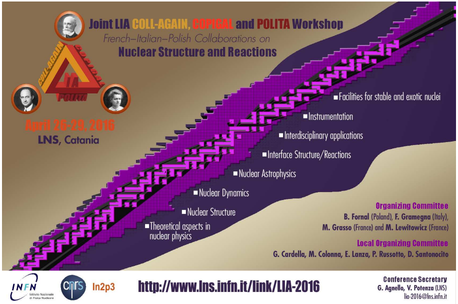
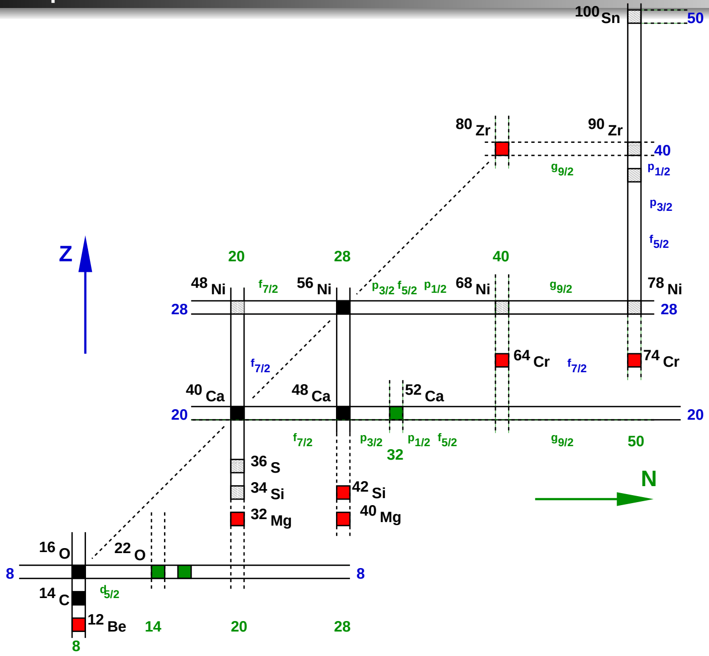
Model Stability from Shell far

Frédéric Nowacki[1]



[1] Strasbourg-Madrid Shell Model collaboration

Landscape of medium mass nuclei



100 Sn 50

UNDERSTANDING REGULARITIES
for both SPHERICAL and DEFORMED systems

- Magic Numbers: ^{24}O, ^{48}Ni, ^{54}Ca, ^{78}Ni, ^{100}Sn (ab-initio approaches)
- Islands of Deformation: ^{12}Be, ^{32}Mg, ^{42}Si, ^{64}Cr, ^{80}Zr ...

- Magicity dictated by simple shell structure and monopole drift
- Deformation in principle much complex to analyse and understand
- But simple pictures can also emerge for deformed sytems resulting from competition between
  - Monopole spherical mean field
  - Quadrupole correlations

Nilsson-SU3 self-consistency in heavy N=Z nuclei
A. P. Zuker, A. Poves, F. N. and S. M. Lenzi
Phys. Rev. C92, 024301 (2015)

8

Be 14 20 28

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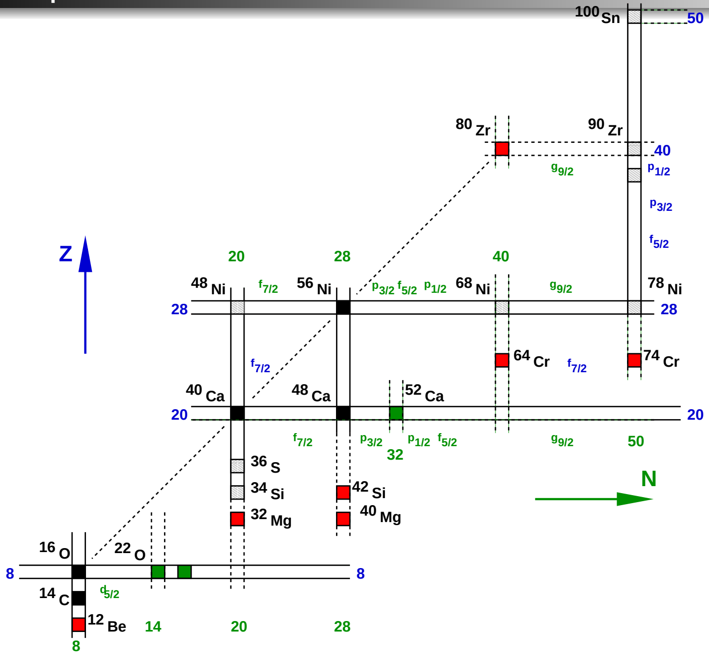
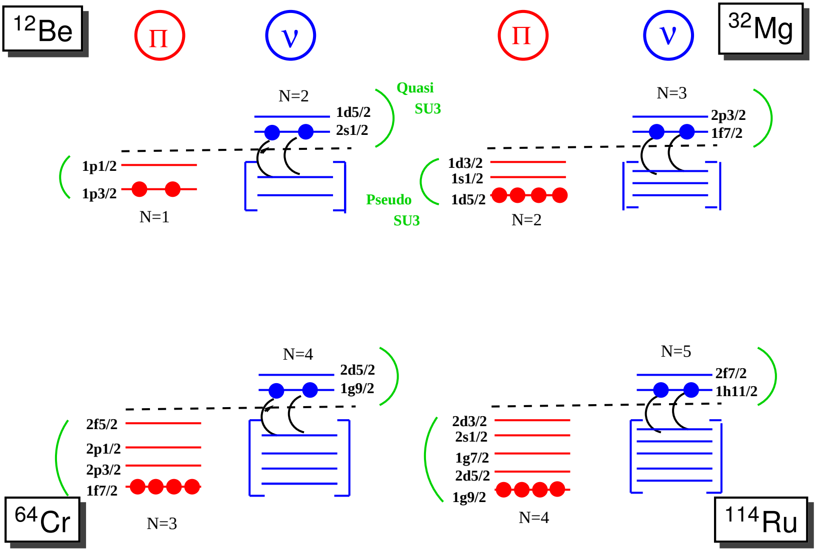
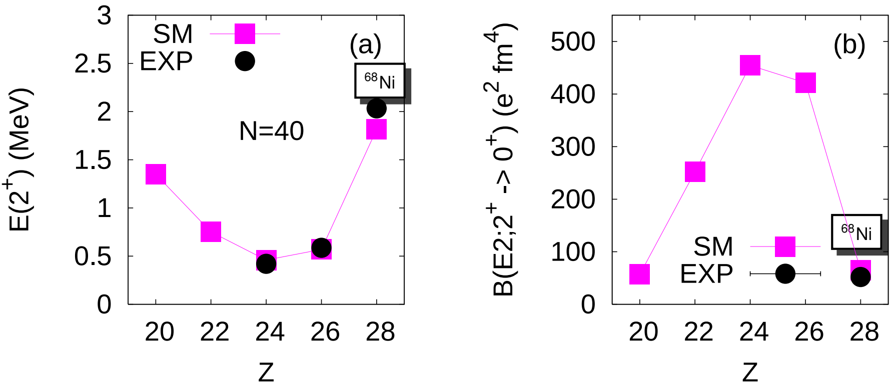
Landscape of medium mass nuclei



