

# Nuclear Tapas: the landscape of medium mass nuclei

Frédéric Nowacki, Alfredo Poves <sup>1</sup>



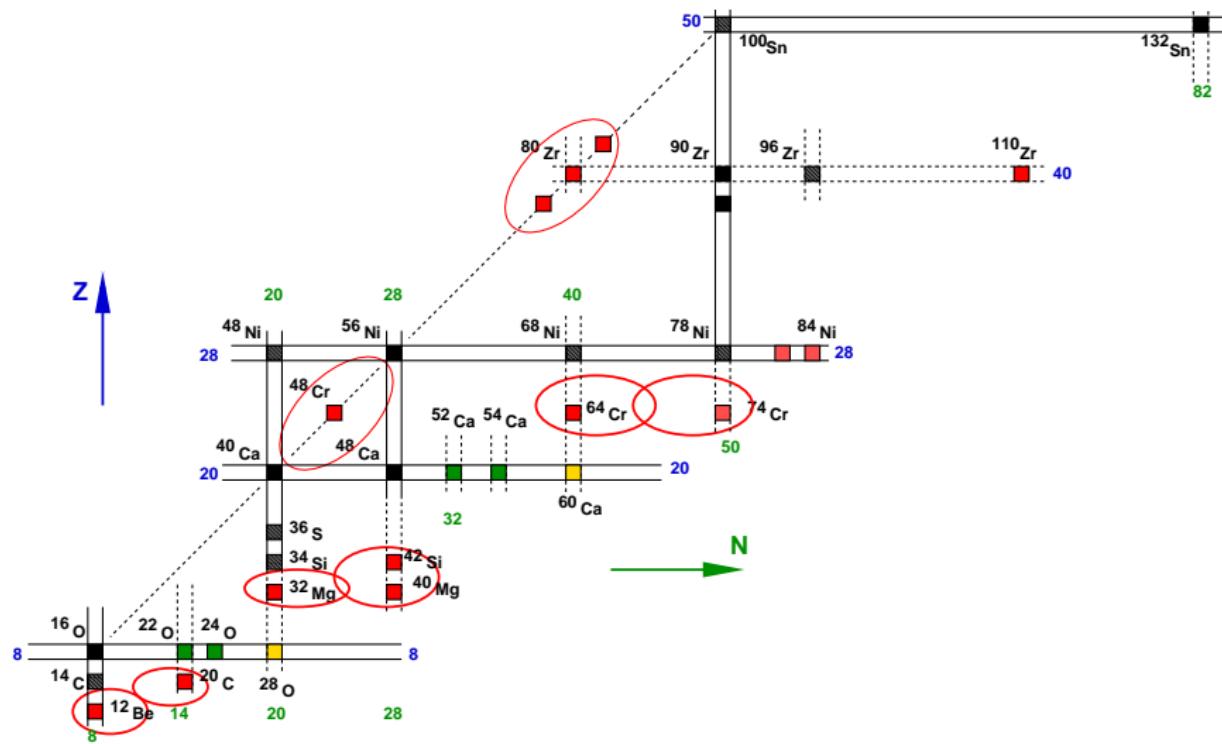
**Nuclear Tapas: the shell model as a cornerstone of nuclear structure**

April 27-28 2023  
Centro Cultural "La Corrala", Madrid (Spain)

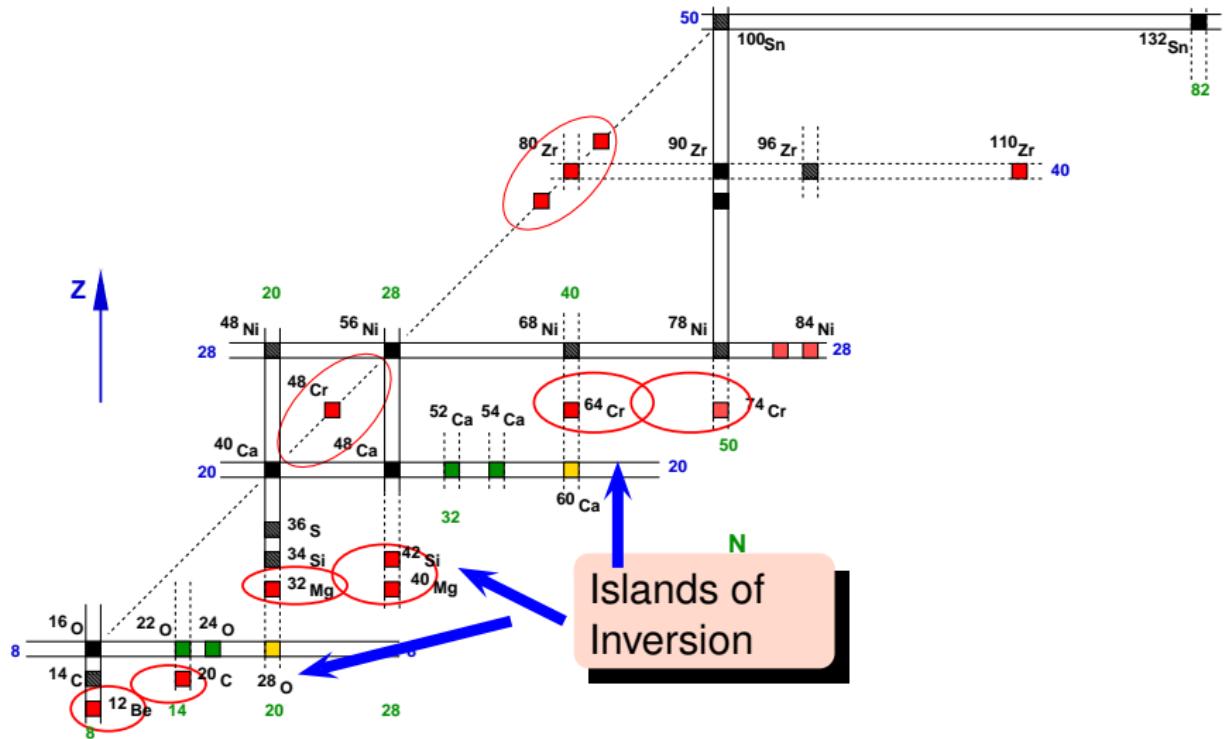
# Landscape of medium mass nuclei



# Landscape of medium mass nuclei



# Landscape of medium mass nuclei



## Landscape of medium mass nuclei

# **UNDERSTANDING REGULARITIES**

for both **SPHERICAL** and **DEFORMED** systems

82

- Magic Numbers:  $^{24}\text{O}$ ,  $^{48}\text{Ni}$ ,  $^{54}\text{Ca}$ ,  $^{78}\text{Ni}$ ,  $^{100}\text{Sn}$
  - Islands of Deformation:  $^{12}\text{Be}$ ,  $^{32}\text{Mg}$ ,  $^{42}\text{Si}$ ,  $^{64}\text{Cr}$ ,  $^{80}\text{Zr}$  ...

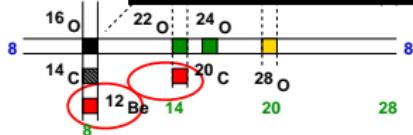
z

- Variety of phenomena dictated by shell structure
  - Close connection between collective behaviour and underlying shell structure

$$\mathcal{H} = \mathcal{H}_m + \mathcal{H}_{\mathcal{M}}$$

## Interplay between

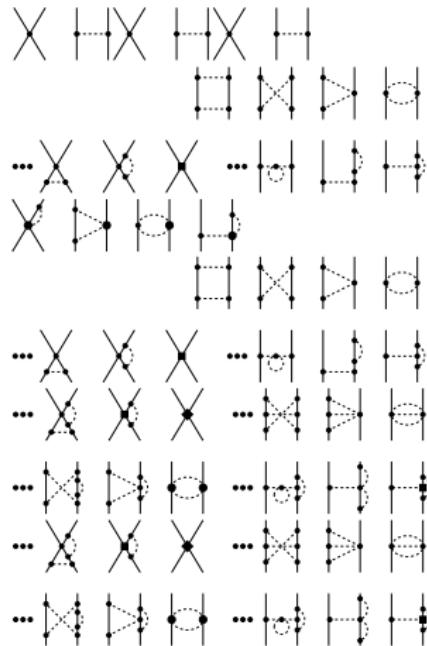
- Monopole field (spherical mean field)
  - Multipole correlations (pairing, Q.Q, ...)



# The nuclear interaction: the complex view

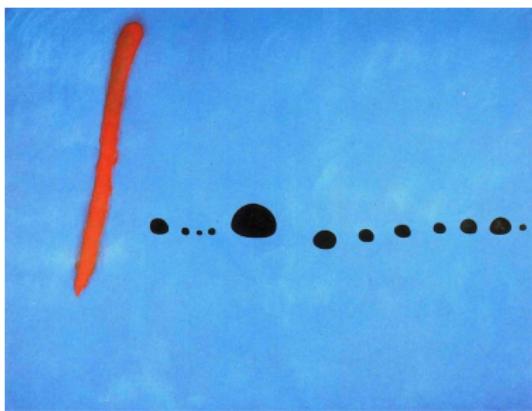


P. Klee, art

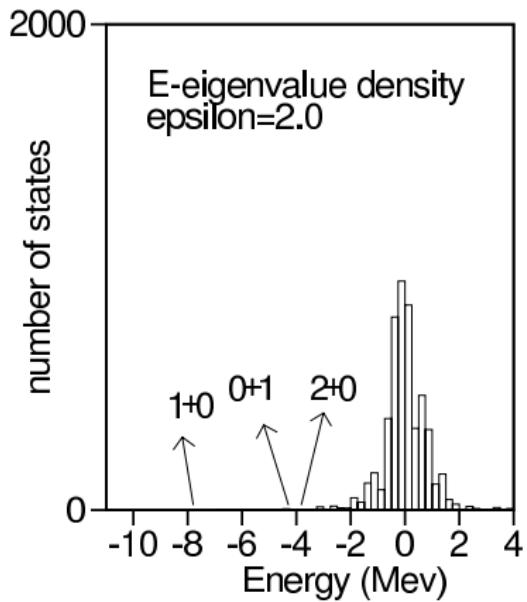


E. Epelbaum, physics

# The nuclear interaction: the simple view



J. Miro, art



A. Zuker, physics

# Separation of the effective Hamiltonian

Monopole and multipole

Multipole expansion:

