Developments in Nuclear Structure

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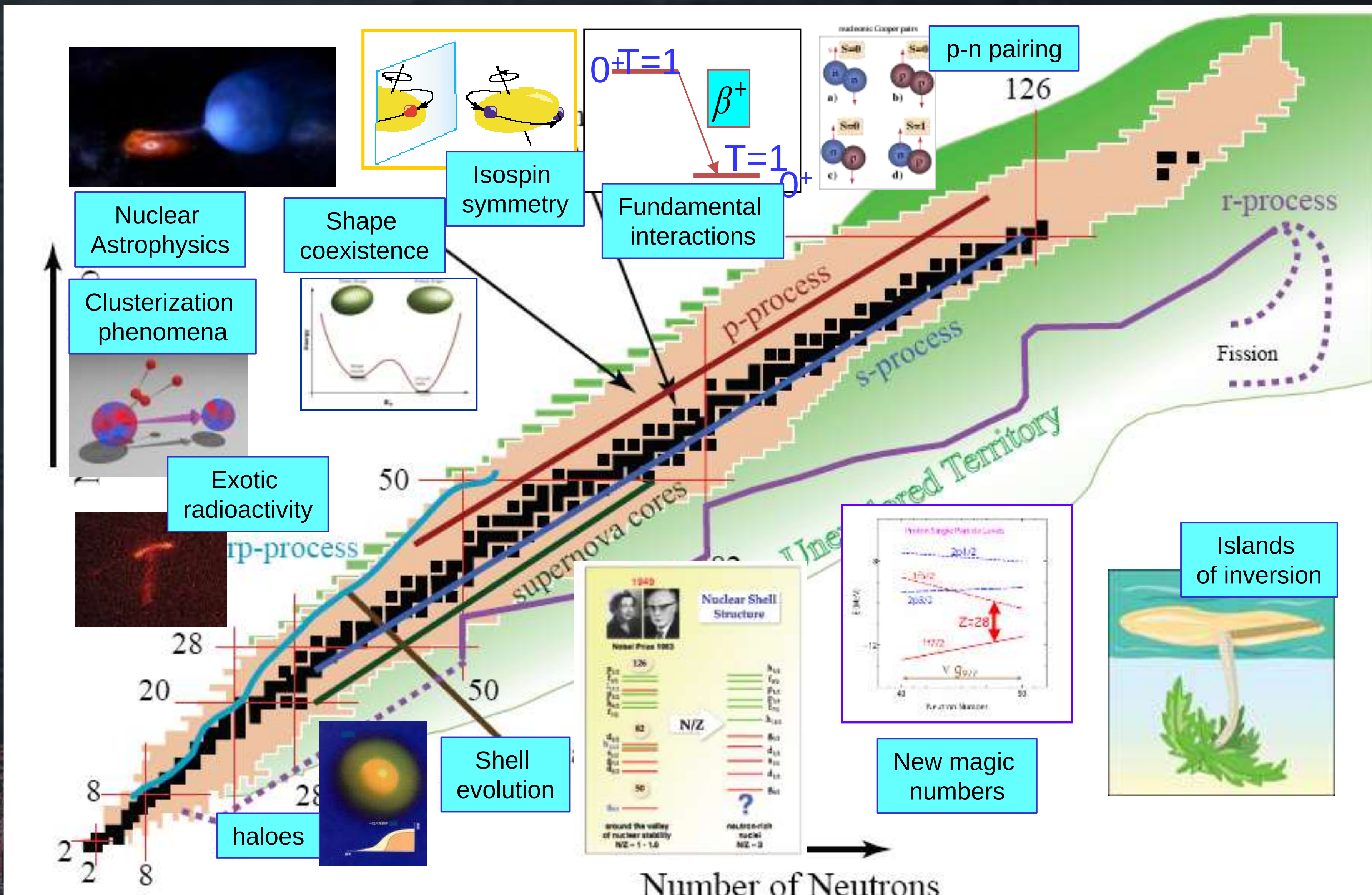
New phenomena far from stability



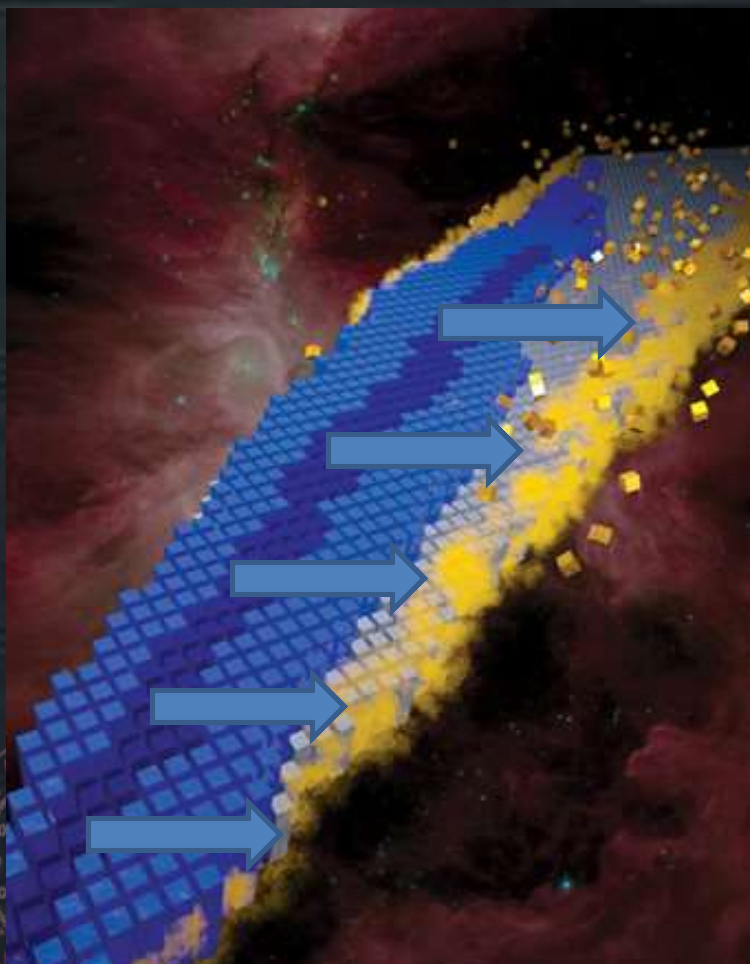
The neutron-rich side

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

How we study neutron-rich nuclei

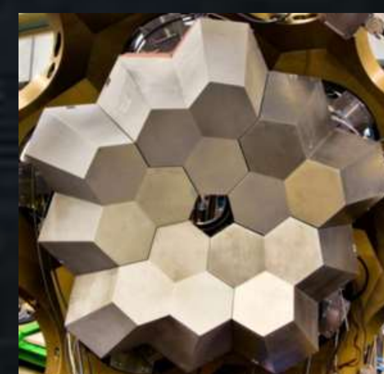
Production:

Stable beams: grazing reactions, fission
Radioactive ion beams: ISOL, fragmentation



