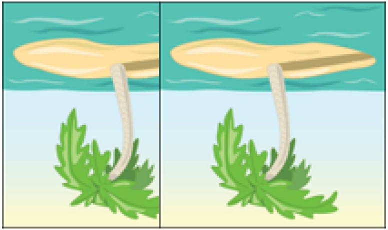
Shell Model Far From Stability: IoI Mergers

Frédéric Nowacki



ENSAR NUPRASEN Workshop, December 6^{th} 2016

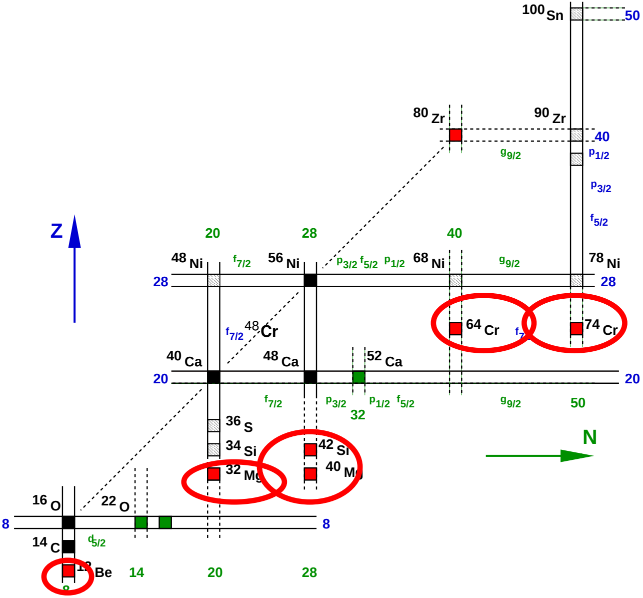
CNRS IN2P3 Les deux infinis
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG
UNIVERSITÉ DE STRASBOURG
USIAS University of Strasbourg Institute for Advanced Study

The Archipelago of Islands of Inversion

N=8	**N=20**	**N=28**	**N=40**	**N=50**
^{11}**Li**	^{32}**Mg**	^{42}**Si**	^{64}**Cr**	^{74}**Cr**

Landscape of medium mass nuclei: Mergers



N=40: SM framework

PHYSICAL REVIEW C **82**, 054301 (2010)

Island of inversion around ^{64}Cr

S. M. Lenzi,[1] F. Nowacki,[2] A. Poves,[3] and K. Sieja[2,*]
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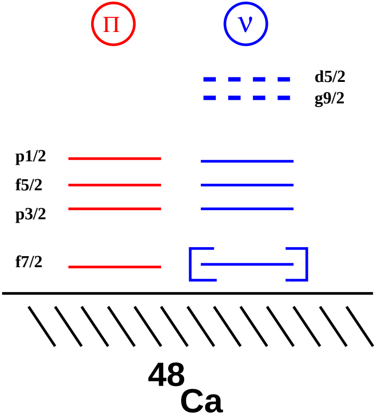
[3]*Departamento de Física Teórica e IFT-UAM/CSIC, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
(Received 10 September 2010; published 2 November 2010)



LNPS interaction:

- based on realistic TBME
- new fit of the pf shell (KB3GR, E. Caurier)
- monopole corrections
- $g_{9/2}$-$d_{5/2}$ gap now constrained to 2.5 Mev in ^{68}Ni

Calculations:

- Up to 14$\hbar\omega$ excitations across Z=28 and N=40 gaps
- Matrix diagonalizations up to 2.10^{10}
- m-scheme code ANTOINE (non public parallel version)

Portal to IoI at N=40: ^{68}Ni

- at first approximation, ^{68}Ni has a double closed shell structure for GS

- But low lying structure much more complex

- three coexisting 0^+ states appear between 0 and $\sim$ 2.5 MeV

- new location of 0_2^+ state !
  Configuration mixing and relative transition rates between low-spin states in ^{68}Ni:
  F. Recchia et al.
  Phys. Rev. **C88**, 041302(R) (2013)

- prediction of very low-lying superdeformed band ($\beta_2 \sim 0.4$) of 6*p*6*h* nature!
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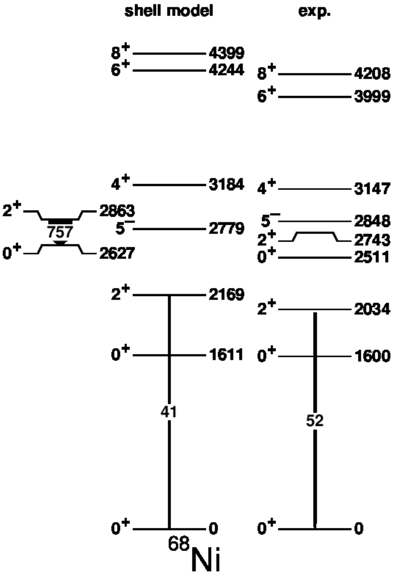
  Phys. Rev. **C85**, 0311301(R) (2012)



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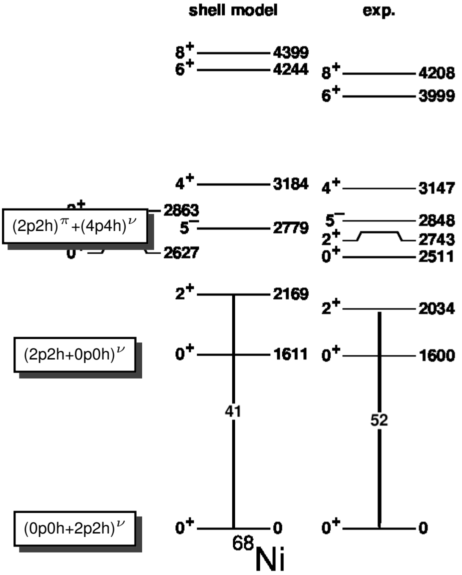

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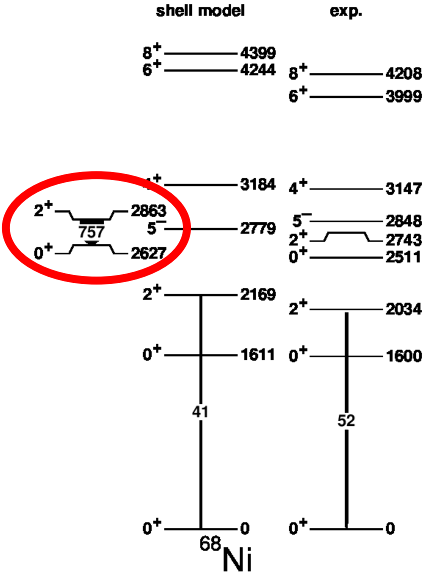
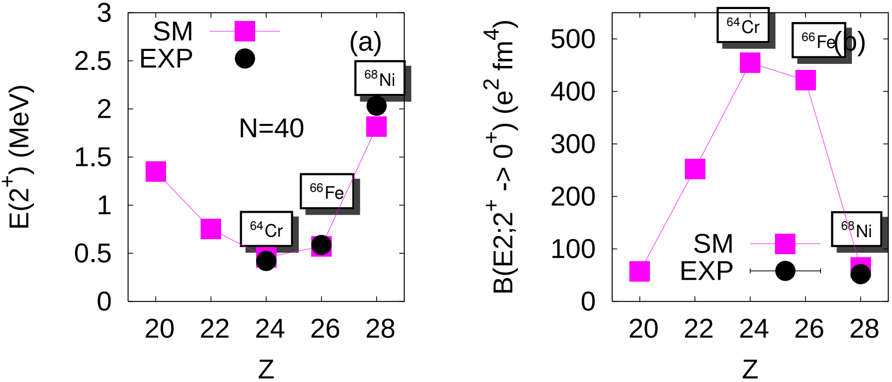


