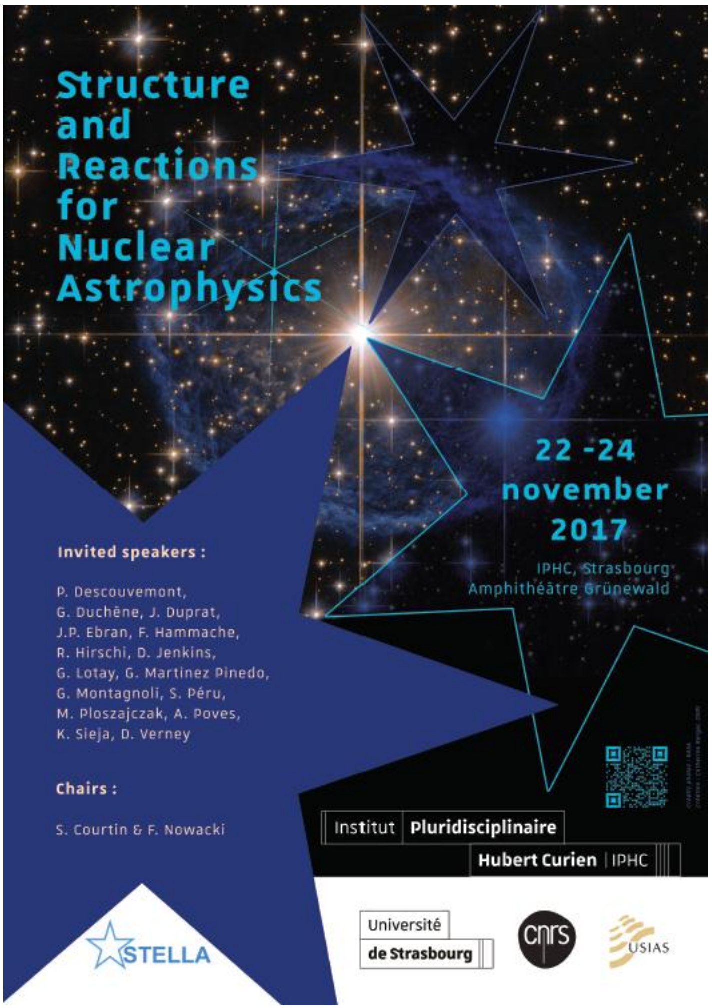
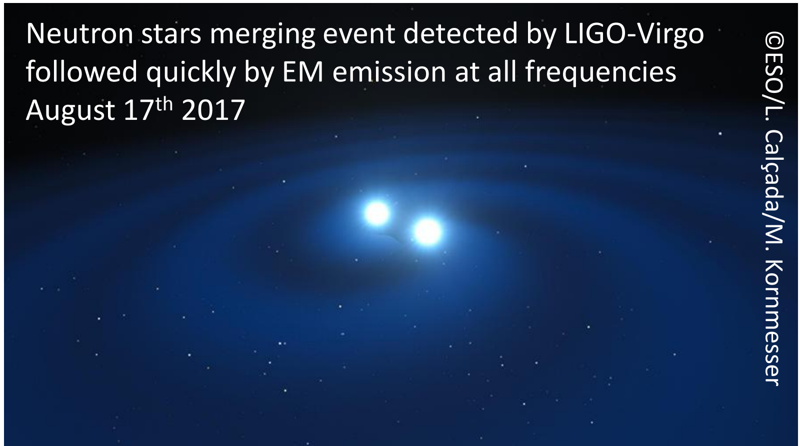
Spectroscopy investigation of the ^{78}Ni region: recent progress and future perspectives

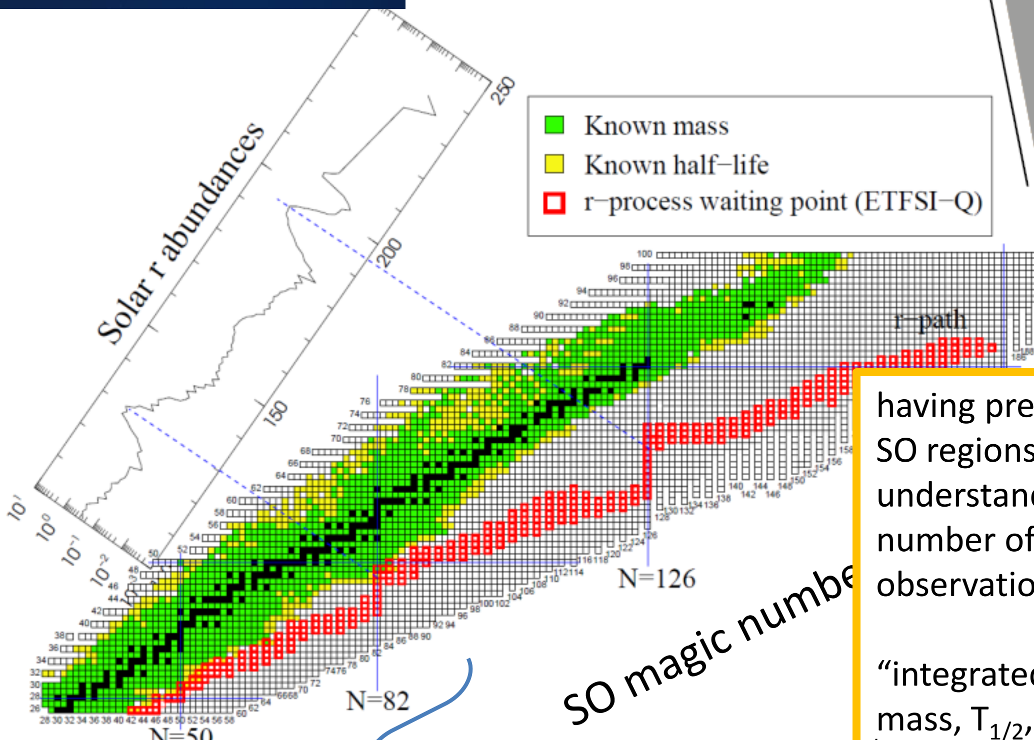
David Verney, IPN Orsay

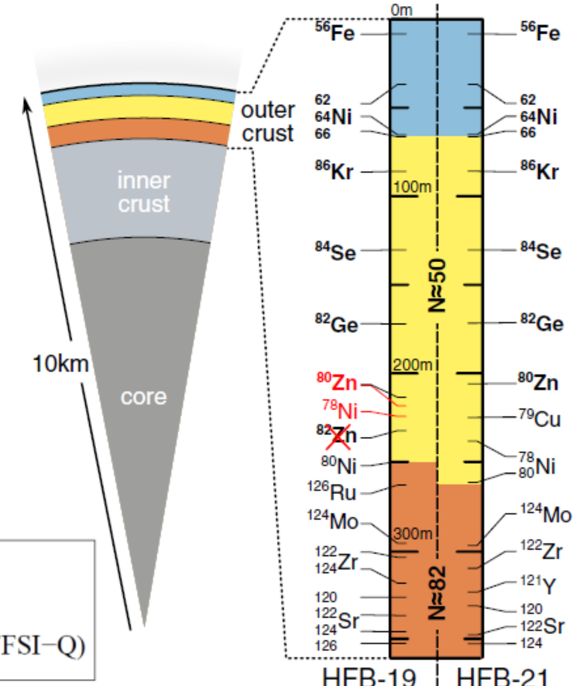


- N=50 in the sequence of the Spin-Orbit (Intruder-Extruder) magic numbers
- gap size $\rightarrow$ Z=32 “singularity”
- shape coexistence
- neutron threshold effects and the question of first-forbidden transitions in the ^{78}Ni region

SO magic numbers in nature







Wolf et al. PRL 110 (2013)

SO magic numbers

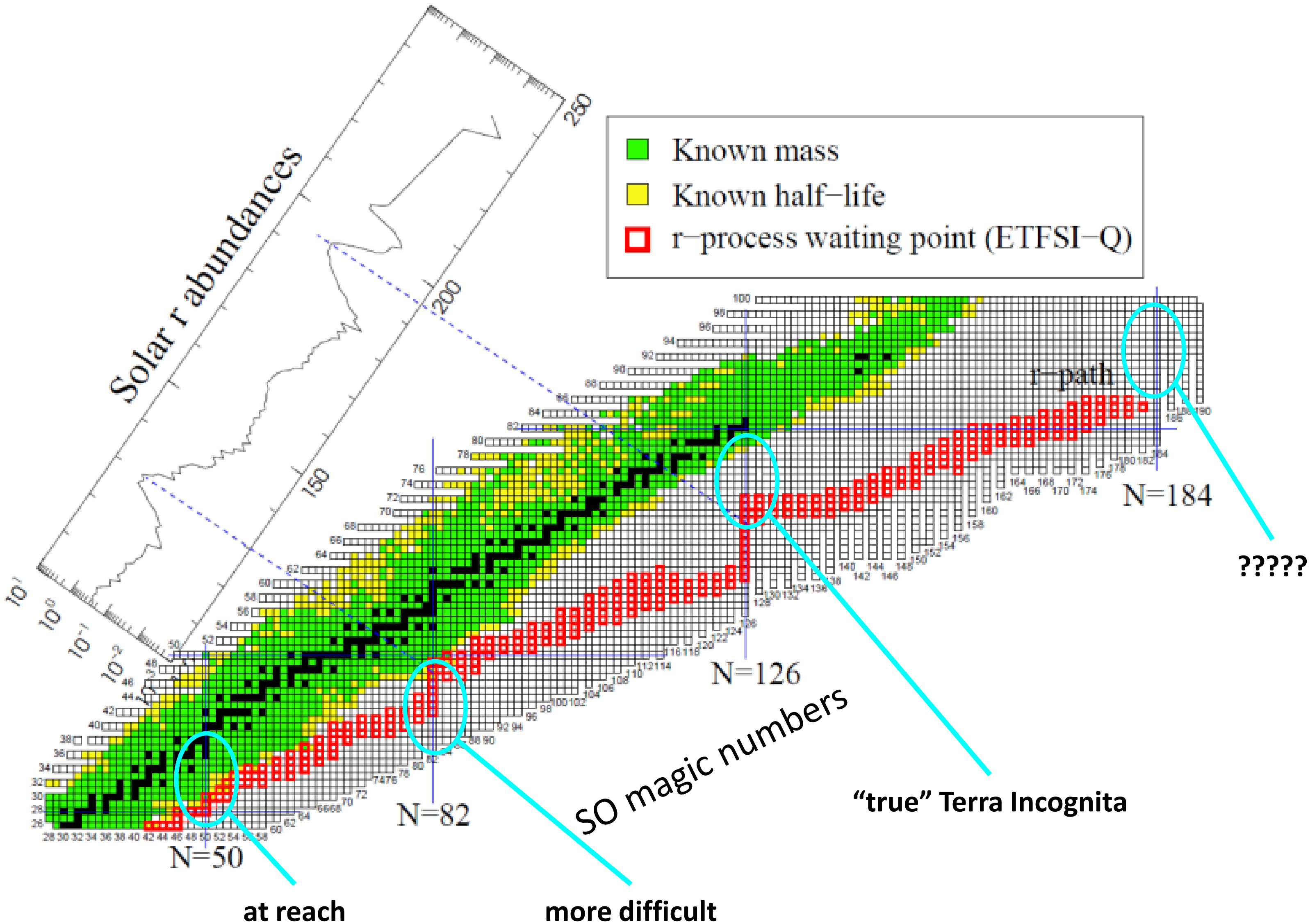
on earth
fission of actinides

having precise nuclear data (in SO regions) will help in understanding an increasing number of astro-physical observations

"integrated" quantities needed: mass, $T_{1/2}$, P_n ...

nuclear structure

SO magic numbers : a long-term roadmap (on earth)



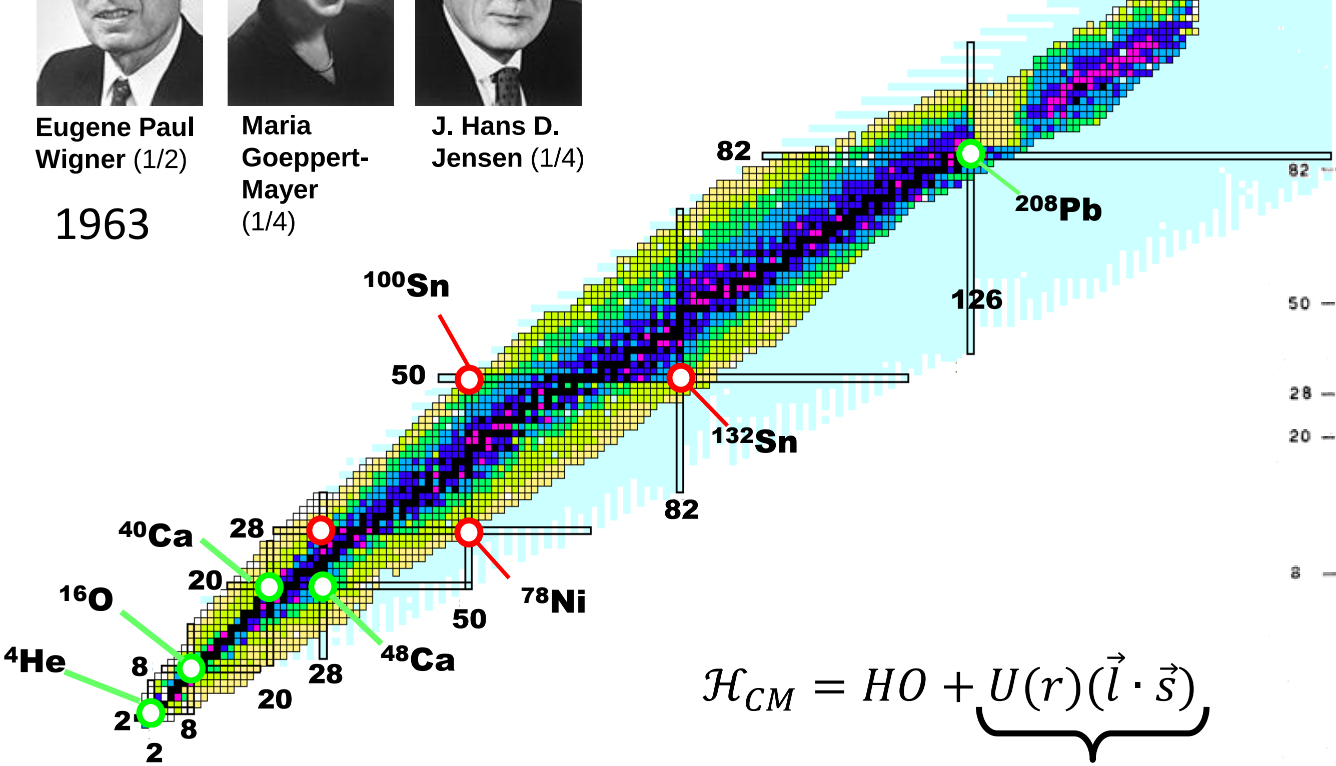
SO magic numbers in historical nuclear physics

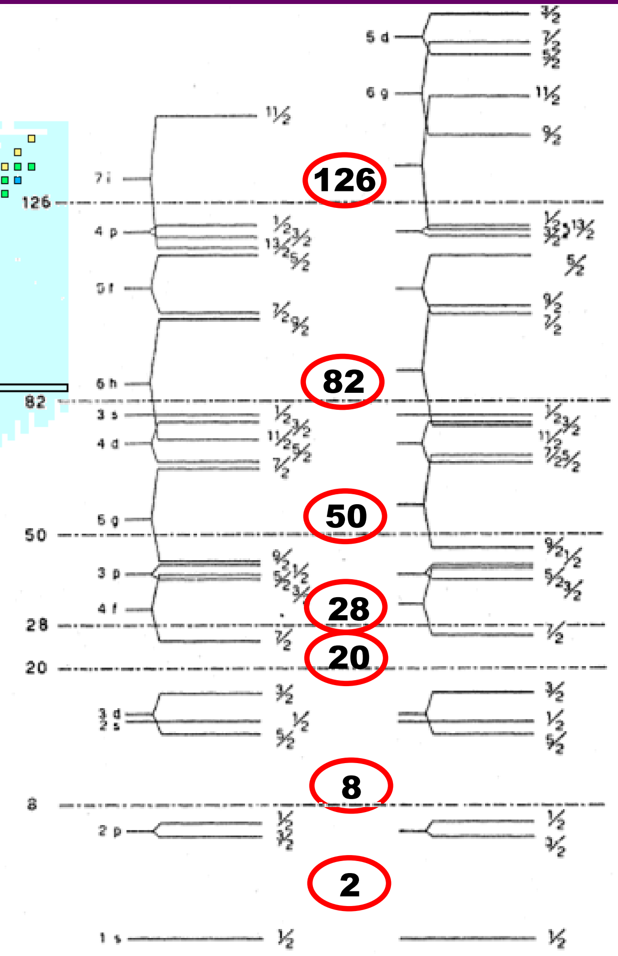
Eugene Paul Wigner (1/2)

Maria Goeppert-Mayer (1/4)

