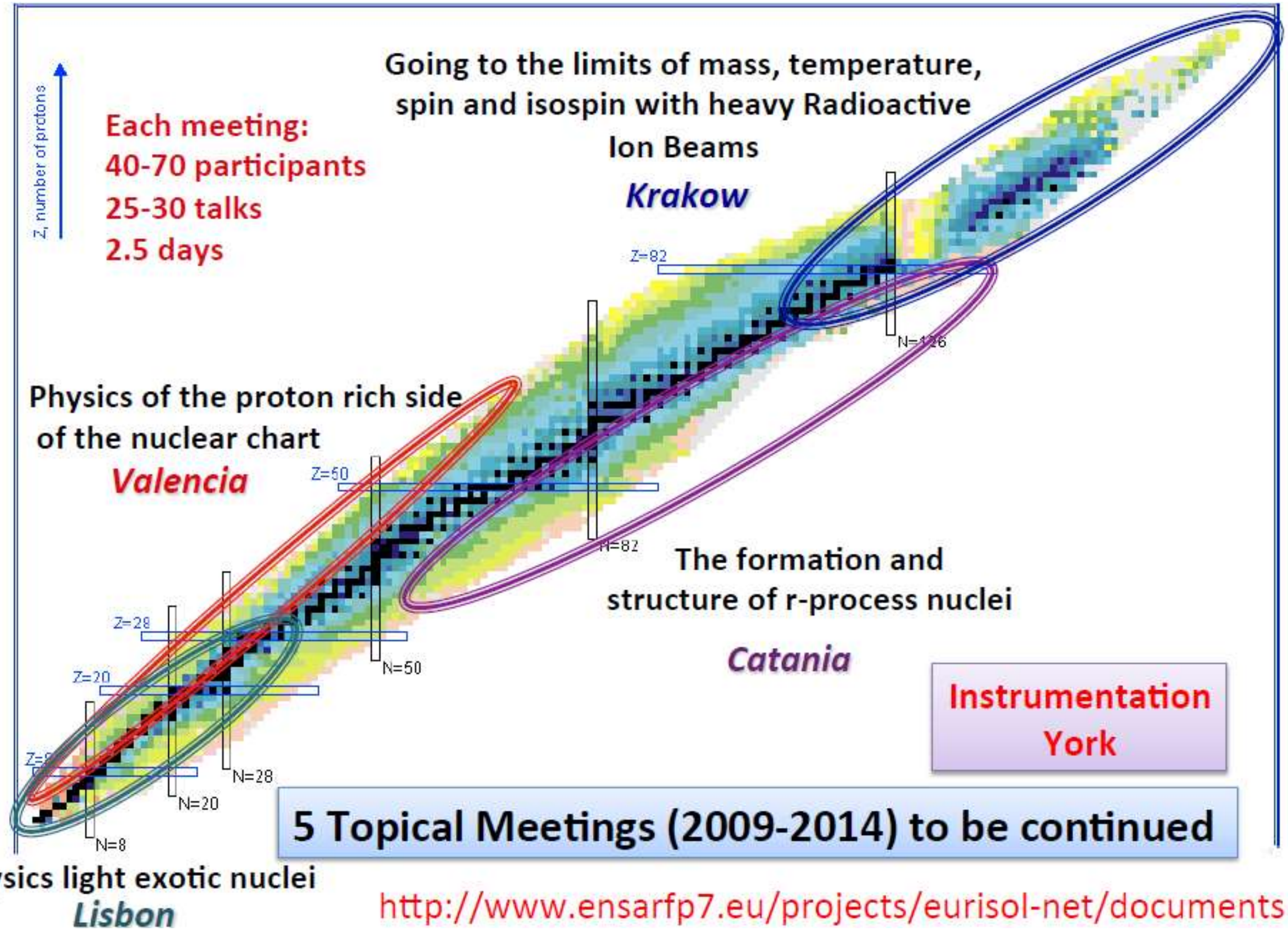
Neutron deficient nuclei

… at EURISOL -DF



http://www.ensarfp7.eu/projects/eurisol-net/documents

EURISOL User Group

Report on the second EURISOL User Group Topical Meeting [1]

Neutron deficient exotic nuclei and the Physics of the *proton rich side* of the nuclear chart.

Colegio Mayor Rector Peset, Valencia, Spain, 21-23 February 2011.

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007- 2013 under Grant Agreement n. 262010 - ENSAR.
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The workshop was partially supported by CPAN and IFIC (CSIC-Univ. of Valencia), Spain.

[1] Coordinated by Berta Rubio, IFIC, Valencia, Spain and Angela Bonaccorso, INFN, Sez. di Pisa, Italy.

one-two -proton radioactivity
cluster radioactivity

✓Studies of the effects of nuclear shape and shell structure on quantum tunneling.

✓Direct measure of the proton separation energy.

✓Quantification of 2p-capture processes bridging bottlenecks at the rp-process waiting points.

❖Most of the one-proton radioactivity cases have been discovered using fusion evaporation reactions.

❖Pursue this approach but using secondary reactions with radioactive post-accelerated proton-rich beams such as ^{56}Ni and ^{72,74}Kr..

Today RIKEN with the in-flight facility is the leader

Nuclear structure of N≈Z Nuclei

- The structure of these nuclei provides essential information *on isospin* symmetry of the nuclear force or proton-neutron correlations.

- Mirror Energy Differences between ^{67}Se and ^{67}As have been well reproduced theoretically.
- Discovery of excited states in the N = Z nucleus ^{92}Pd and the claiming of the presence of an isoscalar T = 0 pairing correlation at low-spins
- ^{92} Pd is today since 2011 the heaviest case studied experimentally.

- Use pn transfer reactions and compare the cross section to 0^+ and 1^+ spin-parity final states to measure the strength of T=1+ over the T=0 paring forces.
- The chain of Sn isotopes starting with ^{100}Sn special emphasis on Coulomb excitation and transfer reactions to locate single particle states (inverse (d,p) reaction at 10 MeV/u)

- Future in-beam studies of exotic neutron-deficient nuclei will mainly require the use of reactions induced by intense radioactive heavy-ion beams

- To map the rest of the N=Z cases up to ^{100}Sn or even above demands very intense beams

- Need of high performance, highly selectivity detectors such as the new generation of gamma-ray array detectors like AGATA and the neutron-detector array NEDA.

Nuclear Astrophysics

The rp-process is the main source of energy and determines the X-ray light curve in the X-ray bursts of thermonuclear explosions in the Galaxy.

The path is dominated by proton captures and -decays.

Observations have shown excellent agreement with theories but have also shown that the nuclear physics of the rp-process is not sufficiently well known to test the calculations at the level of precision provided by observations.

The key (p,γ) reactions happen on unstable nuclei while indirect methods do not reach the desired level of accuracy.

Present efforts are aimed at developing “ad hoc” instrumentation such as the Separator for Capture Reactions (SECAR).

In summary, direct measurement of reaction cross sections at low energy for astrophysics is an excellent physics case

Exotic excitations in proton rich nuclei and clusterisation

In contrast with neutron-rich nuclei, bound nuclei with an excess of protons can be found only below Z=50, and even here the excess of protons is never very large

→ Do pygmy resonances, clearly observed in neutron-rich nuclei, can still appear there ?

The separation between the electric Pygmy Dipole Resonance (PDR) and the Giant Dipole Resonance increases as the nucleus becomes more proton-rich.

Clusterisation of light nuclei into alpha particles in N=Z nuclei is a well known phenomenon which is revealed in the binding energies of nuclei “composed by alpha bonds

Should exist at the proton drip-line ?

Could be studied by fragmenting proton-rich nuclei previously accelerated to 30 MeV/u, or using alpha transfer reactions, at lower energy and measuring the associated spectroscopic factors.

• An area for stopped beams (decay studies, mass measurements and other ground state properties, including traps and laser ionisation…). A hall similar to the present ISOLDE hall

• A

• Co

• In-

BEAM DEVELOPPEMENT &POST-ACCELERATION

• Intermediate energy regime. Ideally with a high resolution spectrometer such as the one at RCNP in Osaka.

Members :

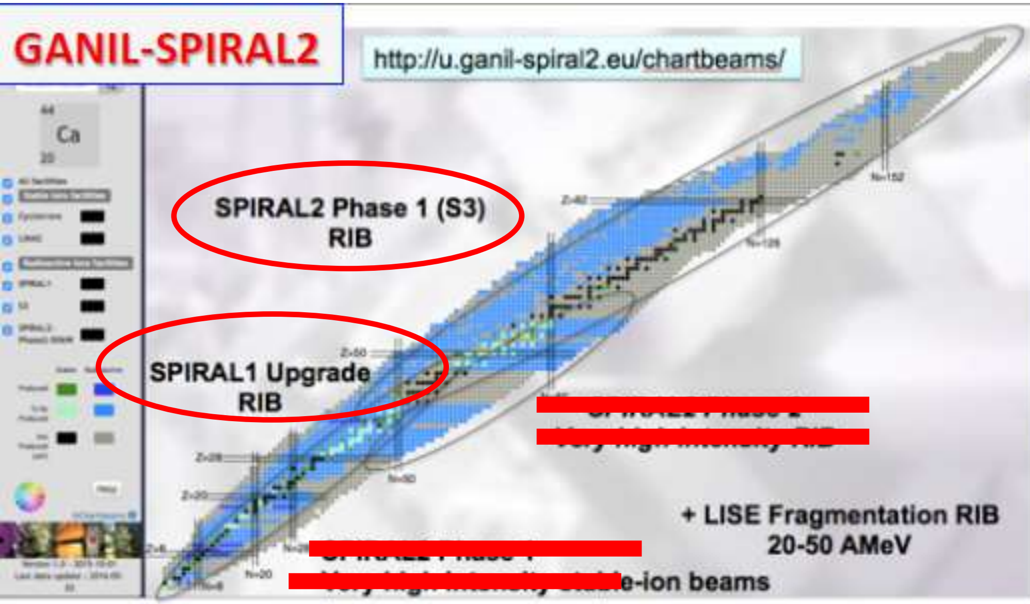
- **HIE-ISOLDE/CERN**
- **SPES-INFN**
- **SPIRAL2-GANIL**

