Correlations and collectivity witihin the Shell Model

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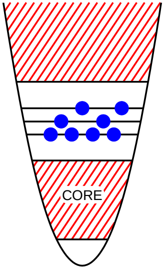
RESANET GT2 Meeting, October 9th, 2018

[1] Strasbourg-Madrid Shell-Model collaboration

Shell Model Problem



- Define a valence space
- Derive an effective interaction

$$\mathcal{H}\Psi = E\Psi \rightarrow \mathcal{H}_{\text{eff}}\Psi_{\text{eff}} = E\Psi_{\text{eff}}$$

- Build and diagonalize the Hamiltonian matrix.

In principle, all the spectroscopic properties are described simultaneously (Rotational band AND β decay half-life).

Separation of the effective Hamiltonian
Monopole and multipole

From the work of M. Dufour and A. Zuker (PRC 54 1996 1641)
Separation theorem:

Any effective interaction can be split in two parts:

$$H = H_{monopole} + H_{multipole}$$

$H_{monopole}$: *spherical mean-field*
☞responsible for the global saturation properties and for the evolution of the spherical single particle levels.
$H_{multipole}$: *correlator*
☞pairing, quadrupole, octupole...

Important property:

$$\langle CS \pm 1|H|CS \pm 1\rangle = \langle CS \pm 1|H_{monopole}|CS \pm 1\rangle$$

Multipole Hamiltonian

$H_{multipole}$ can be written in two representations, particle-particle and particle-hole. Both can be brought into a diagonal form. When this is done, it comes out that only a few terms are coherent, and those are the simplest ones:

- $L = 0$ isovector and isoscalar pairing
- Elliott's quadrupole
- $\vec{\sigma}\vec{\tau} \cdot \vec{\sigma}\vec{\tau}$
- Octupole and hexadecapole terms of the type $r^\lambda Y_\lambda \cdot r^\lambda Y_\lambda$

Besides, they are universal (all the realistic interactions give similar values) and scale simply with the mass number

Interaction	particle-particle		particle-hole		
	$JT = 01$	$JT = 10$	$\lambda\tau = 20$	$\lambda\tau = 40$	$\lambda\tau = 11$
KB3	-4.75	-4.46	-2.79	-1.39	+2.46
FPD6	-5.06	-5.08	-3.11	-1.67	+3.17
GOGNY	-4.07	-5.74	-3.23	-1.77	+2.46

Shell structure and correlations

- at stability
  - double magicity + superdeformed states: ^{16}O, ^{40}Ca, ^{56}Ni
- far from stability
  - Vanishing of shell closure: ^{11}Li, ^{32}Mg, ^{42}Si, ^{68}Ni, ^{80}Zr ...
  - New gaps: ^{24}O, ^{54}Ca ...

Interplay between
- Monopole field (spherical mean field)
- Multipole correlations (pairing, Q.Q, ...)

“Pairing plus Quadrupole propose, Monopole disposes”

A. Zuker, Coherent and Random Hamiltonians, CRN Preprint 1994

For the Monopole field itself,

interplay between
- single particle field
- two-body interaction (T=1, T=0)

Spherical Shell Model and Deformation

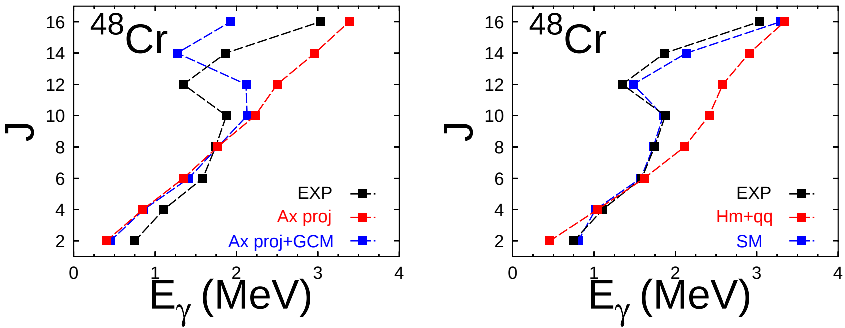
- nuclear shell model often considered to be applied only when nuclear manifestations are dominated by single particle degrees of freedom
- BUT work of Elliot: deformation in light nuclei explained by algebraic SU3 model

- Limitations of SU3 model:
  - as the spin orbit term becomes rapidly important its applicability stops at the sd shell
  - but can be recovered approximately as in the pseudo-SU3 or quasi-SU3 schemes.