Shape transition at N=40



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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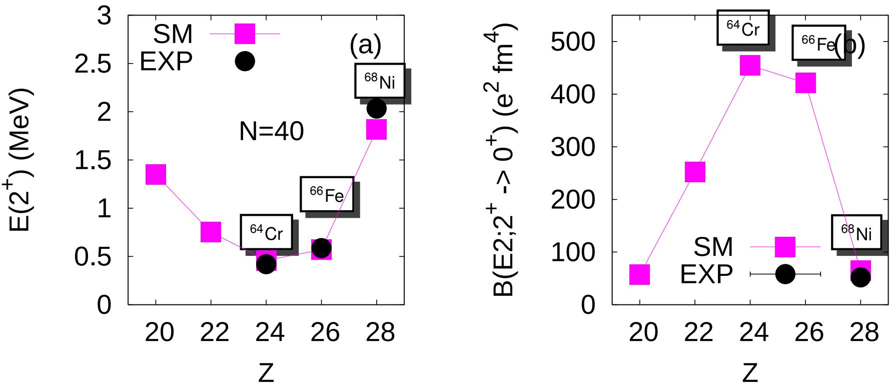

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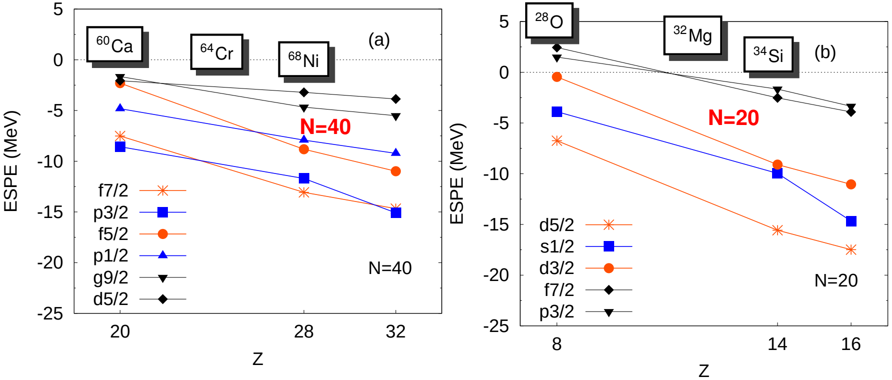
Neutron effective single particle energies



- 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
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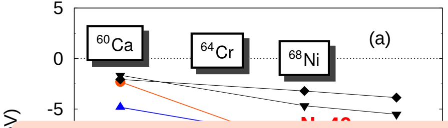


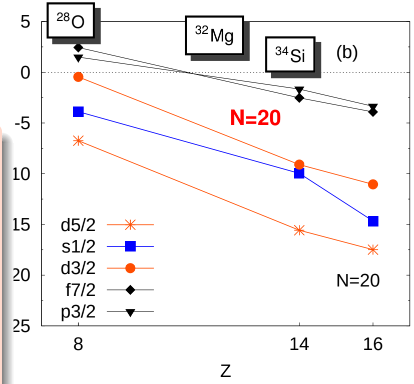
PRL 109, 032502 (2012) PHYSICAL RE

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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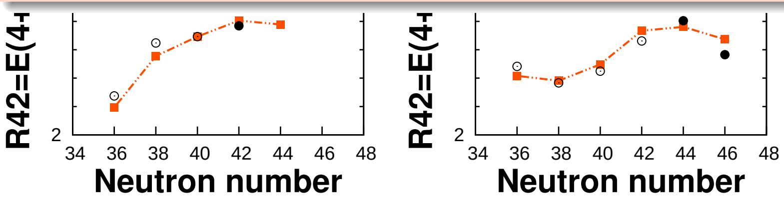
Extension of collectivity N=40 towards N=50

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

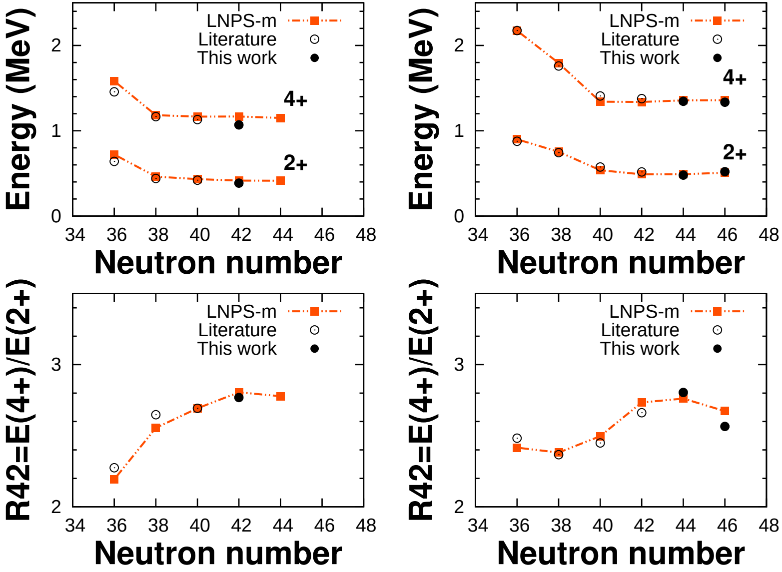
Extension of the $N = 40$ Island of Inversion towards $N = 50$: Spectroscopy of ^{66}Cr, ^{70,72}Fe