J. Hans D. Jensen (1/4)

1963



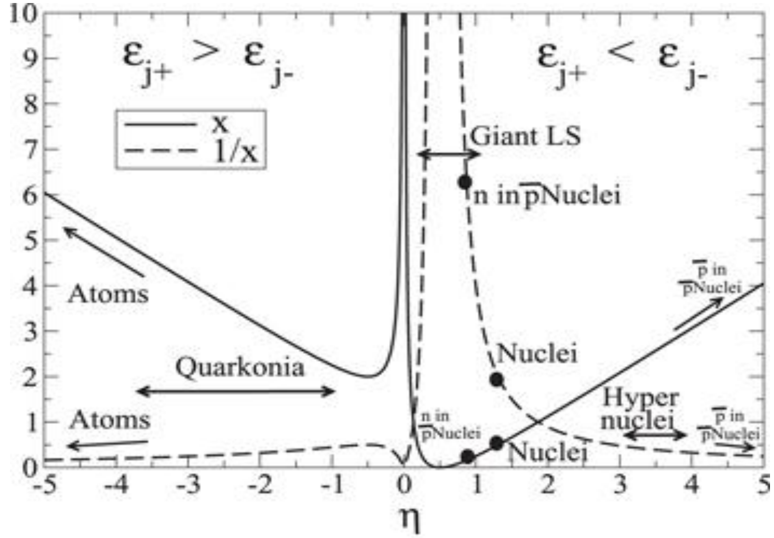


$$\mathcal{H}_{CM} = HO + \underbrace{U(r)(\vec{l}\cdot\vec{s})}_{V^{LS}}$$

the great surprise:

$$x \equiv \frac{\hbar\omega_0}{|\Delta\langle V^{SL}\rangle|} \approx 1$$

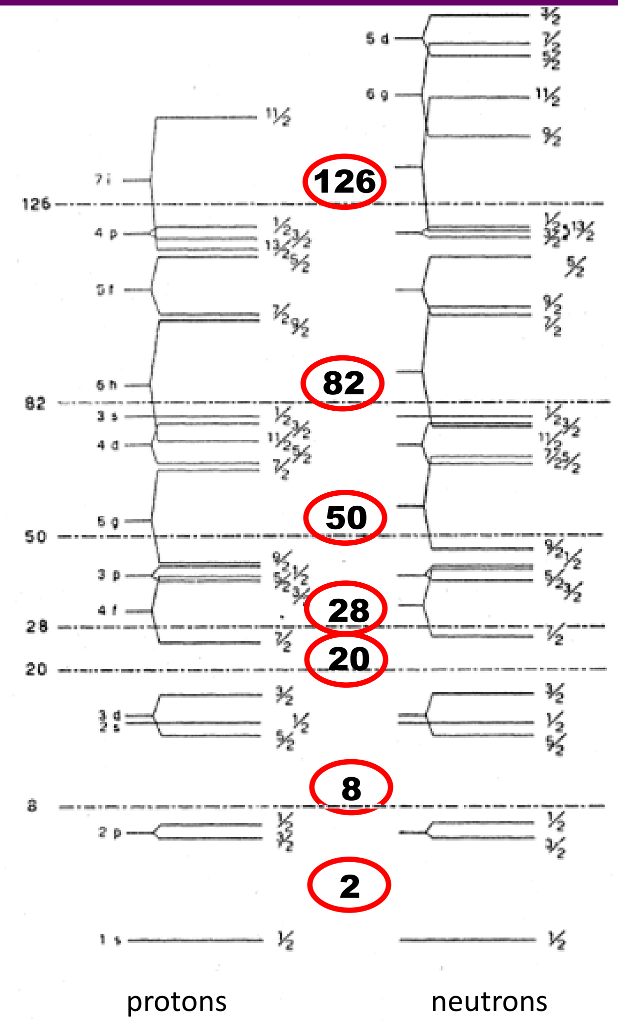
spin-orbit : universal effect for quantum systems made of particles having spin : atoms, nuclei, hyper-nuclei, quarkonia…
important role in condensed matter : cold atoms, spintronics, topological insulators...



J-P Ebran et al 2016 J. Phys. G: Nucl. Part. Phys. 43 085101

$$\eta \equiv \frac{m}{V - S}$$

$$x \equiv \frac{\hbar\omega_0}{|\Delta\langle V^{SL}\rangle|}$$



Dirac equation gouverning the single particle motion dynamics →

$$V^{LS} = \frac{1}{2M^2(r)}\frac{1}{r}\frac{d}{dr}(V(r) - S(r))\vec{l}\cdot\vec{s}$$

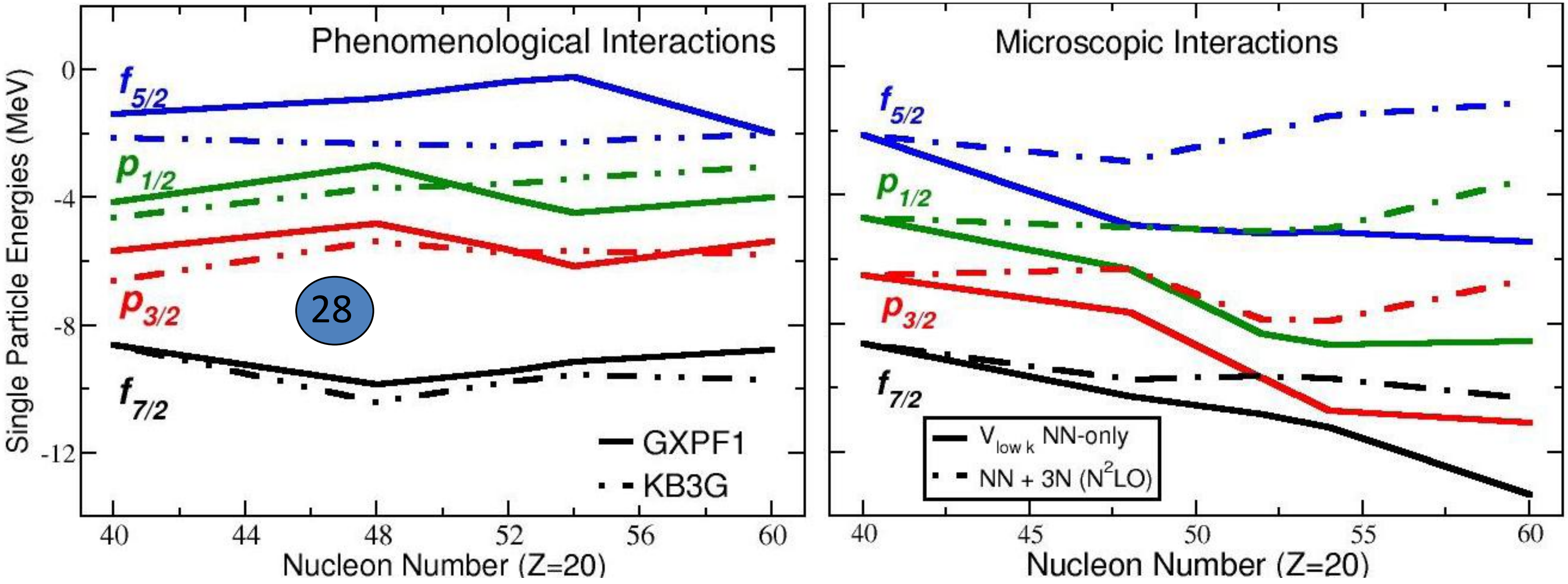
vector potential (short range repulsion) $\approx +350$ MeV

scalar potential (medium range attraction) ≈ -400 MeV

nucleon mass ≈ 940 MeV

in atomic system:

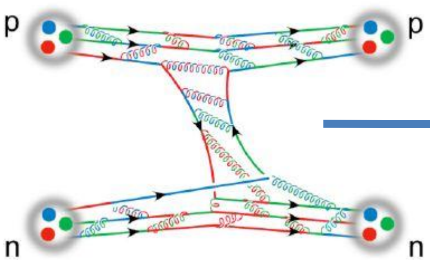
$$x \sim \frac{1}{\alpha^2} \approx 10^4$$



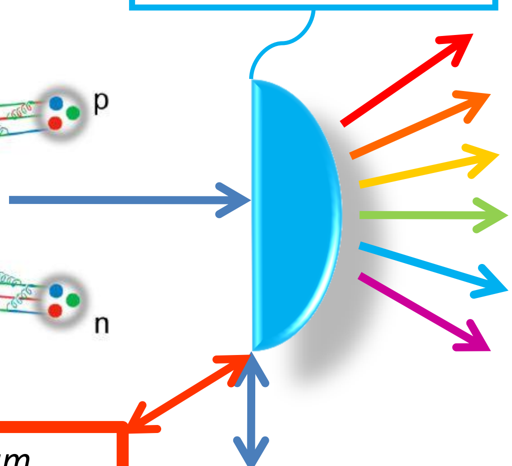
Holt, Otsuka, Schwenk, Suzuki

SO magic numbers : an "emerging" phenomenon

nucleon-nucleon interaction

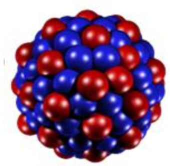


many body problem

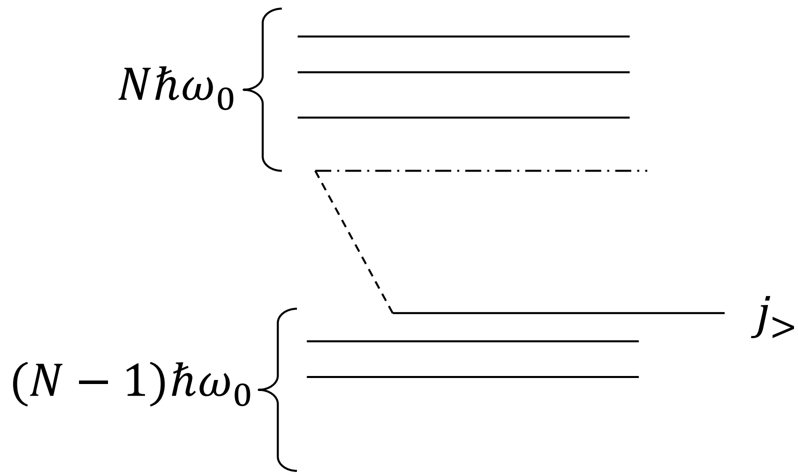


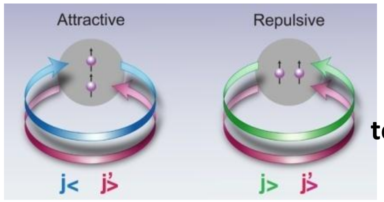
varying *in-medium conditions*
≡ explore exoticity

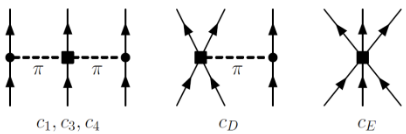
in medium



"effective" nuclear spin-orbit

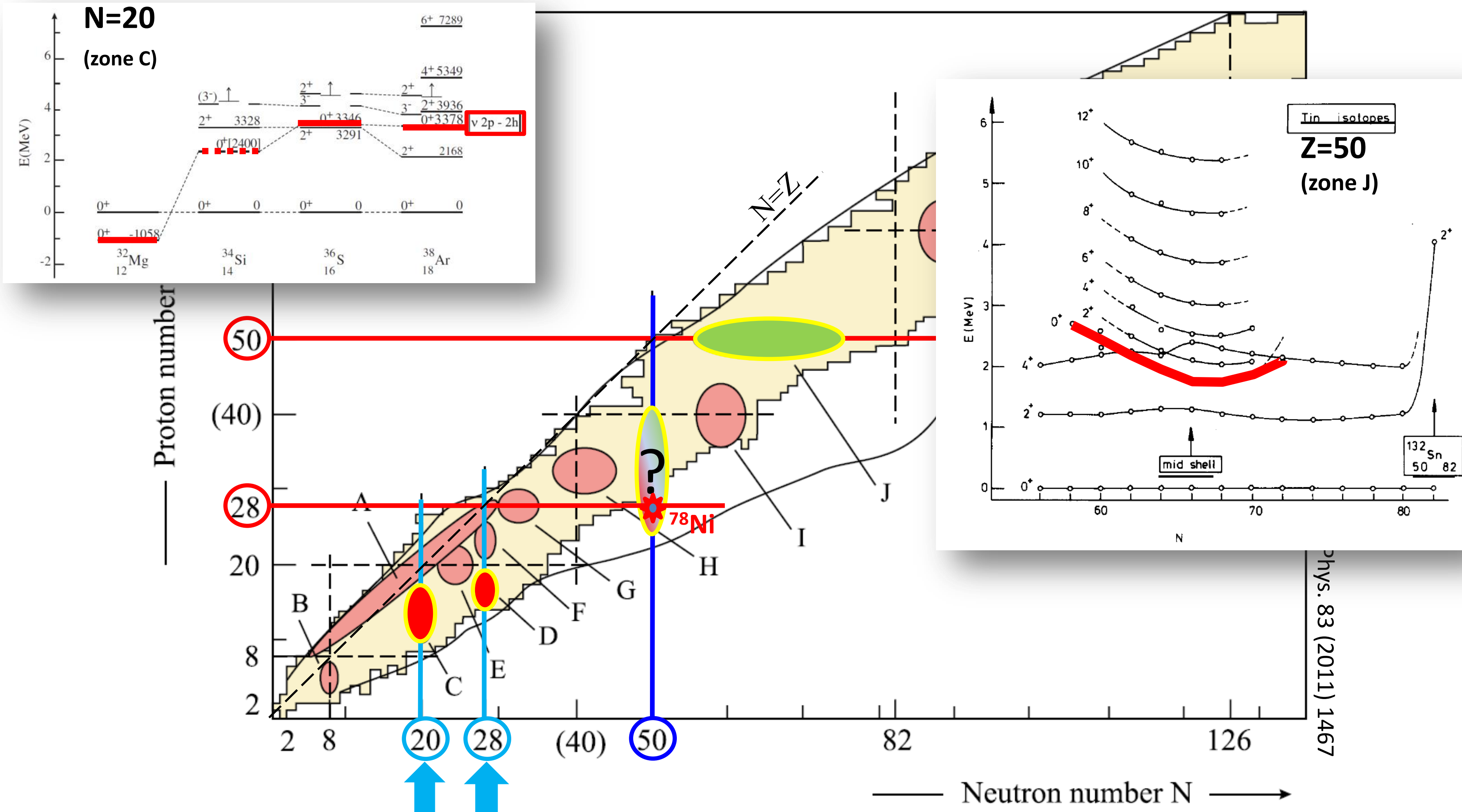






diffusivity, orbit size etc

SO magic numbers from a shape-coexistence point of view

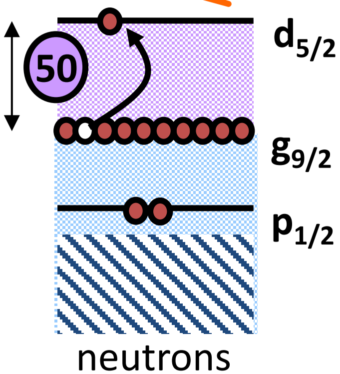


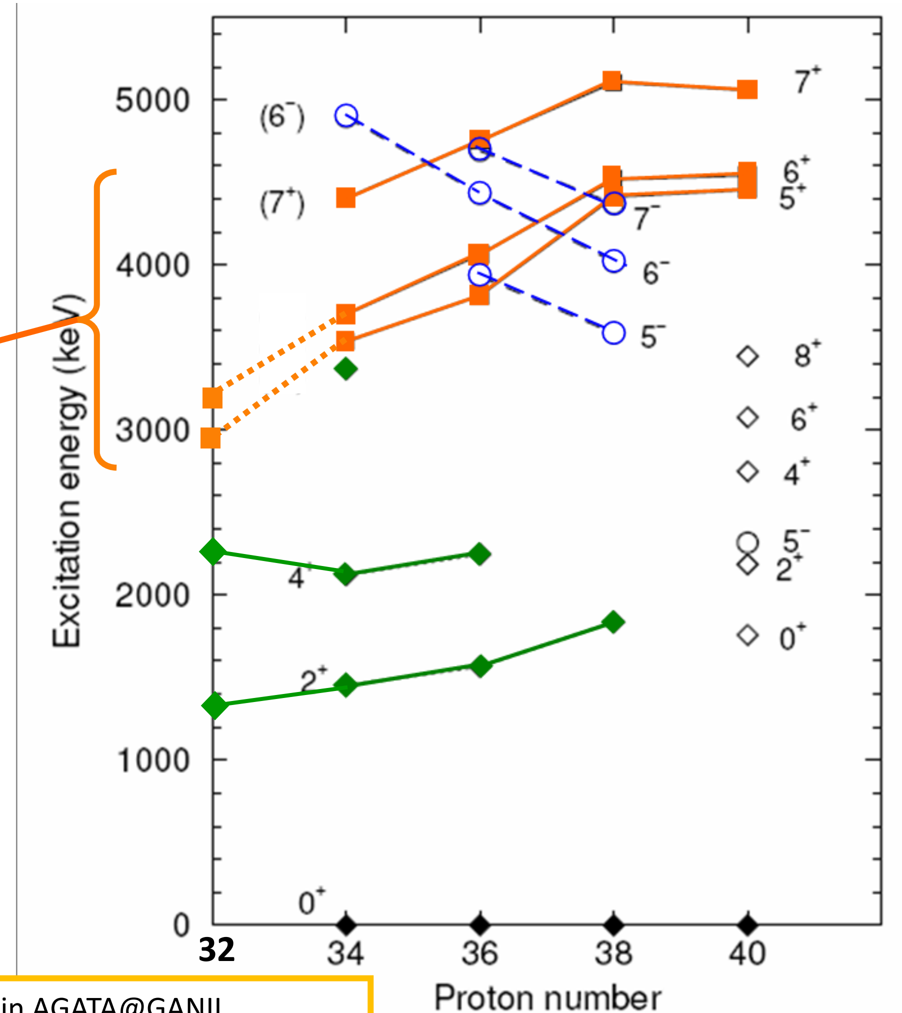
historical case N=20 (^{32}Mg region)
Klapisch PRL 31 118 (1973)
Thibault PRC 12 644 (1975)
Détraz PRC 19 164 (1979)

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

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)





some “shell quenching”