See:

- A. P. Zuker, J. Retamosa, A. Poves, and E. Caurier Phys. Rev. **C52** (1995) R1741
- A. P. Zuker, A. Poves, F. Nowacki and S. M. Lenzi Phys. Rev. **C92** (2015) 024302

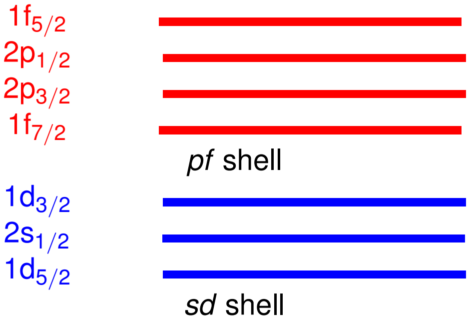
Correlations: ^{48}Cr example



Deformed HF versus SM diagonalisation

Extreme Correlations: the case of ^{40}Ca

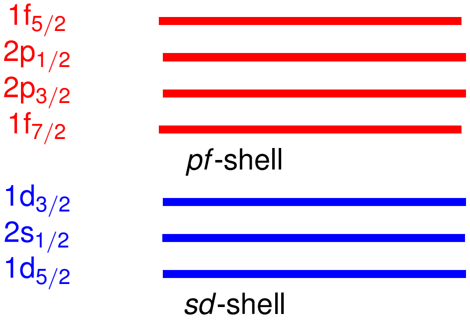
In the valence space of two major shells



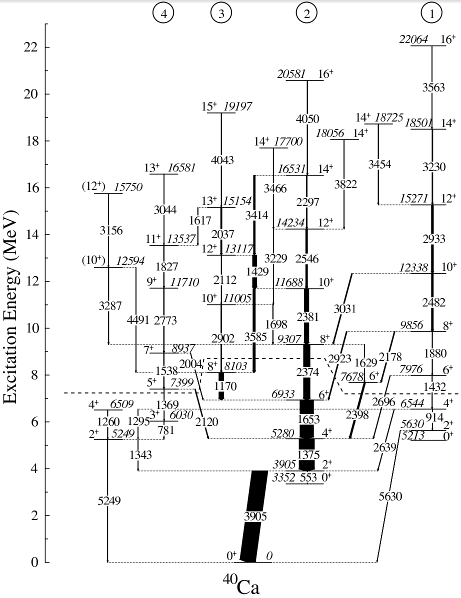
Extreme Correlations: the case of ^{40}Ca

The relevant configurations are:

- $[sd]^{24}$ 0p-0h in ^{40}Ca, SPHERICAL
- $[sd]^{20}[pf]^{4}$ 4p-4h in ^{40}Ca, DEFORMED
- $[sd]^{16}[pf]^{8}$ 8p-8h in ^{40}Ca, SUPERDEFORMED



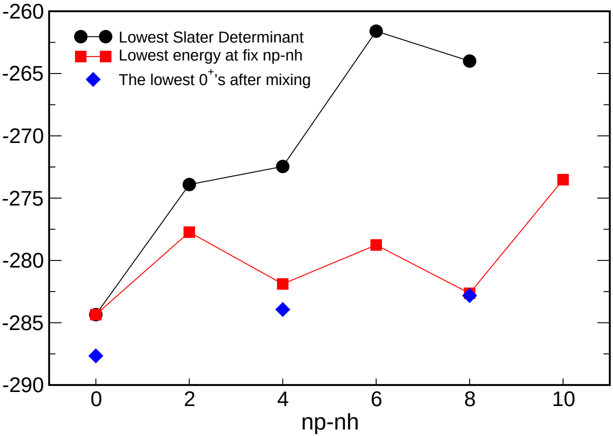
Extreme Correlations: the case of ^{40}Ca



E. Ideguchi et al.,
Phys. Rev. Lett. **87**, 222501-1 (2001)

- good description in terms of *ph* excitations
- decay of SD and ND bands shows mixing between *np* − *nh* configurations
- mixing should not destroy the agreement of 8*p*8*h* calculations
- complex mecanism and theoretical challenge in the shell model framework