Landscape of medium mass nuclei



Shape transition at N=40



Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	configuration
^{68}Ni	0.98	0.10	0p0h(51%)
^{66}Fe	3.17	0.46	4p4h(26%)
^{64}Cr	3.41	0.76	6p6h(23%)
^{62}Ti	3.17	1.09	4p4h(48%)

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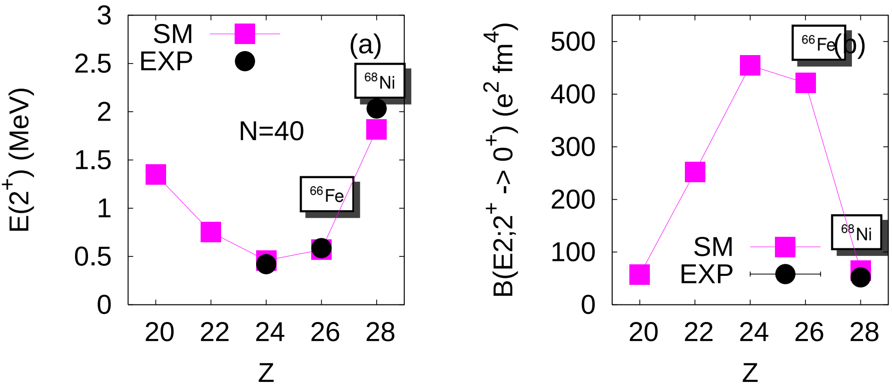

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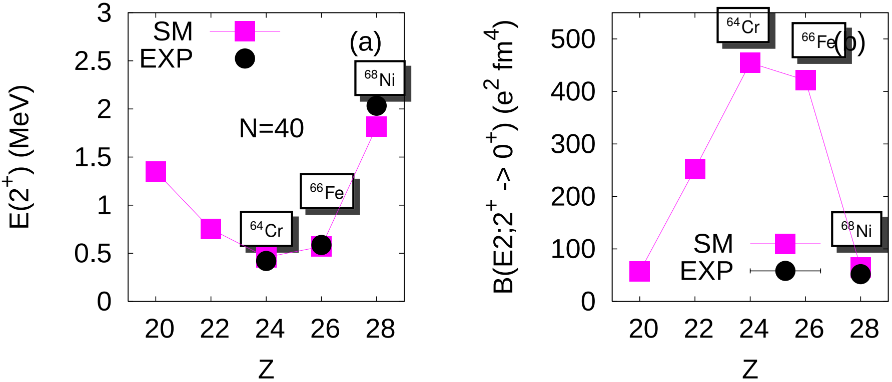

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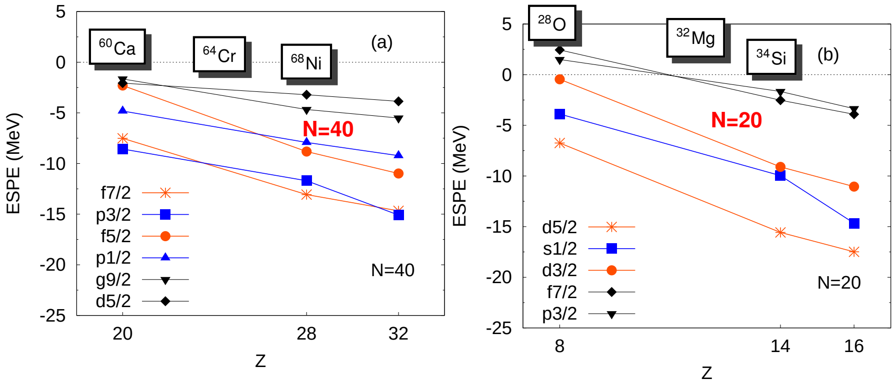
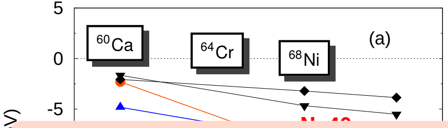
Neutron effective single particle energies

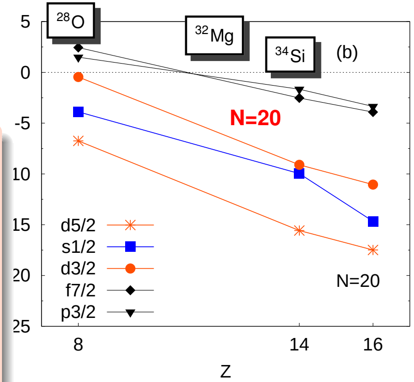


- reduction of the $\nu f_{5/2}$-$g_{9/2}$ gap with removing $f_{7/2}$ protons
- proximity of the quasi-SU3 partner $d_{5/2}$
- inversion of $d_{5/2}$ and $g_{9/2}$ orbitals
  same ordering as CC calculations

- reduction of the $\nu d_{3/2}$-$f_{7/2}$ gap with removing $d_{5/2}$ protons
- proximity of the quasi-SU3 partner $p_{3/2}$
- inversion of $p_{3/2}$ and $f_{7/2}$ orbitals

Neutron effective single particle energies





PRL **109**, 032502 (2012) PHYSICAL RE

TABLE II. Energies of the $5/2^+$ and $9/2^+$ resonances in ^{53,55,61}Ca. Re[E] is the energy relative to the one-neutron emission threshold, and the width is $\Gamma = -2\mathrm{Im}[E]$ (in MeV).