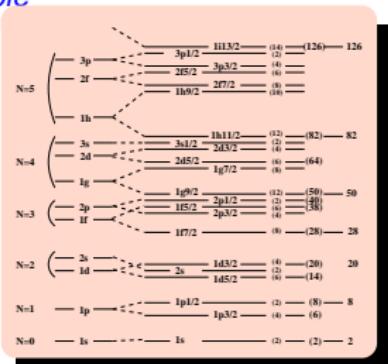
$$H = H_{\text{monopole}} + H_{\text{multipole}}$$

- Spherical mean-field

$H_{\text{monopole}}$ :

- Evolution of the spherical single particle levels

A. Poves and A. Zuker (Phys. Report 70, 235 (1981))

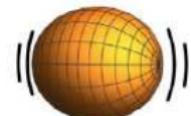


$H_{\text{multipole}}$ :

- Correlations
- Energy gains



pairing, quadrupole



M. Dufour and A. Zuker (PRC 54 1996 1641)

# The monopole hamiltonian

$$V = \sum_{JT} V_{ijkl}^{JT} \left[ (a_i^+ a_j^+)^{JT} (\tilde{a}_k \tilde{a}_l)^{JT} \right]^{00}$$

In order to express the number of particles operators  $n_i = a_i^+ a_i \propto (a_i^+ \tilde{a}_i)^0$ ,

→ particle-hole recoupling :

$$V = \sum_{\lambda\tau} W_{ikjl}^{\lambda\tau} \left[ (a_i^+ \tilde{a}_k)^{\lambda\tau} (a_j^+ \tilde{a}_l)^{\lambda\tau} \right]^{00}$$

$$W_{ikjl}^{\lambda\tau} \propto \sum_{JT} V_{ijkl}^{JT} \left\{ \begin{array}{ccc} i & k & \lambda \\ j & l & 0 \end{array} \right\} \left\{ \begin{array}{ccc} \frac{1}{2} & \frac{1}{2} & \tau \\ \frac{1}{2} & \frac{1}{2} & 0 \end{array} \right\}$$

$\mathcal{H}_m$  corresponds only to the terms  $\lambda\tau = 00$  and  $01$  which implies that  $i = j$  and  $k = l$  and writes as

$$\mathcal{H}_m = \sum_i n_i \epsilon_i + \sum_{i \leq j} n_i \cdot n_j V_{ij}$$

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$$\mathcal{H}_M = \mathcal{H} - \mathcal{H}_m$$

# 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

	pp(JT)			ph( $\lambda\tau$ )			
	10	01	21	20	40	10	11
KB	-5.83	-4.96	-3.21	-3.53	-1.38	+1.61	+3.00
USD-A	-5.62	-5.50	-3.17	-3.24	-1.60	+1.56	+2.99
CCEI	-6.79	-4.68	-2.93	-3.40	-1.39	+1.21	+2.83
NN+NNN-MBPT	-6.40	-4.36	-2.91	-3.28	-1.23	+1.10	+2.43
NN-MBPT	-6.06	-4.38	-2.92	-3.35	-1.31	+1.03	+2.49

# Multipole Hamiltonian

$H_{\text{multipole}}$   
and pa  
When  
cohere

- $L =$
- Ell
- $\vec{\sigma}\vec{\tau}$
- Oc

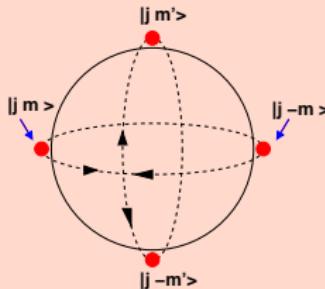
Beside  
similar

- **Pairing regime: spherical nuclei**

ground state = pairs of like-particles coupled at  $J=0$  (seniority  $v=0$ )  
 $2^+$  state (break of pair;  $v=2$ ) at high energy

**Underlying SU2 symmetry**

superfluid nucleus:



Typical example: **Tin isotopes**

- **Quadrupole regime: deformed nuclei**

**Underlying SU3 symmetry**

KB  
USE  
CCE  
NN+  
NN-

prolate nucleus:



Typical example: **open shell N=Z nuclei**

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particle-particle		Interaction	particle-hole		
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-5.42	-5.43	KLS	-2.90	-1.61	+2.38
	-6.24	BONNB	-2.82	-1.39	+3.64
	-5.90		-3.18	-1.60	+3.08
-4.75	-4.46	KB3	-2.79	-1.39	+2.46
	-5.08	FPD6	-3.11	-1.67	+3.17
	-5.74		-3.23	-1.77	+2.46

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<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
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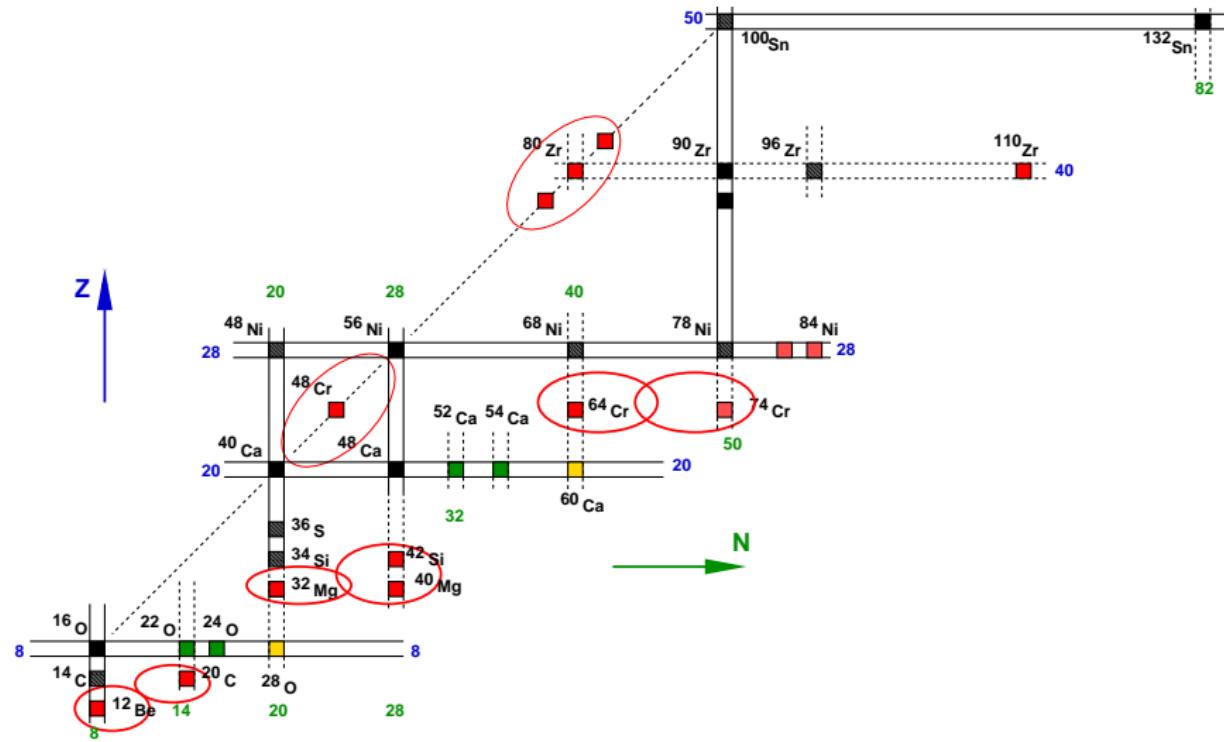
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# Landscape of medium mass nuclei



# Island of inversion at N=20, an old story: 1991

Nuclear Physics A571 (1994) 221–241  
North-Holland

NUCLEAR  
PHYSICS A

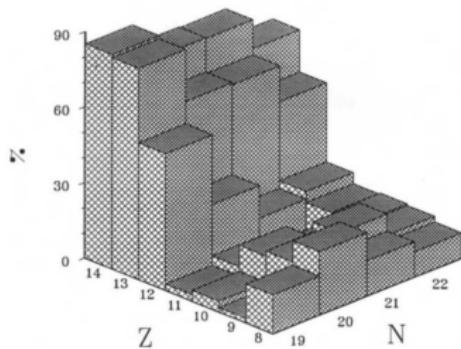
## Theoretical study of the very neutron-rich nuclei around $N = 20$

A. Poves, J. Retamosa

Departamento de Física Teórica C-XI, Universidad Autónoma de Madrid, 28049 Madrid, Spain

Received 5 April 1991  
(Revised 13 October 1993)

A. Poves, J. Retamosa / Very neutron-rich nuclei



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NUCLEAR  
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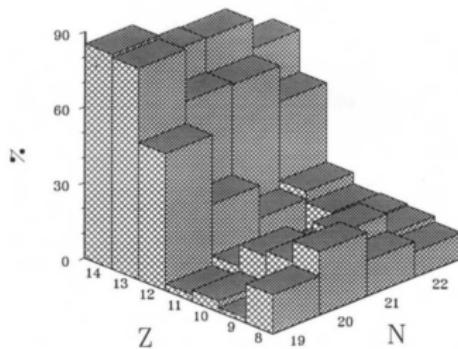
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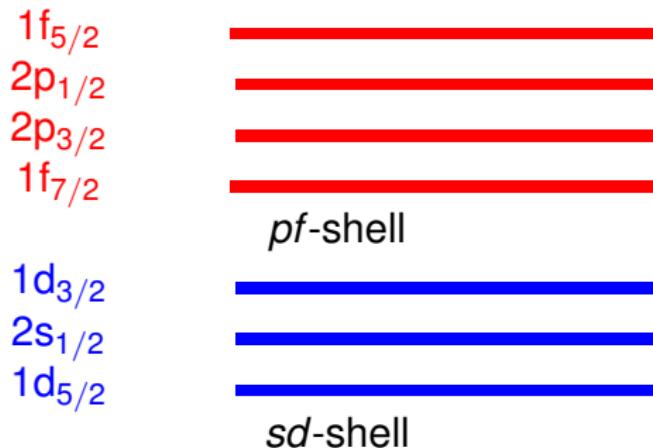
A. Poves, J. Retamosa / Very neutron-rich nuclei



