Perspectives in Nuclear Structure

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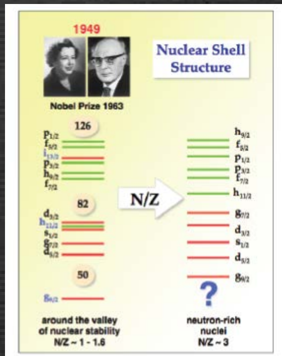
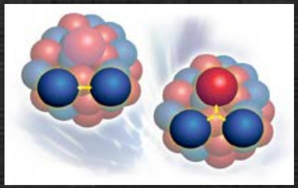
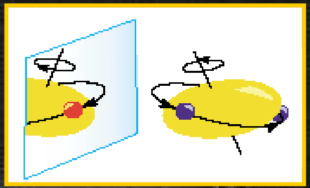
Shell evolution far from stability

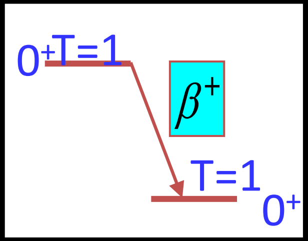




Three-body forces

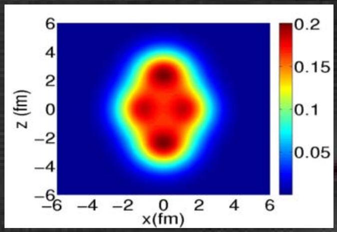
Isospin symmetry breaking





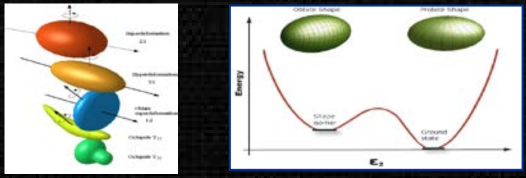
Fundamental interactions

clusterization

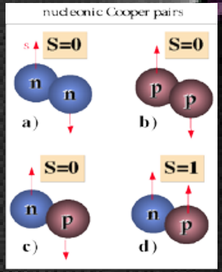


Nuclei far from stability present a richness of properties that allow to study the role of the different components of the nuclear interaction

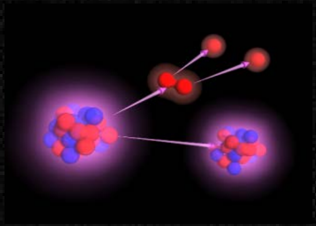
Nuclear shapes and coexistence



p-n pairing



Nuclear Astrophysics



Coupling to the continuum

Outline

- Introduction
- Development of deformation around magic numbers: Islands of Inversion
- Robustness of shell gaps and single-particle energies
- Halo orbits and their role on nuclear structure
- Conclusions and perspectives

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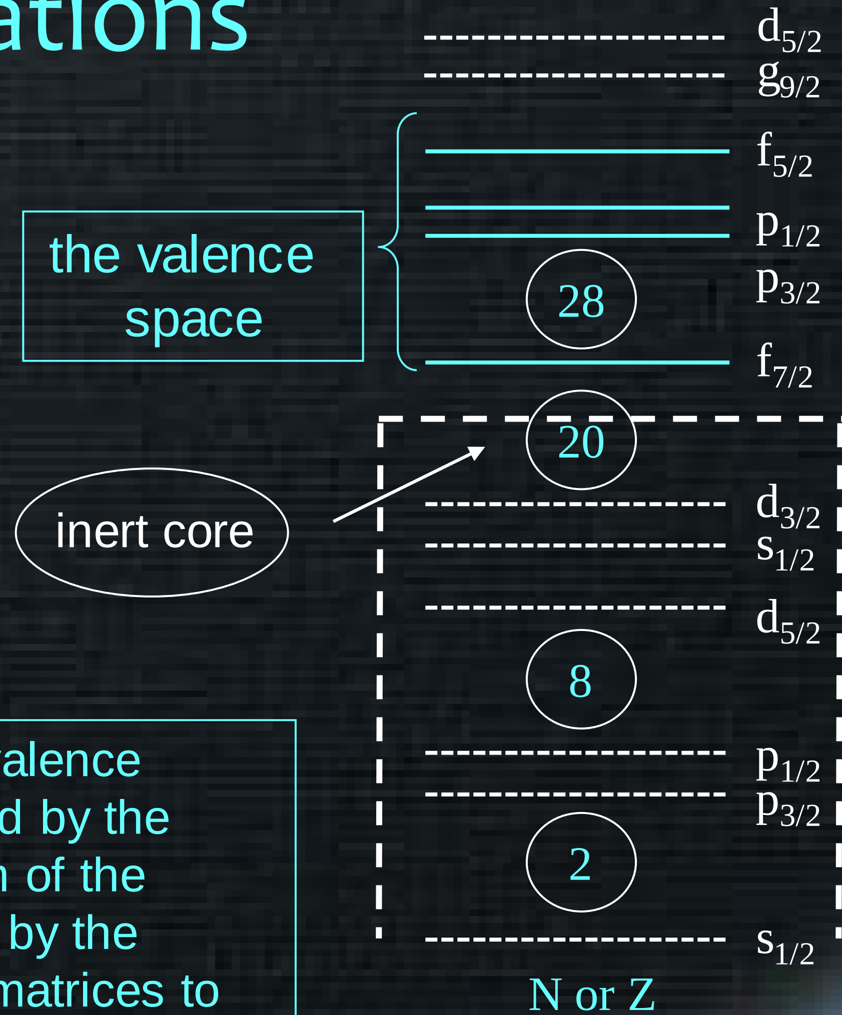
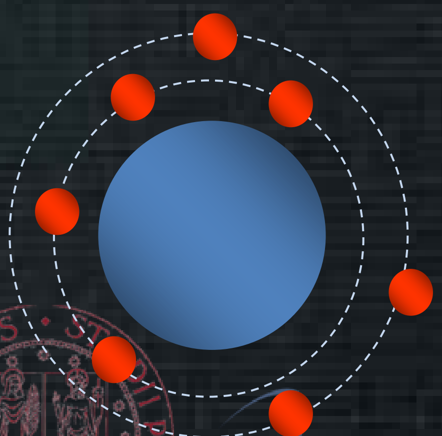
Ingredients for the Shell Model calculations

1) an inert core
2) a valence space
3) an effective interaction that mocks up the general hamiltonian in the restricted basis

$$H_{\mathrm{eff}}\psi_{\alpha} = H_0 + V_{\mathrm{eff}}\psi_{\alpha} = E_{\alpha}\psi_{\alpha}$$

with $H_0 = T + U$





The choice of the valence space is determined by the degrees of freedom of the system and limited by the dimensions of the matrices to be diagonalized

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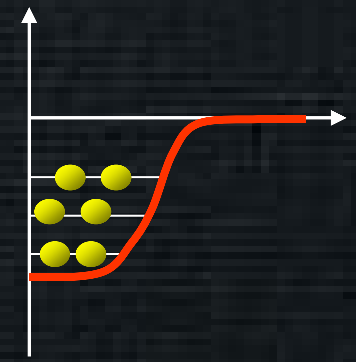
The effective interaction

A multipole expansion

$$\boxed{V_{eff} = V_m + V_M}$$

monopole Multipole



$\boxed{V_m}$

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

$\boxed{V_M}$

- correlations
- energy gains

The multipole interaction

The multipole interaction is responsible of the collective behaviour

The main components are: Pairing and Quadrupole

Pairing dominates in semi-magic nuclei → superfluidity

When quadrupole correlations dominate → deformation

Interplay: Monopole and Multipole

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

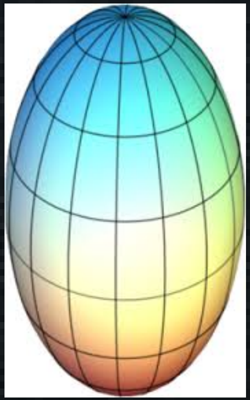
In particular, far from stability new magic numbers appear and new regions of deformation develop giving rise to new phenomena such as:

- islands of inversion
- shape phase transitions
- shape coexistence
- haloes, etc.

Development of deformation and Islands of Inversion

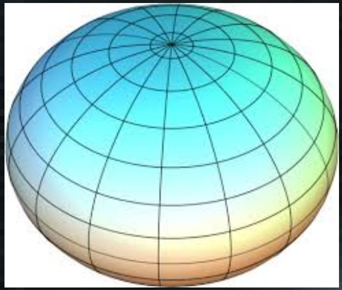
Why nuclei deform?

The spherical nuclear field is close to the harmonic oscillator potential.



In the limit of degeneracy of the single-particle energies of a major harmonica oscillator shell, and in the presence of an attractive Q.Q proton-neutron interaction, the ground state of the many-body nuclear system is maximally deformed

Elliott SU(3) in the sd shell



So, at low energy, nuclear states tend to maximize the intrinsic Quadrupole moment

$$\boxed{Q_0 = (2n_z - n_x - n_y)}$$

where the principal quantum number $N = (n_x + n_y + n_z)$

Example in the sd shell

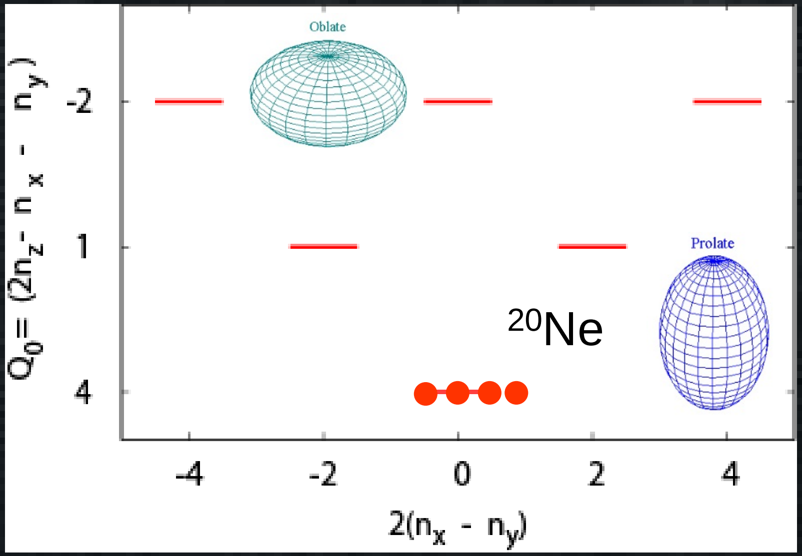
In the *sd* shell $N = 2$
there are 6 possible states:
(2,0,0) (0,2,0) (0,0,2)
(1,1,0)(1,0,1)(0,1,1)

$$Q_0 = (2n_z - n_x - n_y)$$

$$Q_0 = 4, 1, -2$$

Intrinsic states are the determinants obtained by filling these fourfold (2p+2n) degenerate "orbits"

The "intrinsic orbits" in SU3



- start filling from below → prolate deformation
- start filling from above → oblate deformation

A.P. Zuker et al., PRC **92**, 024320 (2015)

Extending the Elliott's SU3

Elliott's SU3 is well suited for the sd shell, but fails when the SO interaction introduces large energy shifts

However, some variants of the SU3 symmetry apply in specific valence spaces and we will be able to compute the quadrupole moments in these framework:

The Quasi SU3 and the Pseudo SU3

A. P. Zuker, J. Retamosa, A. Poves, and E. Caurier, PRC **52**, R1741 (1995).

A.P. Zuker, A. Poves, F. Nowacki, S.M. Lenzi, PRC **92**, 024320 (2015)

SU3 approximate symmetries

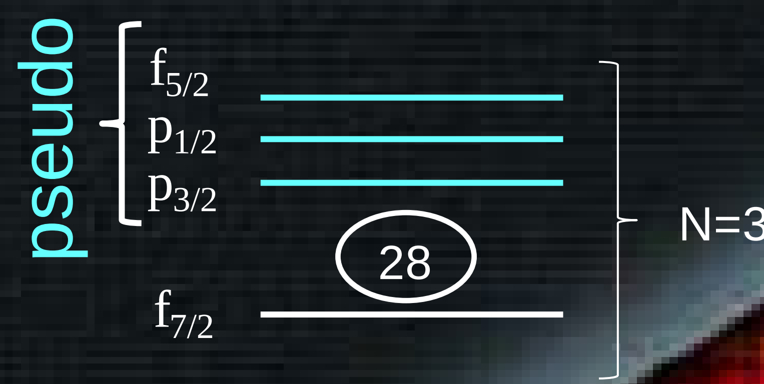
Two variants of SU3 apply in specific spaces