- **JYFL, Finland**
- **ISOL@MYRRHA-SCK*CEN**
- **COPIN Consortium, Poland**

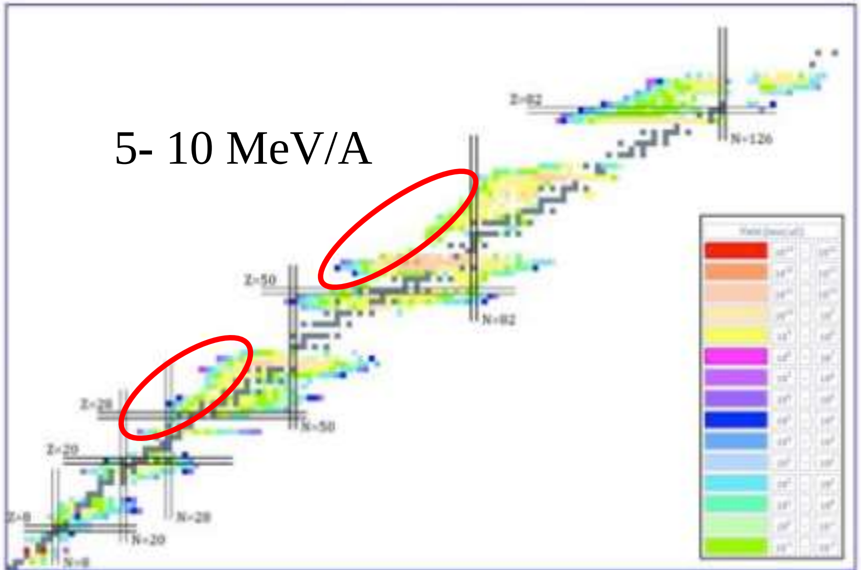
…and hopefully soon
ALTO, Orsay

EURISOL DF

GANIL-SPIRAL2



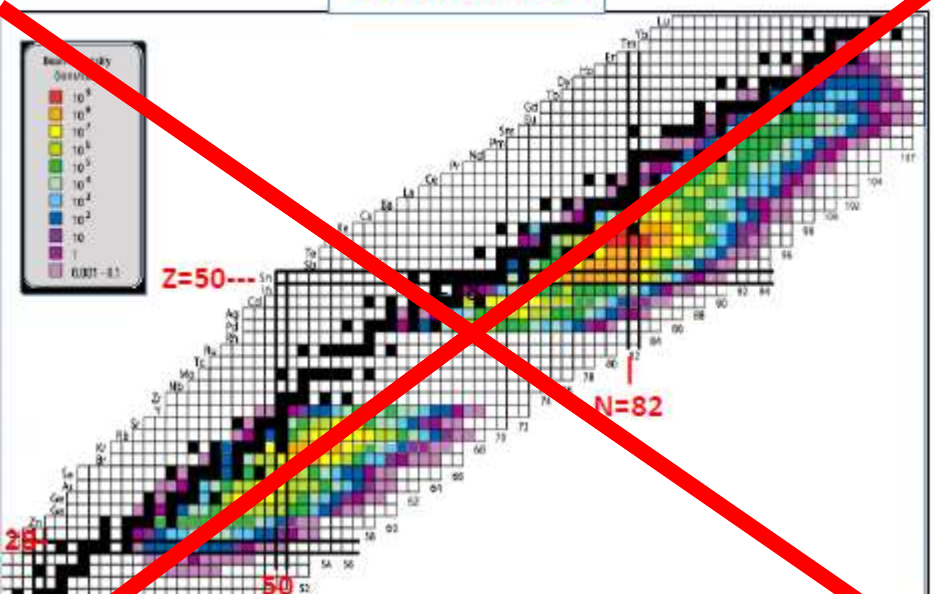
ISOLDE-CERN



http://test-isolde-yields.web.cern.ch/test-isolde-yields/query_tgt.htm

INFN - SPES

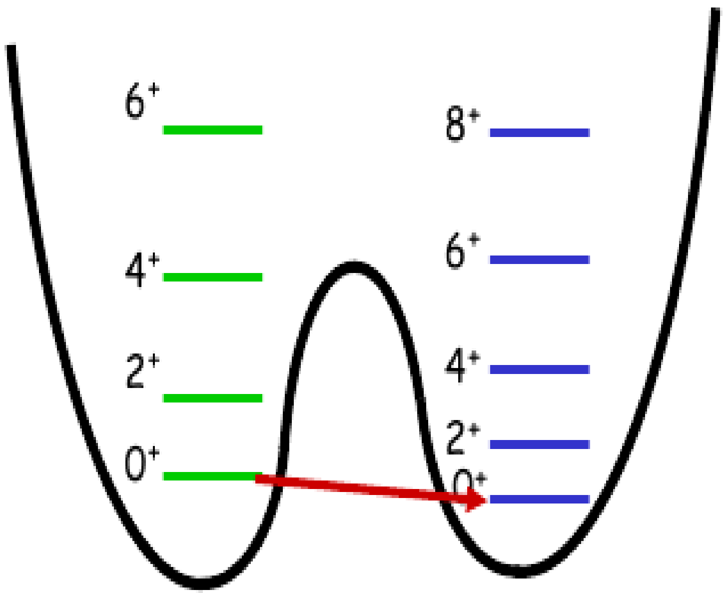
ALTO

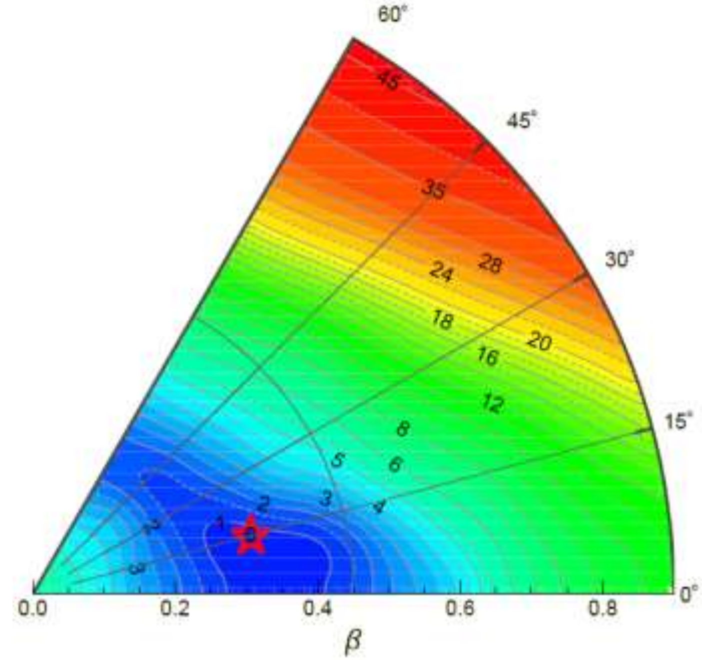


https://web.infn.it/spes/index.php/news/spes-beam-tables

EURISOL-DF:
Enhance complementarities
&
avoid duplication of efforts in the beam developments

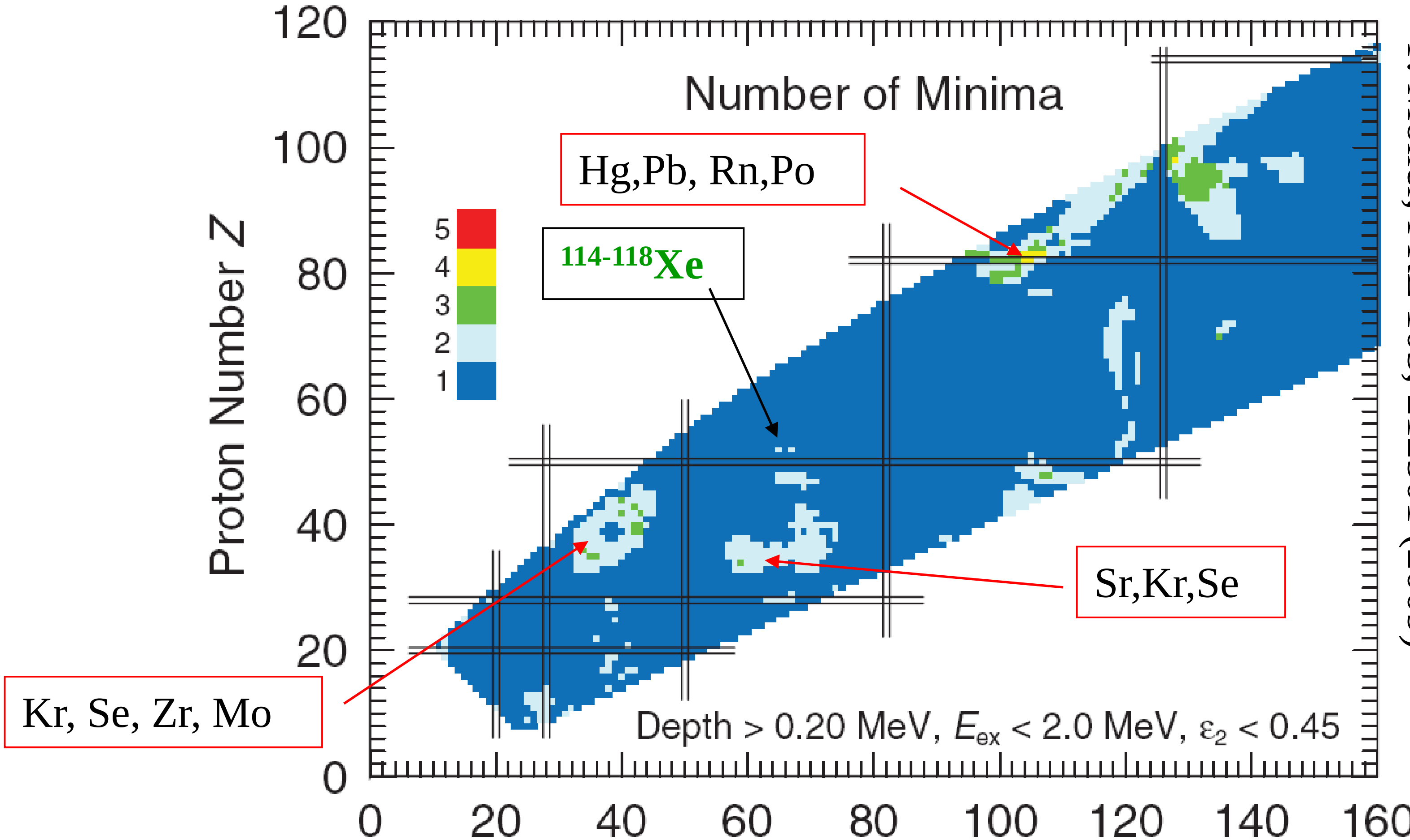
Shape coexistence using RIB facilities



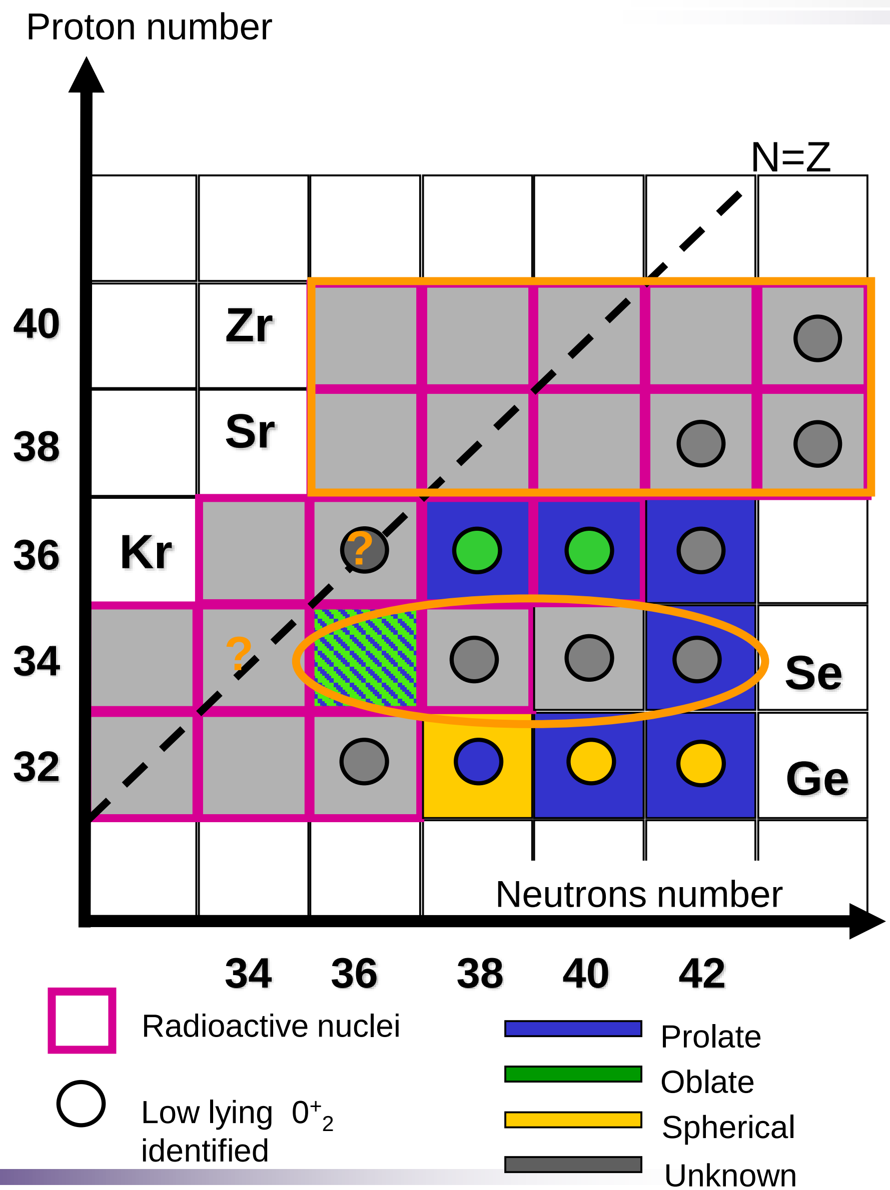


❑ Output experimental values are B(E2), algebric Qs (prolate, oblate), mixing angle, deformation parameter

❑ « Scanning » the potential energy surface of complex nuclei (that you can not measure) by precisely studying the low lying excited states