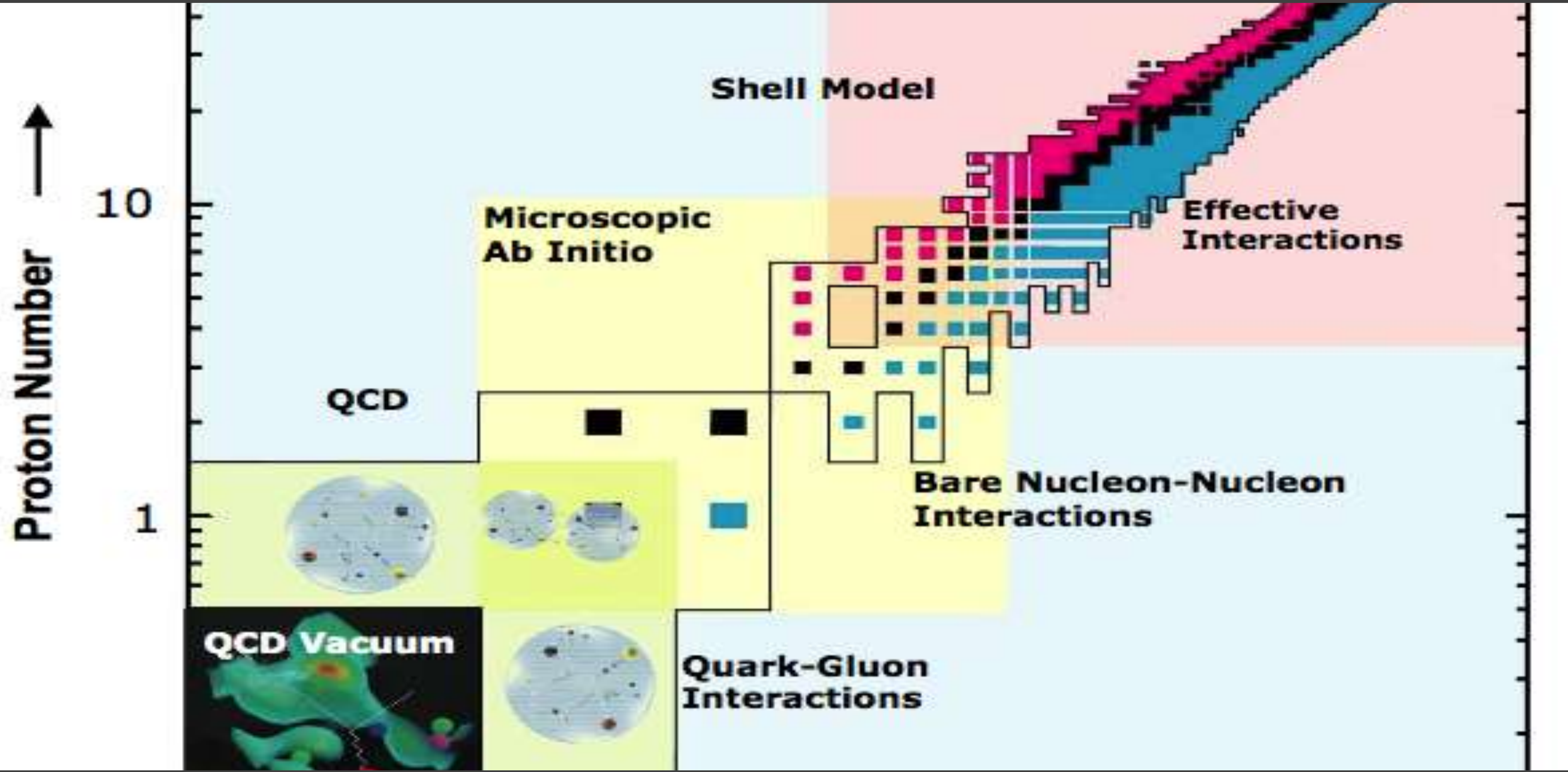
Theoretical description with the shell model

Detailed structure with gamma spectroscopy



Nuclear forces and shell evolution

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



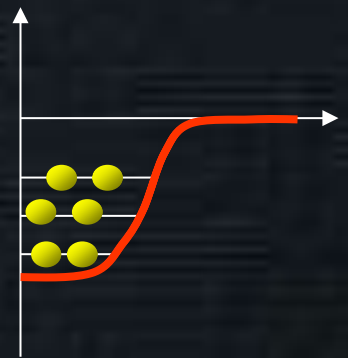
Data on exotic nuclei put in evidence the role of specific terms of the nuclear interaction and demand an improved modelling

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

M. Dufour , A. P. Zuker, PRC 54, 1641(1996).

Interplay: Monopole and Multipole

The interplay of the monopole with the 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

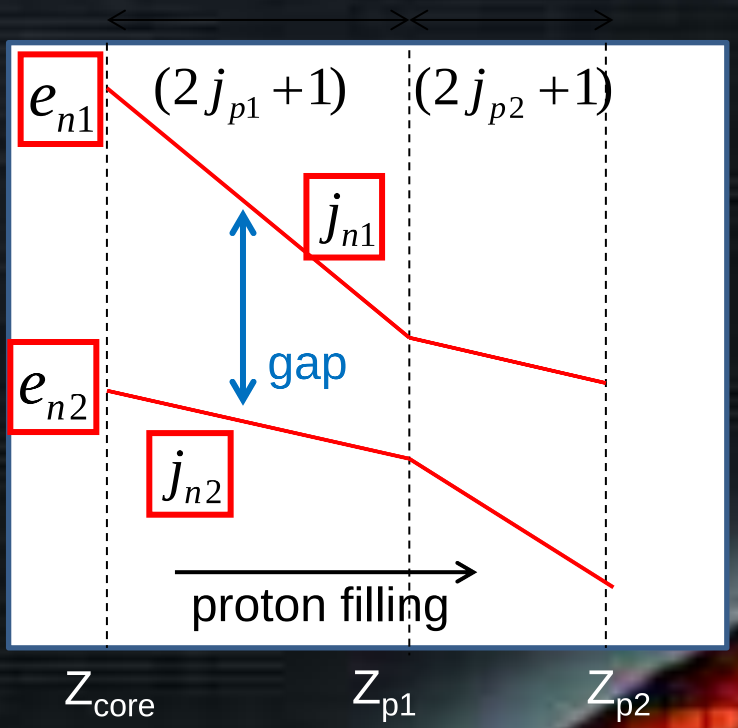
The monopole matrix element of an operator *V* can be written as

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

→ **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)

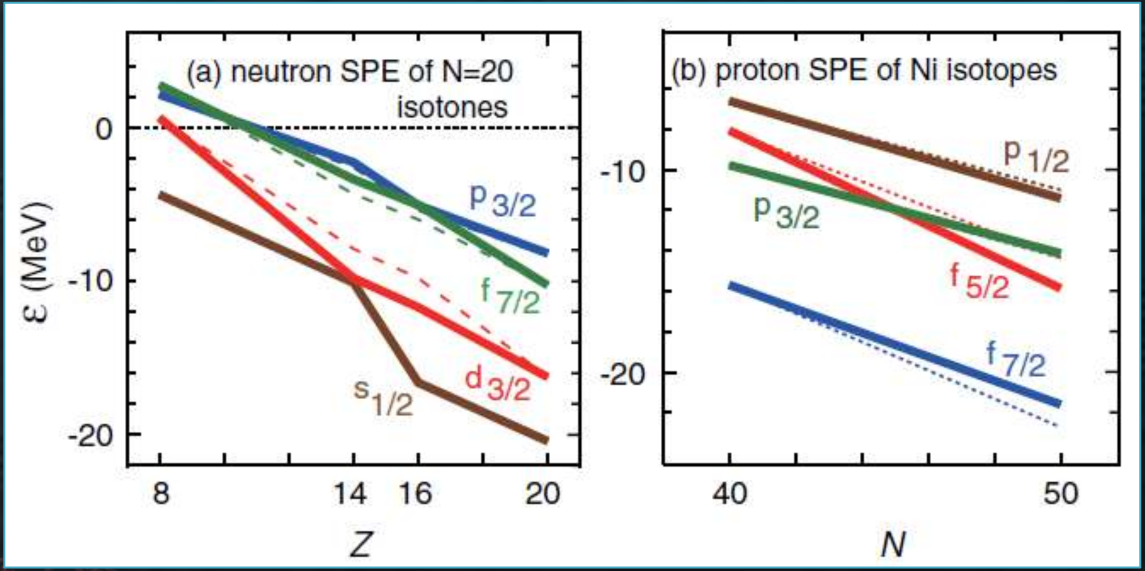
O. Sorlin and M.G. Porquet PPNP 61 (2008) 602-673