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



Extension of collectivity N=40 towards N=50

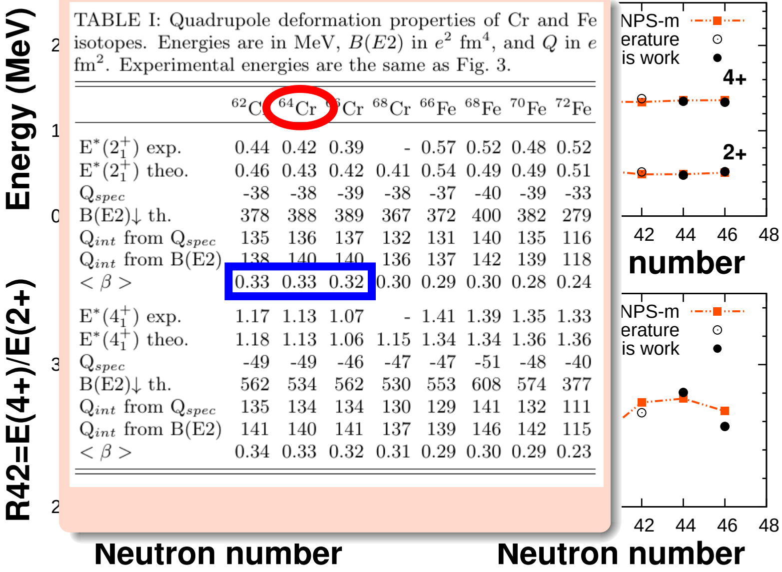
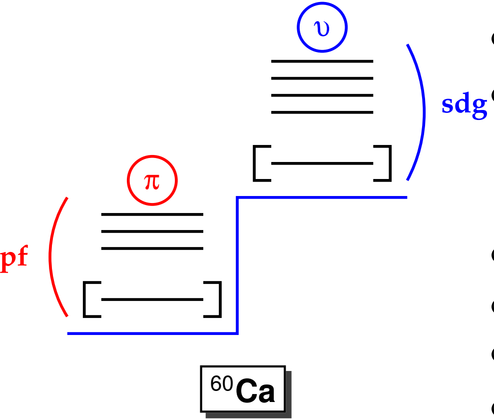


TABLE I: Quadrupole deformation properties of Cr and Fe isotopes. Energies are in MeV, $B(E2)$ in e^2 fm^4, and Q in e fm^2. Experimental energies are the same as Fig. 3.

	^{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

Physics around ^{78}Ni



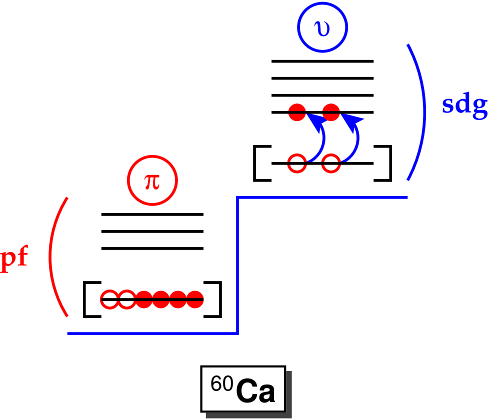
PFSDG-U interaction:

- 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 $2*10^{10}$ Slater Determinant basis states
- 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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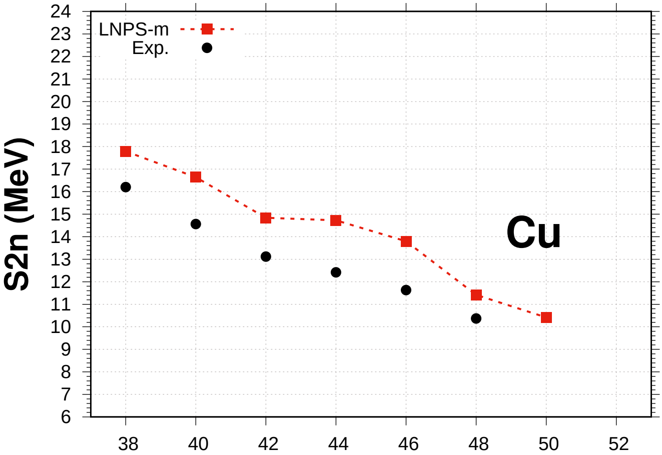
Neutron intruders constraints



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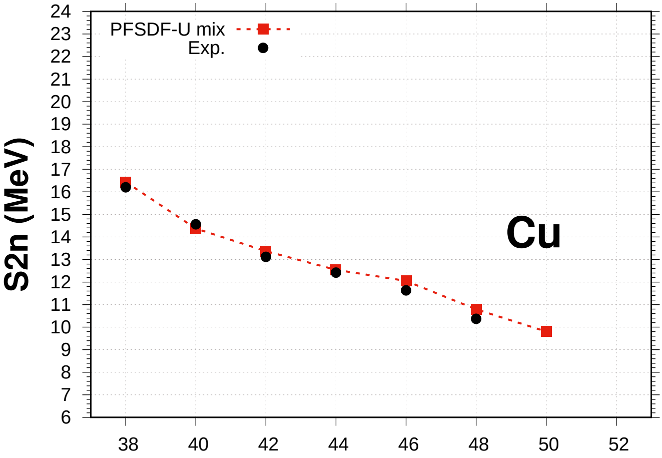

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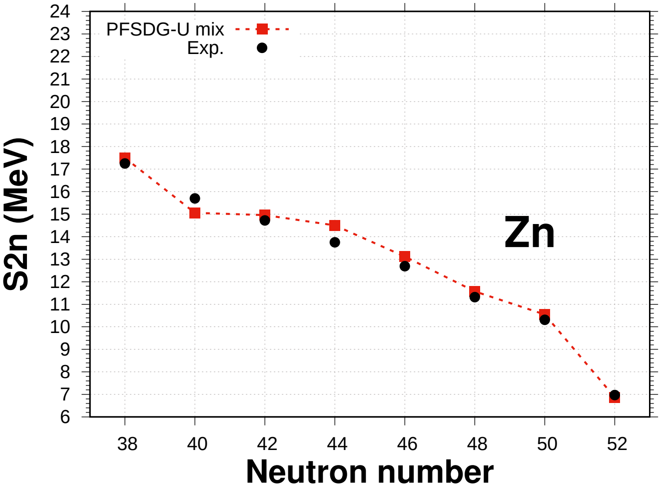