	^{53}Ca		^{55}Ca		^{61}Ca	
J^π	Re[E]	Γ	Re[E]	Γ	Re[E]	Γ
$5/2^+$	1.99	1.97	1.63	1.33	1.14	0.62
$9/2^+$	4.75	0.28	4.43	0.23	2.19	0.02

G. Hagen et al.

Phys. Rev. Lett. **109**, 032502 (2012)

- removing $f_{7/2}$ protons
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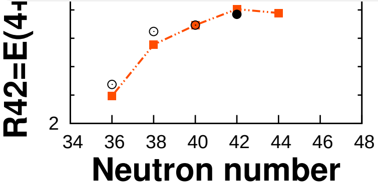
Extension of collectivity N=40 towards N=50

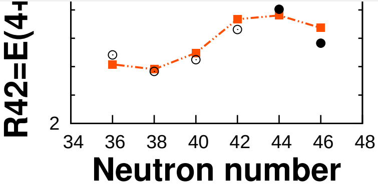
PRL **115,** 192501 (2015) PHYSICAL REVIEW LETTERS week ending 6 NOVEMBER 2015

Extension of the $N = 40$ Island of Inversion towards $N = 50$: Spectroscopy of ^{66}Cr, ^{70,72}Fe

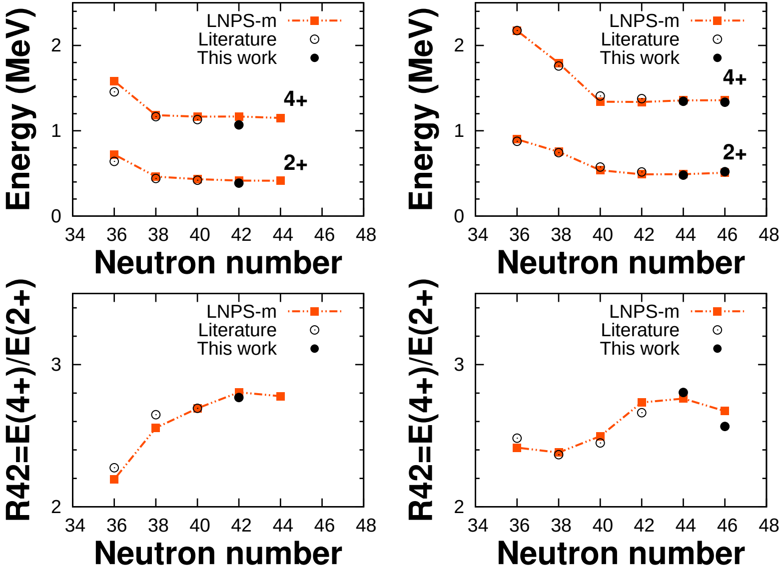
C. Santamaria,[2] C. Louchart,[3] A. Obertelli,[1,2] V. Werner,[3,4] P. Doornenbal,[2] F. Nowacki,[5] G. Authelet,[1] H. Baba,[2] D. Calvet,[1] F. Château,[1] A. Corsi,[1] A. Delbart,[1] J.-M. Gheller,[1] A. Gillibert,[1] T. Isobe,[2] V. Lapoux,[1] M. Matsushita,[6] S. Momiyama,[2,7] T. Motobayashi,[2]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

FIRST MINOS Experiment at RIKEN





Extension of collectivity N=40 towards N=50



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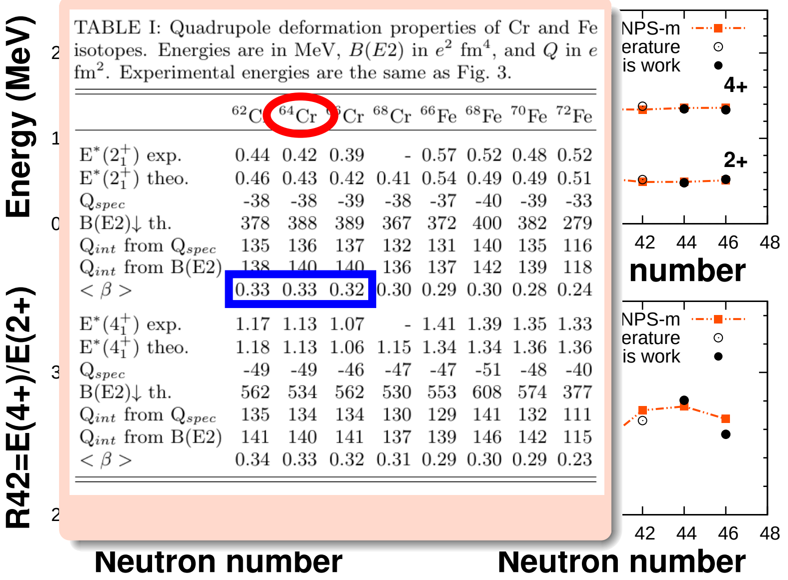
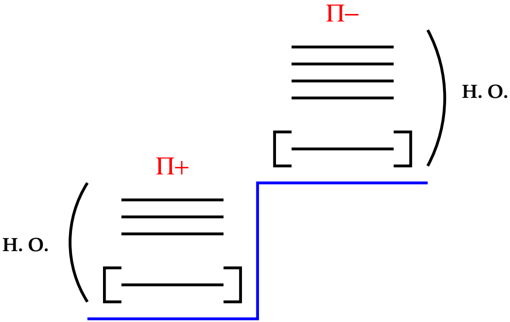


TABLE I: Quadrupole deformation properties of Cr and Fe isotopes. Energies are in MeV, $B(E2)$ in e^2 fm^4, and Q in e fm^2. Experimental energies are the same as Fig. 3.