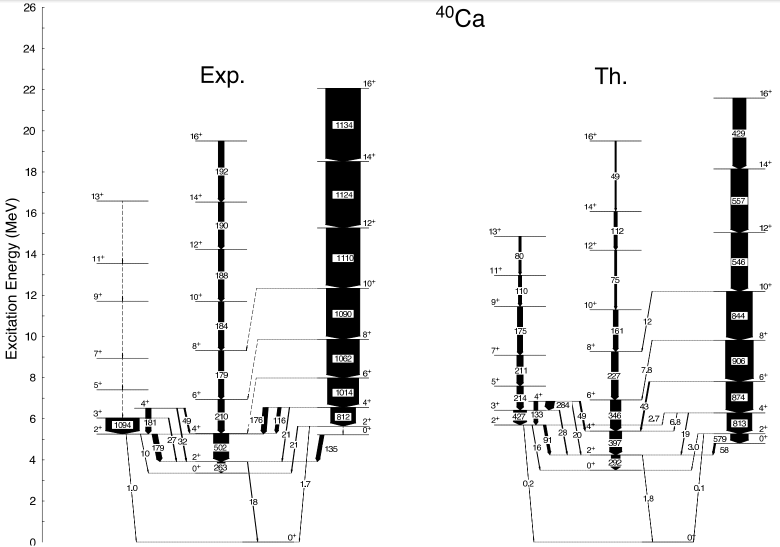
Huge correlation energies!!!



sd — *pf* space diagonalisation

- quasi-particule gap ∼ 7 MeV
- few mixing between 0p0h and 2p2h, few mixing between 4p4h and 6p6h
- no mixing (through 2p2h states) between GS and SD band
- energy gain mainly for ground state

Extreme Correlations: the case of ^{40}Ca



E. Caurier, J. Menedez, F. Nowacki, A. Poves
Phys. Rev. **C75**, 054317 (2007)

- description of transition probabilities varying of 3 orders of magnitude !

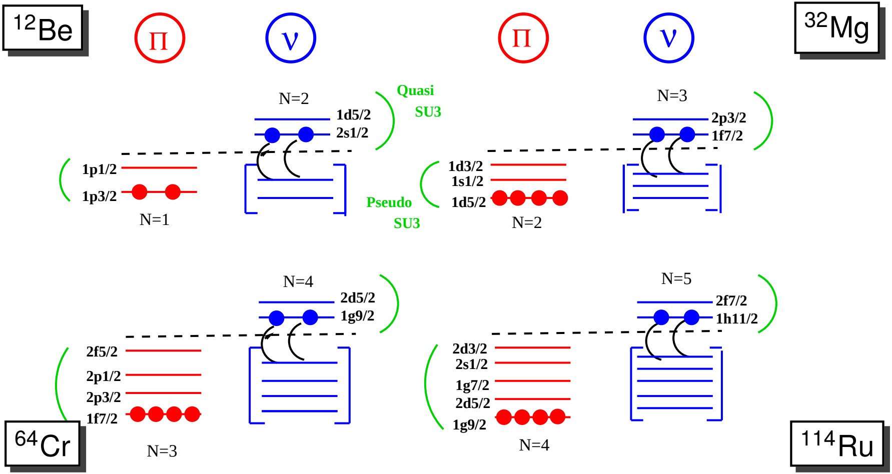
Quasi-SU3 + Pseudo-SU3 interpretation

In the 4p-4h intrinsic state of ^{40}Ca, the two neutrons and two protons in the *pf*-shell can be placed in the lowest K=1/2 quasi-SU3 level of the p=3 shell. This gives a contribution Q_0=25 b^2. In the pseudo-p shell p=1 we are left with eight particles, that contribute with Q_0=7 b^2. For the 8p-8h state the values are Q_0=35 b^2 and Q_0=11 b^2

Using the proper values of the oscillator length it obtains:
^{40}Ca 4p-4h band Q_0=125 e fm^2 (Q_0=148 e fm^2)
^{40}Ca 8p-8h band Q_0=180 e fm^2 (Q_0=226 e fm^2)

In very good accord with the data. The values in blue assume strict SU3 symmetry in both shells. The SM results almost saturate the quasi-SU3 bounds. The SU3 values are a 25% larger.

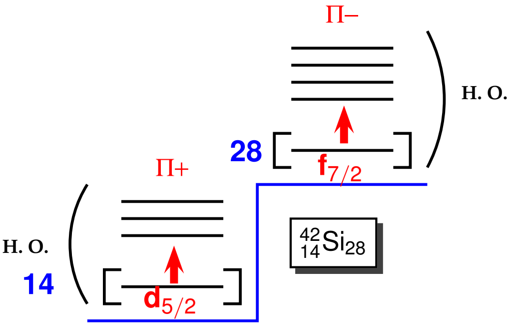
What happens for neutron-rich systems ?



