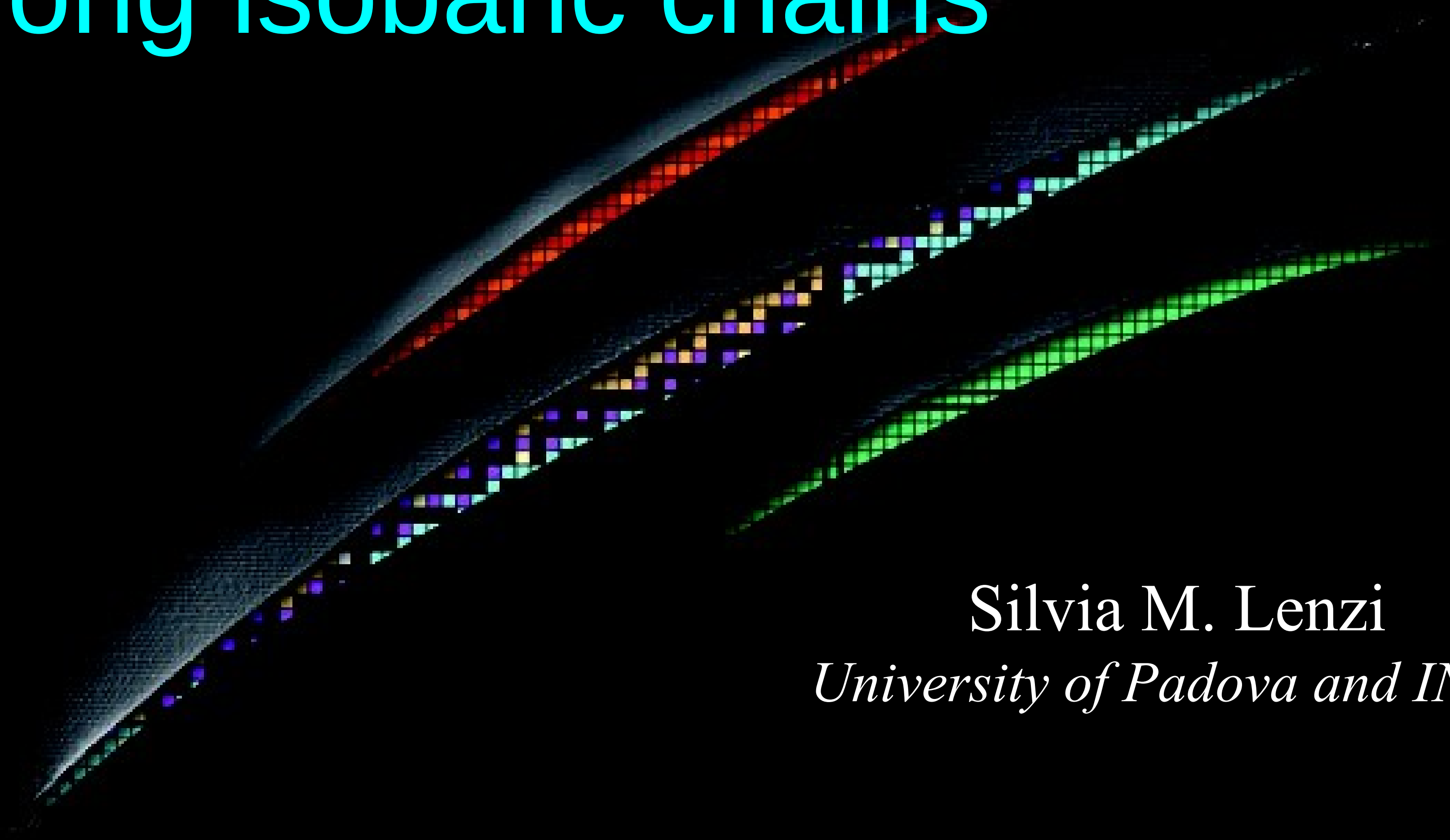
Shell evolution along isobaric chains

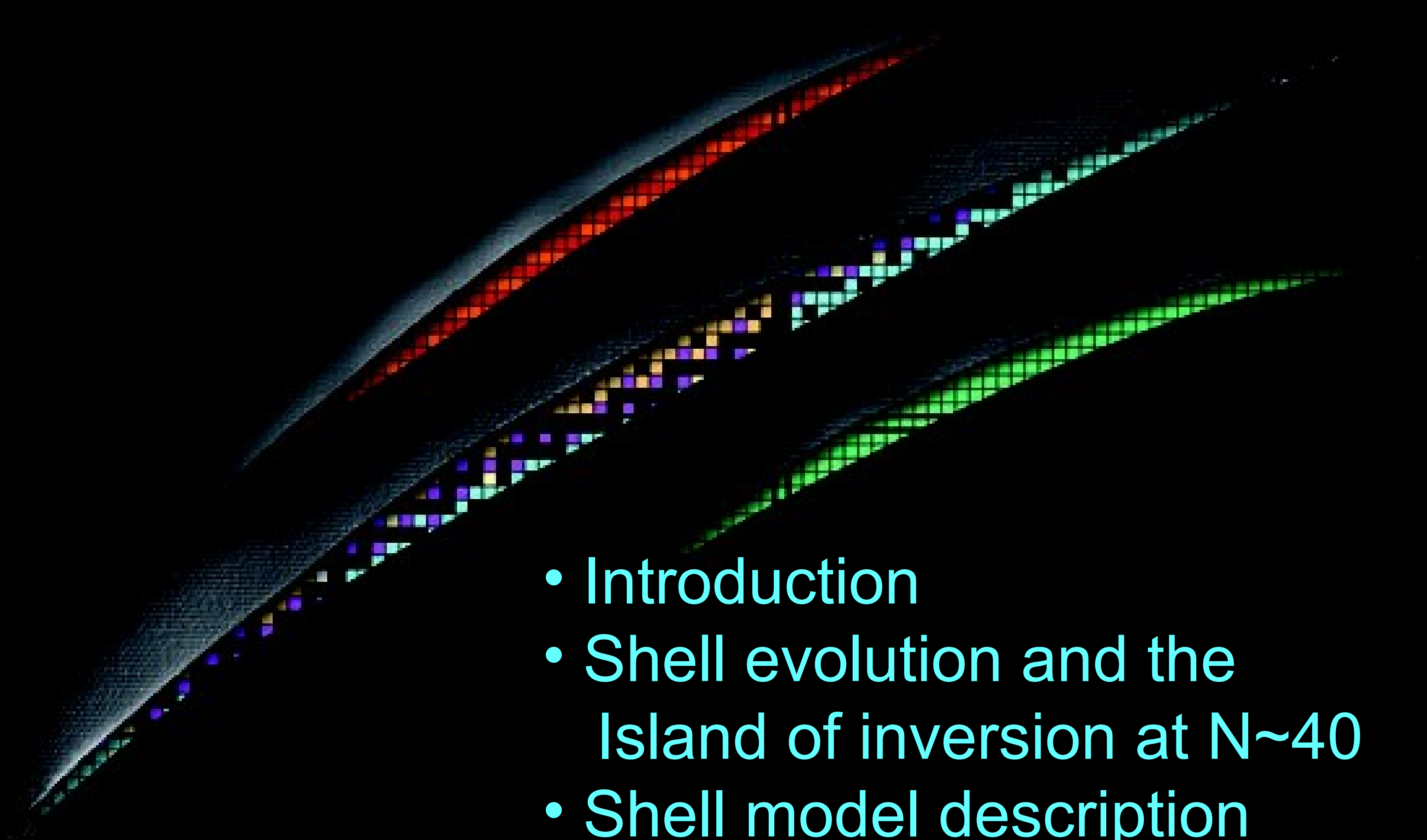


Silvia M. Lenzi

University of Padova and INFN

SPES Workshop – Firenze, September 27-28, 2012

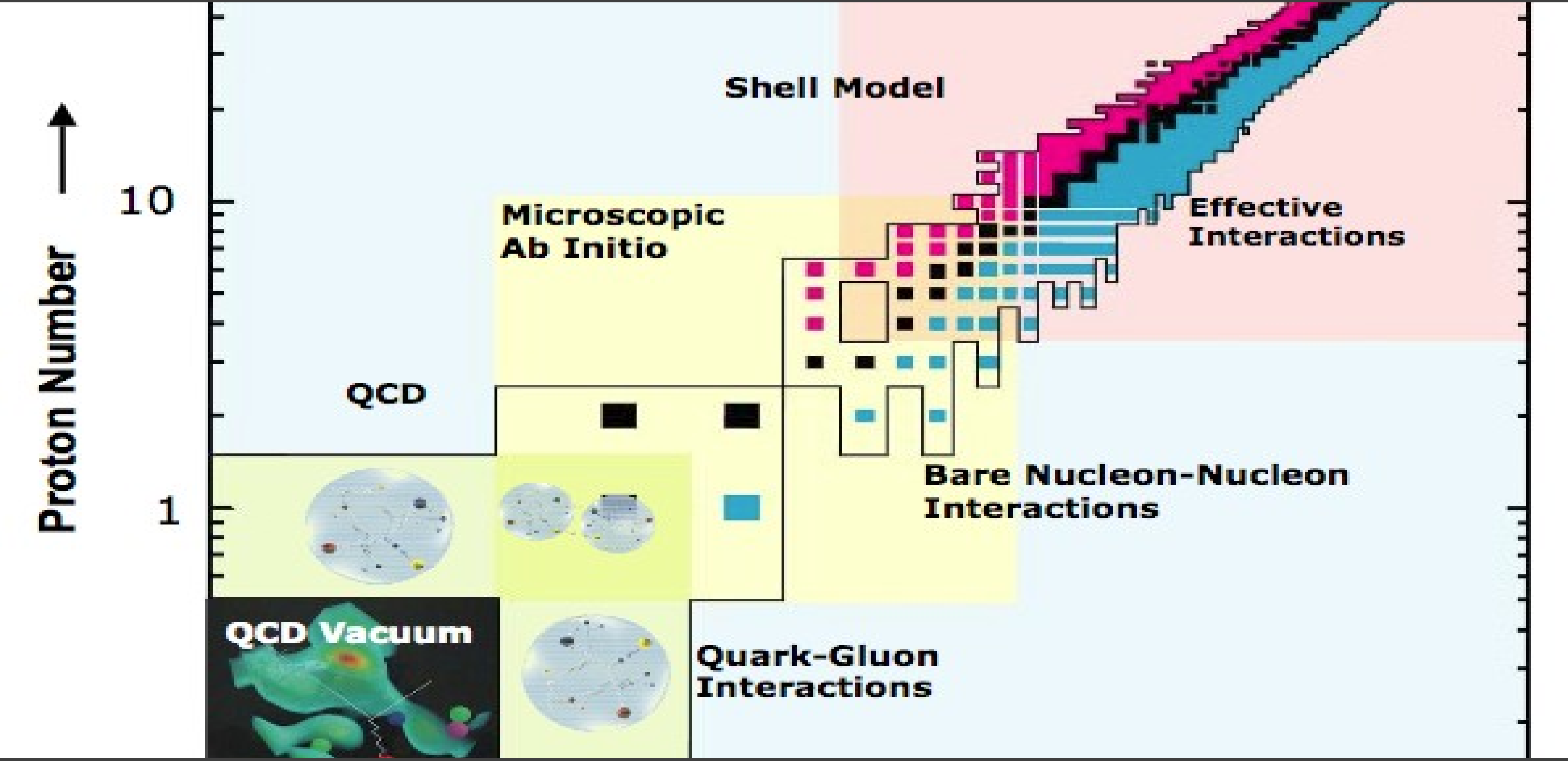
Outline



- Introduction
- Shell evolution and the Island of inversion at N~40
- Shell model description
- The N=50 region
- Proposals with SPES

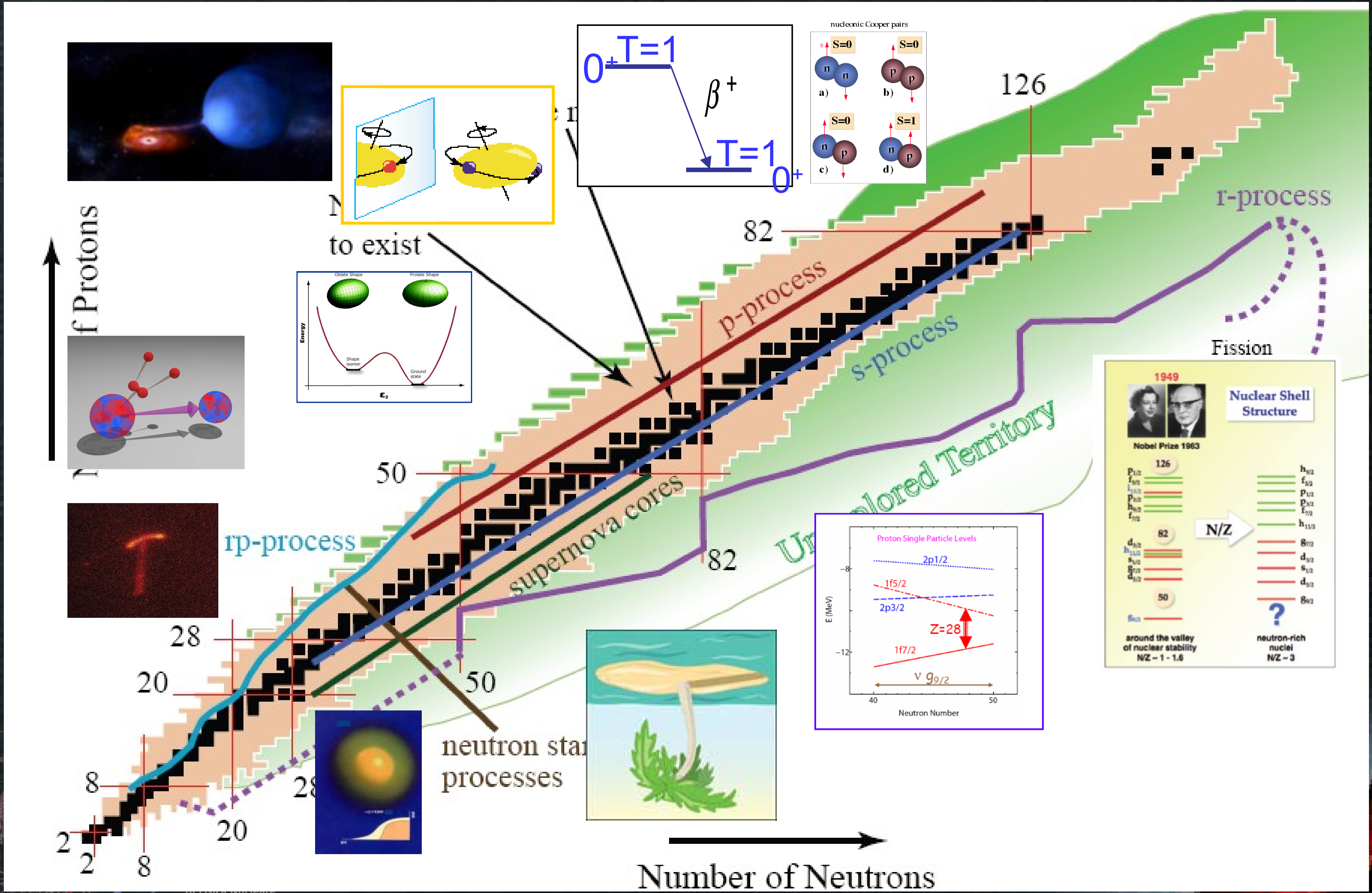
Nuclear forces and shell evolution

Atomic nuclei are characterized by a specific shell structure
How do the magic numbers depend on isospin?