	^{62}Cr	^{64}Cr	^{66}Cr	^{68}Cr	^{66}Fe	^{68}Fe	^{70}Fe	^{72}Fe
$E^*(2_1^+)$ exp.	0.44	0.42	0.39	-	0.57	0.52	0.48	0.52
$E^*(2_1^+)$ theo.	0.46	0.43	0.42	0.41	0.54	0.49	0.49	0.51
Q_{spec}	-38	-38	-39	-38	-37	-40	-39	-33
$B(E2)\downarrow$ th.	378	388	389	367	372	400	382	279
Q_{int} from Q_{spec}	135	136	137	132	131	140	135	116
Q_{int} from $B(E2)$	138	140	140	136	137	142	139	118
$<\beta>$	0.33	0.33	0.32	0.30	0.29	0.30	0.28	0.24
$E^*(4_1^+)$ exp.	1.17	1.13	1.07	-	1.41	1.39	1.35	1.33
$E^*(4_1^+)$ theo.	1.18	1.13	1.06	1.15	1.34	1.34	1.36	1.36
Q_{spec}	-49	-49	-46	-47	-47	-51	-48	-40
$B(E2)\downarrow$ th.	562	534	562	530	553	608	574	377
Q_{int} from Q_{spec}	135	134	134	130	129	141	132	111
Q_{int} from $B(E2)$	141	140	141	137	139	146	142	115
$<\beta>$	0.34	0.33	0.32	0.31	0.29	0.30	0.29	0.23

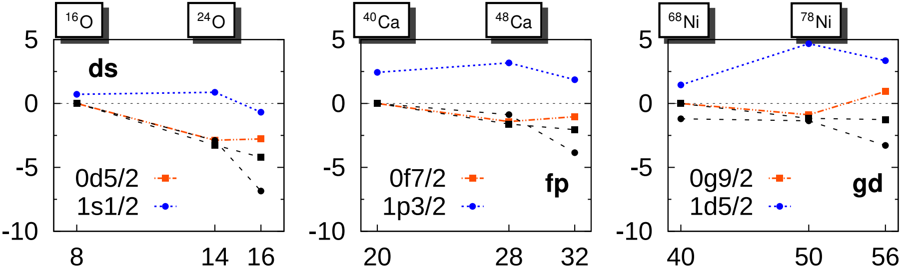
Spin-orbit shell closure far from stability



- sd-pf: deformed ^{42}Si
- pf-sdg: ^{78}Ni ???
- sdg-pfh: doubly magic ^{132}Sn
- pfh-sdgi: stable doubly magic ^{208}Pb

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

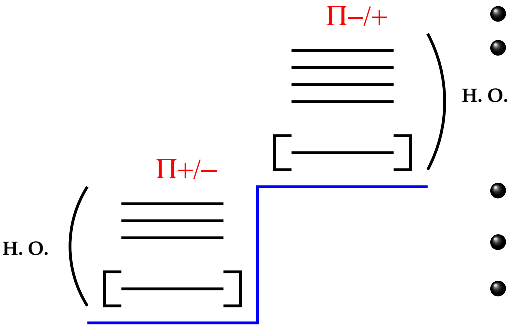
Three-body forces in medium mass nuclei



- Evolution of the neutron effective single-particle energies with neutron filling in ds, fp, and gd shells
- "Universal" mechanism for the generation of T=1 spin-orbit shell closures
- Connection with 3N forces and ab-initio calculations
  - "works" now for for "ab-initio" core shell-model (Coupled-Cluster, IMSRG calculations ...)
  - proton-neutron interaction to be challenged now

Three body forces and persistence of spin-orbit shell gaps in medium-mass nuclei: Towards the doubly magic ^{78}Ni
K. Sieja, F. Nowacki
Phys. Rev. **C85**, 051301(R) (2012)

Physics around ^{78}Ni



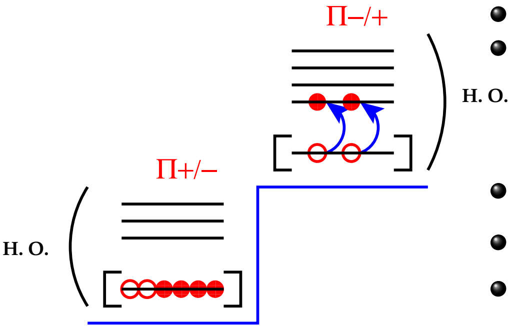
PFSDG-U interaction:

- 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 10^{10} Slater Determinant basis states
- m-scheme code ANTOINE (non public version)
- J-scheme code NATHAN (parallelized version): 10^9 J basis states

Physics around ^{78}Ni



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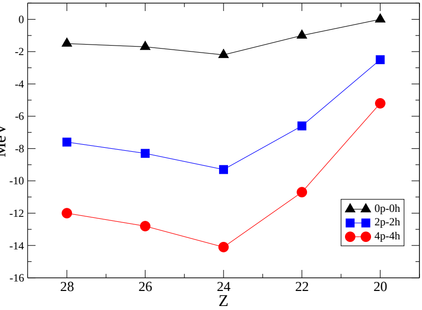
Schematic SU3 predictions

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
- $Q_s = (\langle 2q_{20}\rangle + 3.)b^2)^2/3.5$

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

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

Schematic SU3 predictions

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

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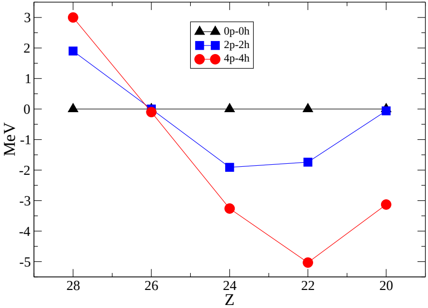

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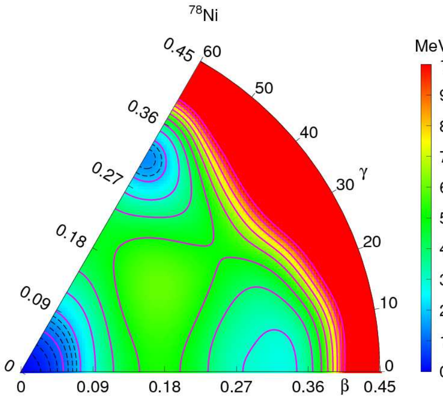
  $G_n^{mp}(50) = \mathrm{n}\,(\frac{3.0}{8} n_f^{\pi} + 2.25) + \Delta(\mathrm{n}) + \delta_p(\mathrm{n})$