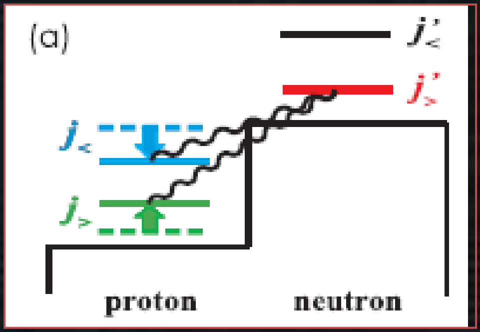
Effect of the monopole tensor force

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

- - - - - - - - only central
——— central + tensor

The effects of the tensor force are put in evidence far from stability

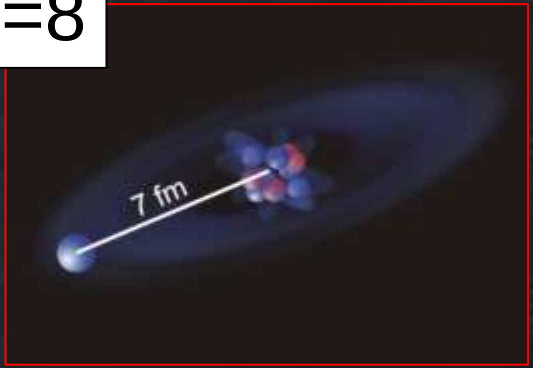




T. Otsuka et al., PRL 104, 012501 (2010)
N. A. Smirnova et al., PLB 686, 109 (2010)

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

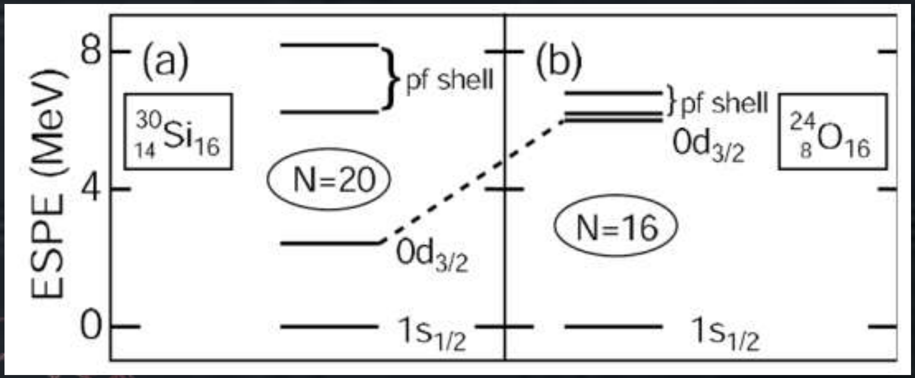
N=8



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

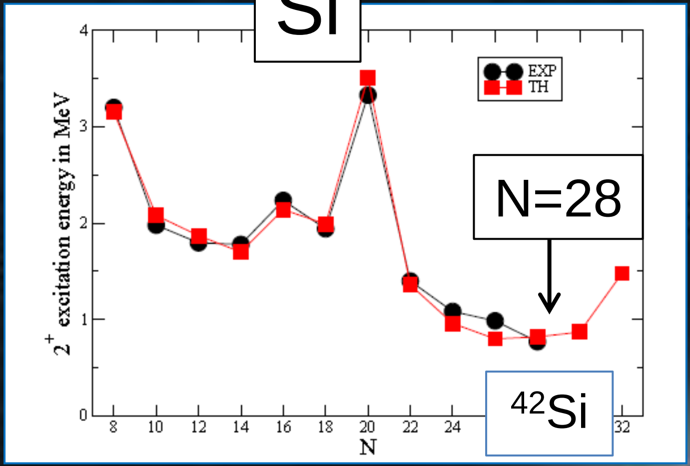
Deformed intruder configurations fall below the spherical ones

N=20



T. Otsuka)

Si

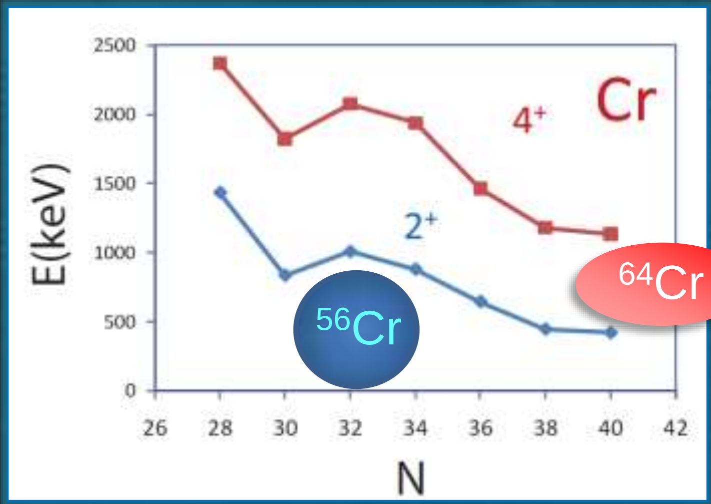


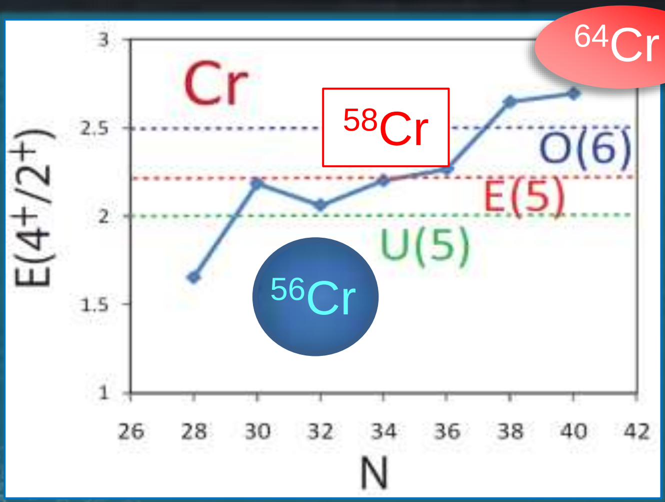
A. Poves

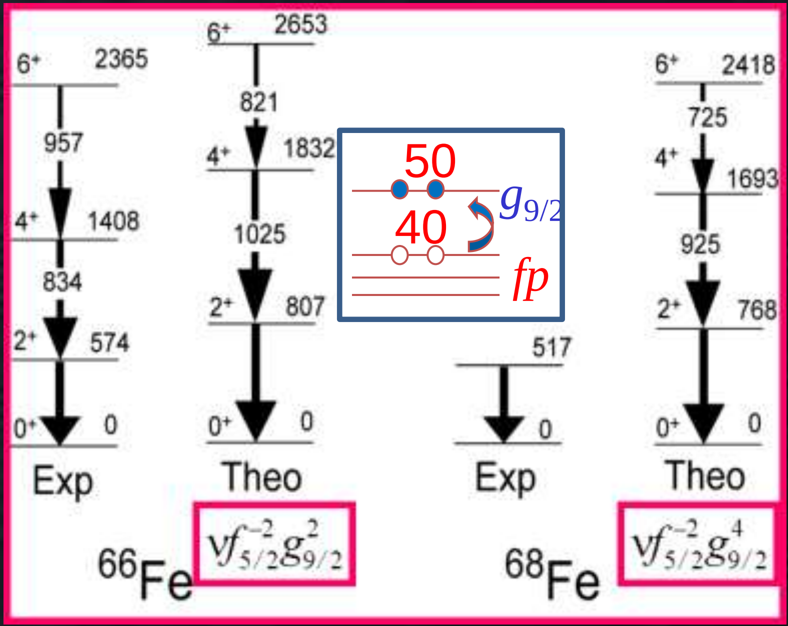
Island of Inversion in N=40

A new region of deformation appears south of ^{68}Ni

Shape changes along isotopic chains







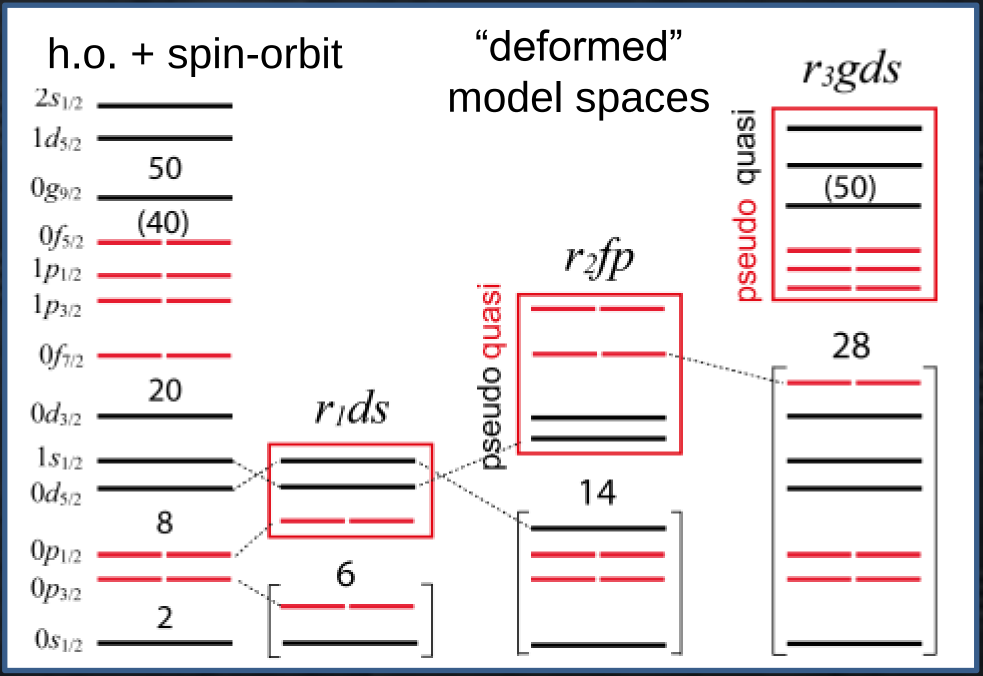
The "normal" model space cannot reproduce the structure far from stability