Quasi SU3

applies to the lowest $\Delta j = 2$, $\Delta \ell = 2$ orbits in a major HO shell

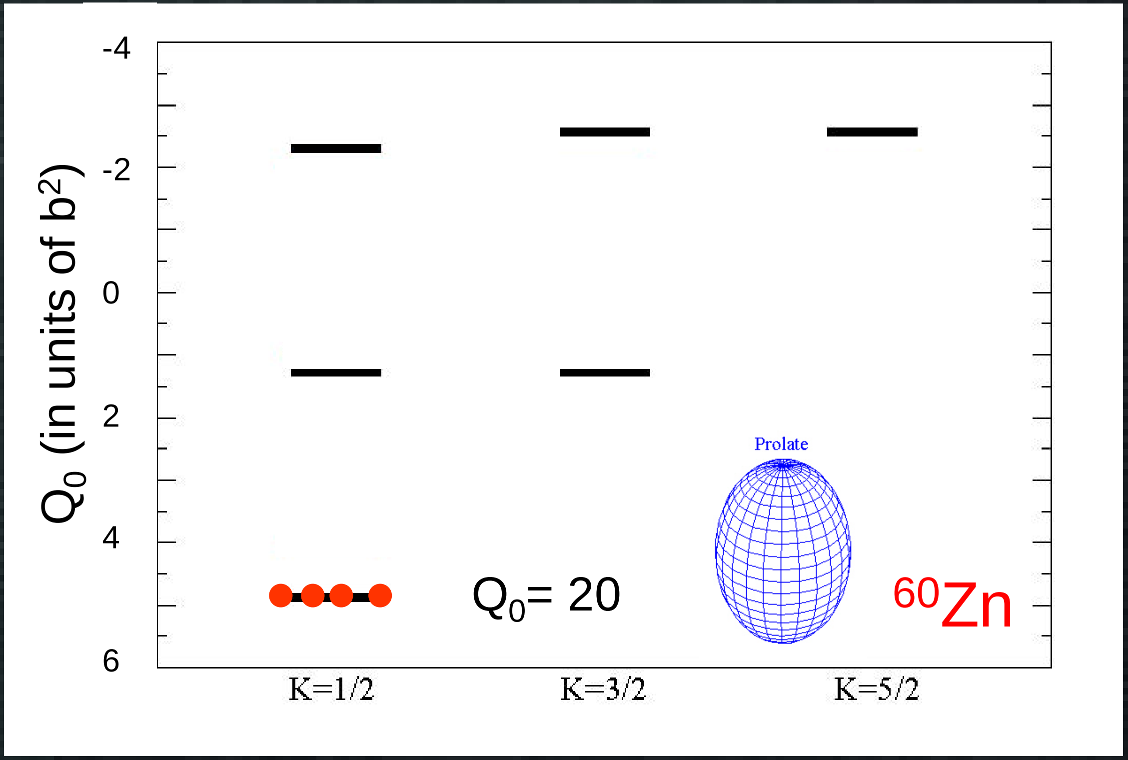
Pseudo SU3

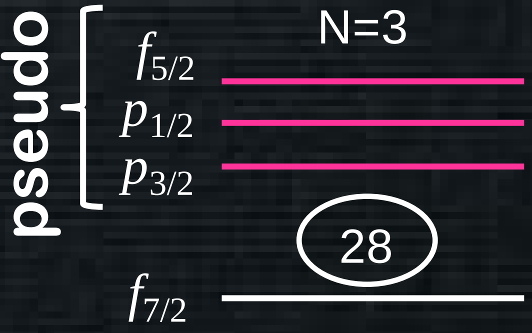
applies to a HO space where the largest *j* orbit has been removed.



A.P. Zuker et al., PRC **92**, 024320 (2015)

Quadrupole moments in Pseudo SU3





We obtain Q_0 by summing those of the single particles/holes in each "orbit"

A.P. Zuker et al., PRC **92**, 024320 (2015)

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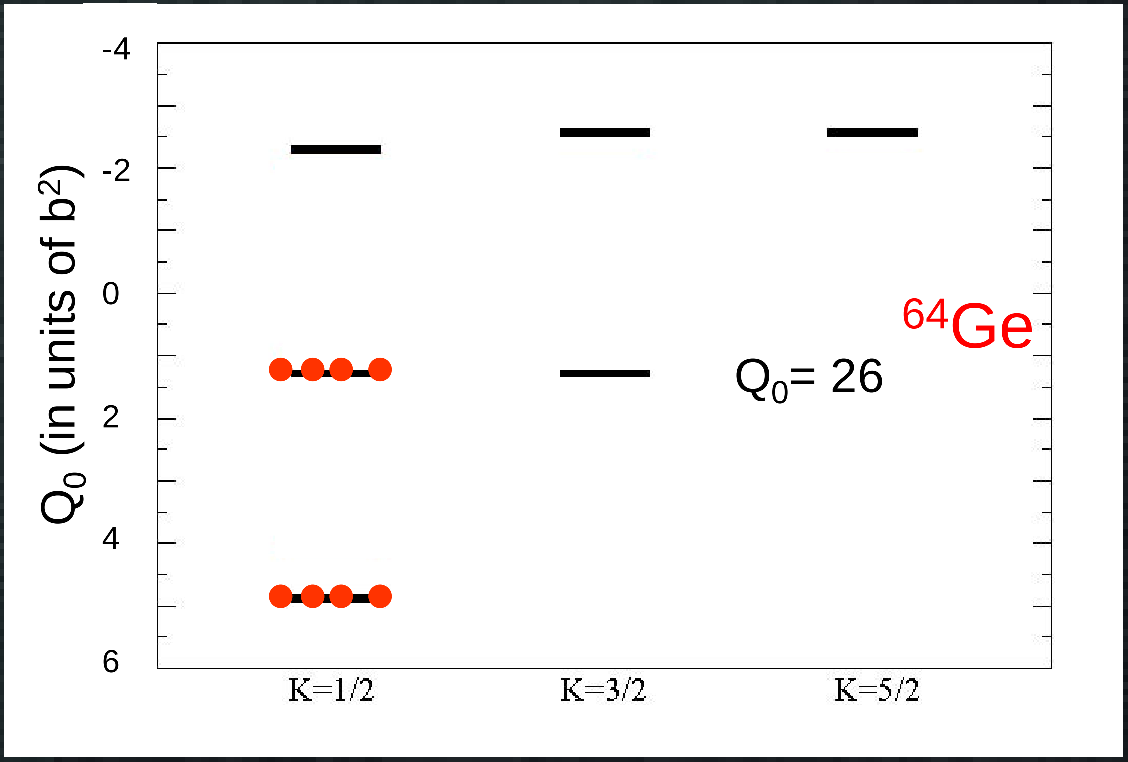

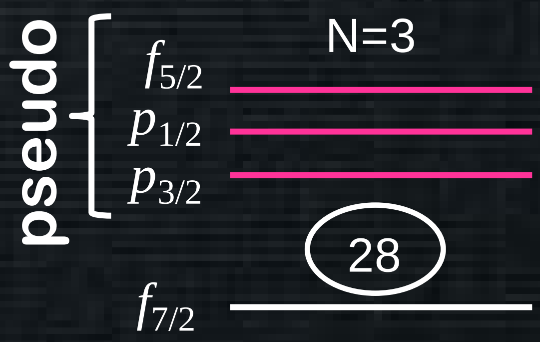

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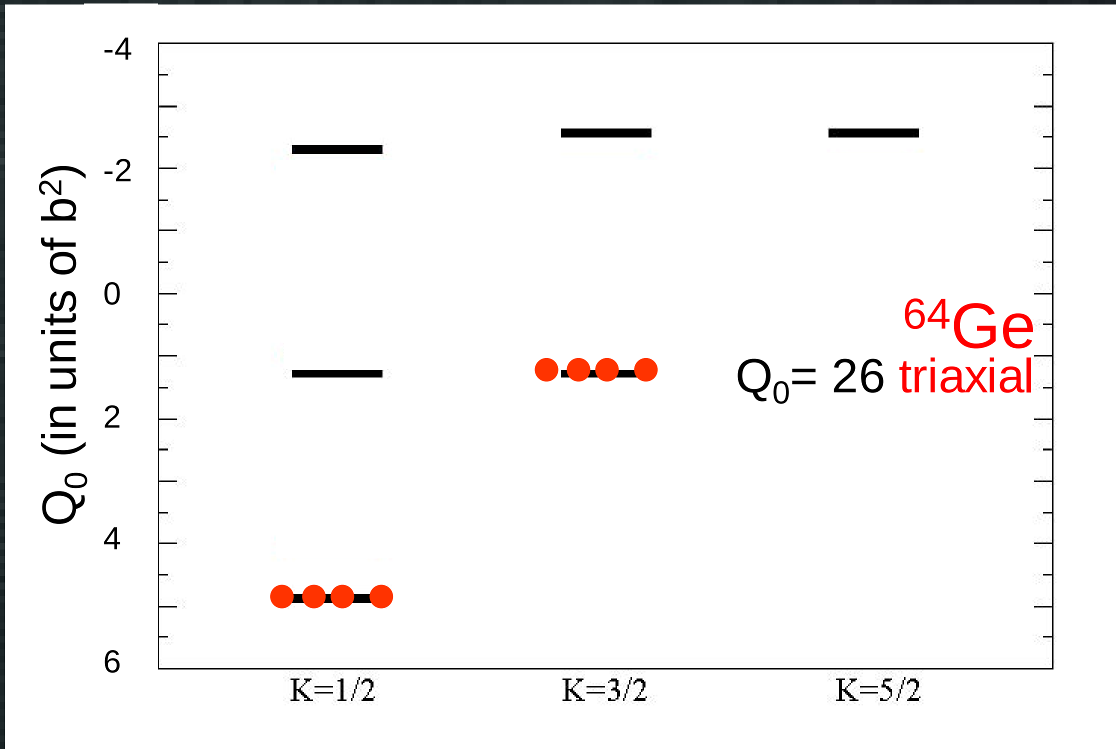

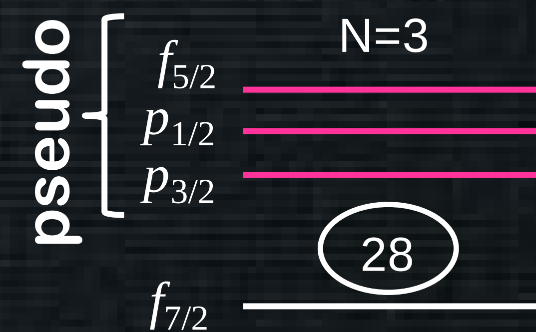

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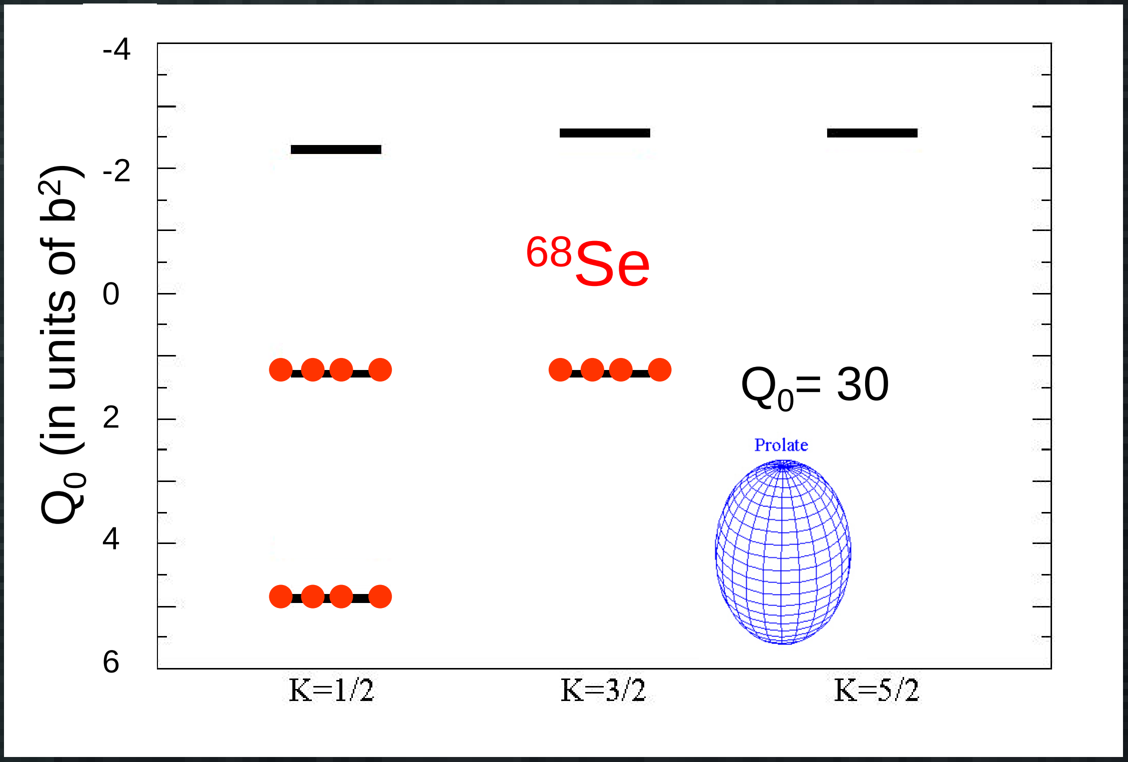