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

Shape coexistence in ^{78}Ni

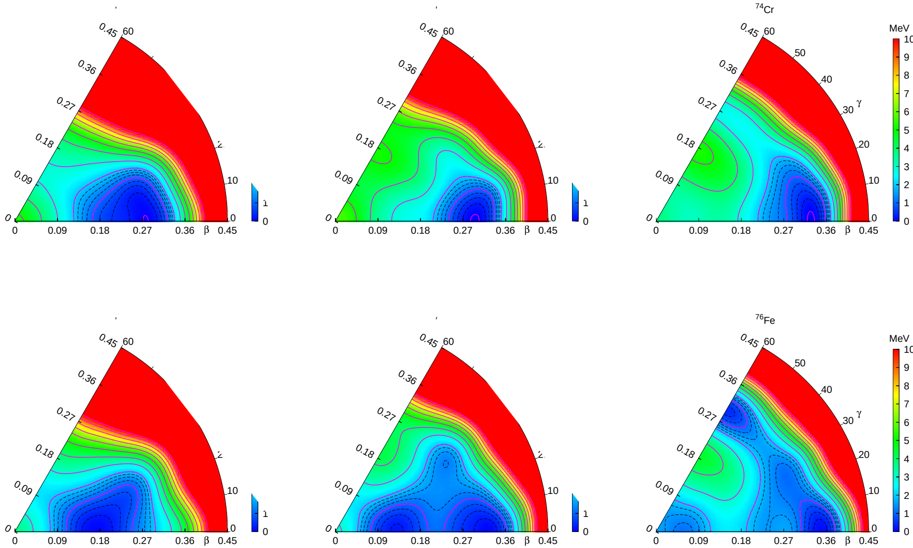
- At first approximation, ^{78}Ni has a double closed shell structure for GS
- But very low-lying competing structures
- From the diagonalization, the first excited states in ^{78}Ni are :
  • 0_2^+-2_1^+ predicted at 2.6-2.9 MeV and to be deformed intruders of a **rotationnal band** !!!
- "1p1h" 2_2^+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



Constrained deformed HF in the SM basis

(B. Bounthong, PhD Thesis, Strasbourg)

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



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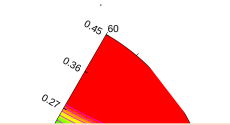
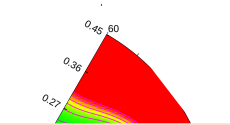
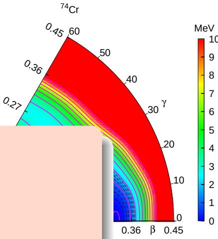
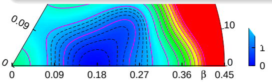
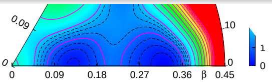


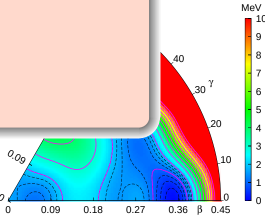




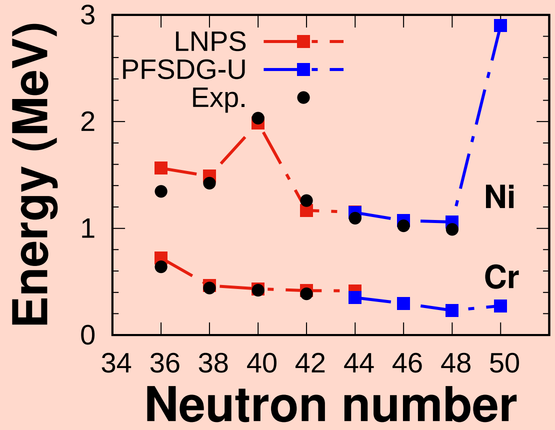
	$E^*(2^+_1)$ (MeV)	Q_s ($e.fm^2$)	BE2↓ ($e^2.fm^4$)	$\overline{Q_i^m}$ ($e.fm^2$)	β^m
^{70}Cr	0.30	-41	420	340	0.26
^{72}Cr	**0.23**	**-48**	**549**	**407**	**0.30**
^{74}Cr	0.27	-46	511	391	0.28
^{72}Fe	0.44	-36	316	289	0.21
^{74}Fe	-	-	-	-	
^{76}Fe	0.35	-39	346	320	0.25

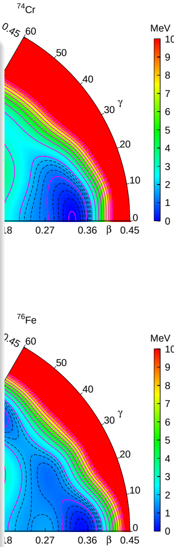






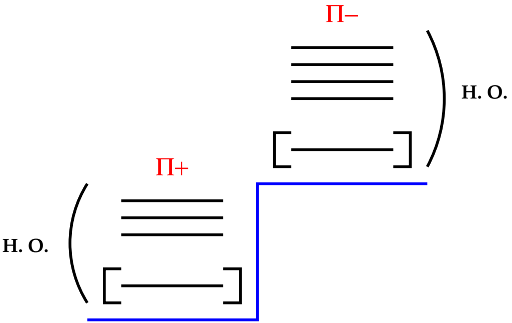
Island of Deformation below ^{78}Ni: PES's





Island of deformation from N=40 to N=50 !!!