Pioneer work at N=20

# Playground

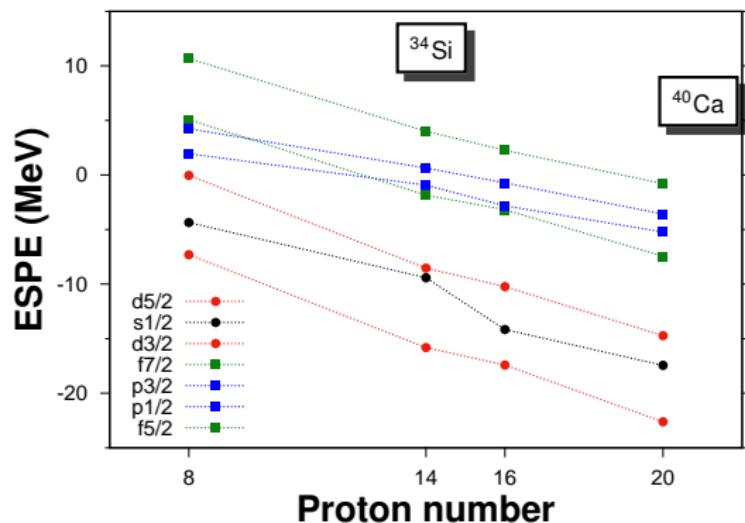
In the valence space of two major shells



EFFECTIVE INTERACTION: SDPF-U-MIX (update 2020)

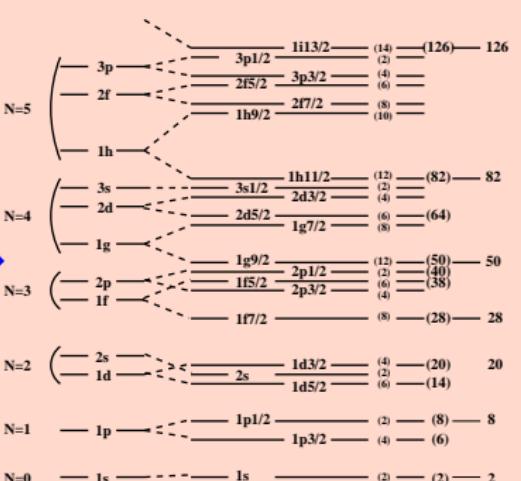
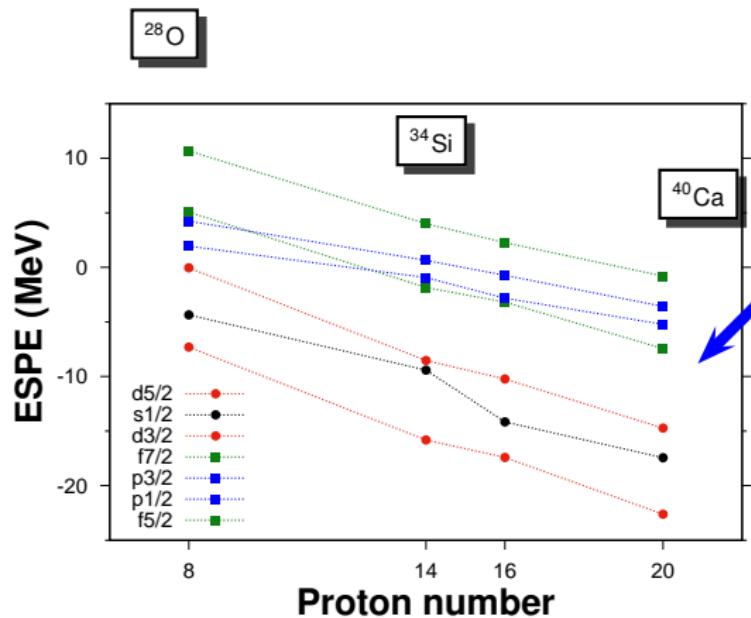
# Island of Inversion: Trends

$^{28}\text{O}$



- At the neutron drip line, the ESPE's of  $^{28}\text{O}$  are completely at variance with those of  $^{40}\text{Ca}$  at the stability valley. The change from the standard ESPE's of  $^{16}\text{O}$  to the anomalous ones in  $^{28}\text{O}$  is totally due to the interactions of *sd* shell neutrons among themselves
- Notice that the *sd* shell orbits remain always below the *pf* shell with the  $\nu 0f_{\frac{5}{2}}$  and  $\nu 0p_{\frac{3}{2}} - 0p_{\frac{1}{2}}$  orbitals DO get inverted
- The monopole part of the neutron-proton interaction restores the N=20 shell gap when the valley of stability is approached
- Spin-Tensor decomposition shows it is mainly a Central and Tensor effect

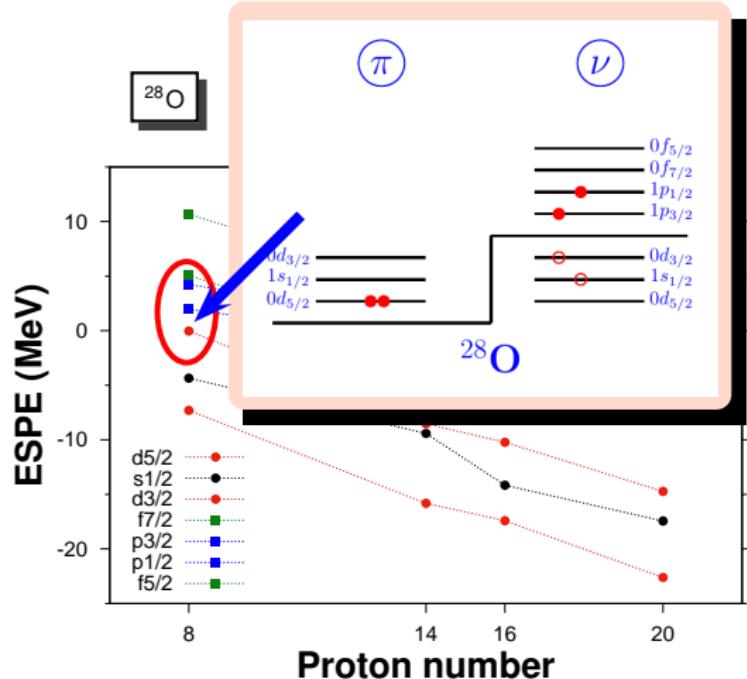
# Islands Of Inversion: Trends



N=20 shell gap when the valley of stability is approached

- Spin-Tensor decomposition shows it is mainly a **Central** and **Tensor** effect

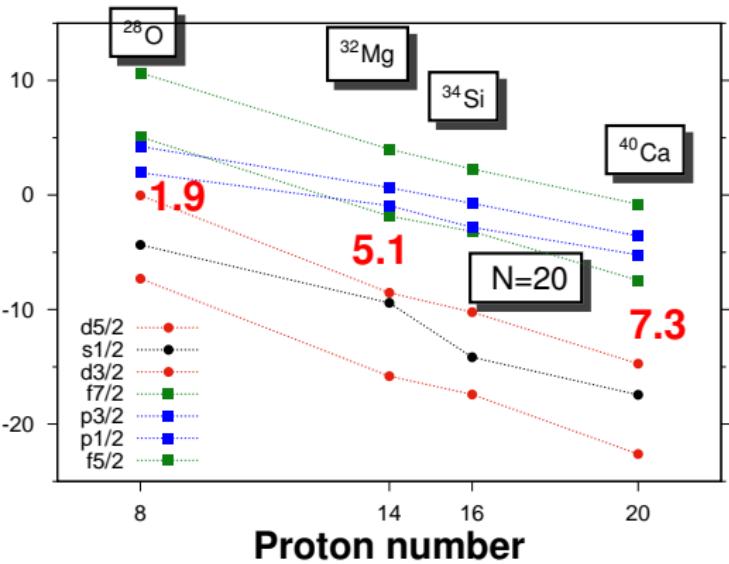
# Further away from Stability



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- Notice that the  $sd$  shell orbits remain always below the  $pf$  shell with the  $\nu 0f_{\frac{5}{2}}$  and  $\nu 0p_{\frac{3}{2}}$  orbitals DO get inverted
- The monopole part of the neutron-proton interaction restores the N=20 shell gap when the valley of stability is approached
- Shell Evolution favors natural geometry for low-lying M1 excitations

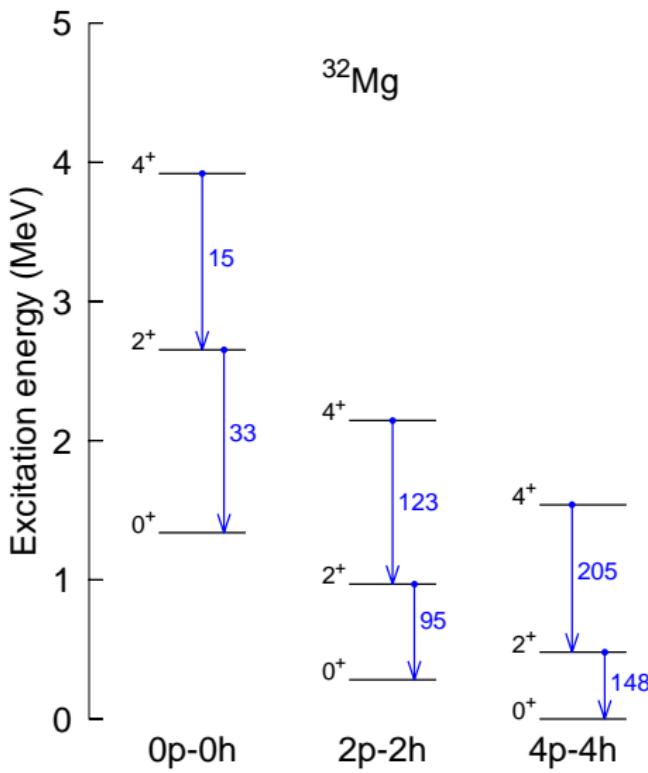
$$\begin{array}{c} \nu 1s_1 \\ \nu 0d_{\frac{3}{2}} \end{array} \otimes \begin{array}{c} \nu 1p_{\frac{3}{2}} \\ \nu 1p_{\frac{1}{2}} \end{array}$$