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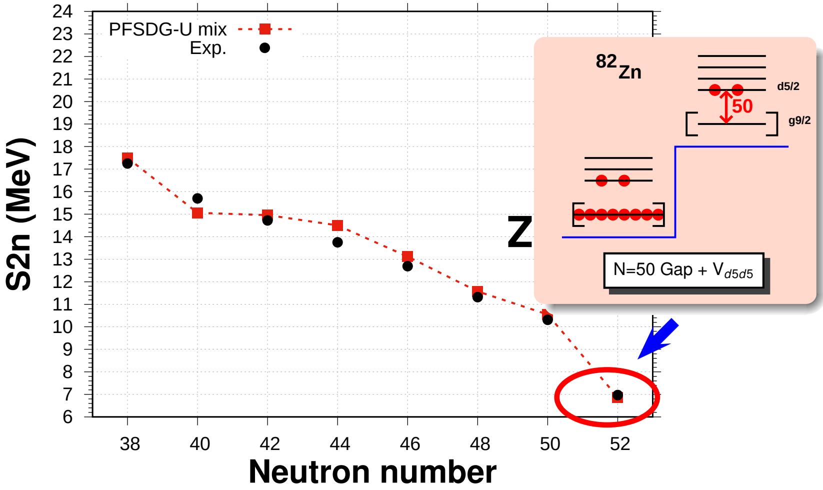
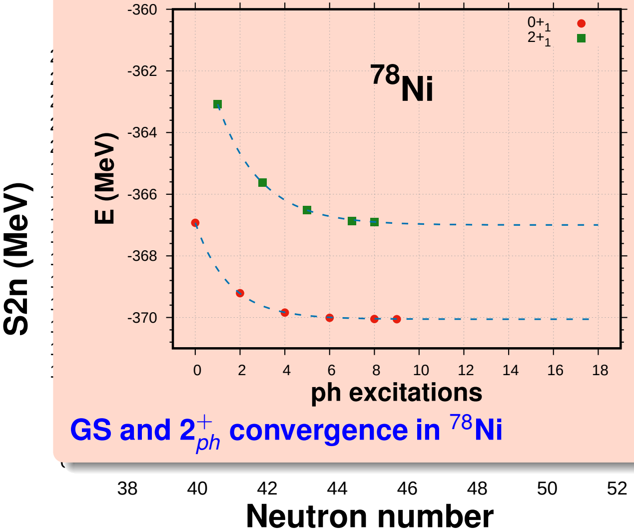
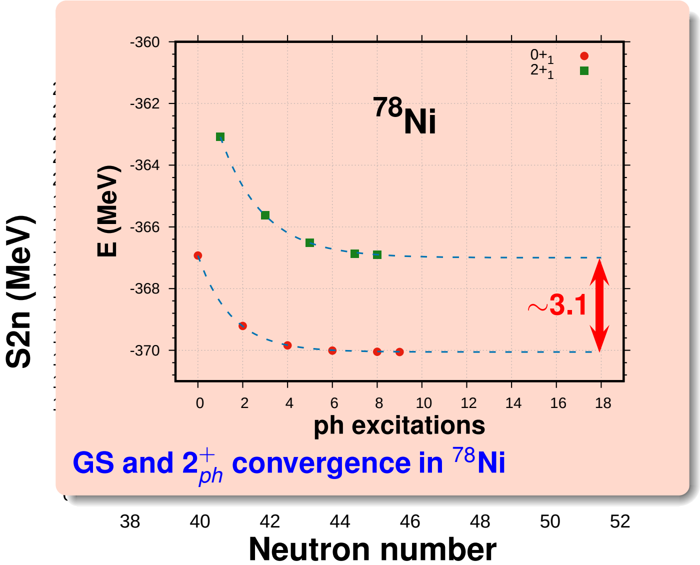




GS and 2^+_{ph} convergence in ^{78}Ni

Neutron intruders constraints



Spherical structure of ^{78}Ni

PRL **117,** 172501 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

Structure of ^{78}Ni from First-Principles Computations

G. Hagen,[1,2] G. R. Jansen,[3,1] and T. Papenbrock[1,2]

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(Received 4 May 2016; revised manuscript received 18 August 2016; published 17 October 2016)

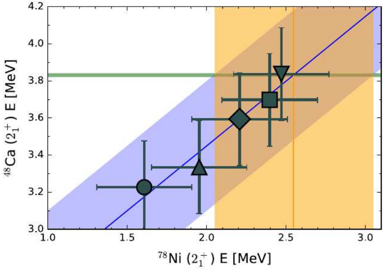
Ab-initio CC predictions for ^{78}Ni

FIG. 2. Correlation between the energies of the 2_1^+ excited state in ^{48}Ca and ^{78}Ni, obtained from the interactions NNLO$_{sat}$ (circle), "2.0/2.0 (PWA)" (square), "2.0/2.0 (EM)" (diamond), "2.2/2.0 (EM)" (triangle up), and "1.8/2.0 (EM)" (triangle down). The error bars estimate uncertainties from enlarging the model space from $N = 12$ to $N = 14$. The thin horizontal line marks the known energy of the 2_1^+ state in ^{48}Ca.

$N=8$ $N=10$ $N=12$ $N=14$ Exp

FIG. 3. Convergence of the first 2_1^+ excited state of ^{48}Ca and ^{78}Ni with increasing model-space size and compared to the data for the interaction 1.8/2.0 (EM) of Ref. [33].

Spherical structure of ^{78}Ni



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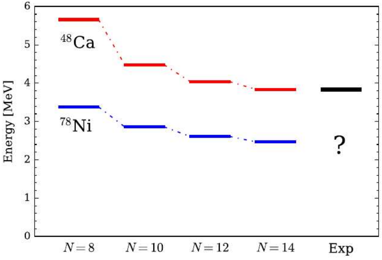

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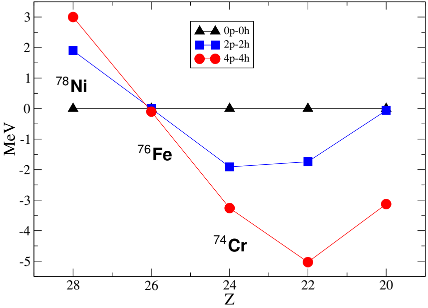
Schematic SU3 predictions

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

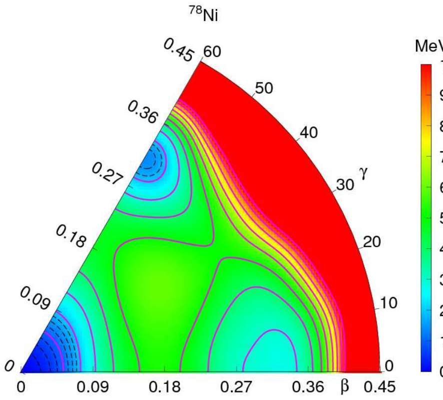
  $E_n = G_n^{mp}(50) - \hbar\omega\kappa\left(\frac{\langle Q_0^m(\pi)\rangle}{15\ b^2} + \frac{\langle Q_0^m(\nu)\rangle}{23\ b^2}\right)^2$

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

- 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 **of** **I**nversion



Constrained deformed HF in the SM basis

(B. Bounthong, PhD Thesis, Strasbourg)

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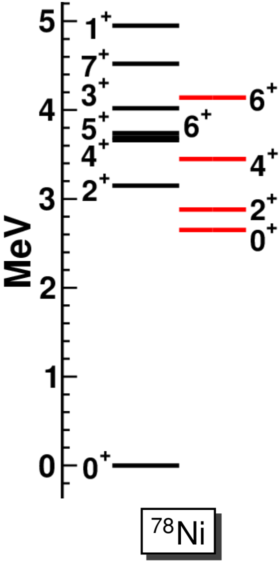