P. Möller, PRL 103, 212501 (2009)



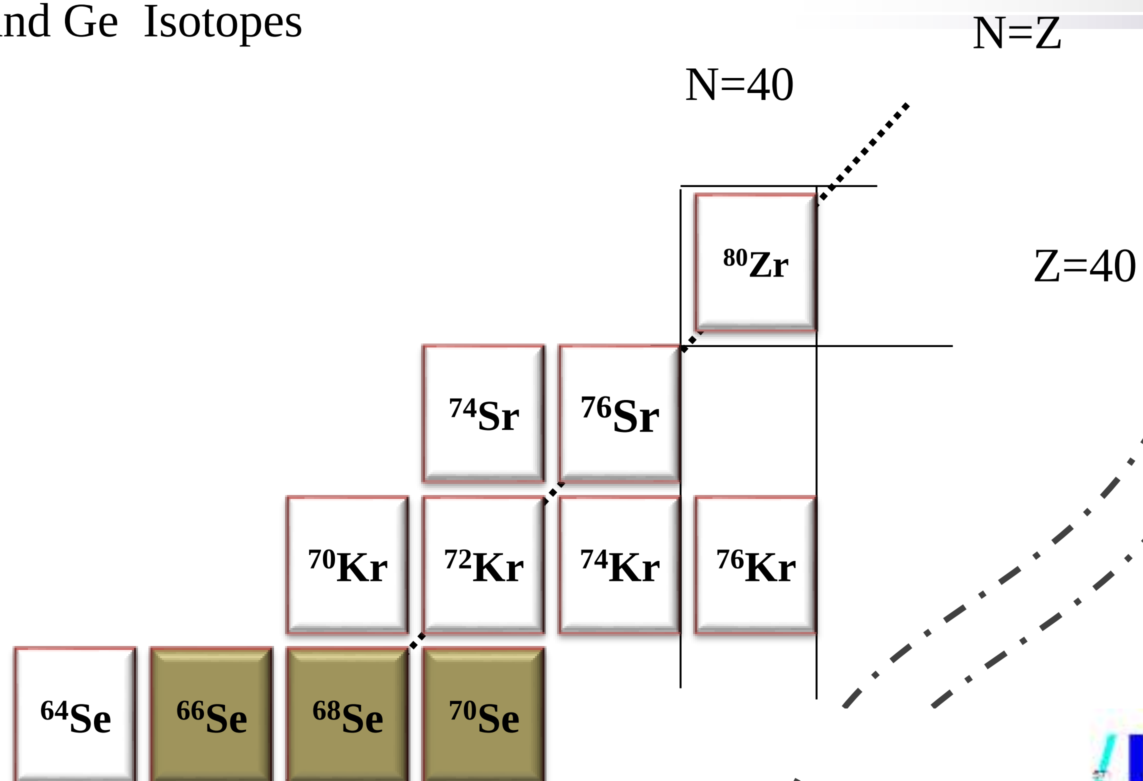
- ^{74}Kr and ^{76}Kr : prolate ground state and oblate 0^+_2 : Shape inversion for ^{72}Kr ?
- ^{70,72}Se have a different behavior than Kr & Ge : ^{68}Se ?
- ^{74}Ge & ^{72}Ge : prolate ground state and spherical 0^+_2.

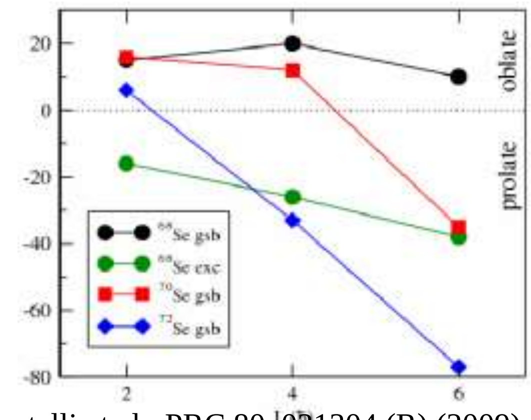
^{70}Ge → Shape Inversion

- Shape coexistence in Sr, low lying 0^+_2 onset of collectivity ?

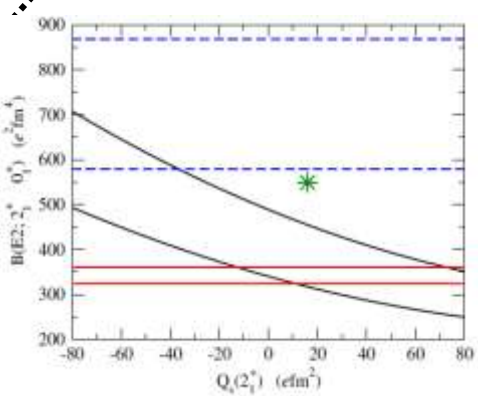
We did not yet reach N=Z !!!

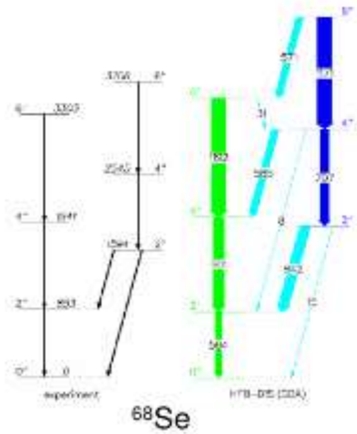
^{70,72}Se behaviors differ from neighboring Kr and Ge Isotopes

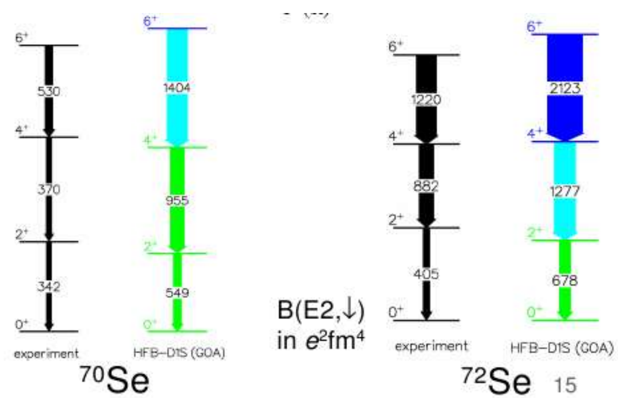


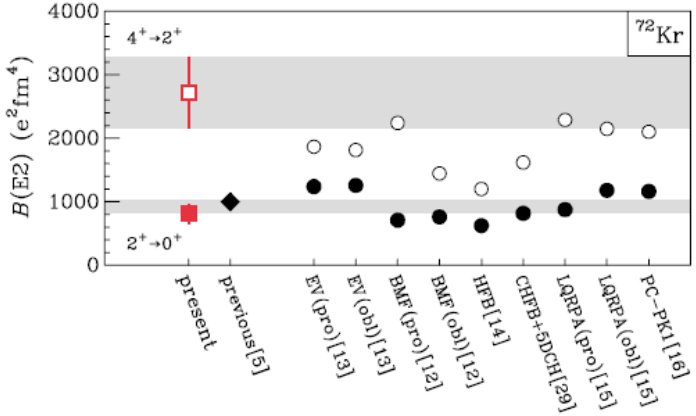


A. Obertelli et al., PRC 80, 031304 (R) (2009)
A. M. Hurst et al., PRL. 98, 072501 (2007).
J. Ljungvall et al., PRL 100, 102502 (2008)
A.J.Nichols et al, PLB 733, 52-57 (2014)