# Island of Inversion: Trends

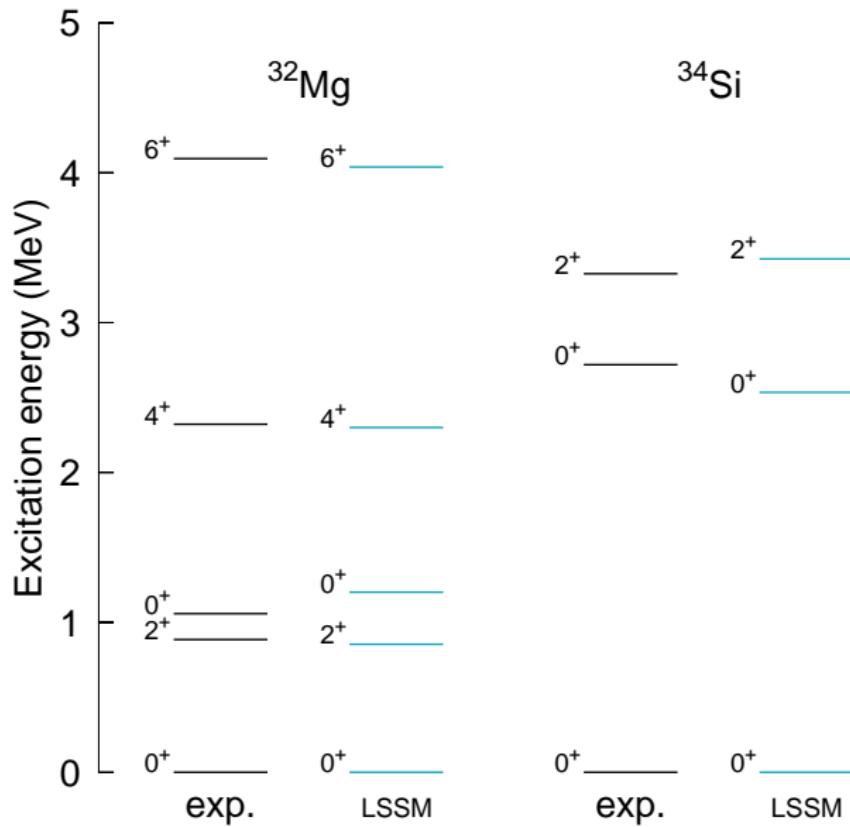


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- Notice that the sd shell orbits remain always below the pf shell with the  $\nu 0f_{\frac{5}{2}}$  and  $\nu 0p_{\frac{3}{2}}$  orbitals DO get inverted
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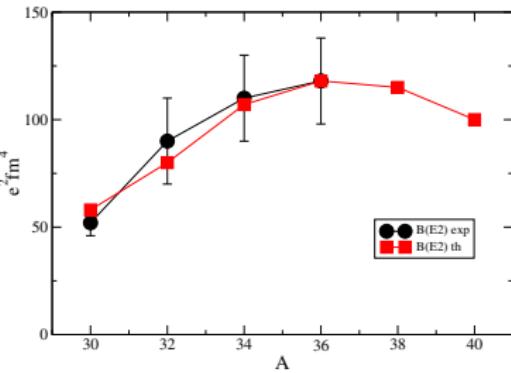
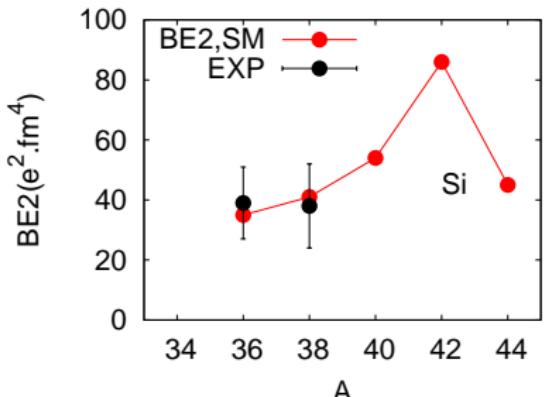
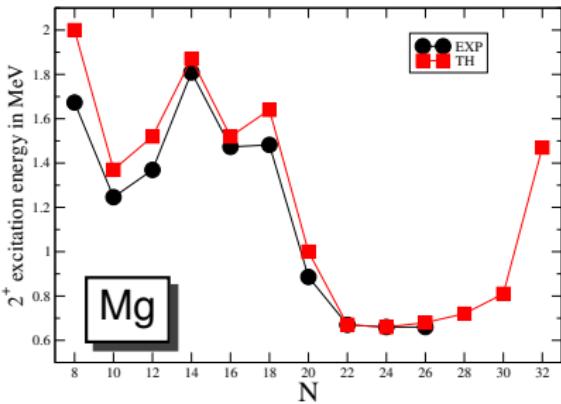
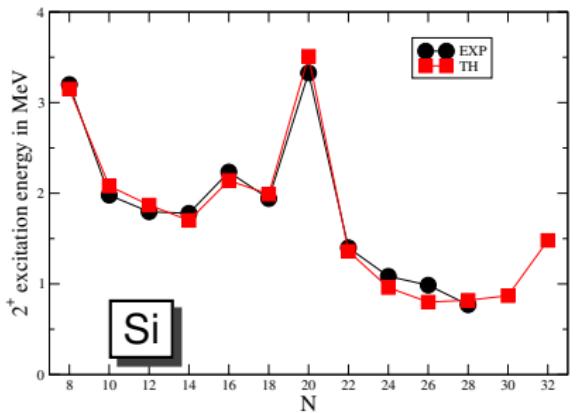
# Spherical, Deformed and Superdeformed states in $^{32}\text{Mg}$



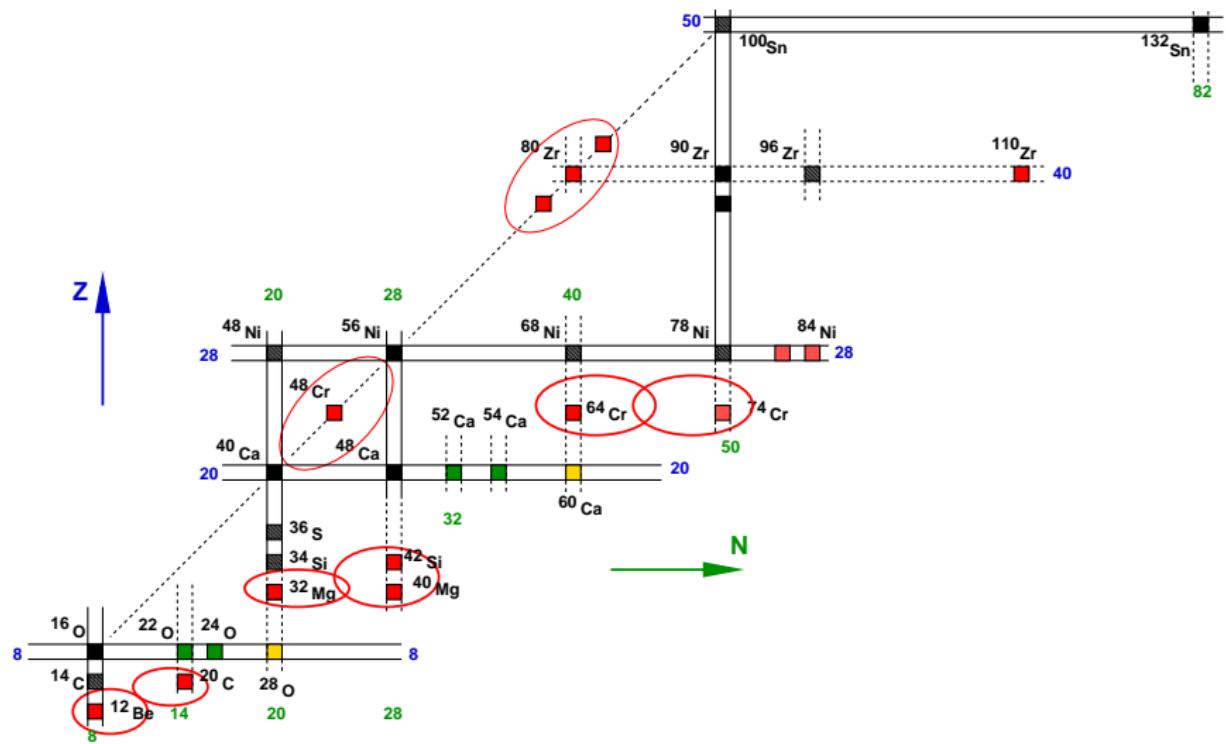
# Inverse shape coexistence Shell closure in $^{32}\text{Mg}$



# Silicium and Magnesium chains



# Landscape of medium mass nuclei



# Island of inversion at N=40, an old story: 1996

## The Physics around the doubly-magic $^{78}\text{Ni}$ Nucleus

Leuven, Belgium  
November 4/5, 1996

A. Poves



$$g(0ph - 2ph) = 5.70$$

$$g(0ph - 4ph) = 8.30$$

$$Q = -9.0 \text{ } b^2 \quad CS < 1\%$$

$$BE2 = 19.8 \text{ } b^4 \quad \omega(d5_{1/2}) = 1.1$$

$$\frac{E(4^+)}{E(2^+)} = 2.7 \quad \left[ \frac{E(4^+)}{E(2^+)} = (3.2)(3.4) \right]$$

in the intruder configurations.

A SITUATION THAT REMINDS WHAT  
IS KNOWN AT N=20 FFS.