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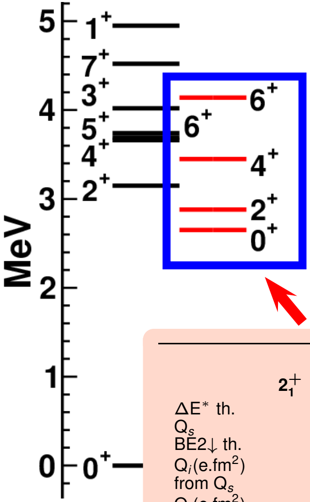

	^{78}Ni
	$2^+_1 \rightarrow 0^+_2$
ΔE^* th.	0.229
Q_s	-39
BE2↓ th.	516
Q_i(e.fm^2) from Q_s	135
Q_i(e.fm^2) from BE2	195
β_2^e	**$\sim$ 0.3 prolate**

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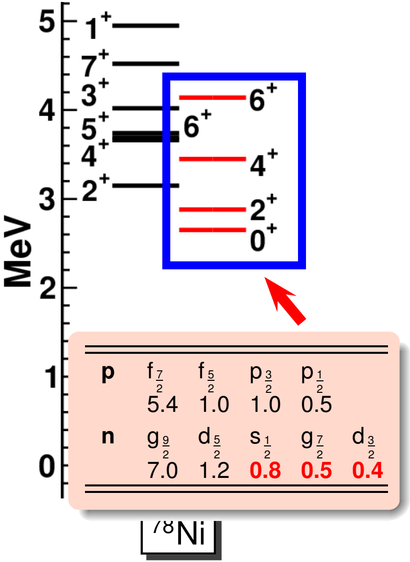
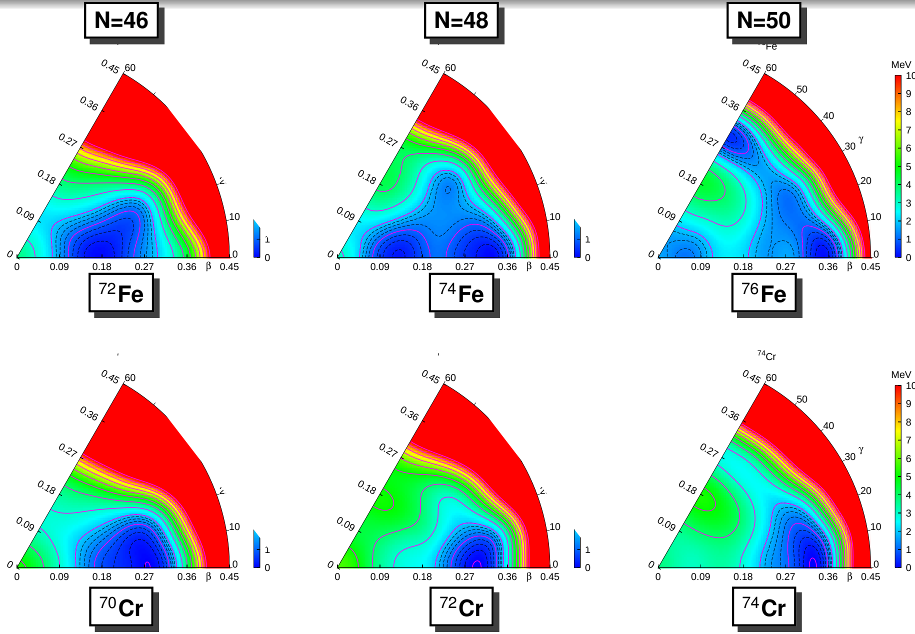
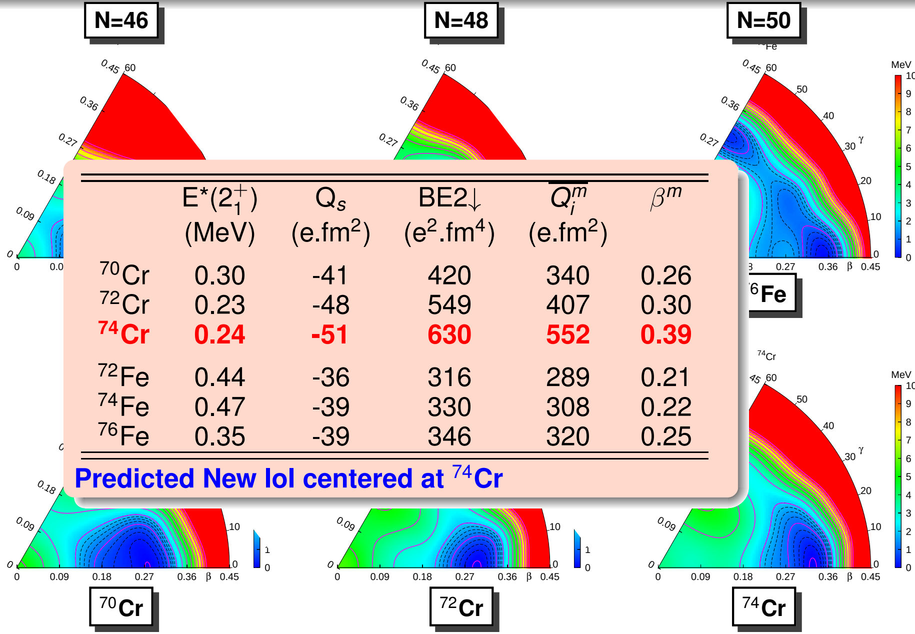
- Necessity to go **beyond** $(fpg_{\frac{9}{2}}d_{\frac{5}{2}})$ **LNPS space** and **beyond ab-initio description**
- Portal to a new **I**sland **of I**nversion



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



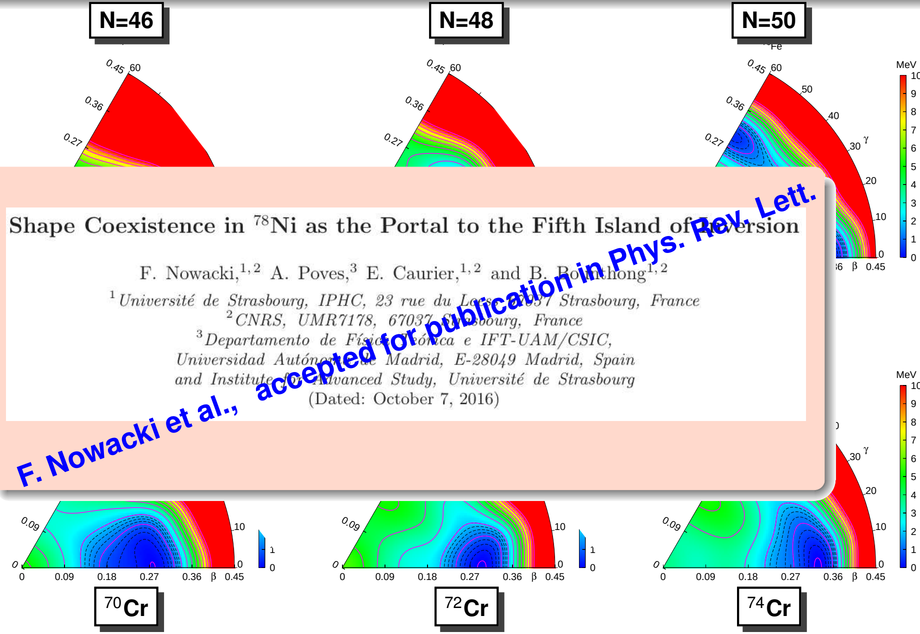
Island of Deformation below ^{78}Ni: PES's



