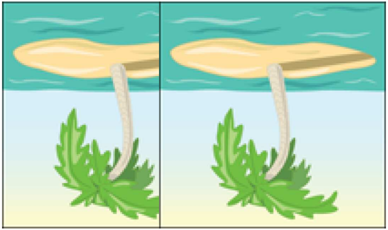
Shell Model Far From Stability: IoI Mergers

Frédéric Nowacki



NUSPIN 2017, June 26th-29th 2017

CNRS IN2P3 Les deux infinis
IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg
Université de Strasbourg
Università degli Studi della Campania Luigi Vanvitelli

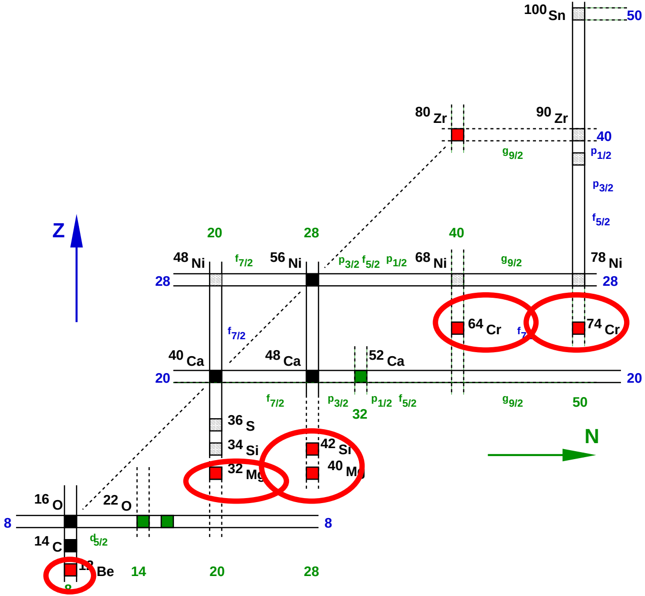
The Archipelago of Islands of Inversion





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



Evolution of nuclear shells due to Tensor force

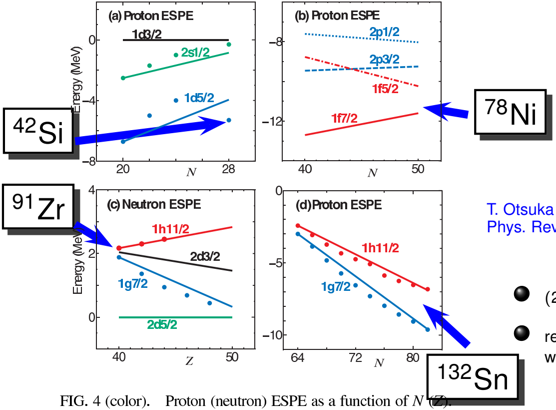
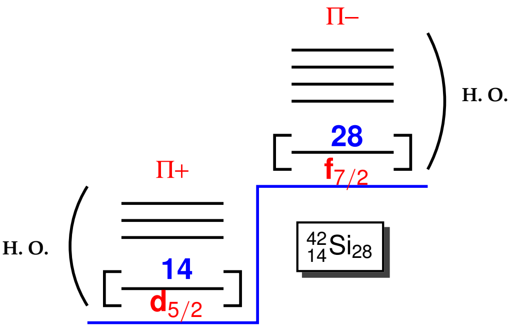


FIG. 4 (color). Proton (neutron) ESPE as a function of N (Z). Lines in (a)–(c) show the change of ESPE's calculated from the $\pi + \rho$ tensor force. Points represent the corresponding experimental data. (a) Proton ESPE's in Ca isotopes relative to $1d_{3/2}$. Points are from [13]. (b) Proton ESPE's in Ni isotopes; calculations only. See [19] for related experimental data. (c) Neutron ESPE's in $N = 51$ isotones relative to $2d_{5/2}$; points are from [21]. (d) Proton ESPE's in Sb isotopes; points are from [18]. Lines include a common shift of ESPE as well as the tensor effect (see the text).

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

- $(2j_> + 1)V^T_{j_>, j'} + (2j_< + 1)V^T_{j_<, j'} = 0$,
- reduction of spin-orbit partners splitting while filling j' shell

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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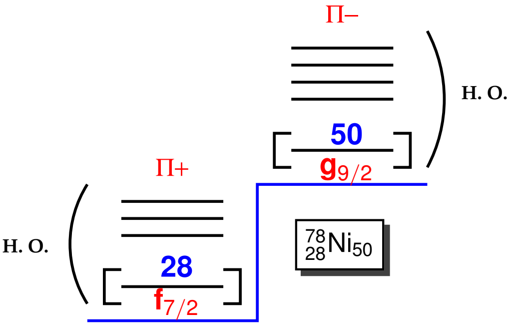

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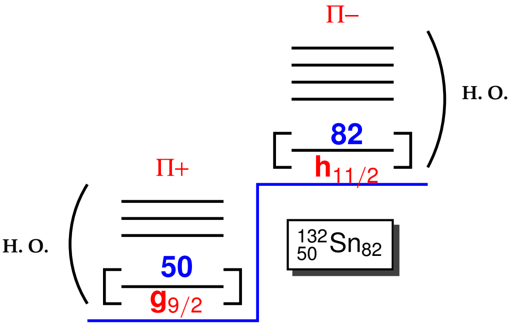

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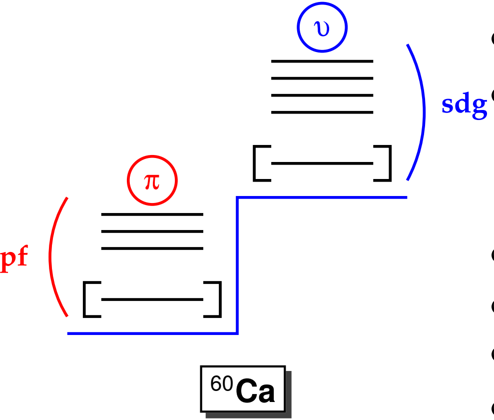
Physics around ^{78}Ni



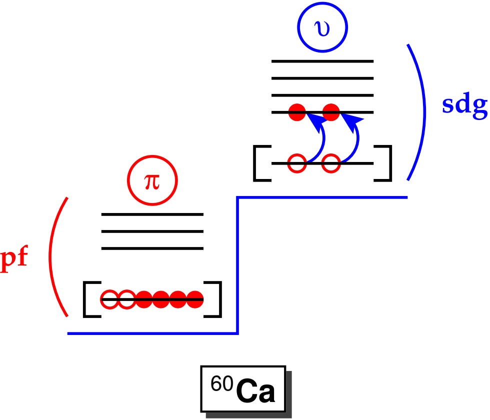
PFSDG-U interaction:

