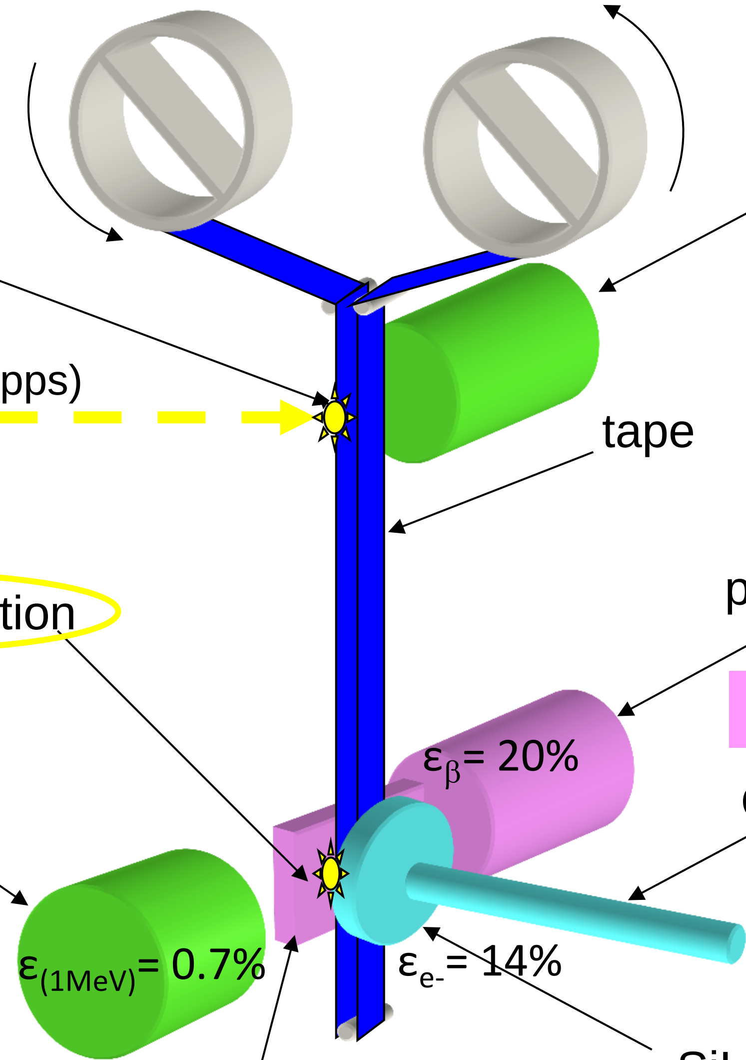
Intruder states at N≈50 : is there a low-lying 0^+_2 state in ^{80}Ge ?

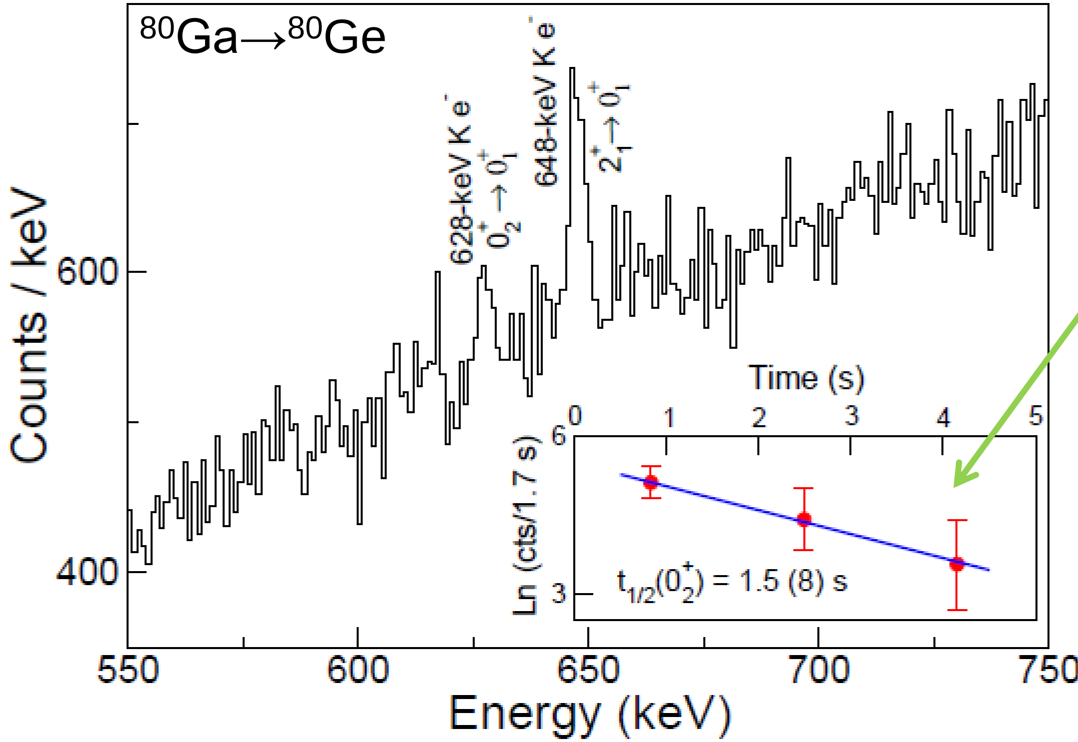


Verney et al. PRC **87** 054307 (2013)

Study of the ^{80}Ga (Z=31, N=49) → ^{80}Ge (Z=32, N=48) decay

at BEDO/ALTO
search for E0 transitions



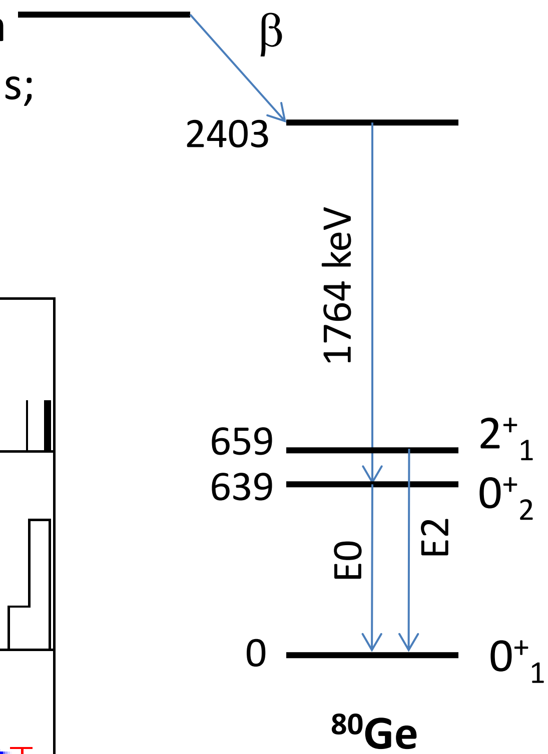


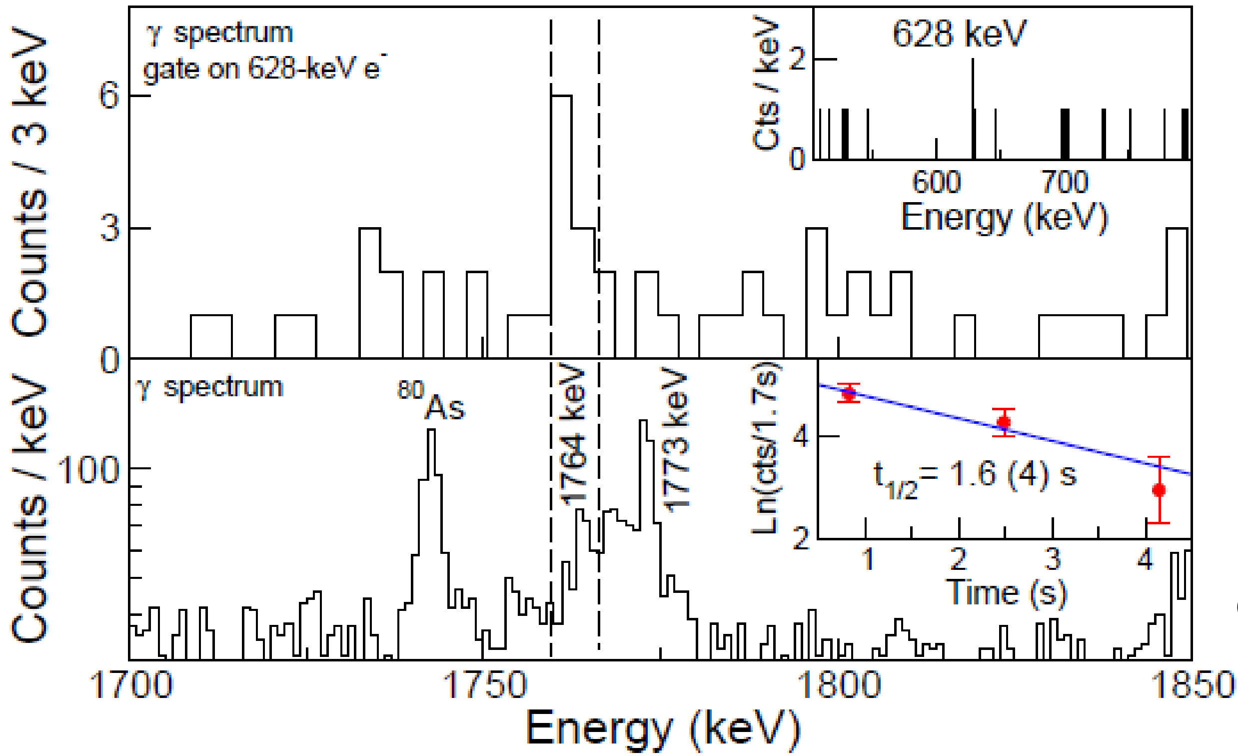
Compatible with the $T_{1/2}$ for the **3⁻** isomer in **^{80}Ga**
[$T_{1/2}$(**3⁻**)=1.3±0,2 s ; PRC 87 (2013)]
A situation very similar : $0^+_2 \rightarrow 0^+_1$ populated in the **3⁻ ^{72}Ga** decay
[Rester et al NPA 162 (1971)]