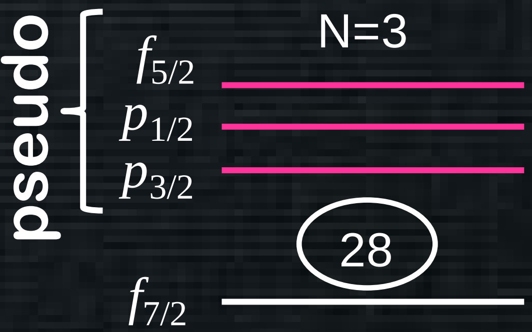

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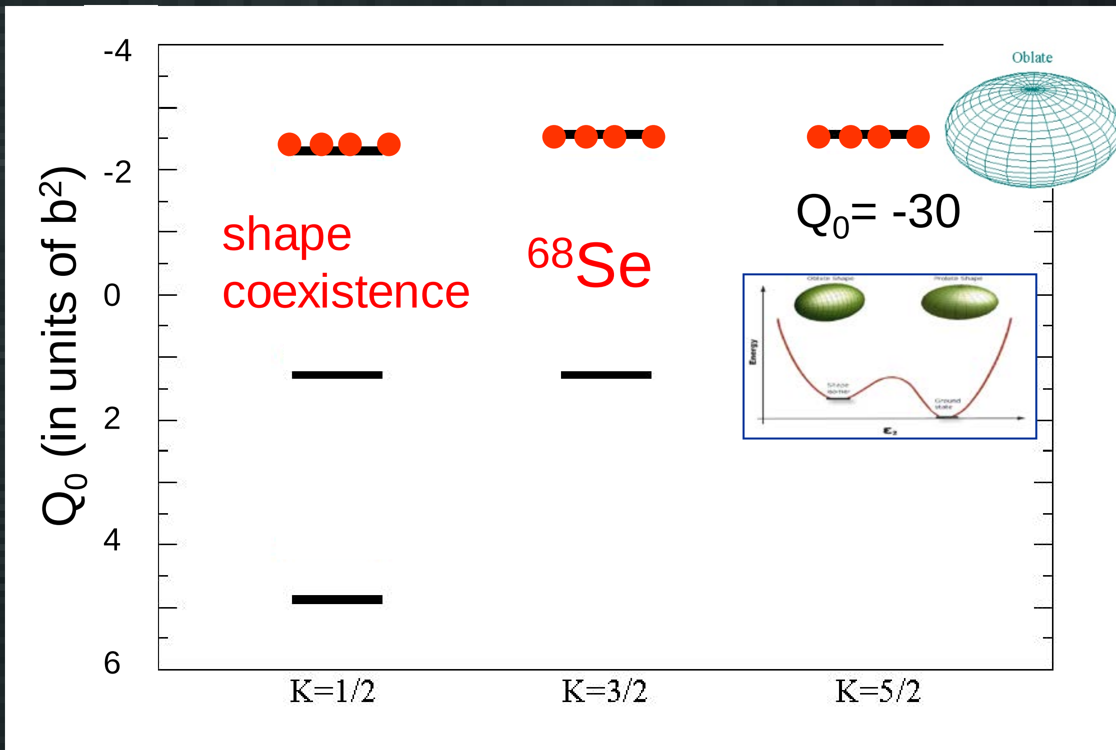
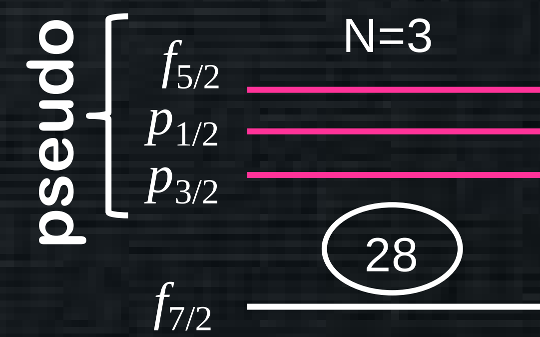
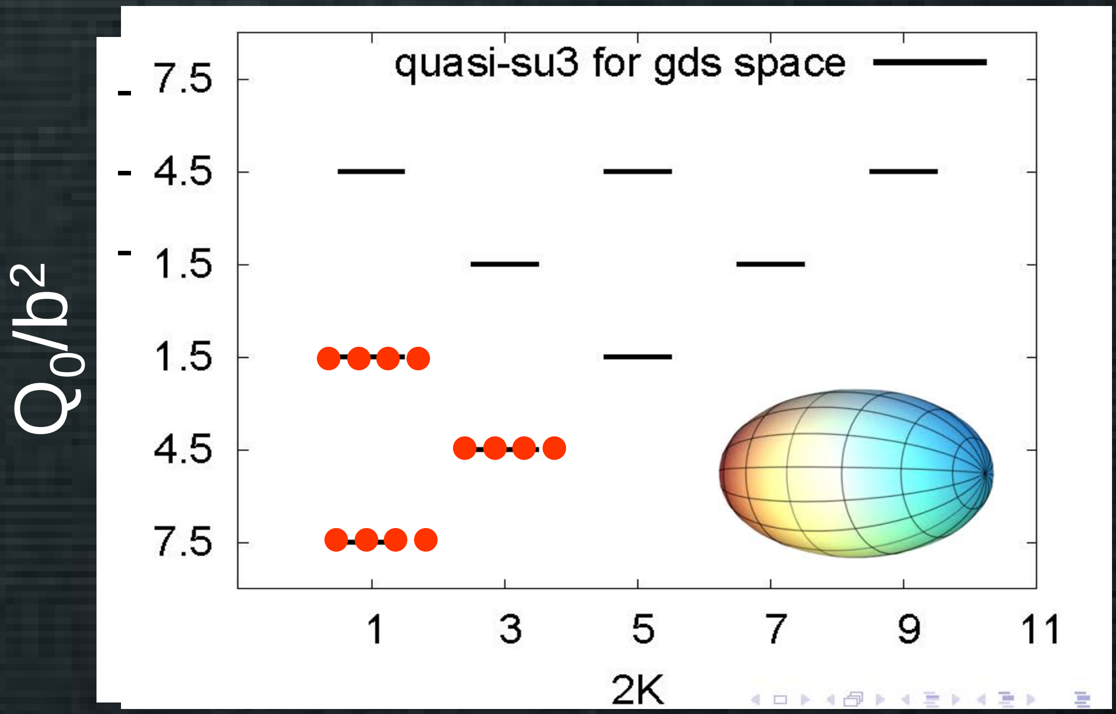




We obtain Q_0 by summing those of the single particles/holes in each "orbit"

A.P. Zuker et al., PRC **92**, 024320 (2015)

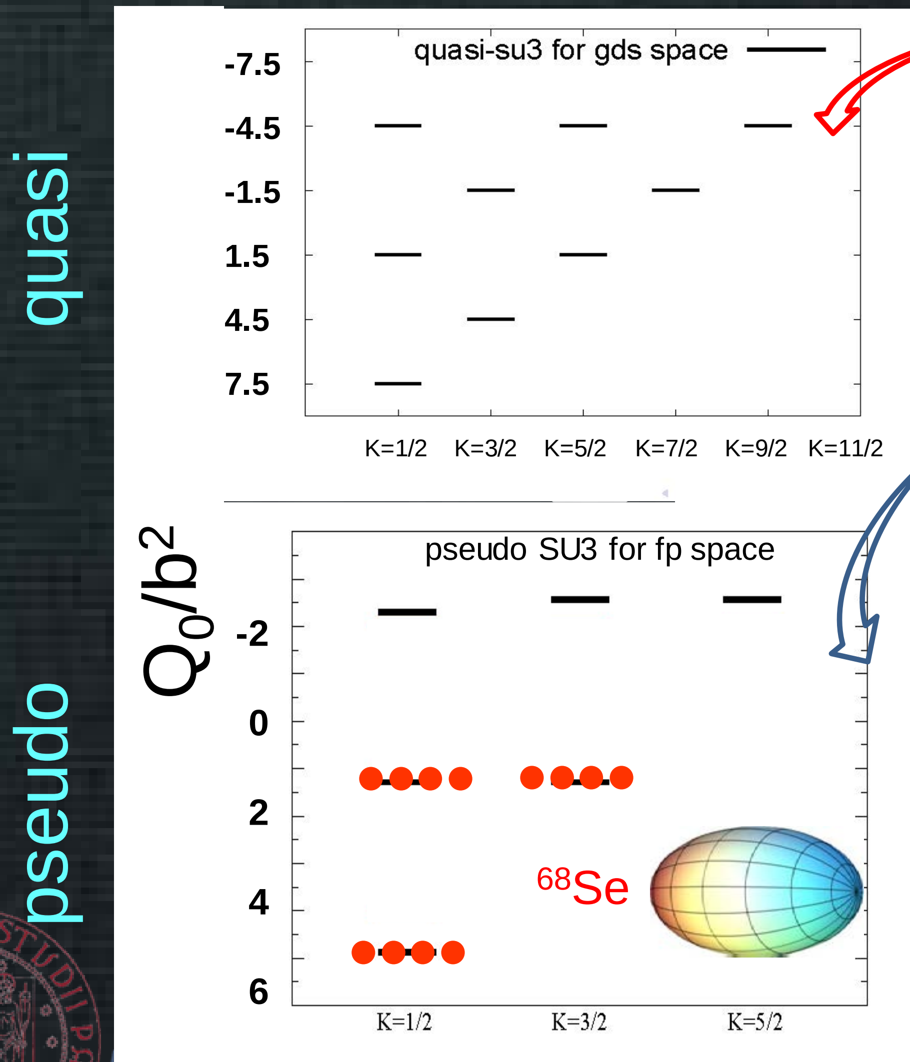
Quadrupole moments in Quasi SU3

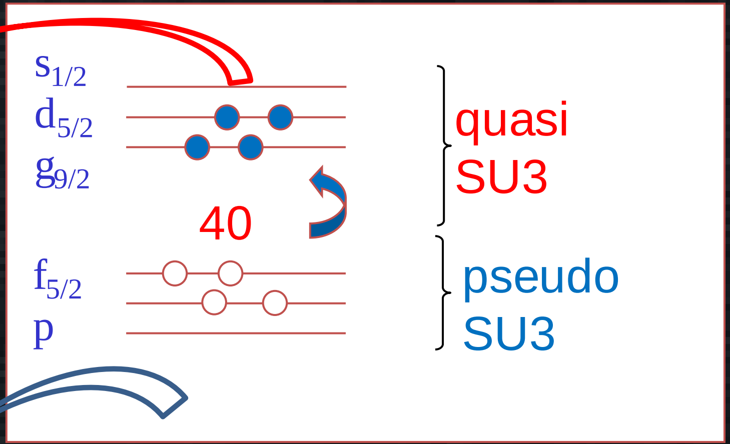


We obtain Q_0 by summing those of the single particles in each "orbit"