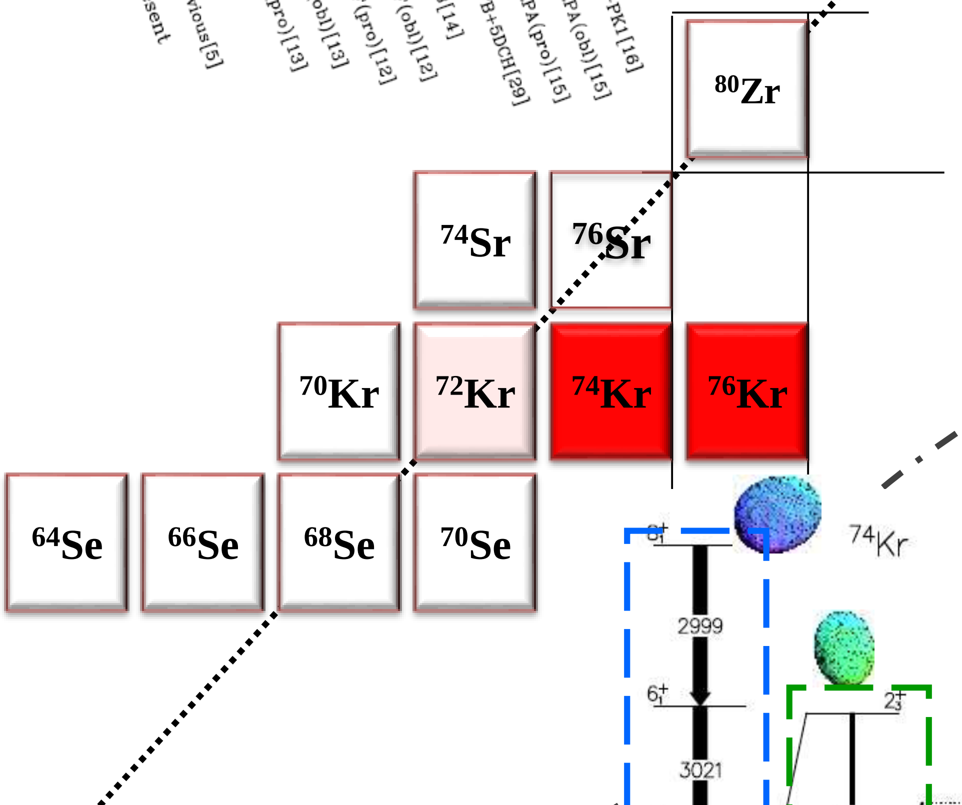


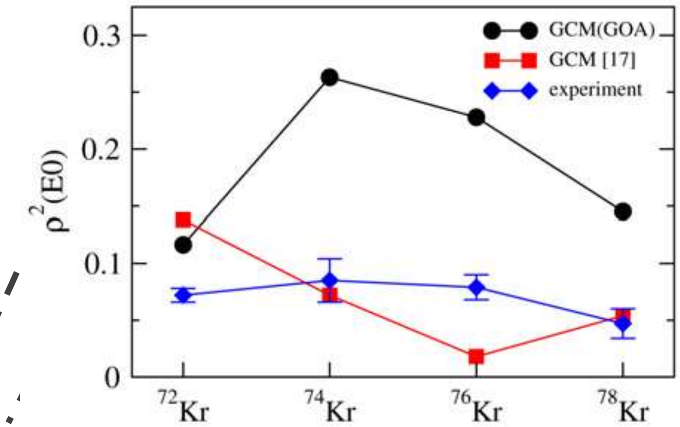


N=Z

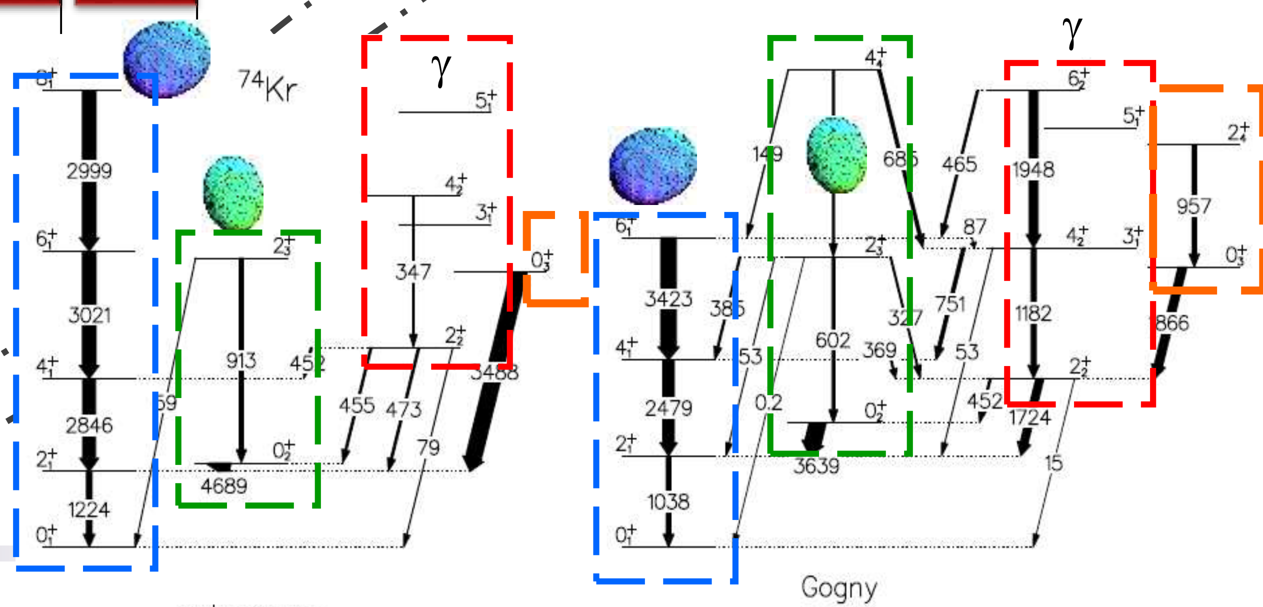
N=40

Z=40



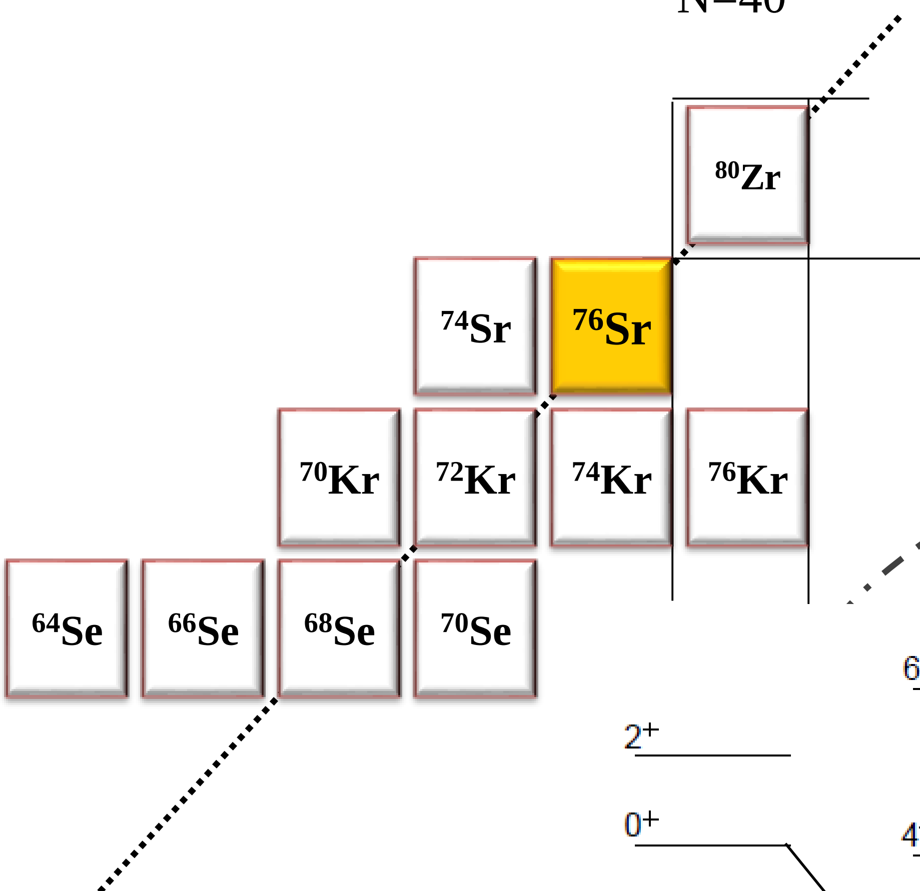


E. Bouchez et al. PRL 90 (2003)
E. Clément et al., PRC 75, 054313 (2007)
H. Iwasaki et al, PRL 112, 142502 (2014)

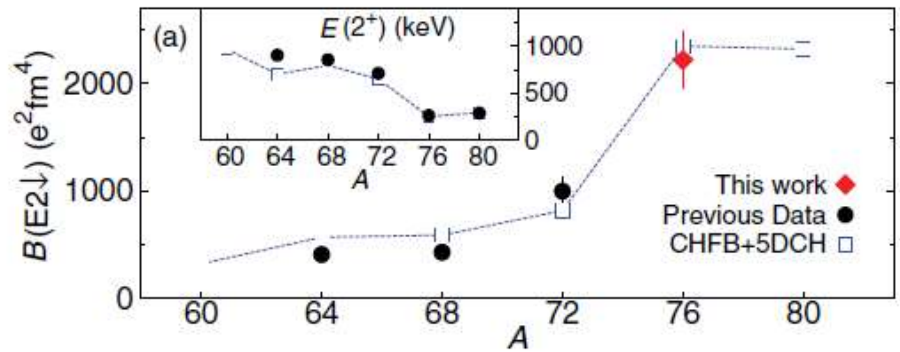


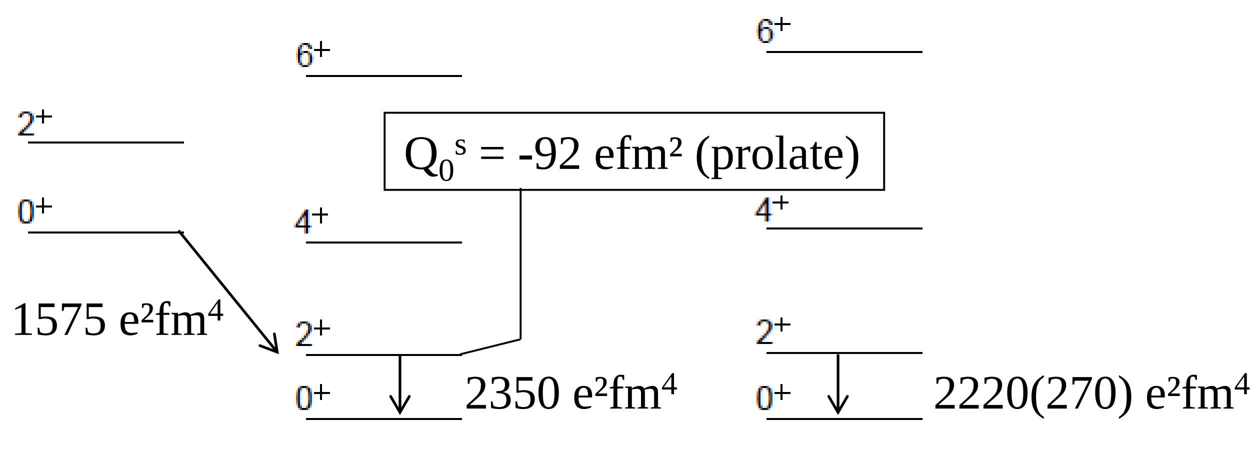
Onset of deformation :

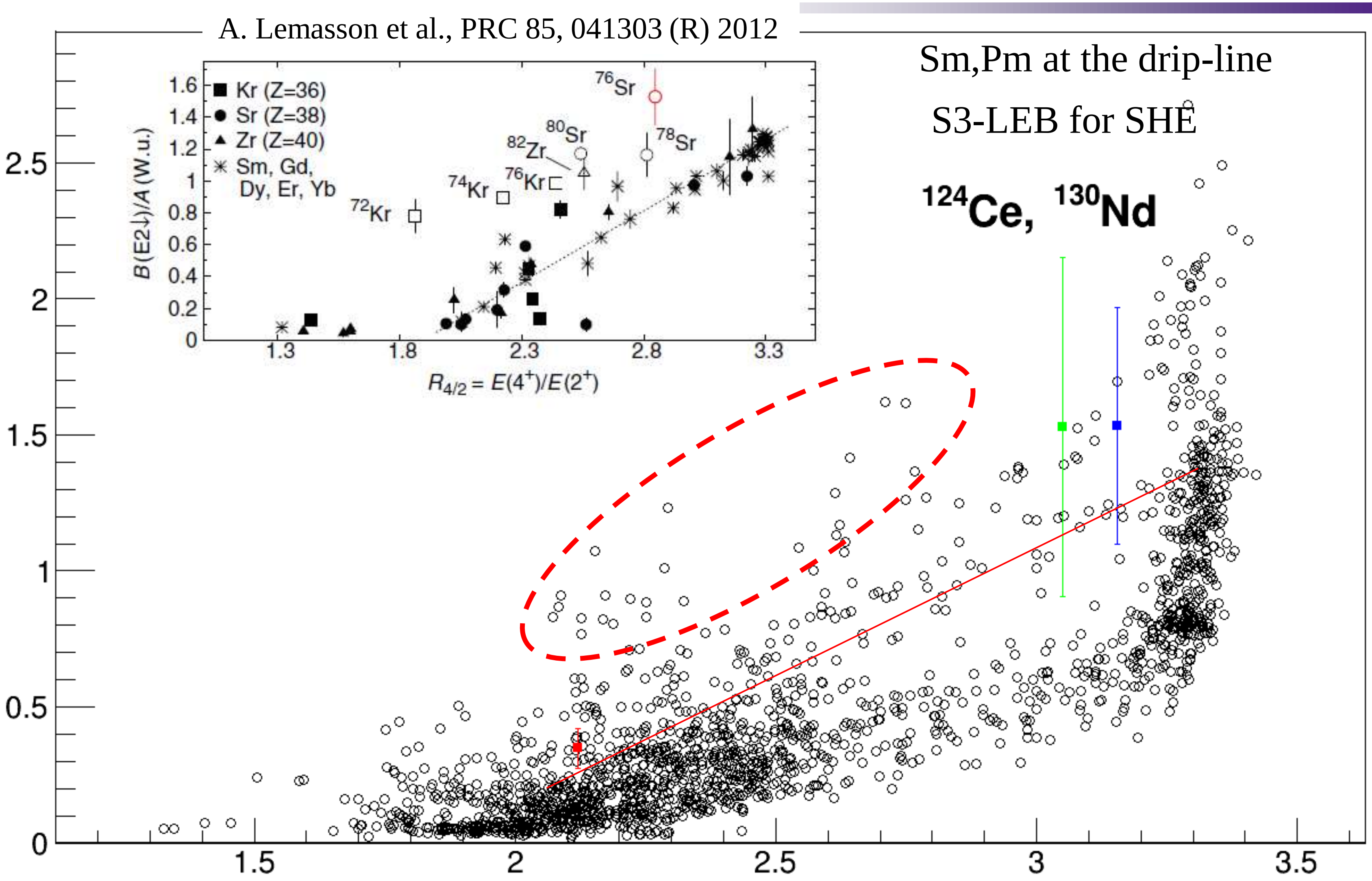
- ❑ Intrinsic higher deformation ?
- ❑ Reduced mixing ? (triaxiality related ?)



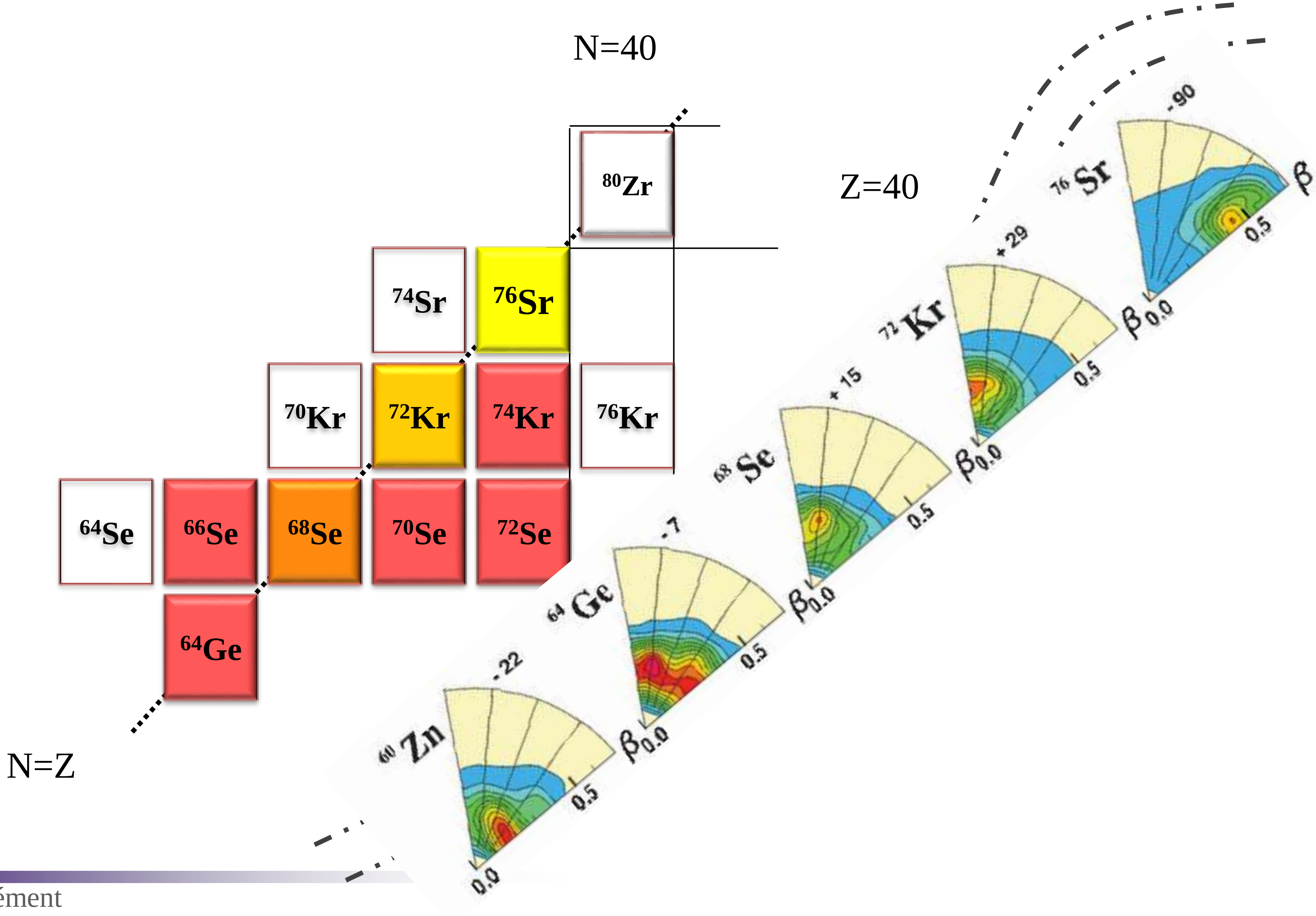
A. Lemasson et al., PRC 85, 041303 (R) 2012