Analysis performed by
Andrea Gottardo (IPN Orsay)

Results

3 $^{-}$ isomer in ^{80}**Ga**
[$T_{1/2}$(**3**$^{-}$)=1.3±0,2 s;
PRC 87 (2013)]

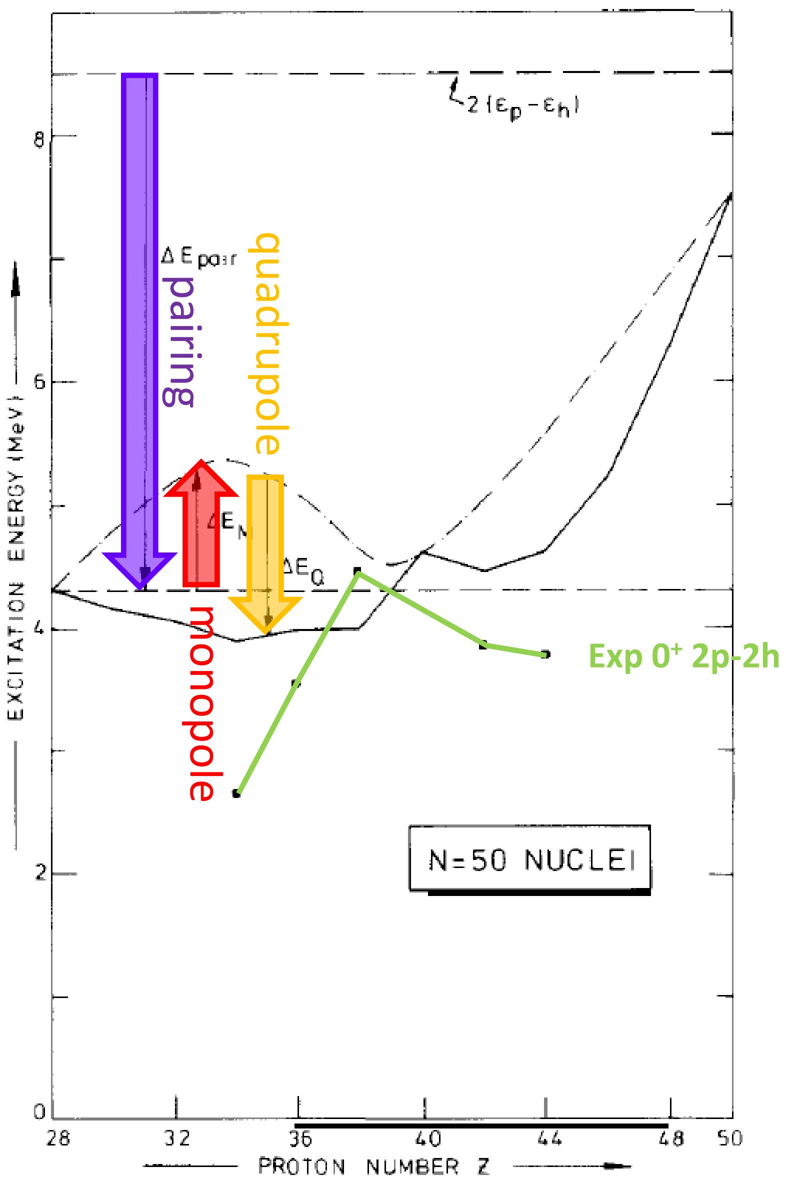


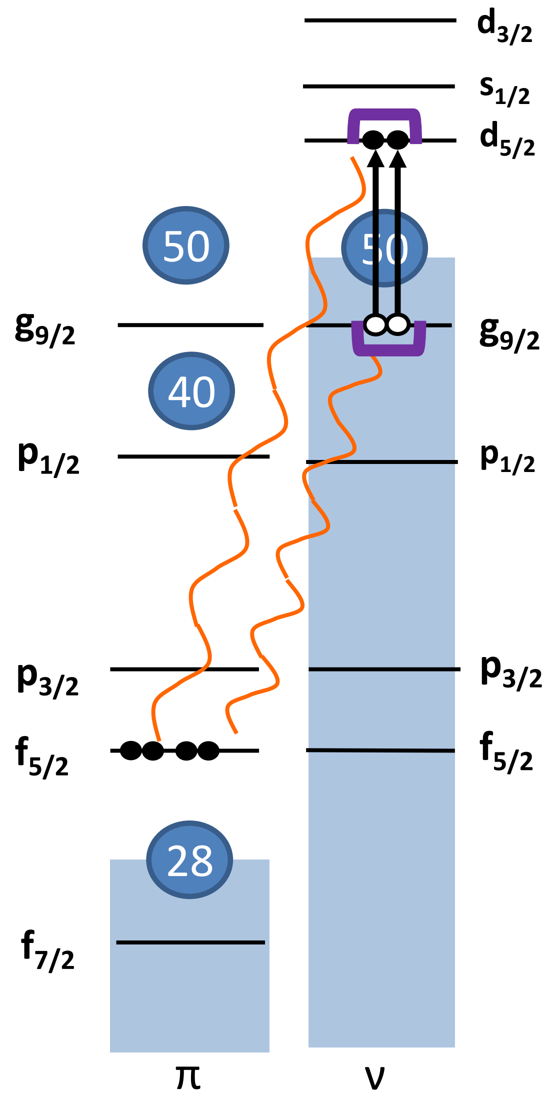


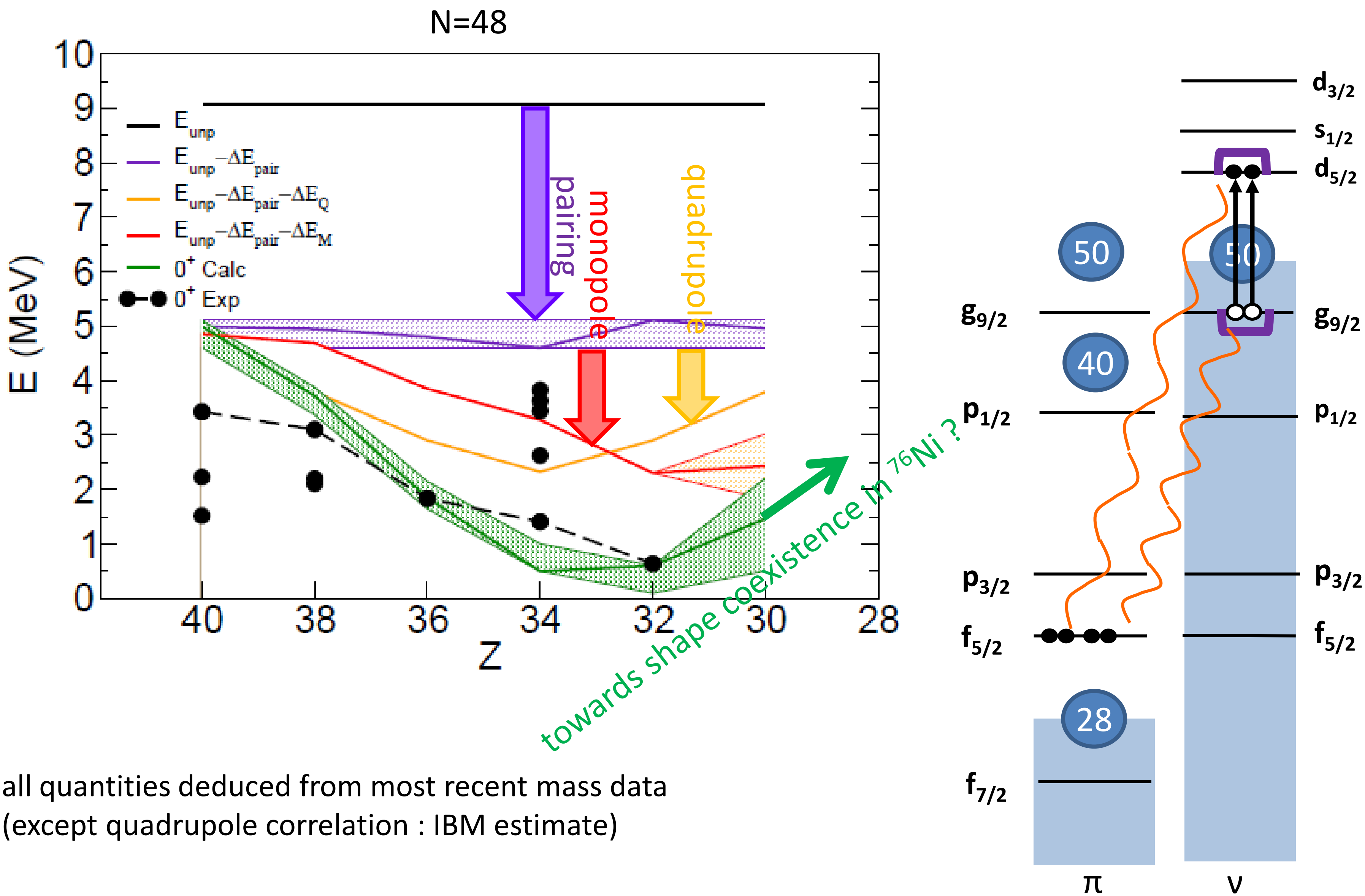
Gottardo et al. PRL 116 (2016)

A real surprise: no microscopic theory reproduces (yet) a 0^+_2 more bound than the 2^+_1.
What to do ?