# More recent experimental information

RAPID COMMUNICATIONS

PHYSICAL REVIEW C 81, 051304(R) (2010)

## Collectivity at $N = 40$ in neutron-rich $^{64}\text{Cr}$

A. Gade,<sup>1,2</sup> R. V. F. Janssens,<sup>3</sup> T. Baugher,<sup>1,2</sup> D. Bazin,<sup>1</sup> B. A. Brown,<sup>1,2</sup> M. P. Carpenter,<sup>3</sup> C. J. Chiara,<sup>3,4</sup> A. N. Deacon,<sup>5</sup> S. J. Freeman,<sup>5</sup> G. F. Grinyer,<sup>1</sup> C. R. Hoffman,<sup>3</sup> B. P. Kay,<sup>3</sup> F. G. Kondev,<sup>6</sup> T. Lauritsen,<sup>3</sup> S. McDaniel,<sup>1,2</sup> K. Meierbachtol,<sup>1,7</sup> A. Ratkiewicz,<sup>1,2</sup> S. R. Stroberg,<sup>1,2</sup> K. A. Walsh,<sup>1,2</sup> D. Weisshaar,<sup>1</sup> R. Winkler,<sup>1</sup> and S. Zhu<sup>3</sup>

<sup>1</sup>National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

<sup>2</sup>Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

<sup>3</sup>Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

RAPID COMMUNICATION

PHYSICAL REVIEW C 81, 061301(R) (2010)

## Onset of collectivity in neutron-rich Fe isotopes: Toward a new island of inversion?

J. Ljungvall,<sup>1,2,3</sup> A. Görgen,<sup>1</sup> A. Obertelli,<sup>1</sup> W. Korten,<sup>1</sup> E. Clément,<sup>2</sup> G. de France,<sup>2</sup> A. Bürger,<sup>4</sup> J.-P. Delaroche,<sup>5</sup> A. Dewald,<sup>6</sup> A. Gadea,<sup>7</sup> L. Gaudefroy,<sup>5</sup> M. Girod,<sup>5</sup> M. Hackstein,<sup>6</sup> J. Libert,<sup>8</sup> D. Mengoni,<sup>9</sup> F. Nowacki,<sup>10</sup> T. Pissulla,<sup>6</sup> A. Poves,<sup>11</sup> F. Recchia,<sup>12</sup> M. Rejmund,<sup>2</sup> W. Rother,<sup>6</sup> E. Sahin,<sup>12</sup> C. Schmitt,<sup>2</sup> A. Shrivastava,<sup>2</sup> K. Sieja,<sup>10</sup> J. J. Valiente-Dobón,<sup>12</sup> K. O. Zell,<sup>6</sup> and M. Zielińska<sup>13</sup>

<sup>1</sup>CEA Saclay, IRFU, Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France

<sup>2</sup>GANIL, CEA/DSM-CNRS/IN2P3, Bd Henri Becquerel, BP 55027, F-14076 Caen, France

<sup>3</sup>Facultad de Ciencias Físicas, UAM, E-28049 Madrid, Spain

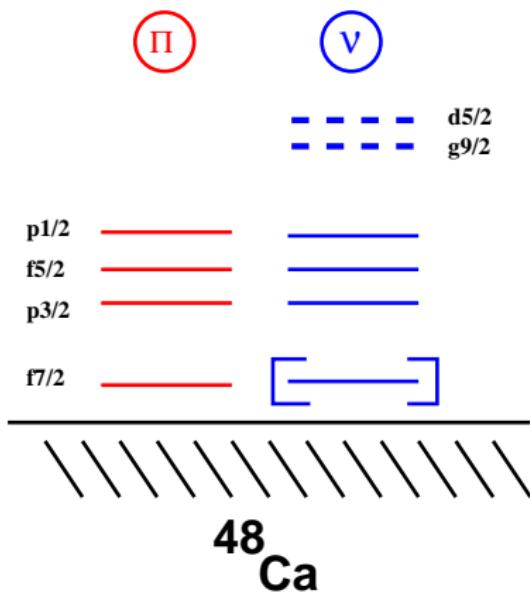
# SM framework



Island of inversion around  $^{64}\text{Cr}$

S. Lenzi, F. Nowacki, A. Poves and K. Sieja

Phys. Rev. C82, 054301, 2010



## LNPS interaction:

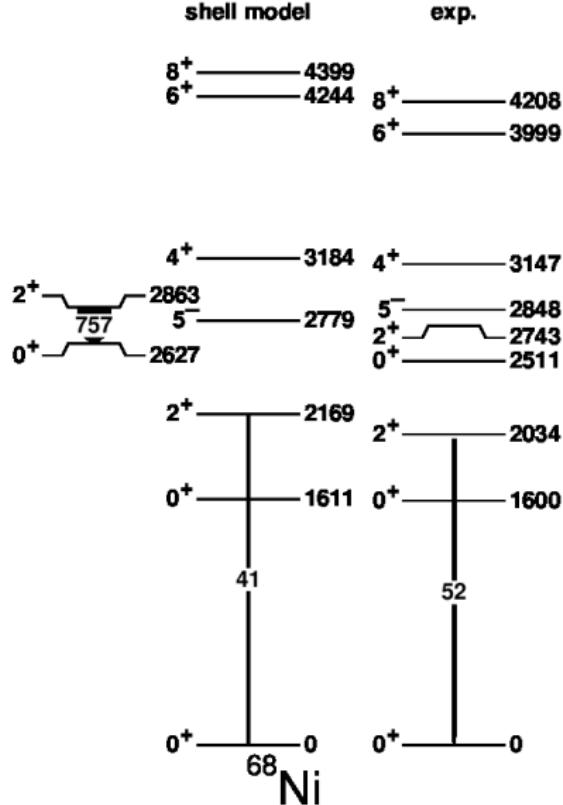
- based on realistic TBME
- new fit of the pf shell (KB3GR, E. Caurier)
- monopole corrections
- $g_{9/2}-d_{5/2}$  gap now constrained to 2.5 Mev in  $^{68}\text{Ni}$

## Calculations:

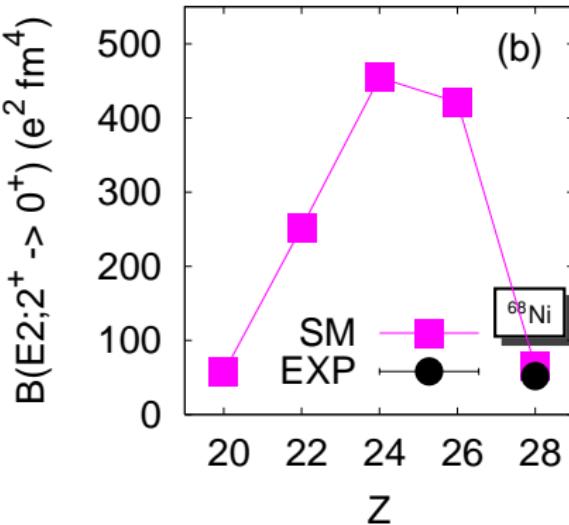
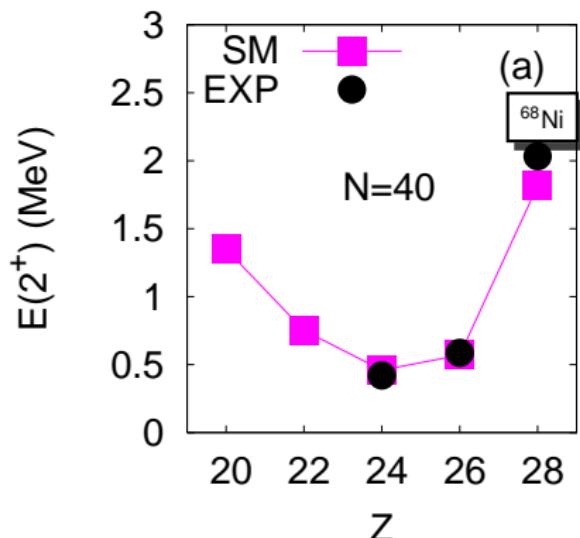
- Up to  $14\hbar\omega$  excitations across Z=28 and N=40 gaps
- Matrix diagonalizations up to  $2 \cdot 10^{10}$
- m-scheme code ANTOINE (non public parallel version)

# Triple coexistence in $^{68}\text{Ni}$

- at first approximation,  $^{68}\text{Ni}$  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  $^{68}\text{Ni}$ :  
F. Recchia et al.  
*Phys. Rev. C88*, 041302(R) (2013)
- prediction of very low-lying superdeformed band ( $\beta_2 \sim 0.4$ ) of  $6p6h$  nature!
  - S. Lenzi et al.  
*Phys. Rev. C82*, 054301 (2010)
  - A. Dijon et al.  
*Phys. Rev. C85*, 0311301(R) (2012)

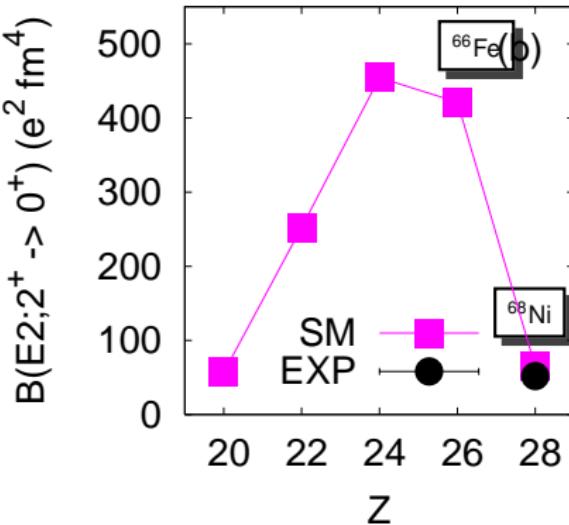
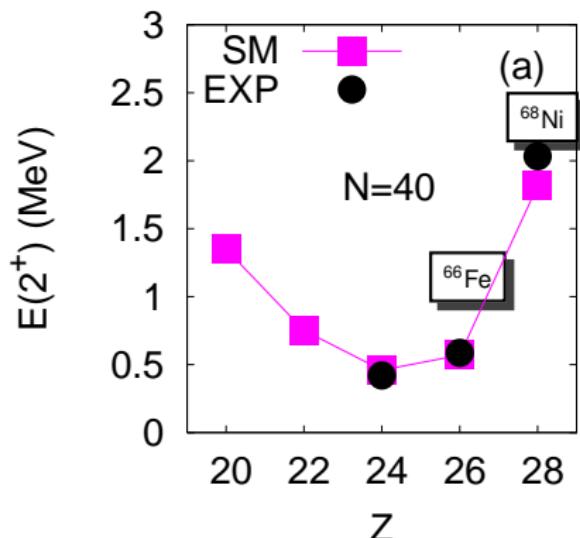