A.P. Zuker et al., PRC **92**, 024320 (2015)

Maximizing quadrupole correlations

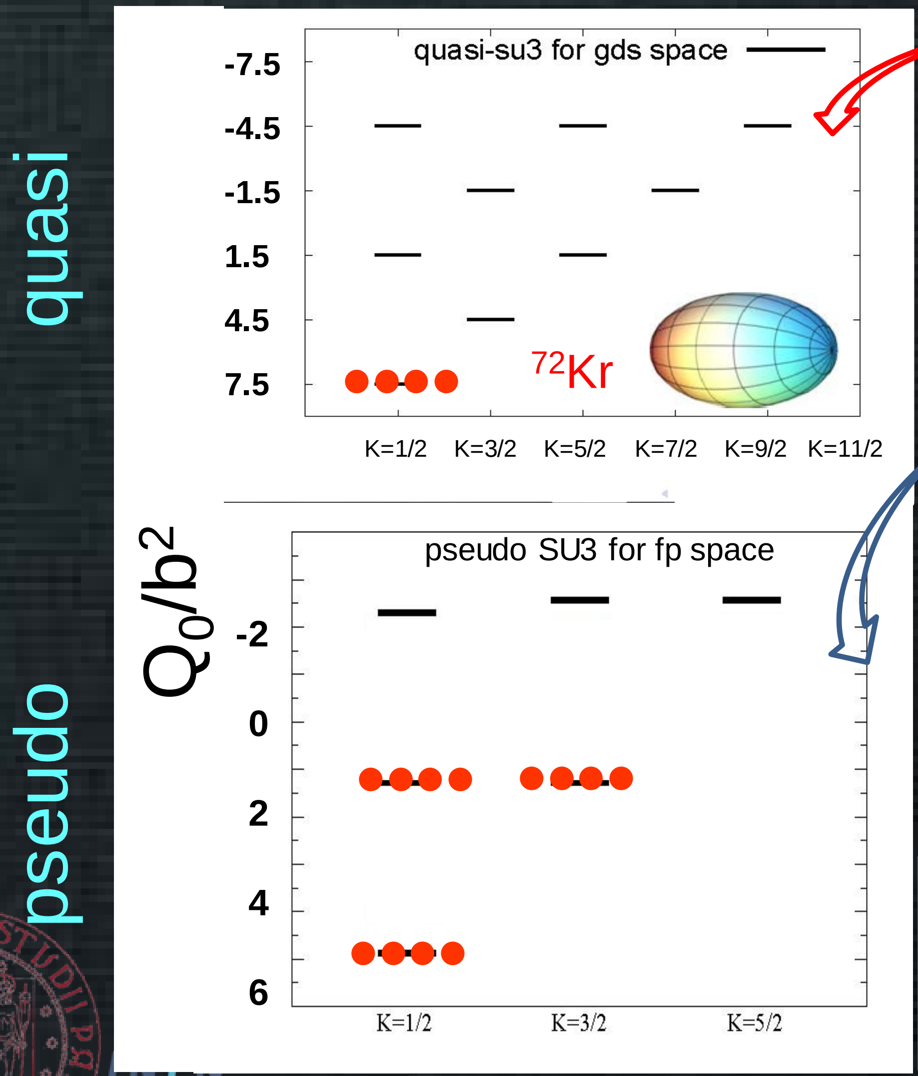


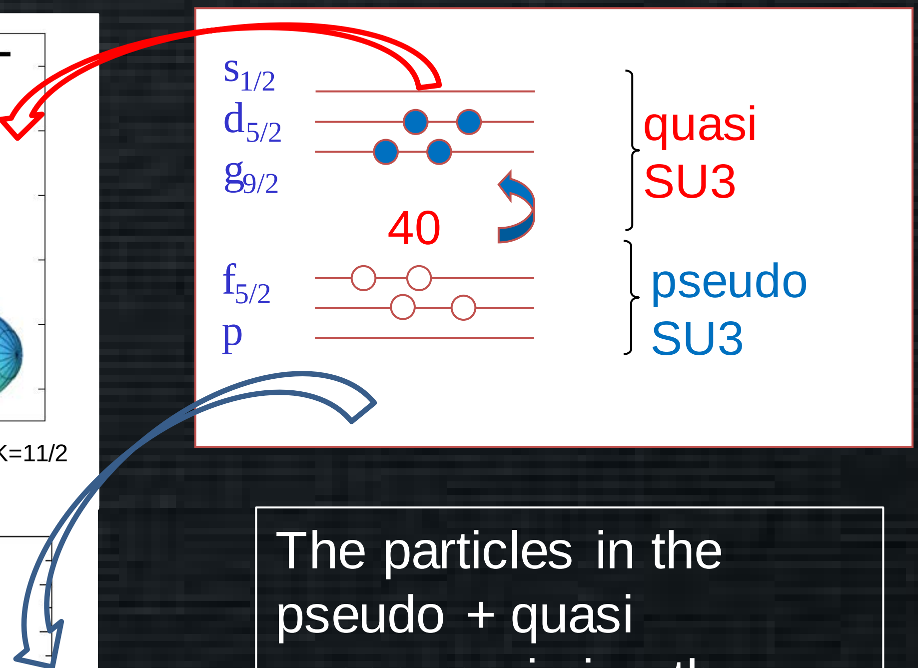


The particles in the pseudo + quasi space maximize the quadrupole moment.

The quadrupole correlation energy results much larger than the energy cost to promote the particles

Maximizing quadrupole correlations





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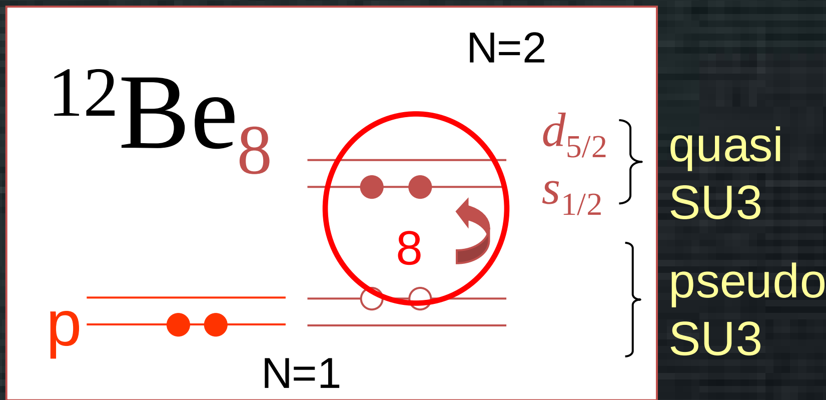
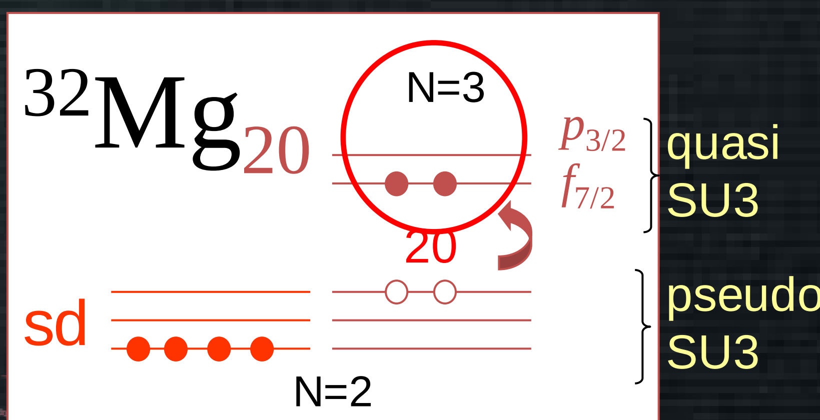
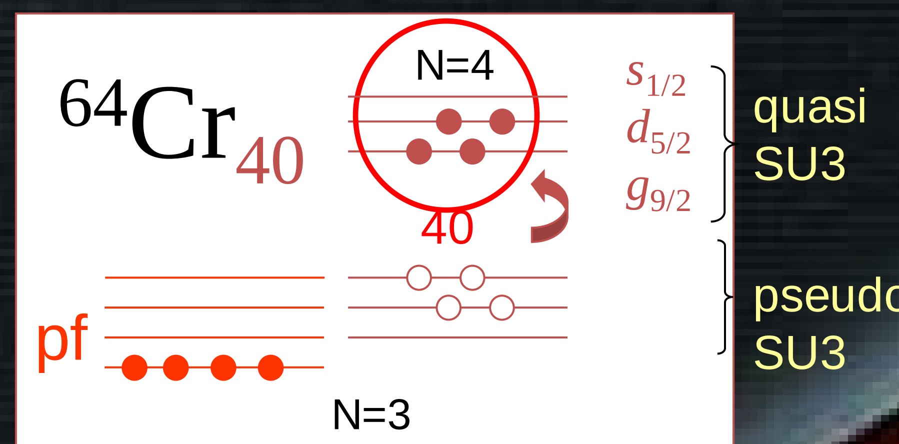
Islands of inversion and symmetries

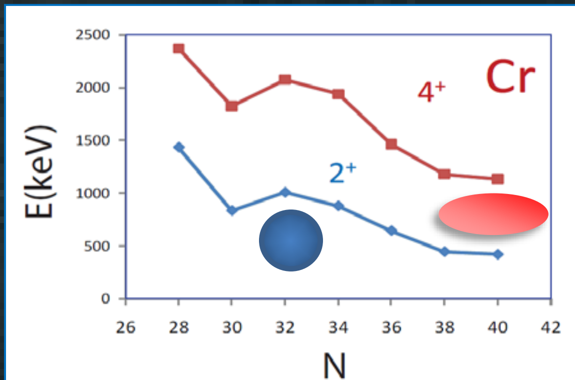


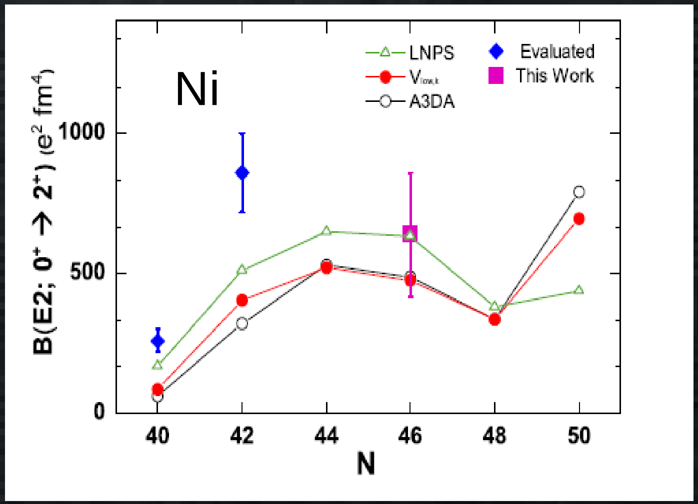
Islands of Inversion at the magic numbers can be understood in terms of dynamical symmetries





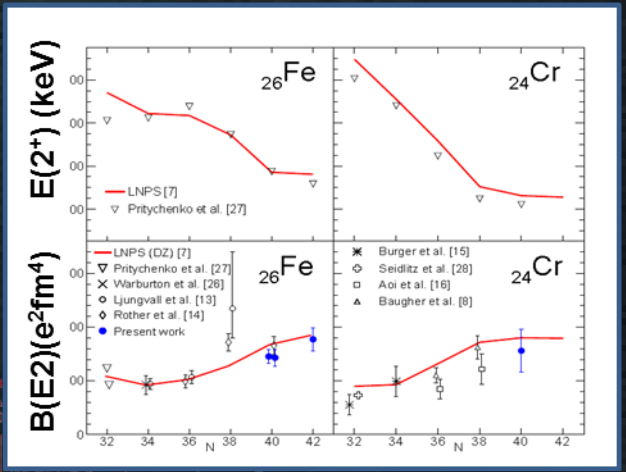
Shape evolution along isotopic chains





Both excitation energies and transition probabilities are well described by SM in the pseudo+quasi SU3 model space

T. Marchi et al., PRL 113, 182501 (2014)



H. L. Crawford et al., PRL 110, 242701 (2013)

Effective interactions:

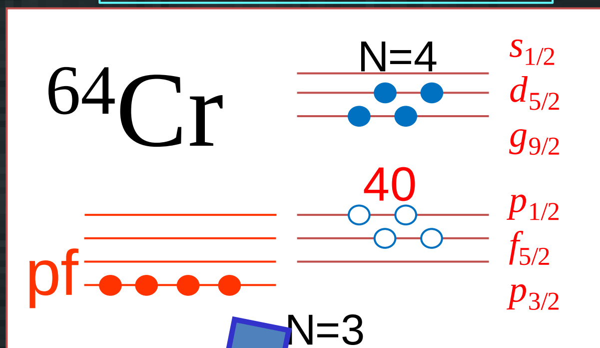
LNPS: Lenzi, Nowacki, Poves, Sieja,
PRC 82, 054301 (2010).