	$E^*(2_1^+)$ (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	**0.24**	**-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

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



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

F. Nowacki,[1,2] A. Poves,[3] E. Caurier,[1,2] and B. Bounthong[1,2]

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[2] *CNRS, UMR7178, 67037 Strasbourg, France*
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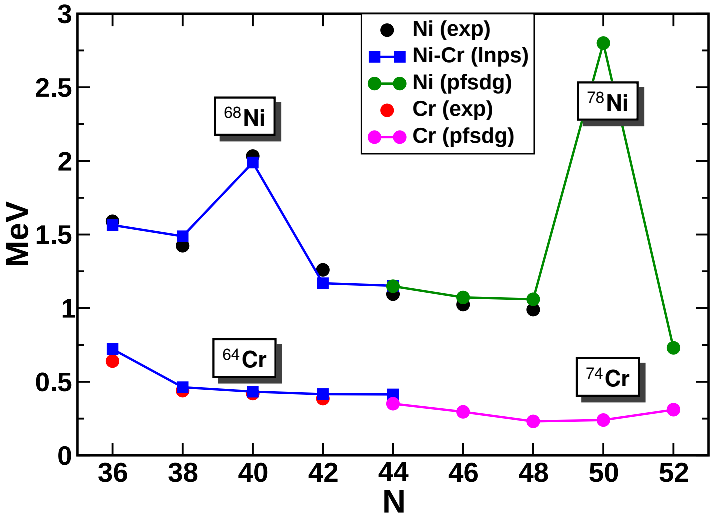
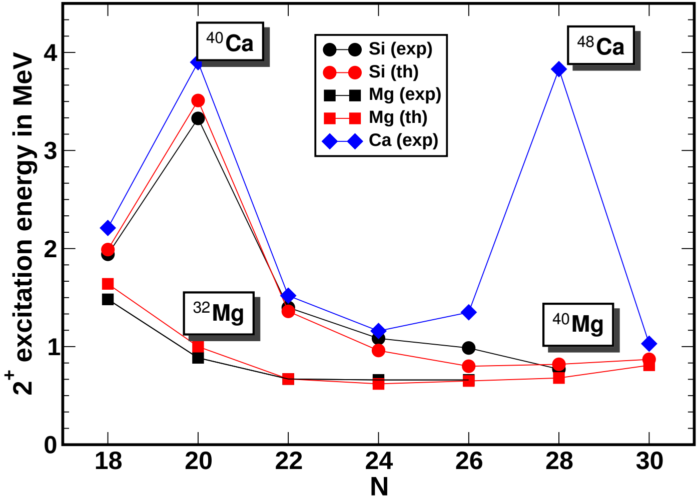
(Dated: October 7, 2016)

F. Nowacki et al., accepted for publication in Phys. Rev. Lett.

The N=40 and N=50 IoI's Merge



Like the N=20 and N=28 IoI's did



Summary

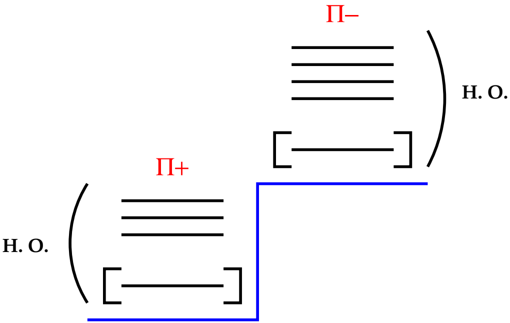
- The physics around magic or semi-magic closures depends of subtle balances between the spherical mean field and the (very large) correlation energies of the open shell configurations at play
- There is a common mechanism explaining the appearance of ”islands of inversion/deformation” (IoI’s) in nuclei with large neutron excess, and shape coexistence usually shows up as a its portal
- The IoI’s at N=20 and N=28 merge in the Magnesium isotopes.
- ^{68}Ni is a case of triple coexistence, precursor of the N=40 IoI
- Shape coexistence in ^{78}Ni is the portal to a new IoI at N=50
- The IoI’s at N=40 and N=50 merge in the Chromium isotopes.

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

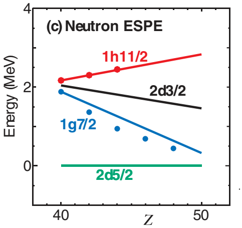
Spin-orbit shell closure far from stability



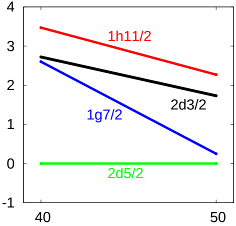
- sd-pf: ^{42}Si deformed
- pf-sdg: ^{78}Ni ???
- sdg-phf: ^{132}Sn doubly magic