Wood et al. Phys. Rep. 215 (1992)



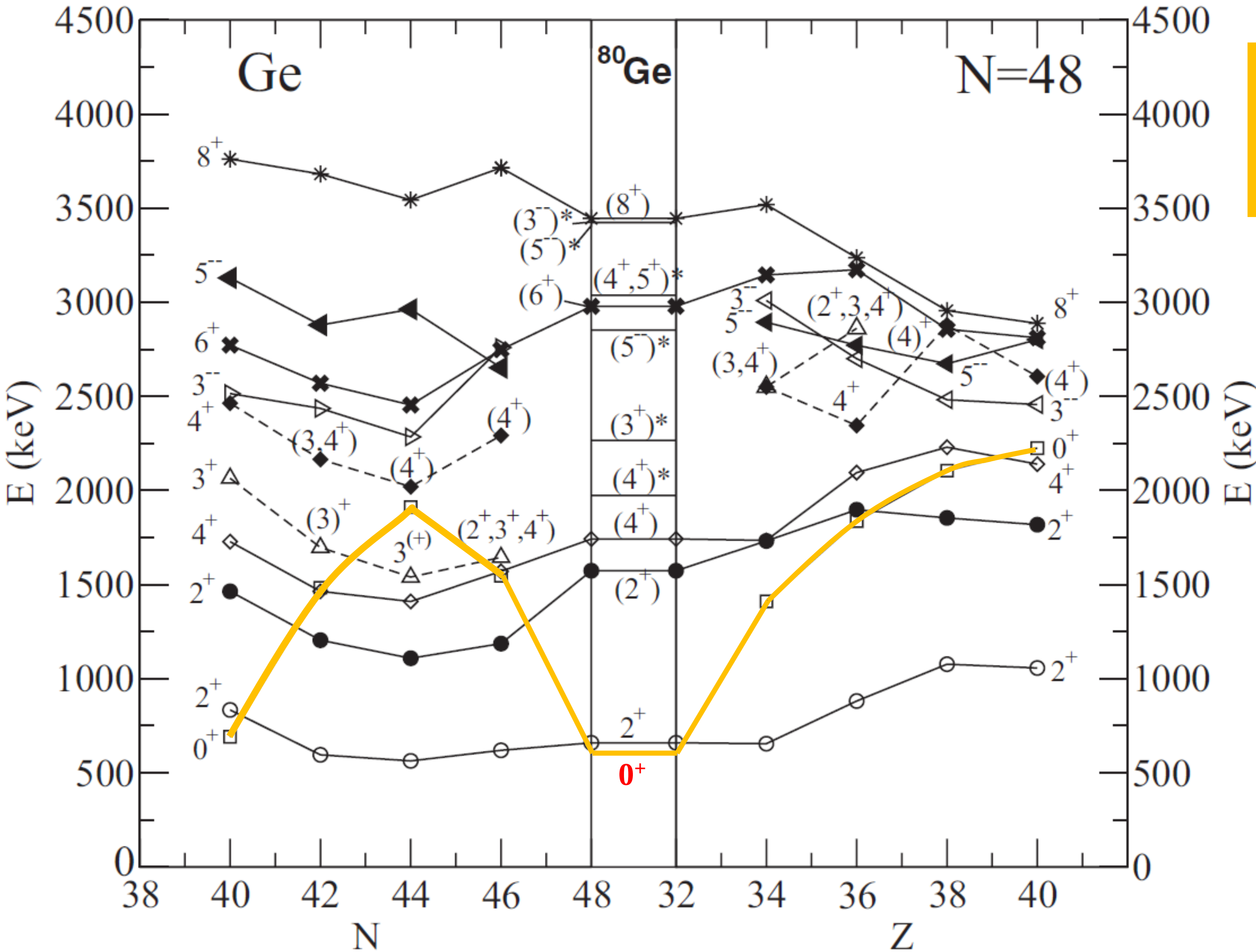




all quantities deduced from most recent mass data
(except quadrupole correlation : IBM estimate)

Intruder states at N≈50 : is there a low-lying 0^+_2 state in ^{80}Ge ? → yes

Z=32 : definitely a “special” proton number



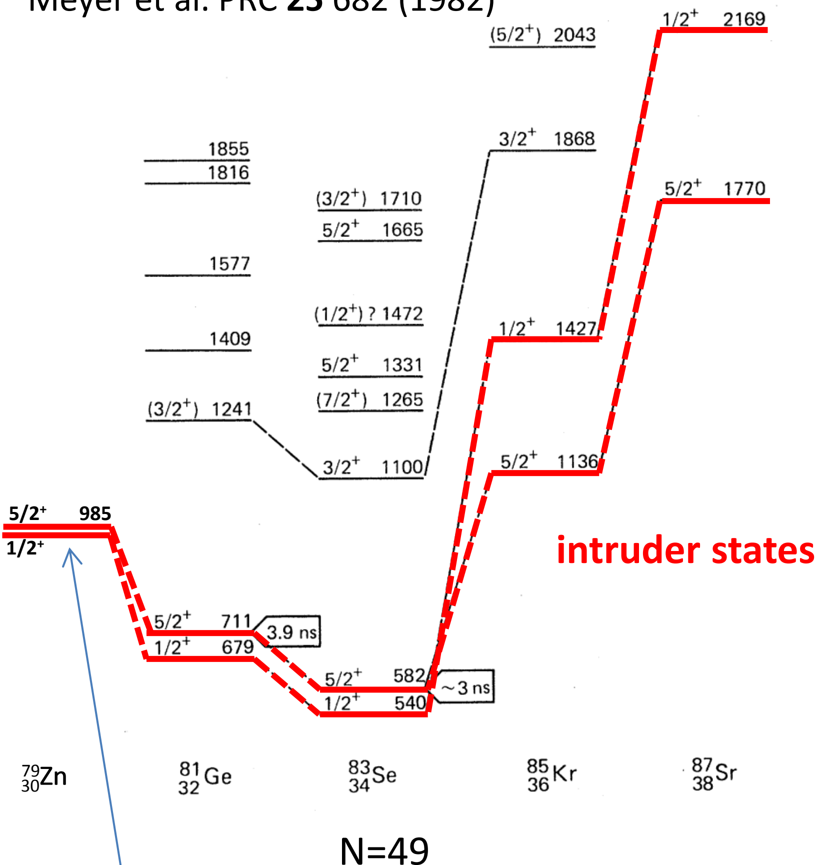
→ next steps

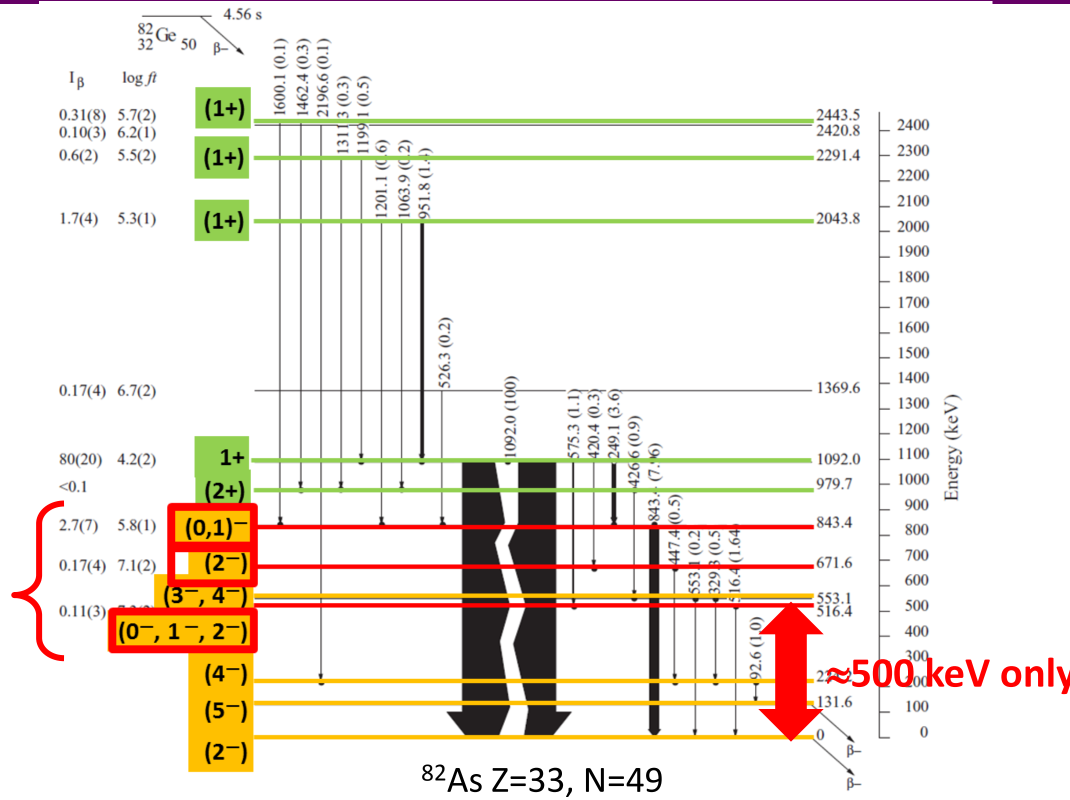
Z=32 (N=50) : ^{82}Ge

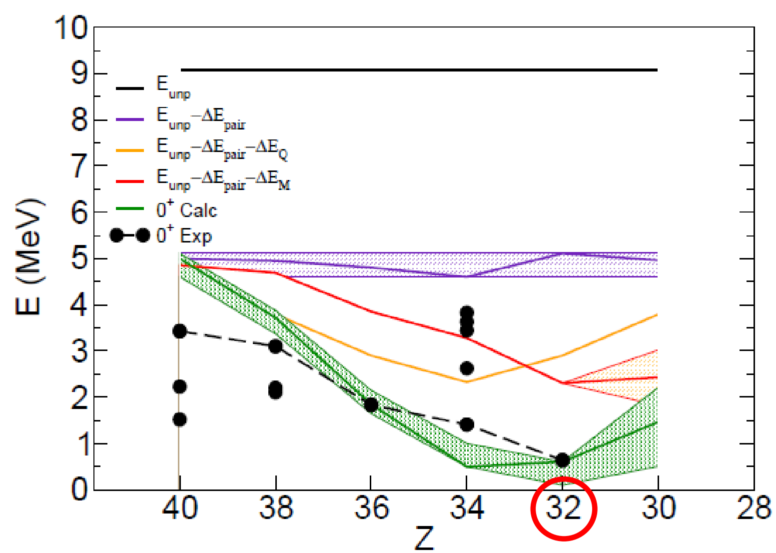
N=48 (Z=30) : ^{78}Zn

Intruder states at N≈50 : closer to Z=28

Meyer et al. PRC **25** 682 (1982)