# Shape transition at N=40



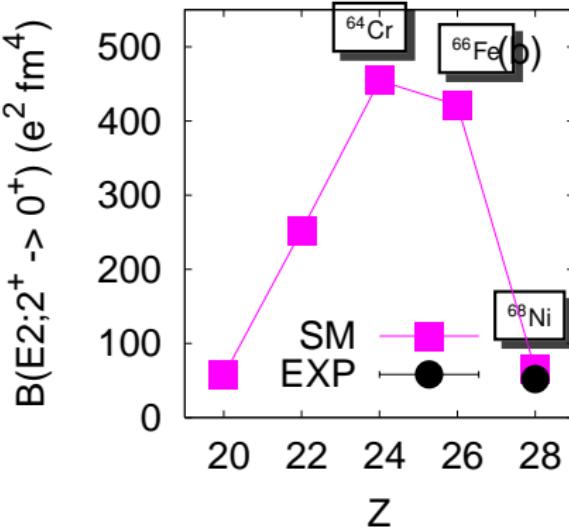
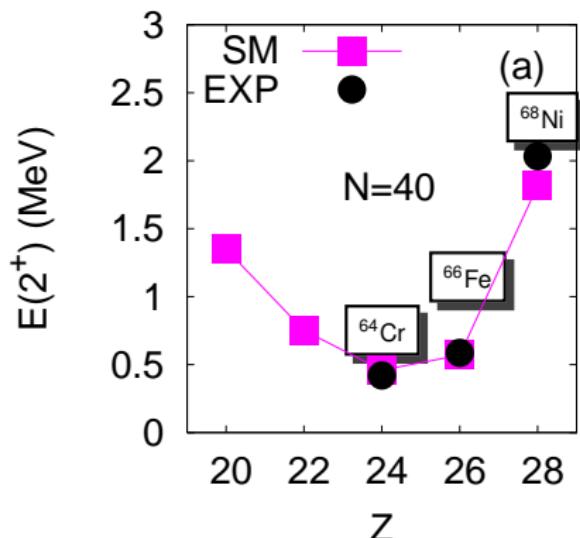
Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	configuration
$^{68}\text{Ni}$	0.98	0.10	0p0h(51%)
$^{66}\text{Fe}$	3.17	0.46	4p4h(26%)
$^{64}\text{Cr}$	3.41	0.76	6p6h(23%)
$^{62}\text{Ti}$	3.17	1.09	4p4h(48%)

# Shape transition at N=40



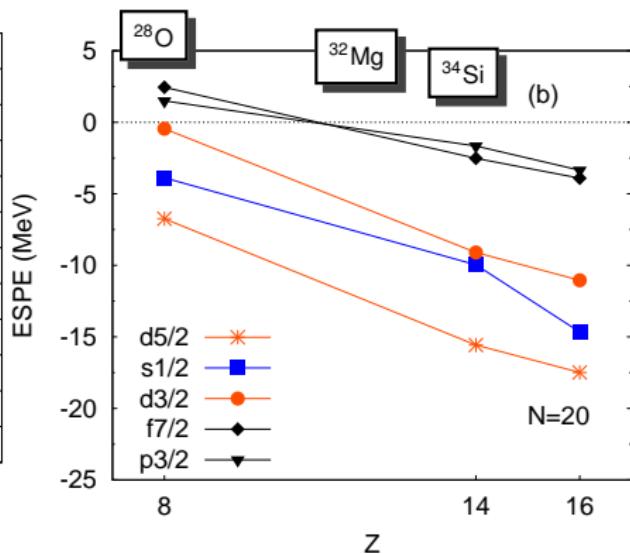
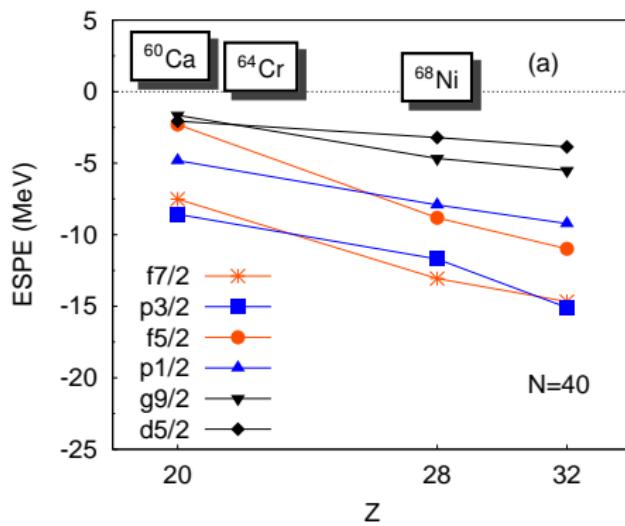
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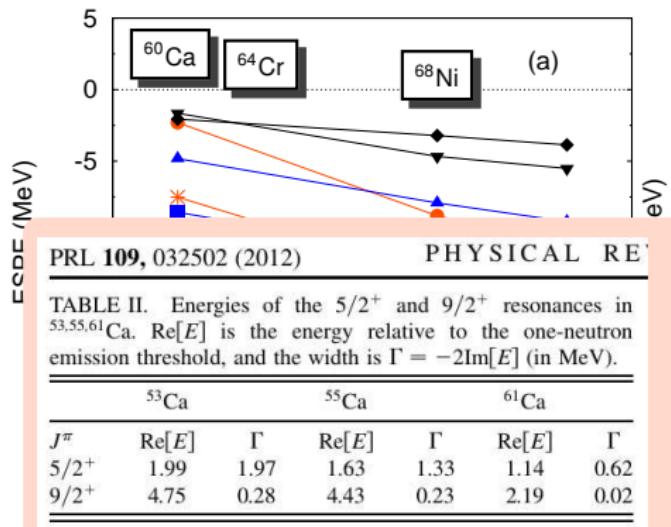
# Neutron effective single particle energies



- 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

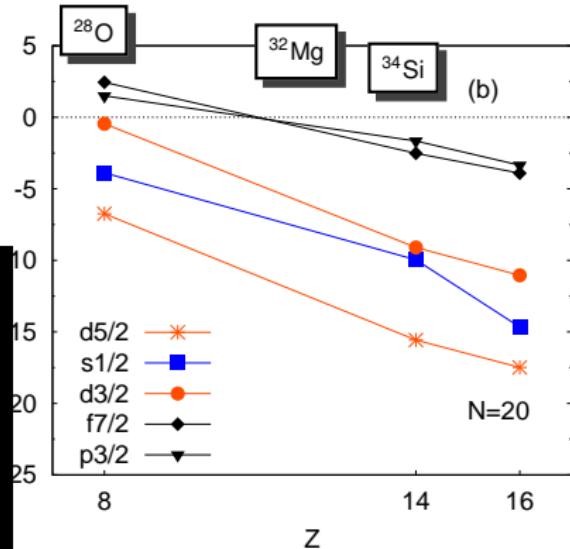


G. Hagen et al.

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

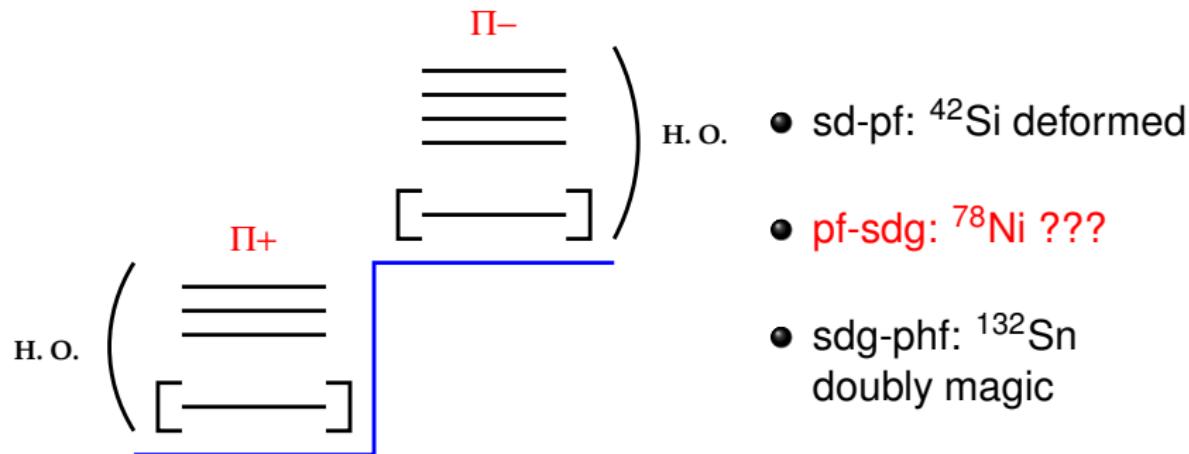
removing  $f_{7/2}$  protons

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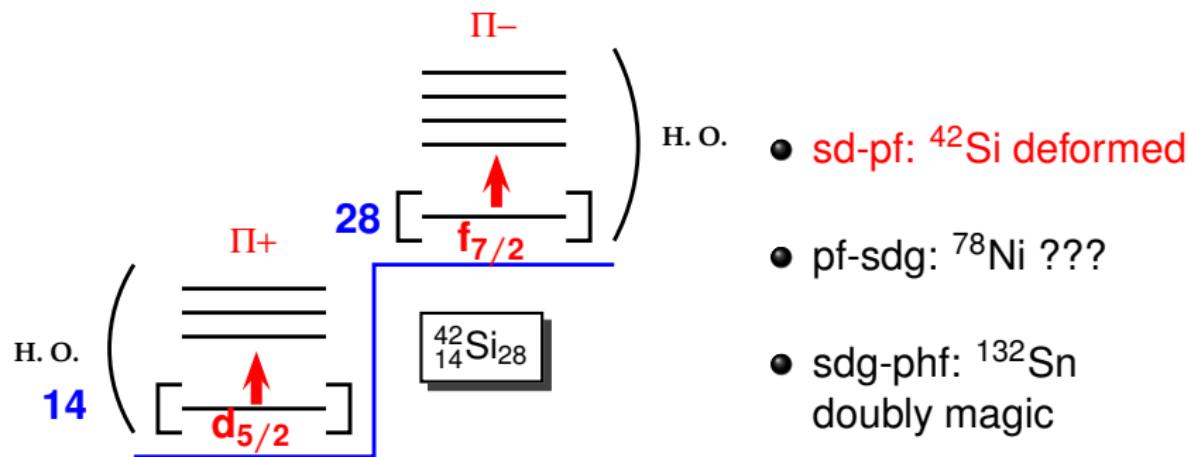
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# Spin-orbit shell closure far from stability