Development of deformation at N=8,20,40,70

Harmonic Oscillator Closures

Spin-orbit shell closure far from stability



- sd-pf: ^{42}Si deformed
- pf-sdg: ^{78}Ni ???
- sdg-phf: ^{132}Sn doubly magic

- Evolution of Z=14 from N=20 to N=28
- Evolution of Z=28 from N=40 to N=50
- Evolution of N=50 from Z=40 to Z=28

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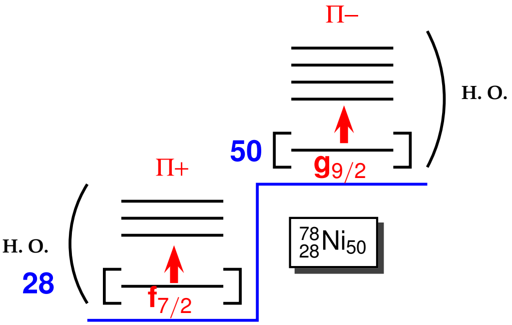

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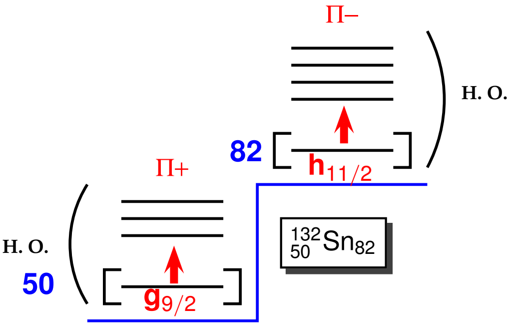

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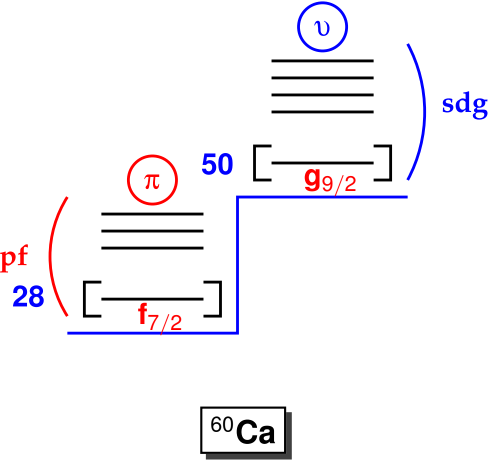
Physics around ^{78}Ni



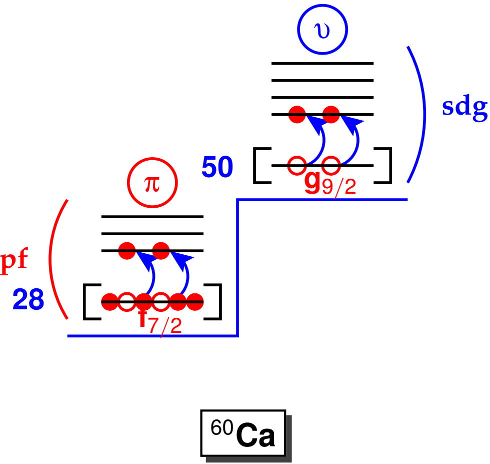
PFSDG-U interaction:

- realistic TBME
- pf shell for protons and gds shell for neutrons
- monopole corrections (3N forces)
- proton and neutrons gap ^{78}Ni fixed to phenomenological derived values

Calculations:

- excitations across Z=28 and N=50 gaps
- up to 5*10^{10} Slater Determinant basis states
- up to 3*10^{13} non-zero terms in the matrix!
- m-scheme code ANTOINE (non public version)
- J-scheme code NATHAN (parallelized version): 0.5*10^{9} J basis states

Physics around ^{78}Ni



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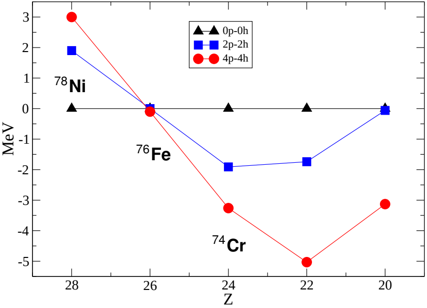
Schematic SU3 predictions

PHYSICAL REVIEW C **92**, 024320 (2015)