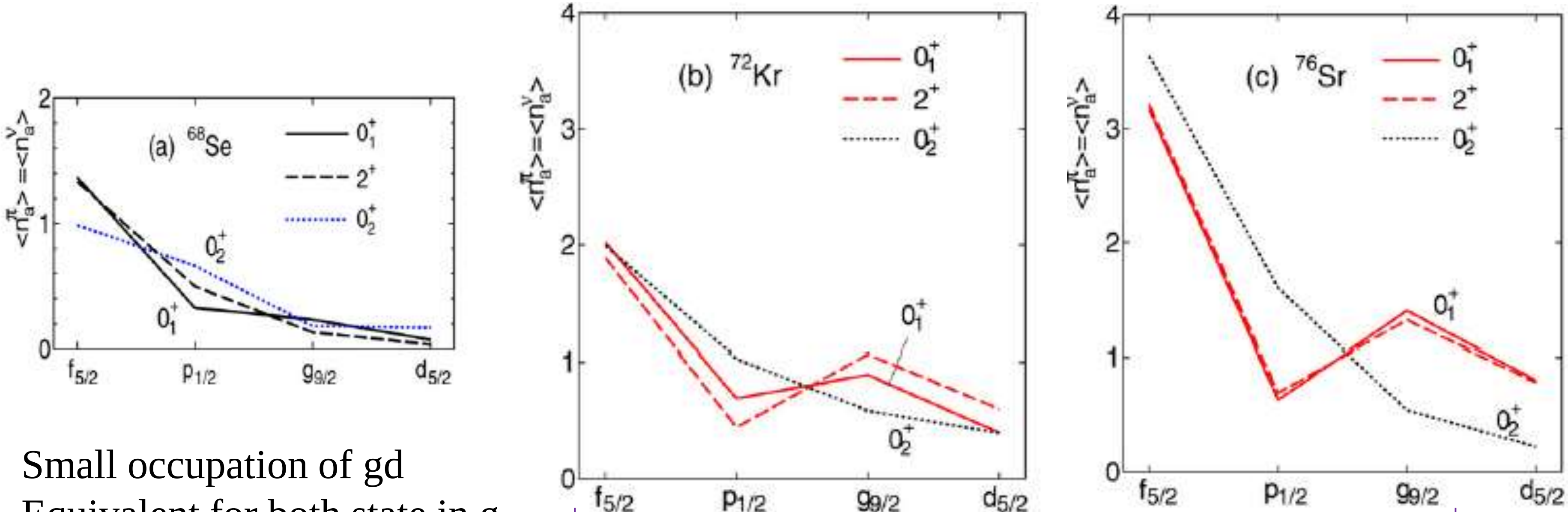
Extracted from J.-P. Delaroche et al, PRC 81, 014303 (2010) with R. F. Casten and N. V. Zamfir PRL 70 , 402 (1993)


N=40
80Zr
Z=40
74Sr
76Sr
70Kr
72Kr
74Kr
76Kr
64Se
66Se
68Se
70Se
72Se
64Ge
N=Z
60 Zn
-22
64 Ge
-7
68 Se
+15
72 Kr
+29
76 Sr
-90
β
0.0
0.5

M. Hasegawa et al. , Physics Letters B 656 (2007) 51–55

Exp: increase of the B(E2) → higher deformation

→ less mixing



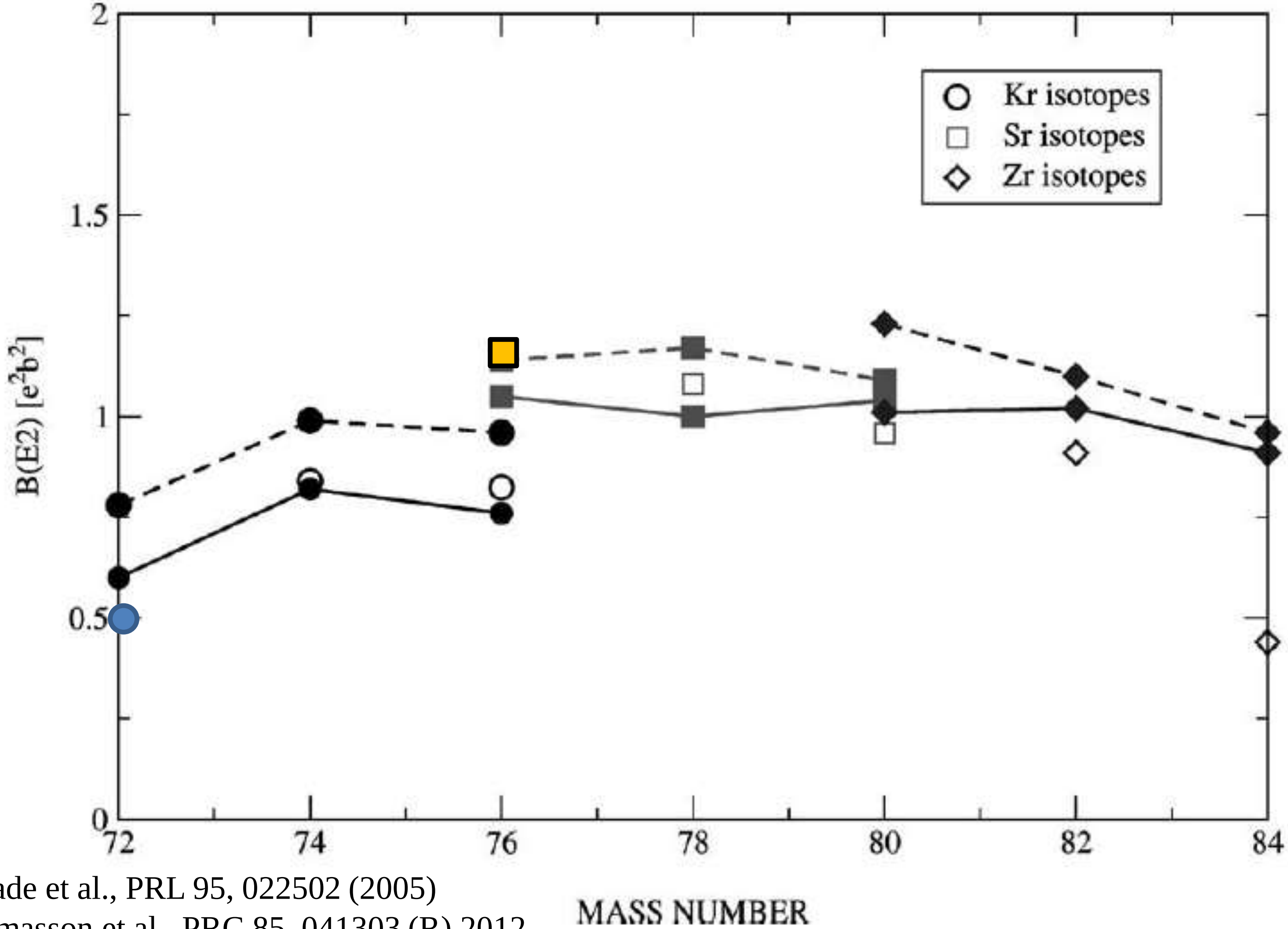
Small occupation of gd
Equivalent for both state in g
Favor large mixing and
smaller deformation?

Increased occupation of gd
Large difference for both state in gd
Coherent particle in g9/2 increase
deformation and disable mixing ?

- $g_{9/2}$ plays a central rôle
- $B(E2, 2^+)$ not reproduced at all→ lack of the $p_{3/2}$
- Higher lying state ? Qs ? Other B(E2) ?

K. Langanke et al. / Nuclear Physics A 728 (2003) 109–117

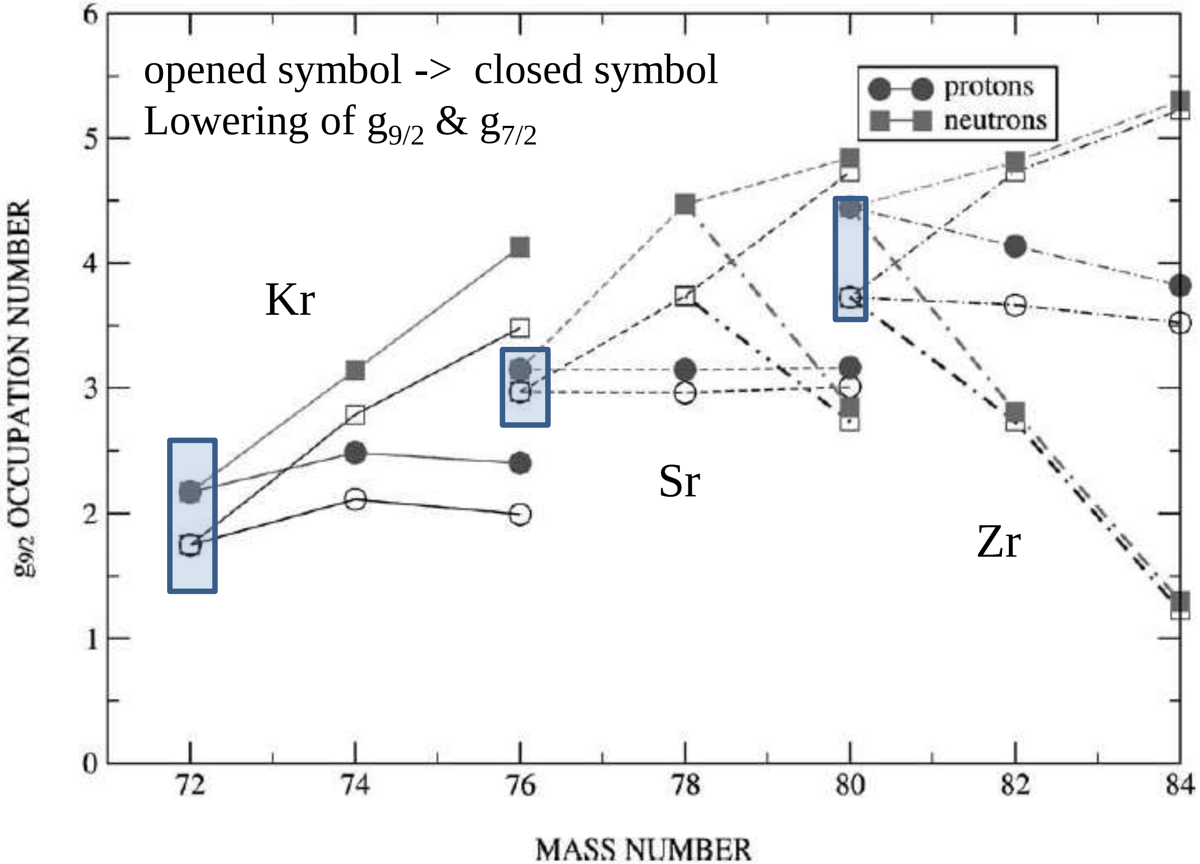
Shell model Monte Carlo with complete 0f 1p–0g1d2s model space