$V_{low\ k}$: Coraggio, Covello, Gargano, Itaco,
PRC 89, 024319 (2014).

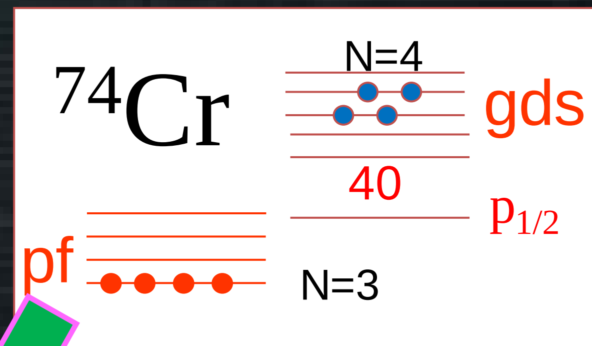
A3DA: Tsunoda, Otsuka, Shimizu, Honma, Utsuno,
PRC 89, 031301 (2014).

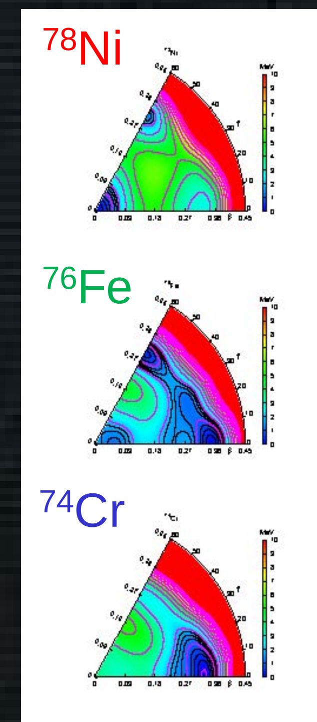
Extension of the IoI from N=40 to N=50

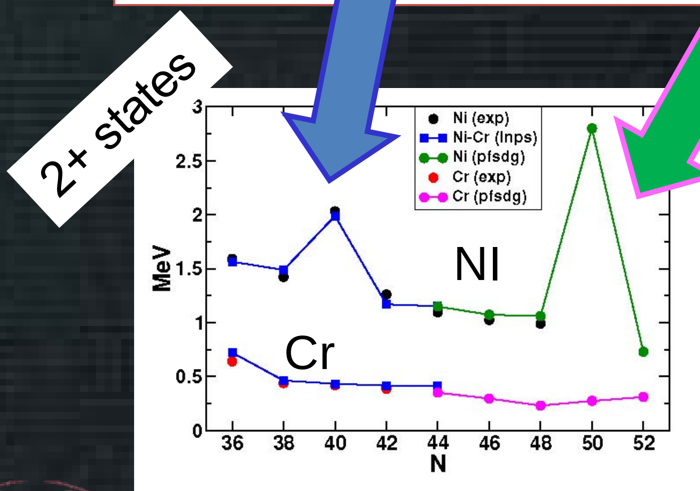
LNPS Model space

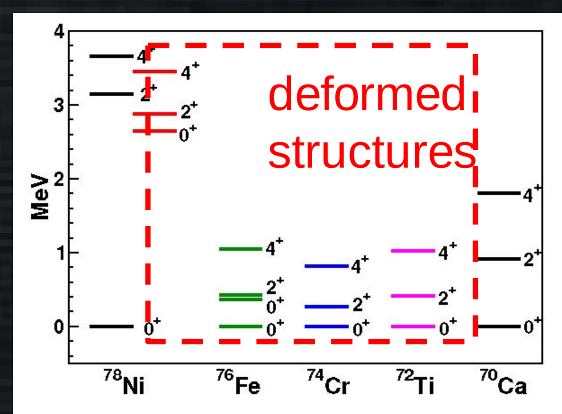


pf-sdg Model space



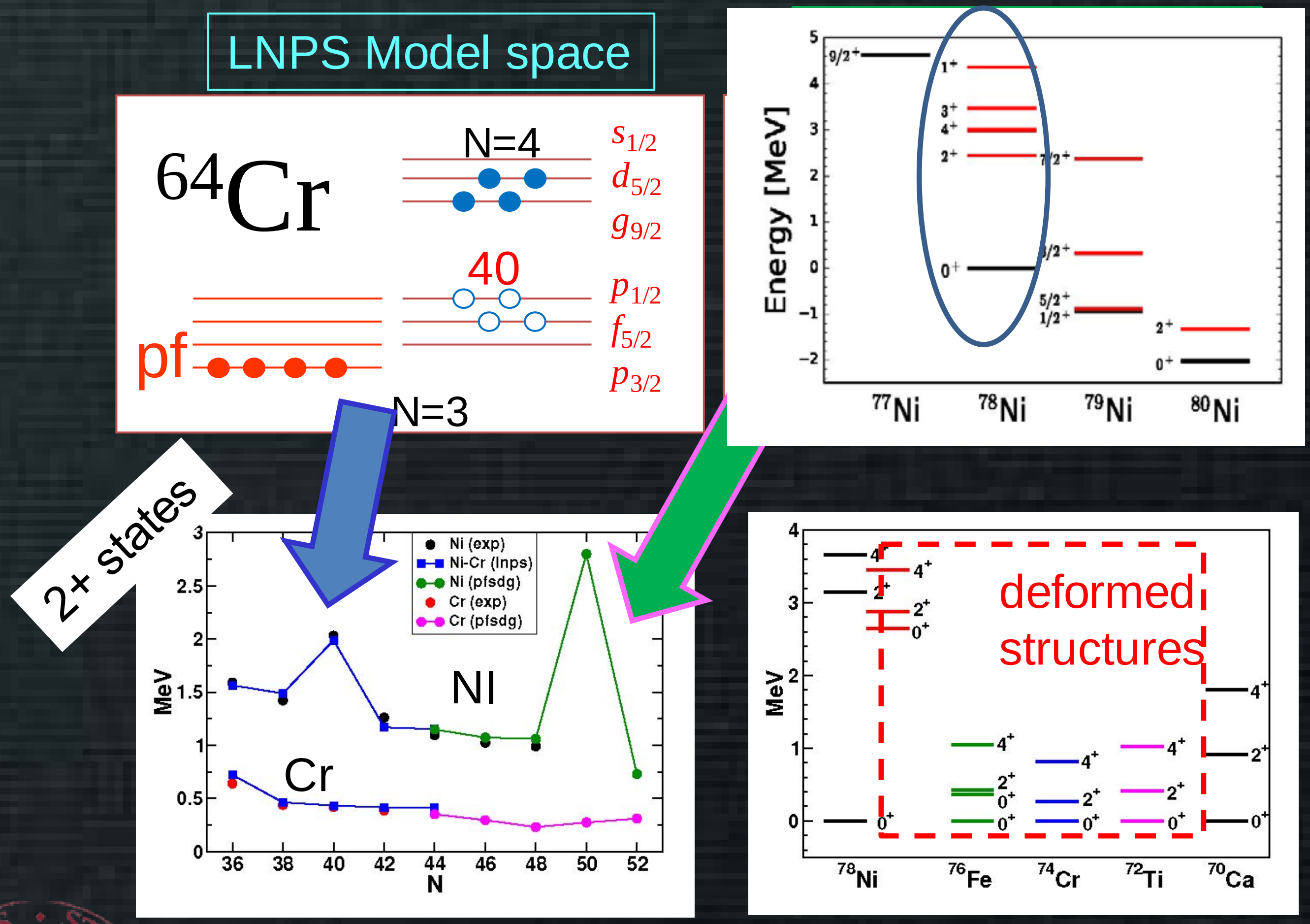




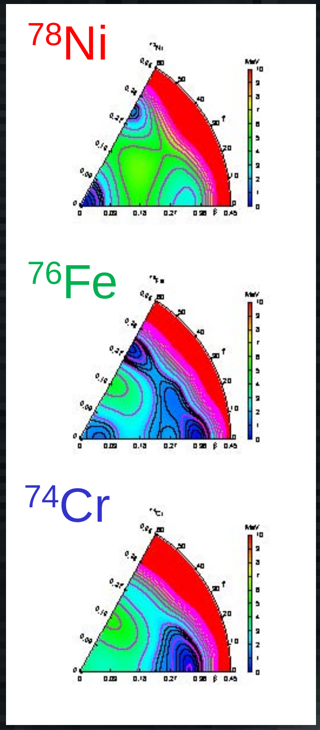


Shell model calculations by
F. Nowacki et al., arXiv:1605.05103v1 (2016)

Extension of the IoI from N=40 to N=50



Coupled-cluster calculations by Hagen et al., arXiv:1605.01477v1 (2016)

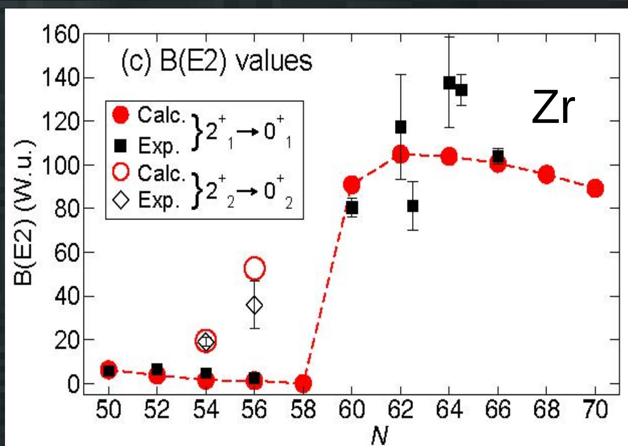


Shell model calculations by
F. Nowacki et al., arXiv:1605.05103v1 (2016)

Deformation at Z~40

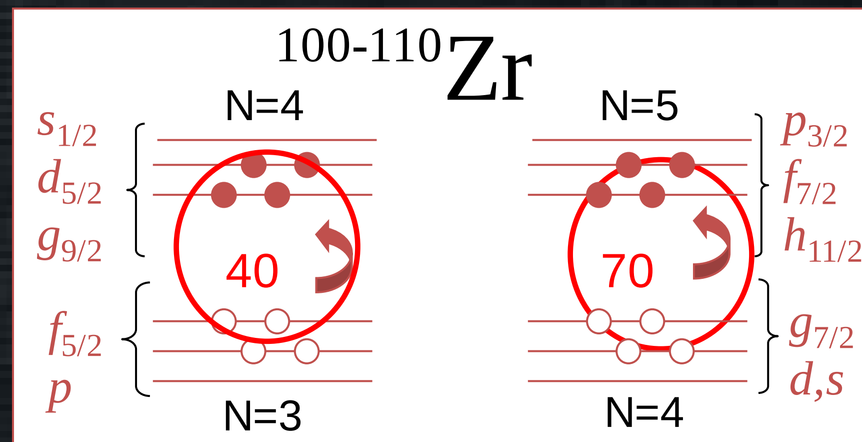
Similar to what happens in N~40 south of ^{68}Ni