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

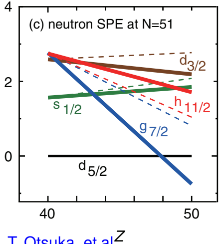
Tensor mechanism in mid-mass nuclei



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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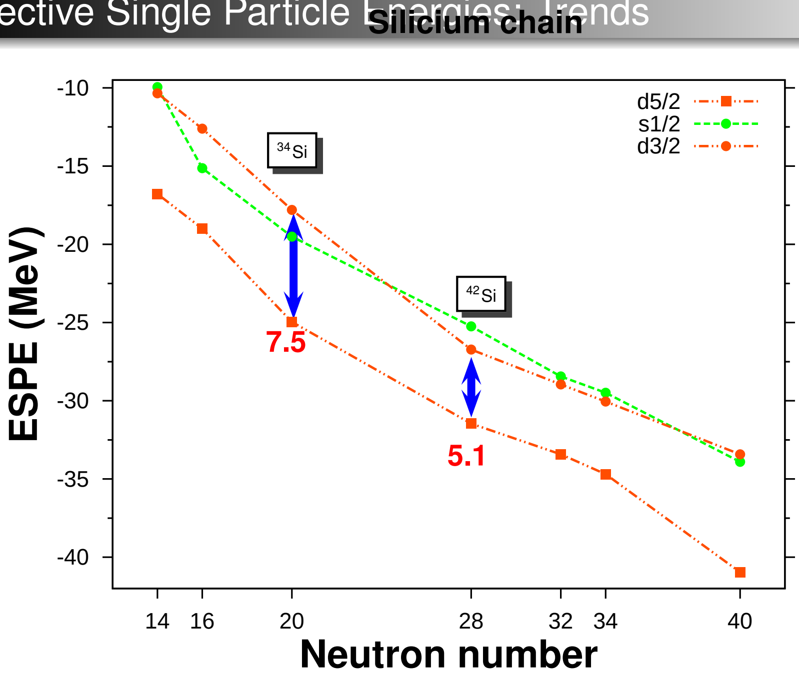
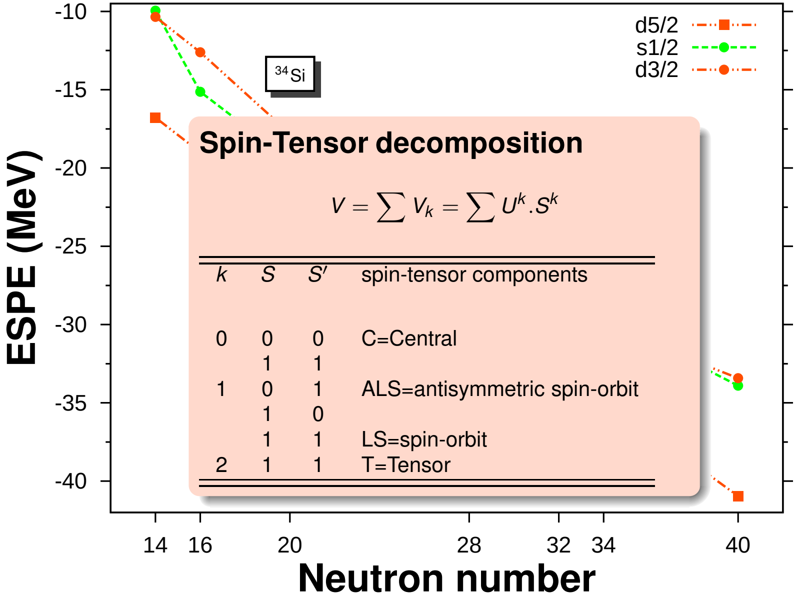
Effective Single Particle Energies: Trends



Effective Single Particle Energies: Trends



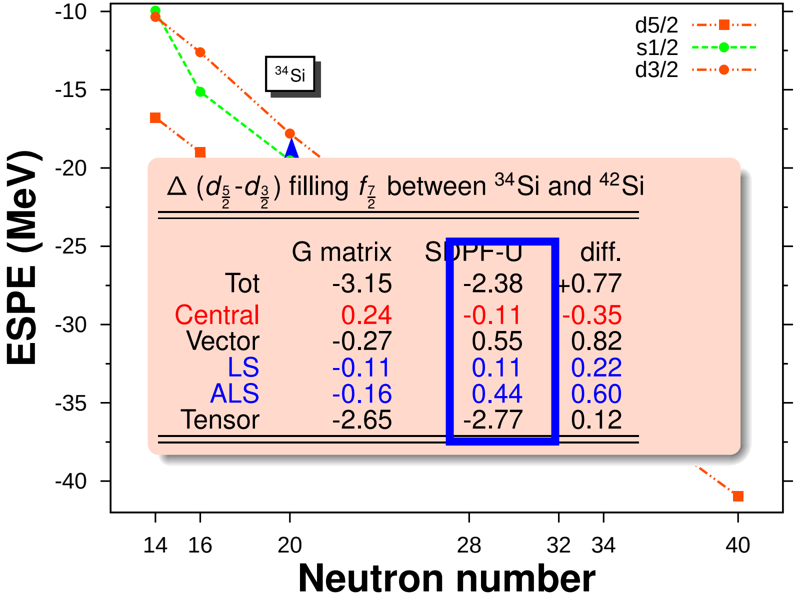
Spin-Tensor decomposition

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

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

Effective Single Particle Energies: Trends

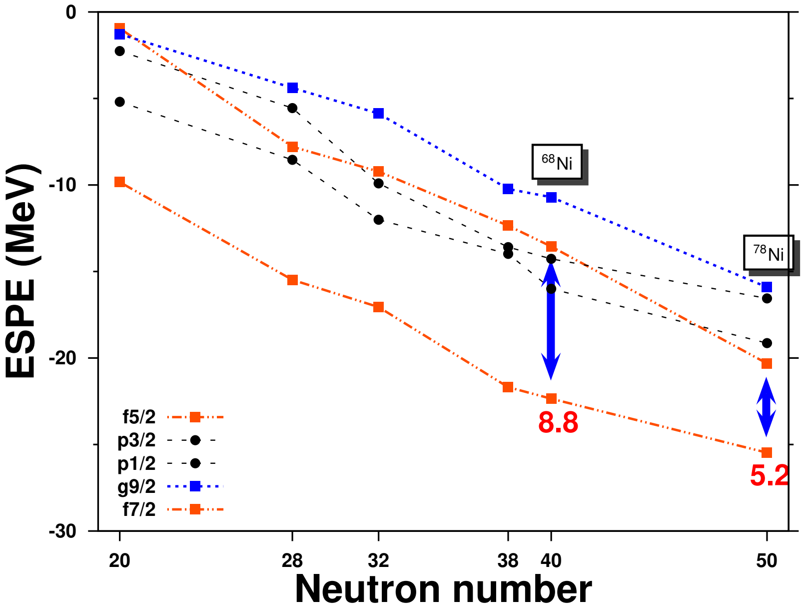
Silicium chain



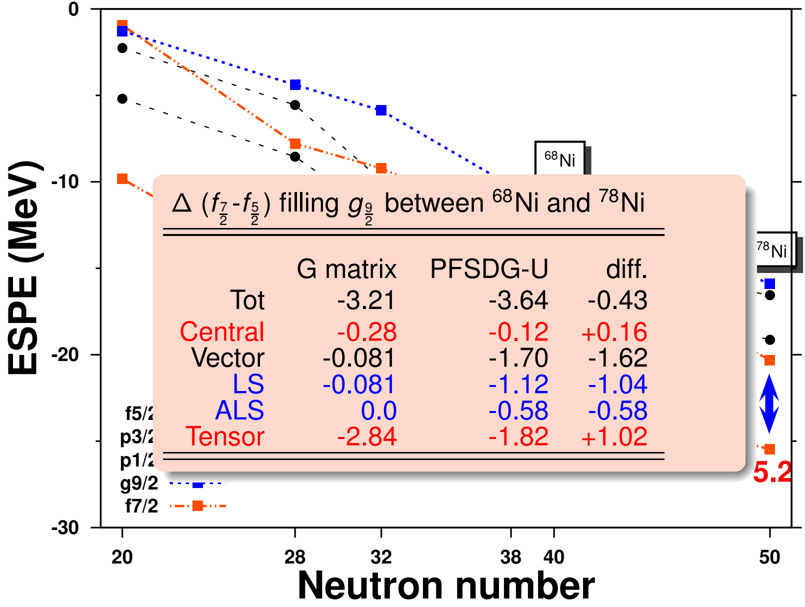
Δ ($d_{\frac{5}{2}}$-$d_{\frac{3}{2}}$) filling $f_{\frac{7}{2}}$ between ^{34}Si and ^{42}Si