Data on exotic nuclei put in evidence the role of specific terms of the nuclear interaction and demand an improved modelling

New phenomena far from stability



The neutron-rich side

- How does the shell structure change far from stability?
- How do new regions of deformation develop at “magic” numbers?
- How does the effective interaction describe shape evolution and shape coexistence?
- Will new excitation/decay modes be observed far from stability?
- New dynamical symmetries or new shapes?
- Connection with Astrophysics

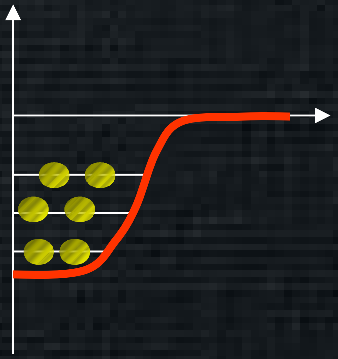
Istituto Nazionale di Fisica Nucleare

The effective interaction

A multipole expansion

$$V = V_m + V_M$$

monopole Multipole



V_m

- represents a spherical mean field extracted from the interacting shell model
- determines the single particle energies or ESPE

V_M

- correlations
- energy gains

Interplay: Monopole and Multipole

The interplay of the monopole with multipole terms, like pairing and quadrupole, determines the different phenomena we observe.

In particular, far from stability new magic numbers appear and new regions of deformation develop giving rise to new phenomena such as islands of inversion, shape phase transitions, shape coexistence, haloes, etc.

Understanding monopole effects

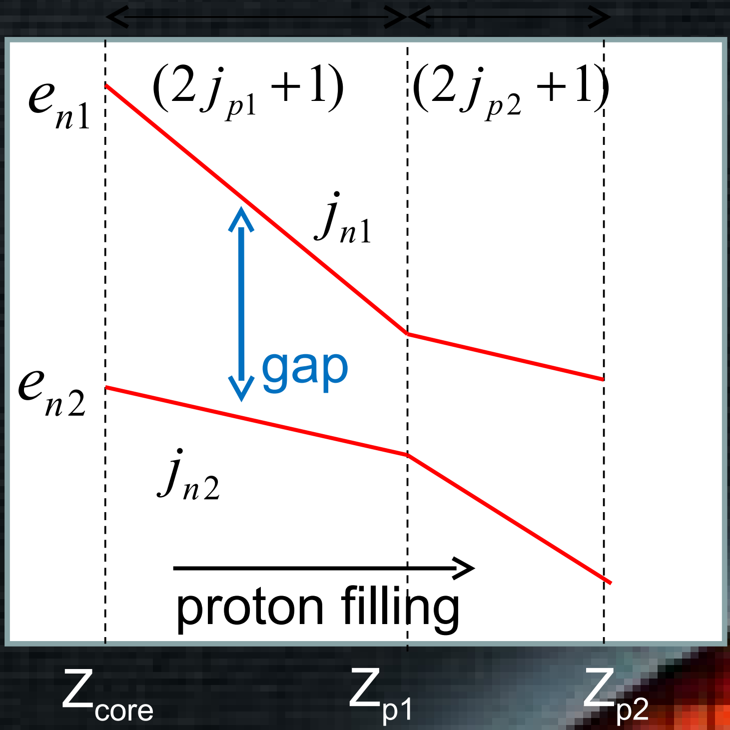
The monopole matrix element of an operator *V* can be written as

$$V^{T}_{jj'} = \frac{\sum_J (2J+1)\langle jj'|V|jj'\rangle_{JT}}{\sum_J (2J+1)}$$

→ **Averaged over possible orientations**

As the orbit *j'* is occupied, the single-particle energy of an orbit *j*, e_j changes linearly:

$$\Delta e_j = V_{jj'} n_{j'}$$



T. Otsuka et al.,
PRL 104, 012501 (2010)

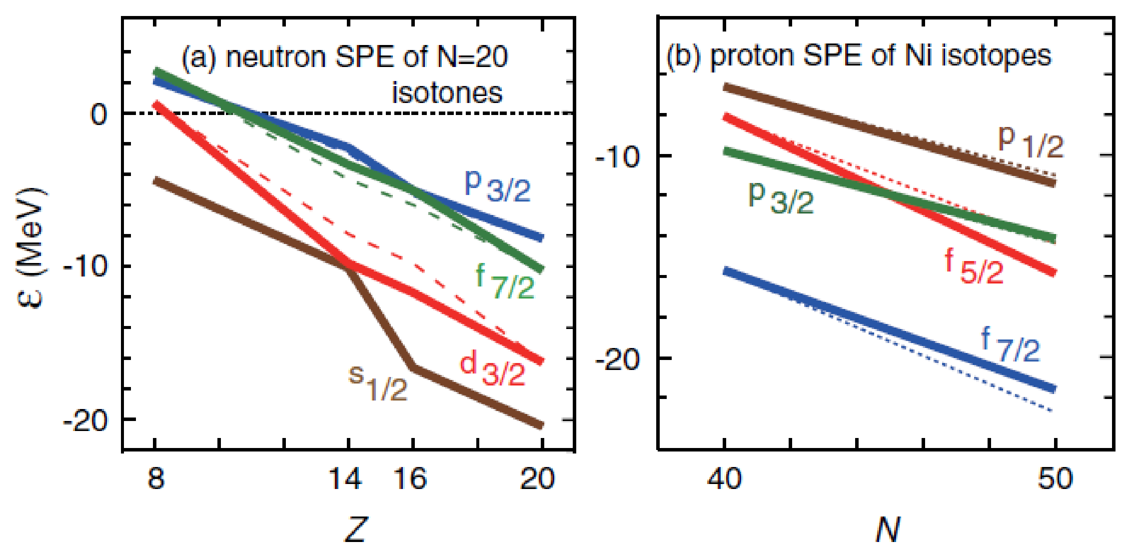
O. Sorlin and M.G. Porquet
PPNP 61 (2008) 602-673

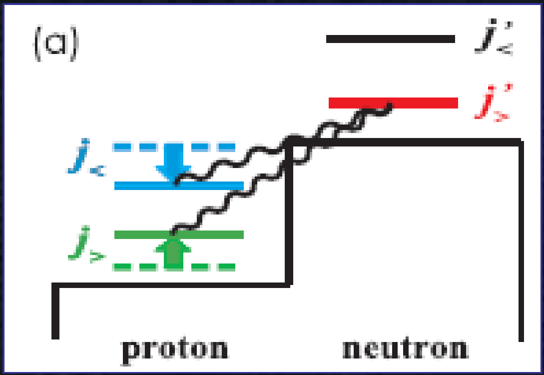
The monopole tensor force and the spe

Central part: global variation of the single-particle energies
Tensor part: characteristic behavior of spin–orbit partners, etc.

······ only central
—— central + tensor

$$j_> = l + \frac{1}{2}$$
$$j_< = l - \frac{1}{2}$$

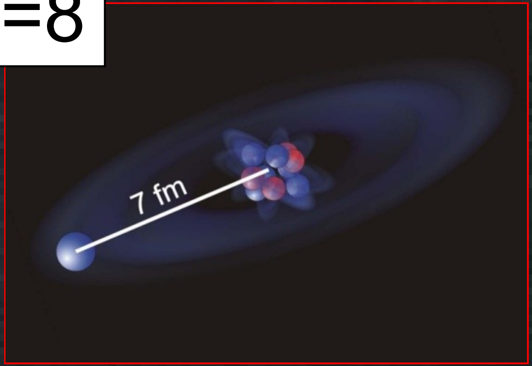




T. Otsuka et al., PRL 104, 012501 (2010)
N. A. Smirnova et al., PLB 686, 109 (2010)

The islands of inversion (N=8,20,28)

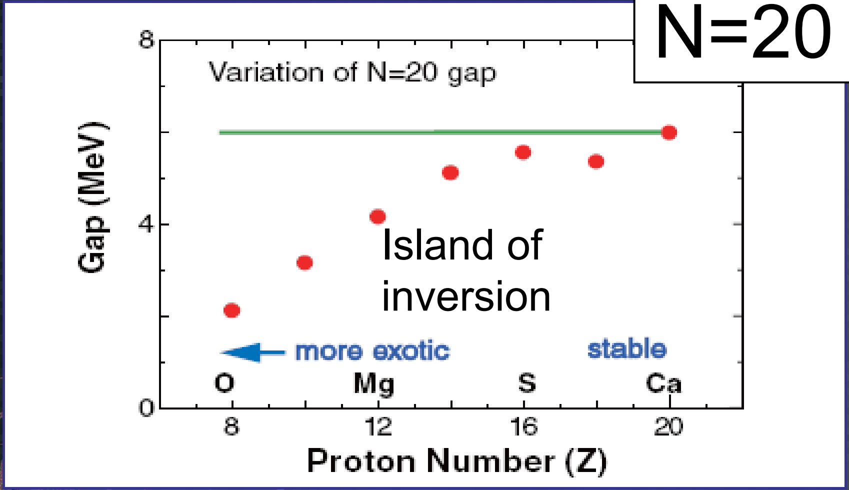
N=8



At N=8 and N=20 the h.o. shell gap vanishes for very neutron rich nuclei.

Deformed intruder configurations fall below the spherical ones

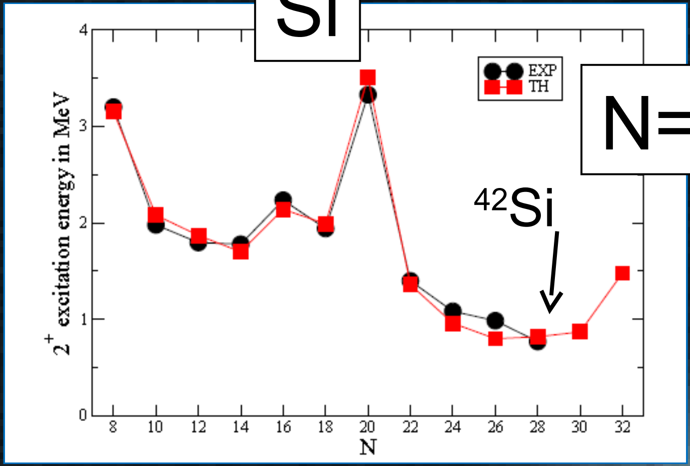
N=20



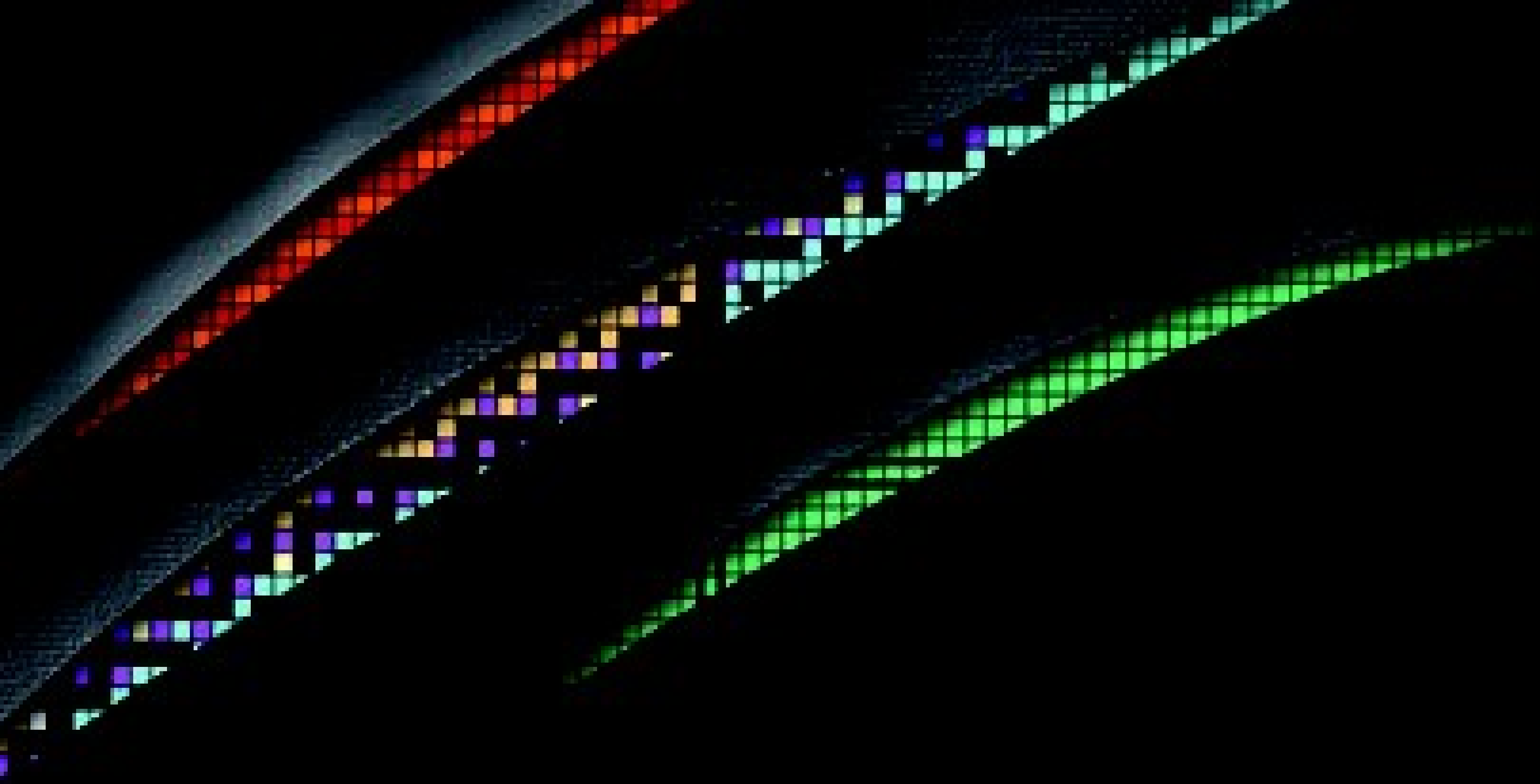
T. Otsuka EPJ S. Top. 156, 169 (2008)