- 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
- 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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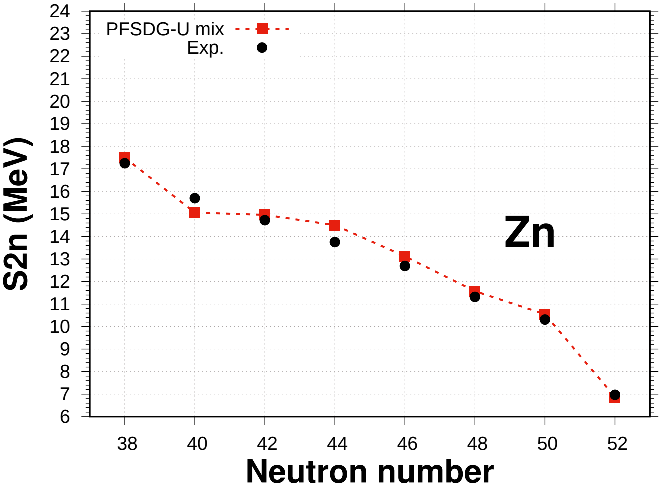
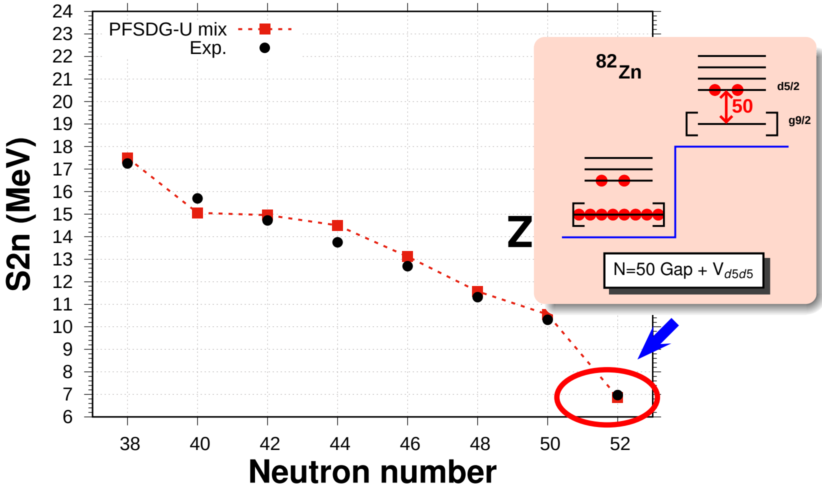
Neutron intruders constraints



Neutron intruders constraints



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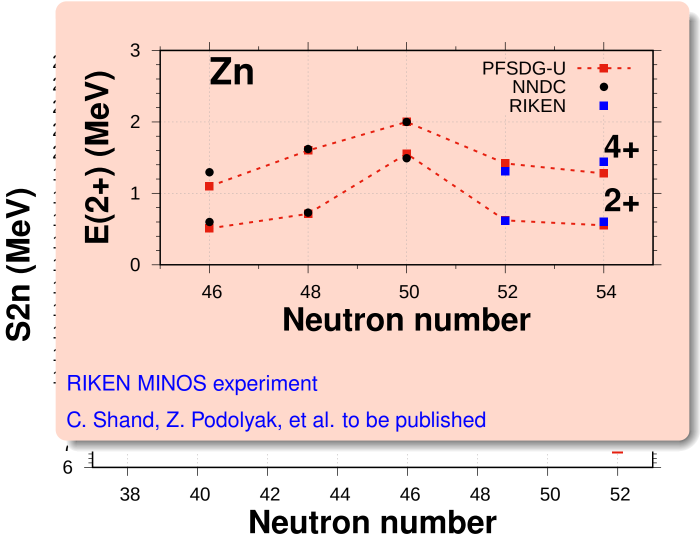
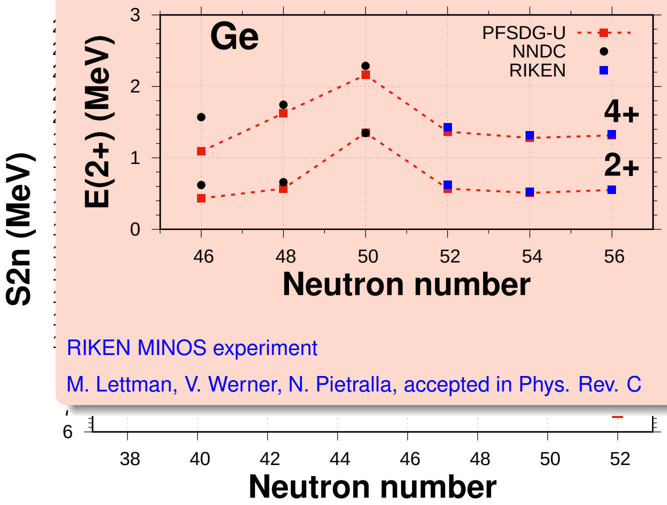


RIKEN MINOS experiment

C. Shand, Z. Podolyak, et al. to be published

Neutron intruders constraints



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M. Lettman, V. Werner, N. Pietralla, accepted in Phys. Rev. C

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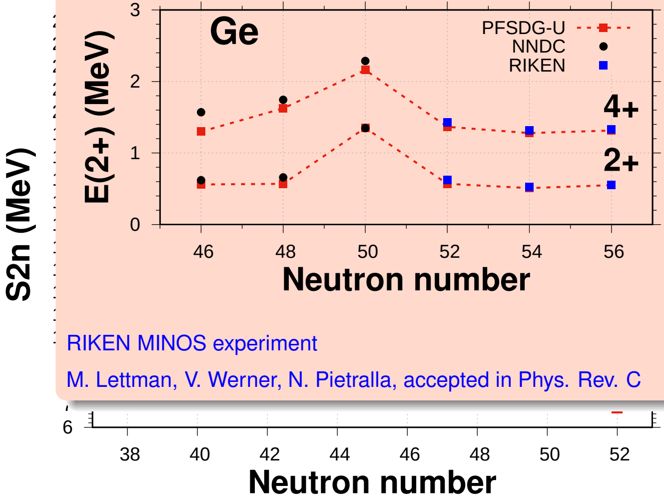