Beta decay: O. Sorlin et al., EPJA 16, 55 (2003)
Multinucleon transfer: N. Marginean et al., PLB 633, 696 (2006)
S. Zhu et al., PRC 74, 064315 (2006)
S.M.Lenzi et al, LNL Ann. Rep. (2008)
(p,p'): N. Aoi et al., PRL 102 012502 (2009)
Inelastic scattering: A. Gade et al., PRC 81, 051304(R) (2010)

"Deformed" model spaces

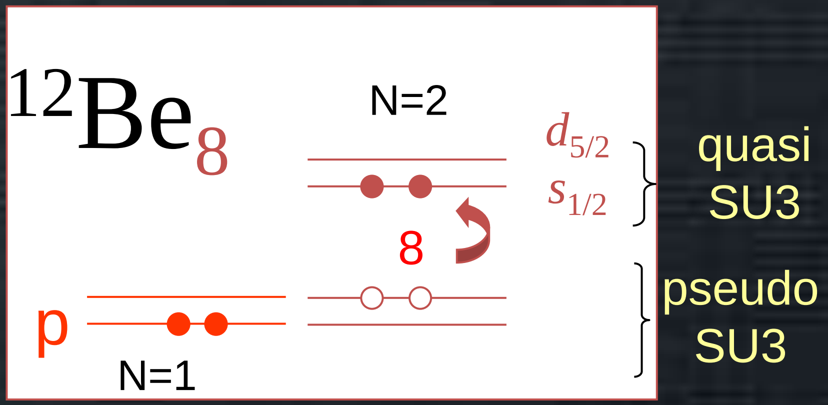
The onset of the different modes of quadrupole collectivity depend on the structure of the spherical mean field

Deformed structures can be described with the shell model provided a suitable (symmetry-based) model space is considered

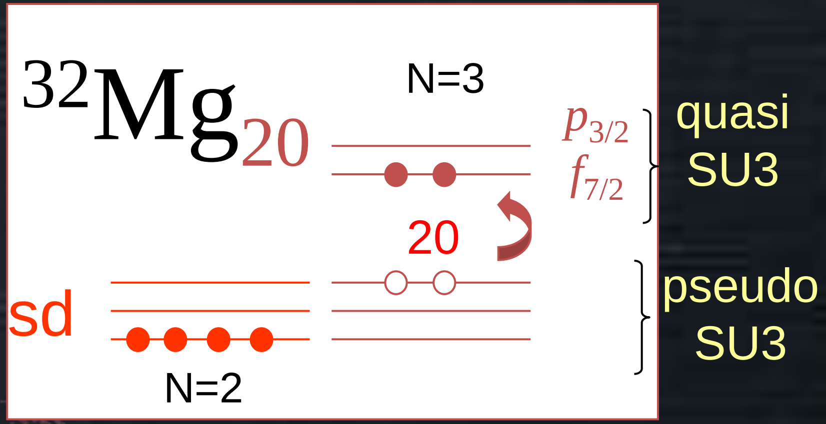


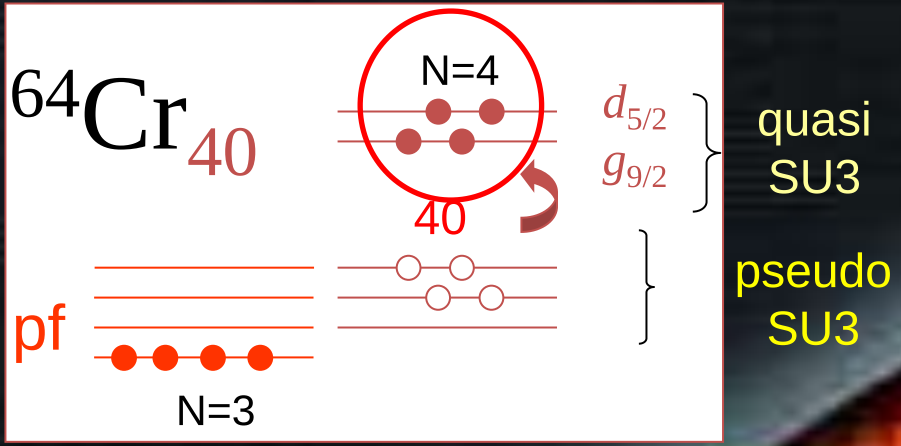
Zuker, Poves, Nowacki, Lenzi, arXiv:1404.0224v2

Islands of inversion and symmetries



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





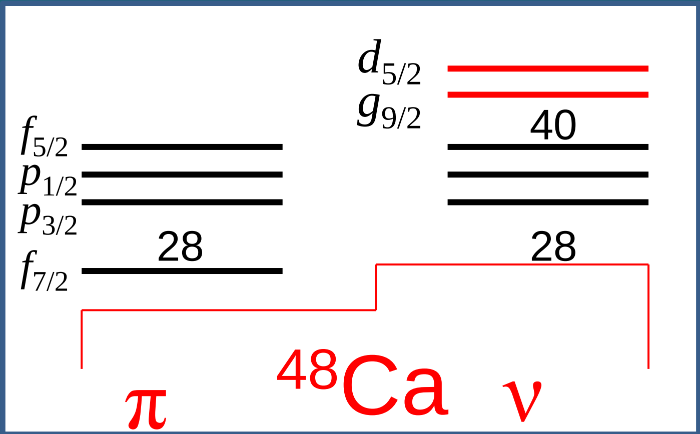
Deformation and SM in the fpgd space

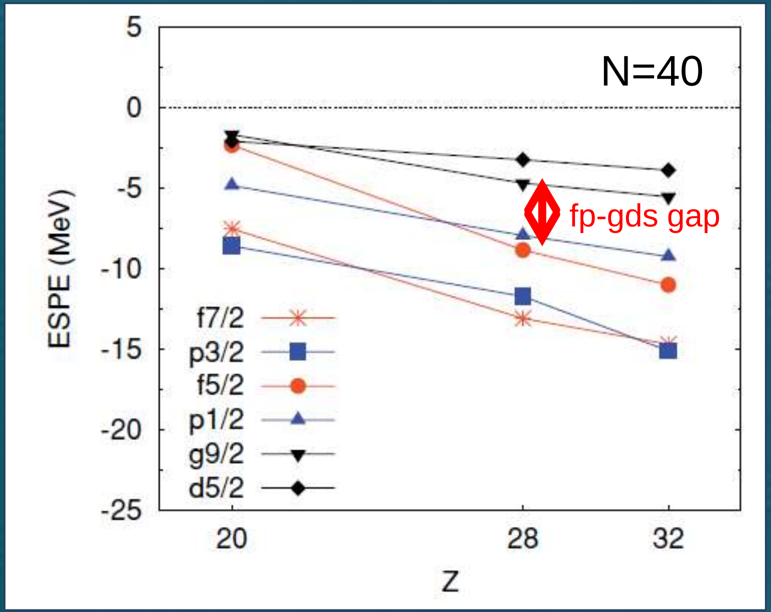
LNPS interaction: renormalized realistic interaction + monopole corrections

^{48}Ca core

protons: full pf shell

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



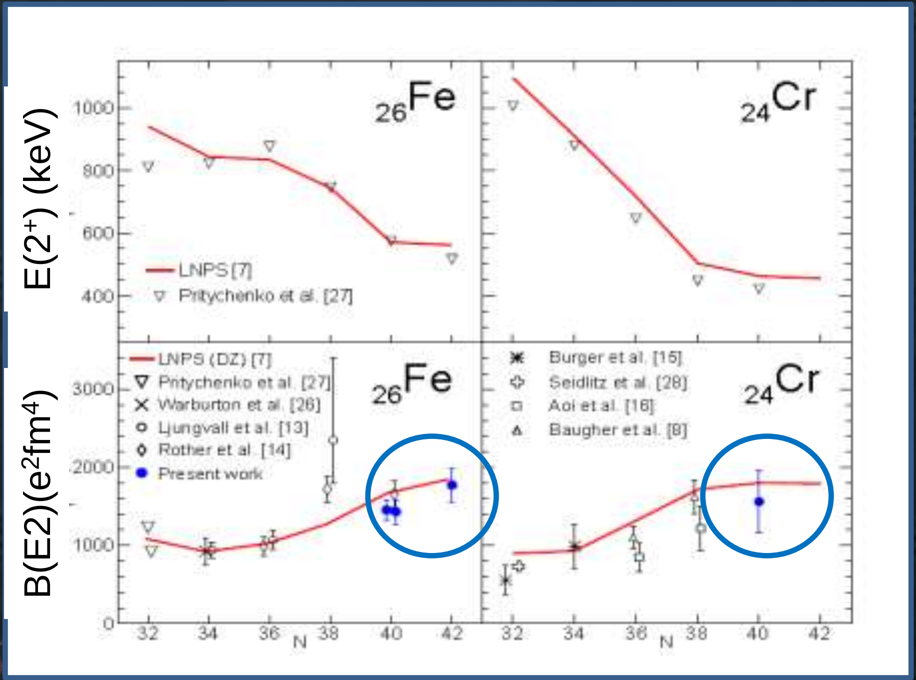


Note: the ground-state deformation properties result from the total balance between the monopole and the correlation energies