Si

N=28



A. Poves, 2011

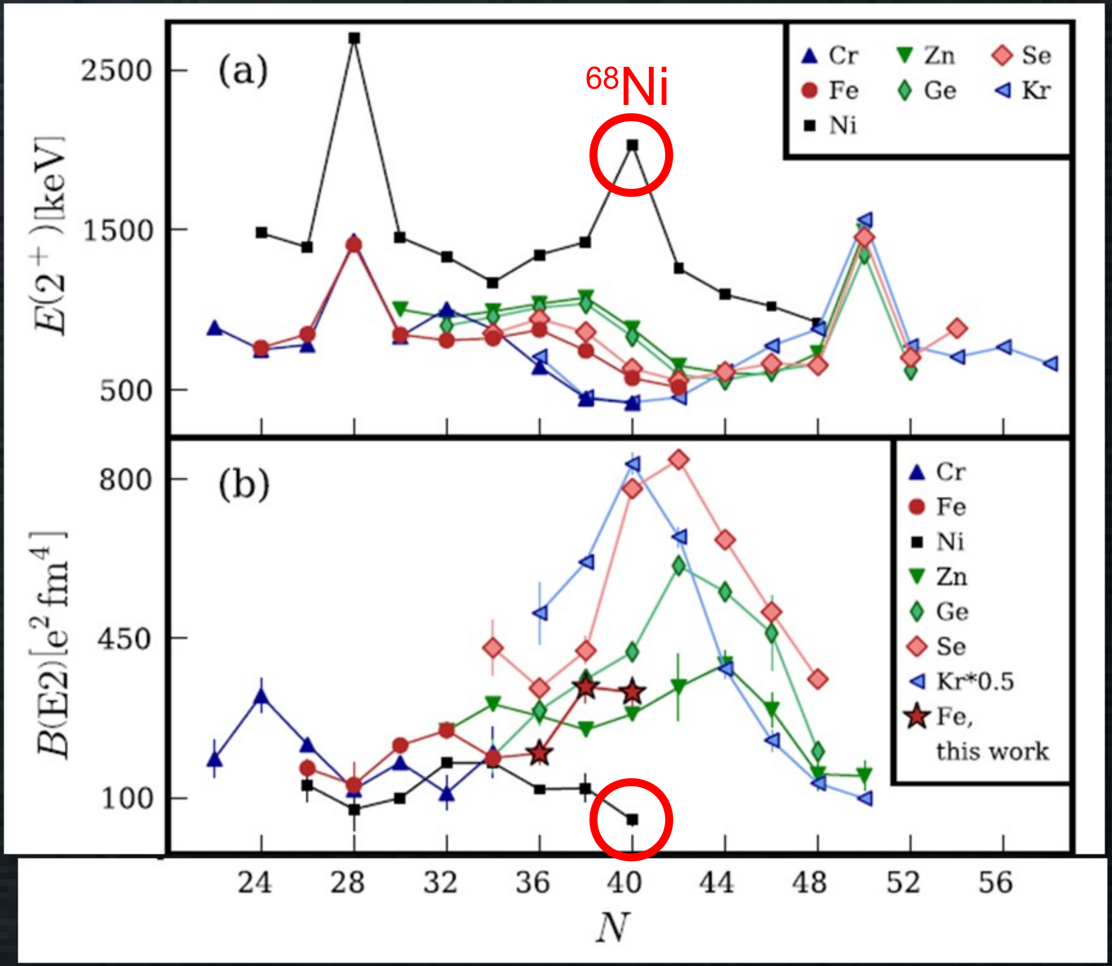


The island of inversion at N~40

Island of Inversion in N=40

E(2⁺)

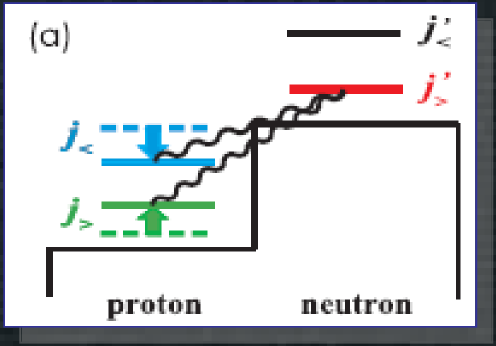
B(E2)

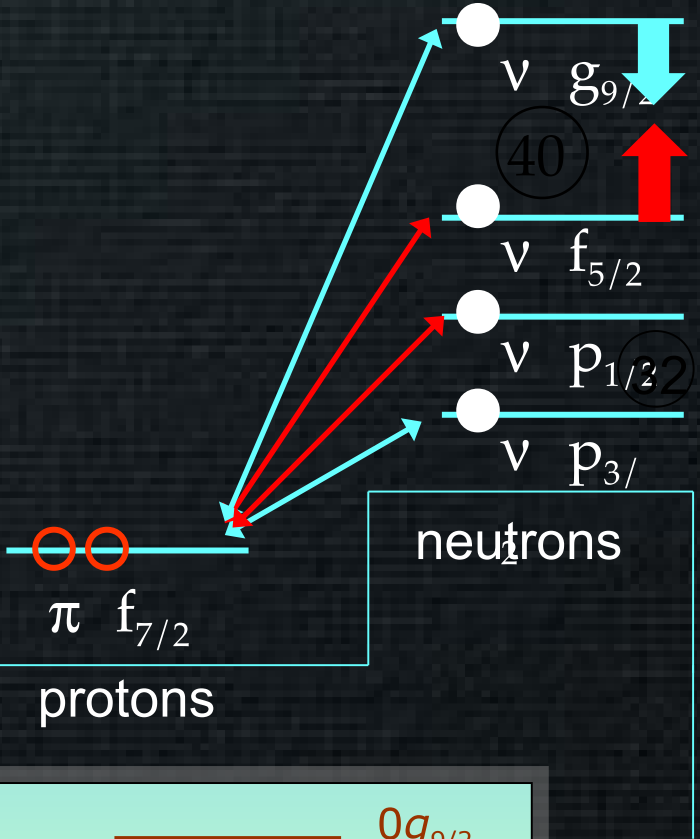


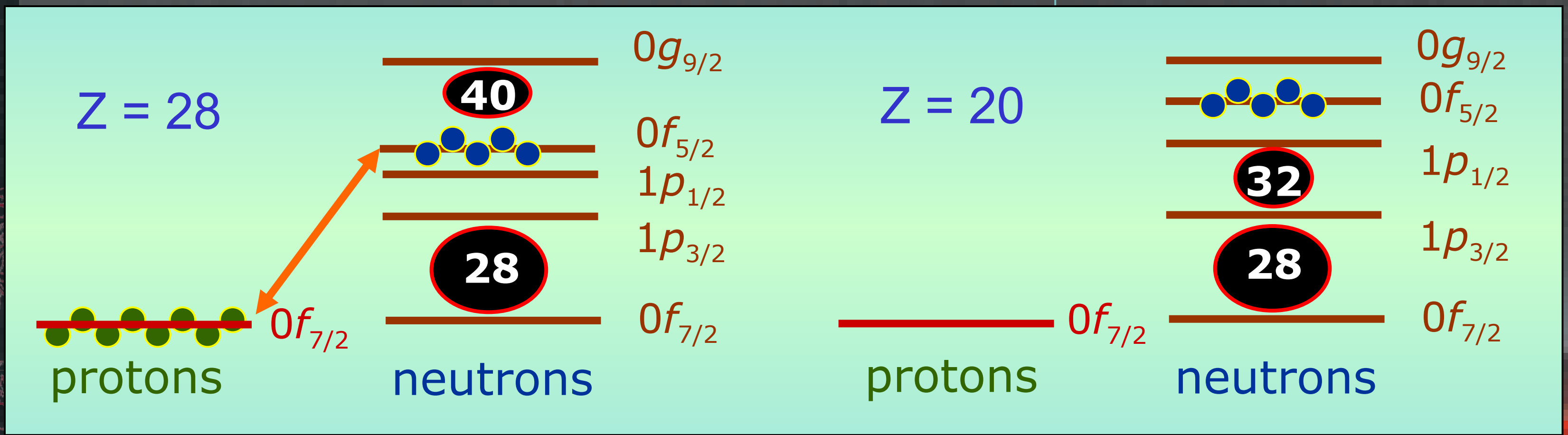
W. Rother et al., PRL 106, 022502 (2011)

Neutron excess and shell migration

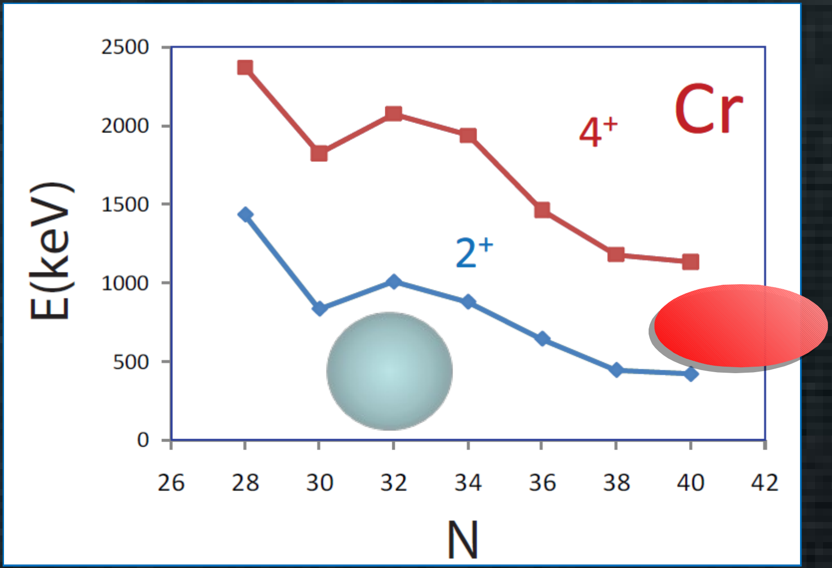
Monopole shifts

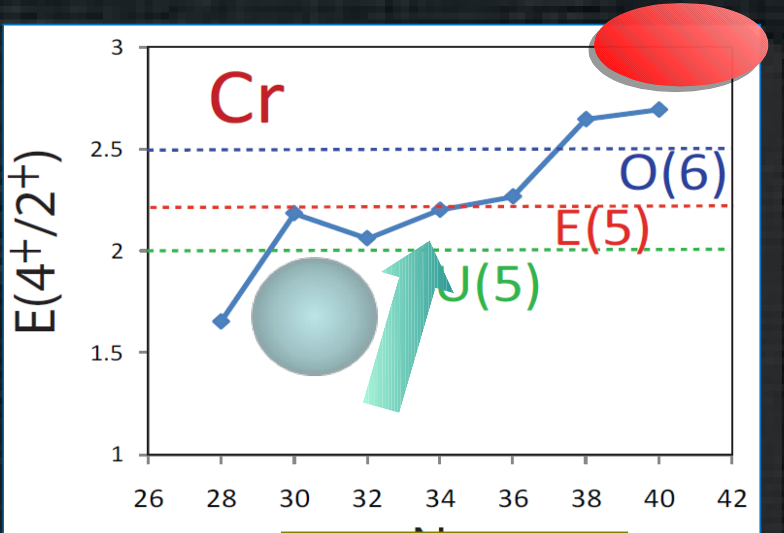




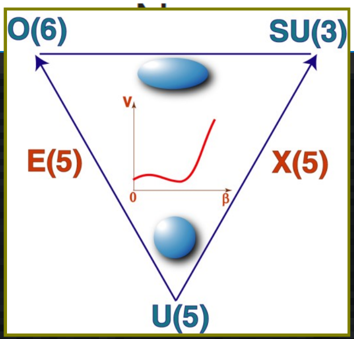


Cr isotopic chain





^{58}Cr



at the shape phase
transition critical point?

Marginean et al.
Phys. Lett. B 633 (2006) 696.

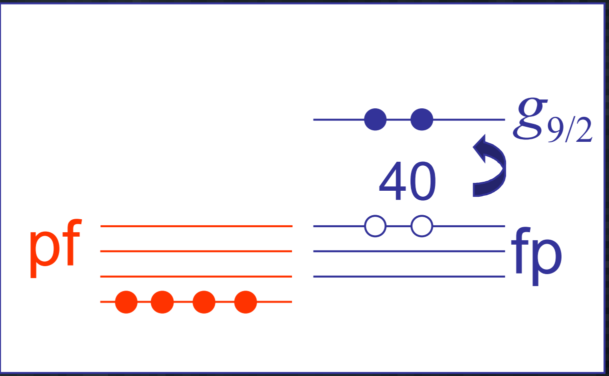
Recent plunger experiment at MSU to measure the lifetimes and test the E(5).

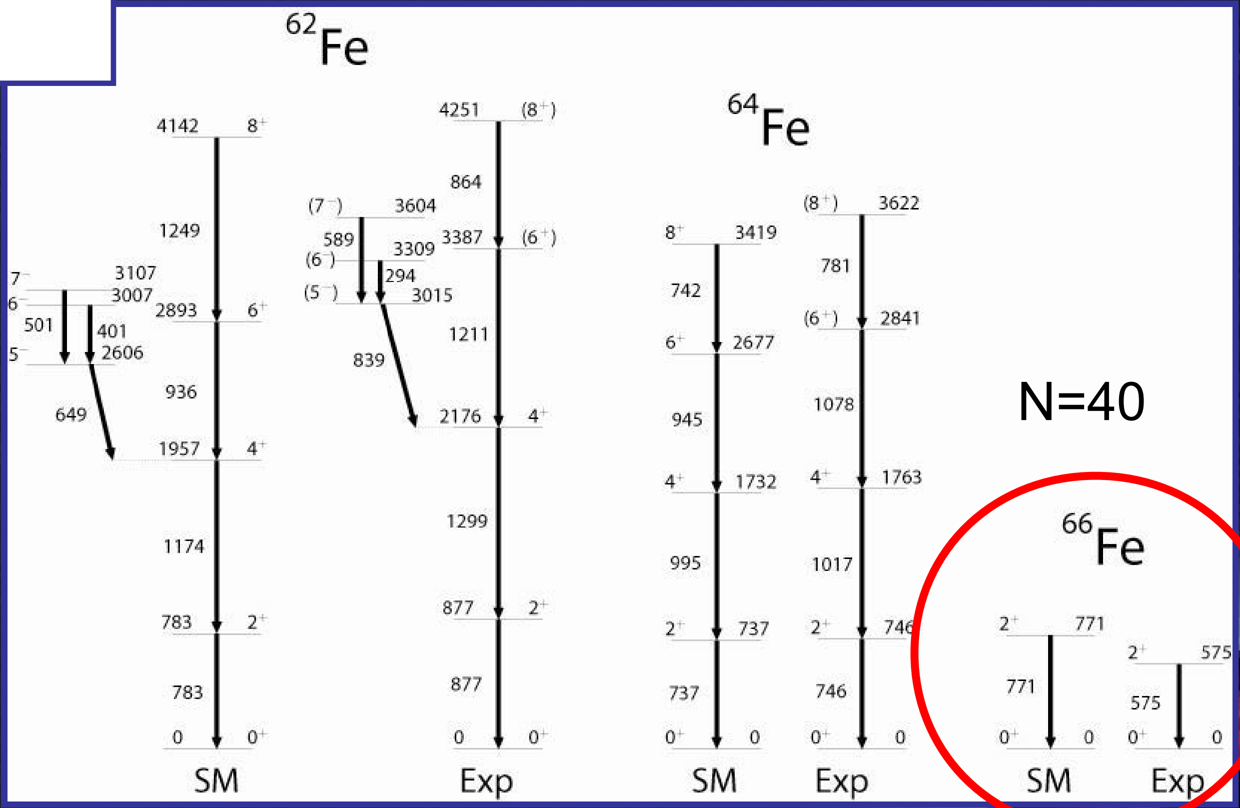
Fe isotopes and the shell model

Approaching N=40, Fe and Cr isotopes become deformed

Shell model calculations
Core ^{48}Ca
valence space: full *fp* for protons
$p_{3/2}, f_{5/2}, p_{1/2}, g_{9/2}$ for neutrons