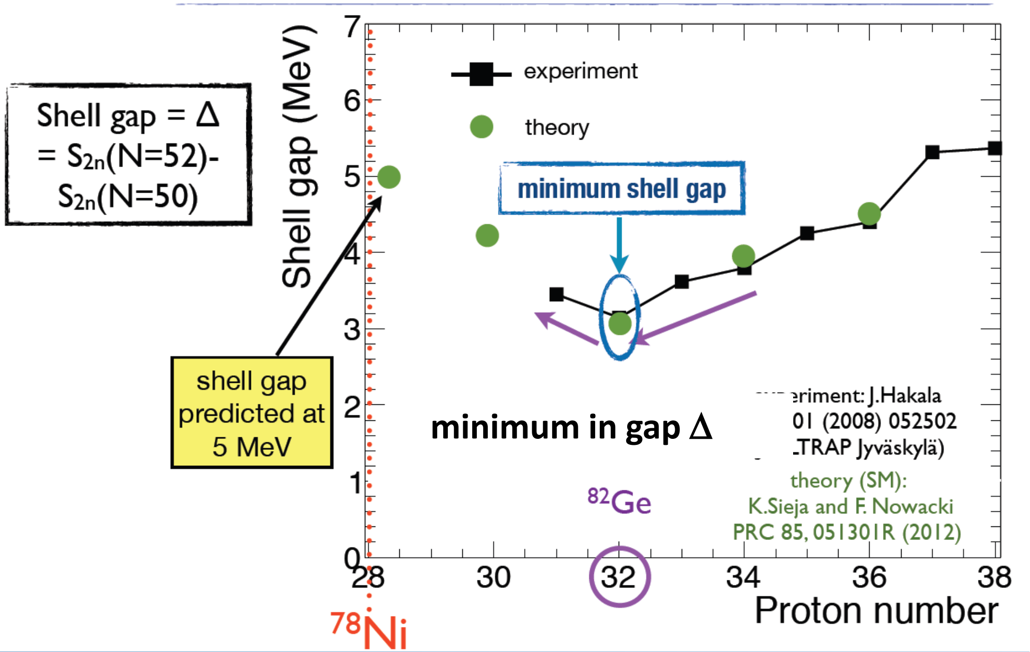
O. Sorlin, M.G. Porquet
Prog. Part. Nucl. Phys. 61 (2008) 602

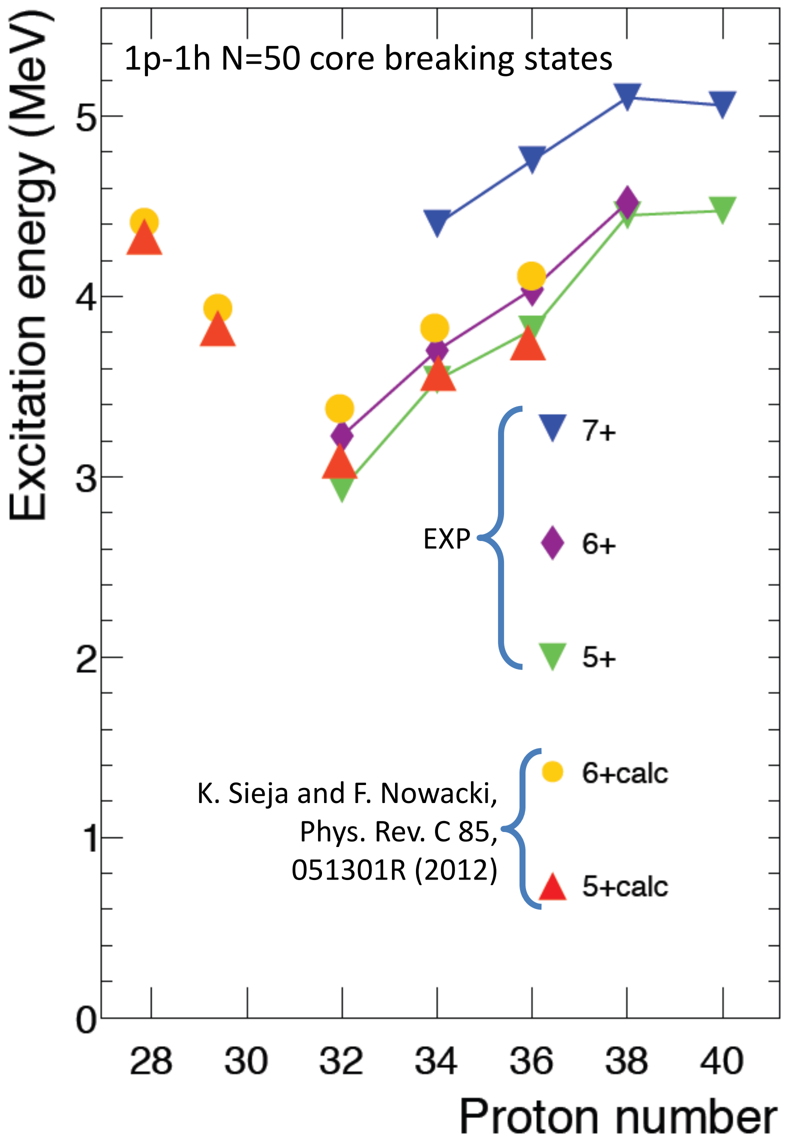
N=50 gap extrapolation
→ ^{78}Ni =3.0(5) MeV

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

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





5^+ 6^+ lifetime measurement soon available:
plunger AGATA + VAMOS – Exp. E669 GANIL

High-precision mass spectrometry (JYFLTRAP and ISOLTRAP)

Hakala et al PRL 101, 052502 (2008); S. Baruah et al PRL 101, 262501 (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)

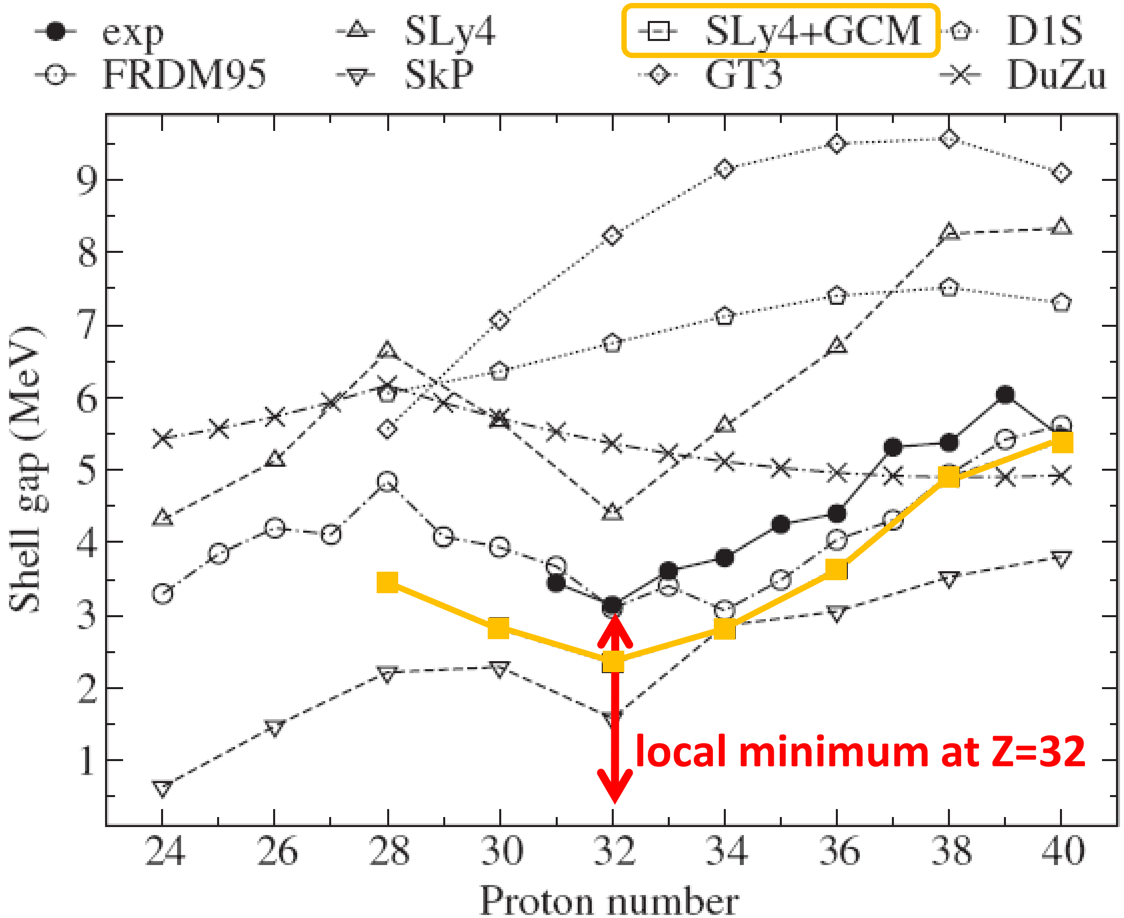
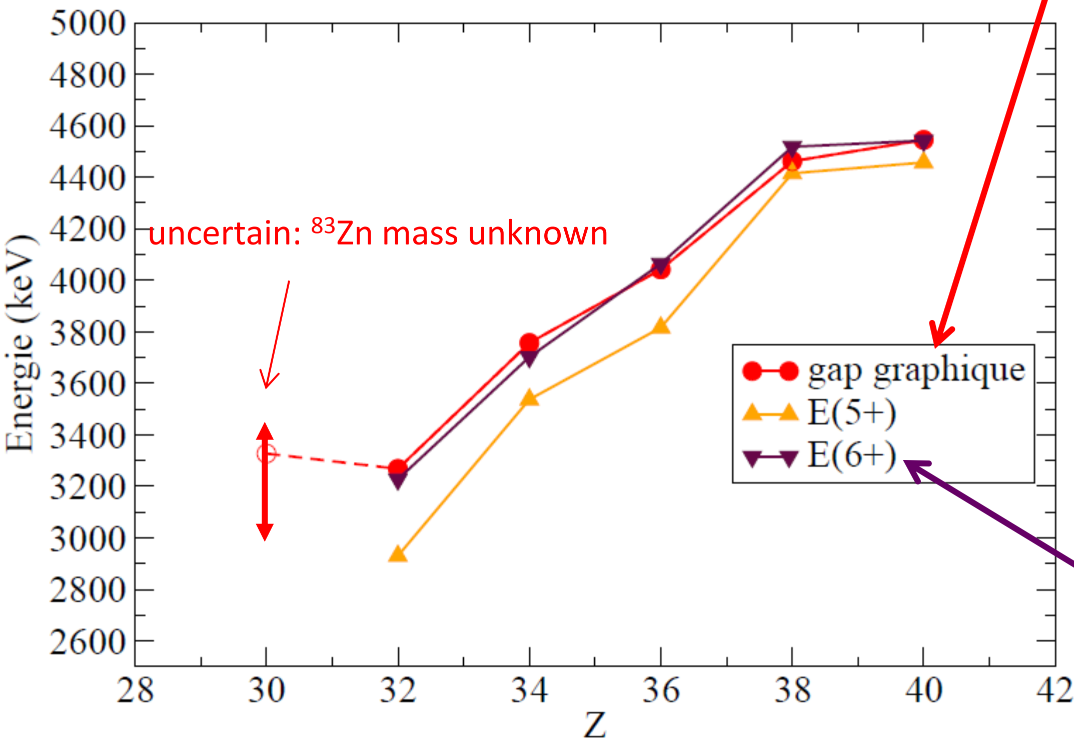
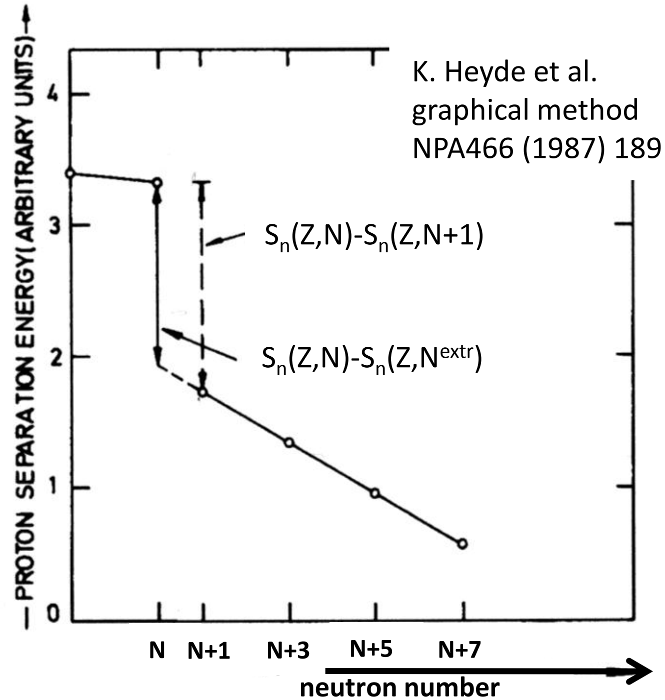


FIG. 4. Evolution of the $N = 50$ shell gap and comparison to theoretical models.

Striking similitude

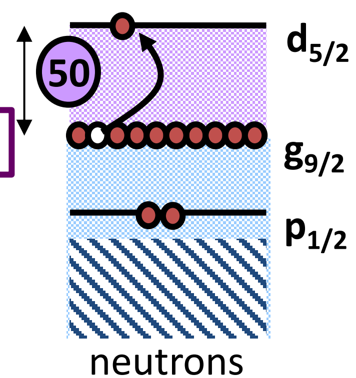
from mass measurements (after correction of upper shell effects)





K. Heyde et al. graphical method NPA466 (1987) 189

from γ-spectroscopy

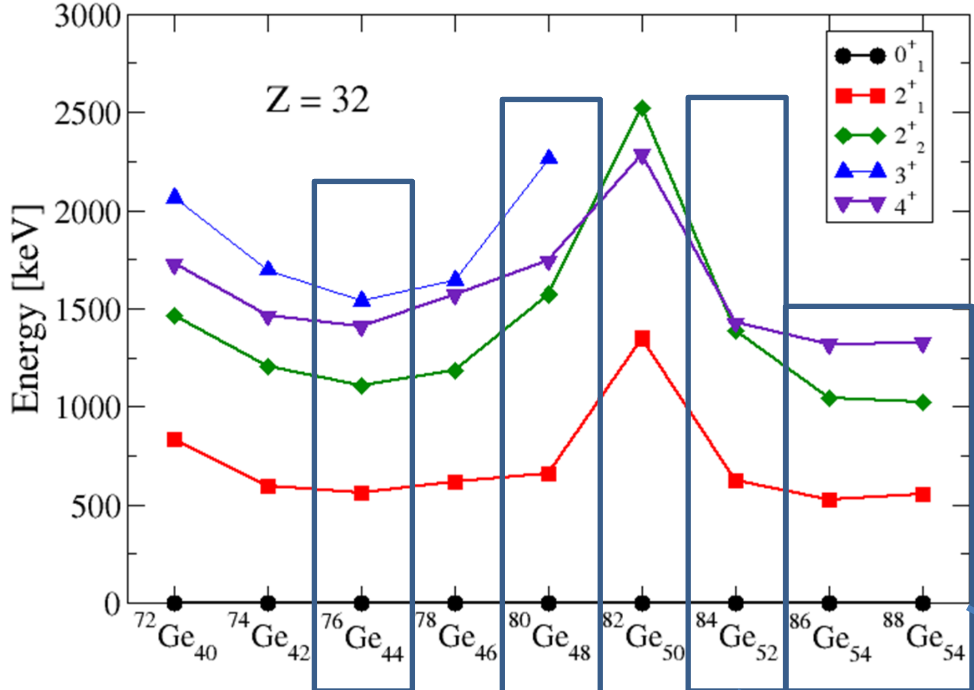


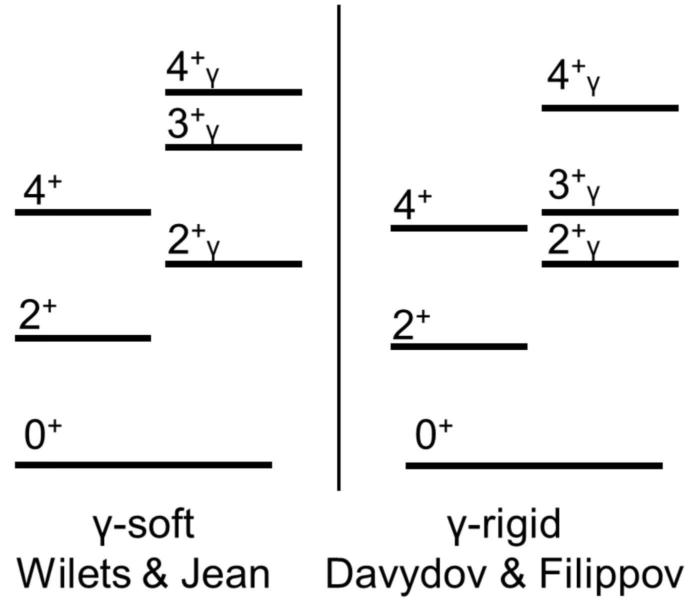
→ pure monopole effect ?

→ how to disentangle spherical mean field from correlation effects ?

→ what correlations ?

Z=32 : a triaxiality "corridor" ?