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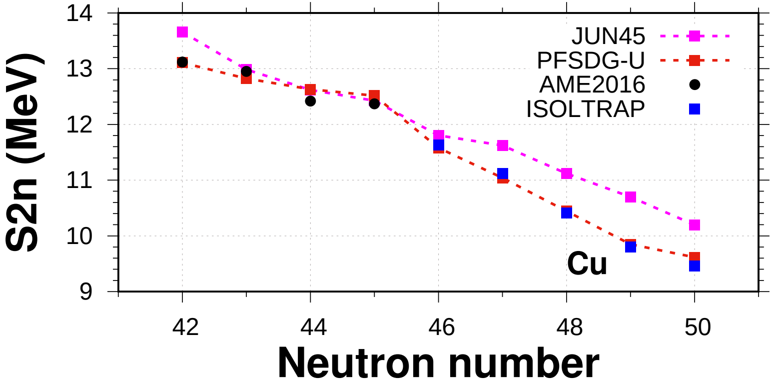
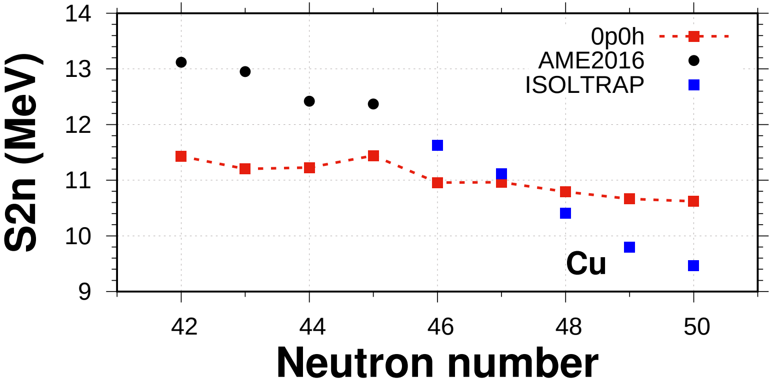


- data: AME2016 and ISOLTRAP Collaboration 2017

NpNh excitations



- theory PFSDG-U
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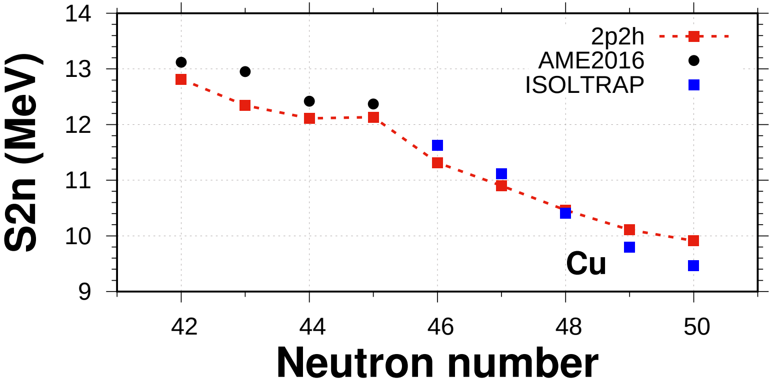

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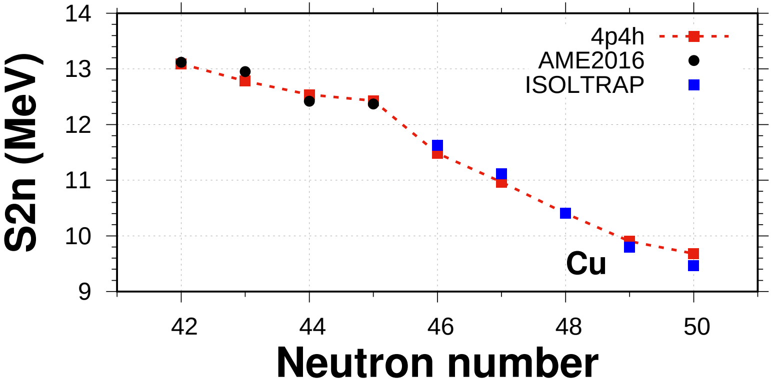

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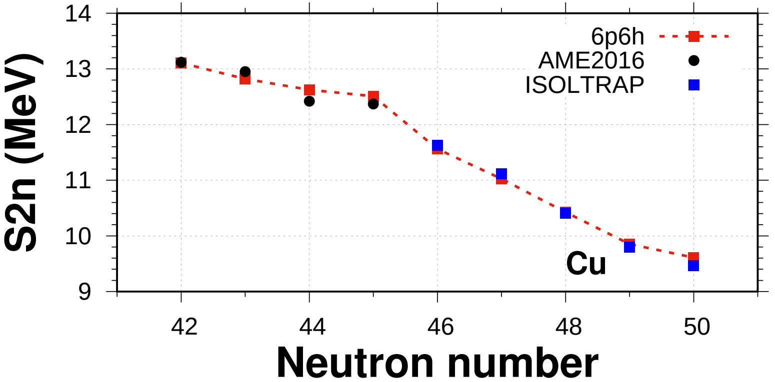

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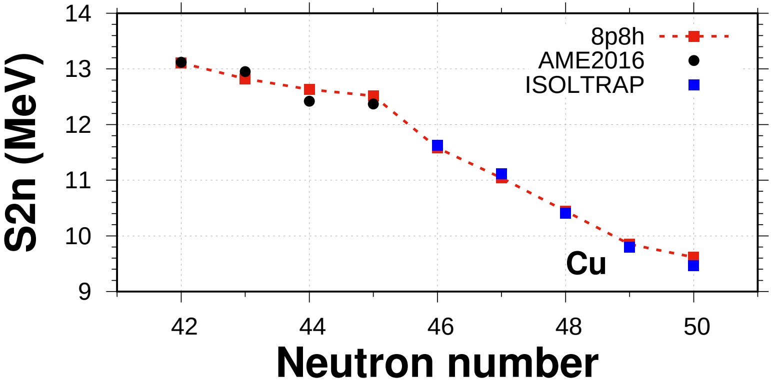

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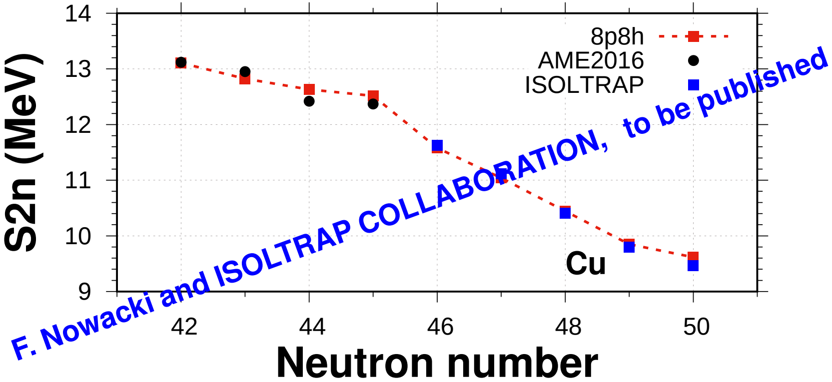