A. Gade et al., PRL 95, 022502 (2005)

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

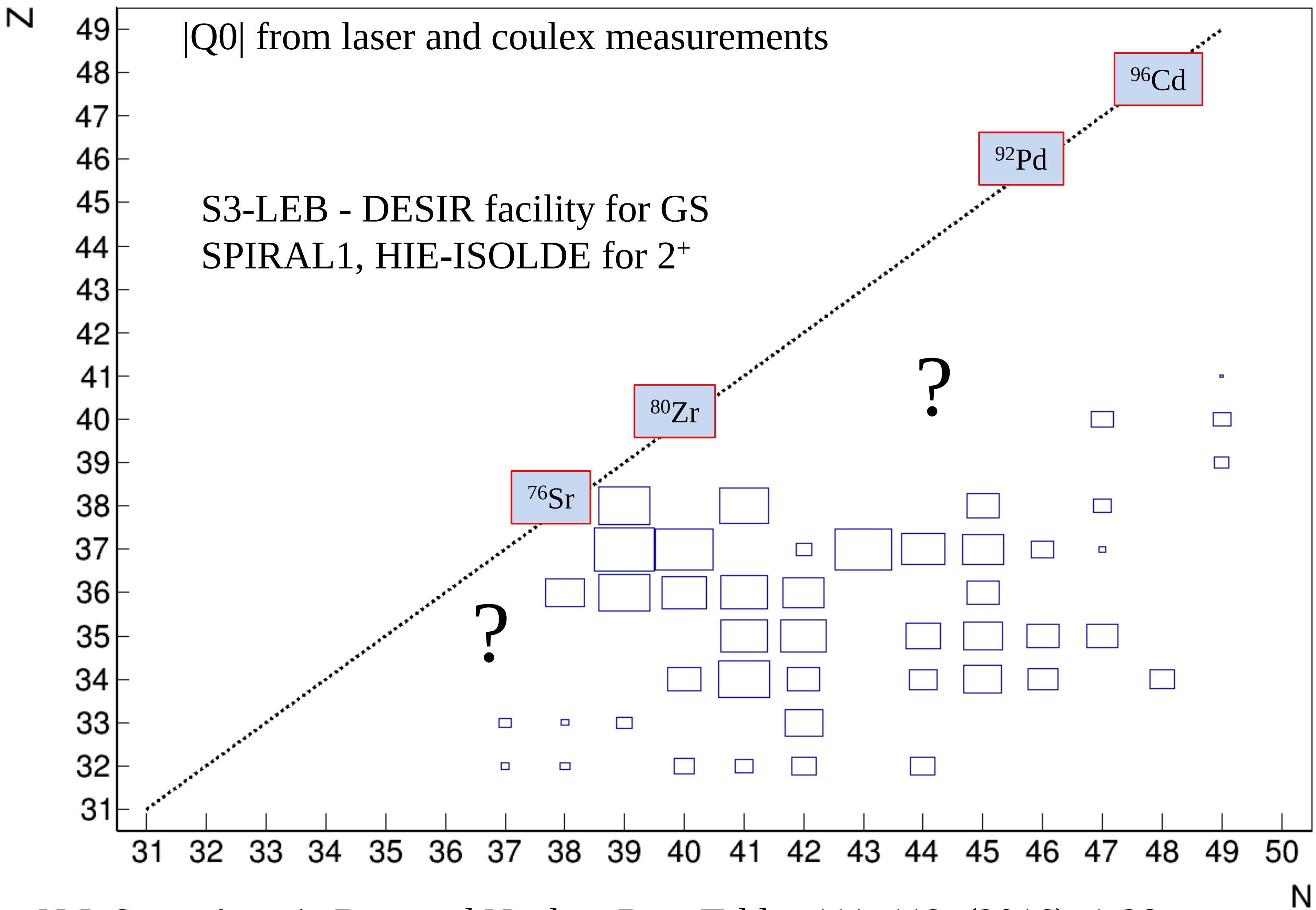
K. Langanke et al. / Nuclear Physics A 728 (2003) 109–117



- The increase of B(E2) between N=Z nuclei is correlated to the increase of $g_{9/2}$ occupation
- The shape change & configuration mixing change in Kr isotope is not « visible » through the $g_{9/2}$ occupancy
- The rigidity enhancement is also not explicitly visible in the $g_{9/2}$ occupancy

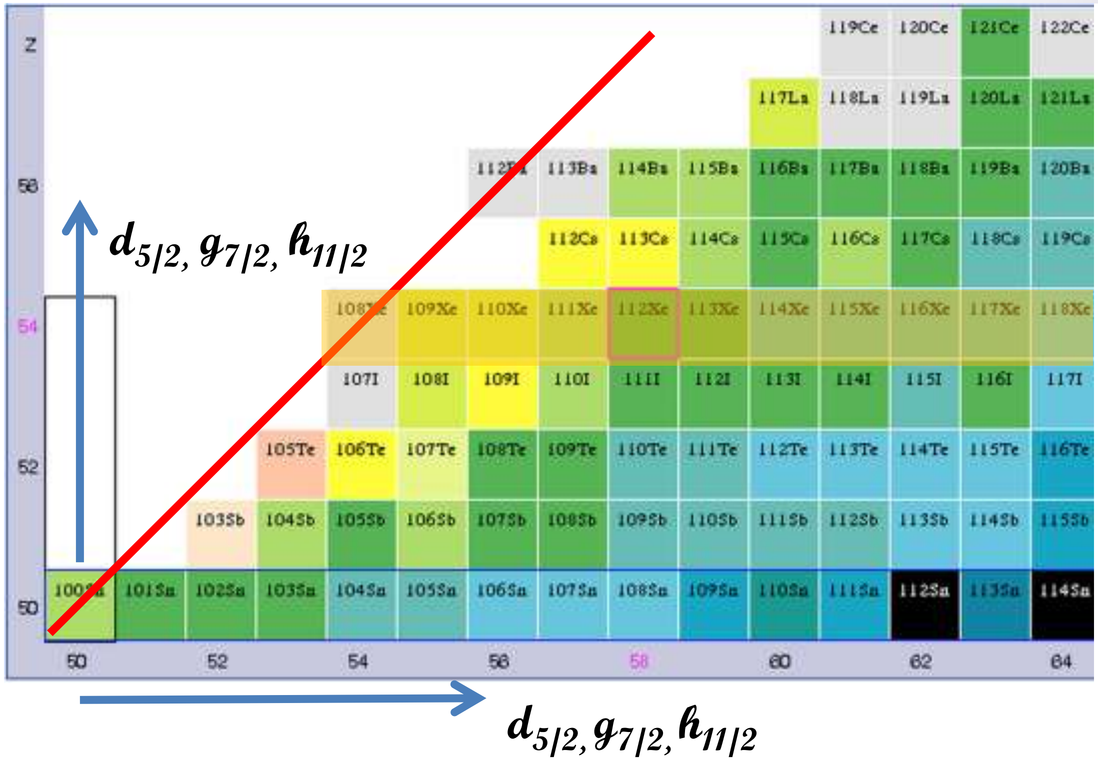
Transfer reaction were never attempted in this mass region

Holistic …



Compiled from N.J. Stone Atomic Data and Nuclear Data Tables 111–112, (2016), 1-28

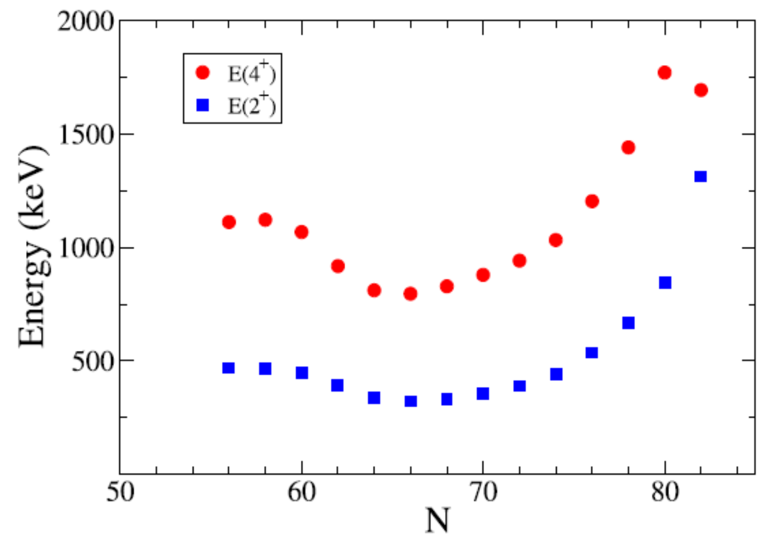
Shell evolution and collectivity using a ^{100}Sn core



Nuclear structure using a ^{100}Sn core

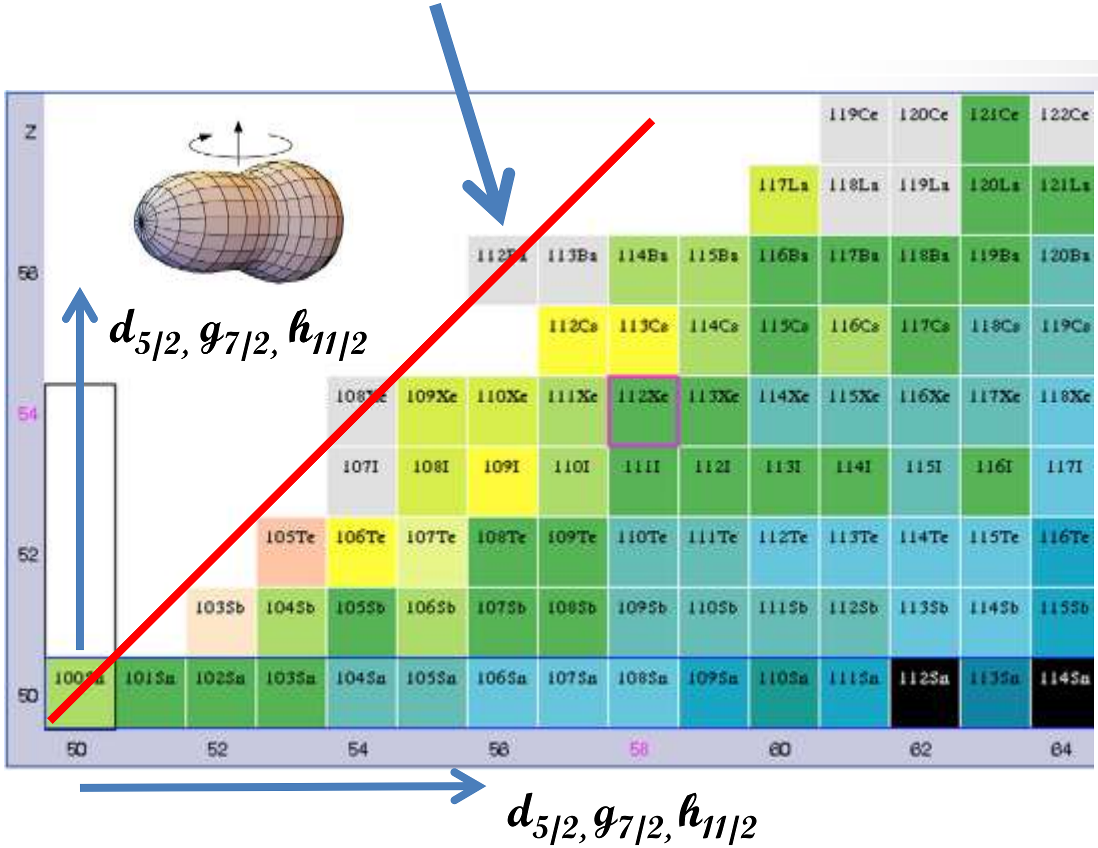
C.B.Hinke et al., Nature(London) 486, 341 (2012)
B. Cederwall et al., Nature(London) 469, 68 (2011)
L.P.Gaffney et al., Nature (London) 497, 199 (2013)

M. Sandzelius et al Phys. Rev. Lett 99, 022501 (2007)



- ❑Maximum of 2^+ and 4^+ excitation energies at N=82
- ❑ Maximum of collectivity at mid-shell
- ❑ Collectivity approaching N=50 ?

^{112}Ba should corresponds to the best octupole N=Z=56 for p and n



Enhanced octupole due to the interaction of ΔL=3, ΔJ=3, inverse parity : $d_{5/2}$ and $h_{11/2}$

3^- states dominate by $d_{5/2} \times h_{11/2}$ orbital configuration

Removing neutron from the $h_{11/2}$ orbital gradually decreases the 3^- excitation energy and enhances the B(E3) value