M. Lettman et al. PRC 96, 011301(R) (2017)

E(4⁺)/E(2⁺) ratio + shell model

stable

Y. Toh et al. PRC 87, 041304(R) (2013)
(multistep-coulex)

M. Lebois et al. PRC 80, 044308 (2009)

S. Mukhopadhay et al. PRC 95, 014327 (2017)
(n,n'γ)

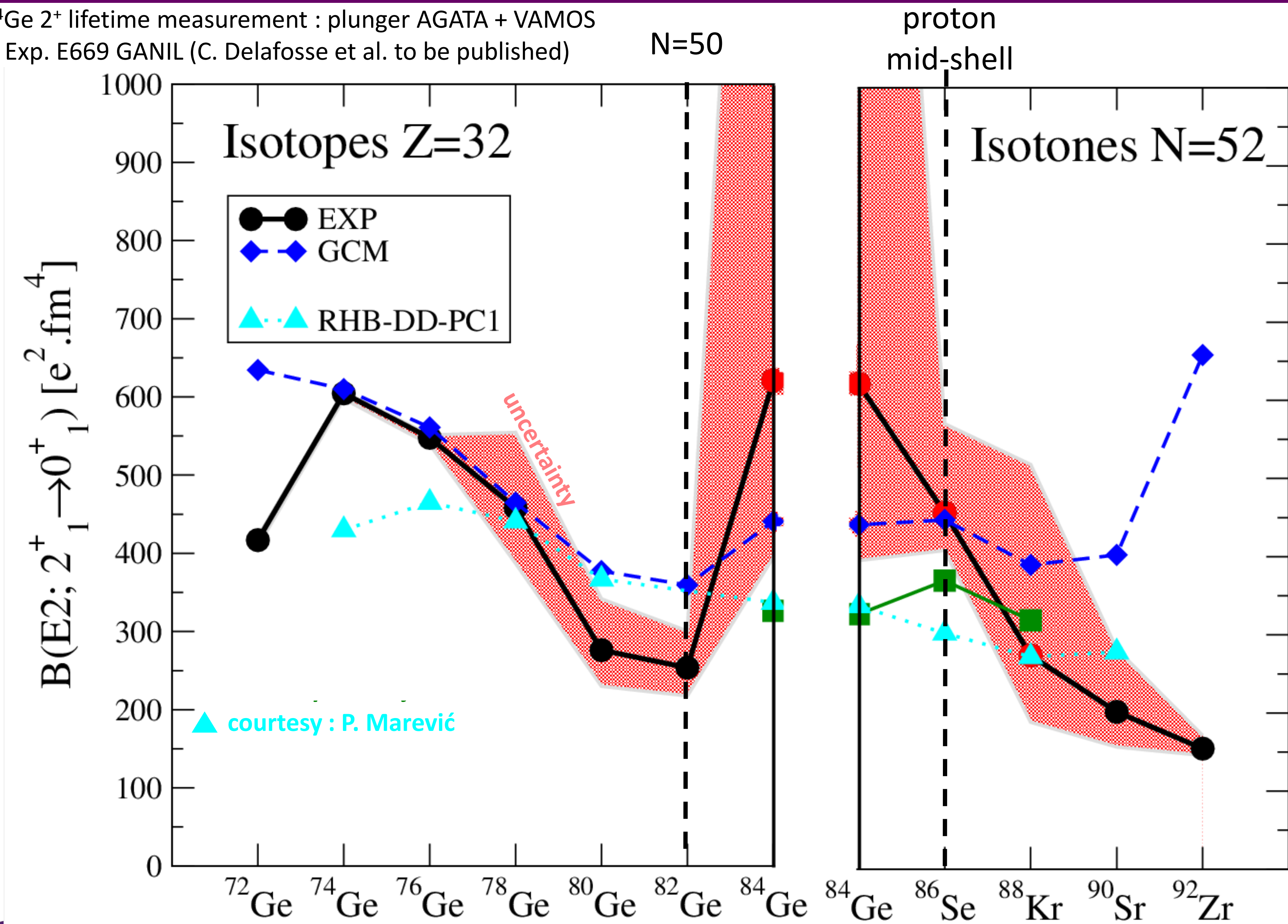
E(4⁺)/E(2⁺) ratio + beyond mean field

→ clearly triaxial

D. Verney et al. PRC 87, 054307 (2013)

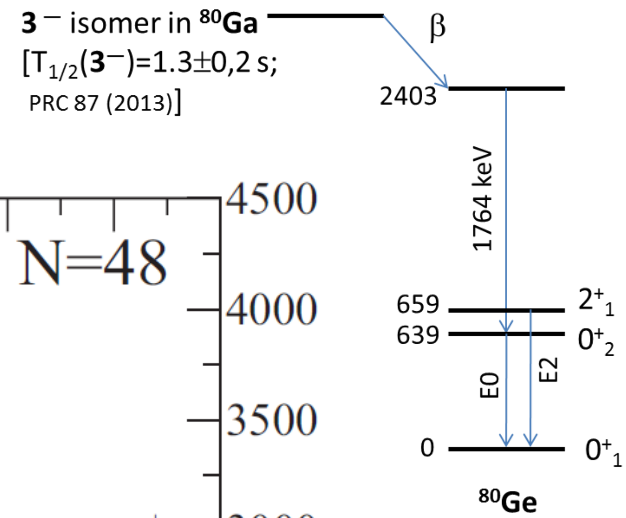
Level scheme and spin assignment (2⁺,(3⁺),4⁺ states)
+ shell model

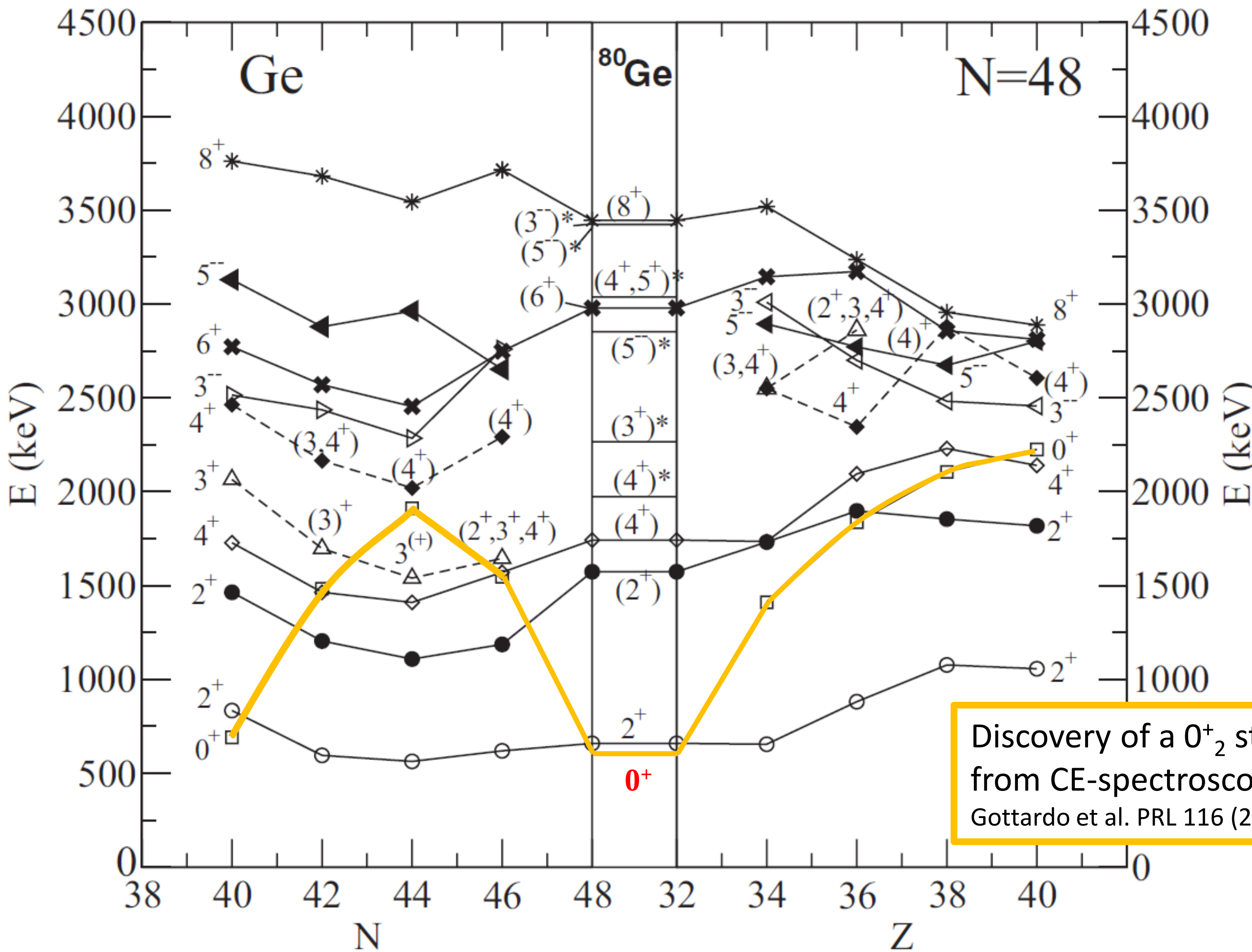
^{84}Ge 2^{+} lifetime measurement : plunger AGATA + VAMOS – Exp. E669 GANIL (C. Delafosse et al. to be published)



The Z=32 “singularity”

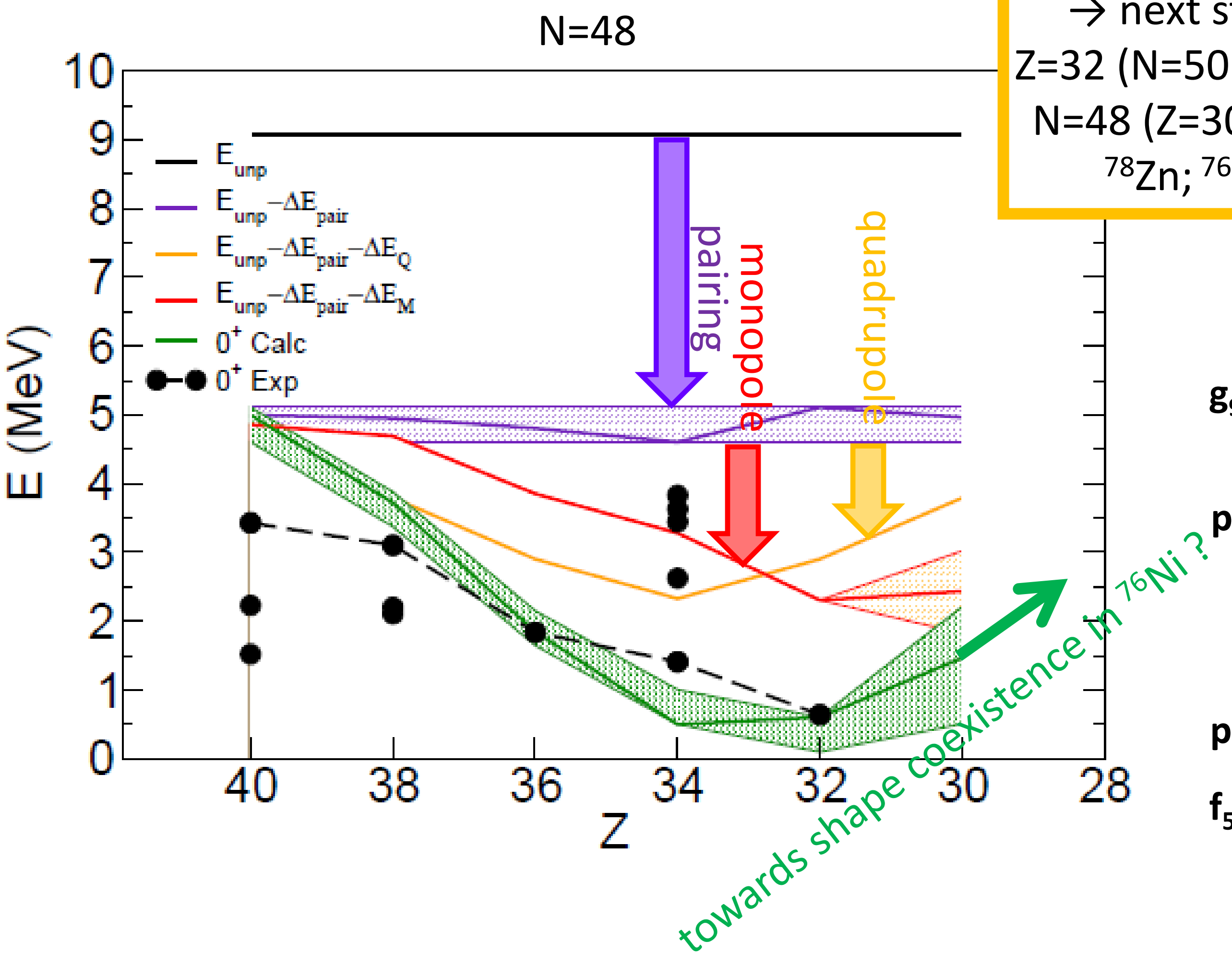
Z=32 : definitely a “special” proton number



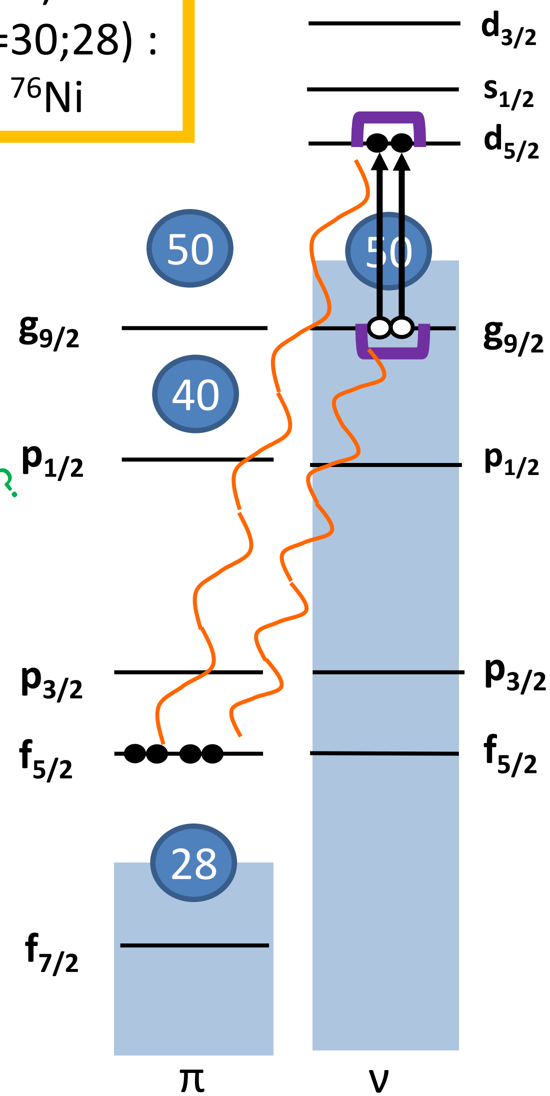


Discovery of a 0^+_2 state in ^{80}Ge from CE-spectroscopy at ALTO

Gottardo et al. PRL 116 (2016)

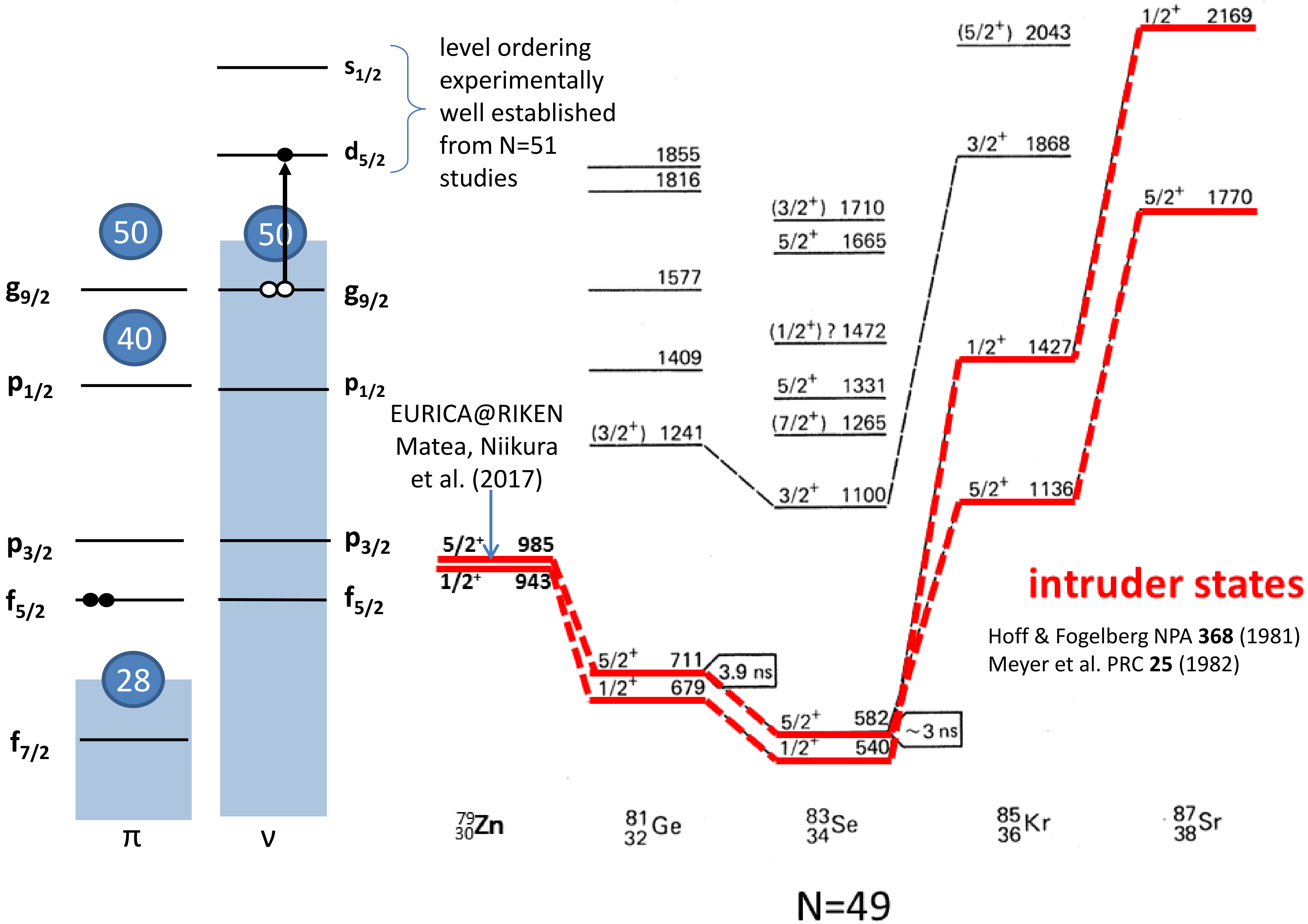


→ next steps
Z=32 (N=50) : ^{82}Ge
N=48 (Z=30;28) :
^{78}Zn; ^{76}Ni



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

Gottardo et al. PRL 116 (2016)