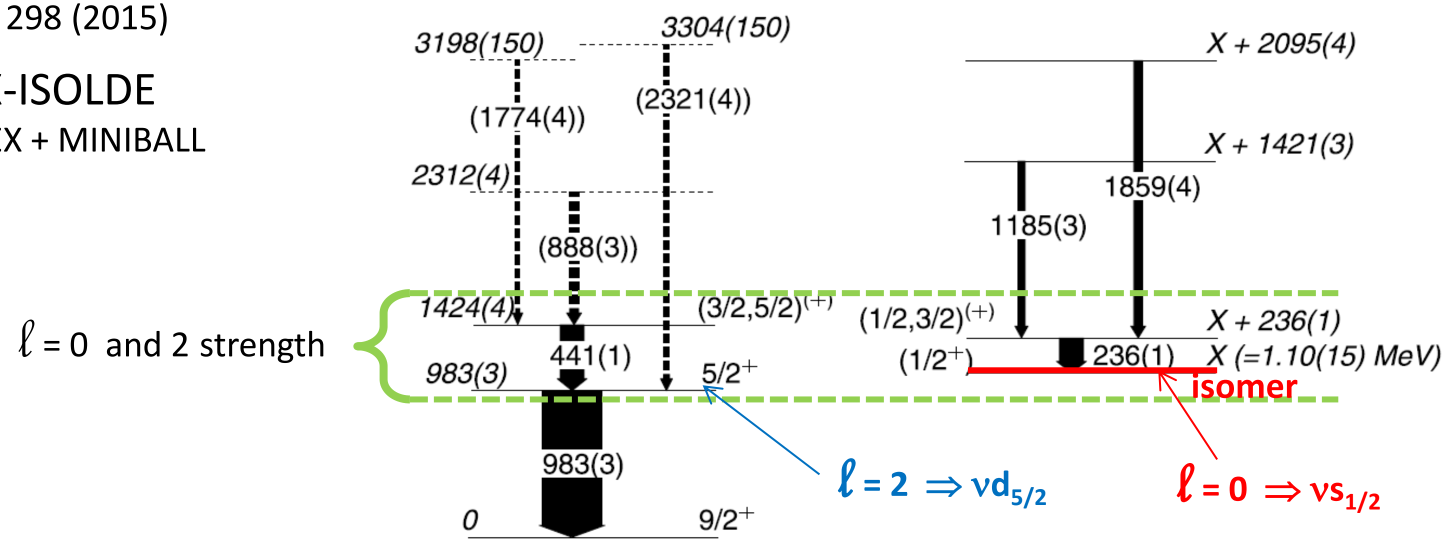


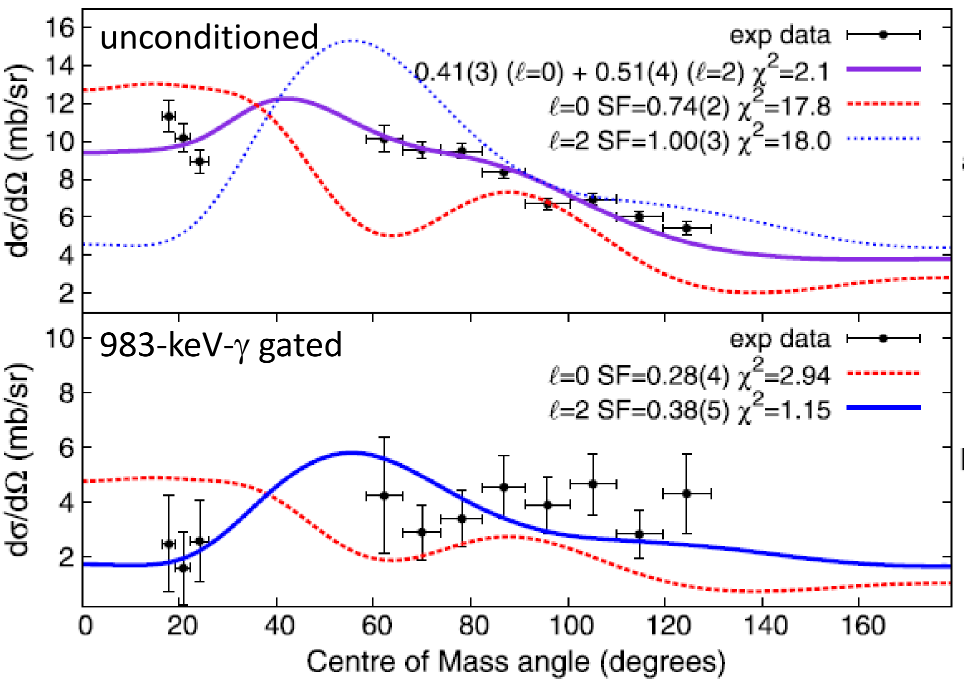
- low energy $\ell = 0$ and 2 strength observed in ^{78}Zn(d,p)^{79}Zn
  [PLB 740, 298 (2015)] **ISOLDE**
- laser spectroscopy
  [PRL 116, 182502 (2016)] **ISOLDE**
- detailed γ spectroscopy ^{79}Cu β- decay
  EURICA/**RIKEN** - unpublished