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

Measurement of deformation with fast radioactive beams

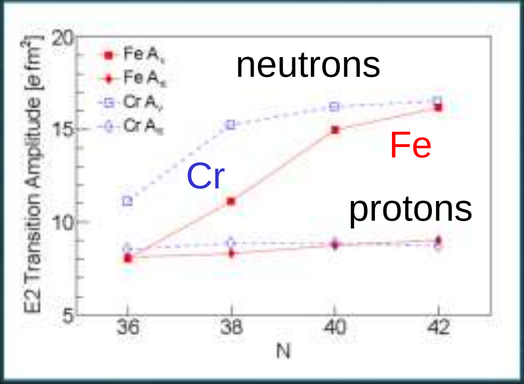
Coulomb excitation experiment
LNPS calculations



$$B(E2:2_1^+ \to 0_1^+) = (e_\pi A_\pi + e_\nu A_\nu)^2$$
$$Q_0 = \sqrt{16\pi\ B(E2\downarrow)} = \sqrt{16\pi}(e_\pi A_\pi + e_\nu A_\nu)$$

The most deformed nuclei are $^{62-64}$Cr.
While the B(E2) is larger for Fe,
the mass quadrupole moment

$$Q_0(mass) = \sqrt{16\pi}\ q_m(A_\pi + A_\nu)$$



$\beta = 0.3$

H. L. Crawford et al., PRL110, 242701 (2013)

Triple shape coexistence in ^{68}Ni

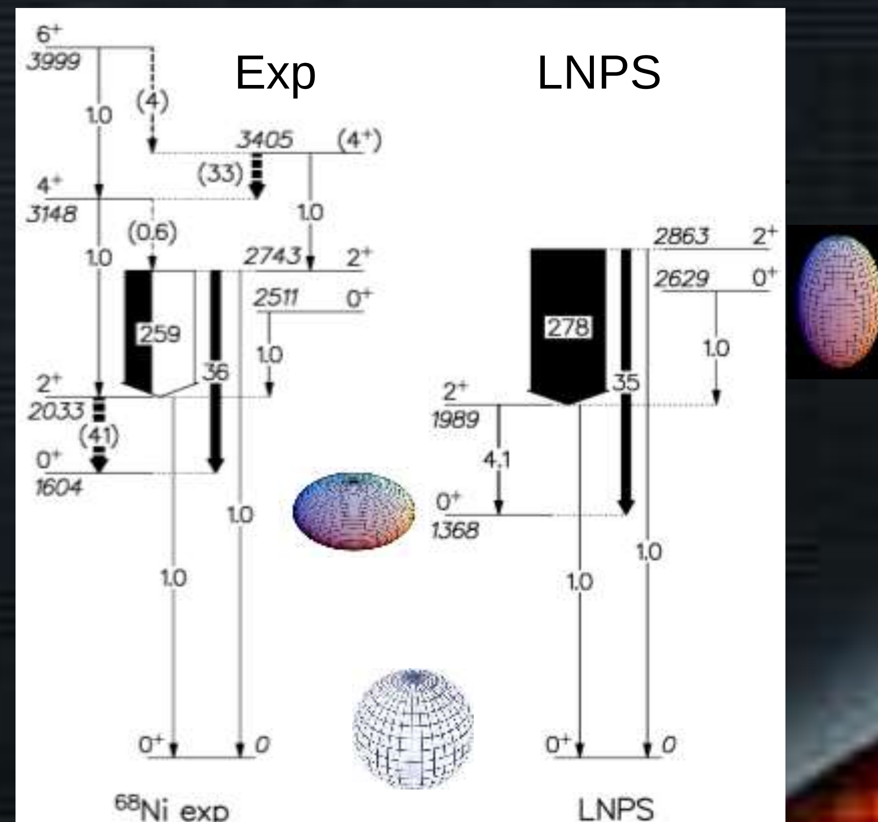
In first approximation, ^{68}Ni has a double closed shell structure in the g.s.

The first three 0+ states are predicted to have different shapes

Shell model calculations reproduce well all these structures

F. Nowacki, LNPS calculations (2013)

N. Tsunoda et al., Phys.Rev. C 89, 024313 (2014)



F. Recchia et al.
Phys. Rev. **C88**, 041302(R) (2013)

Beyond Z=28: Zn isotopes with AGATA at LNL

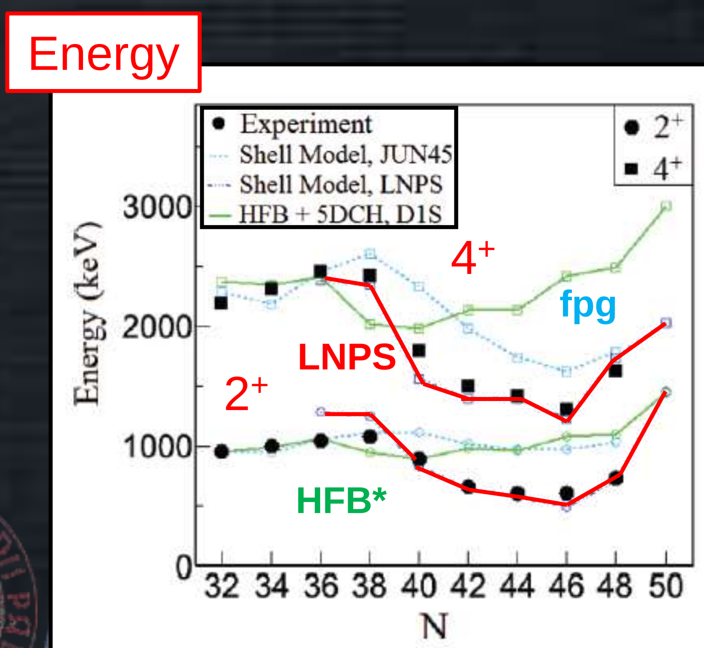
PHYSICAL REVIEW C **87**, 054302 (2013)

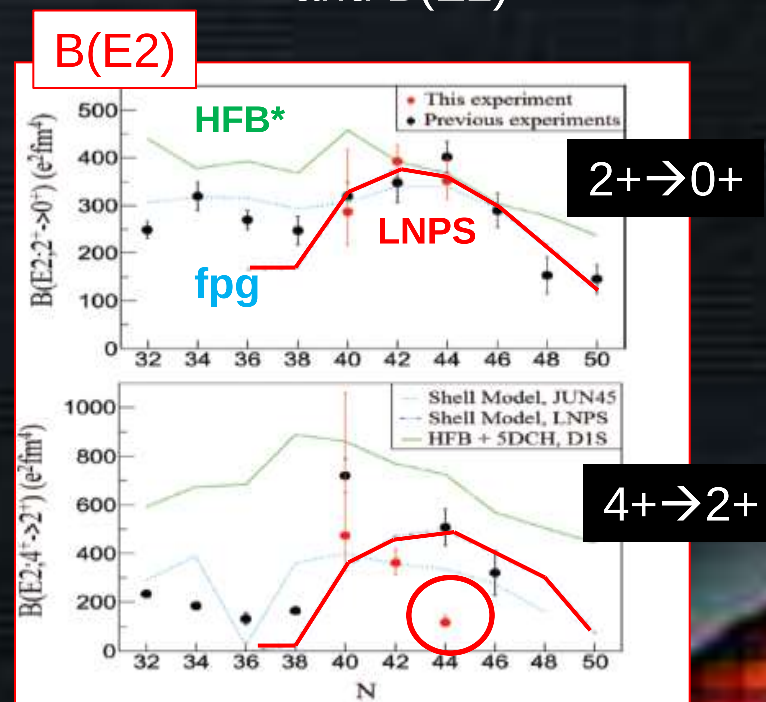
Collective nature of low-lying excitations in ^{70,72,74}Zn from lifetime measurements using the AGATA spectrometer demonstrator