Nilsson-SU3 self-consistency in heavy $N = Z$ nuclei

A. P. Zuker,[1] A. Poves,[2,3] F. Nowacki,[1] and S. M. Lenzi[4]



- monopole + quadrupole model
- proton gap (5MeV) and neutron gap (5 MeV) estimates
- Quasi-SU3 (protons) and Pseudo-SU3 (neutrons) blocks
- $Q_s = (\langle 2q_{20}\rangle + 3.)b^2)^2/3.5$

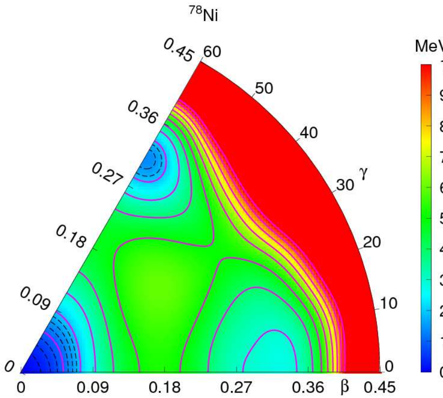
  $E_n = G_n^{mp}(50) - \hbar\omega\kappa \left(\frac{\langle Q_0^m(\pi)\rangle}{15\ b^2} + \frac{\langle Q_0^m(\nu)\rangle}{23\ b^2}\right)^2$

  $G_n^{mp}(50) = \mathrm{n}\,(\frac{3.0}{8} n_f^\pi + 2.25) + \Delta(\mathrm{n}) + \delta_p(\mathrm{n})$

- Prediction of Island of strong collectivity below ^{78}Ni !!!

Shape coexistence in ^{78}Ni

- At first approximation, ^{78}Ni has a double closed shell structure for GS
- But very low-lying competing structures
- From the diagonalization,
  the first excited states in ^{78}Ni are :
  • 0_2^+-2_1^+ predicted at 2.6-2.9 MeV and to be deformed intruders of a **rotationnal band** !!!
- "1p1h" 2_2^+ predicted at $\sim$ 3.1 MeV
- Necessity to go **beyond** ($fpg_{\frac{9}{2}}d_{\frac{5}{2}}$) **LNPS space** and **beyond ab-initio description**
- Portal to a new **I**sland **o**f **I**nversion



Constrained deformed HF in the SM basis

(B. Bounthong, PhD Thesis, Strasbourg)

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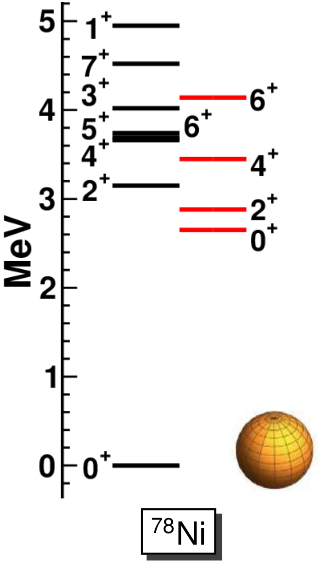

Shape coexistence in ^{78}Ni

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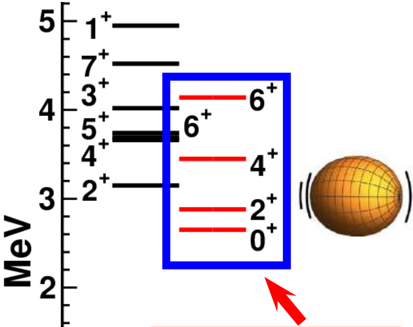

	^{78}Ni
	$2^+_1 \rightarrow 0^+_2$
ΔE^* th.	0.229
Q_s	-39
BE2↓ th.	516
Q_i(e.fm^2) from Q_s	135
Q_i(e.fm^2) from BE2	195
β_2^e	$\sim$ **0.3 prolate**

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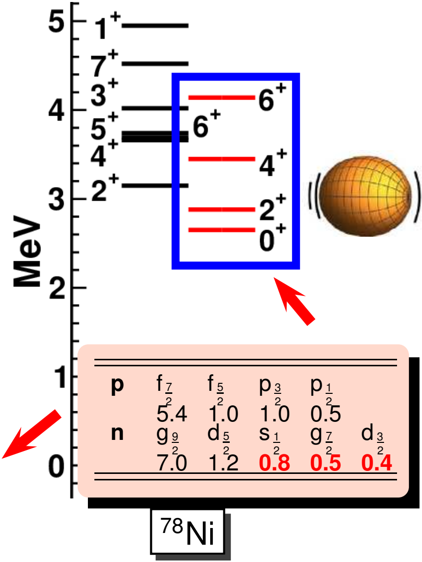