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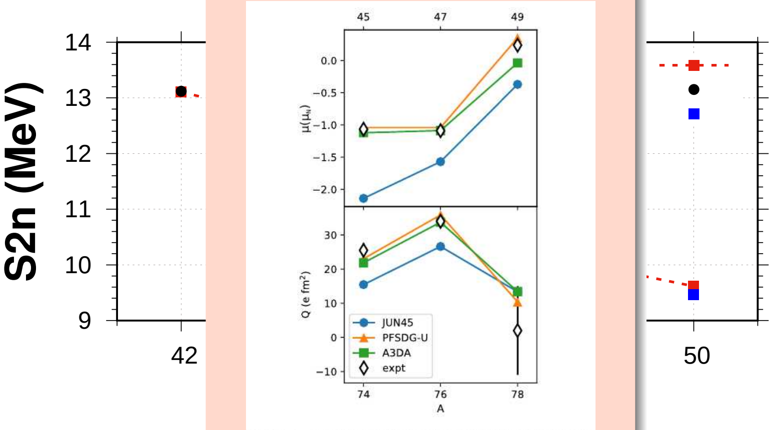


Figure 5. Experimental moments compared to calculations for odd-odd isotopes. Where possible, the weighted mean of this work and literature values are plotted.

- theory PFSDG-
- data: AME2016

R. P. de Groote and the CRIS collaboration

in preparation

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]
[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[3]*National Center for Computational Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
(Received 4 May 2016; revised manuscript received 18 August 2016; published 17 October 2016)

Ab-initio CC predictions for ^{78}Ni

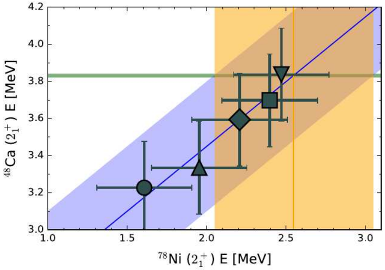
^{48}Ca (2^+_1) E [MeV]

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

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.

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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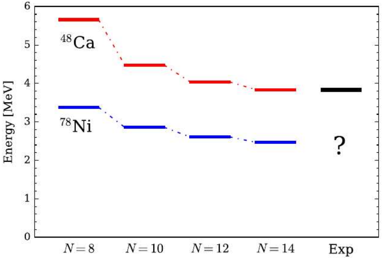

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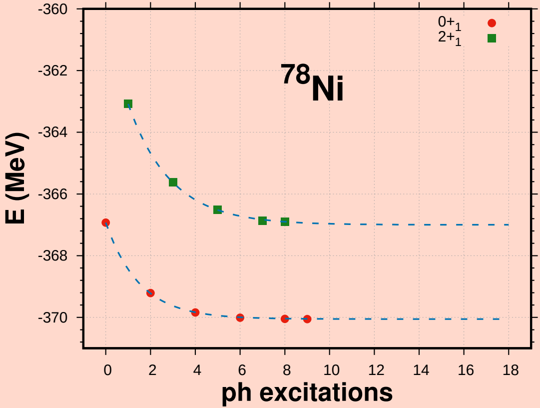

GS and 2^+_{ph} in ^{78}Ni

^{48}Ca (2^+_1) E [MeV]

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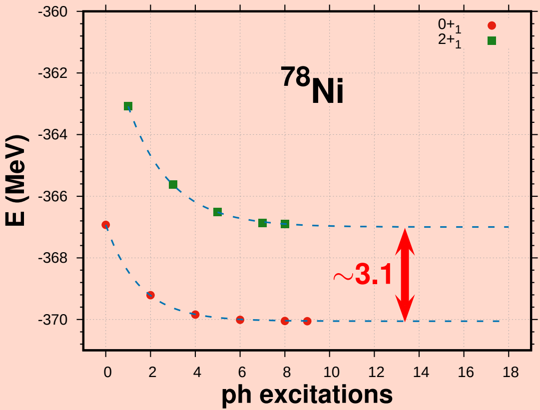
Spherical structure of ^{78}Ni



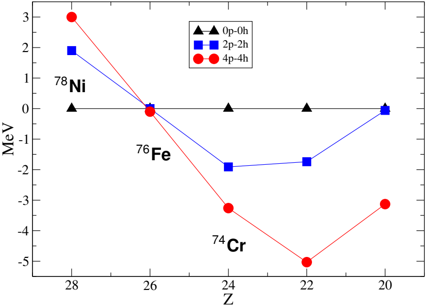
GS and 2^+_{ph} in ^{78}Ni

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

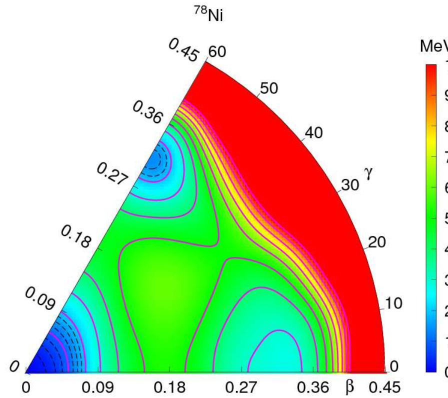
  $E_n = G_n^{mp}(50) - \hbar\omega\kappa\left(\frac{\langle Q_0^m(\pi)\rangle}{15\ b^2} + \frac{\langle Q_0^m(\nu)\rangle}{23\ b^2}\right)^2$

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

- 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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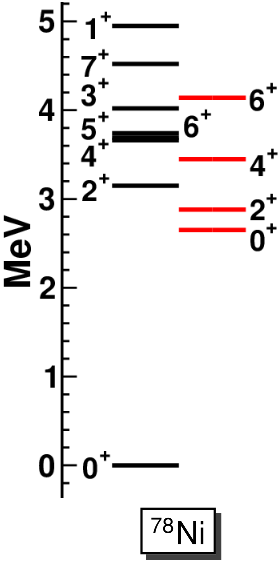