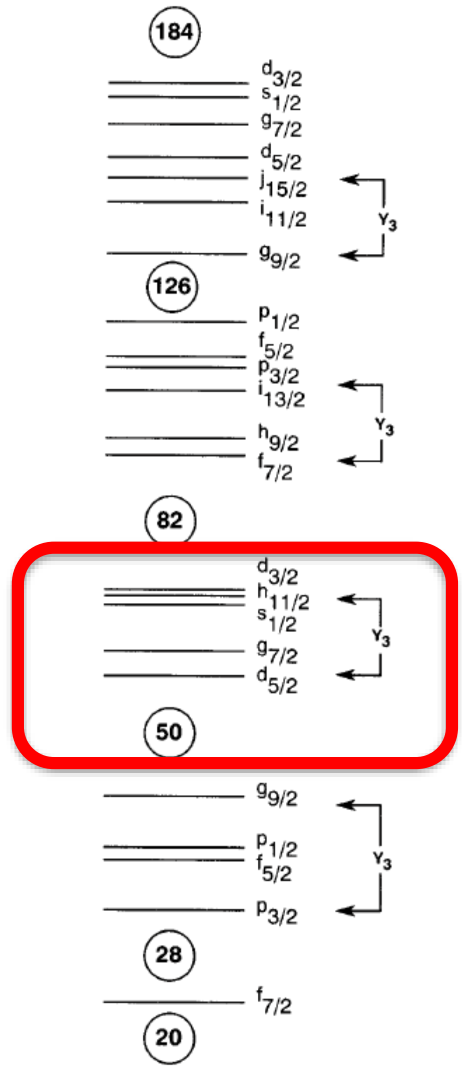
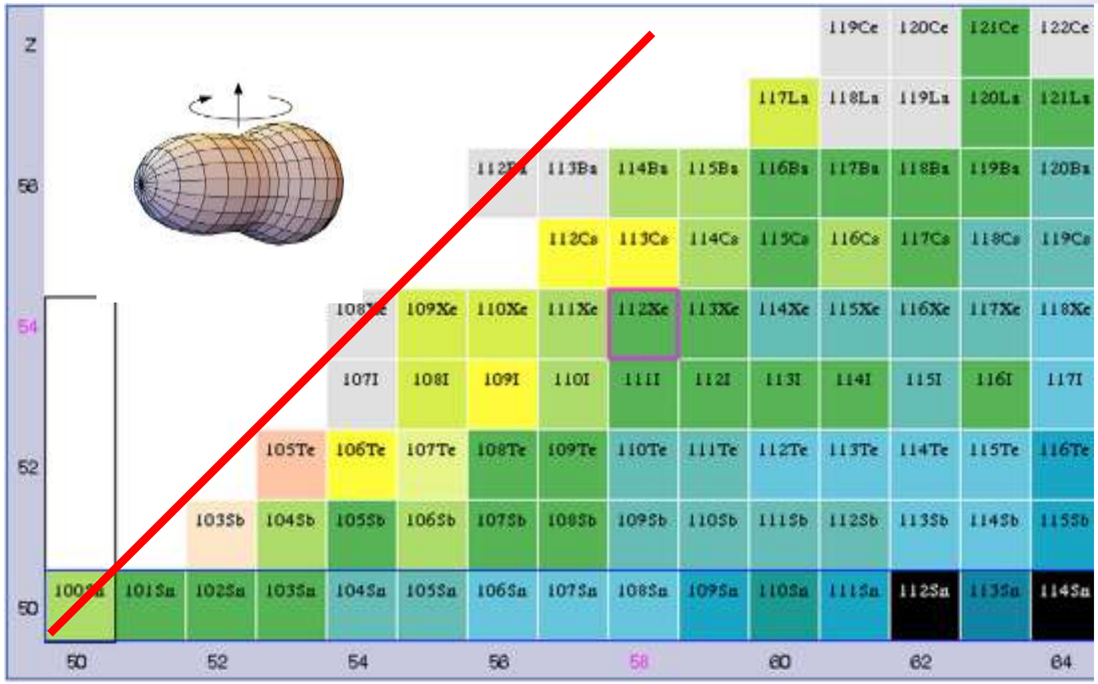
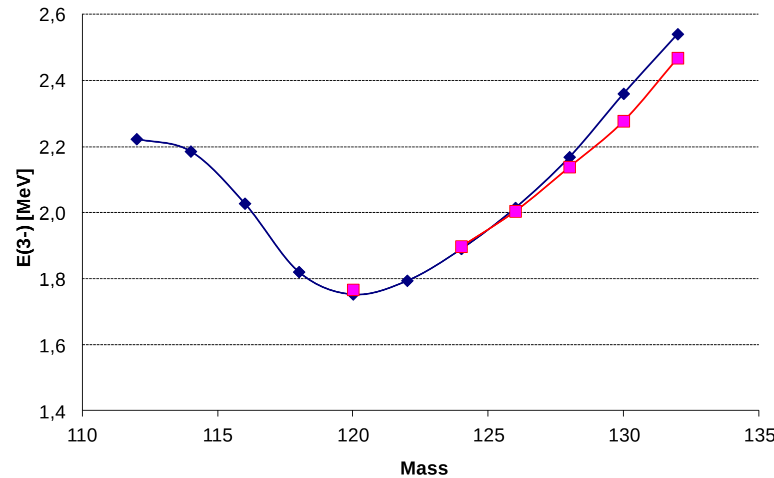


FIG. 4. Nuclear spherical single-particle levels. The most important octupole couplings are indicated.

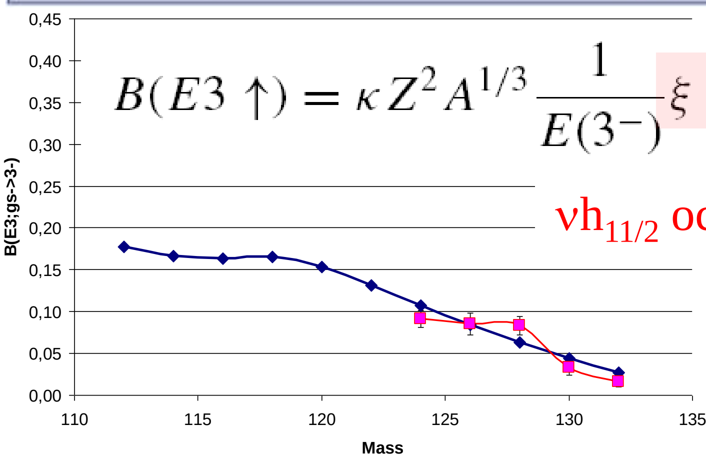




Collective octupole motion in such nuclei is strongly influenced by quadrupole softness

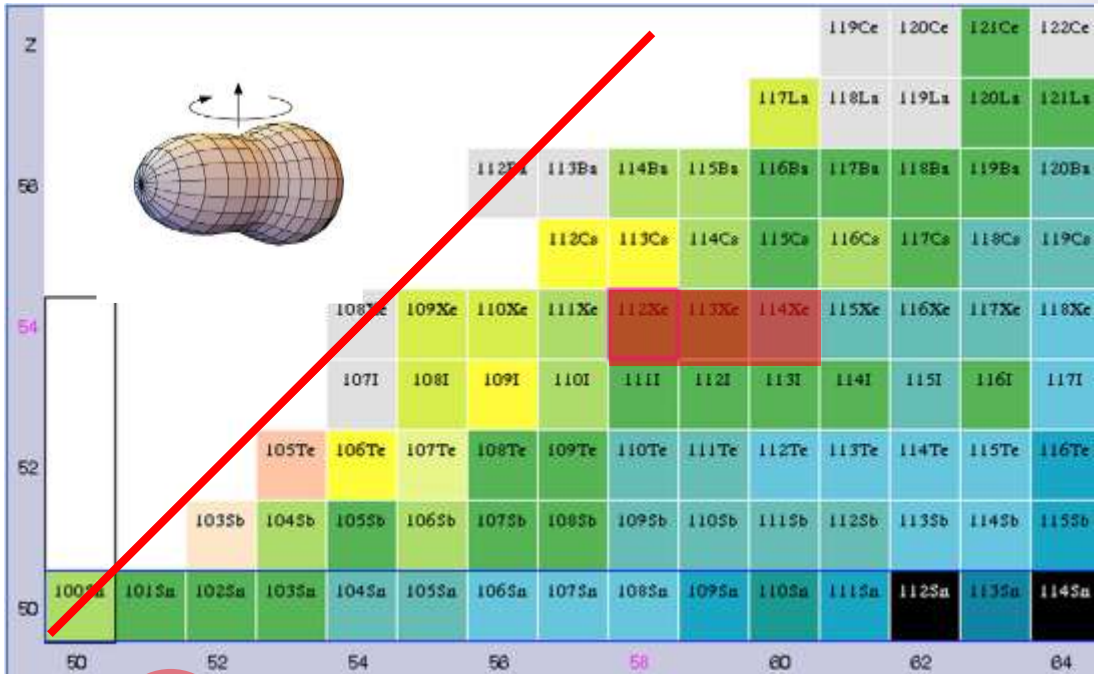
$$E(3^-) = E_0 - \frac{B^2}{E(2_1^+)}.$$

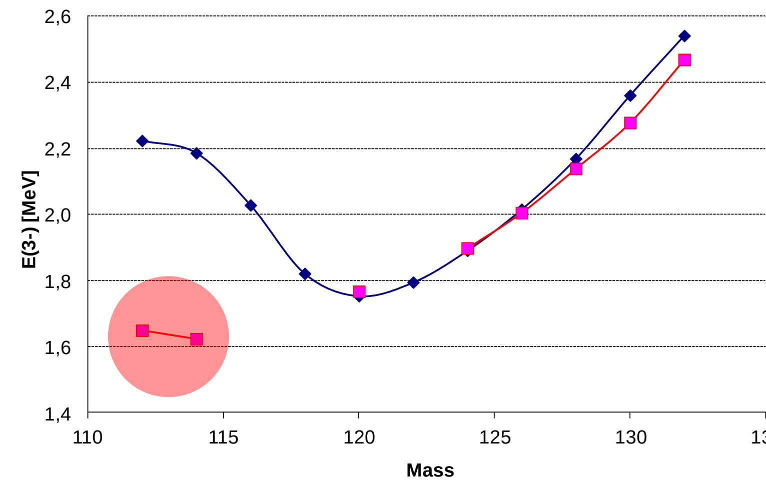
[M. P. Metlay Phys. Rev. C ***52****, 1801 (1995)]*



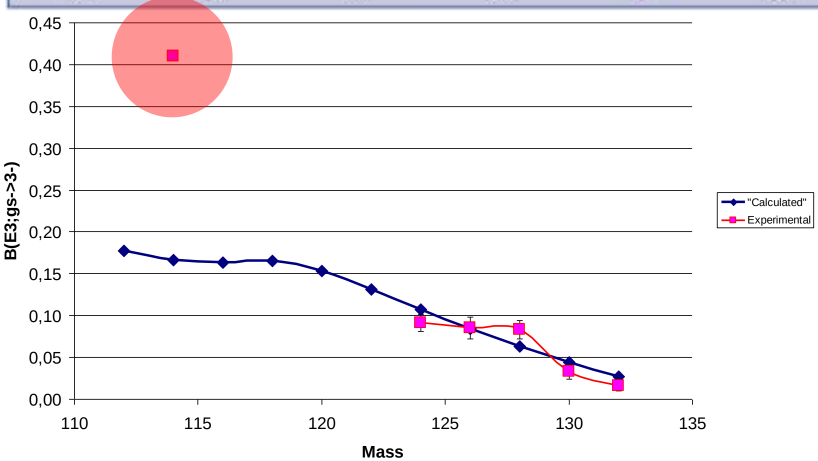
$$B(E3\uparrow) = \kappa Z^2 A^{1/3} \frac{1}{E(3^-)} \xi \; [e^2 b^3]$$

$\nu h_{11/2}$ occupancy





G. de Angelis et al., Phys. Lett. B 535 (2002) 93
J.F. Smith et al., Phys. Lett. B 523 (2001) 13.



HIE-ISOLDE or SP1-fusion
AGATA-NEDA

^{114}Xe : B(E3:3$^-$ → 0$^+$) = 77(27) W.u

	^{114}Xe	^{112}Xe	^{118}Ba
E (3-)$_{theo}$ (MeV) / Exp	1.84 /1.62	1.99/1.65	2.11
B(E3: 3- → 0+)$_{theo}$ W.u.	17	25	18.7
B(E3: 3- → 0+)$_{exp}$ W.u.	77(27)	-	-

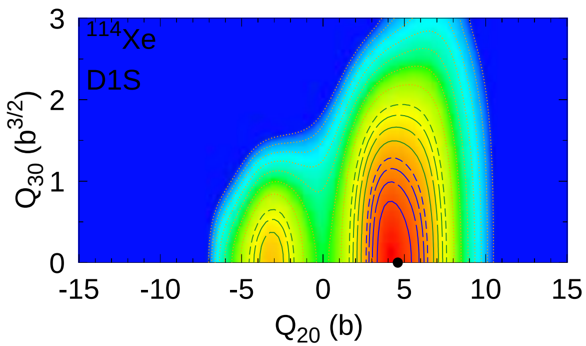
Factor 4.5

- The $h_{11/2}$-$d_{5/2}$ octupole in ^{146}Gd for protons is 37 W.u. reproduced by the same GCM HFB calculations

- Quadrupole-octupole coupling is a key contribution
  → Reproduces the Ra-Rn octupole transition strength
  L.M. Robledo and P.A. Butler, PRC 88 051302 (R) (2013)

- Q2-Q3 does not change the B(E3)