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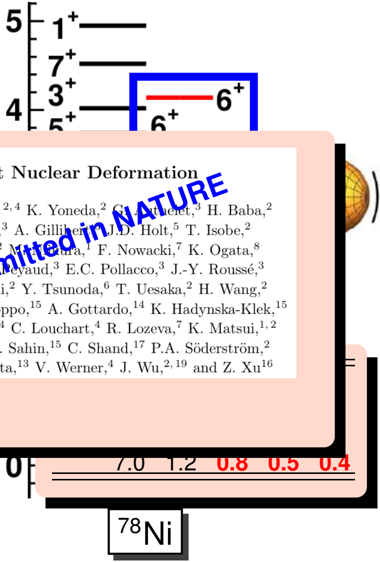


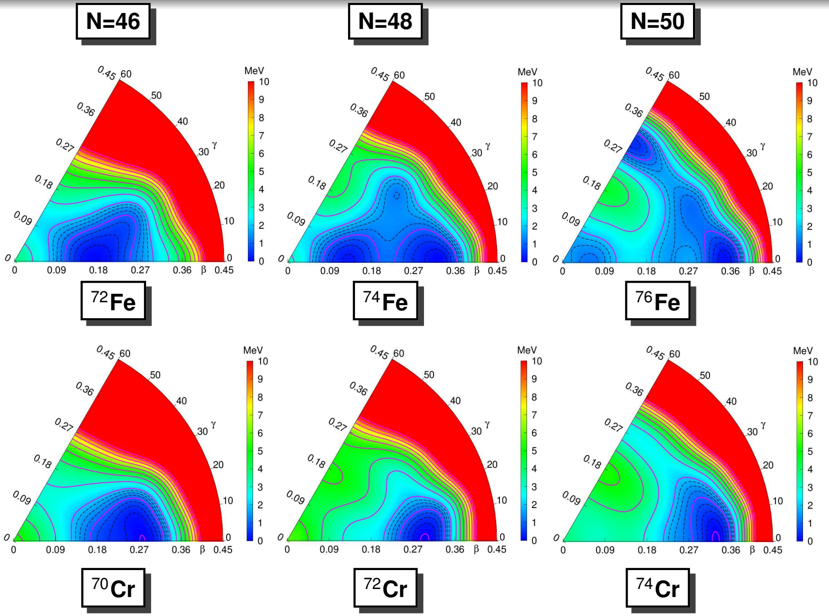
Doubly-Magic ^{78}Ni: A Stronghold against Nuclear Deformation

R. Taniuchi,[1,2,*] C. Santamaria,[3,2] P. Doornenbal,[2] A. Obertelli,[3,2,4] K. Yoneda,[2] G. Authelet,[3] H. Baba,[2] D. Calvet,[3] F. Château,[3] A. Corsi,[3] A. Delbart,[3] J.-M. Gheller,[3] A. Gillibert,[3] J.D. Holt,[5] T. Isobe,[2] V. Lapoux,[3] M. Matsushita,[6] S. Momiyama,[1,2] T. Motobayashi,[2] M. Niikura,[1] F. Nowacki,[7] K. Ogata,[8] H. Otsu,[2] T. Otsuka,[6,1,2] J. Menéndez,[6] C. Péron,[3] S. Péru,[9] A. Peyaud,[3] E.C. Pollacco,[3] J.-Y. Roussé,[3] H. Sakurai,[1,2] M. Sasano,[2] A. Schwenk,[4] Y. Shiga,[2,10] S. Takeuchi,[2] Y. Tsunoda,[6] T. Uesaka,[2] H. Wang,[2] F. Browne,[11] L.X. Chung,[12] Zs. Dombradi,[13] S. Franchoo,[14] F. Giacoppo,[15] A. Gottardo,[14] K. Hadynska-Klek,[15] Z. Korkulu,[13] S. Koyama,[1,2] Y. Kubota,[2,6] J. Lee,[16] M. Lettmann,[4] C. Louchart,[4] R. Lozeva,[7] K. Matsui,[1,2] T. Miyazaki,[1,2] S. Nishimura,[2] L. Olivier,[14] S. Ota,[6] Z. Patel,[17] E. Sahin,[15] C. Shand,[17] P.A. Söderström,[2] I. Stefan,[14] D. Steppenbeck,[6] T. Sumikama,[18] D. Suzuki,[14] Zs. Vajta,[13] V. Werner,[4] J. Wu,[2,19] and Z. Xu[16]