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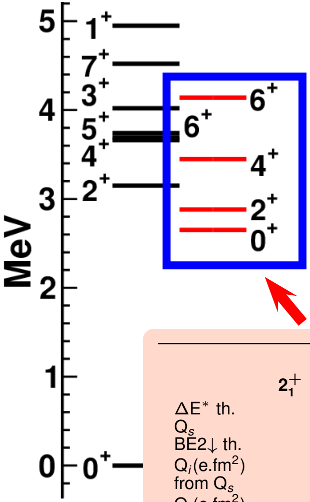

	^{78}Ni $2_1^+ \rightarrow 0_2^+$
ΔE^* th.	0.229
Q_s	-39
BE2↓ th.	516
Q_i(e.fm^2) from Q_s	135
Q_i(e.fm^2) from BE2	195
β_2^e	$\sim$ **0.3 prolate**

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**
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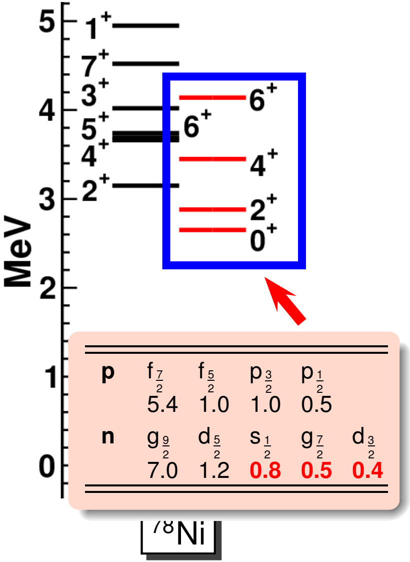
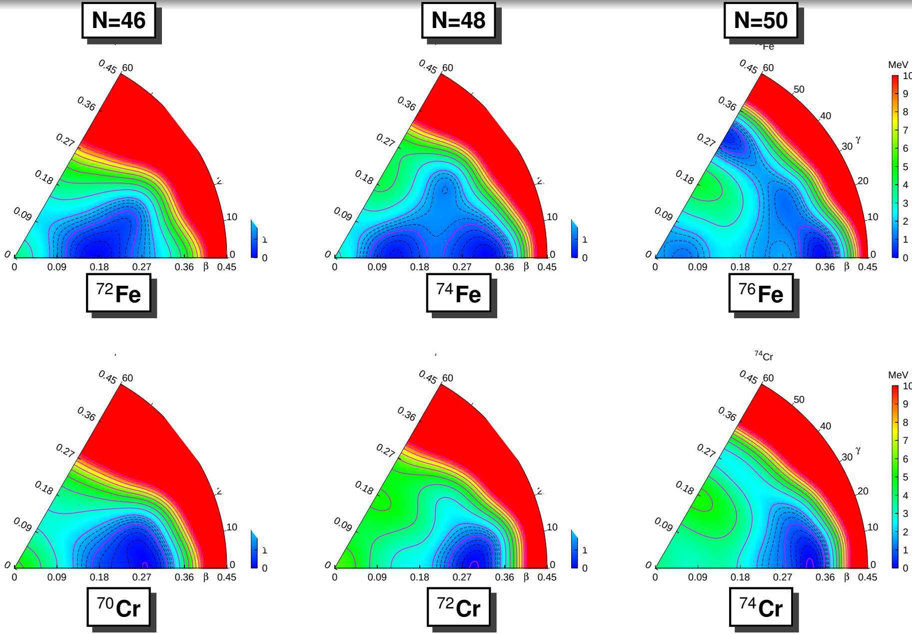


p	$f_{\frac{7}{2}}$ 5.4	$f_{\frac{5}{2}}$ 1.0	$p_{\frac{3}{2}}$ 1.0	$p_{\frac{1}{2}}$ 0.5	
n	$g_{\frac{9}{2}}$ 7.0	$d_{\frac{5}{2}}$ 1.2	$s_{\frac{1}{2}}$ **0.8**	$g_{\frac{7}{2}}$ **0.5**	$d_{\frac{3}{2}}$ **0.4**

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



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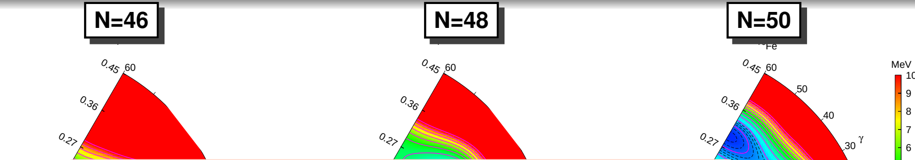
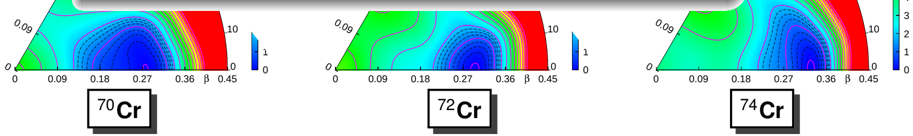


	$E^*(2_1^+)$ (MeV)	Q_s (e.fm^2)	BE2↓ (e^2.fm^4)	$\overline{Q_i^m}$ (e.fm^2)	β^m
^{70}Cr	0.30	-41	420	340	0.26
^{72}Cr	0.23	-48	549	407	0.30
^{74}Cr	**0.24**	**-51**	**630**	**552**	**0.39**
^{72}Fe	0.44	-36	316	289	0.21
^{74}Fe	0.47	-39	330	308	0.22
^{76}Fe	0.35	-39	346	320	0.25

Predicted New IoI centered at ^{74}Cr



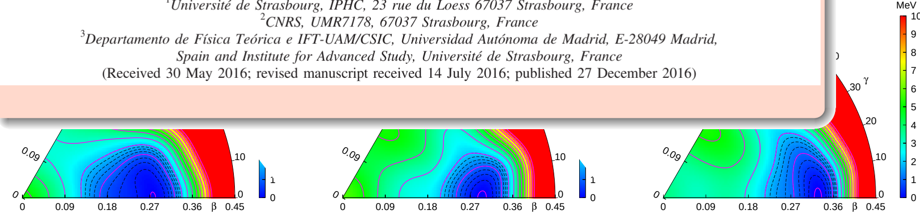
Island of Deformation below ^{78}Ni: PES's