	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

Effective Single Particle Energies: Trends



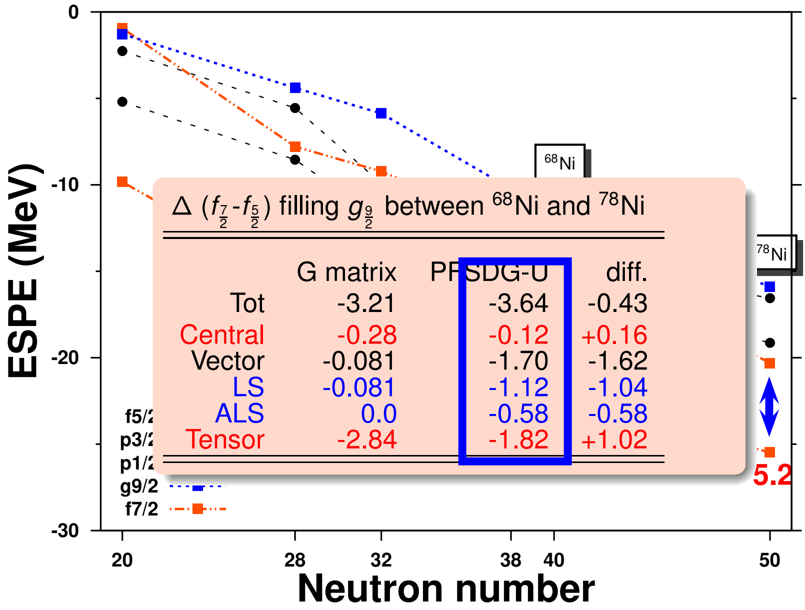
Effective Single Particle Energies: Trends



$\Delta\ (f_{\frac{7}{2}} - f_{\frac{5}{2}})$ 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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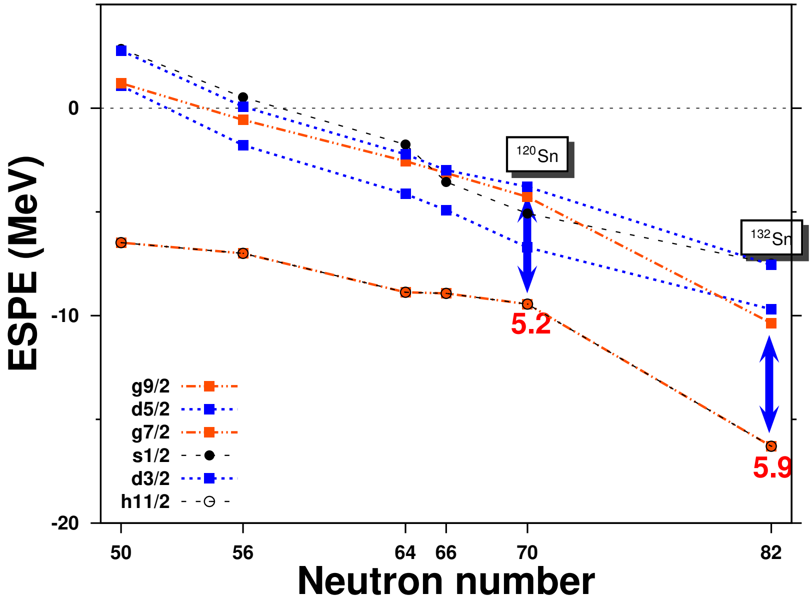
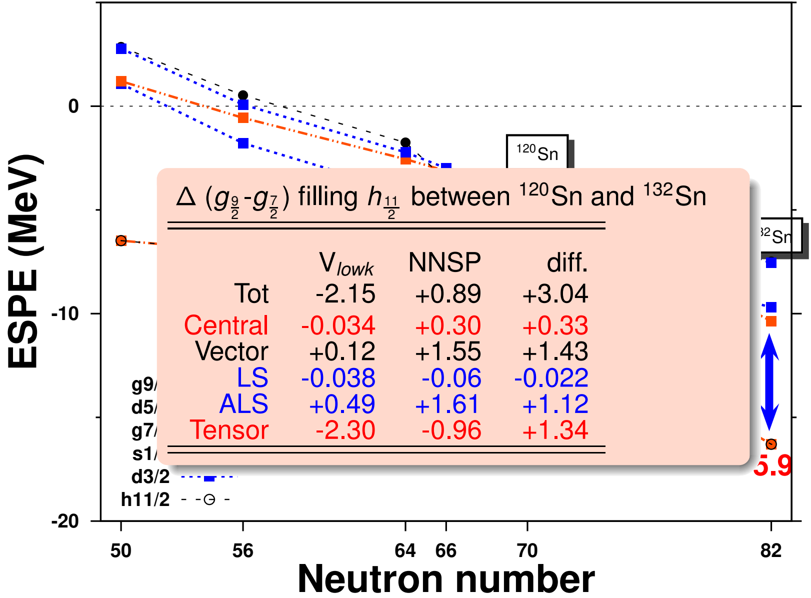
Effective Single Particle Energies: Trends



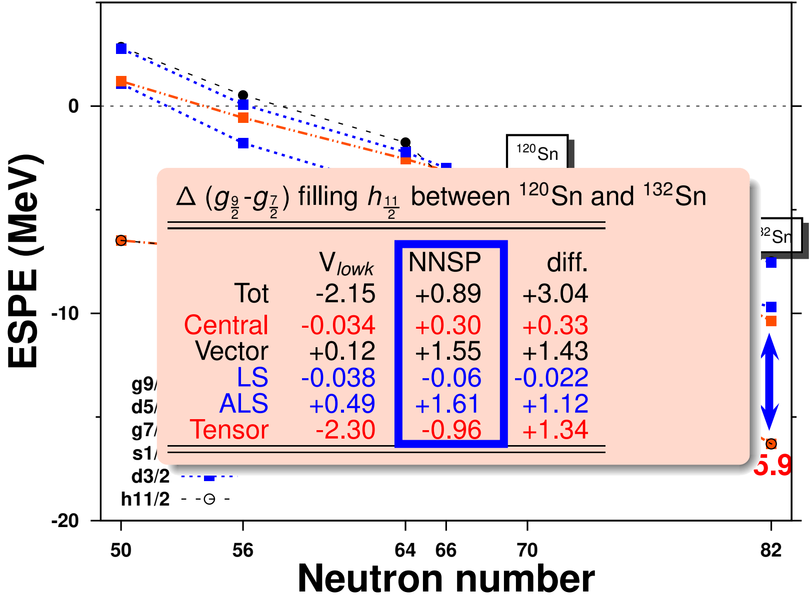
Effective Single Particle Energies: Trends



Δ ($g_{\frac{9}{2}}$-$g_{\frac{7}{2}}$) 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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