R. Taniuchi et al., to be submitted in NATURE

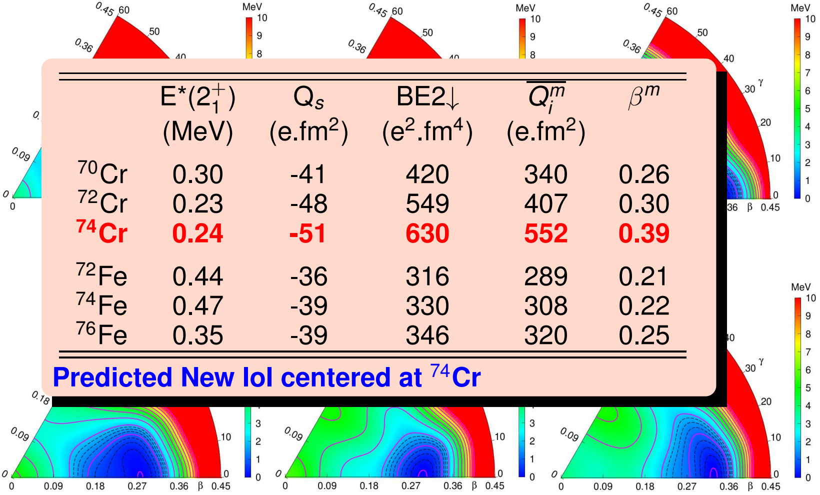
- Portal to a new **I**sland **o**f **I**nversion

Island of Deformation below ^{78}Ni: PES's



Island of Deformation below ^{78}Ni: PES's

N=46 **N=48** **N=50**

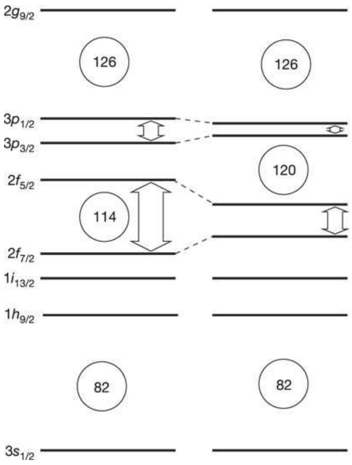


	$E^*(2_1^+)$ (MeV)	Q_s ($e.fm^2$)	$BE2\downarrow$ ($e^2.fm^4$)	$\overline{Q_i^m}$ ($e.fm^2$)	β^m
^{70}Cr	0.30	-41	420	340	0.26
^{72}Cr	0.23	-48	549	407	0.30
^{74}Cr	**0.24**	**-51**	**630**	**552**	**0.39**
^{72}Fe	0.44	-36	316	289	0.21
^{74}Fe	0.47	-39	330	308	0.22
^{76}Fe	0.35	-39	346	320	0.25

Predicted New IoI centered at ^{74}Cr

^{70}Cr **^{72}Cr** **^{74}Cr**

Heavier systems



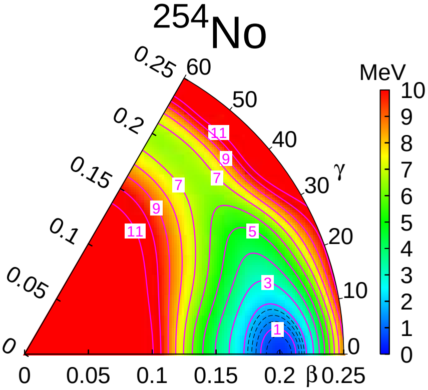
Kuo-Herling interaction:

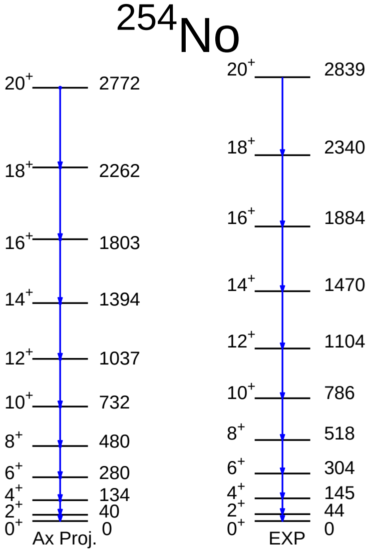
- realistic TBME and ^{208}Pb core
- $82 \leq Z \leq 126$ shells for protons
- $126 \leq N \leq 184$ shells for neutrons
- monopole corrections (3N forces)

Calculations:

- seniority diagonalisations along N=126 and N=184 chains
- Deformed HF for open shell nuclei