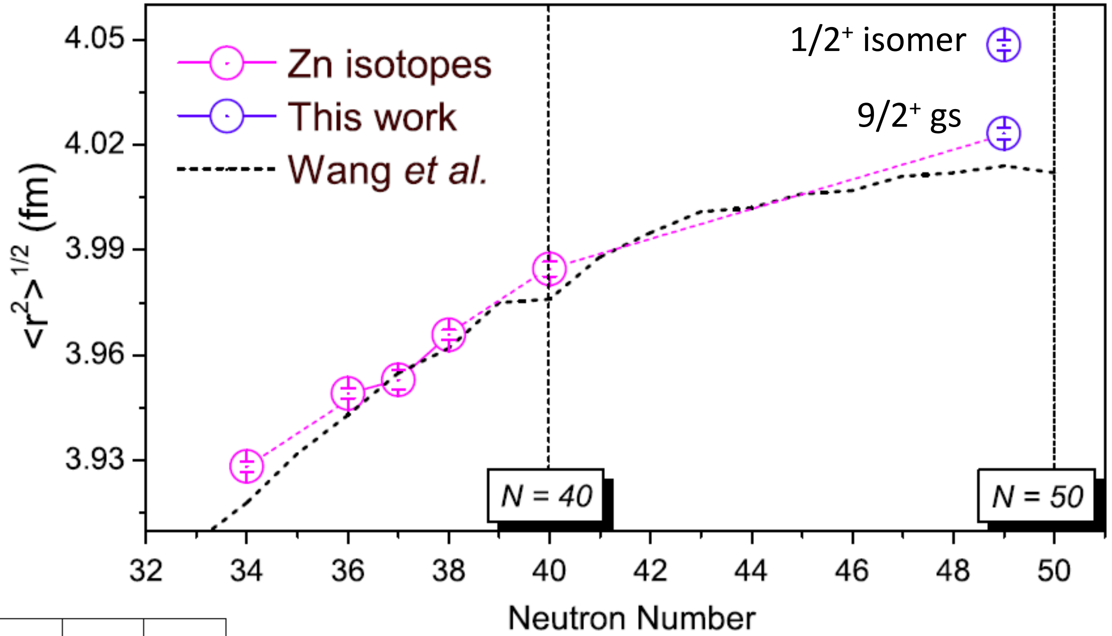
s1/2
d5/2
g9/2
p1/2
p3/2
f5/2
f7/2
50
50
40
28
π
ν
level ordering experimentally well established from N=51 studies
EURICA@RIKEN Matea, Niikura et al. (2017)
5/2+ 985
1/2+ 943
1855
1816
1577
1409
(3/2+) 1241
5/2+ 711
1/2+ 679
3.9 ns
(3/2+) 1710
5/2+ 1665
(1/2+) ? 1472
5/2+ 1331
(7/2+) 1265
3/2+ 1100
5/2+ 582
1/2+ 540
~3 ns
(5/2+) 2043
3/2+ 1868
1/2+ 1427
5/2+ 1136
1/2+ 2169
5/2+ 1770
intruder states
Hoff & Fogelberg NPA 368 (1981)
Meyer et al. PRC 25 (1982)
79 30 Zn
81 32 Ge
83 34 Se
85 36 Kr
87 38 Sr
N=49

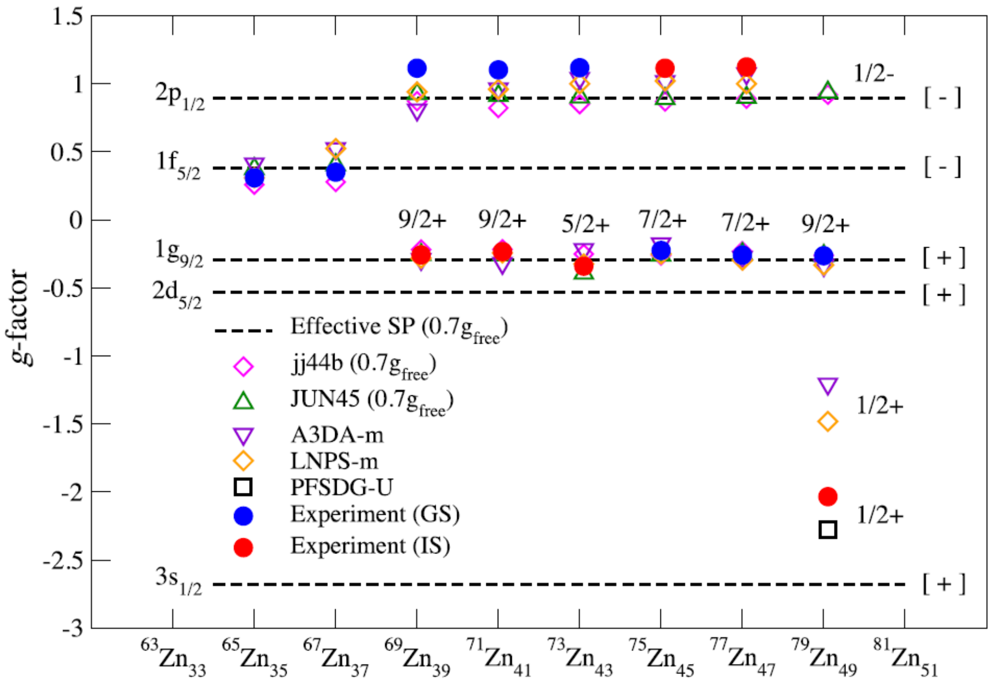
X. Yang et al. PRL 116 (2016)

^{79}Zn : isomer shift measured

COLLAPS collaboration

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

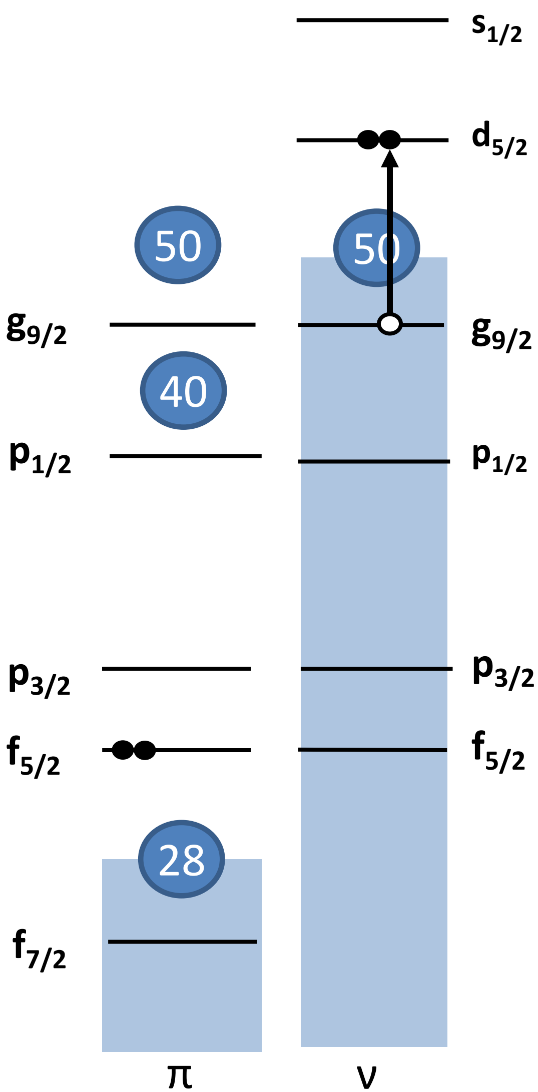




C. Wraith et al. PLB 771 385 (2017)

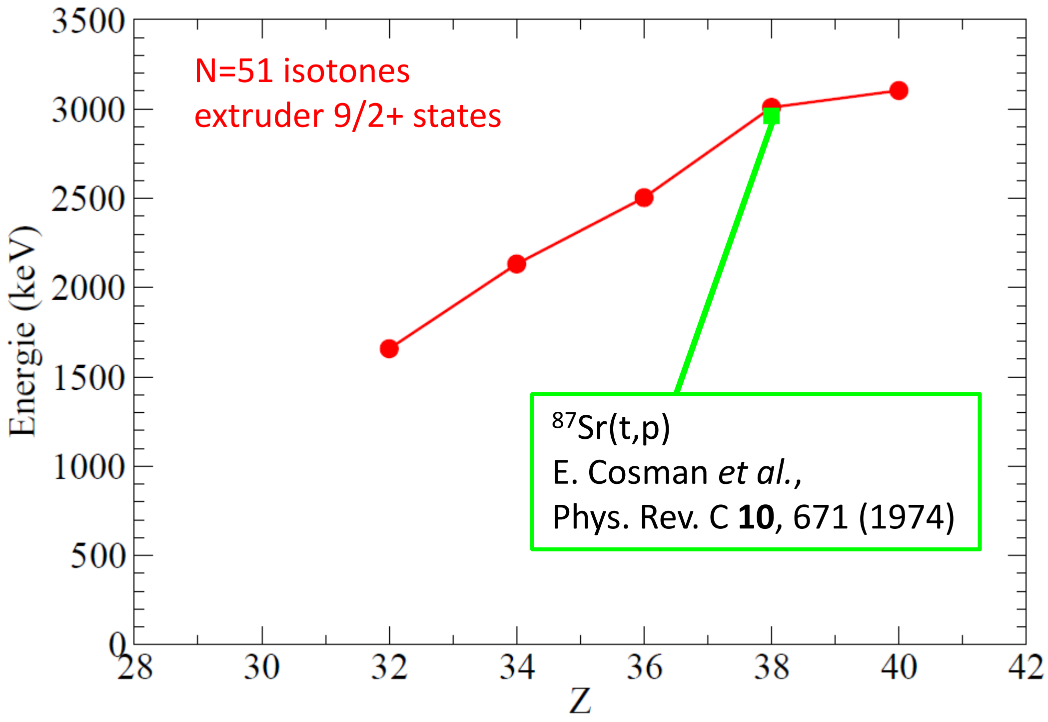
PFSDG-U based shell model calculations
→ $\mathbf{s_{1/2}}$ $d_{5/2}$ ($d_{3/2}$ $g_{7/2}$) composition
of the 1/2$^+$ intruder state seems under control

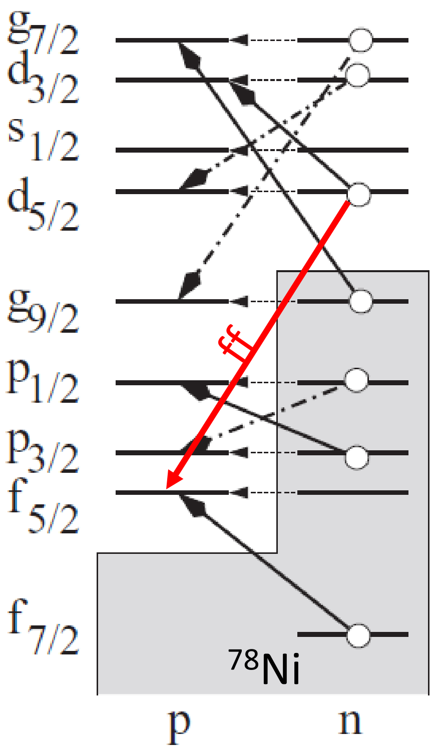
Extruder counterparts at N=51 : none identified so far



using the same mass ingredients as for the evaluation of the 0^+_2 intruder energy in ^{80}Ge →

$$E^{\mathrm{unp}}_{d^2_{5/2}g^{-1}_{9/2}} = \tilde{\epsilon}_{d_{5/2}} - \tilde{\epsilon}_{g_{9/2}} + \Delta E_{\mathrm{pairing}}(p)$$

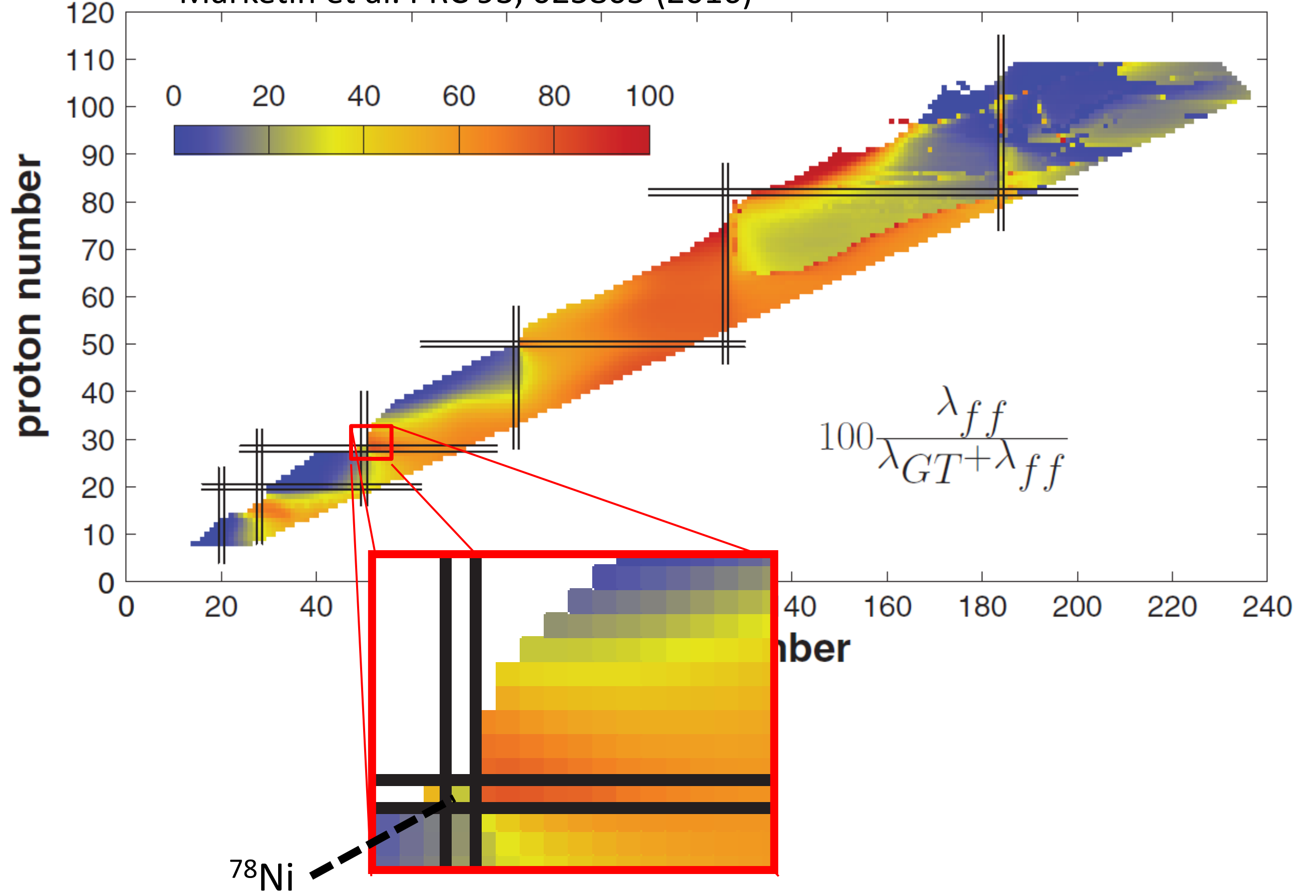




Because of the structure of the valence space in very N/Z asymmetric nuclei first-forbidden transition are believed to play a major role just after closed neutron shell

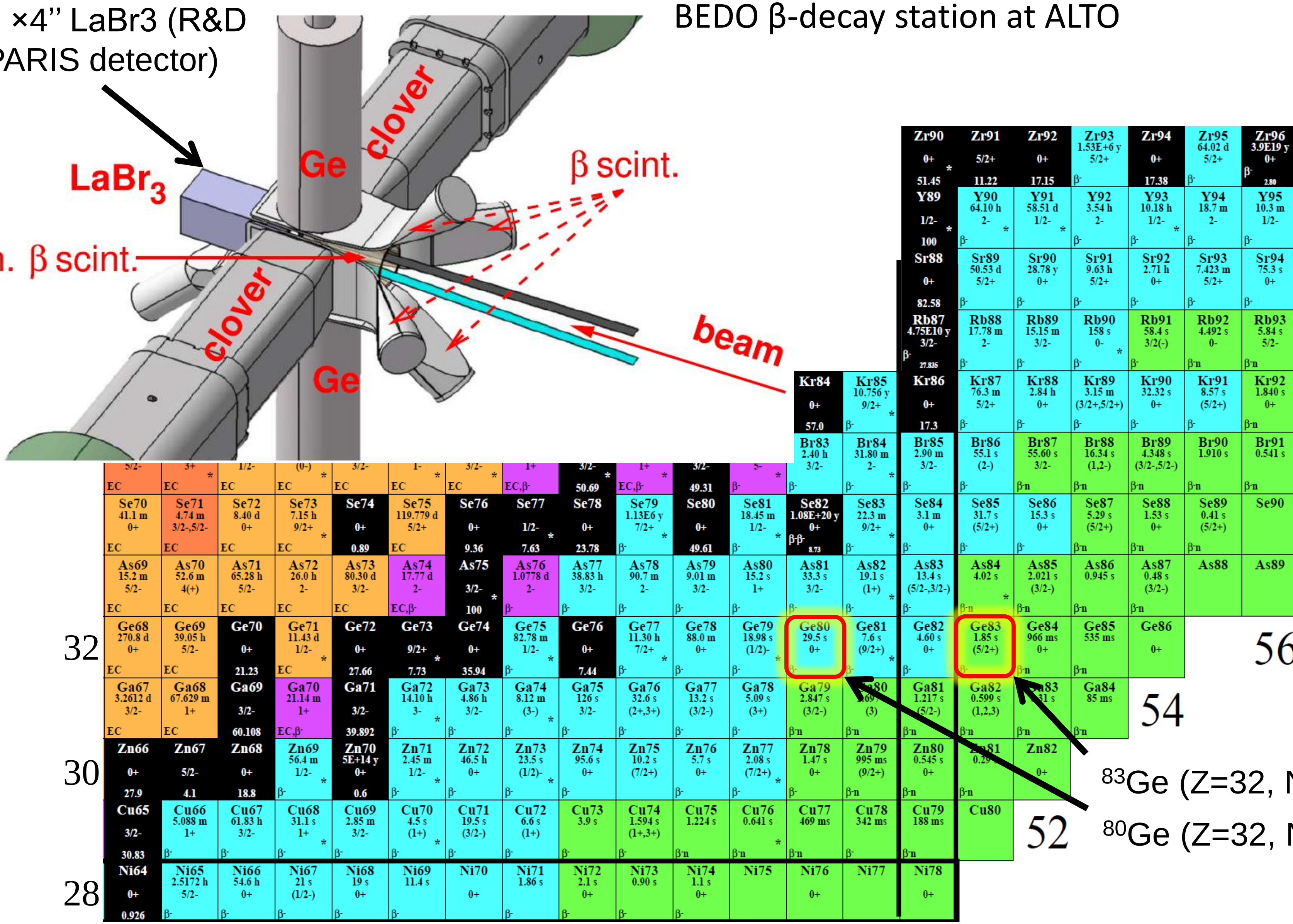
→ consequences for r-process modeling

Marketin et al. PRC 93, 025805 (2016)