Sudden shape transition at N=60 in Zr isotopes



quasi SU3

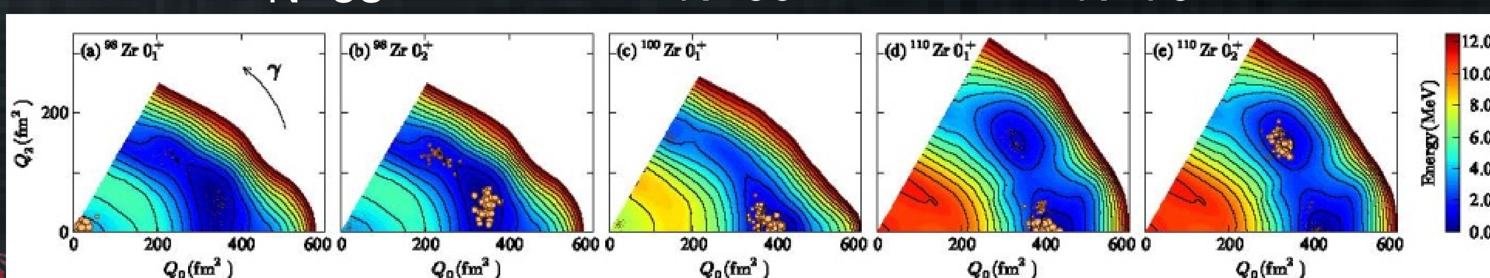
pseudo SU3



quasi SU3

pseudo SU3

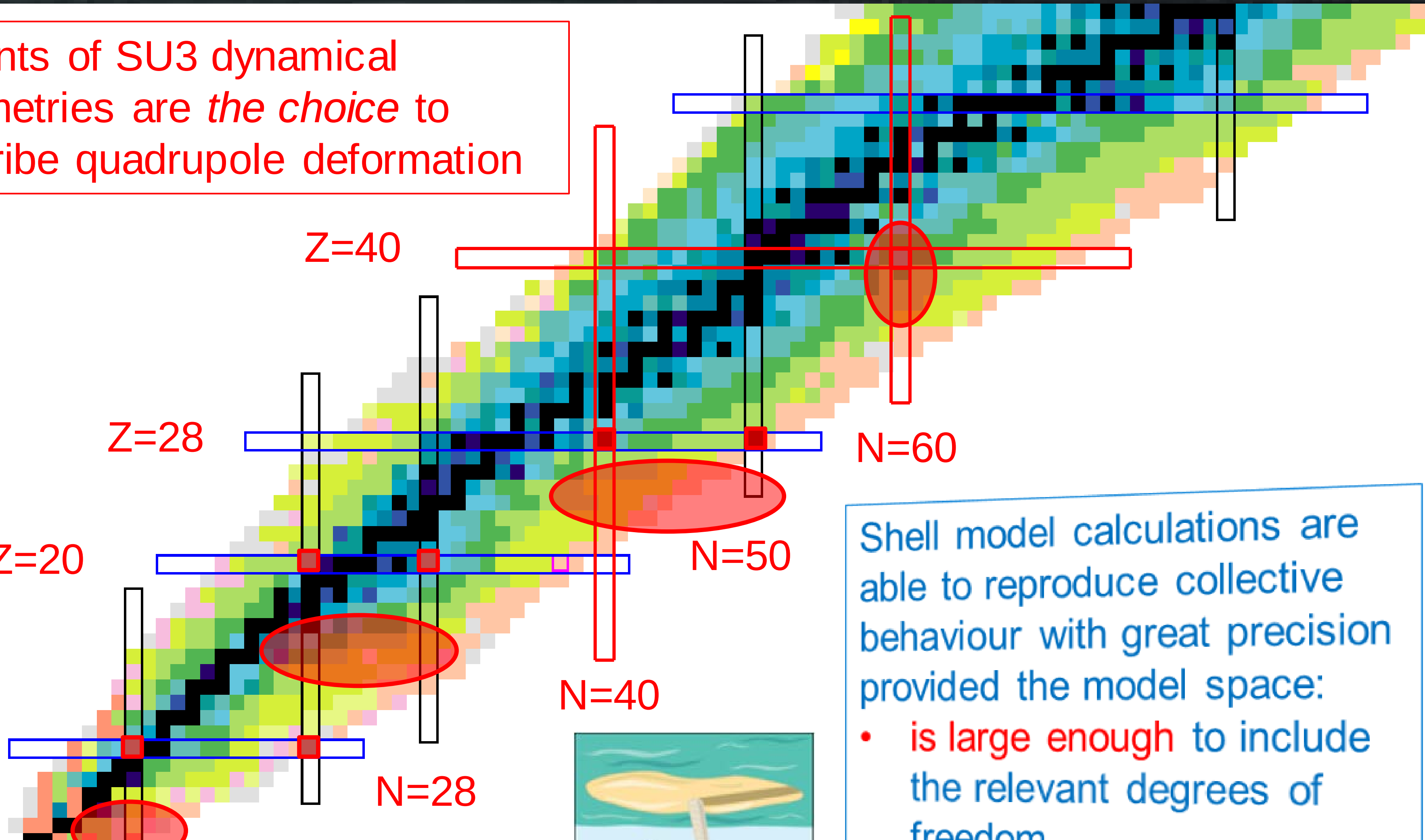
N=58 N=60 N=70

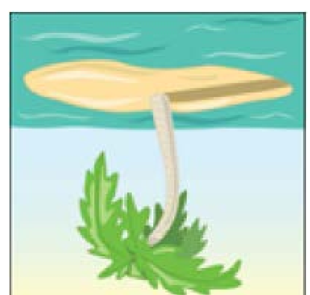


T. Togashi et al, arXiv:1606.09056v1, accepted in PRL (2016)

Islands of Inversion

Variants of SU3 dynamical symmetries are *the choice* to describe quadrupole deformation





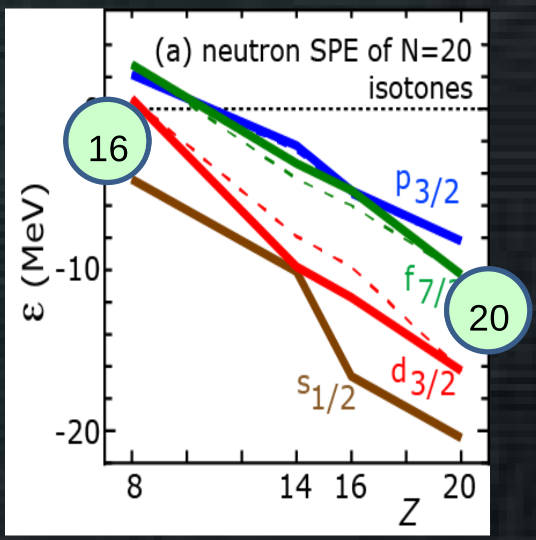
Shell model calculations are able to reproduce collective behaviour with great precision provided the model space:

- is large enough to include the relevant degrees of freedom
- is small enough to make the calculations affordable

Single-particle properties

Effective single-particle energies

The effective single-particle energies and their evolution as a function of N/Z are essential ingredients to determine the development of new magic numbers, the disappearance of the traditional ones or their robustness



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

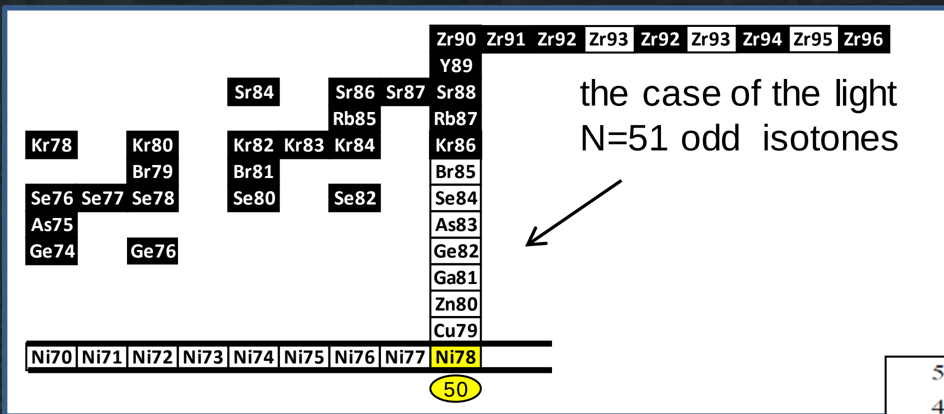
The mechanism of this evolution is not well understood

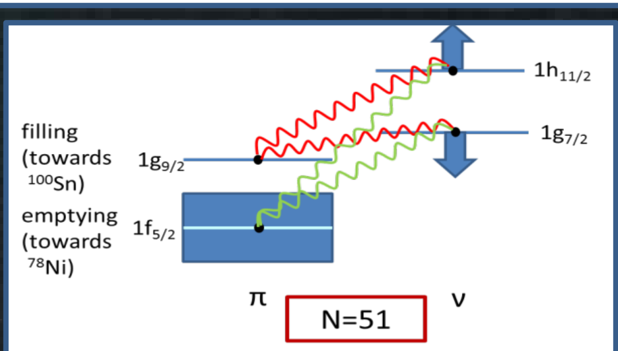
The single-particle energies are not an observable but can be deduced from spectroscopic factors and the energy of the nuclear states around closed shells.

Transfer reactions in inverse kinematics are one of the ideal tools to study the single-particle behaviour far from stability.

Single particle energies above N=50

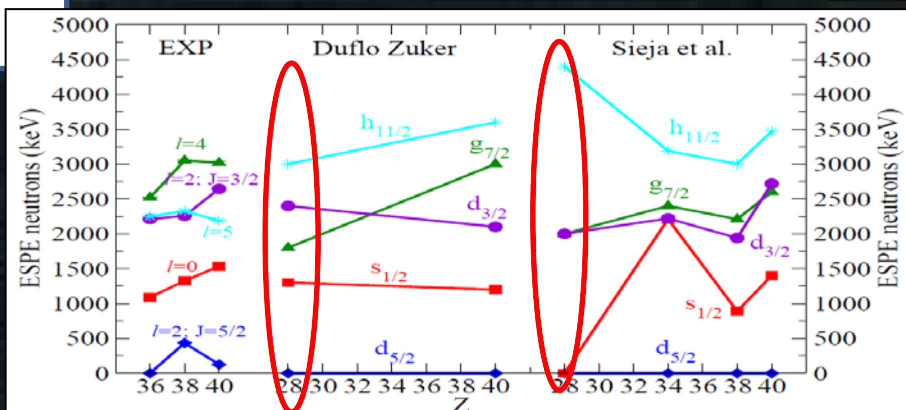
The isotones N=51 can give valuable information to deduce the s.p. energies around N=50. Several observables need to be measured.