N=46 N=48 N=50

PRL 117, 272501 (2016) PHYSICAL REVIEW LETTERS week ending 30 DECEMBER 2016

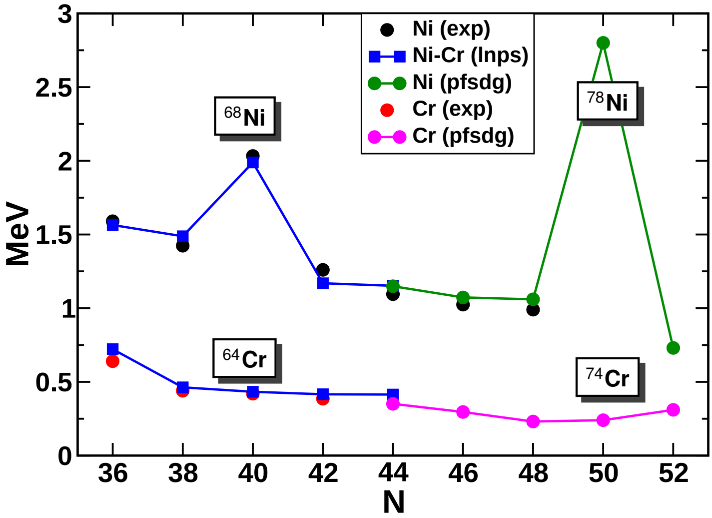
Shape Coexistence in ^{78}Ni as the Portal to the Fifth Island of Inversion

F. Nowacki,[1,2] A. Poves,[3] E. Caurier,[1,2] and B. Bounthong[1,2]
[1]*Université de Strasbourg, IPHC, 23 rue du Loess 67037 Strasbourg, France*
[2]*CNRS, UMR7178, 67037 Strasbourg, France*
[3]*Departamento de Física Teórica e IFT-UAM/CSIC, Universidad Autónoma de Madrid, E-28049 Madrid, Spain and Institute for Advanced Study, Université de Strasbourg, France*
(Received 30 May 2016; revised manuscript received 14 July 2016; published 27 December 2016)

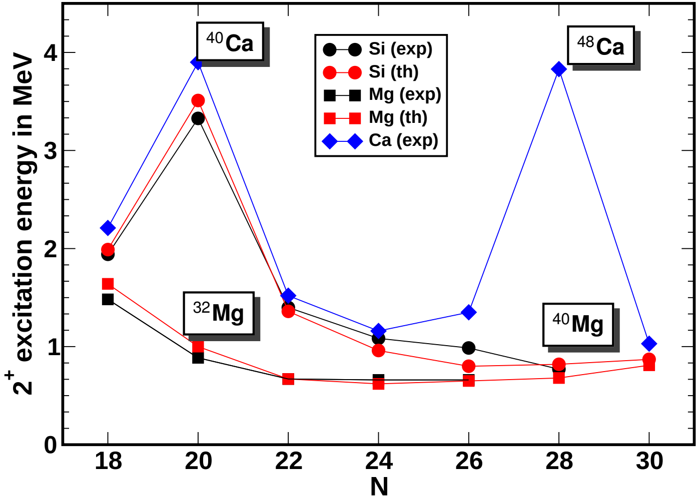


^{70}Cr ^{72}Cr ^{74}Cr

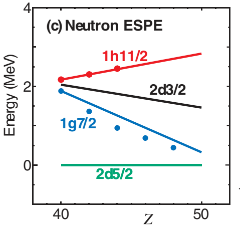
The N=40 and N=50 IoI's Merge



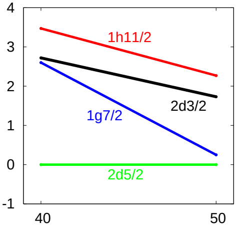
Like the N=20 and N=28 IoI's did



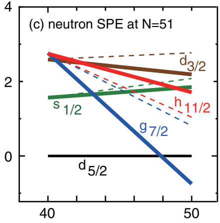
Shell evolution and Tensor mechanism in mid-mass nuclei



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*

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Novel Features of Nuclear Forces and Shell Evolution in Exotic Nuclei

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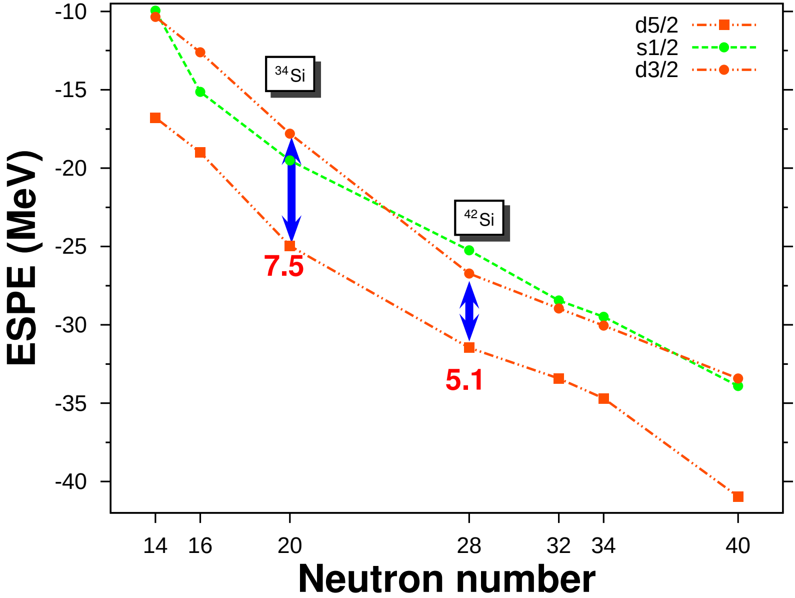
Effective Single Particle Energies: Trends

Silicium chain



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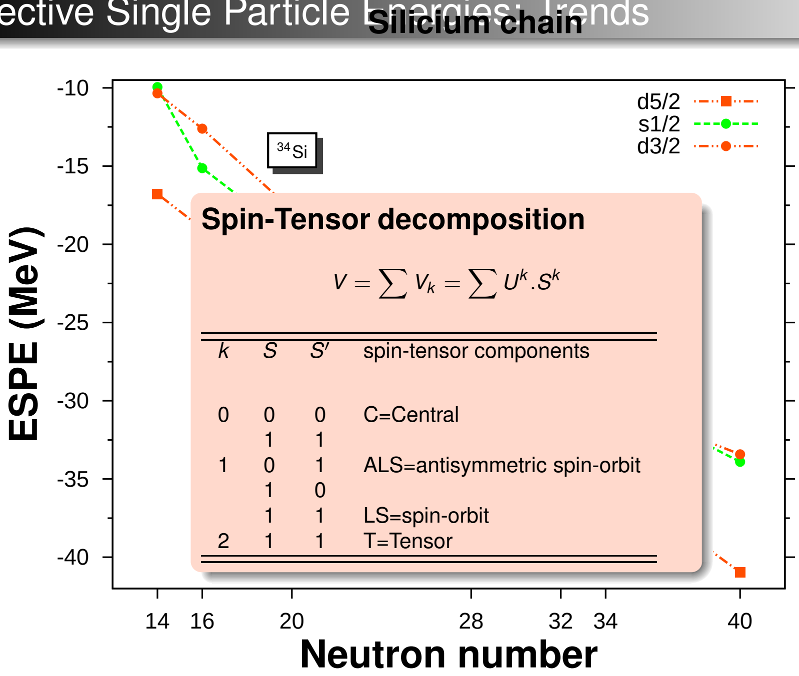