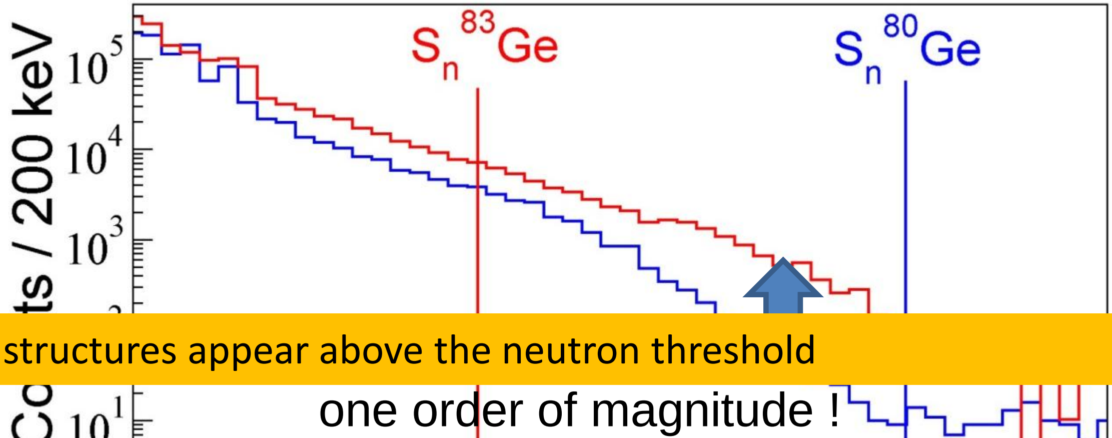


2 ×2 ×4'' LaBr3 (R&D for PARIS detector)

BEDO β-decay station at ALTO



Gottardo et al. Phys. Lett. B 772 359 (2017) comparison of ^{80}Ge vs ^{83}Ge spectra (below vs above N=50) up to ≈Q_β

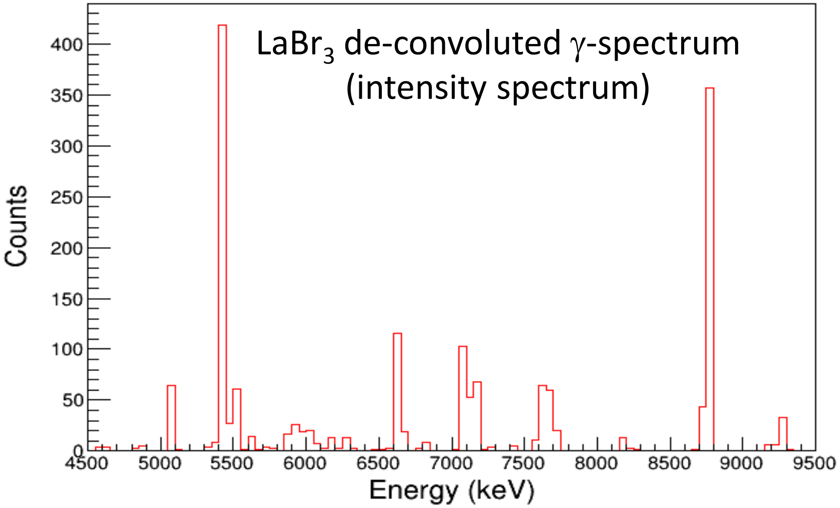


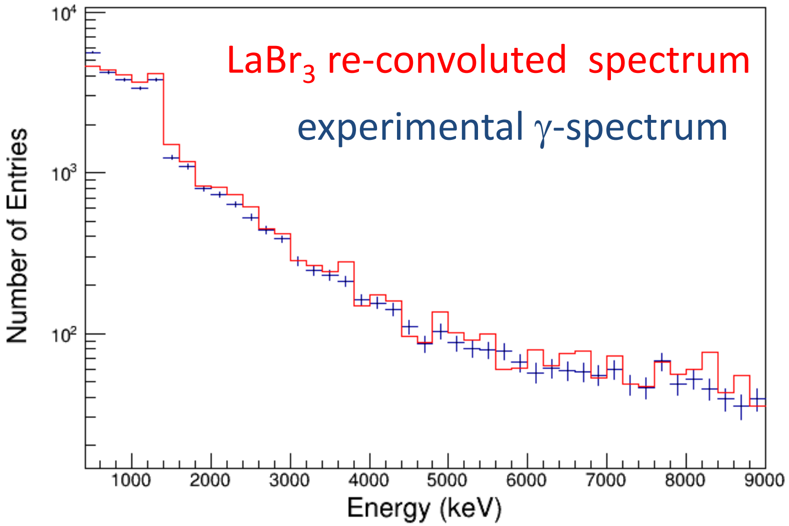
Response function + energy linearity of LaBr3 detector fully characterized up to 11 MeV using ^{27}Al(p,γ)^{28}Si reaction at the ARAMIS accelerator (CSNSM in Orsay)

structures appear above the neutron threshold

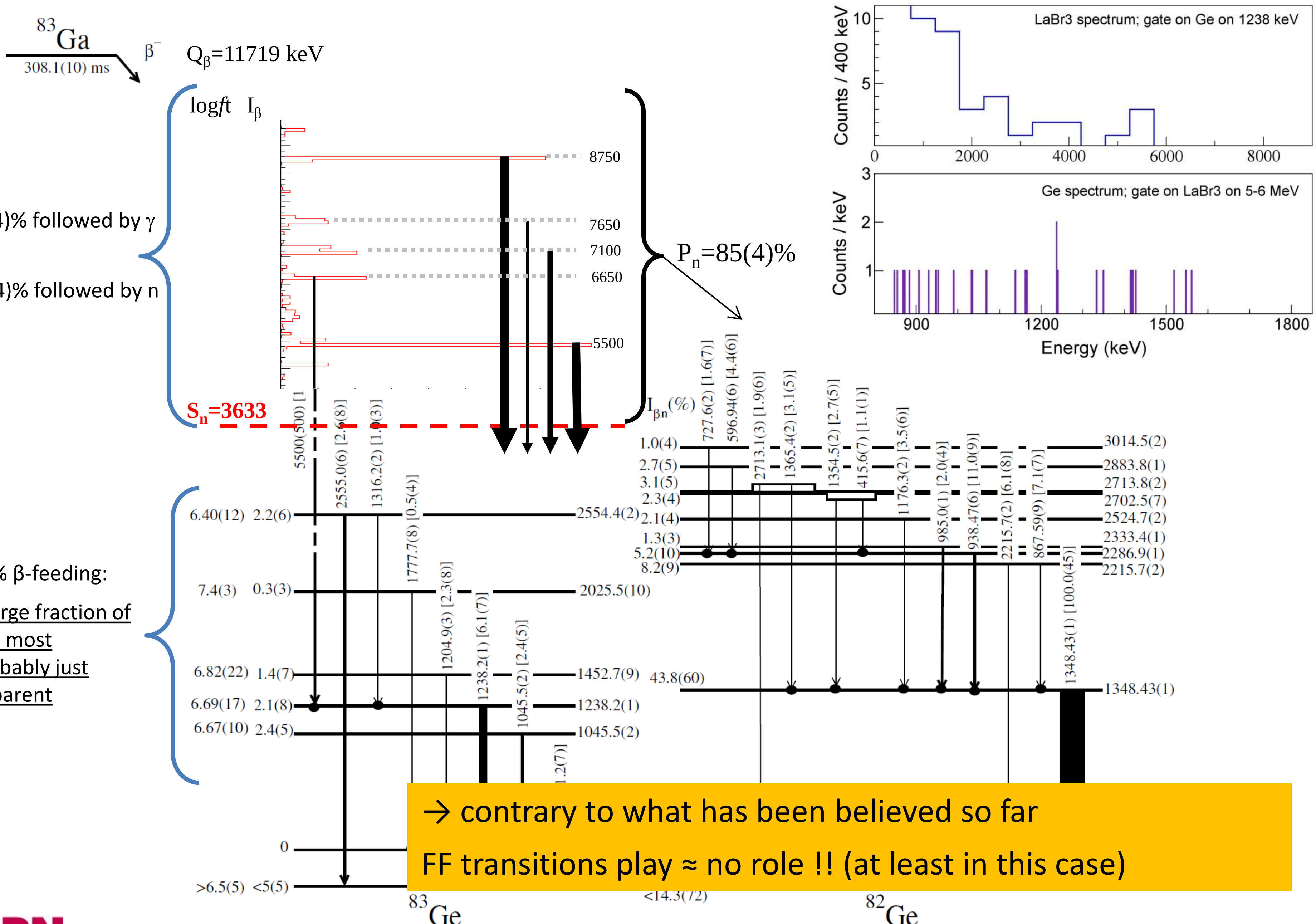
16(4) % of the β decay strength above n-threshold and followed by γ-emission

β-n branching measured with TETRA= 85(4)% [Verney et al. PRC 054320 95 (2017)]





Gottardo et al. Phys. Lett. B 772 359 (2017)



16(4)% followed by γ

85(4)% followed by n

12% β-feeding:

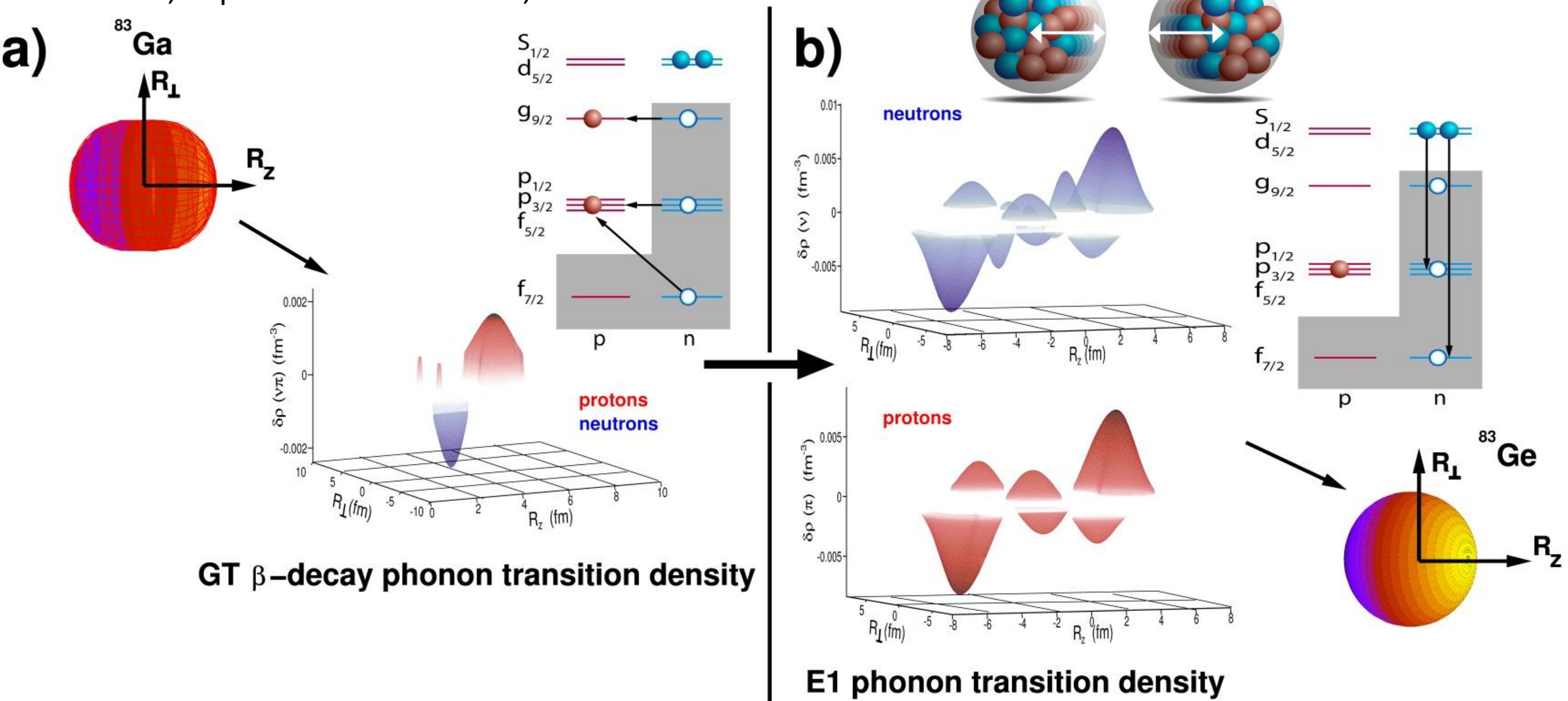
a large fraction of it is most probably just apparent

→ contrary to what has been believed so far

FF transitions play ≈ no role !! (at least in this case)

Transition densities from
Gogny D1M – QRPA (Bruyères-le-Châtel)

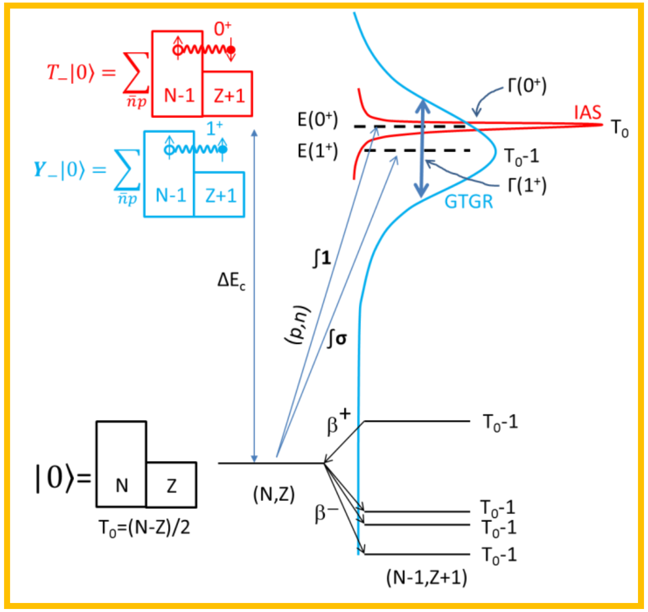
I. Deloncle, Sophie Peru-Desenfants, M. Martini

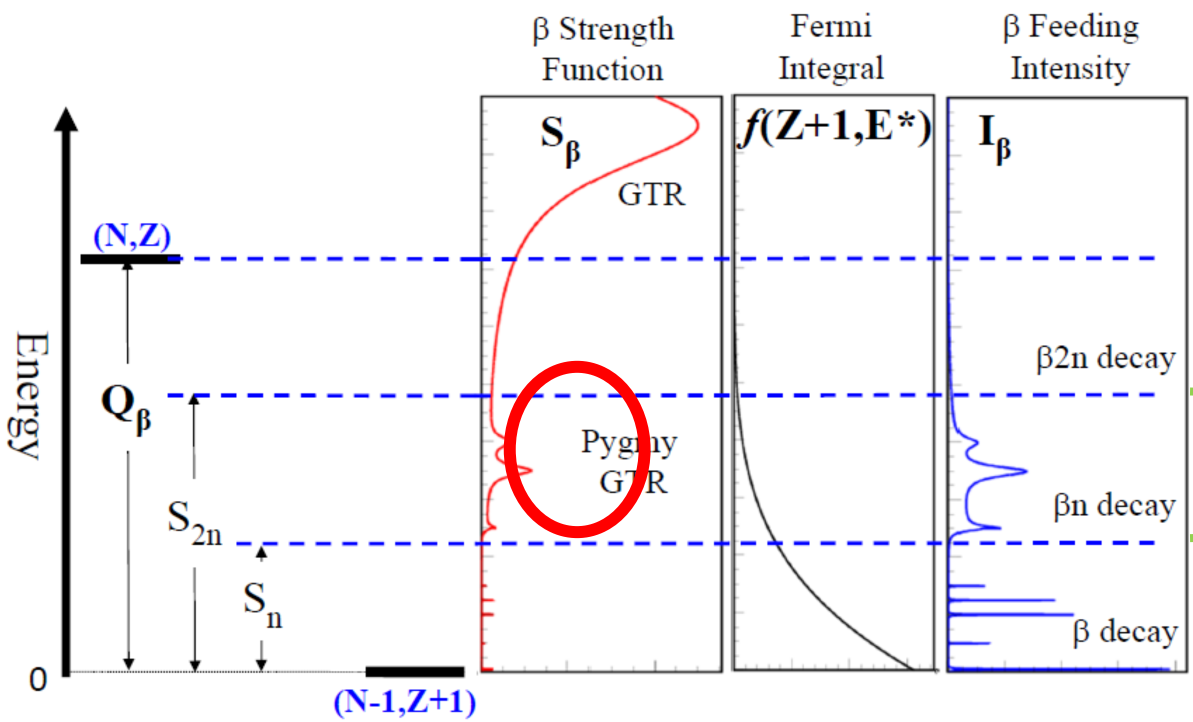


a) GT decay create a depletion of neutron density in the core; adds a proton on the surface
b) The excited ^{83}Ge states can then decay via E1 γ emission with a «PDR-like» transition density

neutron-skin related effect ?