R. Orlandi et al. PLB 740 298 (2015)

$^{78}Zn(d,p\gamma)^{79}Zn$ REX-ISOLDE

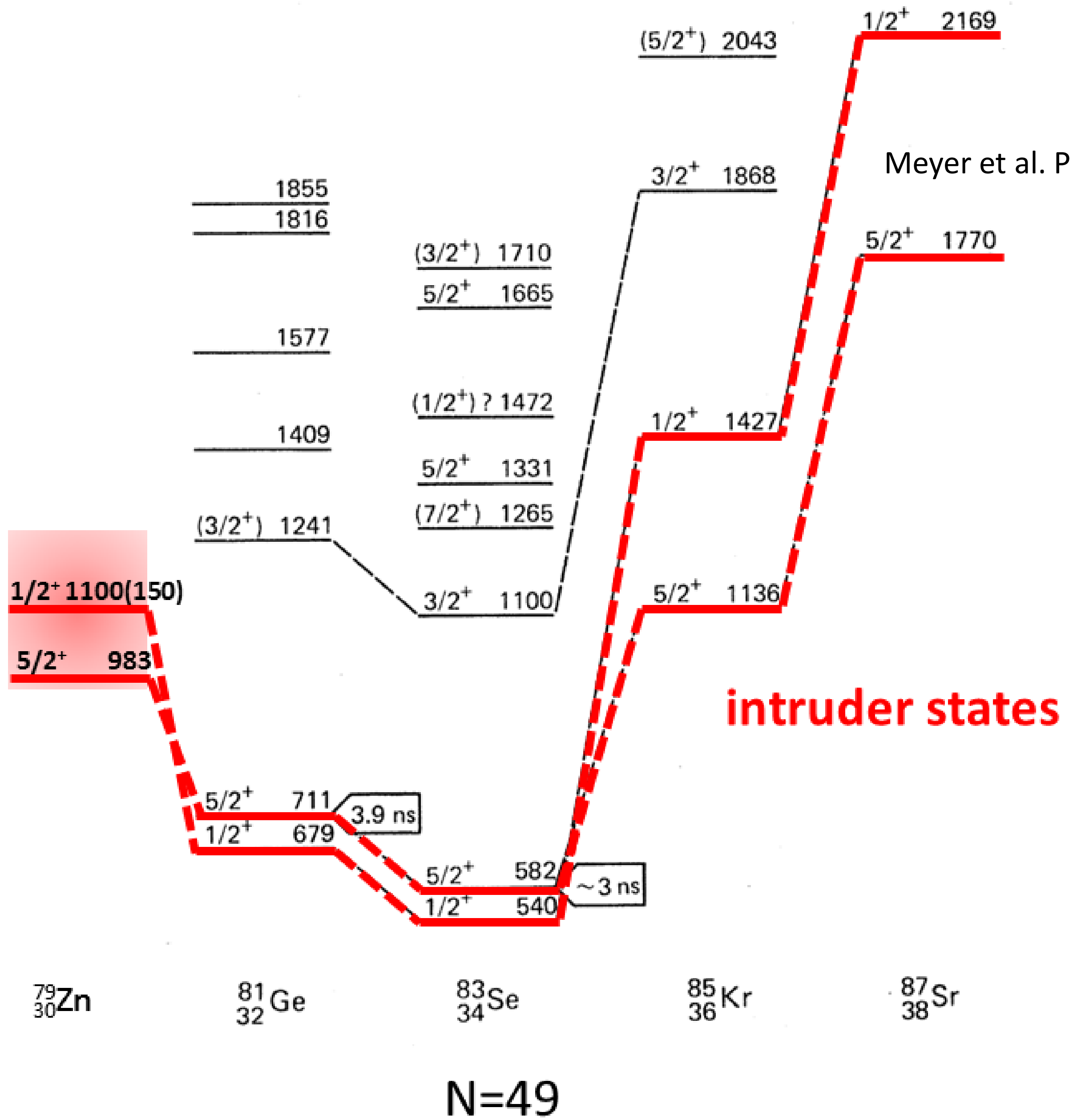
T-REX + MINIBALL





R. Orlandi et al.
PLB 740 298 (2015)

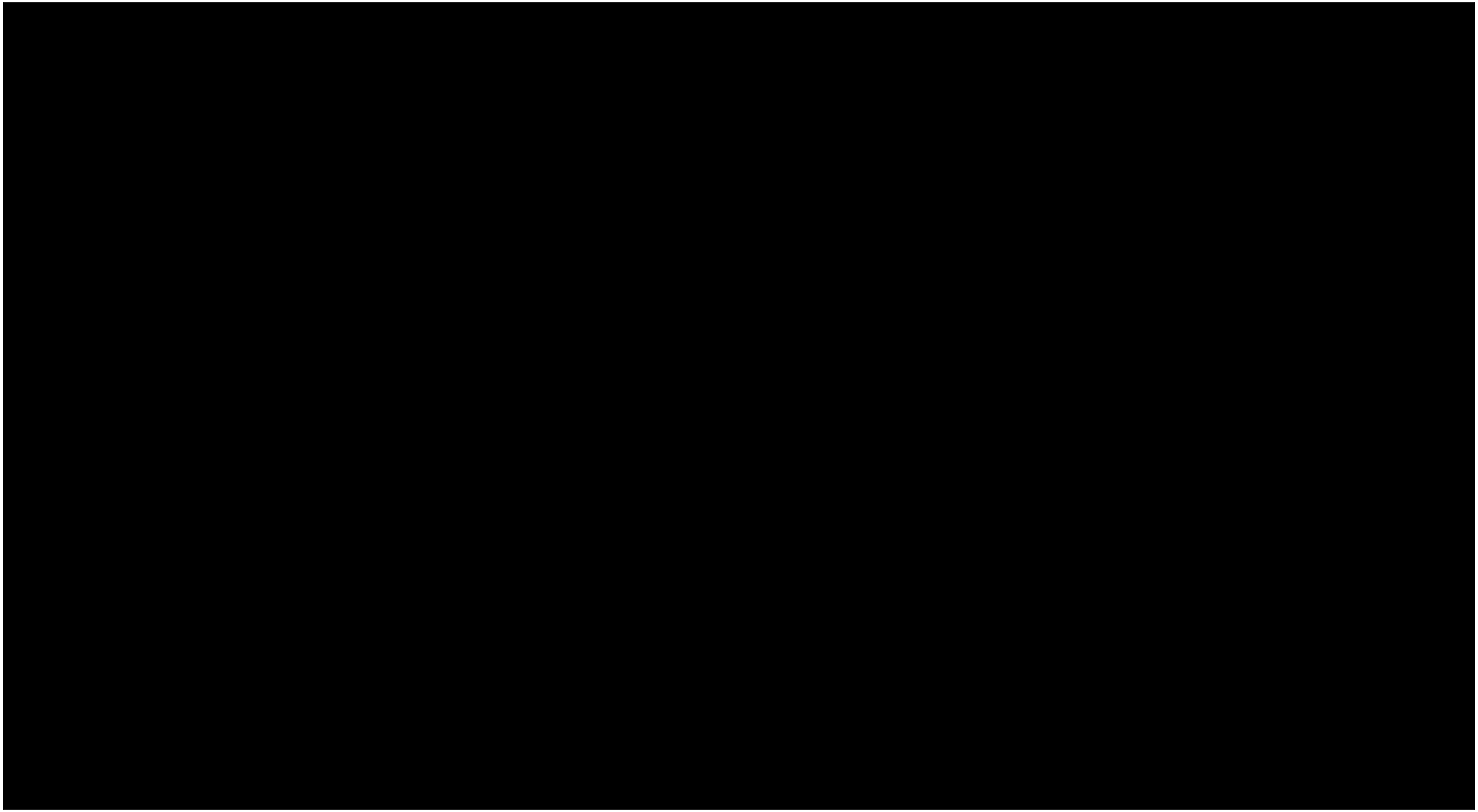
Meyer et al. PRC **25** 682 (1982)



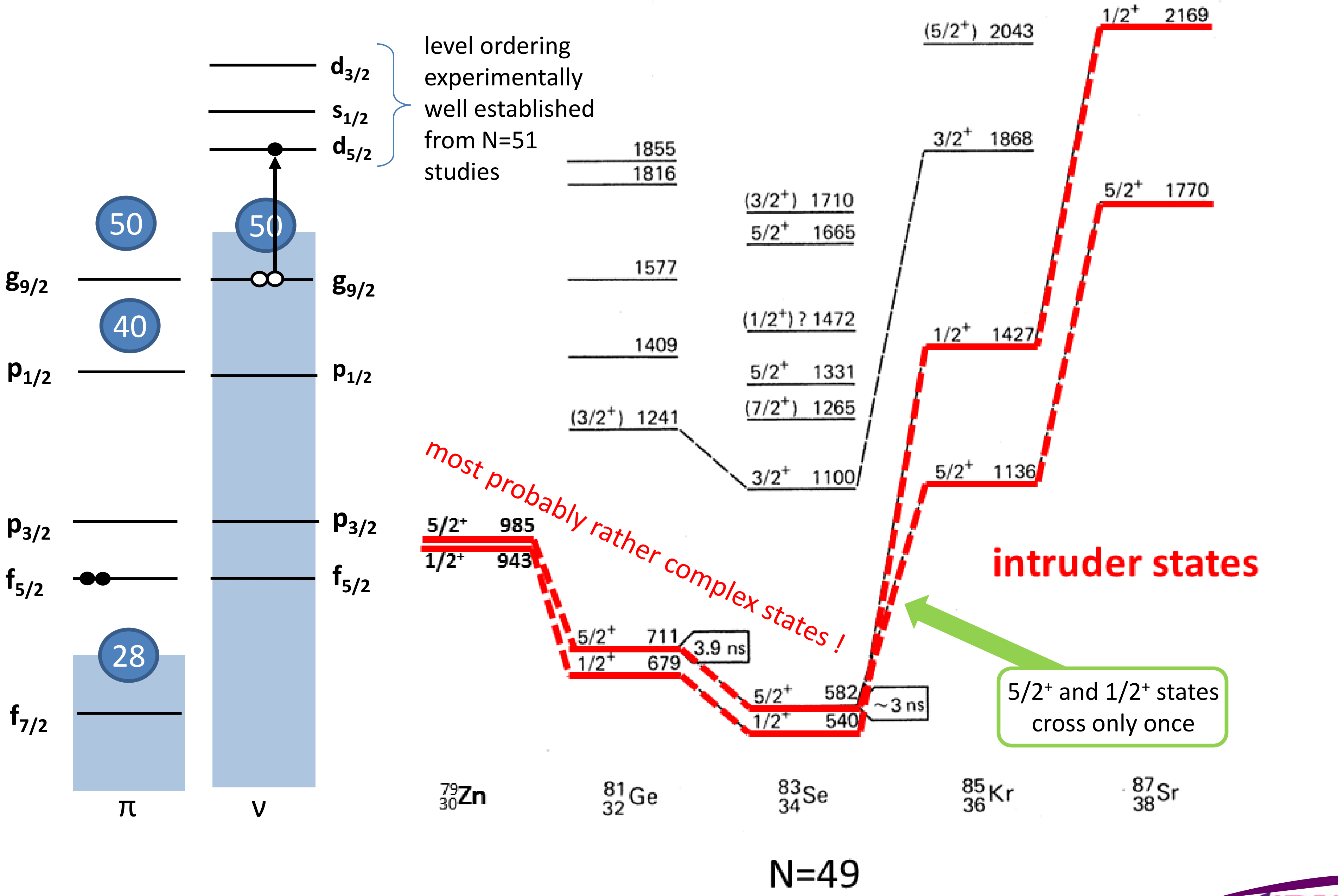
M.-C. Delattre PhD U. Paris Sud
I. Matea, M. Niikura et al. in preparation

RIBF/RIKEN
WAS3aBi + EUROBALL clusters (EURICA)

^{79}Cu β-decay γ-spectroscopy



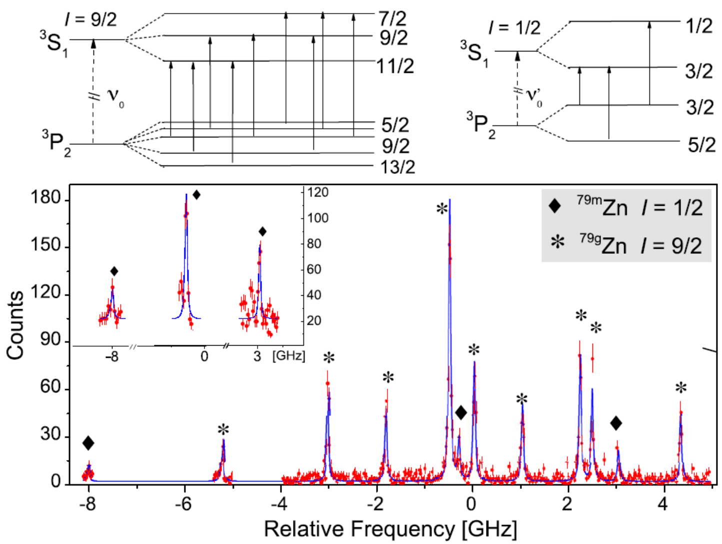
Intruder states at N≈50 : closer to Z=28

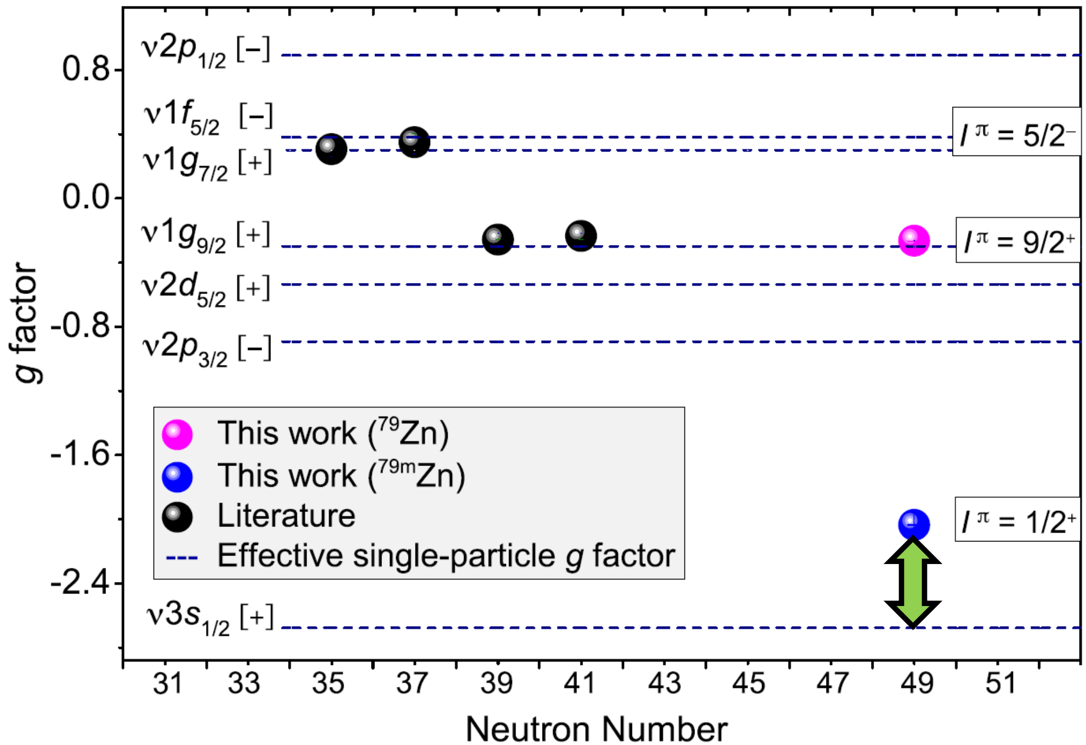


X. Yang et al. PRL 116 182502 (2016)

^{79}Zn laser spectroscopy investigation at ISOLDE

COLLAPS collaboration





- confirms the $\nu s_{1/2}$ nature of the isomeric state already proposed from ^{78}Zn(d,p)^{79}Zn