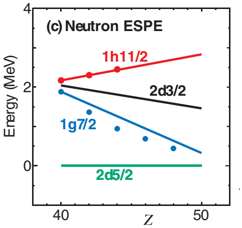
Spin-orbit shell closure far from stability



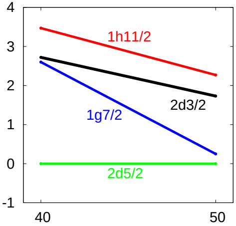
- sd-pf: ^{42}Si deformed
- pf-sdg: ^{78}Ni ???
- sdg-phf: ^{132}Sn doubly magic

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

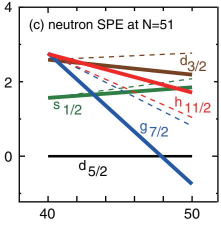
Tensor mechanism in mid-mass nuclei



T. Otsuka, et al.
Phys. Rev. Lett. **95**, 232502-1 (2005)



K. Sieja, et al.
Phys. Rev. **C79**, 064310 (2009)



T. Otsuka, et al.
Phys. Rev. Lett. **104**, 012501 (2010)

Selected for a Viewpoint in *Physics*
PRL **104,** 012501 (2010) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2010

Novel Features of Nuclear Forces and Shell Evolution in Exotic Nuclei

Takaharu Otsuka,[1,2] Toshio Suzuki,[3] Michio Honma,[4] Yutaka Utsuno,[5] Naofumi Tsunoda,[1] Koshiroh Tsukiyama,[1] and Morten Hjorth-Jensen[6]

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[5]*Japan Atomic Energy Agency, Tokai, Ibaraki, 319-1195 Japan*
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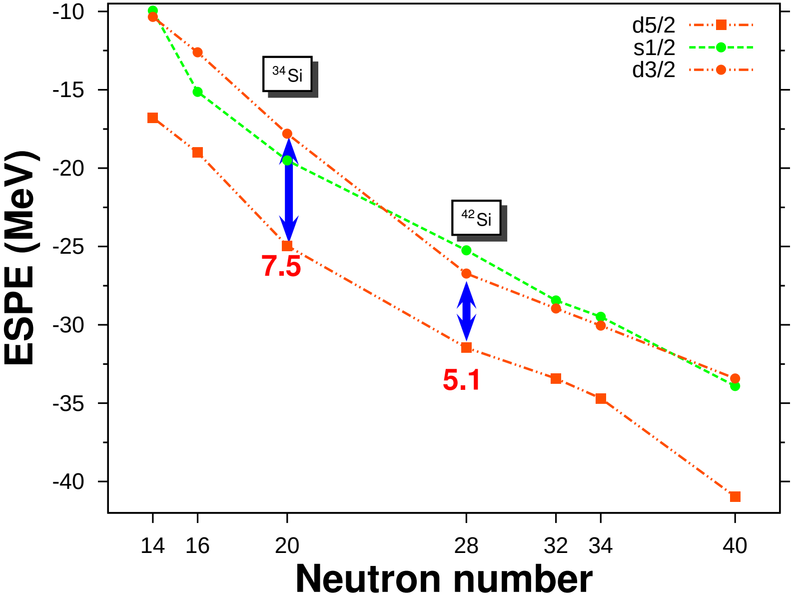
(Received 29 September 2009; published 4 January 2010)

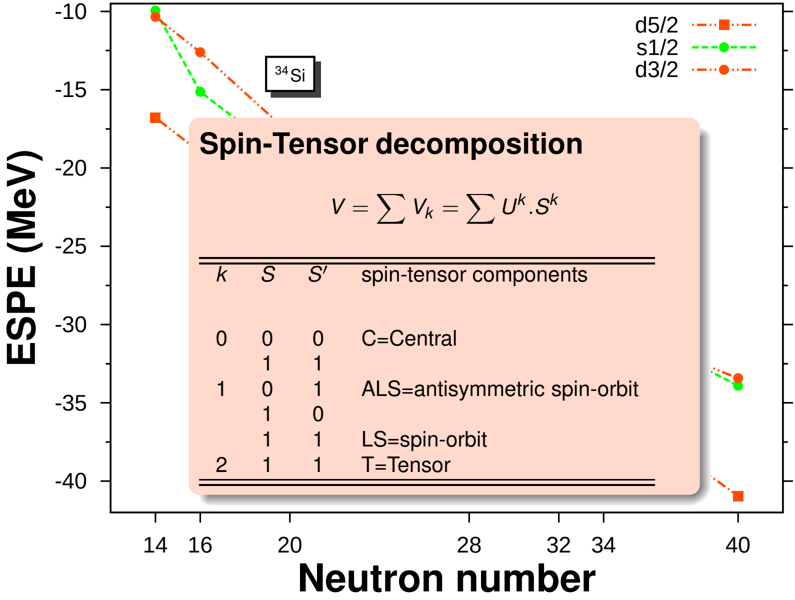
Effective Single Particle Energies: Trends

Silicium chain



Effective Single Particle Energies: Trends

Silicium chain



Spin-Tensor decomposition

$$V = \sum V_k = \sum U^k . S^k$$

k	S	S'	spin-tensor components
0	0	0	C=Central
	1	1	
1	0	1	ALS=antisymmetric spin-orbit
	1	0	
	1	1	LS=spin-orbit
2	1	1	T=Tensor

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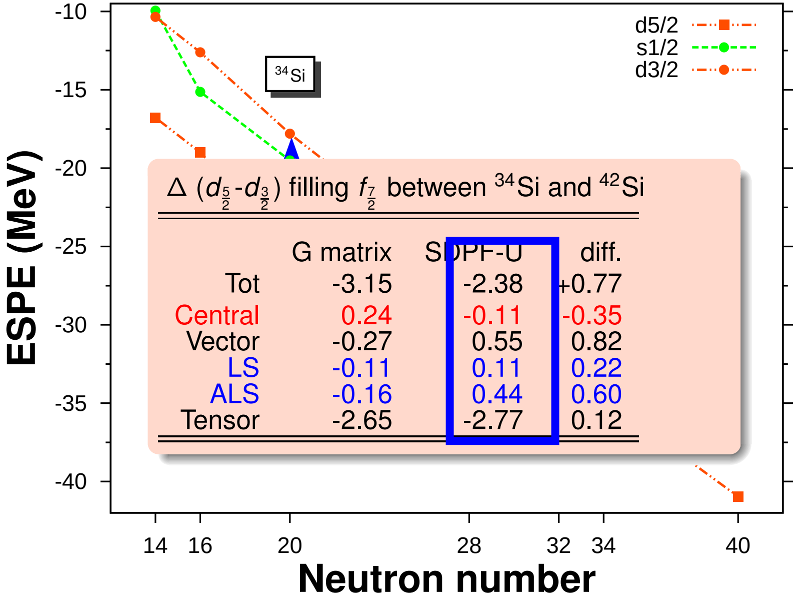