Hm vs Correlations: heavier systems





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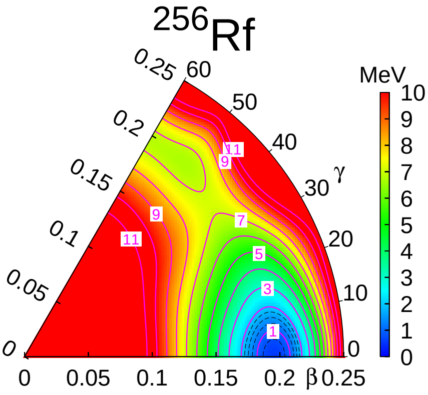

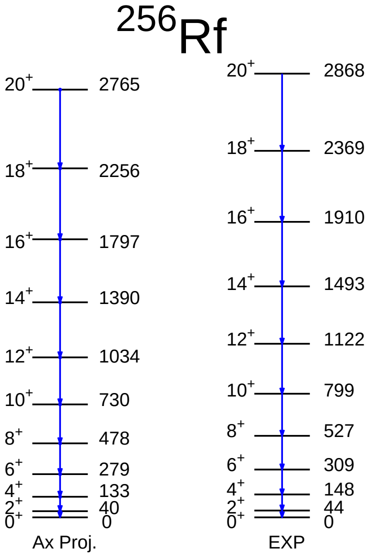

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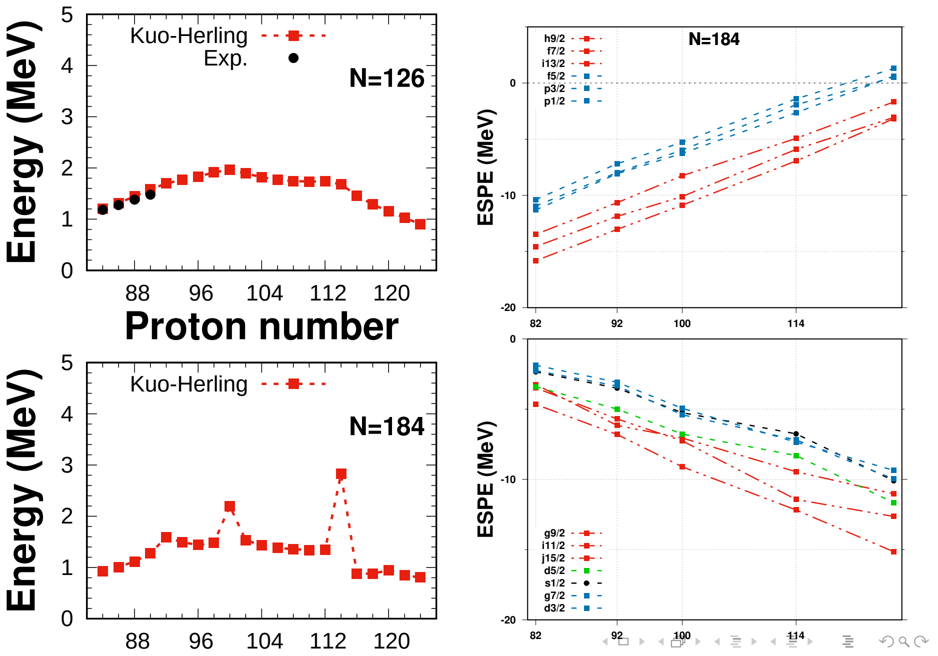

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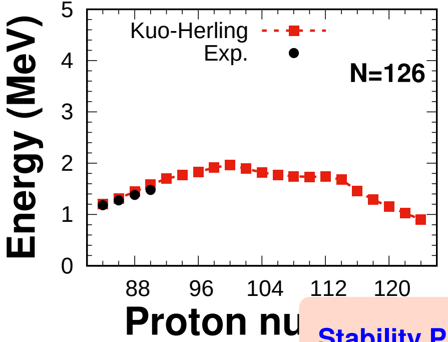

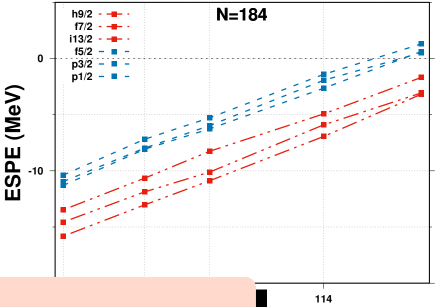

Stability Predicted for Z=114 !!!