C. Wraith et al. PLB 771 385 (2017)

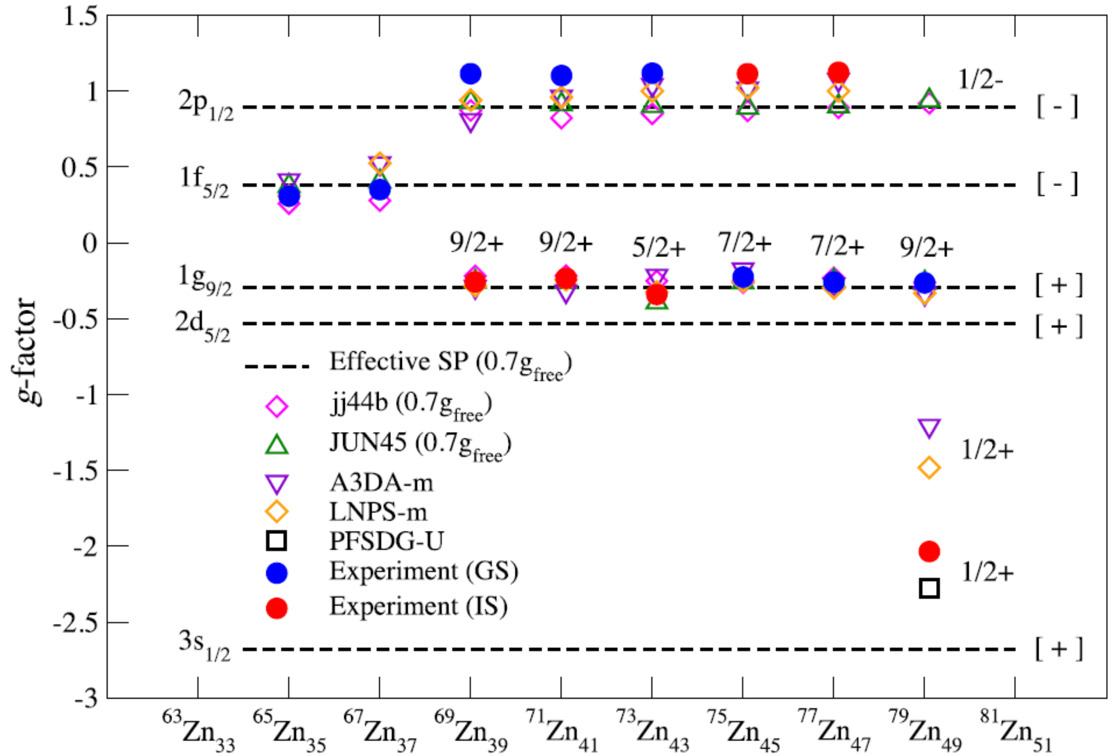
What shell model says ?

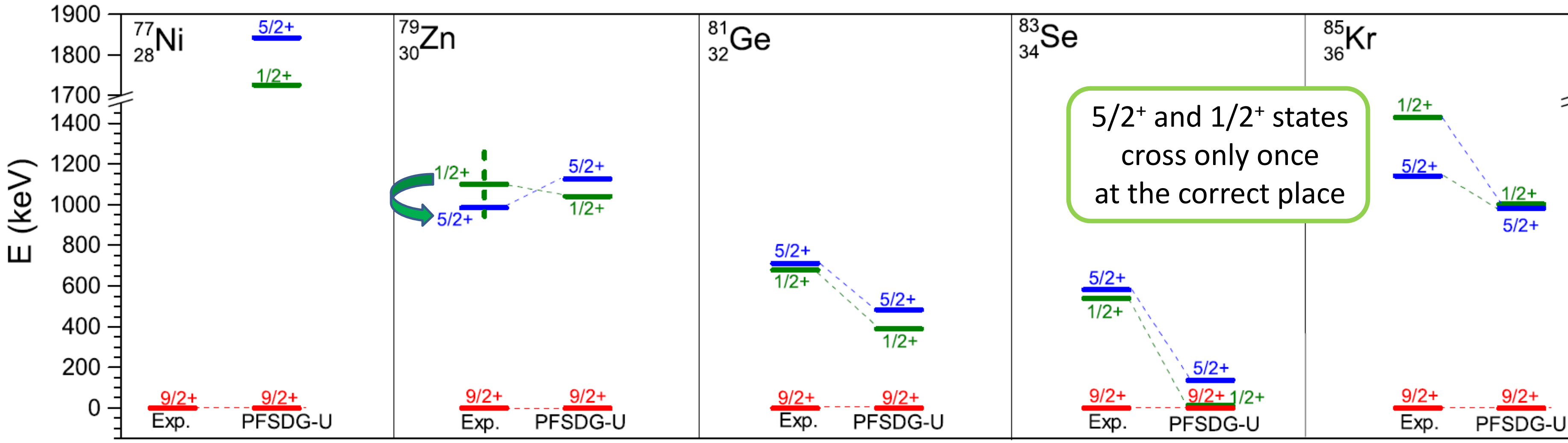
Strasbourg-Madrid collaboration's model space now includes :

- fp protons and neutrons
- + gds neutrons

PFSDG-U interaction
[Nowacki et al PRL 117, 272501 (2016)]
(see Alfredo's talk)

The "complexity" of the intruder states seems to be under control





C. Wraith et al. PLB 771 385 (2017)

What shell model says ?

Strasbourg-Madrid collaboration's model space now includes :

- fp protons and neutrons
- + $d_{5/2}$ $s_{1/2}$ neutrons

PFSDG-U interaction
[Nowacki et al PRL 117, 272501 (2016)]
(see Alfredo's talk)

The "complexity" of the intruder states seems to be under control

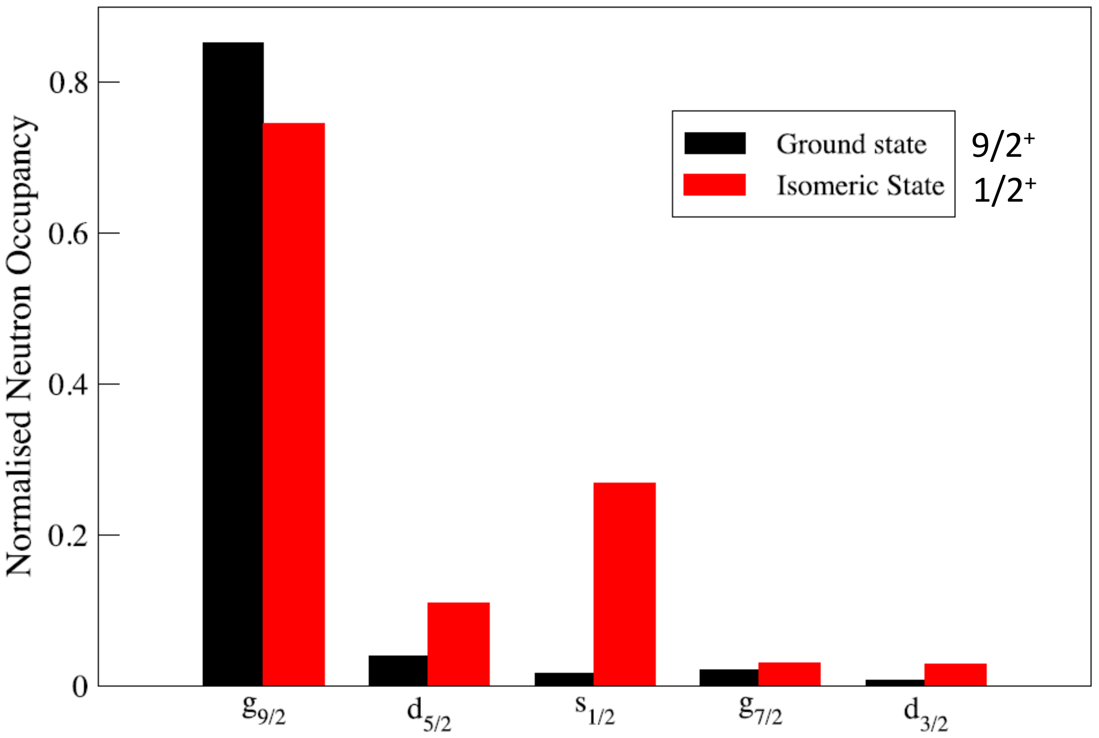


Fig. 6. Neutron occupancy normalised to the maximum orbital nucleon number for the ground and isomeric states in ^{79}Zn from the PFSDG-U interaction.

Shape coexistence ? What shapes ?