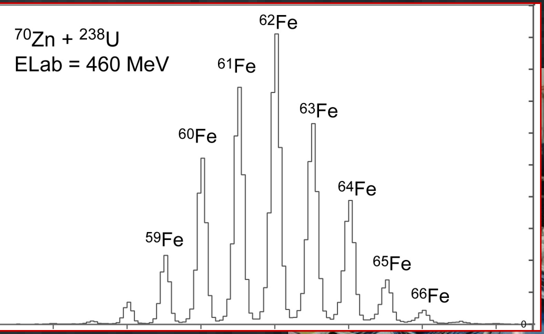
The inclusion of the $g_{9/2}$ orbital is not enough to allow a good theoretical description of ^{66}Fe



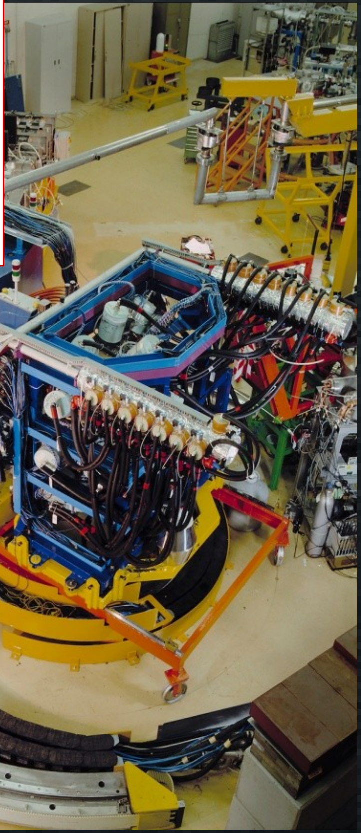


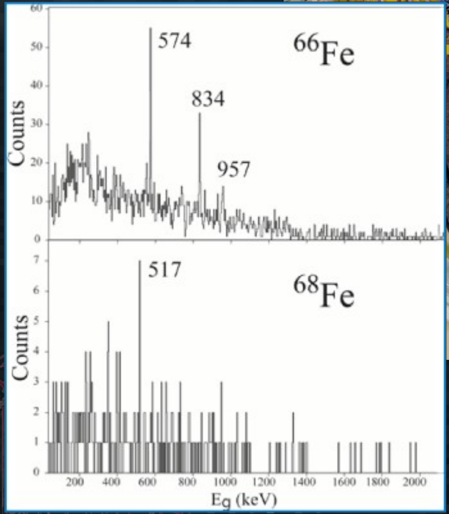
S. Lunardi *et al.*,
PRC **76**, 034303 (2007)

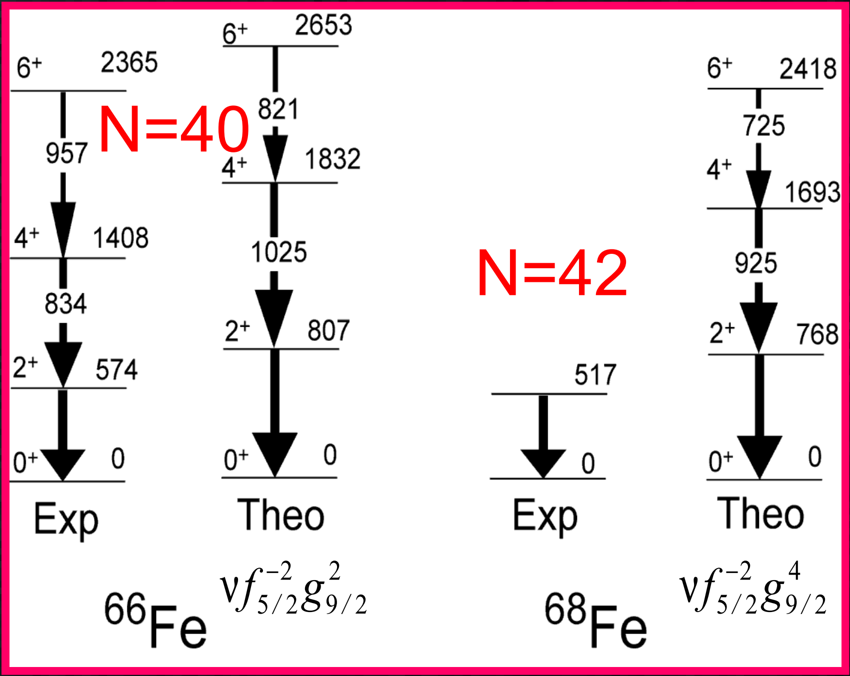
At and beyond N=40



Clara+Prisma



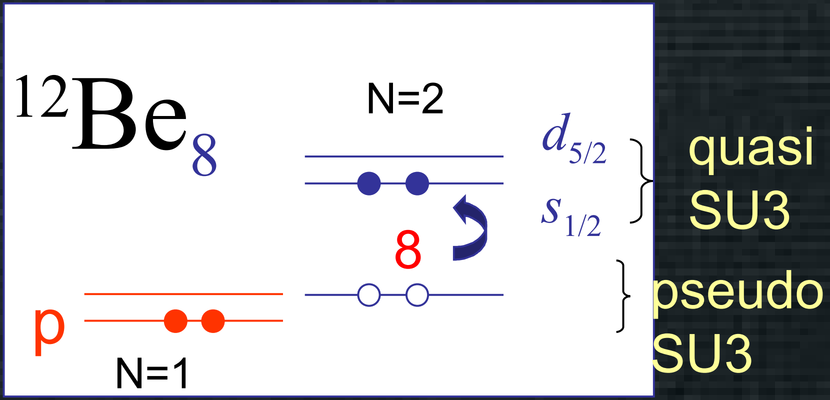




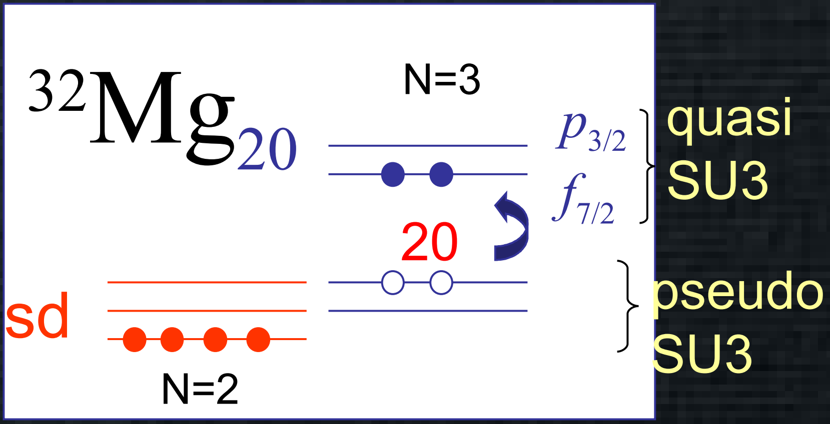
SML et al.,
LNL Ann. Rep. 2008

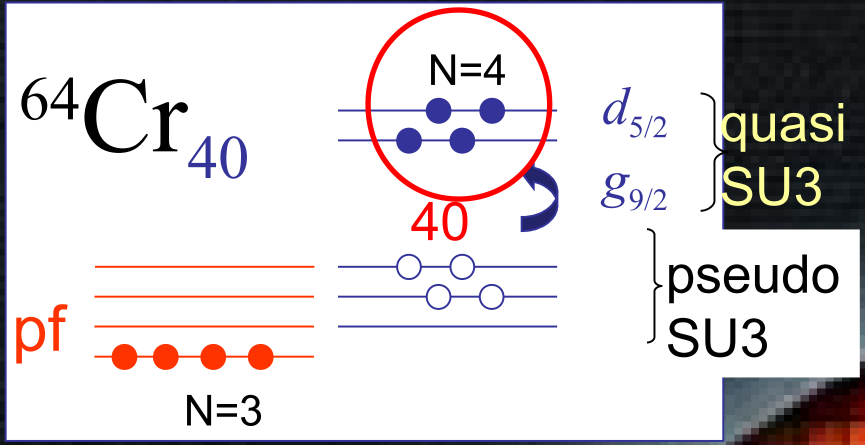
The fpg model space is not able to reproduce the increase of collectivity of Cr and Fe isotopes approaching N=40

Islands of inversion and symmetries



Islands of Inversion at the magic numbers can be understood in terms of symmetries.





A.P. Zuker et al., PRC 52 (1995)

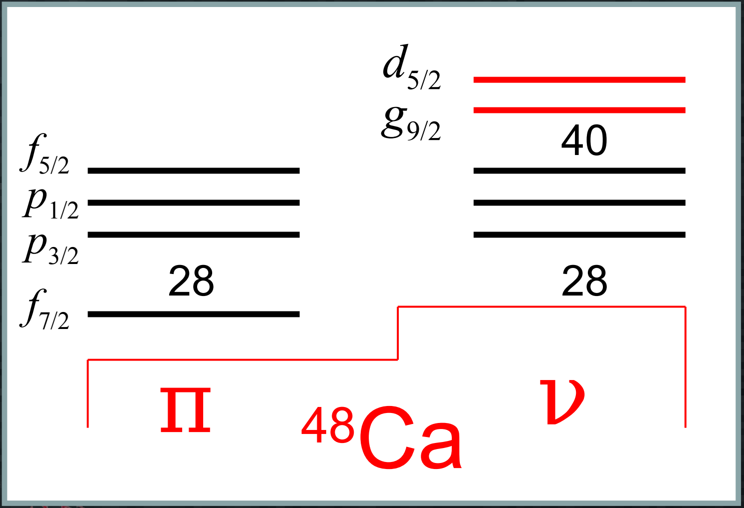
The new interaction in the fpgd space

LNPS interaction: renormalized realistic interaction
+ monopole corrections

^{48}Ca core

protons: full pf shell

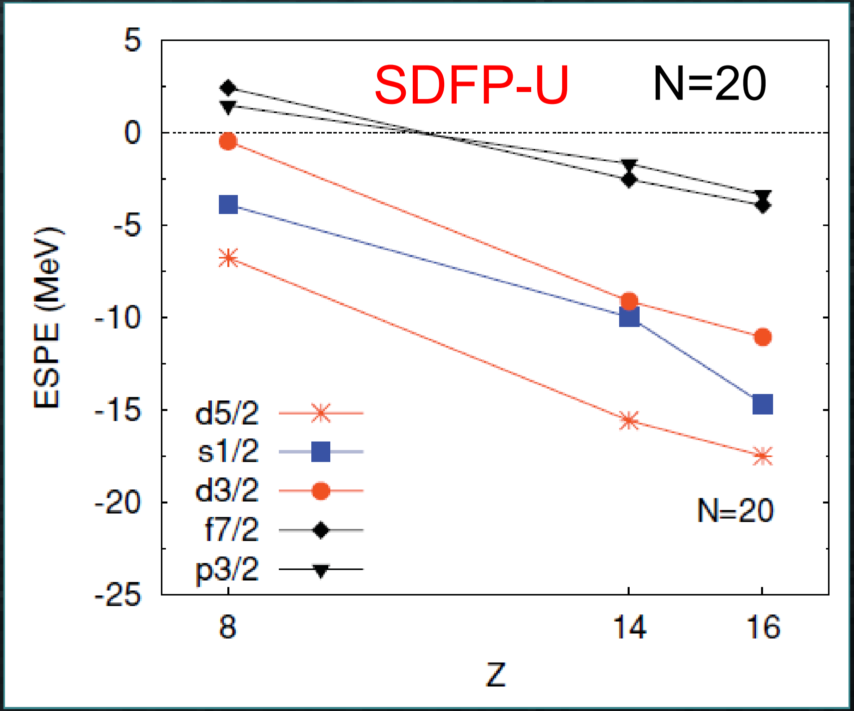
neutrons: $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, $d_{5/2}$

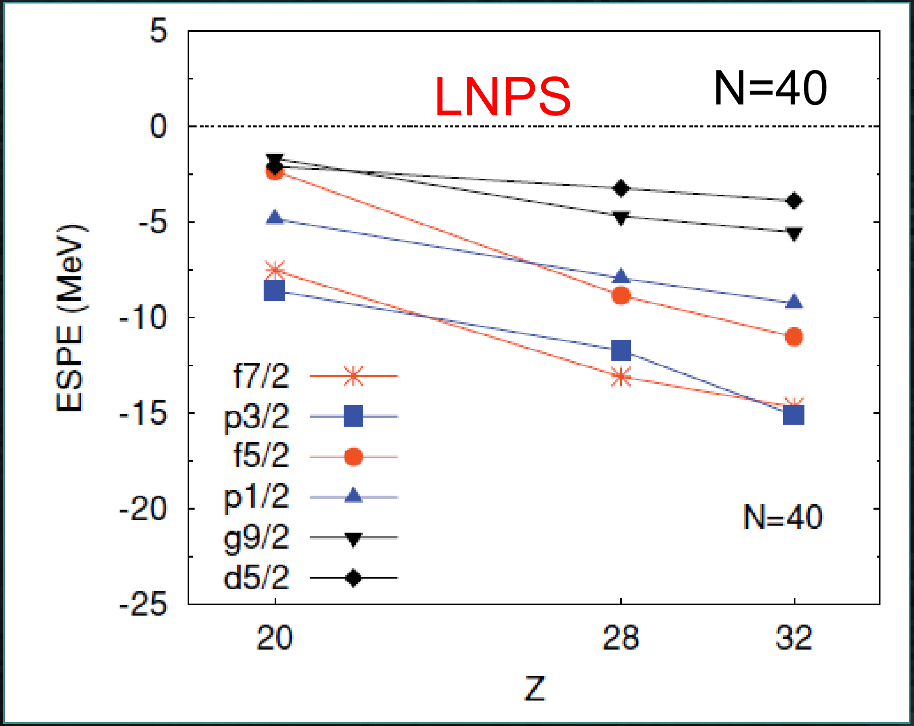


- KB3gr for the pf-shell
- renormalized G-matrix with monopole corrections for the remaining matrix elements involving the p3/2, p1/2, f5/2 and g9/2 neutron orbits
- the G-matrix based on the Kahana-Lee-Scott potential for the matrix elements involving the d5/2 orbit
- monopole corrections to reproduce the Z=28 and N=50 gaps in 78Ni based on data of neighboring nuclei

SML, F. Nowacki, A. Poves and K. Sieja (LNPS), PRC 82, 054301 (2010)

ESPE in N=20 and N=40



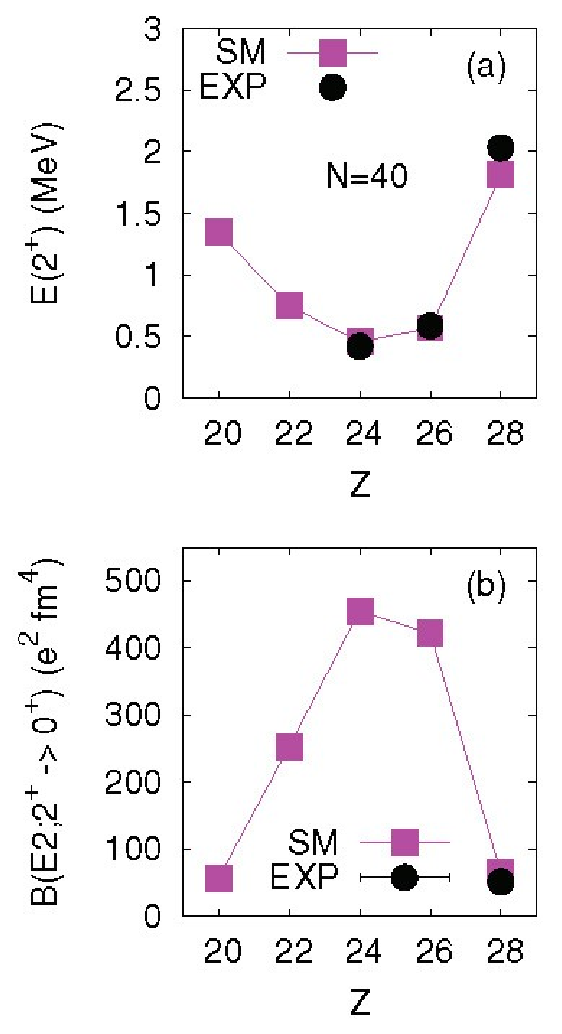


Note: the ground-state deformation properties result from the total balance between the monopole and the correlation energies