C. Louchart,[1,*] A. Obertelli,[1] A. Görgen,[1,†] W. Korten,[1] D. Bazzacco,[2] B. Birkenbach,[3] B. Bruyneel,[1] E. Clément,[4] P. J. Coleman-Smith,[5] L. Corradi,[6] D. Curien,[7] G. de Angelis,[6] G. de France,[4] J.-P. Delaroche,[8] A. Dewald,[3] F. Didierjean,[7] M. Doncel,[9] G. Duchêne,[7] J. Eberth,[3] M. N. Erduran,[10] E. Farnea,[2] C. Finck,[7] E. Fioretto,[6] C. Fransen,[3] A. Gadea,[11] M. Girod,[8] A. Gottardo,[6] J. Grebosz,[12] T. Habermann,[13] M. Hackstein,[3] T. Huyuk,[11] J. Jolie,[3] D. Judson,[14] A. Jungclaus,[15] N. Karkour,[16] S. Klupp,[17] R. Krücken,[17] A. Kusoglu,[18] S. M. Lenzi,[2] J. Libert,[8] J. Ljungvall,[16,1] S. Lunardi,[2] G. Maron,[6] R. Menegazzo,[2] D. Mengoni,[19,2] C. Michelagnoli,[2] B. Million,[20] P. Molini,[2] O. Möller,[21] G. Montagnoli,[2] D. Montanari,[2] D. R. Napoli,[6] R. Orlandi,[19] G. Pollarolo,[22] A. Prieto,[9] A. Pullia,[20] B. Quintana,[9] F. Recchia,[2] P. Reiter,[3] D. Rosso,[6] W. Rother,[3] E. Sahin,[6] M.-D. Salsac,[1] F. Scarlassara,[2] M. Schlarb,[17] S. Siem,[23] P. P. Singh,[6] P.-A. Söderström,[24] A. M. Stefanini,[6] O. Stézowski,[25] B. Sulignano,[1] S. Szilner,[26] Ch. Theisen,[1] C. A. Ur,[2] J. J. Valiente-Dobón,[6] and M. Zielinska[1]

Lifetimes obtained with the RDDS method

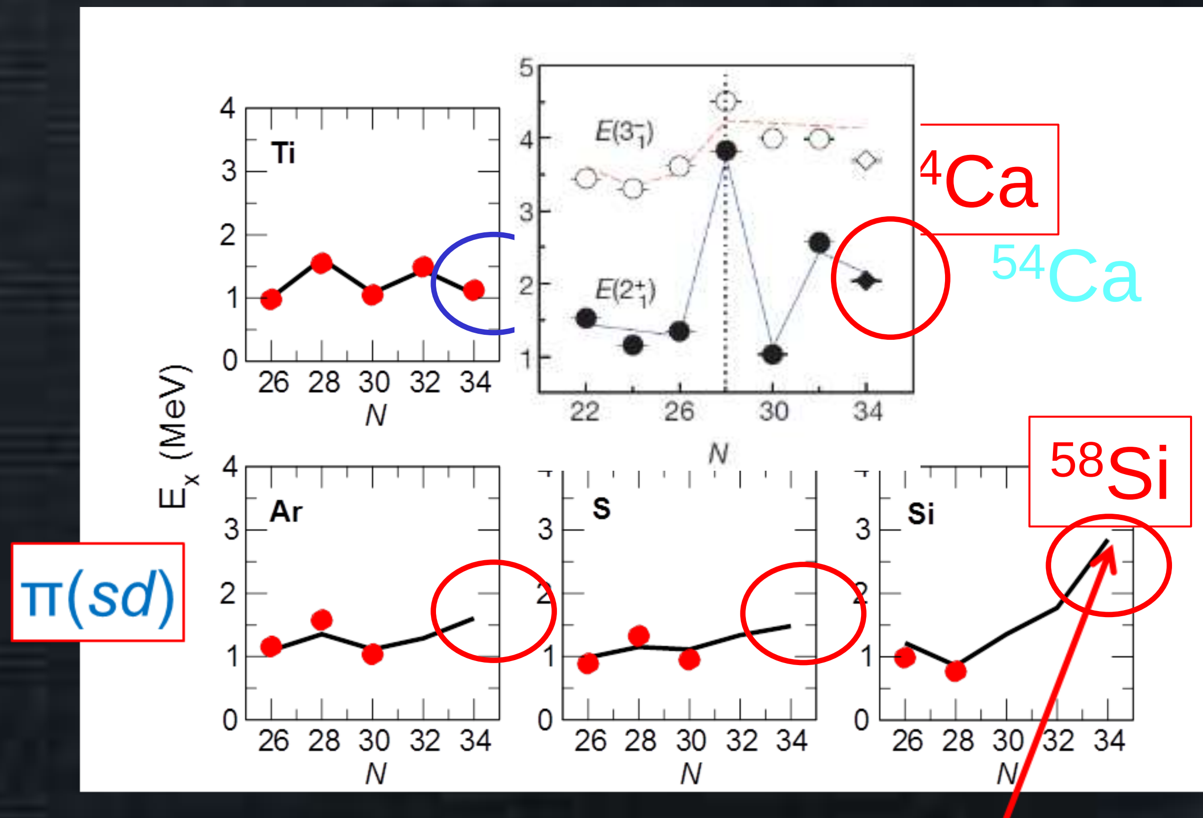
LNPS calculations in very good agreement for the energies and B(E2)





A new magic number at N=34

D. Steppenbeck et al.,
Nature 502, 207 (2013)



Y. Utsuno et al, ARIS2014 presentation
MCSM calculations in the sdfp space

doubly magic

Three-body forces important (see Holt, Menendez, Schwenk 2013)

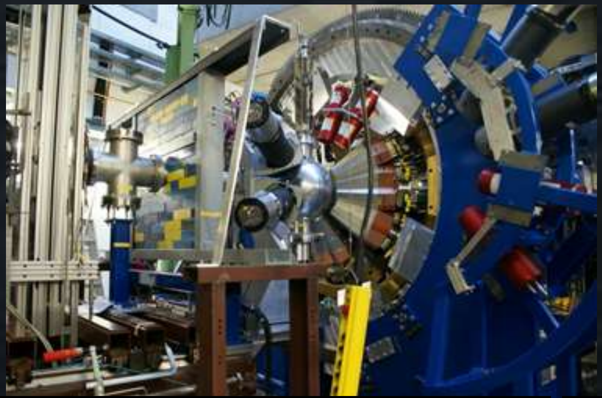
Nuclear Structure with FAIR

The NUSTAR collaboration foresees different experimental methods, setups and energy ranges for nuclear structure studies

HISPEC: in-beam gamma-spectroscopy at low and intermediate energy
DESPEC: α-decay, β-decay, γ-decay, p-decay,n-decay,cluster-decay

Both will make use of high-efficient, high-resolution gamma-ray arrays

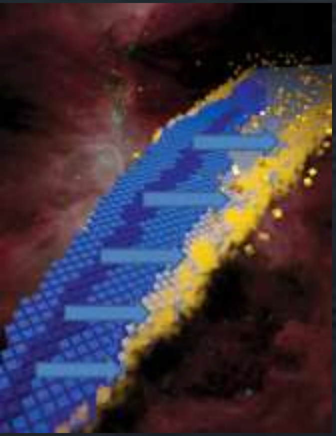
10/10/2014



LNL 2010-2011 → **GSI 2012-2014** → **GANIL 2014-2018**

Conclusions

Neutron-rich nuclei at the harmonic oscillator closures show sudden changes in their structure and give rise to islands of inversion.



This gives information on the evolution of the shell structure and can be interpreted in terms of symmetries and described with state-of-the-art shell model calculations.

The structure of nuclei far from stability put in evidence terms of the interaction that are “hidden” near stability

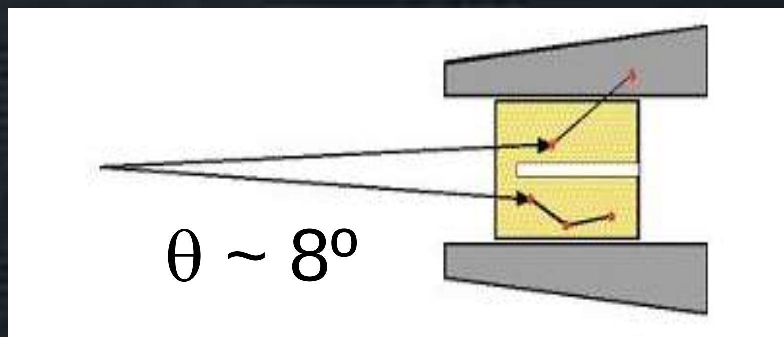
Experiments at the ISOL and Fragmentation Facilities are complementary in understanding nuclear structure properties