X. Yang et al. PRL 116 (2016)

^{79}Zn : isomer shift measured

COLLAPS collaboration

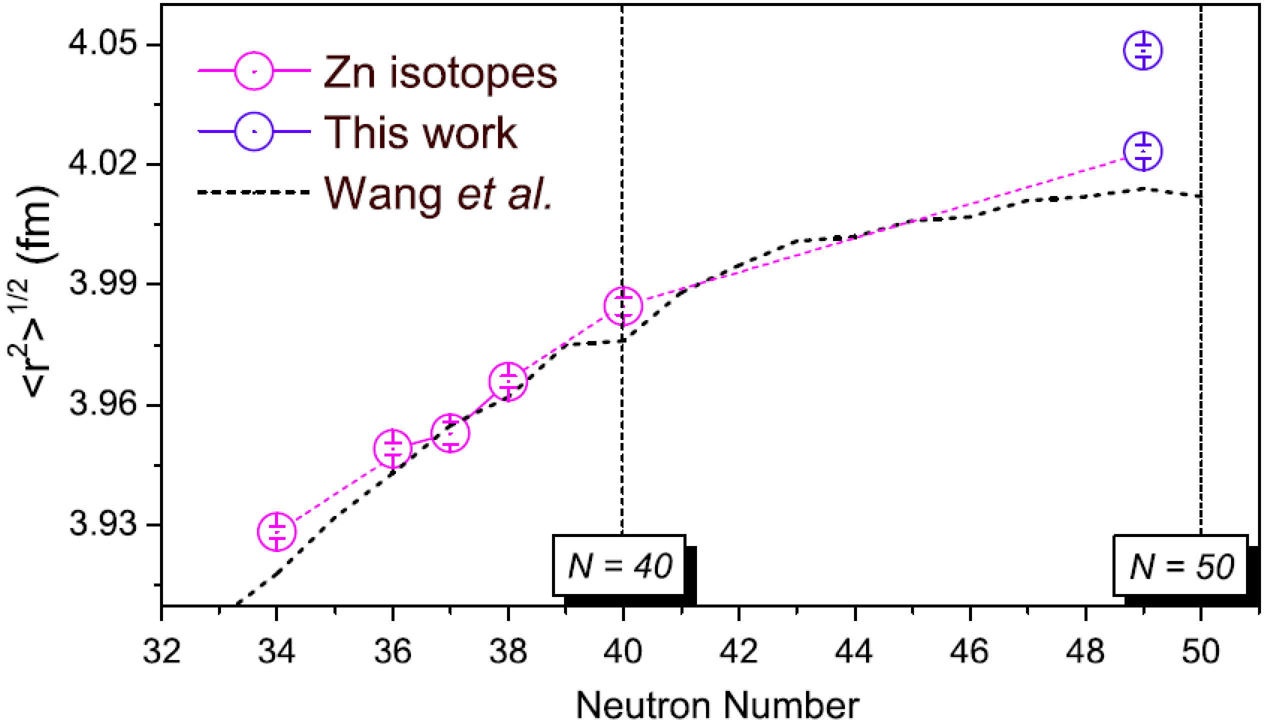
A. Gottardo et al. PRL 116 (2016)

^{80}Ge : no ρ(E0) extracted

ALTO collaboration

Shape coexistence ? The clearest direct experimental evidence :

$$\langle r_c^2\rangle(^{79m}\mathrm{Zn}) - \langle r_c^2\rangle(^{79g}\mathrm{Zn}) = 0.204(6)[36]\ \mathrm{fm}^2$$



^{80}Ge : “normal” configuration : soft or triax [Verney et al. PRC **87** 054307 (2013)]

→ lots of similarities with Tl case

Shape coexistence in ^{78}Ni ?

PRL **117,** 272501 (2016) PHYSICAL REVIEW LETTERS week ending 30 DECEMBER 2016

Shape Coexistence in ^{78}Ni as the Portal to the Fifth Island of Inversion

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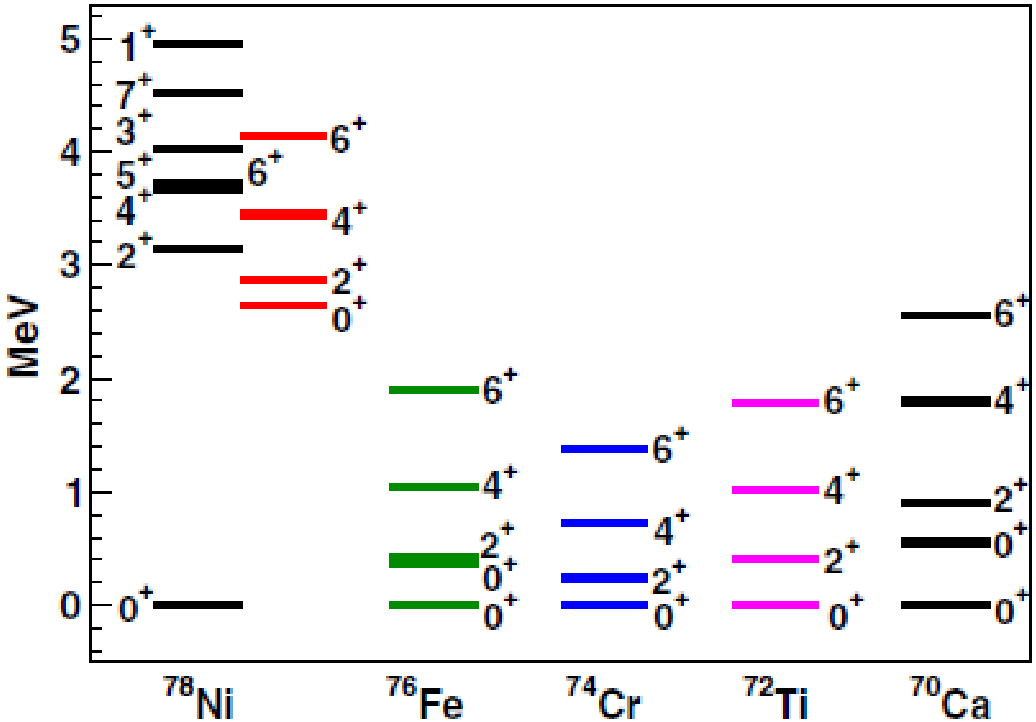
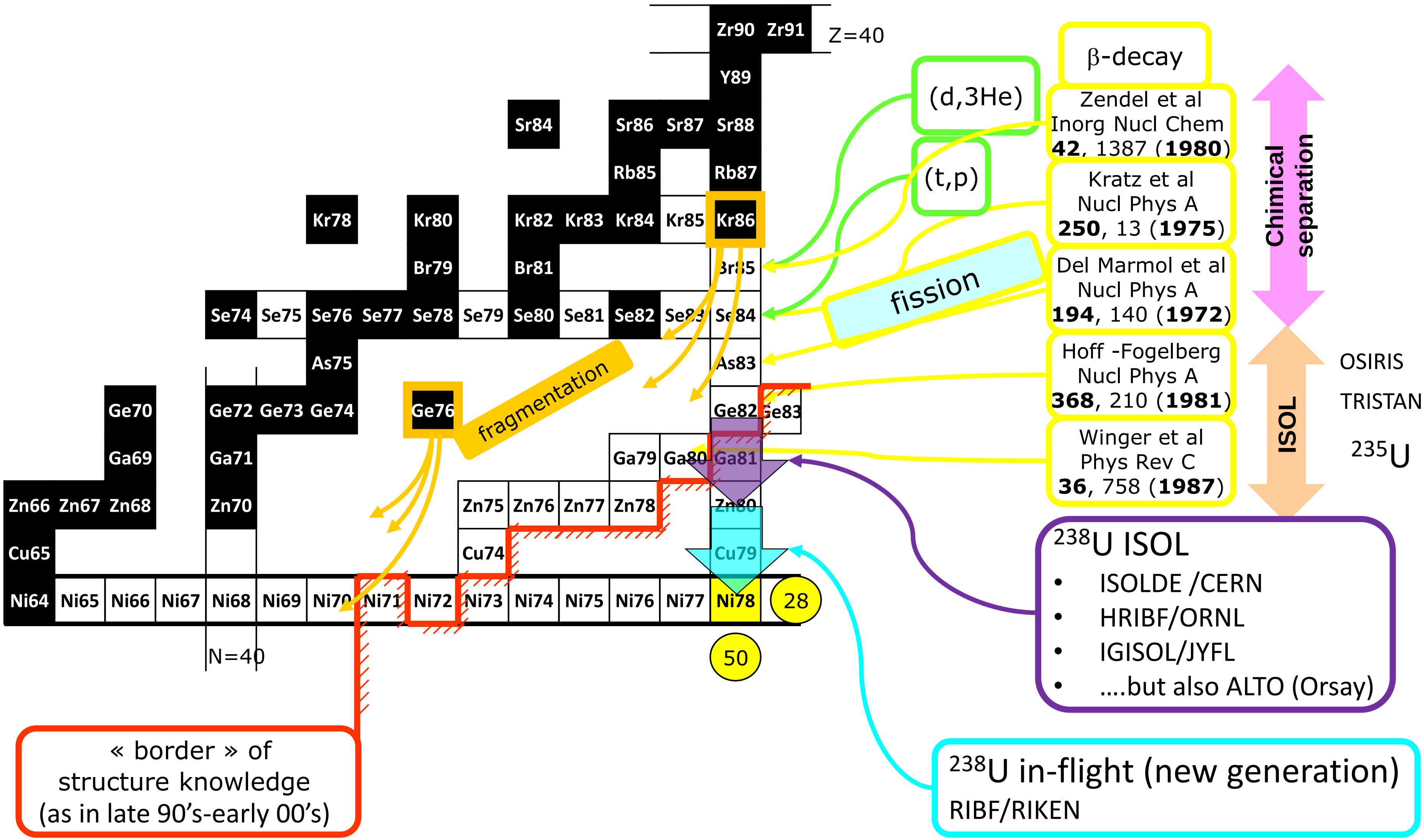
[1]*Université de Strasbourg, IPHC, 23 rue du Loess 67037 Strasbourg, France*
[2]*CNRS, UMR7178, 67037 Strasbourg, France*
[3]*Departamento de Física Teórica e IFT-UAM/CSIC, Universidad Autónoma de Madrid, E-28049 Madrid, Spain and Institute for Advanced Study, Université de Strasbourg, France*
(Received 30 May 2016; revised manuscript received 14 July 2016; published 27 December 2016)