Δ $(d_{\frac{5}{2}}-d_{\frac{3}{2}})$ filling $f_{\frac{7}{2}}$ between ^{34}Si and ^{42}Si

	G matrix	SDPF-U	diff.
Tot	-3.15	-2.38	+0.77
Central	0.24	-0.11	-0.35
Vector	-0.27	0.55	0.82
LS	-0.11	0.11	0.22
ALS	-0.16	0.44	0.60
Tensor	-2.65	-2.77	0.12

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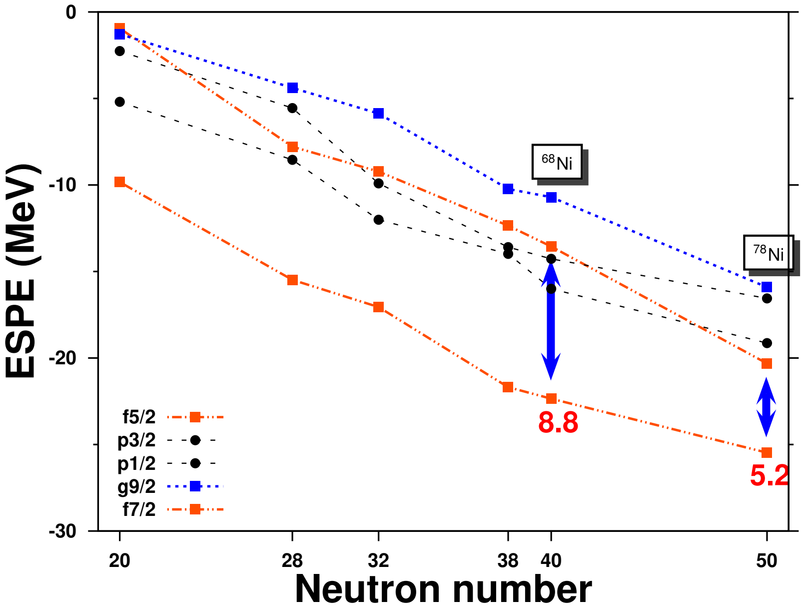

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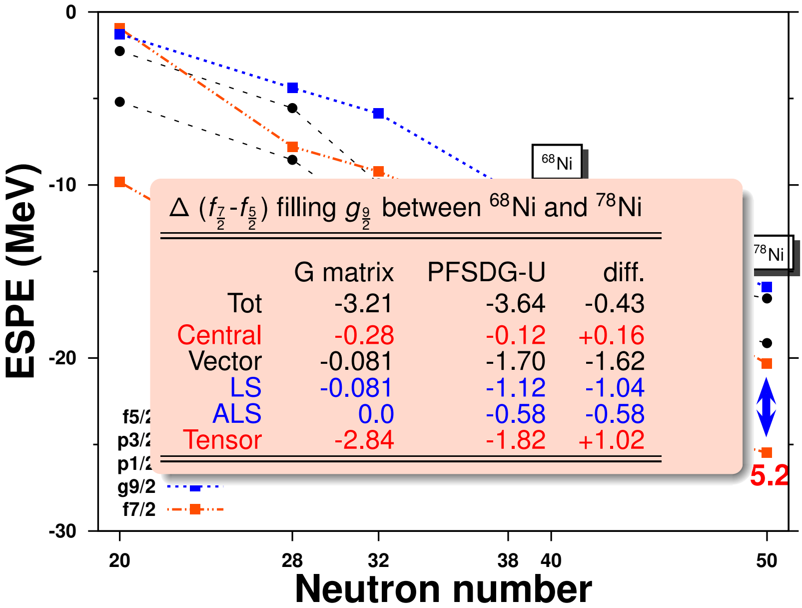
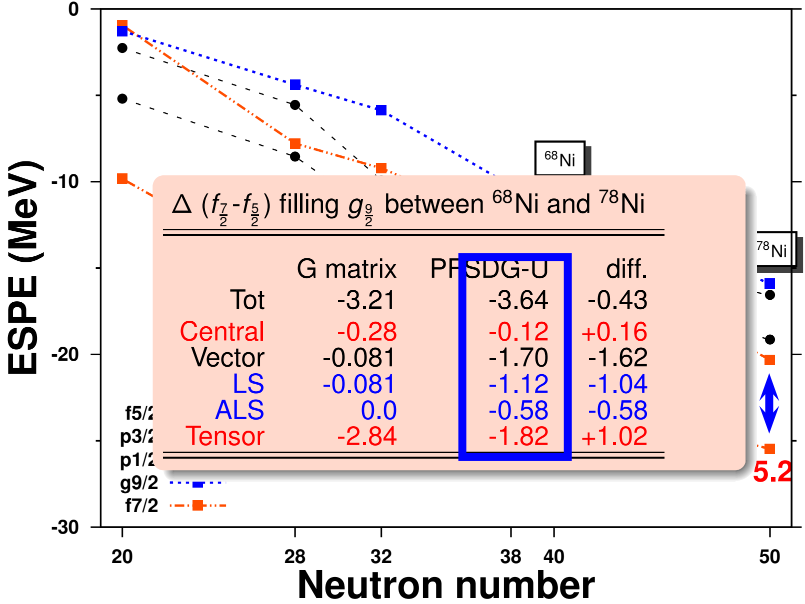


$\Delta\ (f_{\frac{7}{2}} - f_{\frac{5}{2}})$ filling $g_{\frac{9}{2}}$ between ^{68}Ni and ^{78}Ni

	G matrix	PFSDG-U	diff.
Tot	-3.21	-3.64	-0.43
Central	-0.28	-0.12	+0.16
Vector	-0.081	-1.70	-1.62
LS	-0.081	-1.12	-1.04
ALS	0.0	-0.58	-0.58
Tensor	-2.84	-1.82	+1.02