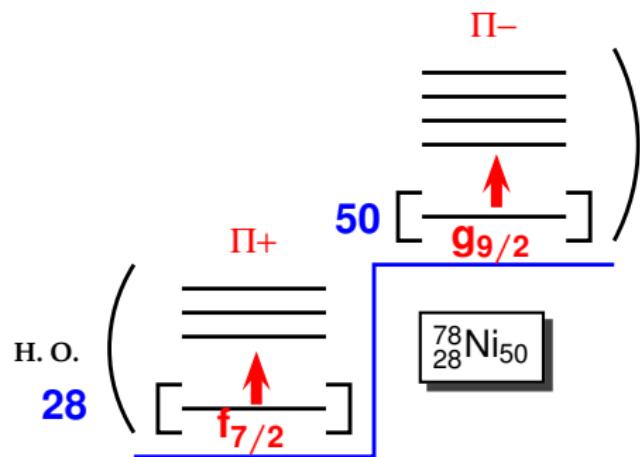
- Evolution of Z=28 from N=40 to N=50
- Evolution of N=50 from Z=40 to Z=28

# Spin-orbit shell closure far from stability



- 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  $Z=28$

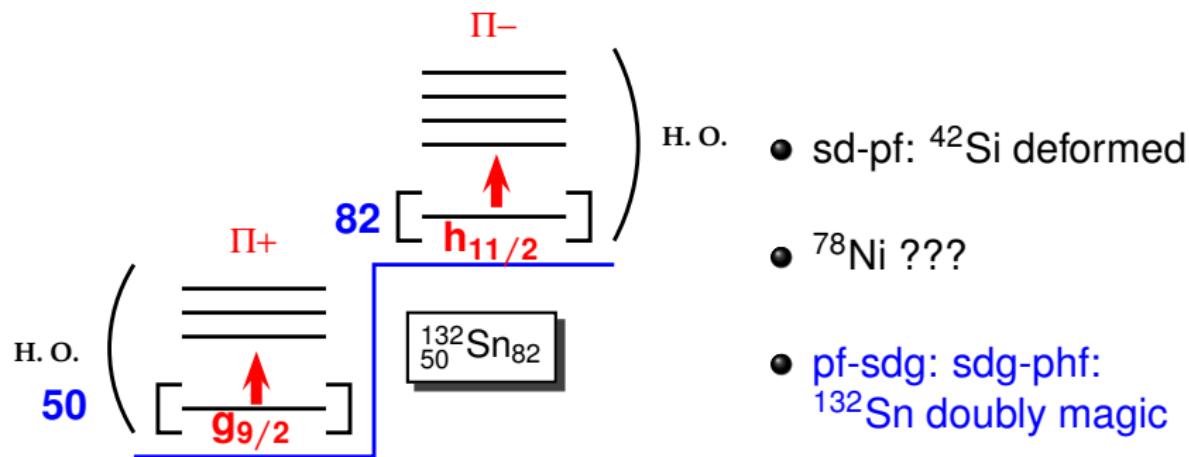
# Spin-orbit shell closure far from stability



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

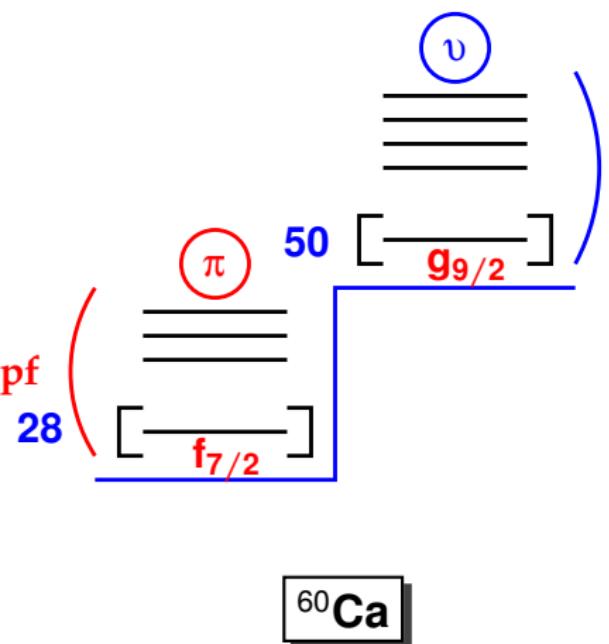
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# Physics around $^{78}\text{Ni}$



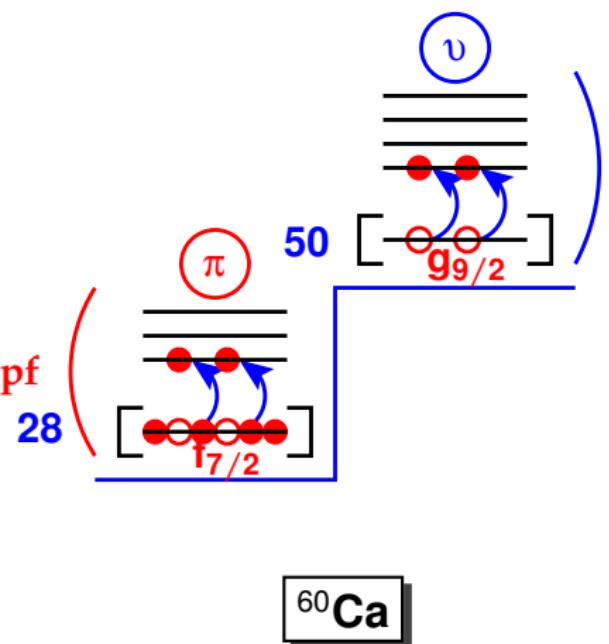
## PFSDG-U interaction:

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

## Calculations:

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

# Physics around $^{78}\text{Ni}$



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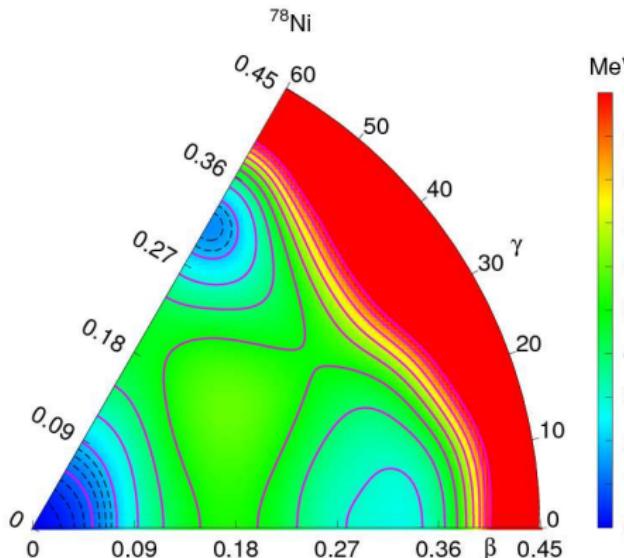
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# Shape coexistence in $^{78}\text{Ni}$

- At first approximation,  $^{78}\text{Ni}$  has a double closed shell structure for GS
- But very low-lying competing structures
- From the diagonalization, the first excited states in  $^{78}\text{Ni}$  are :
  - $0_2^+ - 2_1^+$  predicted at 2.6-2.9 MeV and to be deformed intruders of a **rotational 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 **Island of Inversion**

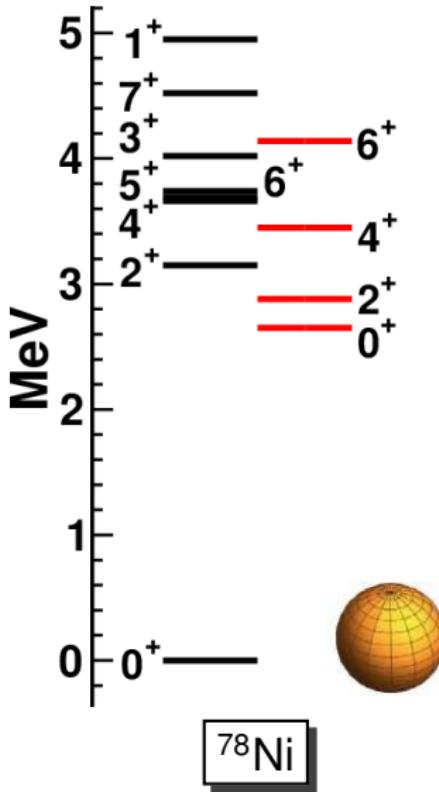


Constrained deformed HF in the SM basis

(Duy Duc Dao, DNO-SM calc., Strasbourg)

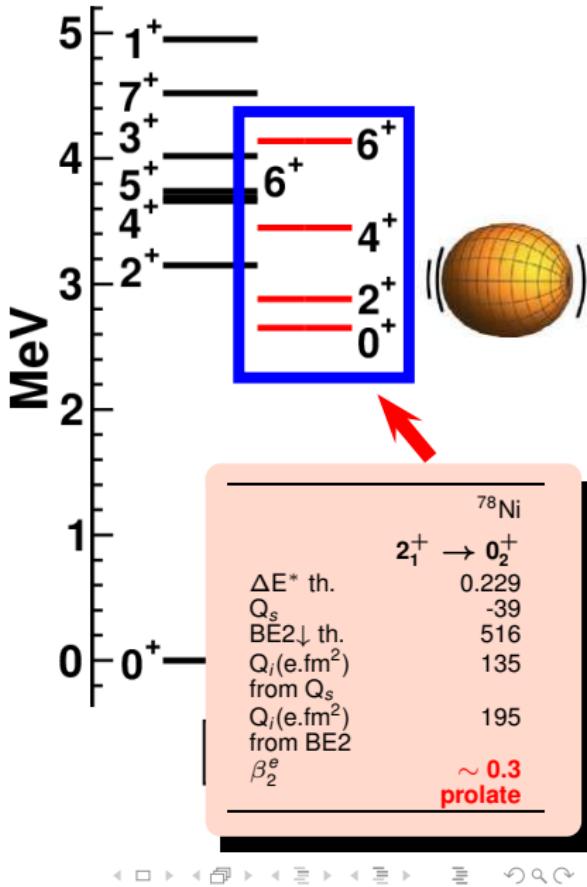
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F. Nowacki et al., PRL 177, 272501 (2016)