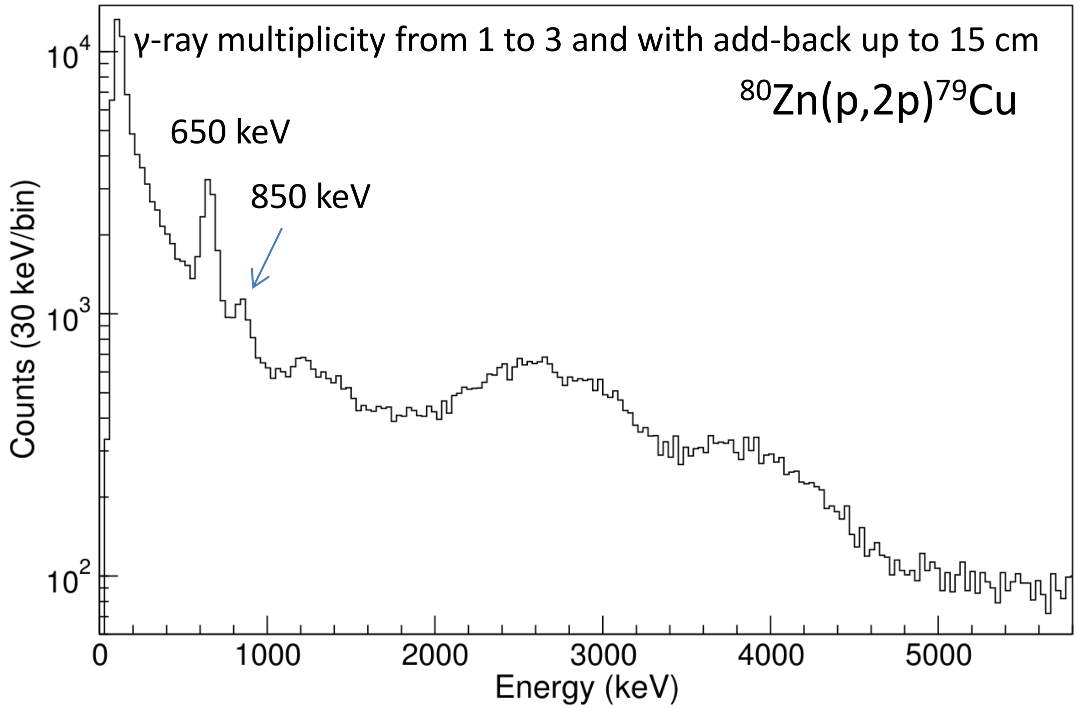
Shape coexistence in ^{78}Ni ?



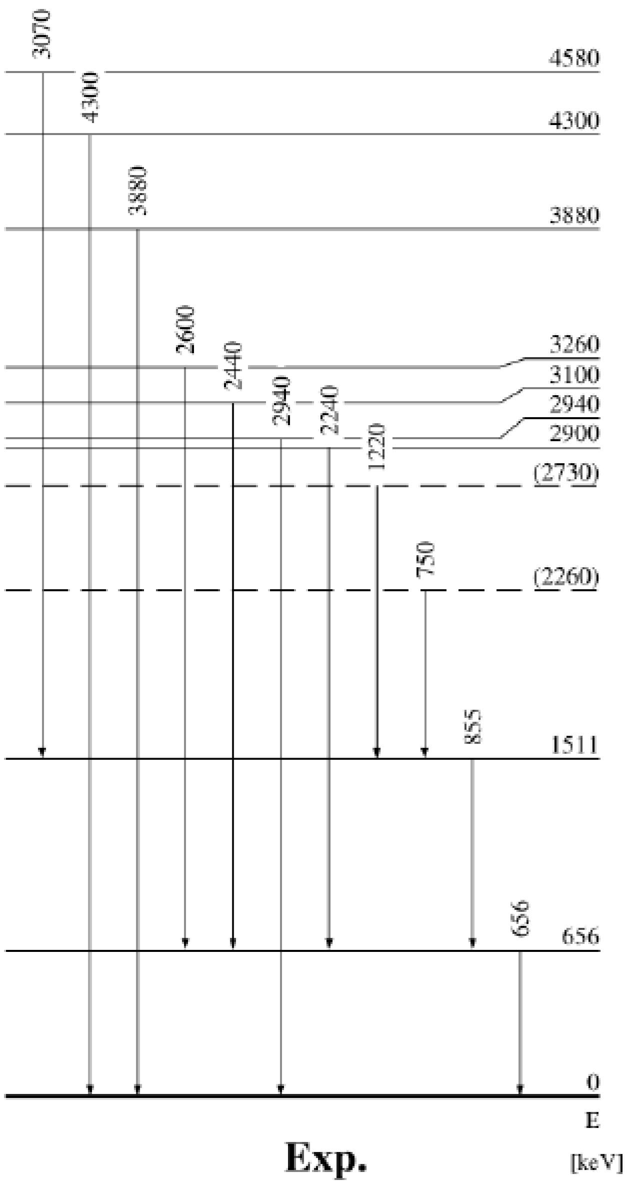
Proton intruder states in ^{79}Cu ?

L. Olivier PhD U. Paris Sud
L. Olivier, S. Franchoo et al. PRL in press

RIBF/RIKEN
BigRIPS+MINOS+DALI2



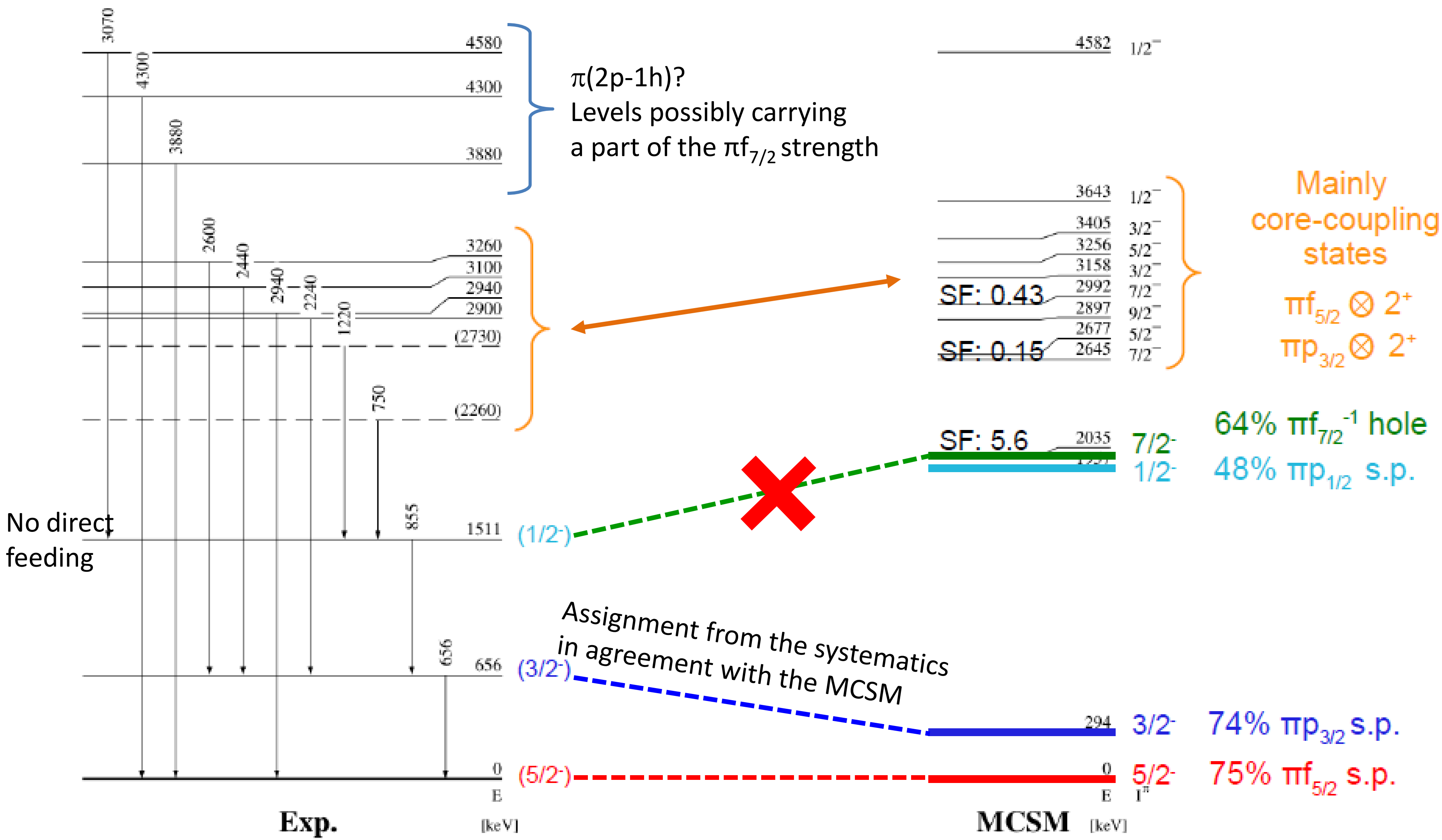
courtesy Louis Olivier



Proton intruder states in ^{79}Cu ?

^{79}Cu

π(2p-1h) high in energy
$\pi f_{7/2}$ strength looks unexpectedly fragmented



Y. Tsunoda, T. Otsuka *et al.*,
PRC 89, 031301(R) (2014)

Perspectives: a lot of (challenging) work ahead

We have just scratched the surface of the question of shape coexistence near ^{78}Ni

Second 0^+

- confirm Orsay finding
- find other cases : ^{82}Ge, ^{78}Zn
- measure $\rho(E0)$

→ recent attempt to study isomerically separated 3^- ^{80}Ga decay at CRIS/ISOLDE with TATRA (exp IS571 T. Cocolios et al.)

→ approved proposal at ISAC/TRIUMF: ^{80,82}Ga decay investigated with GRIFFIN and PACES (exp S1749 C. Andreoiu et al.)

→ follow-up program at ALTO, Orsay

Intruder states

- **N=49** : 1/2+ magnetic properties in ^{81}Ge to better understand the 2h-1p structures
- **N=51** : no intruder 1h-2p experimentally identified : the question is completely open
- **N=50** : energy location of Yrast 1p-1h in ^{80}Zn

→ AGATA@VAMOS proposal by J. Dudouet, A. Lemasson, E. Clément et al.

What shapes ?

- better understand the Z=32 "singularity"

→ Plunger+AGATA lifetime data being analyzed (C. Delafosse PhD U. Paris Sud)

towards an even busier decade

Third golden age : >2016

A new dawn for shape coexistence studies near N=50 towards ^{78}Ni