Effective Single Particle Energies: Trends



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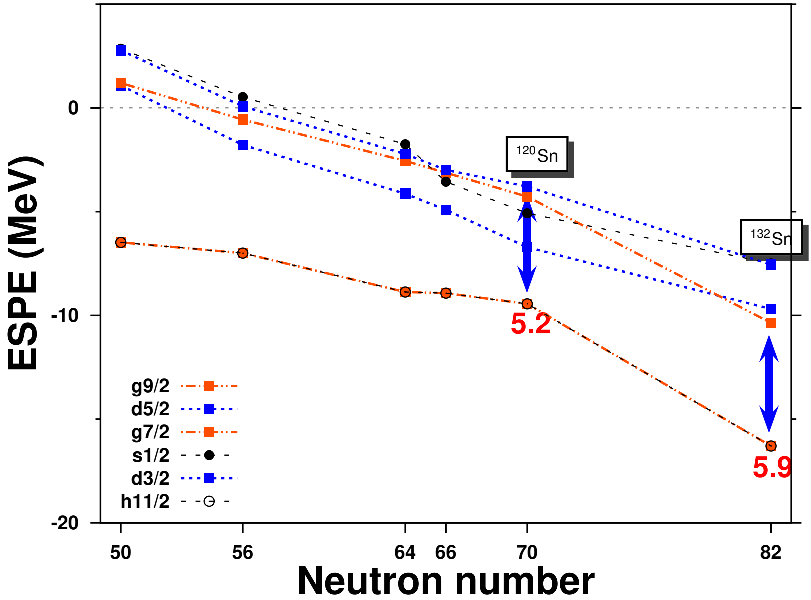
Effective Single Particle Energies: Trends



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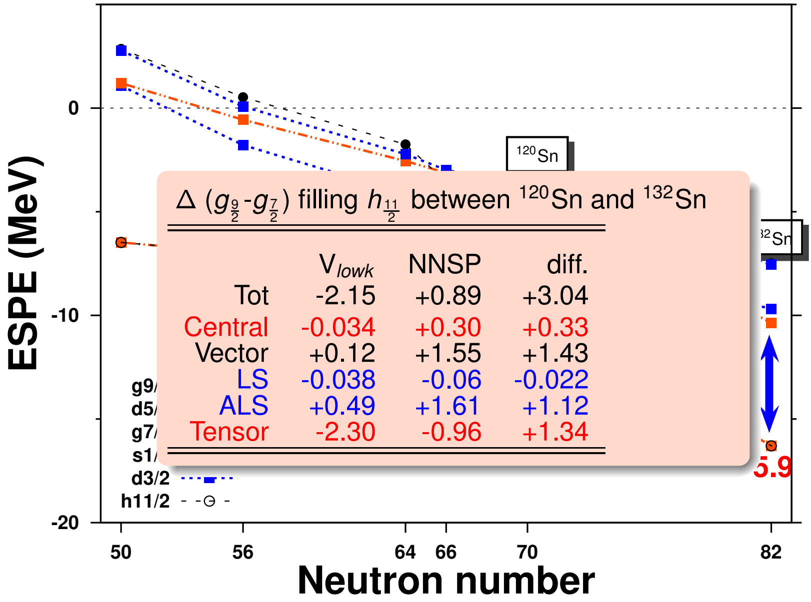
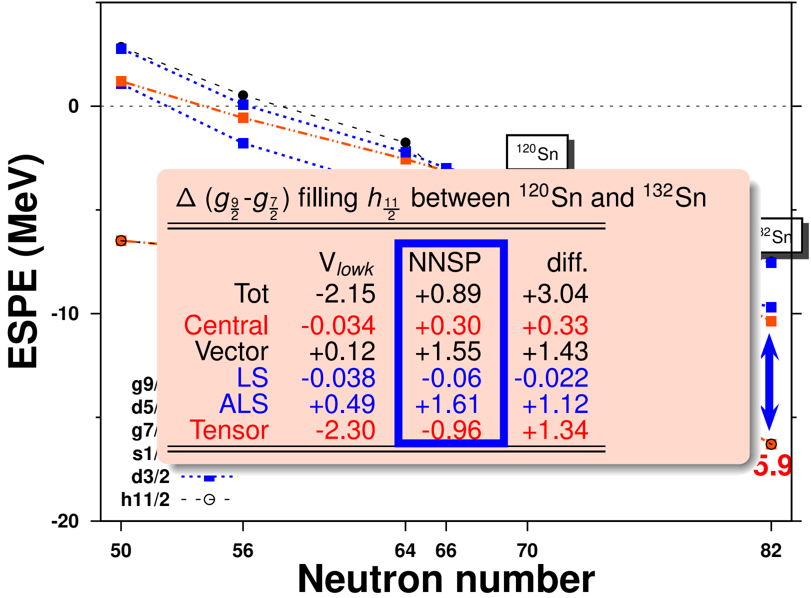


$\Delta\ (g_{\frac{9}{2}}\text{-}g_{\frac{7}{2}})$ filling $h_{\frac{11}{2}}$ between ^{120}Sn and ^{132}Sn

	V_{lowk}	NNSP	diff.
Tot	-2.15	+0.89	+3.04
Central	-0.034	+0.30	+0.33
Vector	+0.12	+1.55	+1.43
LS	-0.038	-0.06	-0.022
ALS	+0.49	+1.61	+1.12
Tensor	-2.30	-0.96	+1.34

Effective Single Particle Energies: Trends



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Summary

- Monopole drift develops in all regions but the Interplay between correlations (pairing + quadrupole) and spherical mean-field (monopole field) determines the physics.
  It can vary from :
  - island of inversion at N=20 and N=40
  - deformation at Z=14, N=28 for ^{42}Si and shell weakening at Z=28, N=50 for ^{78}Ni
  - deformation extending from N=40 to N=50 for Z=24-26 for ^{74}Cr and ^{76}Fe
- The “islands of inversion” appear due to the effect of the correlations, hence they could also be called “islands of enhanced collectivity”. As quadrupole correlations are dominant in this region, most of thei inhabitants are deformed rotors. Shape transitions and coexistence show up everywhere
- Quadrupole energies can be huge and understood in terms of symmetries
- Spin-Tensor Analysis show competing trends but varying significantly from light to middle mass nuclei :
  Tensor counter-balanced by Spin-Orbit

Summary

Special Thanks to:

- B. Bounthong, E. Caurier, H. Naidja, K. Sieja, A. Zuker
- A. Poves
- M. Hjorth-Jensen
- H. Grawe, S. Lenzi, O. Sorlin
- J. Herzfeld