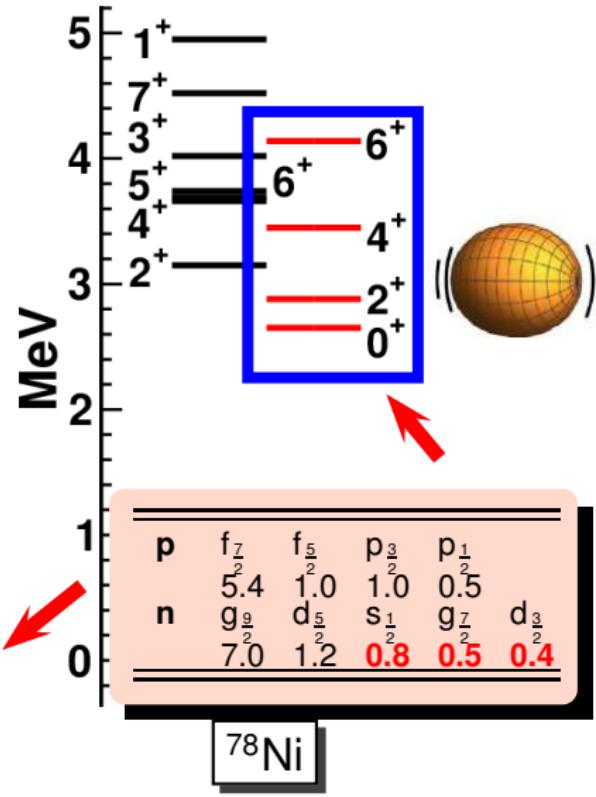
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F. Nowacki et al., PRL 177, 272501 (2016)



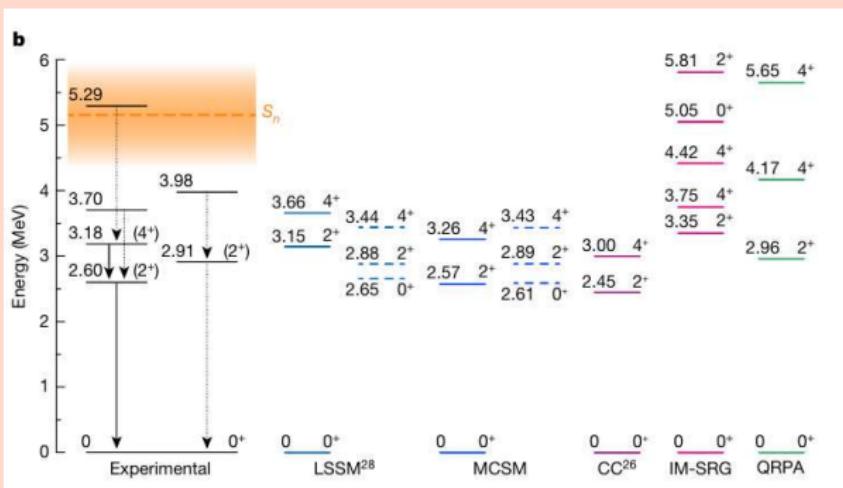
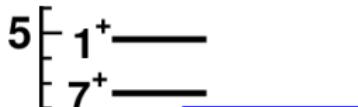
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F. Nowacki et al., PRL 177, 272501 (2016)



# Shape coexistence in $^{78}\text{Ni}$

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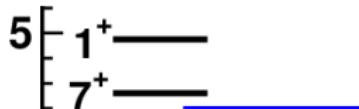


R. Taniuchi et al., NATURE 569, 53-58 (2019)

F. Nowacki et al., PRL 177, 272501 (2016)

$^{78}\text{Ni}$

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## ARTICLE

<https://doi.org/10.1038/s41586-019-1155-x>

# $^{78}\text{Ni}$ revealed as a doubly magic stronghold against nuclear deformation

R. Taniuchi<sup>1,2</sup>, C. Santamaría<sup>2,3</sup>, P. Doornenbal<sup>2\*</sup>, A. Obertelli<sup>2,3,4</sup>, K. Yoneda<sup>2</sup>, G. Authelet<sup>3</sup>, H. Baba<sup>2</sup>, D. Calvet<sup>3</sup>, F. Château<sup>3</sup>, A. Corsi<sup>3</sup>, A. Delbart<sup>3</sup>, J.-M. Gheller<sup>3</sup>, A. Gillibert<sup>3</sup>, J. D. Holt<sup>5</sup>, T. Isobe<sup>2</sup>, V. Lapoux<sup>3</sup>, M. Matsushita<sup>6</sup>, J. Menéndez<sup>6</sup>, S. Momiyama<sup>1,2</sup>, T. Motobayashi<sup>2</sup>, M. Niikura<sup>1</sup>, F. Nowacki<sup>7</sup>, K. Ogata<sup>8,9</sup>, H. Otsu<sup>2</sup>, T. Otsuka<sup>1,2,6</sup>, C. Péron<sup>3</sup>, S. Péru<sup>10</sup>, A. Peyaud<sup>3</sup>, E. C. Pollacco<sup>3</sup>, A. Poves<sup>11</sup>, J.-Y. Rousse<sup>3</sup>, H. Sakurai<sup>1,2</sup>, A. Schwenk<sup>4,12,13</sup>, Y. Shiga<sup>2,14</sup>, J. Simonis<sup>4,12,15</sup>, S. R. Stroberg<sup>5,16</sup>, S. Takeuchi<sup>2</sup>, Y. Tsunoda<sup>6</sup>, T. Uesaka<sup>2</sup>, H. Wang<sup>2</sup>, F. Browne<sup>17</sup>, L. X. Chung<sup>18</sup>, Z. Dombradi<sup>19</sup>, S. Franchoo<sup>20</sup>, F. Giacoppo<sup>21</sup>, A. Gottardo<sup>20</sup>, K. Hadynska-Klek<sup>21</sup>, Z. Korkulu<sup>19</sup>, S. Koyama<sup>1,2</sup>, Y. Kubota<sup>2,6</sup>, J. Lee<sup>22</sup>, M. Lettmann<sup>4</sup>, C. Louchart<sup>4</sup>, R. Lozeva<sup>7,23</sup>, K. Matsui<sup>1,2</sup>, T. Miyazaki<sup>1,2</sup>, S. Nishimura<sup>2</sup>, L. Olivier<sup>20</sup>, S. Ota<sup>6</sup>, Z. Patel<sup>24</sup>, E. Şahin<sup>21</sup>, C. Shand<sup>24</sup>, P.-A. Söderström<sup>2</sup>, I. Stefan<sup>20</sup>, D. Steffenbeck<sup>6</sup>, T. Sumikama<sup>25</sup>, D. Suzuki<sup>20</sup>, Z. Vajta<sup>19</sup>, V. Werner<sup>4</sup>, J. Wu<sup>2,26</sup> & Z. Y. Xu<sup>22</sup>

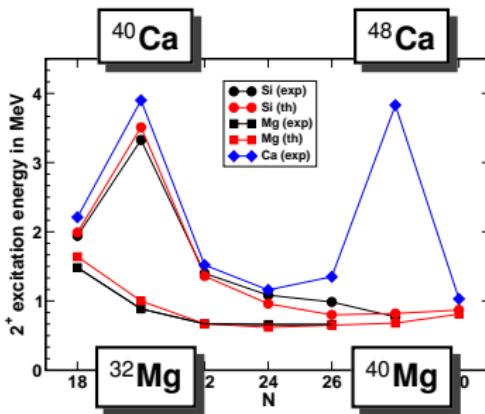
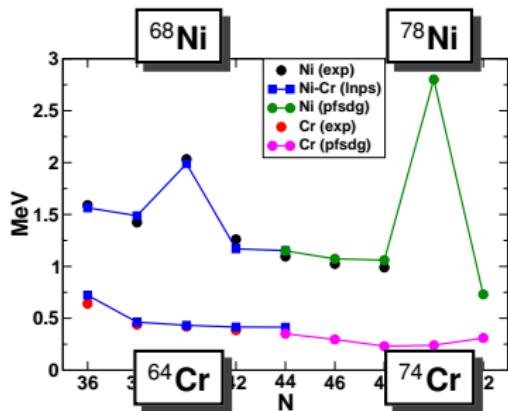
R. Taniuchi et al., NATURE 569, 53-58 (2019)

Portal to a new island of inversion:  
F. Nowacki et al., PRL 177, 272501 (2016)

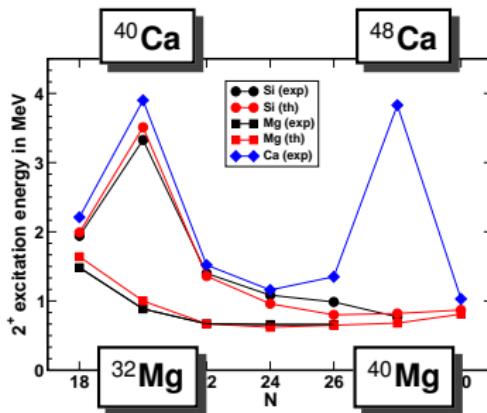
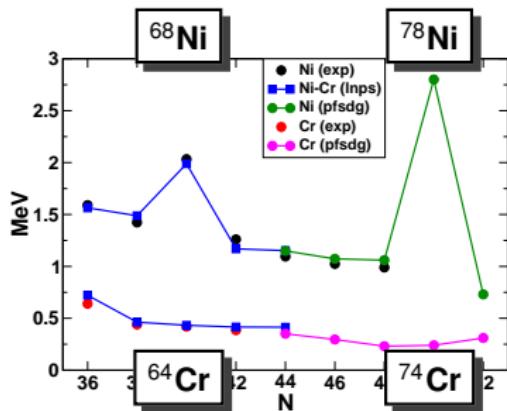
$^{78}\text{Ni}$

$d_{\frac{3}{2}}$   
0.4

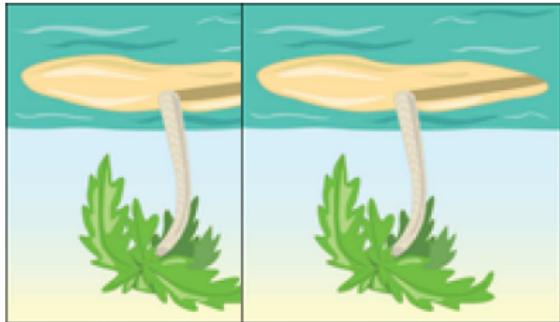
# Island of Inversion Mergers



# Island of Inversion Mergers



The N=40 and N=50 IoI's merge like the N=20 and N=28 IoI's did



# Summary of exotic nuclei

- Simple understanding of realistic effective interactions
- Pioneer work for description of neutron-rich systems
- Appealing similar mechanism for Island of inversion at  $N=20/N=40$  and  $N=28/N=50$
- Much more to follow ...