β-delayed neutron emission probability : P_n,
like other global quantities $T_{1/2}$, mass, $\delta\langle r_c\rangle$ etc.
are not straightforwardly interpretable in terms of structure





Pn value gives information on the integral β-feeding of states above Sn
(a first step before n-spectroscopy)

⇒provides an experimental test of the consistency of β-strength theories

Volume 109B, number 6 PHYSICS LETTERS 11 March 1982

THE ^{49}K BETA DECAY

The ISOLDE Collaboration

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[h] *IN2P3, F-91406 ORSAY, France*
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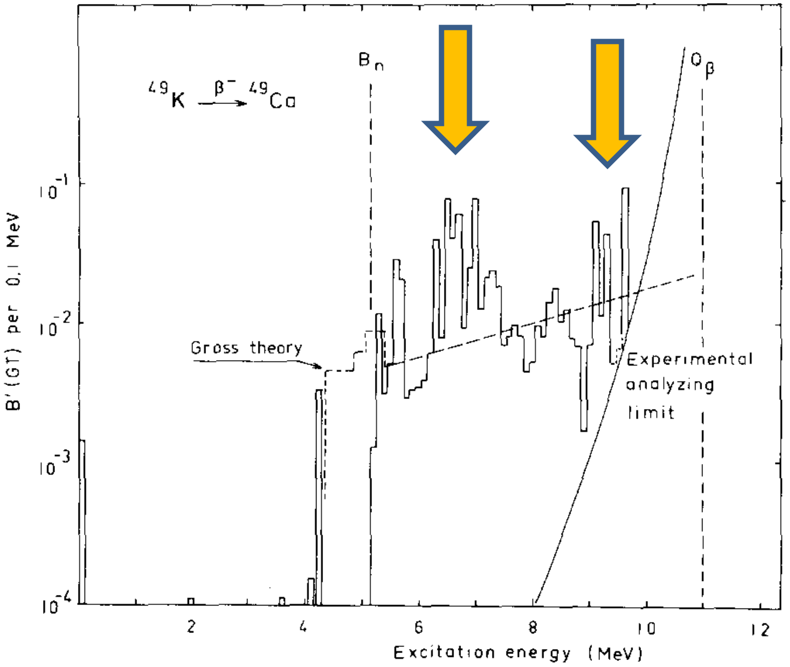


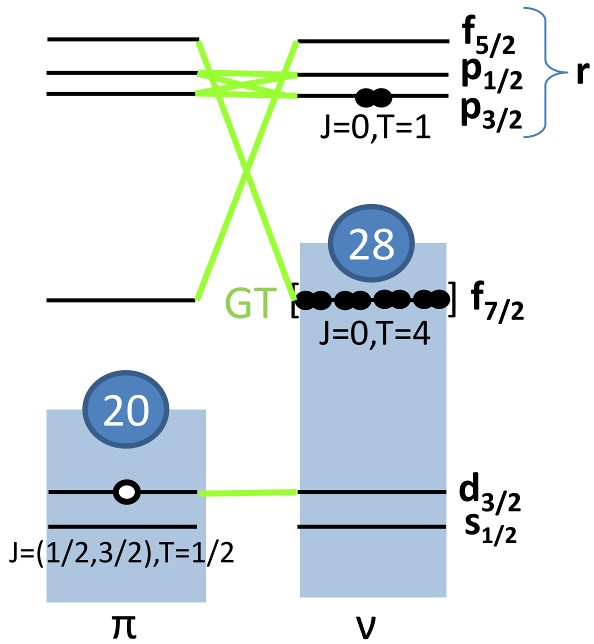
Fig. 2. The beta strength function of ^{49}K decay in terms of reduced GT transition probabilities.

More about beyond-threshold effects

Table 2
$T = 9/2$ particle–hole states in ^{49}Ca.

	Configurations	E_X a) (MeV)
a	$\{[(sd)^{-1}f^8(T=4)]_{9/2}r^2(T=1)\}_{9/2}$	9.4
b	$\{[(sd)^{-1}f^8(T=4)]_{9/2}r^2(T=0)\}_{9/2}$	9.7
c	$\{[(sd)^{-1}f^8(T=4)]_{7/2}r^2(T=1)\}_{9/2}$	5.0
d	$\{[(sd)^{-1}f^8(T=3)]_{7/2}r^2(T=1)\}_{9/2}$	12.0
e	$\{[(sd)^{-1}f^9(T=7/2)]_4 r^1(T=1/2)\}_{9/2}$	6.2

a) For $r = p_{3/2}$.



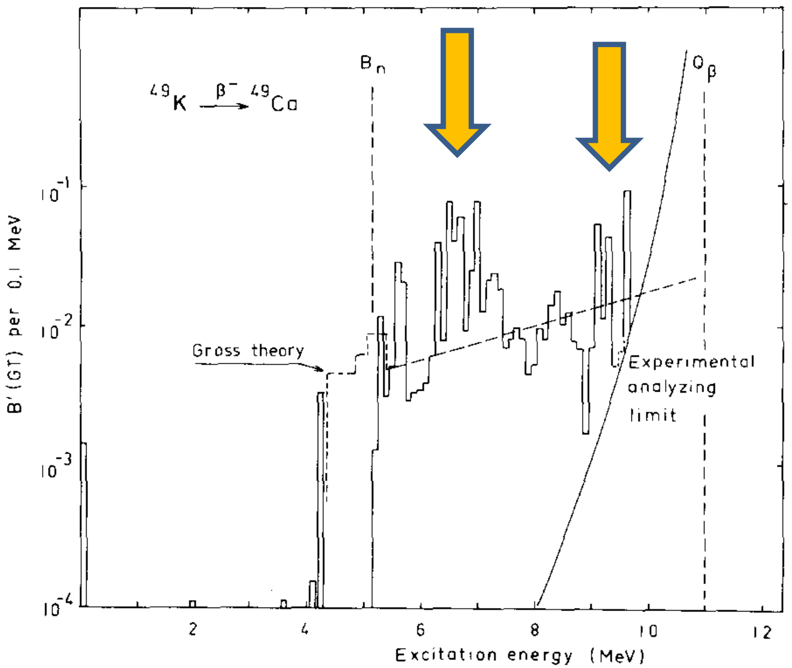
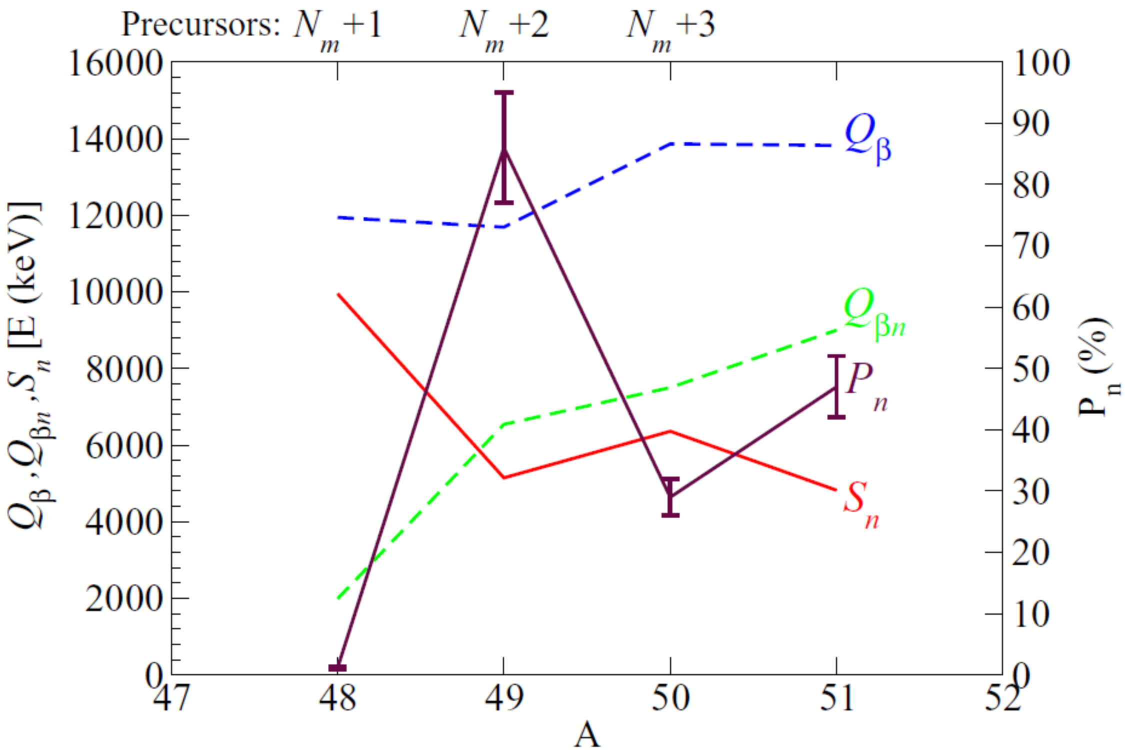


Fig. 2. The beta strength function of ^{49}K decay in terms of reduced GT transition probabilities.

P_n "oscillation" at closed-shell + 1, 2, 3 neutrons

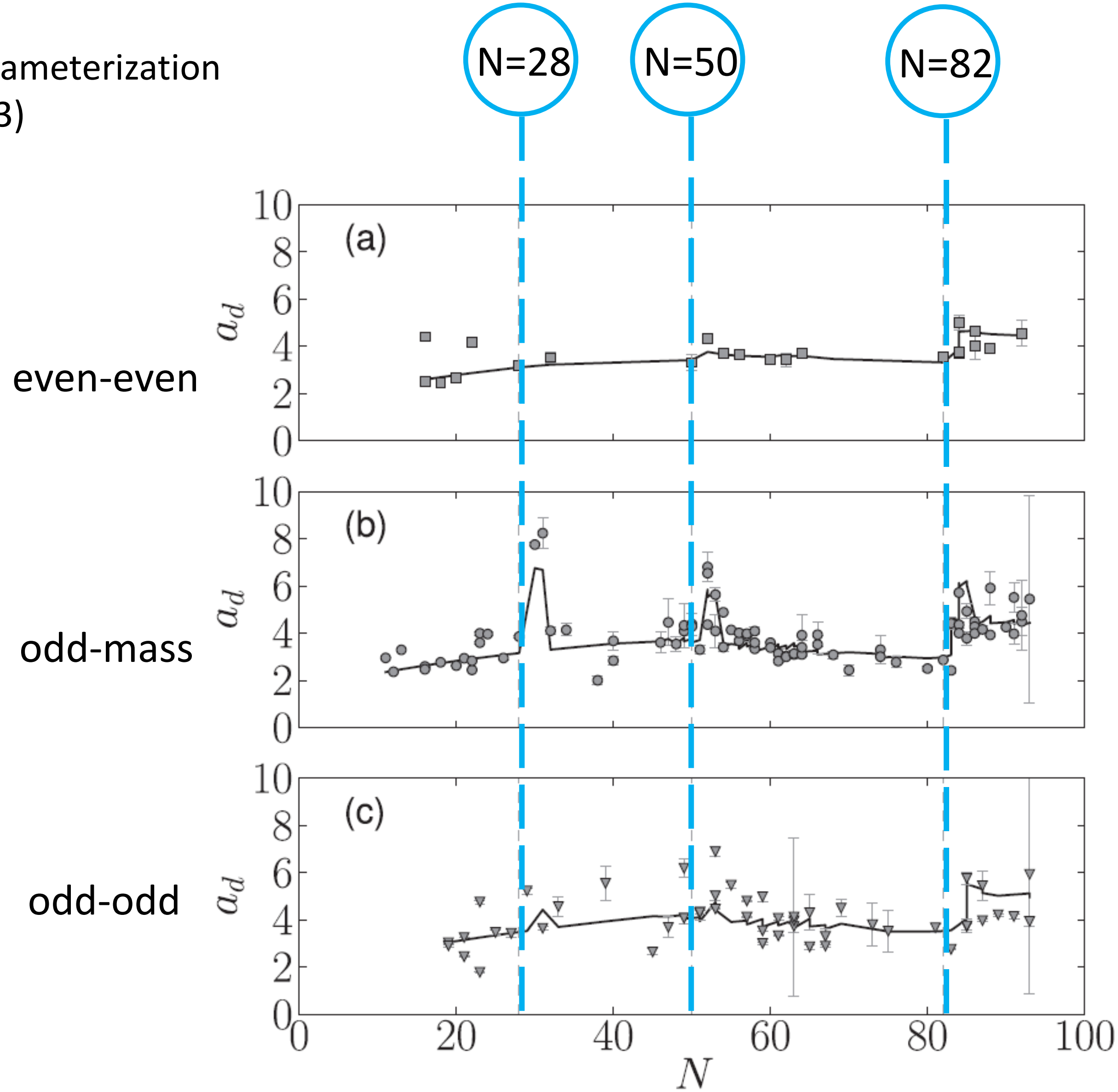
	N_m=28	N_m+1	N_m+2	N_m+3	
emitter	48Ca	49Ca	50Ca	51Ca	
S_n=	9952	5146	6360	4821	
precursor		48K	49K	50K	51K
Q_β=		11940	11688	13861	13820#
$Q_{\beta n}$=		1988	6542	7501	9002
P_n=		1.14%	86%	29%	47%



is it just a local curiosity
or a more general effect ?

Maybe general indeed…
from Miernik level density parameterization
Phys Rev C 88 041301(R) (2013)

$$S_\beta(E) \sim \rho(E) = \frac{\exp(a_d\sqrt{E})}{E^{3/2}}$$

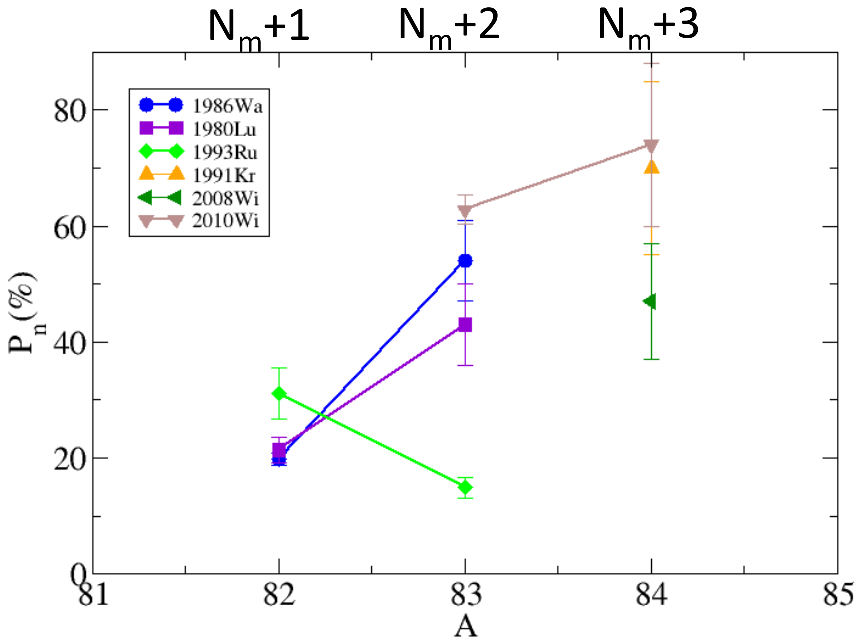


What is the situation near $N_m=50$?

The case of Ga (Z=31) precursors: ^{82}Ga (N_m+1); ^{83}Ga (N_m+2) ; ^{84}Ga (N_m+3)

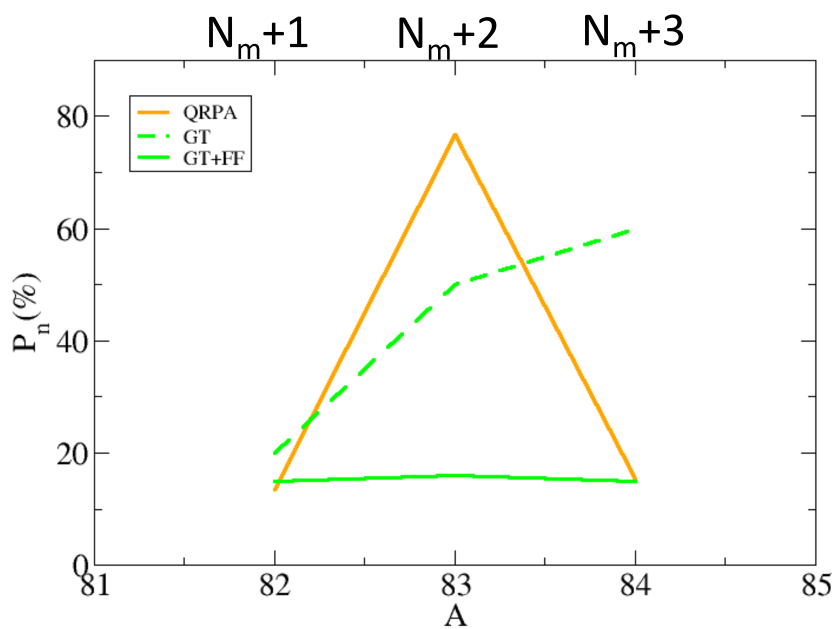
The situation before our experiment:

experiment



1986Wa: Reeder, Warner et al Rad Eff 94 (1986)
1980Lu: Lund et al Z Phys A 294 (1980)
1993Ru: Rudstam et al Atom. Nat. Nucl. Dat. Tab. 340 (1991)
1991Kr: Kratz et al Z Phys A 340 (1991)
2008Wi: Winger et al Sanibel Conf Proc (2008)
2010Wi: Winger et al. PRC 81 (2010)