Backup slides

The idea of tracking

Compton Shielded Ge

ε_{ph}~ 10%
P/T~ 60%



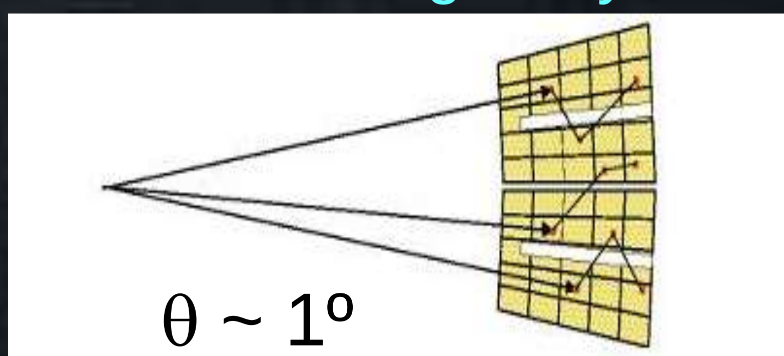
Limiting factors:

solid angle covered by anti-Compton

Doppler broadening

Ge Tracking Array

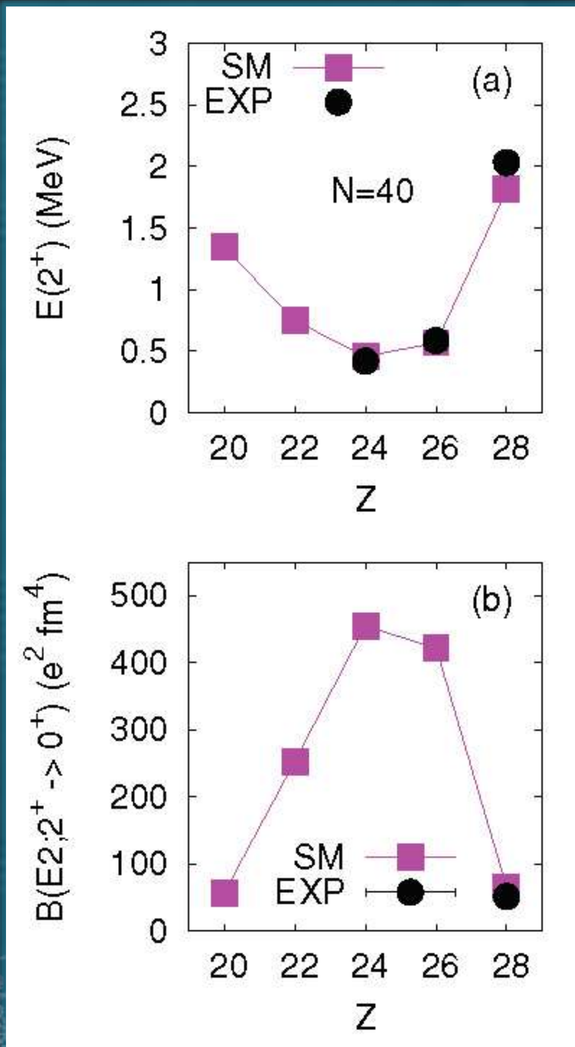
ε_{ph}~ 50%
P/T~ 60%



Combination of:

- segmented detector
- digital electronics
- pulse processing
- tracking the γ-ray

The N=40 isotones



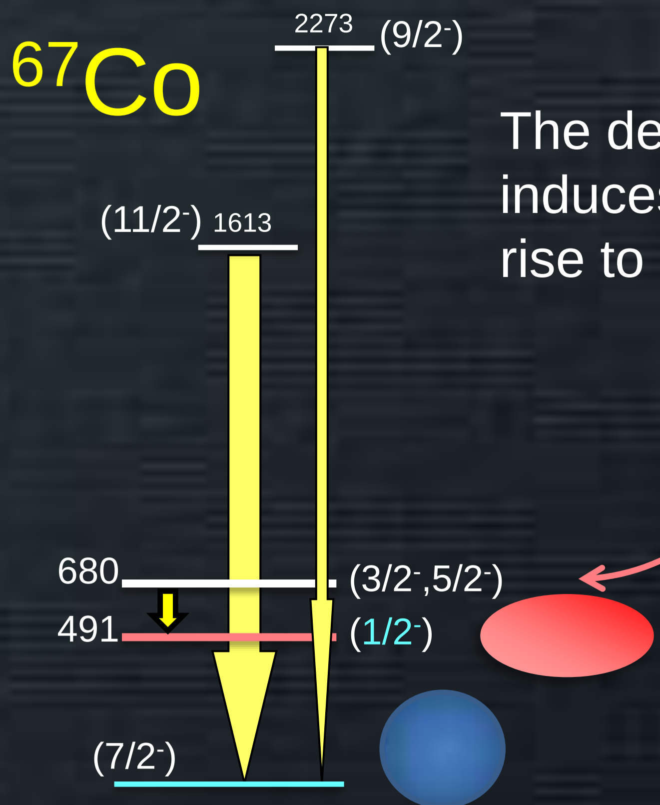
A change of structure is observed along the isotonic chain in good agreement with the available data

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

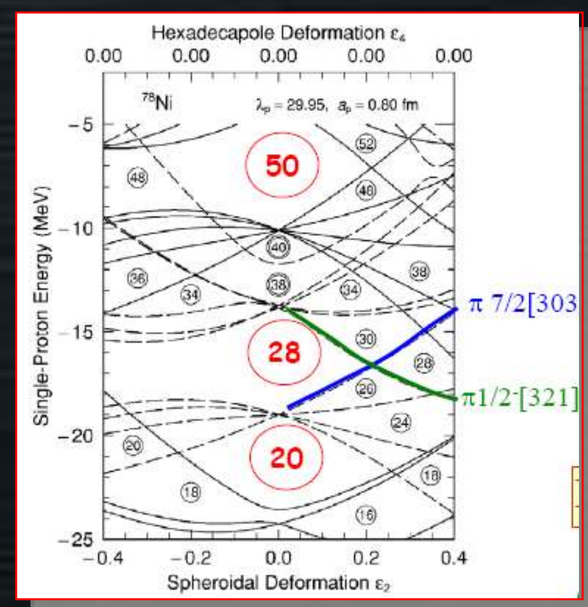
Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	0p0h	2p2h	4p4h	6p6h	E_{corr}
^{68}Ni	0.98	0.10	55.5	35.5	8.5	0.5	−9.03
^{66}Fe	3.17	0.46	1	19	72	8	−23.96
^{64}Cr	3.41	0.76	0	9	73	18	−24.83
^{62}Ti	3.17	1.09	1	14	63	22	−19.62
^{60}Ca	2.55	1.52	1	18	59	22	−12.09

LNPS, PRC 82, 054301 (2010)