LNPS, PRC 82, 054301 (2010)

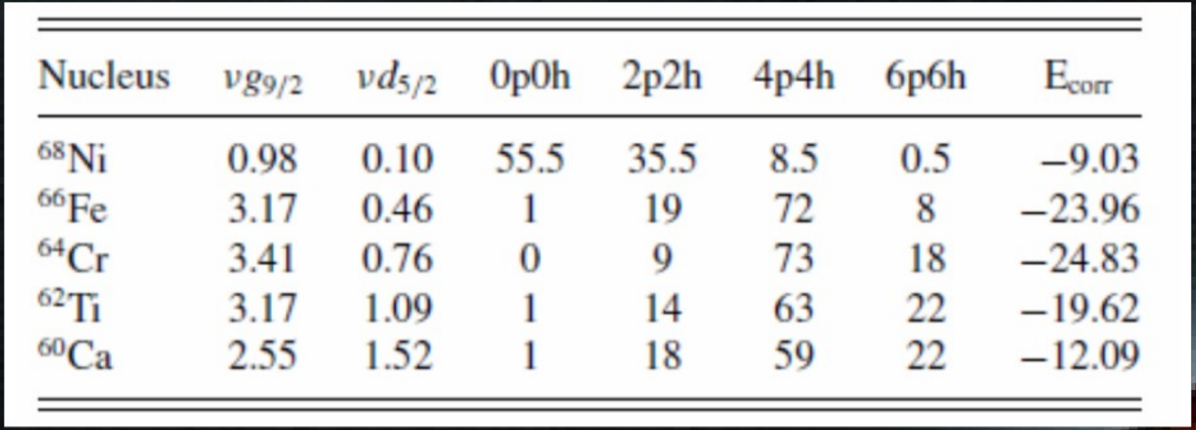
The N=40 isotones

E (2^+)



A change of structure is observed along the isotonic chain in good agreement with the available data

Occupation of intruder orbitals and percentage of p-h in g.s. configurations



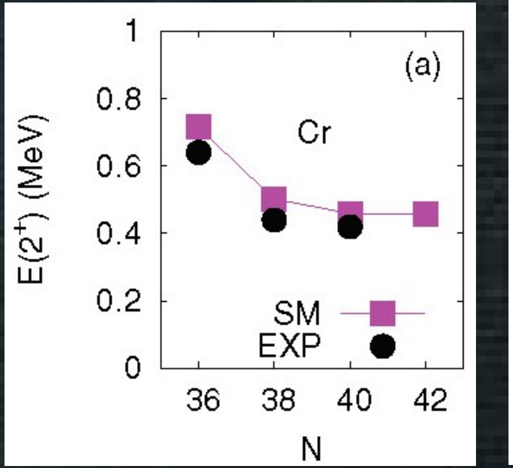
Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	0p0h	2p2h	4p4h	6p6h	E_{corr}
^{68}Ni	0.98	0.10	55.5	35.5	8.5	0.5	−9.03
^{66}Fe	3.17	0.46	1	19	72	8	−23.96
^{64}Cr	3.41	0.76	0	9	73	18	−24.83
^{62}Ti	3.17	1.09	1	14	63	22	−19.62
^{60}Ca	2.55	1.52	1	18	59	22	−12.09

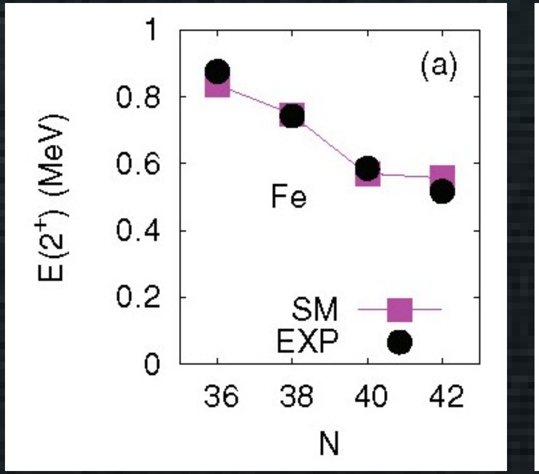
LNPS, PRC 82, 054301 (2010)

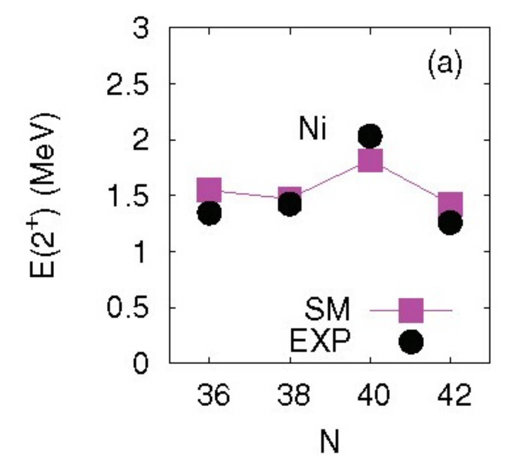
Cr, Fe and Ni isotopic chains

Cr Fe Ni

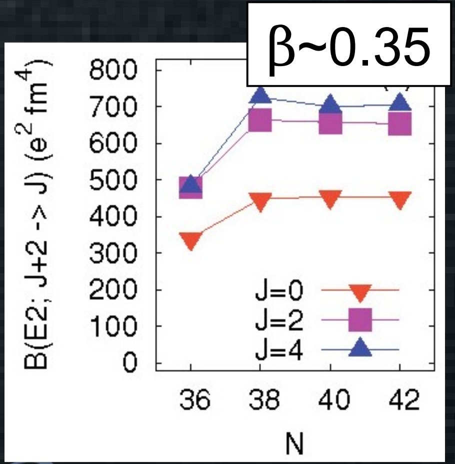
E (2^+)

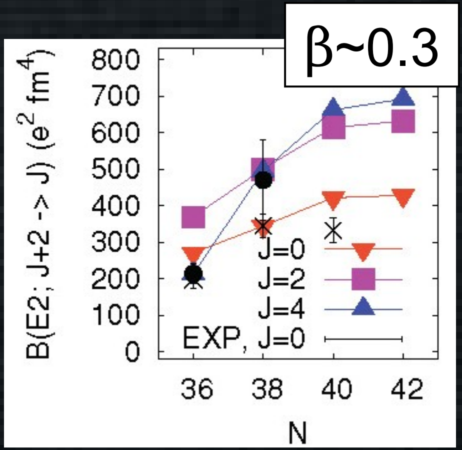


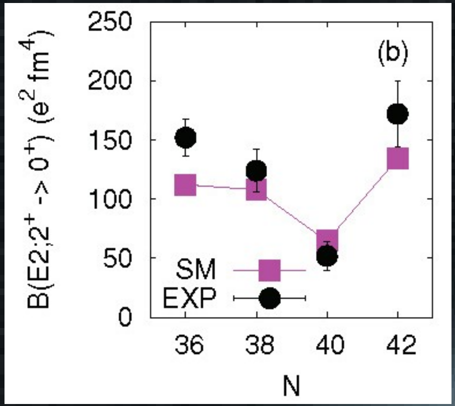




B(E2)


β~0.35

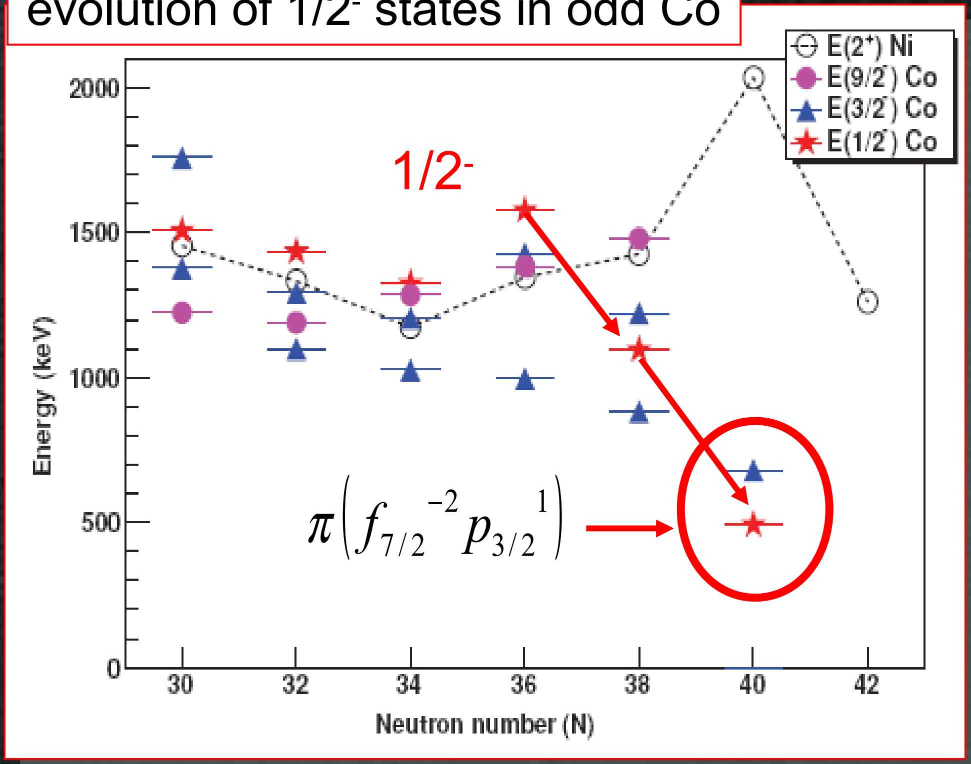

β~0.3

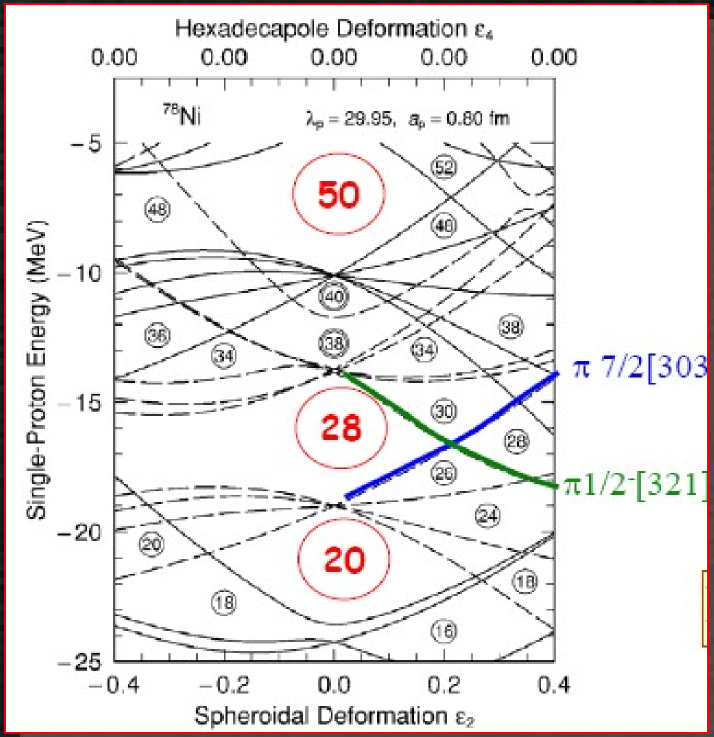


LNPS, PRC 82, 054301 (2010)

Proton intruder states and shape coexistence in ^{67}Co

evolution of $1/2^-$ states in odd Co



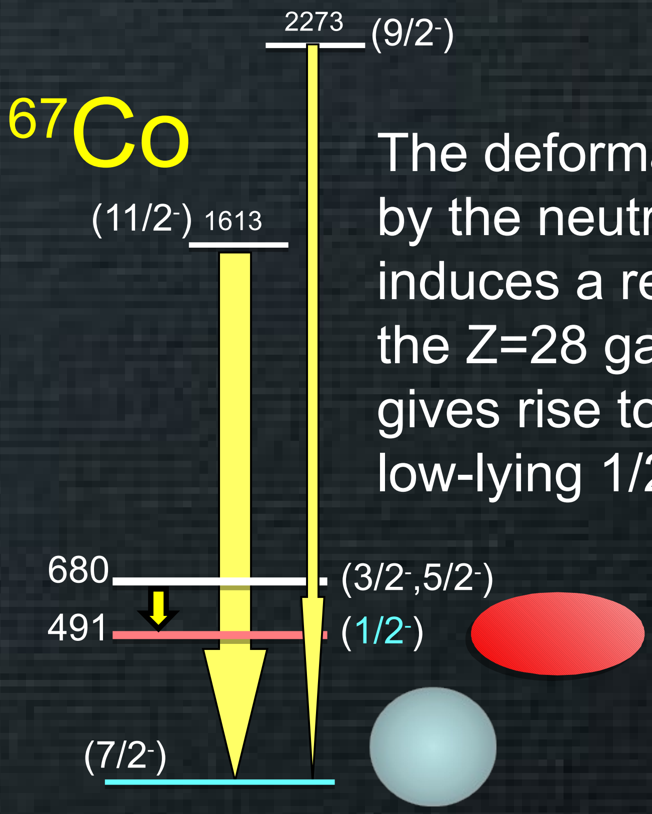


The $1/2^-$ state lowers due to deformation increase at Z<28 N=40

D. Pauwels et al., PRC 78, 041307 (2008)
and PRC 79, 044309 (2009)

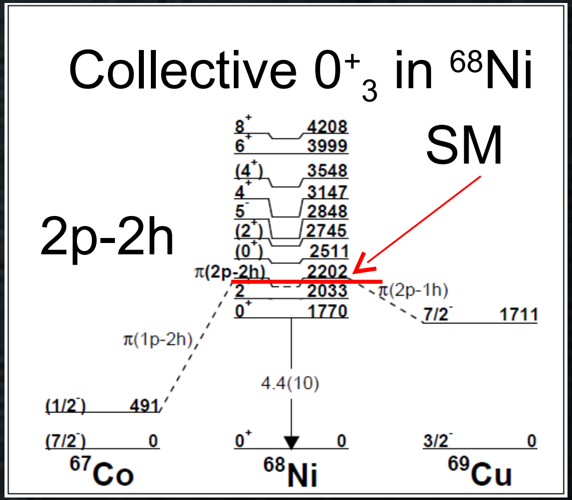
Courtesy D. Pauwels
and P. Van Duppen

Shape coexistence in ^{67}Co and ^{68}Ni



The deformation driven by the neutrons induces a reduction of the Z=28 gap and gives rise to a deformed low-lying 1/2- state

^{68}Ni



Prediction: D. Pauwels et al.,
Phys.Rev. C 82, 027304 (2010)
Data: A. Dijon et al., PRC 85, 031301 (2012)