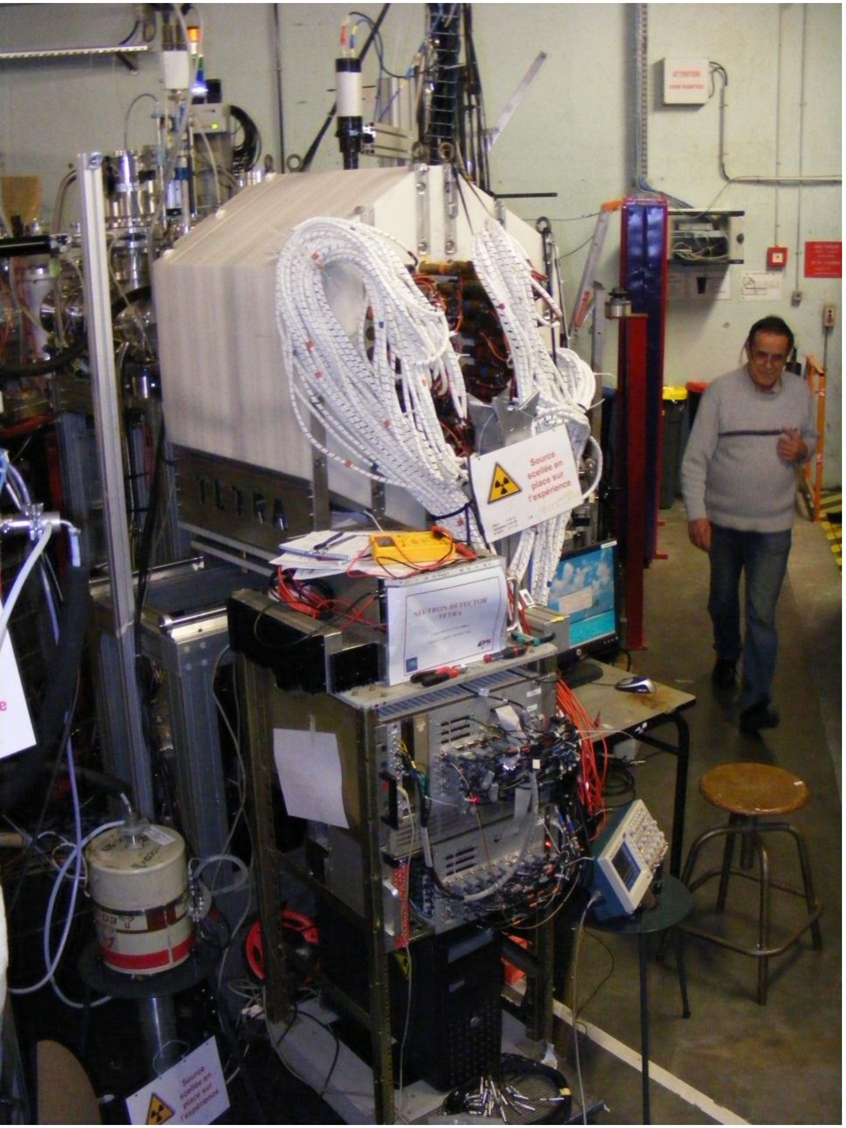
theory

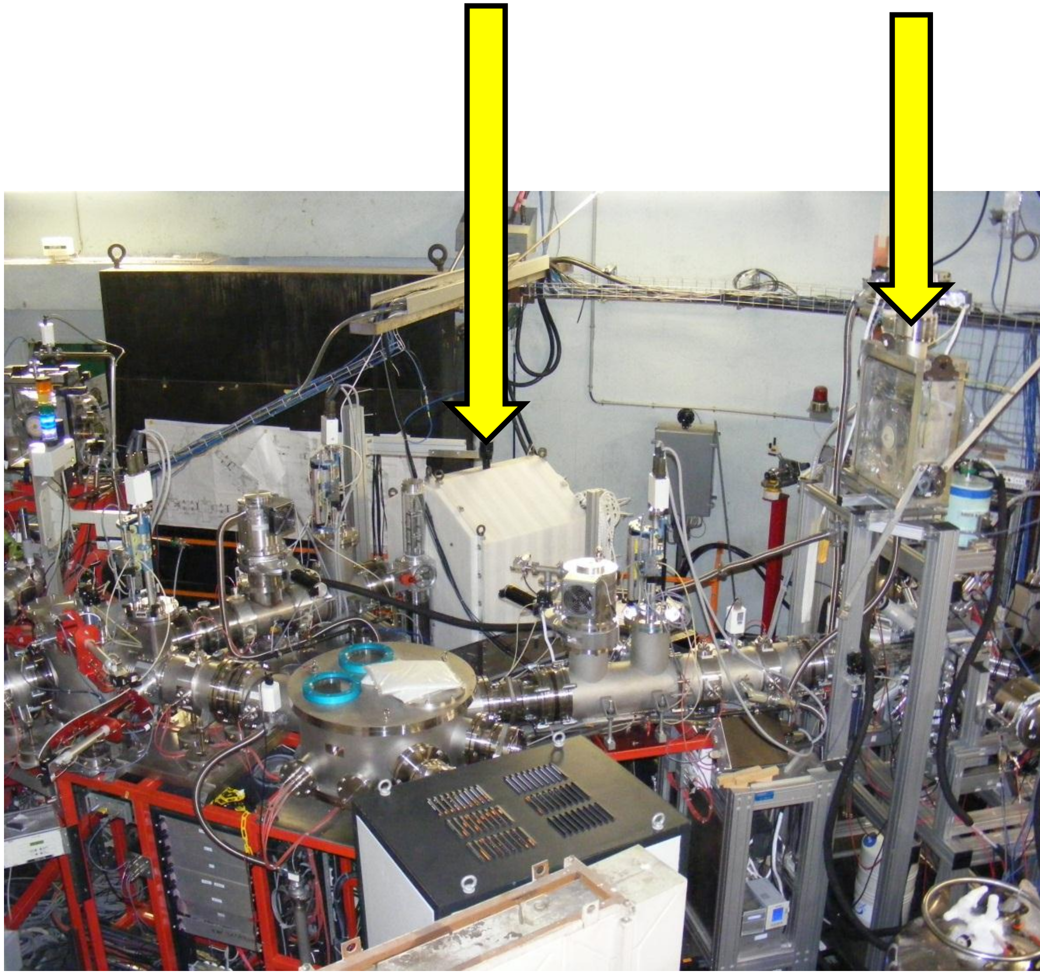


QRPA: Pfeiffer et al Prog Nucl Energy 41 (2002)
GT/GT+FF: Borzov PRC 71 (2005)

More about beyond-threshold effects

The ^{3}He long counter TETRA at ALTO (collaboration with JINR Dubna)



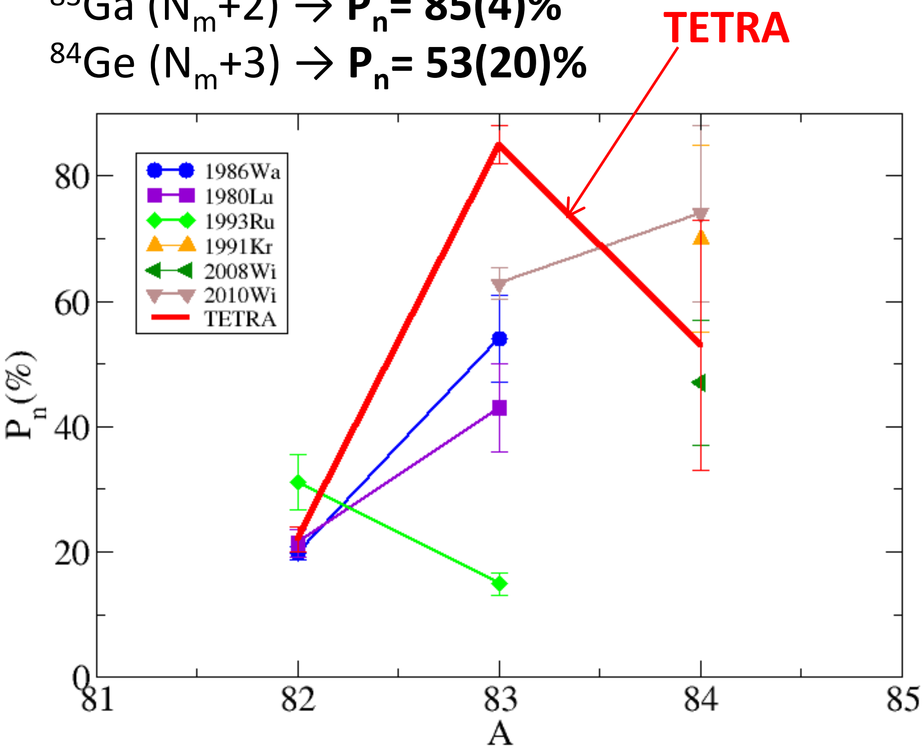


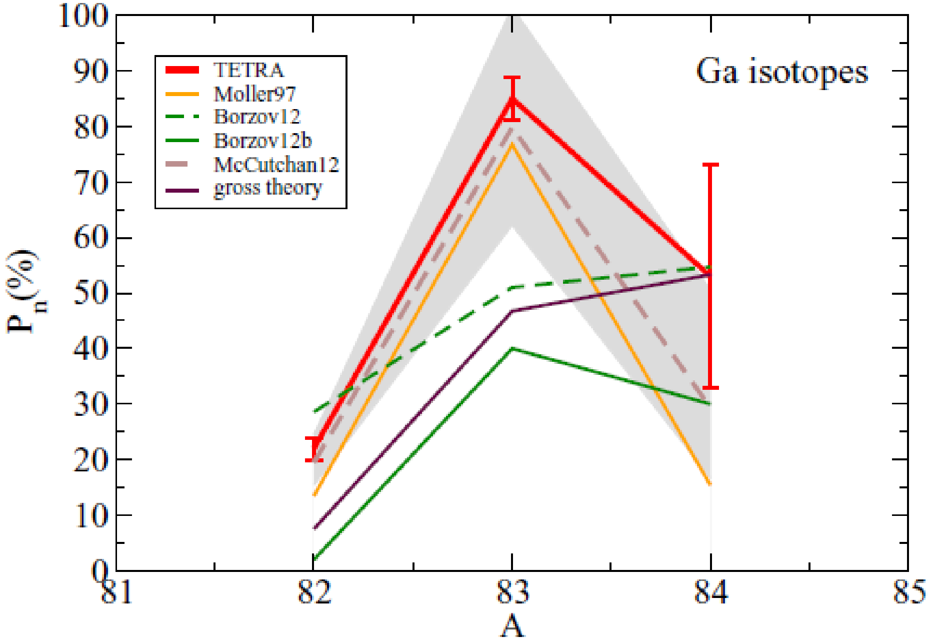
The case of Ga (Z=31) precursors:

^{82}Ga (N_m+1) → $\mathbf{P_n}$**= 22(2)%** (test case- Testov et al. NIM A 815 (2016) 96)

^{83}Ga (N_m+2) → $\mathbf{P_n}$**= 85(4)%**

^{84}Ge (N_m+3) → $\mathbf{P_n}$**= 53(20)%**





Verney et al., PRC 95, 054320 (2017)

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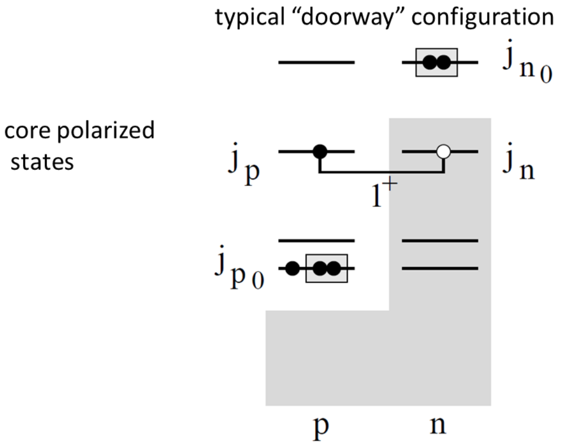
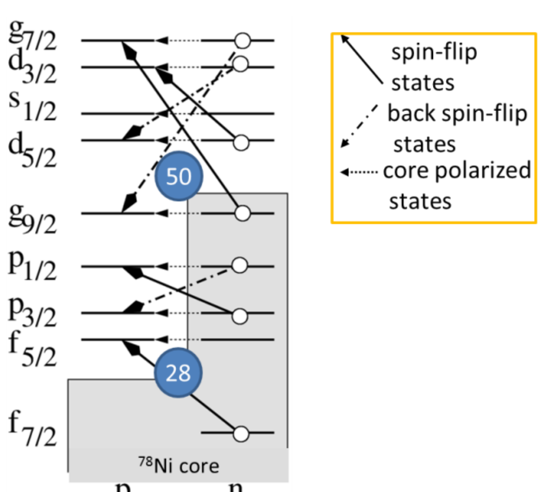
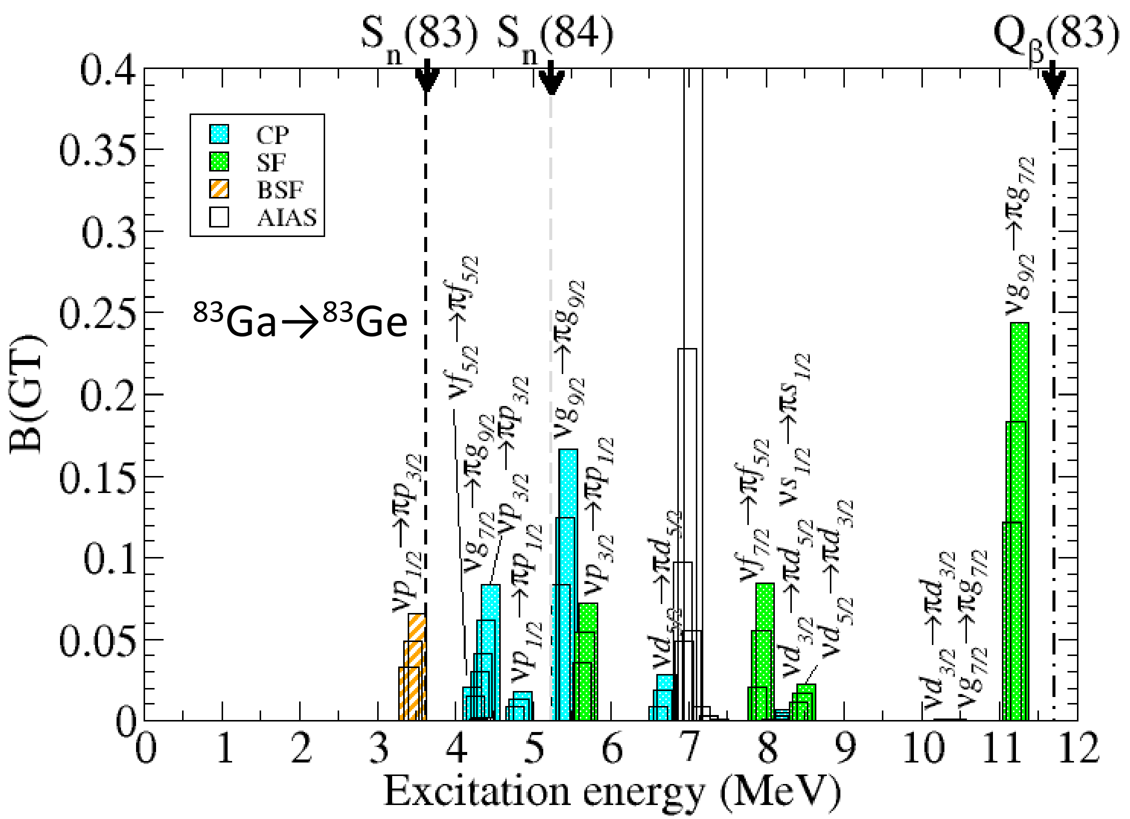


$$V_{0i} = V_\tau(r_{0i})\,\vec{\tau}_0\cdot\vec{\tau}_i + V_{\sigma\tau}(r_{0i})(\vec{\sigma}_0\cdot\vec{\sigma}_i)(\vec{\tau}_0\cdot\vec{\tau}_i)$$



single(quasi)-particle GT transitions

Calculated β-strength function for the case $^{83}Ga \rightarrow ^{83}Ge$



$P_n(^{83}Ga)_{calc}$=85% [$P_n(^{83}Ga)_{TETRA}$=85(3)%]

$P_n(^{84}Ga)_{calc}$=50% [$P_n(^{83}Ga)_{TETRA}$=53(20)%]

- gap size → Z=32 "singularity"
  - monopole effect ? (quadratic ??) → ^{83}Zn : key missing mass
  - dynamical effect ? (triaxiality corridor ??) → n-rich Ge coulex (after Oak Ridge pioneering work on Ge [PRL94 (2012)]: nothing !)

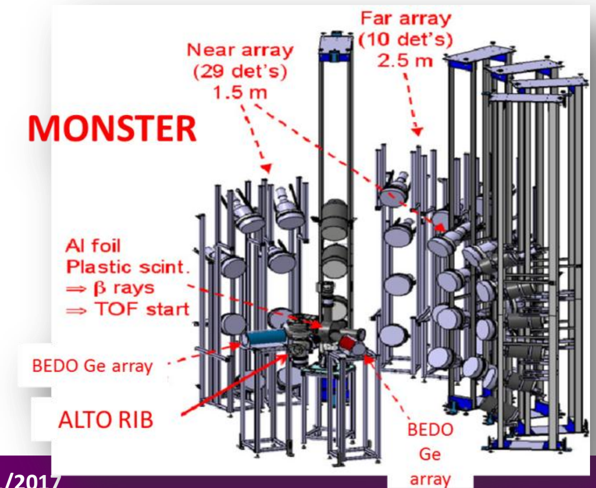
- shape coexistence
  - 0^+_2 states → β-delayed e- spectroscopy → ^{82}Ge and ^{78}Zn possibly at ALTO
  - "extruder" $9/2^+$ states at N=51 → direct nucleon exchange (t,p) also lifetime with plunger

- neutron valence space above ^{78}Ni : high ℓ → direct nucleon exchange (d,p) and (α,^{3}He) → ACTAR ?

- neutron threshold effects and the question of first-forbidden transitions in the ^{78}Ni region → β-delayed neutron and high-energy γ spectroscopy

forthcoming (2018) campaign at BEDO/ALTO

- a TOF neutron detector (MONSTER) for neutron energy spectroscopy
- a high efficiency high-energy γ-array : PARIS ??



thank you !