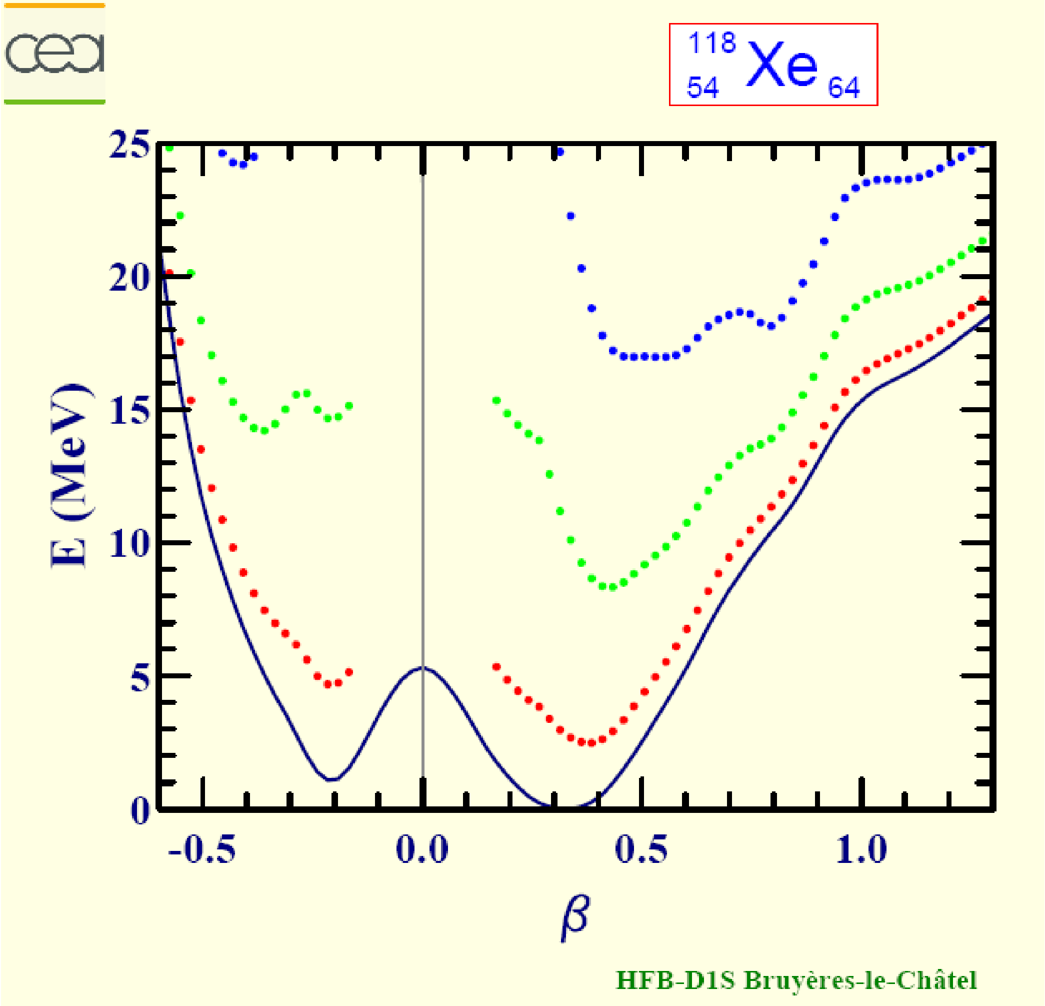
L.M. Robledo private communication



The large B(E3) might be due to the presence of an isoscalar the proton-neutron $\pi(\nu)\ d_{5/2} - \nu\ (\pi)\ h_{11/2}$ term

Should increase toward N=Z

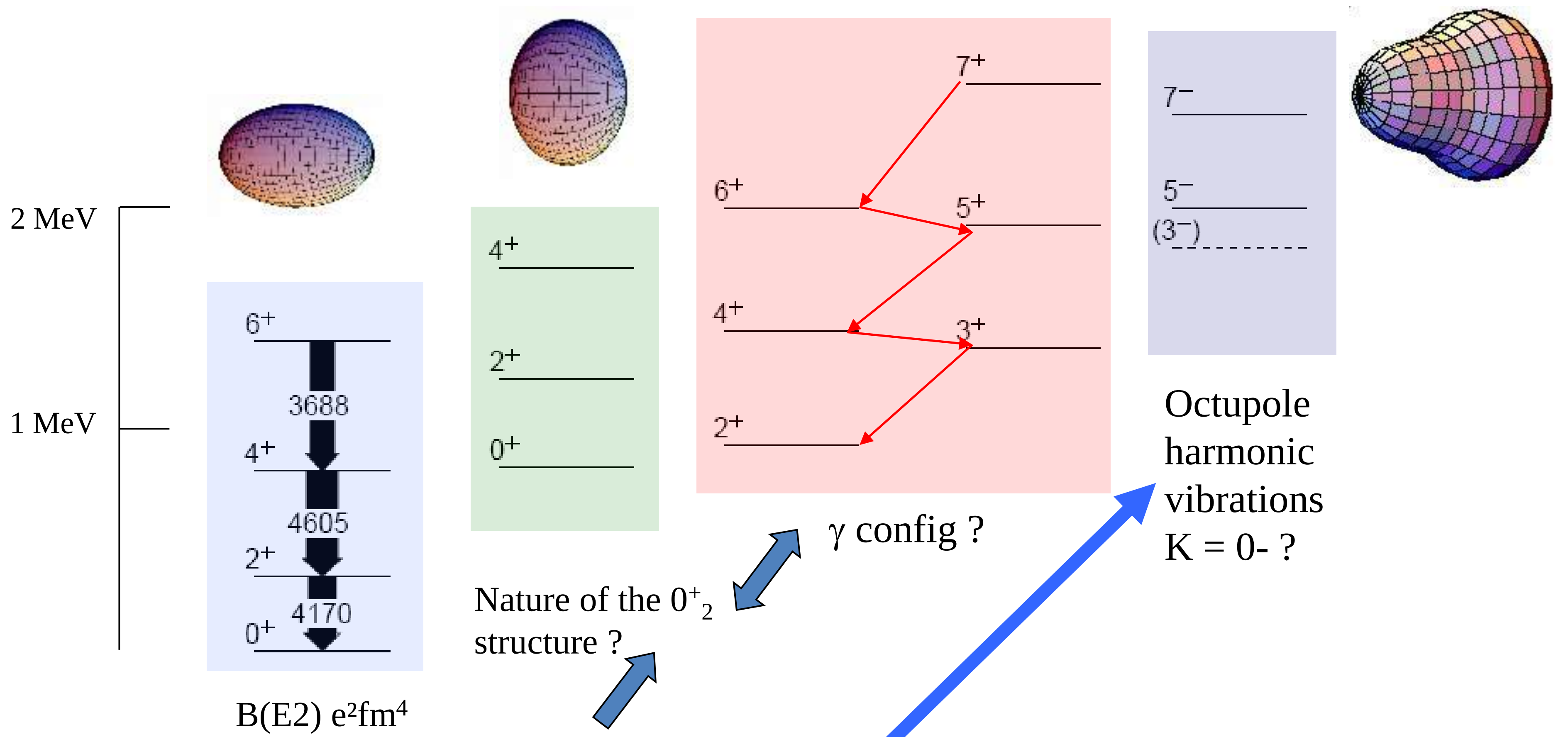
Shape coexistence beyond ^{100}Sn



Shape competition between prolate and oblate minima

- *Different shells, new degree of freedom*
- *Can we describe the nuclei above Sn as well as below ?*
- *B(E2) connecting these structure*
- *Spectroscopic quadrupole moment Qs*
- *Mixing of wave function*

Shape coexistence in Xe isotopes (^{118}Xe case)



Mixing ?

O6 compatible (γ soft rotor ?)

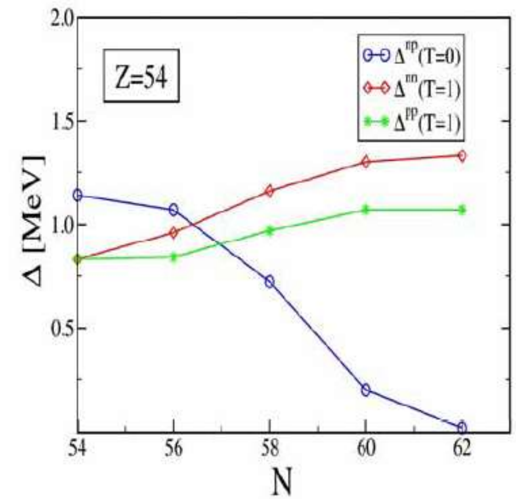
== Spectroscopic quadrupole moment should be null

HIE-ISOLDE or SP1-fusion

Approaching ^{108}Xe ?

Calculations for Xe

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

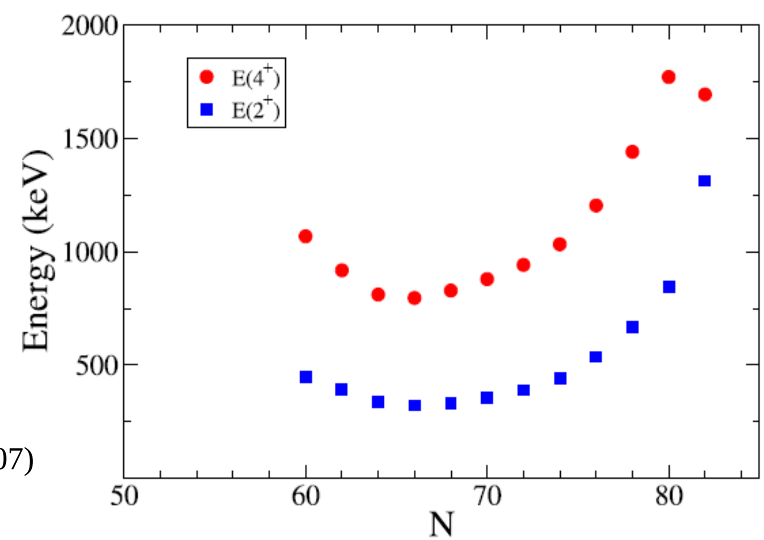


The isoscalar (np) pair gap is predicted to increase as N~Z

❑Direct evidence are difficult to find experimentally

→ comparison between state-of-the art calculation and spectroscopic data

❑ Call naturally for more data

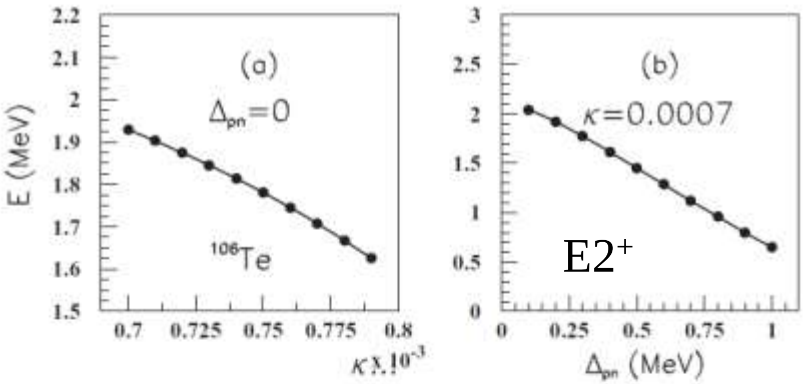


J.F. Smith et al, Phys. Lett. B 523, 13 (2001)

M. Sandzelius et al Phys. Rev. Lett 99, 022501 (2007)

QRPA (Pairing + Quadrupole Hamiltonian)

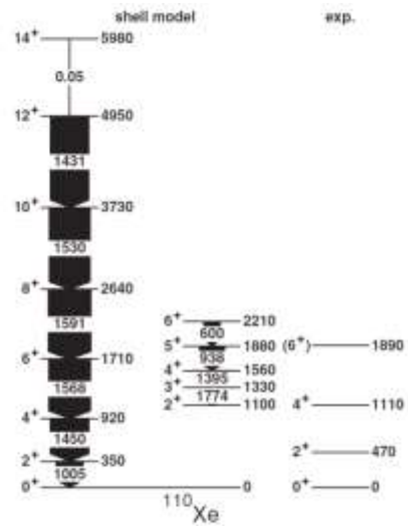
Delion et al, Phys. Rev. C 82, 024307 (2010)

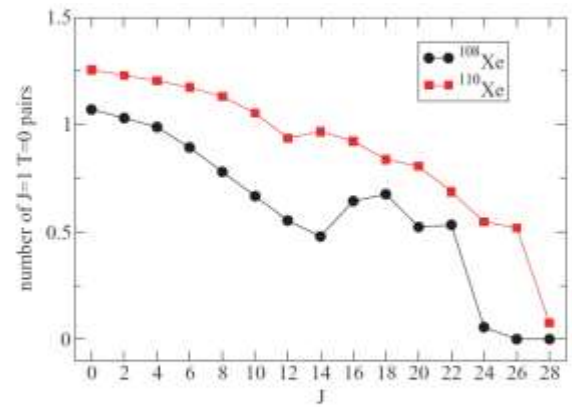


- ❑Q driven : Decrease 2^{+} and increase B(E2)
- ❑Δ_{pn} driven : Decrease 2^{+} and B(E2)

Large Scale Shell Model Calculations

Caurier et al PRC 82, 064304 (2010).





❑No need for strong np isoscalar pairing & depletion of the ^{100}Sn core.

❑Calculated J=0 T=1 and J=1 T=0 pairs are small

❑20% increase of quadrupole collectivity when including a 1p-1h excitation for ^{112}Xe.

^{100}Sn core breaking or confirmations of the contribution of T=0 pairing are based from theoretical calculations supported by known spectroscopic experimental data: in the present situation, only excitation energies. → B(E2) ? Other data g-factor, masses, Qs, transfer reactions …

Conclusion

• An area for stopped beams (decay studies, mass measurements and other ground state properties, including traps and laser ionisation…). A hall similar to the present ISOLDE hall

• A low energy area for reactions of astrophysical interest

• Coulex and transfer reaction.

• In-beam, gamma, electron spectroscopy and decay tagging station.

• Need for developments of RIB beams at N~Z and need for post-acceleration