Discrepancies in the prediction of the evolution of ESPE energies for neutron-rich nuclei

Effective s.p. energies



D. K. Sharp et al., PRC **87**, 014312 (2013) | J. Duflo and A.P. Zuker, PRC **59**, R2347 (1999) | K. Sieja et al., PRC **79**, 064310 (2009)

Courtesy of A. Gottardo

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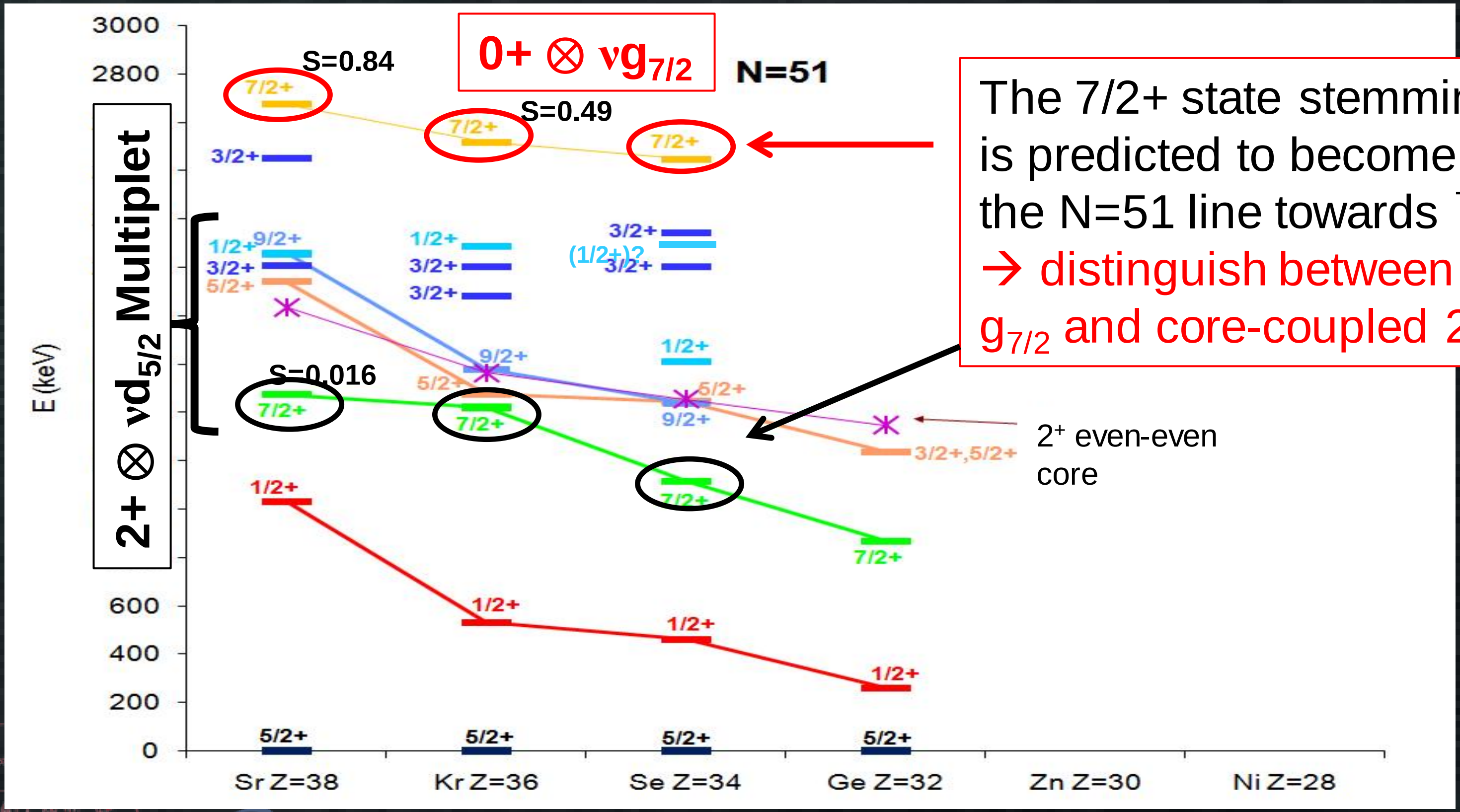
Characterizing the s.p. states

Importance of disentangling the nature of the 7/2- states for the isotones N=51

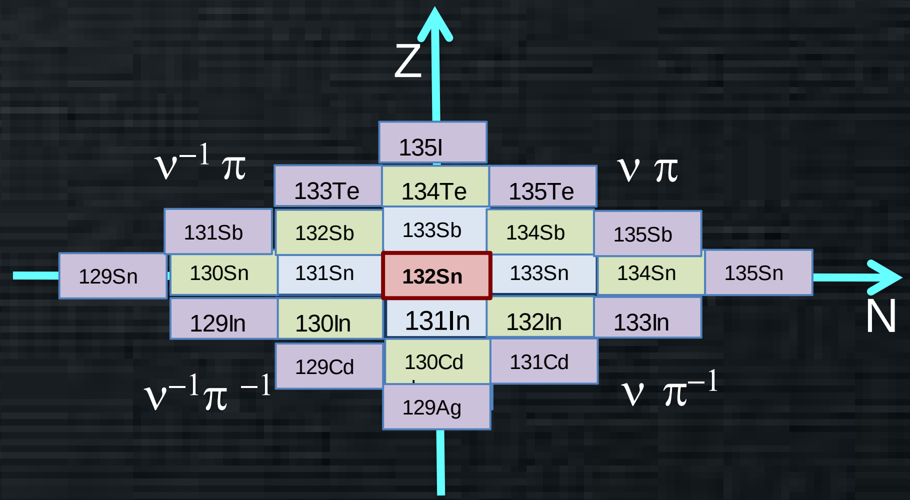


The 7/2+ state stemming from $\nu g_{7/2}$ is predicted to become yrast along the N=51 line towards ^{79}Ni
→ distinguish between $7/2^+$ from $g_{7/2}$ and core-coupled $2^+ \otimes d_{5/2}$

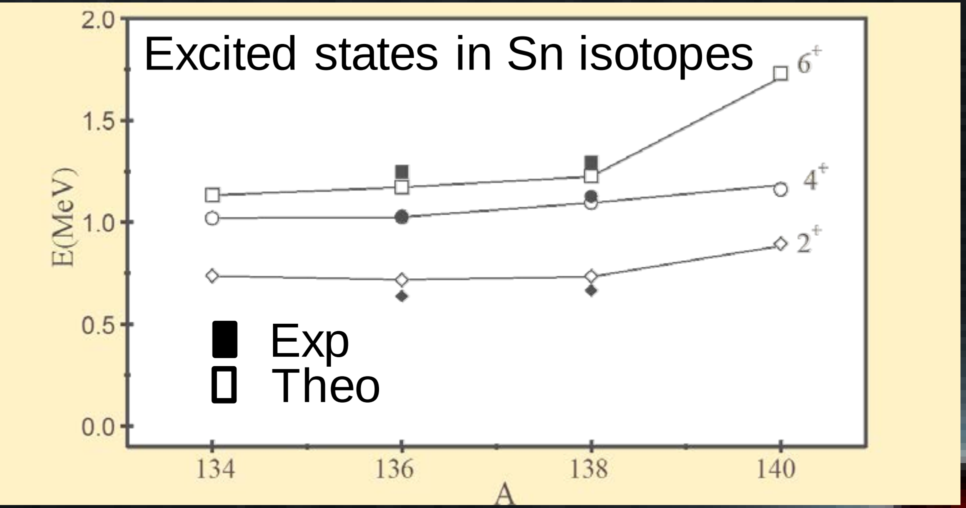
Courtesy of F. Didierjean and A. Gottardo

The ^{132}Sn region

The region around ^{132}Sn is the heaviest doubly-closed shell region experimentally accessible today



Ideal ground to test nuclear models and to ascertain their capability to provide reliable predictions for nuclei which are still inaccessible for present experiments



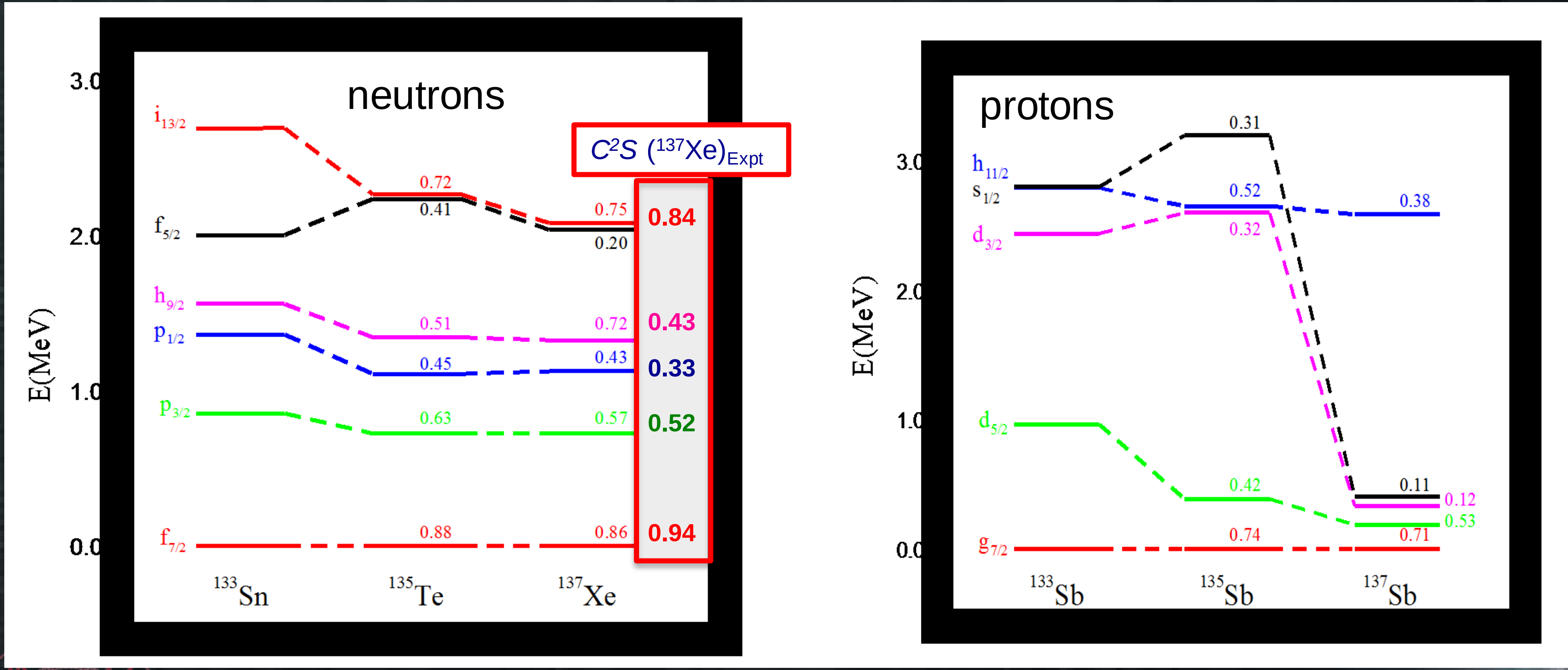
Recent shell model calculations using a realistic interaction by the Napoli group

Courtesy of A. Gargano

INFN Istituto Nazionale di Fisica Nucleare

Evolution of the s.p. energies around ^{132}Sn

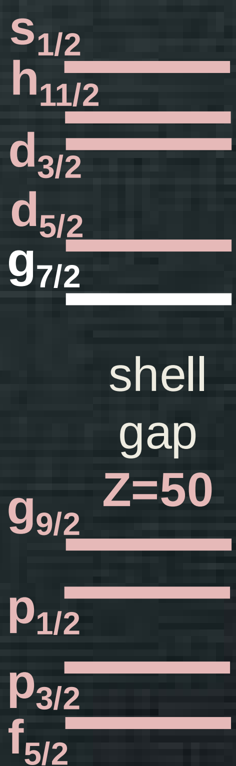
states with the largest spectroscopic factor