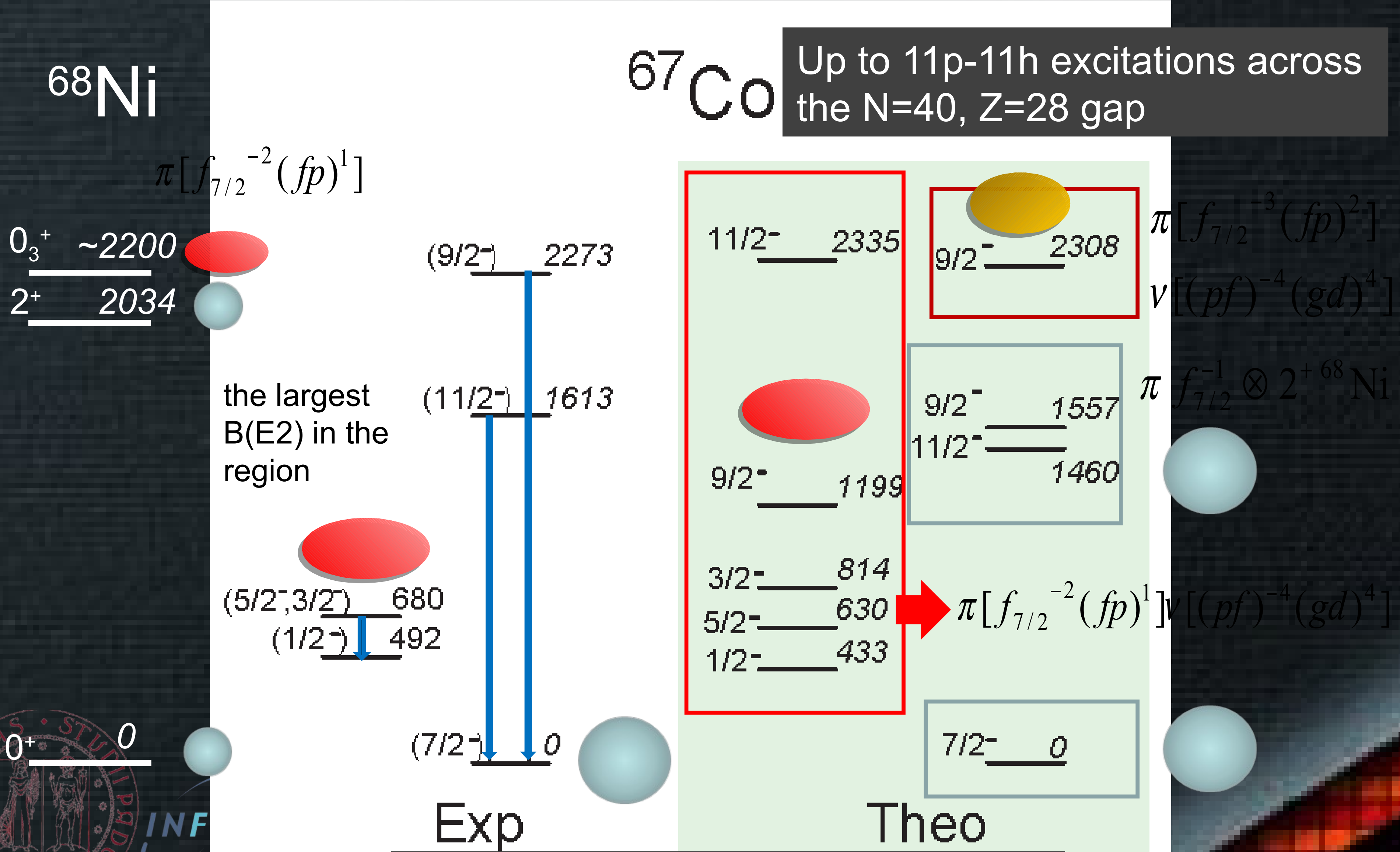
F. Recchia et al., PRC 85, 064305 (2012)

D. Pauwels et al., PRC 78, 041307 (2008)
and PRC 79, 044309 (2009)

The LNPS interaction is able to reproduce these structures

The 1/2$^-$ state gains a total of ~ 8 MeV of correlation energy and ~ 5 MeV relative to the ground state

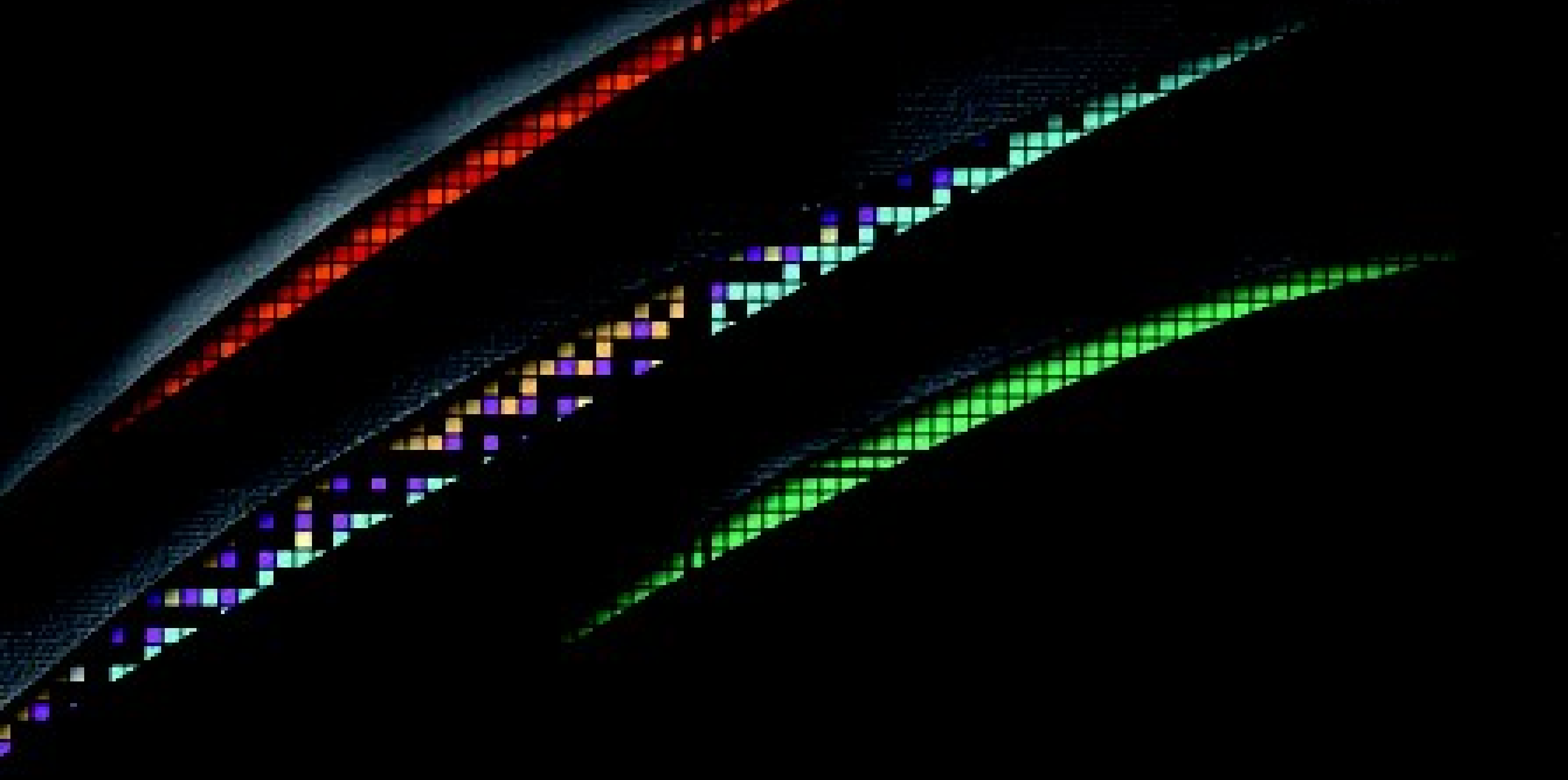
Shape coexistence in ^{67}Co



Up to 11p-11h excitations across the N=40, Z=28 gap

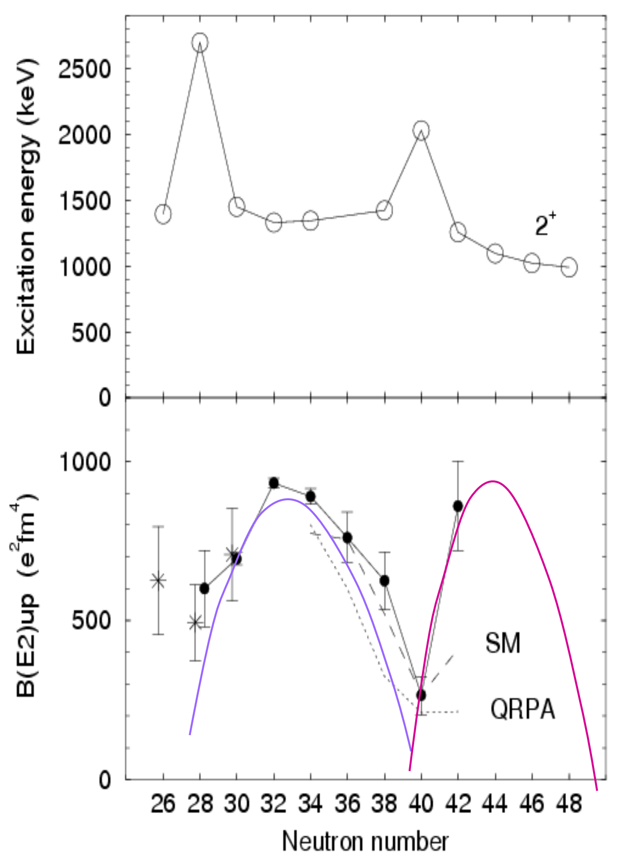
the largest B(E2) in the region

F. Recchia et al., PRC 85, 064305 (2012)



The N=50 shell gap

Evolution along the Ni isotopic chain



The rigidity of the gap in ^{78}Ni is an important issue in astrophysics because it is a waiting point in the r-process.

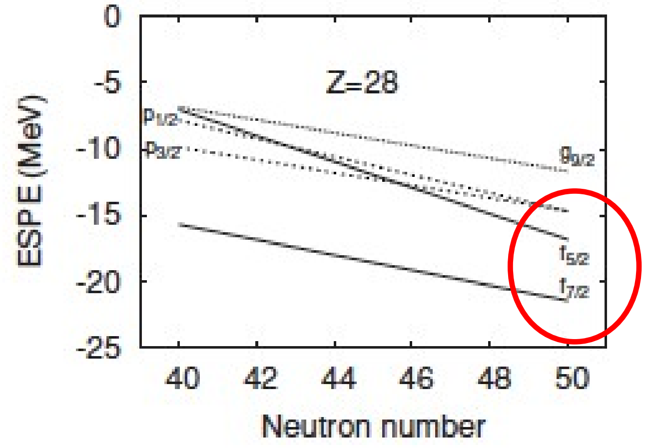


FIG. 1. Evolution of proton effective single-particle energies between ^{68}Ni and ^{78}Ni.

K. Sieja and Nowacki., PRC81, 061303 (2010)

fpg model space

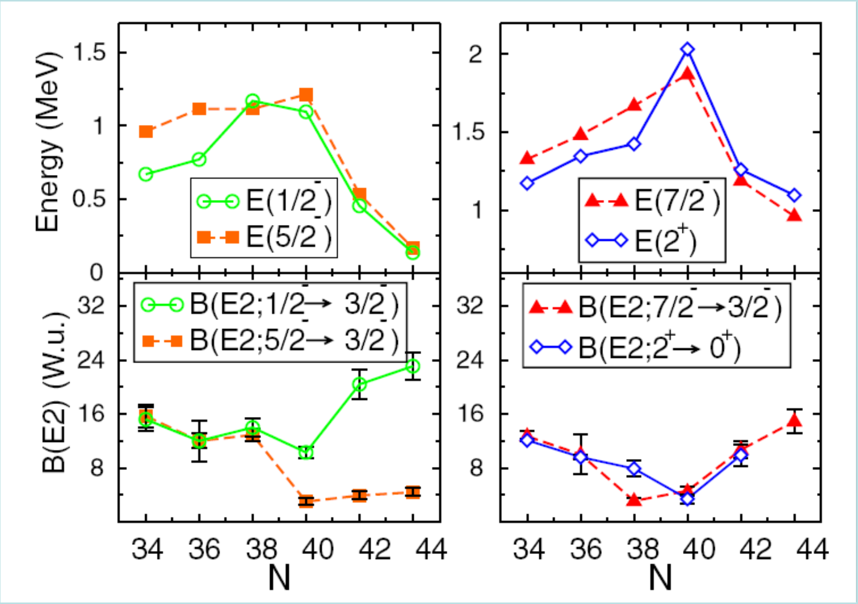
O. Sorlin et al. PRL 88 (2002) 092501
O. Perru et al. PRL 96 (2006) 232501
G. Kraus et al. PRL 73 (1994) 1773.