Spin-Tensor decomposition

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

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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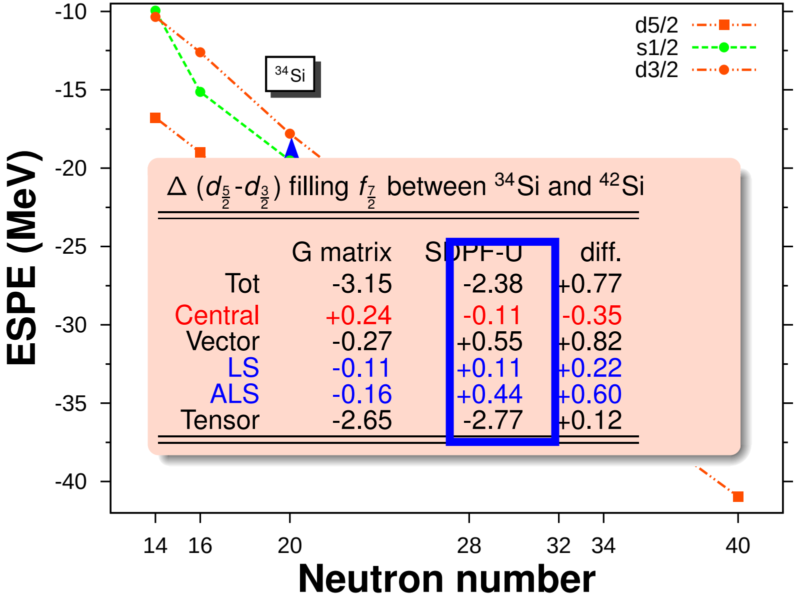

$\Delta\ (d_{\frac{5}{2}}\text{-}d_{\frac{3}{2}})$ filling $f_{\frac{7}{2}}$ between ^{34}Si and ^{42}Si

	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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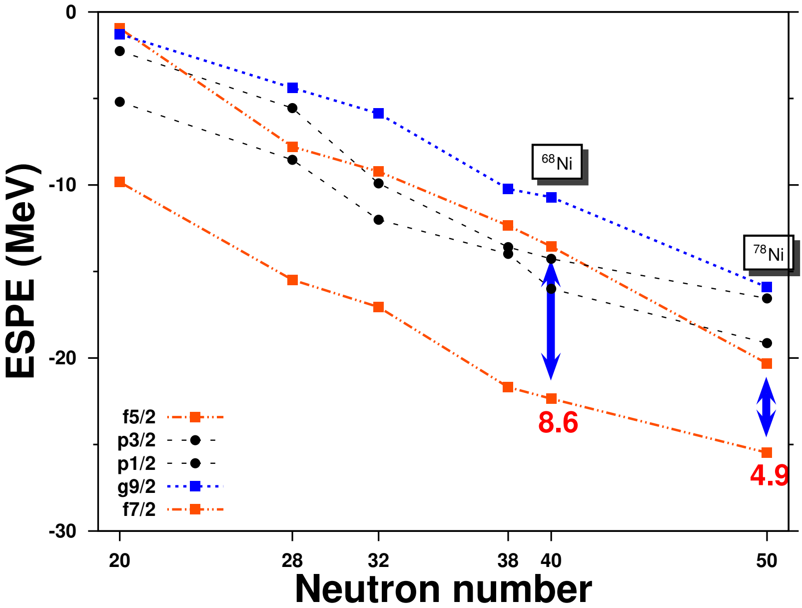

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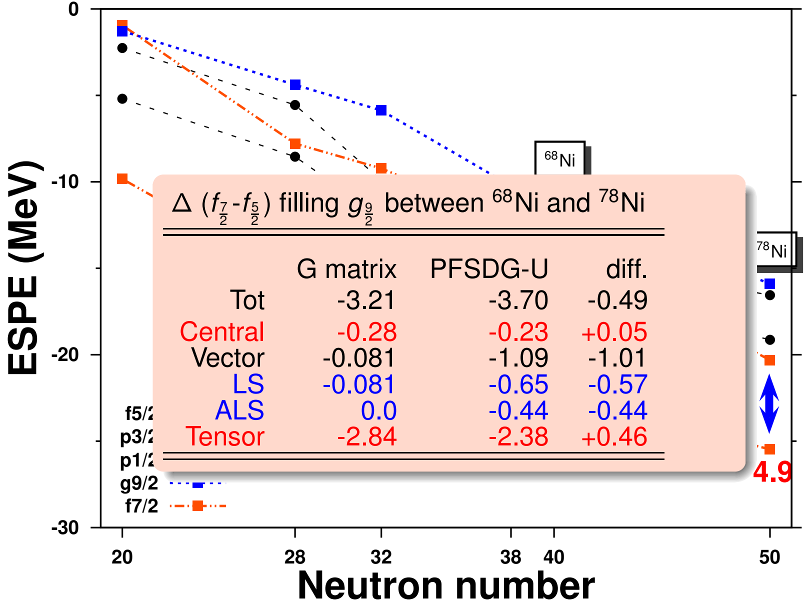
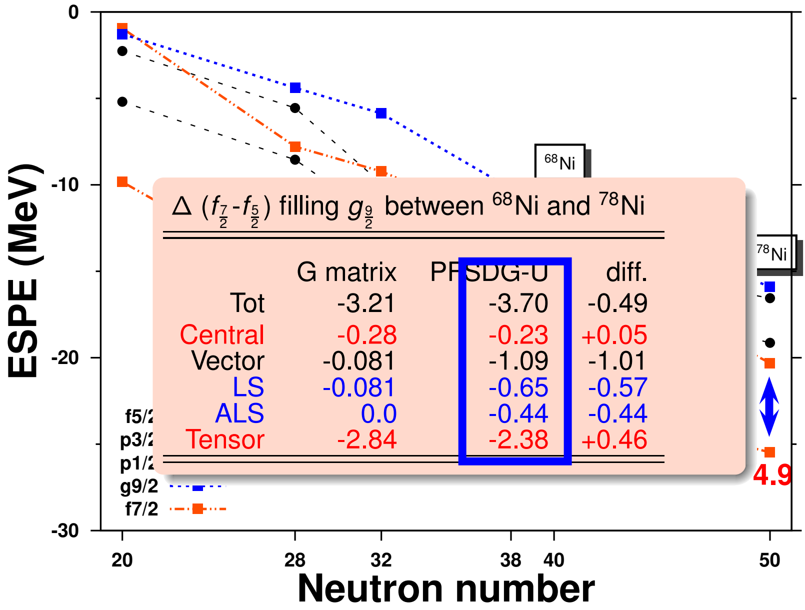