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

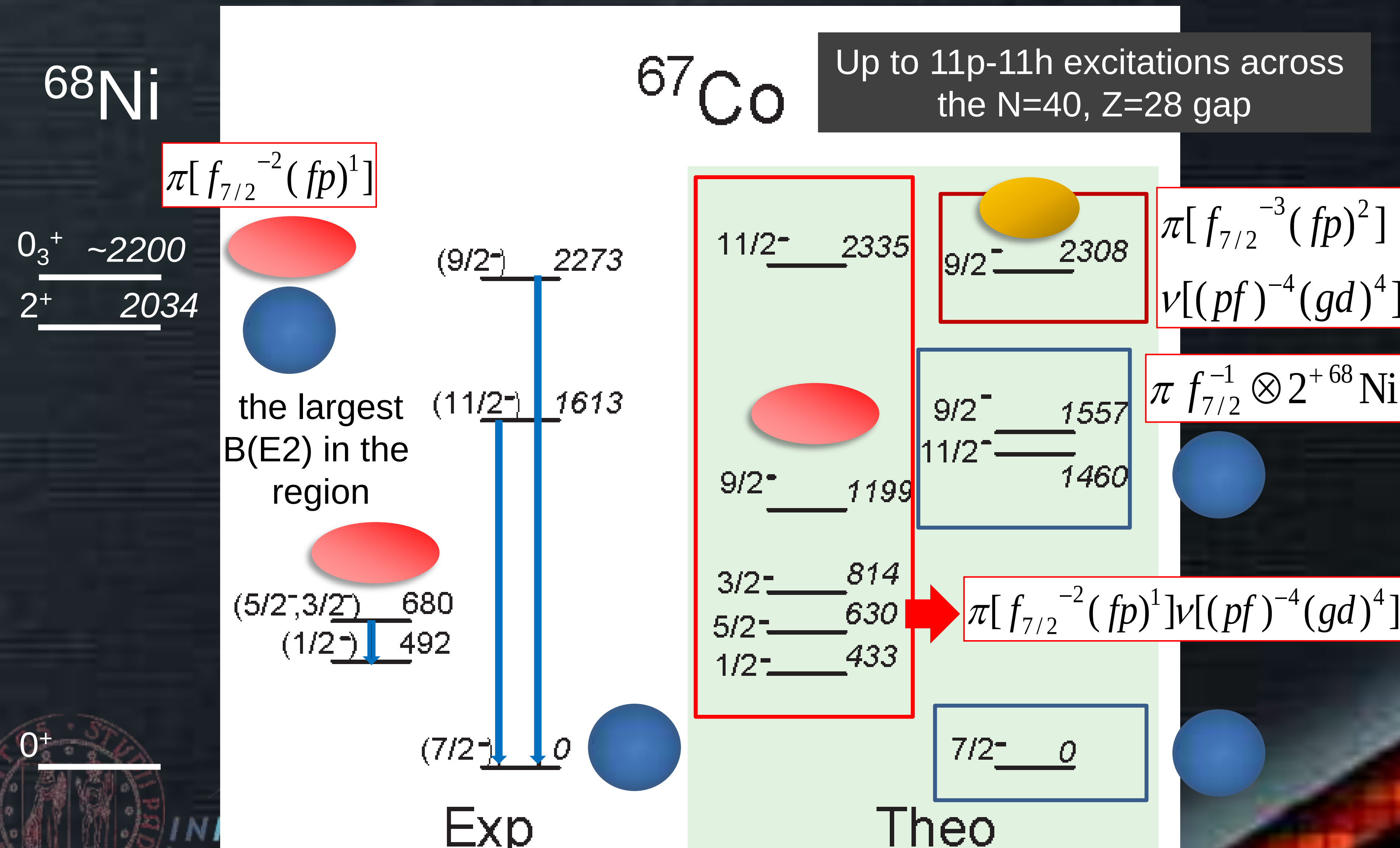


F. Recchia et al., PRC 85, 064305 (2012)

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

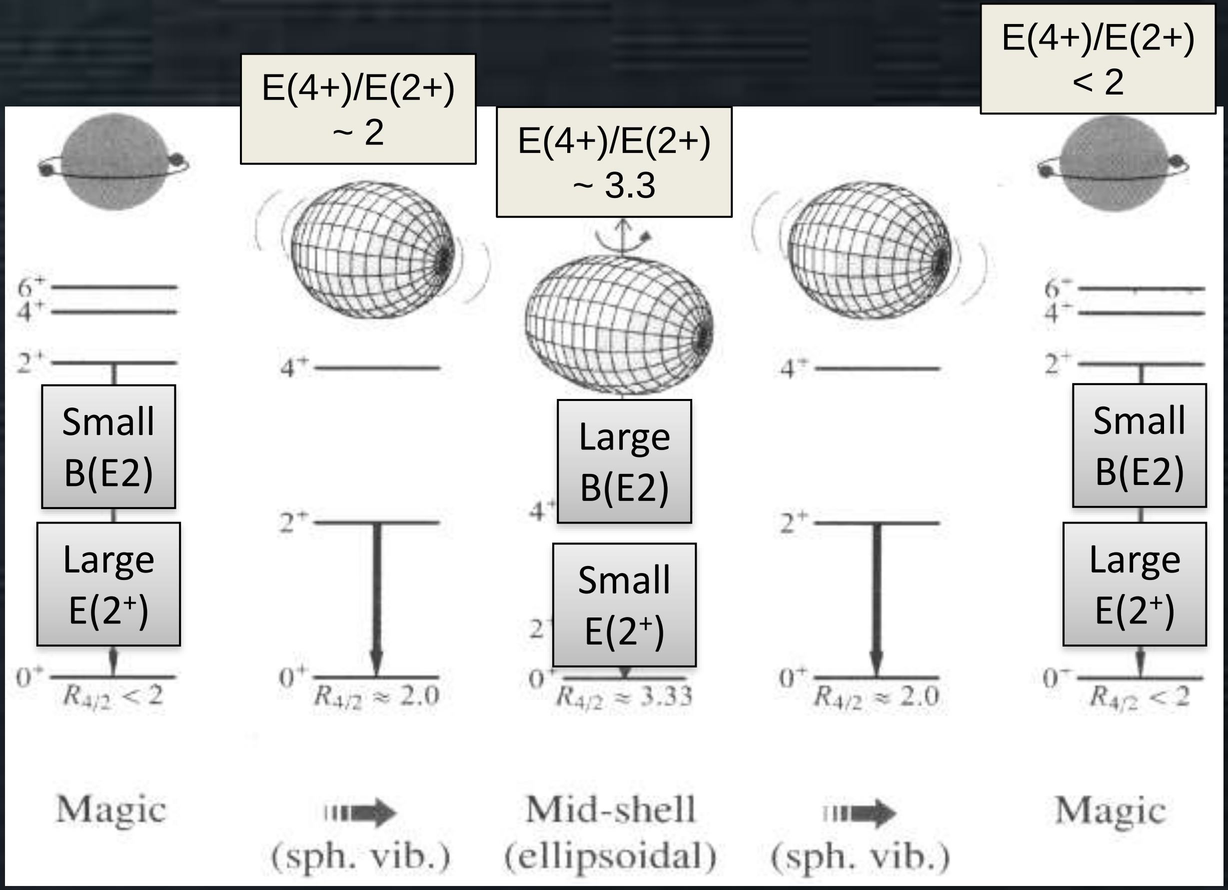
The LNPS interaction is able to reproduce these structures

Shape coexistence in ^{67}Co



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

Some useful observables

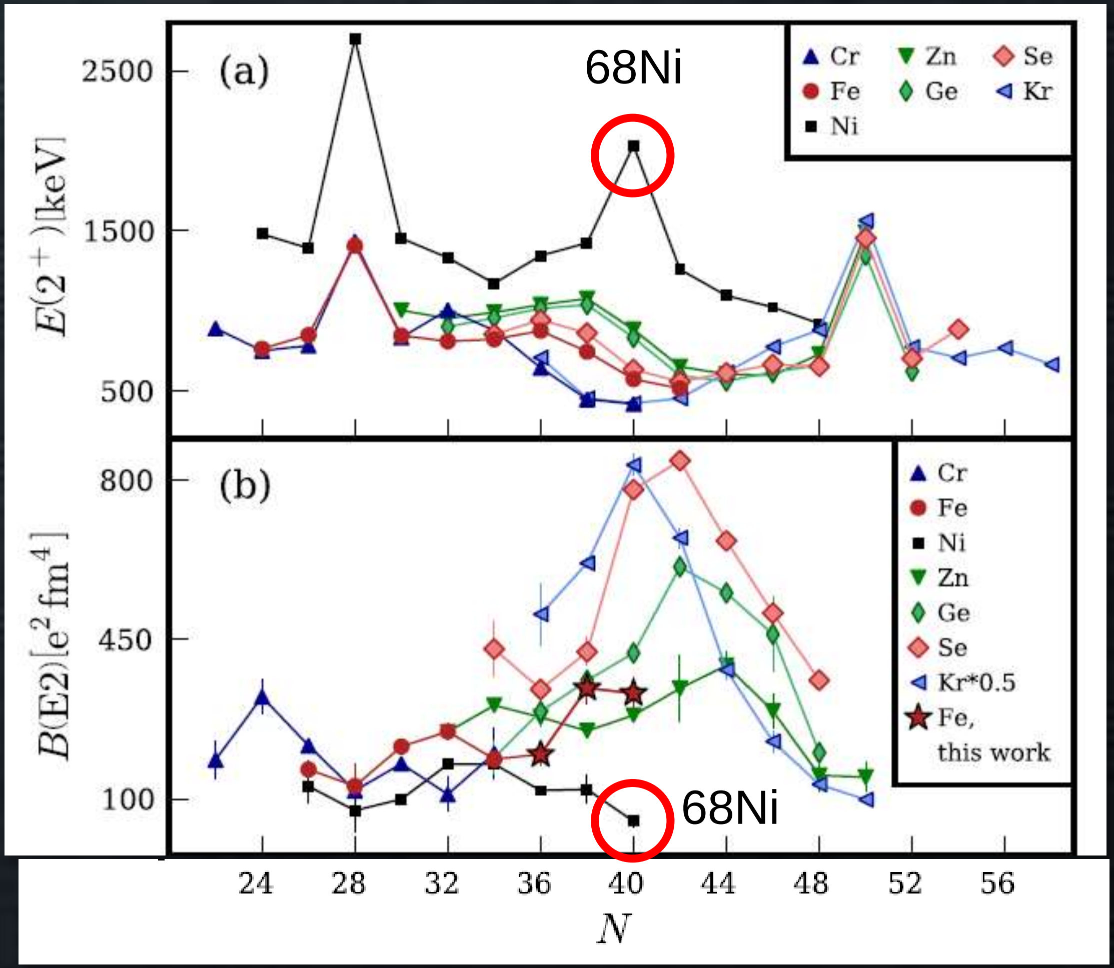


These are just fingerprints that need to be verified with further measurements

Island of Inversion in N=40

E(2+)

B(E2)



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