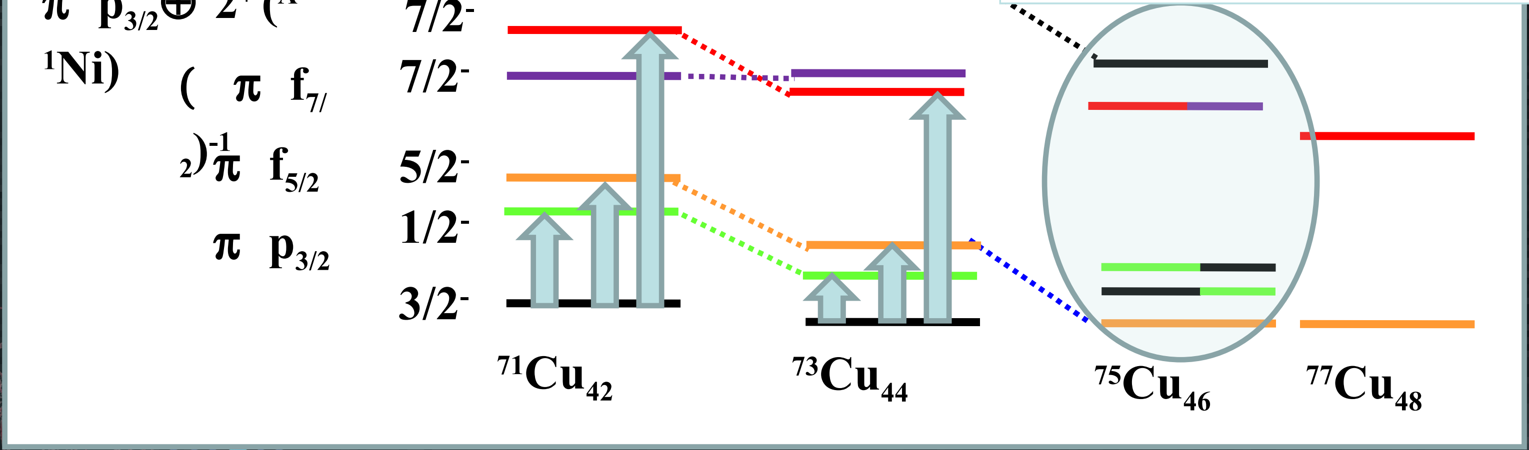
JJ Valiente-Dobon

Cu isotopes, Z=29

Magnetic moment measurement confirmed the inversion of the $f_{5/2}$ with the $p_{3/2}$ in ^{75}Cu

Collectivity of the $7/2^-$ state probe the BE2($0^+ \rightarrow 2^+$) in Ni isotopes





S. Franchoo et al., PRL 81, 3100(1998), I. Stefanescu *et al.*, PRL 100, 112502 (2008) , K. Flanagan PRL, 103, 142501 (2009), J. M. Daugas *et al.*, PRC 81, 034304 (2010)

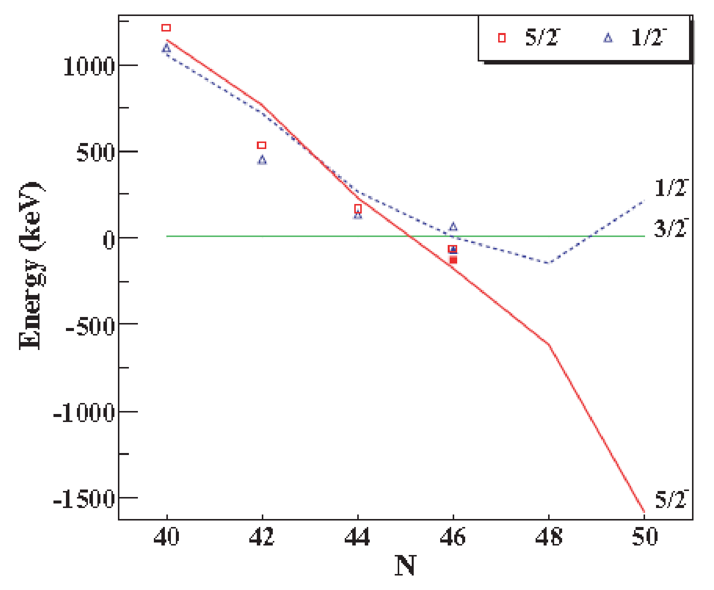
JJ Valiente-Dobon

The Cu isotopes in the fpg space

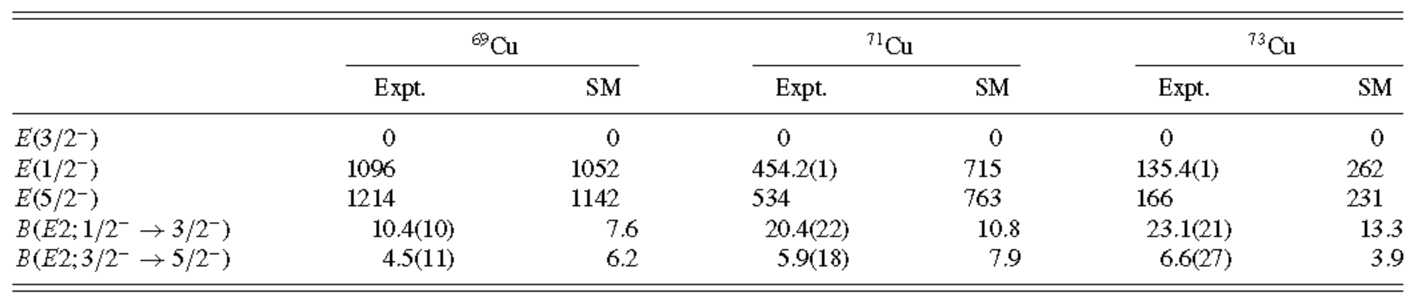
J. M. Daugas et al., PRC 81, 034304 (2010)

Reproduce the experimental data, the crossing of the f5/2 and the p3/2 and a quenching of the N=50 gap

Coexistence of s.p. and collective states at low excitation energy



K. Sieja and Nowacki., PRC81, 061303 (2010)



	^{69}Cu		^{71}Cu		^{73}Cu	
	Expt.	SM	Expt.	SM	Expt.	SM
$E(3/2^-)$	0	0	0	0	0	0
$E(1/2^-)$	1096	1052	454.2(1)	715	135.4(1)	262
$E(5/2^-)$	1214	1142	534	763	166	231
$B(E2; 1/2^- \rightarrow 3/2^-)$	10.4(10)	7.6	20.4(22)	10.8	23.1(21)	13.3
$B(E2; 3/2^- \rightarrow 5/2^-)$	4.5(11)	6.2	5.9(18)	7.9	6.6(27)	3.9

Discrepancy of predictions for the gap

Highly precision mass measurements

Two neutron shell gap energy
S_{2n}(N =50)- S_{2n} (N=52)

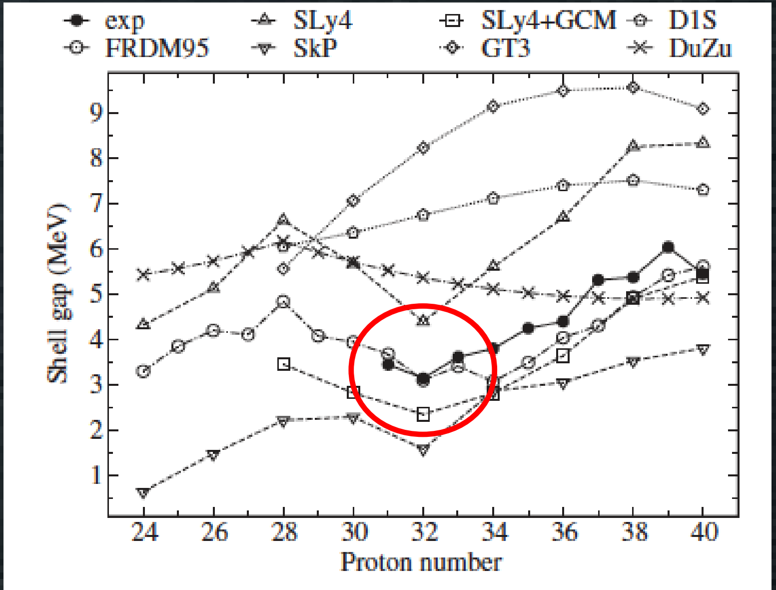


FIG. 4. Evolution of the $N = 50$ shell gap and comparison to theoretical models.

J. Hakala et al., PRL101, 052502 (2008)

^{80}Zn Coulex

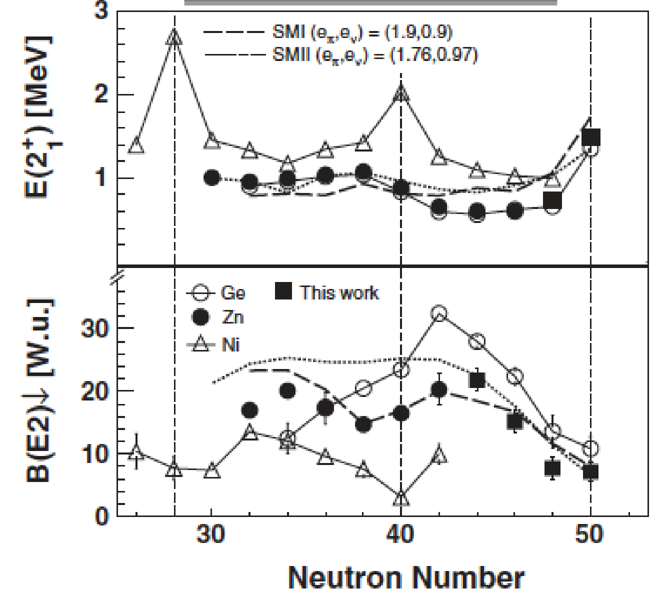


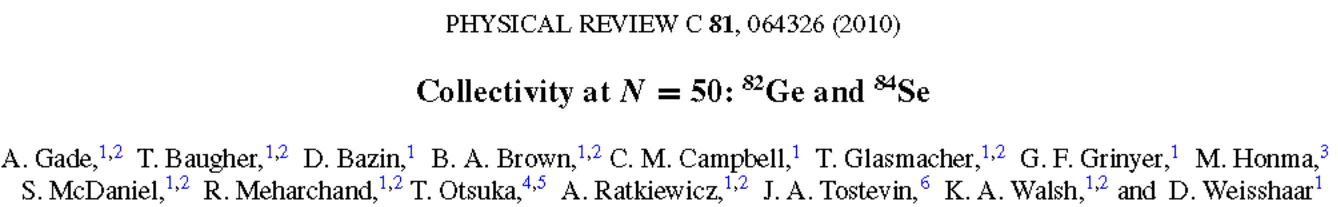
FIG. 2. $E(2^+_1)$ and $B(E2)\downarrow$ systematics for Ni ($Z = 28$), Zn ($Z = 30$), and Ge ($Z = 32$) isotopes. $B(E2)\downarrow$ values were taken from Refs. [6,7,9,10,18,30]. The dashed and dotted lines correspond to SM calculations for Zn isotopes.

core ^{56}Ni, no proton excitations from $f_{7/2}$

J. Van de Walle et al., PRL99, 142501 (2007)

JJ Valiente-Dobon

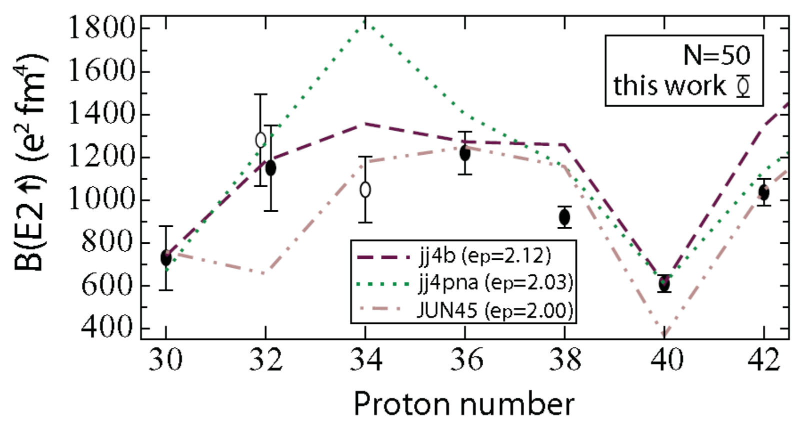
Coulomb excitation of ^{82}Ge and ^{84}Se

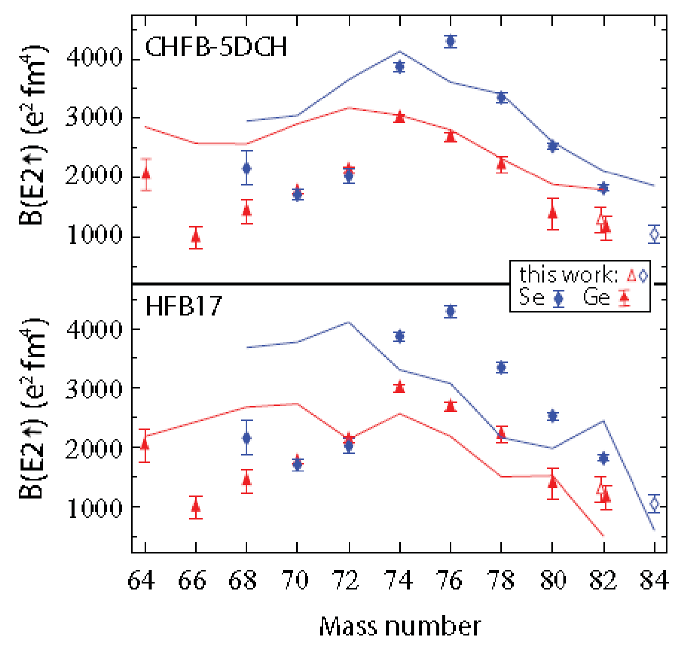


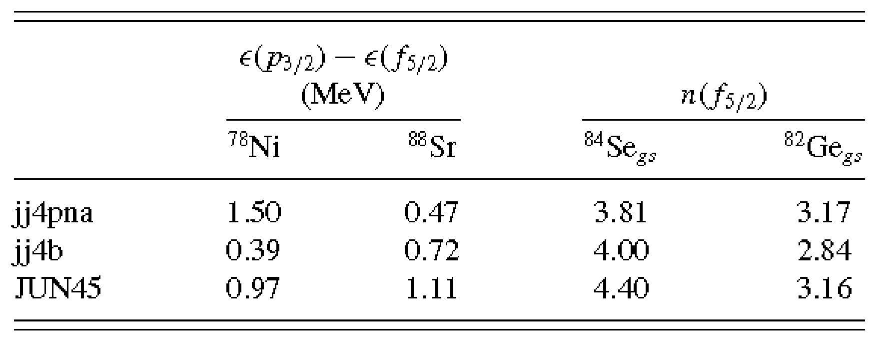
PHYSICAL REVIEW C **81**, 064326 (2010)

Collectivity at $N = 50$: ^{82}Ge and ^{84}Se

A. Gade,[1,2] T. Baugher,[1,2] D. Bazin,[1] B. A. Brown,[1,2] C. M. Campbell,[1] T. Glasmacher,[1,2] G. F. Grinyer,[1] M. Honma,[3]
S. McDaniel,[1,2] R. Meharchand,[1,2] T. Otsuka,[4,5] A. Ratkiewicz,[1,2] J. A. Tostevin,[6] K. A. Walsh,[1,2] and D. Weisshaar[1]

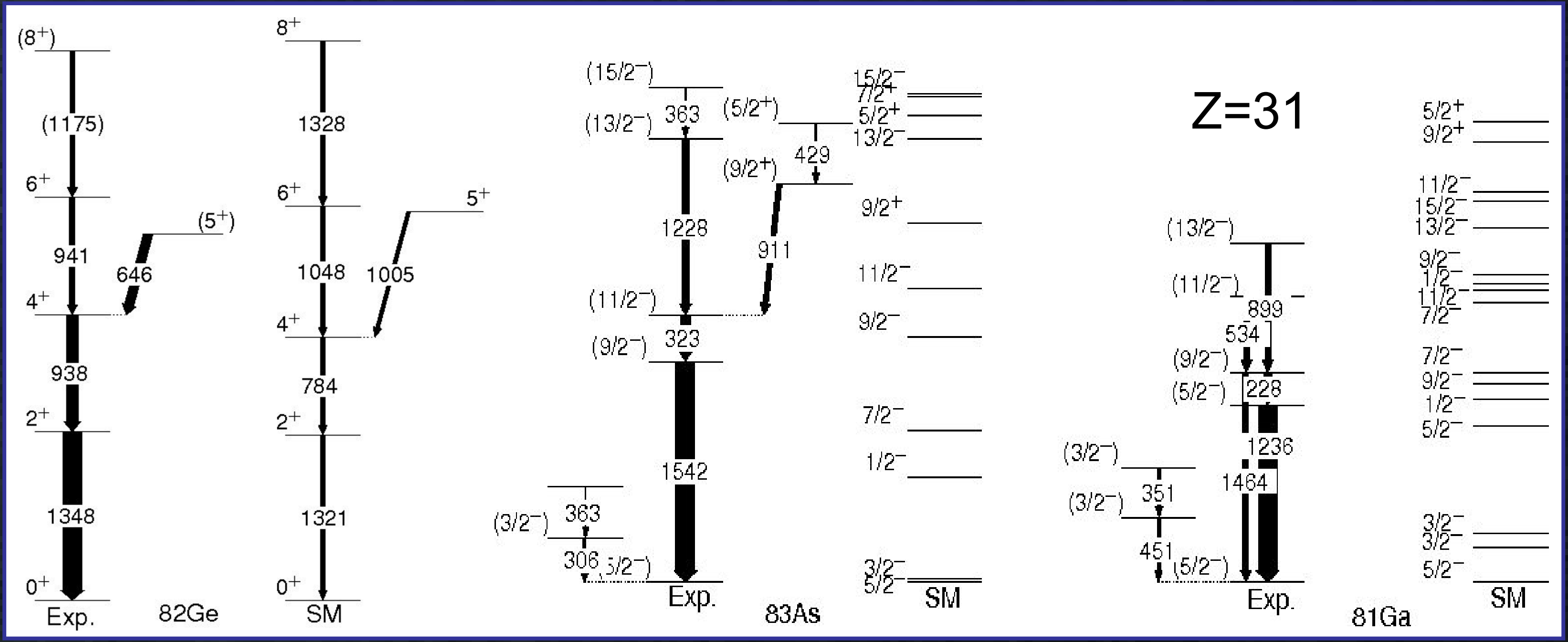






	$\epsilon(p_{3/2}) - \epsilon(f_{5/2})$ (MeV)		$n(f_{5/2})$	
	^{78}Ni	^{88}Sr	^{84}Se$_{gs}$	^{82}Ge$_{gs}$
jj4pna	1.50	0.47	3.81	3.17
jj4b	0.39	0.72	4.00	2.84
JUN45	0.97	1.11	4.40	3.16