$\Delta\ (f_{\frac{7}{2}} - f_{\frac{5}{2}})$ filling $g_{\frac{9}{2}}$ between ^{68}Ni and ^{78}Ni

	G matrix	PFSDG-U	diff.
Tot	-3.21	-3.70	-0.49
Central	-0.28	-0.23	+0.05
Vector	-0.081	-1.09	-1.01
LS	-0.081	-0.65	-0.57
ALS	0.0	-0.44	-0.44
Tensor	-2.84	-2.38	+0.46

Effective Single Particle Energies: Trends



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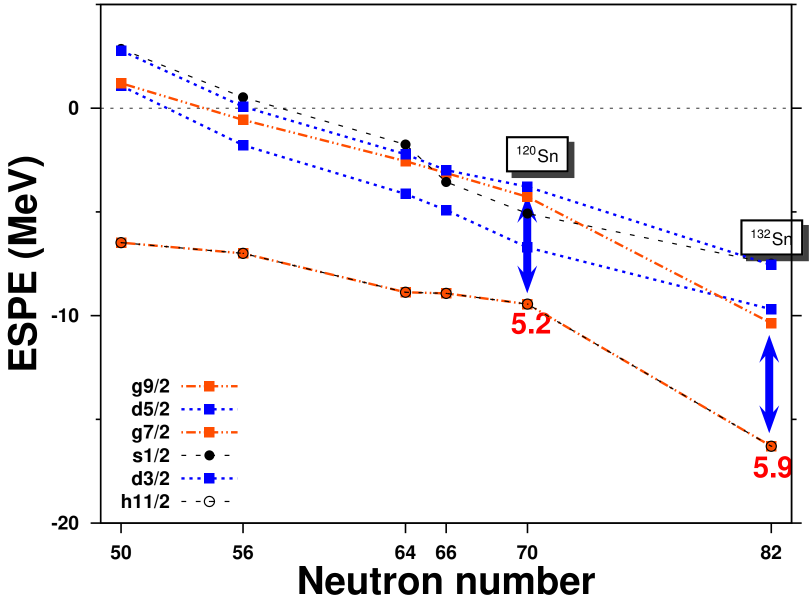

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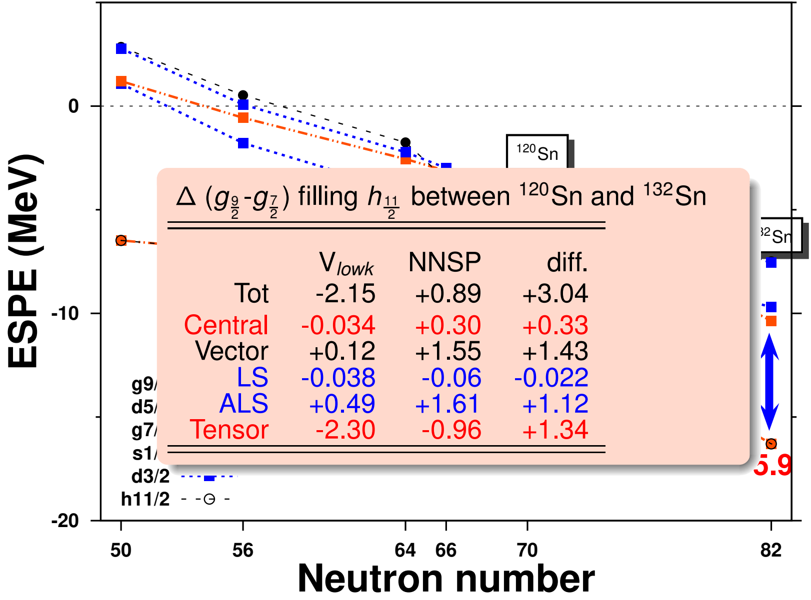
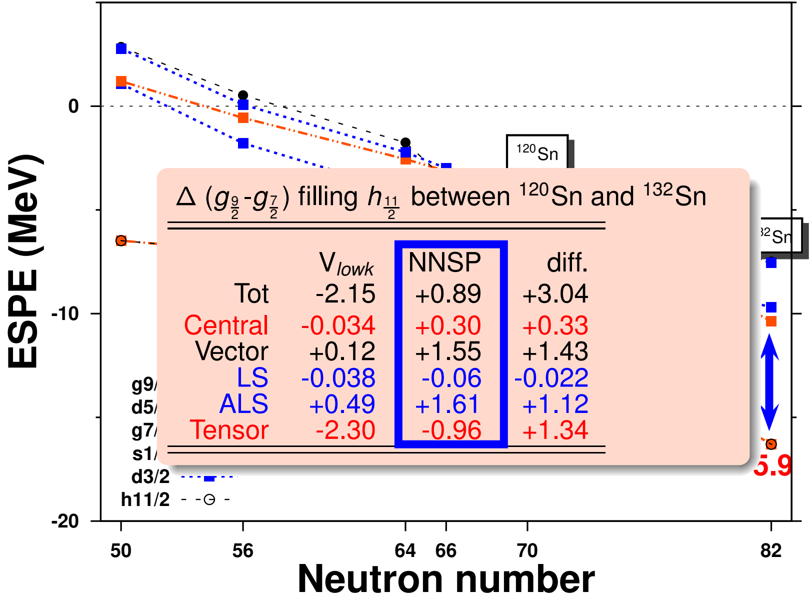


$\Delta\ (g_{\frac{9}{2}}\text{-}g_{\frac{7}{2}})$ filling $h_{\frac{11}{2}}$ between ^{120}Sn and ^{132}Sn

	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

- 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.
- 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.
- Increasing role of spin-orbite force in intermediate mass region

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