The N=50 isotones



E. Sahin and G. De Angelis NPA 893, 1 (2012)
Y.H. Zhang PRC70, 024301 (2004)

Shell Model calculations: 2p-2h excitations across the N=50 shell to $2d_{5/2}$-$1g_{7/2}$-$3s_{1/2}$ (Lisetsky) for **4.7 MeV** of the shell gap value→No reduction of the shell gap

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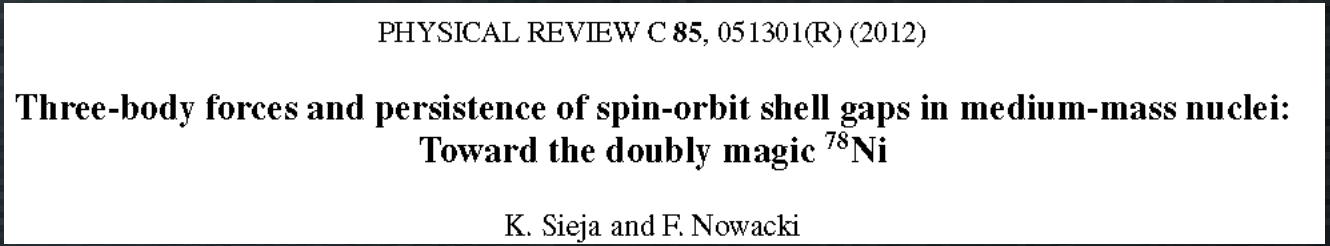
N=50 using the LNPS interaction

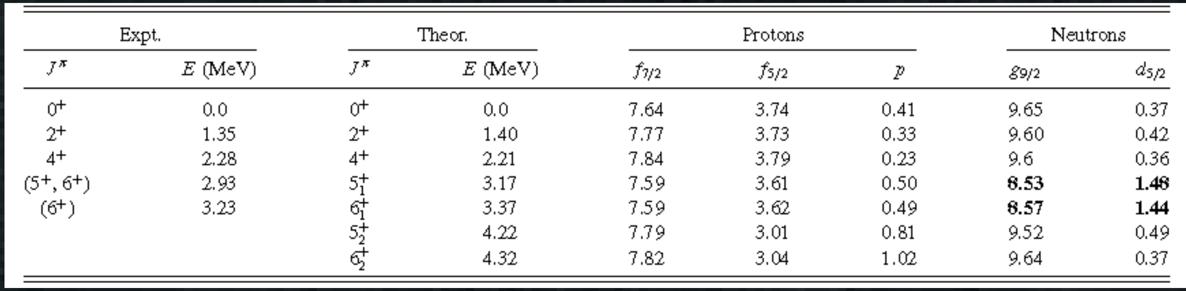


PHYSICAL REVIEW C **85**, 051301(R) (2012)

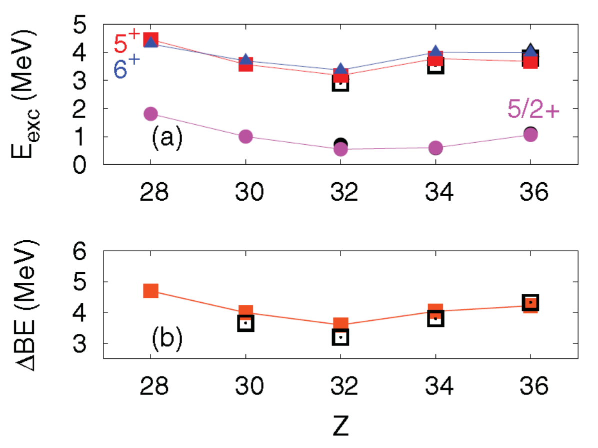
Three-body forces and persistence of spin-orbit shell gaps in medium-mass nuclei: Toward the doubly magic ^{78}Ni

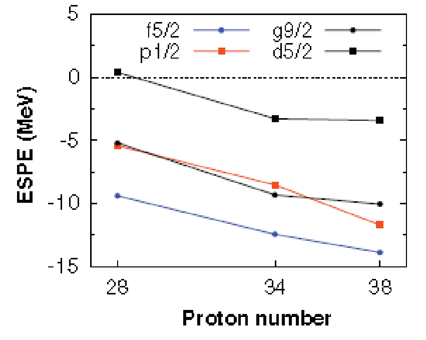
K. Sieja and F. Nowacki

82Ge



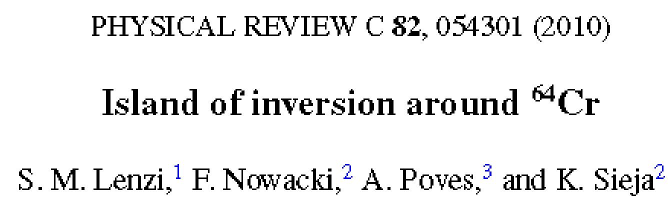
Expt.		Theor.		Protons			Neutrons	
J^π	E (MeV)	J^π	E (MeV)	$f_{7/2}$	$f_{5/2}$	p	$g_{9/2}$	$d_{5/2}$
0^+	0.0	0^+	0.0	7.64	3.74	0.41	9.65	0.37
2^+	1.35	2^+	1.40	7.77	3.73	0.33	9.60	0.42
4^+	2.28	4^+	2.21	7.84	3.79	0.23	9.6	0.36
$(5^+, 6^+)$	2.93	5^+_1	3.17	7.59	3.61	0.50	**8.53**	**1.48**
(6^+)	3.23	6^+_1	3.37	7.59	3.62	0.49	**8.57**	**1.44**
		5^+_2	4.22	7.79	3.01	0.81	9.52	0.49
		6^+_2	4.32	7.82	3.04	1.02	9.64	0.37





N=50

LNPS interaction



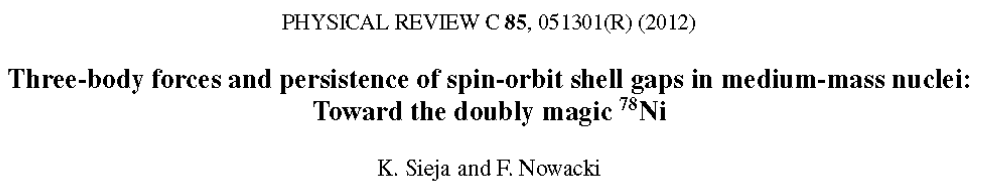
PHYSICAL REVIEW C **82**, 054301 (2010)

Island of inversion around ^{64}Cr

S. M. Lenzi,[1] F. Nowacki,[2] A. Poves,[3] and K. Sieja[2]

No reduction of the N=50 gap is predicted

Three-body forces needed?

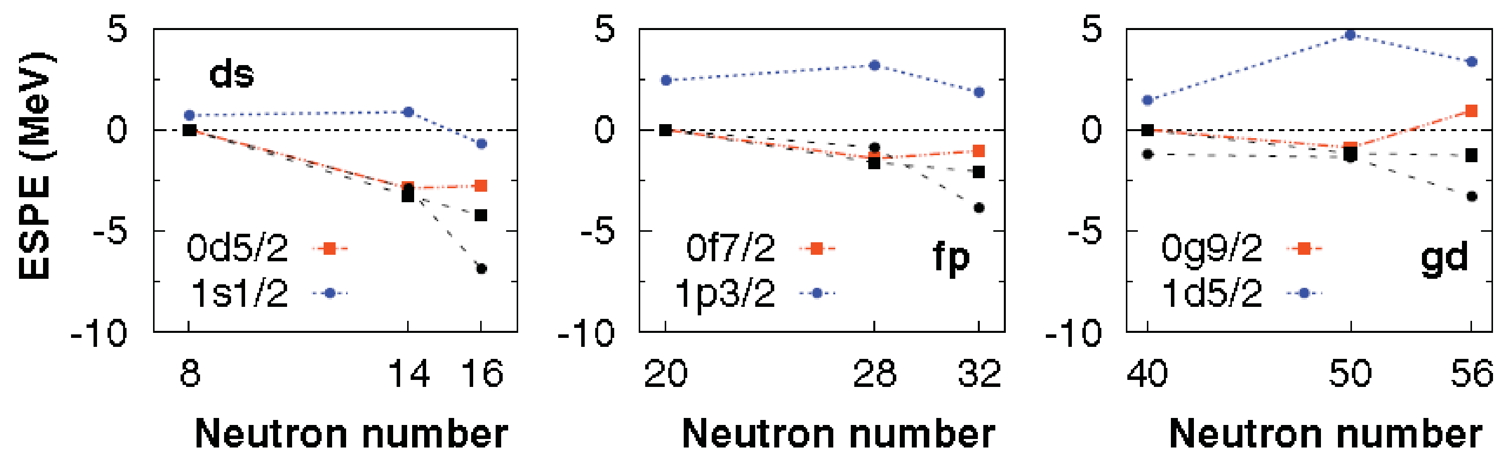


PHYSICAL REVIEW C **85**, 051301(R) (2012)

Three-body forces and persistence of spin-orbit shell gaps in medium-mass nuclei: Toward the doubly magic ^{78}Ni

K. Sieja and F. Nowacki

The missing repulsive NNN terms in the realistic interaction could be responsible of the wrong ESPE behaviour



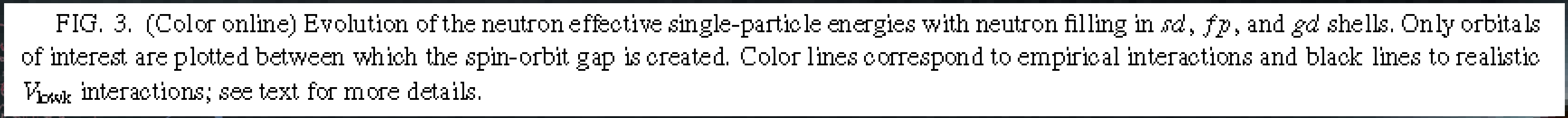


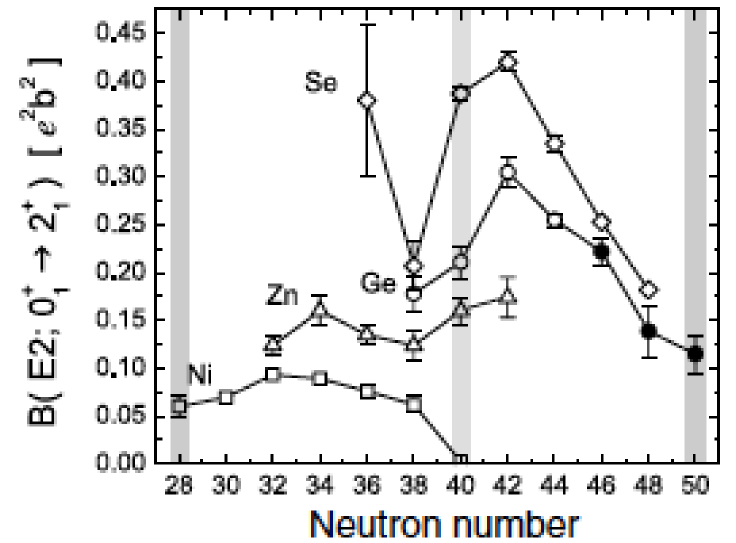
FIG. 3. (Color online) Evolution of the neutron effective single-particle energies with neutron filling in *sd*, *fp*, and *gd* shells. Only orbitals of interest are plotted between which the spin-orbit gap is created. Color lines correspond to empirical interactions and black lines to realistic V_{lowk} interactions; see text for more details.

The 2+ state in 78Ni is predicted at 4 MeV

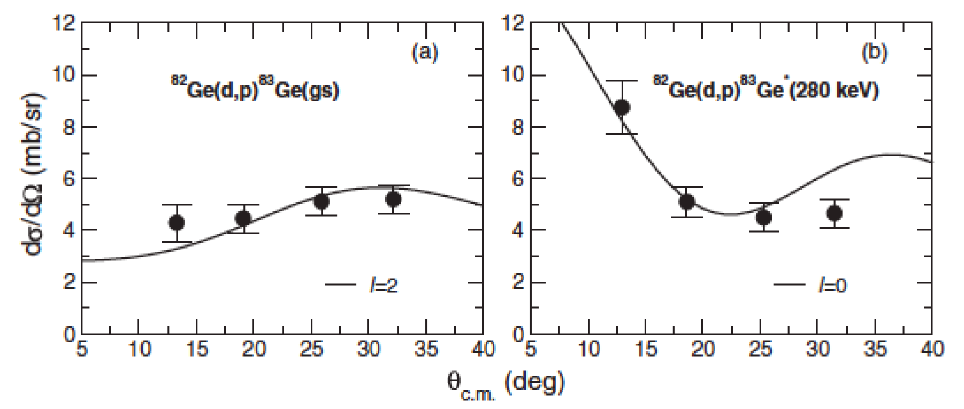
Beyond N=50

The neutron-rich isotopes of Ge and Se can be populated at and beyond N=50 and study the evolution of deformation.

^{78,80,82}Ge Coulex



^{84}Se(d,p)^{85}Se (N=51)



- Coulex: ^{78,80,82}Ge E. Padilla-Rodal et al., PRL94, 122501 (2005)
- Relativistic Coulex + knockout: ^{82}Ge and ^{84}Se A. Gade et al., PRC81, 064326 (2010)
- (d,p): ^{83}Ge and ^{85}Se: J.S. Thomas et al., PRC76, 044302 (2007)

JJ Valiente-Dobon

Physics cases proposed with SPES

JJ Valiente-Dobon et al.

- Coulomb excitation neutron-rich ^{86,88}Se and ^{84}Ge

Evolution of deformation

- Coulomb excitation ^{73,75,77}Cu

Population of collective states : the presence of collectivity at low excitation energy may play an interesting role in the evolution of the structure near the doubly magic nucleus ^{78}Ni. In particular, these data will give information on the collectivity of the 2+ states in neutron-rich Ni isotopes

INFN Istituto Nazionale di Fisica Nucleare