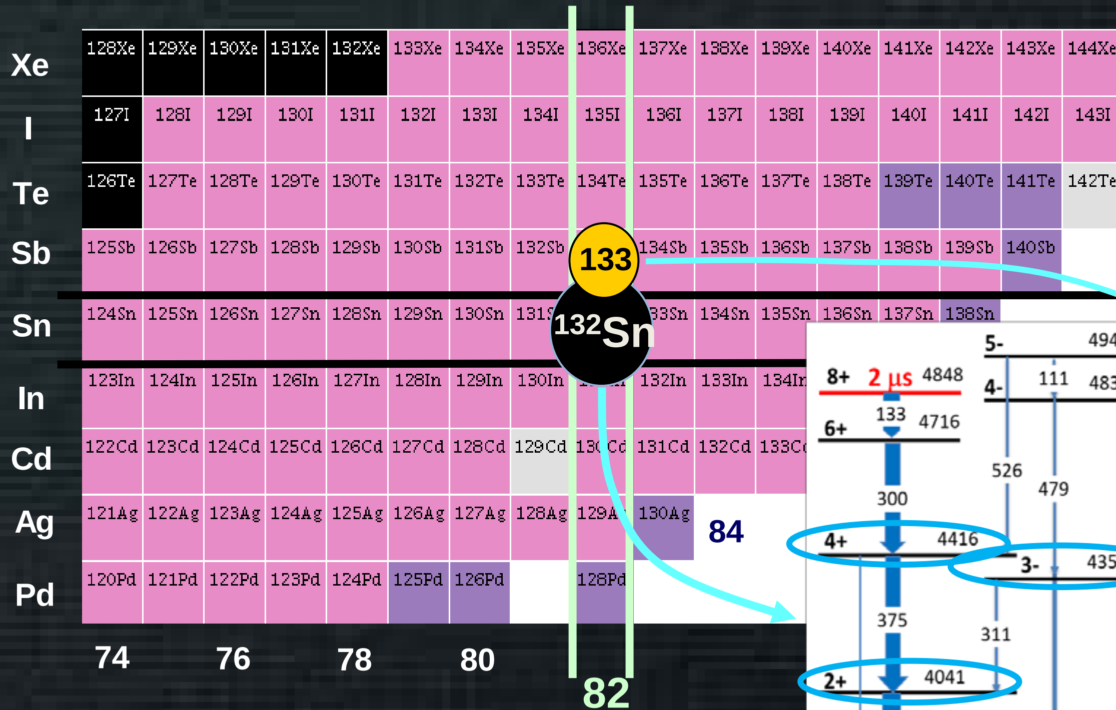


Experimental information is available only for ^{137}Xe

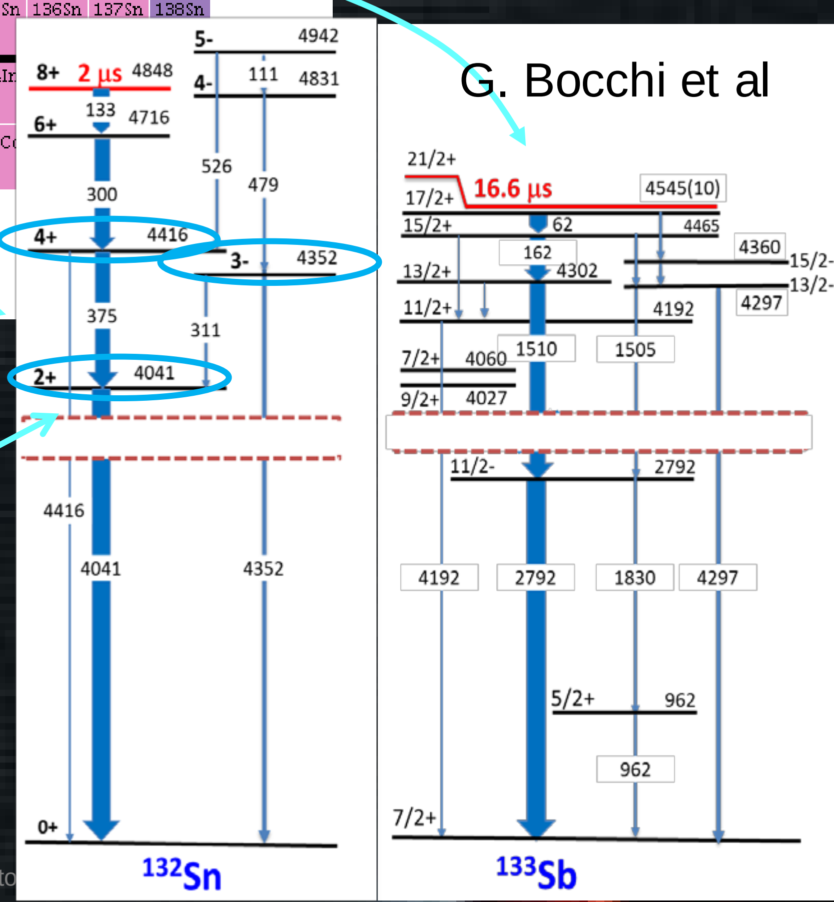
Courtesy of A. Gargano

Coupling s.p. to collective states





^{133}Sb



- Low spin states may come from the coupling of the odd proton to 2^+, 3^-, 4^+ phonons in ^{132}Sn.

- High spin states can only come from $\pi g_{7/2}$ coupled to $h_{11/2}^{-1}$ $f_{7/2}$ neutron p-h states.

Hybrid Configuration-Mixing Model

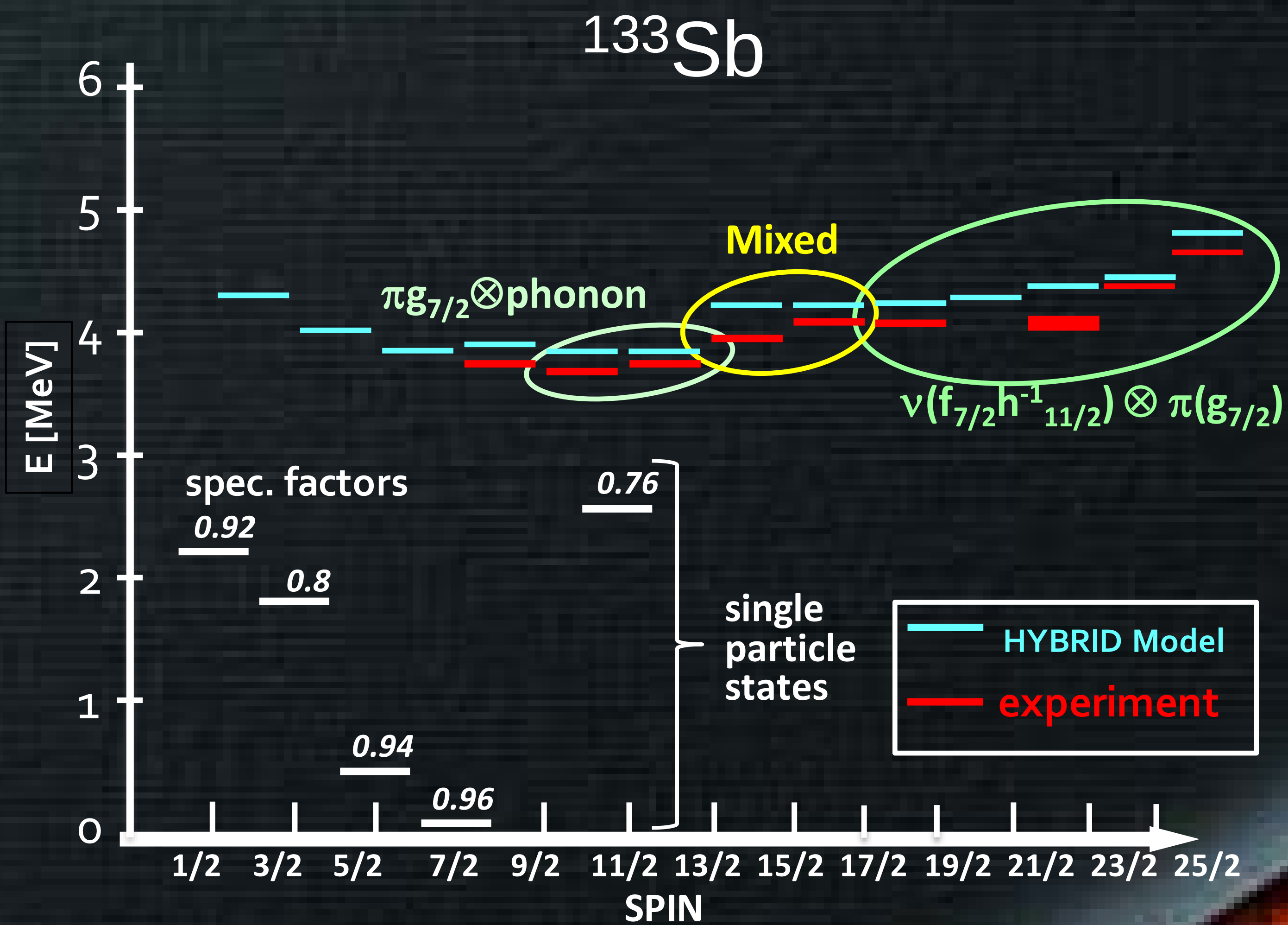
by G. Colò and P.F. Bortignon

Start from a **basis** made up with particles (or holes) around a core, and with excitations of the same core.

Diagonalize the Hamiltonian

H = T + V

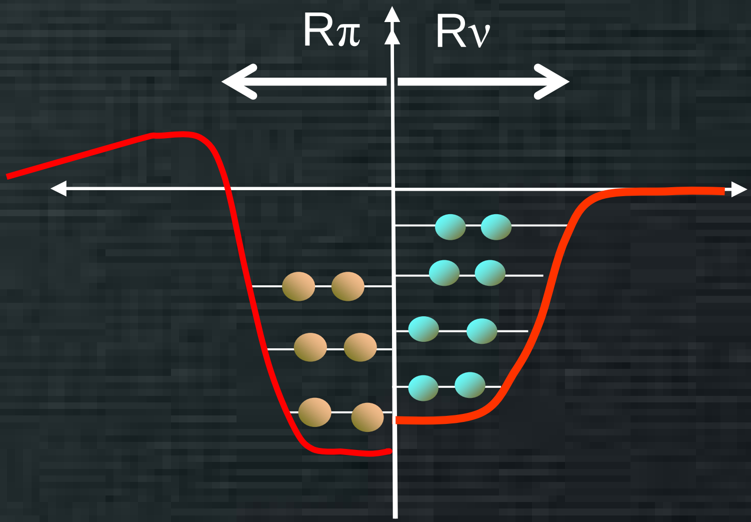
Goal: treat cases in which **states have mixed character**, namely they can be particle states, 2p-1h, …, particle-phonon states.

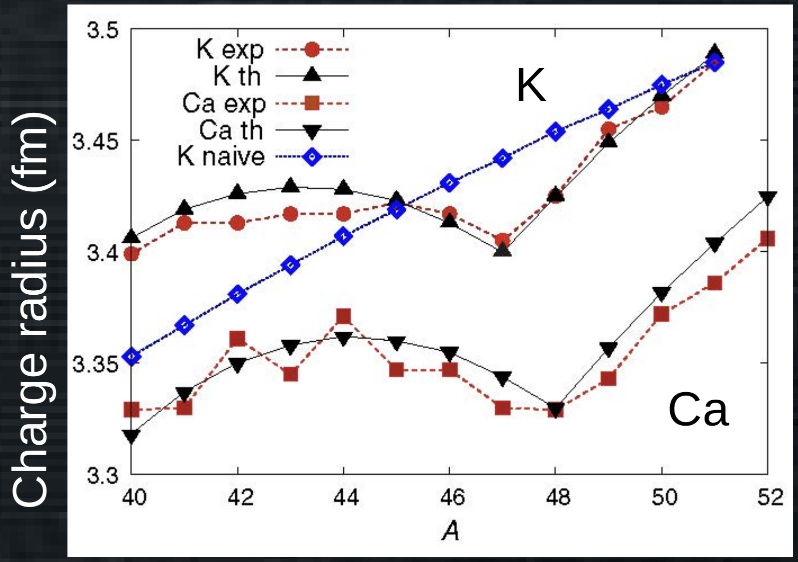


Courtesy of G. Colò

Halo orbits

Halo orbits and charge radii





neutrons filling $f_{7/2}$ filling p orbits

Why the charge radius does not increase when filling f orbits and increases when filling p orbits?

Because p orbits are MUCH LARGER than f orbits!

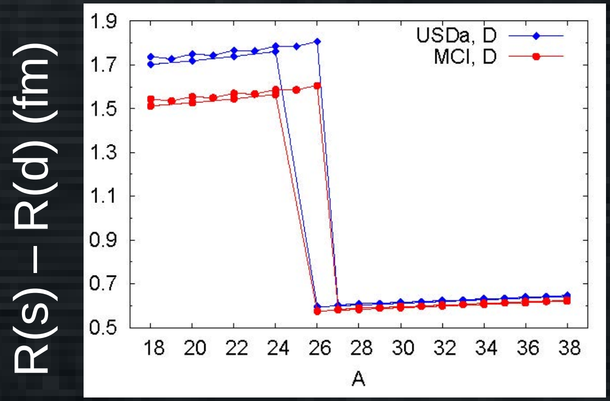
It is found that the radial difference may arrive to ~ 1 fm in the fp shell!

The increase of the size of charge radii along an isotopic chain (or isotope shifts) reflects the orbital occupancies associated with low-ℓ orbits

no-core realistic shell model calculations by J. Bonnard et al., PRL 116, 212501 (2016)

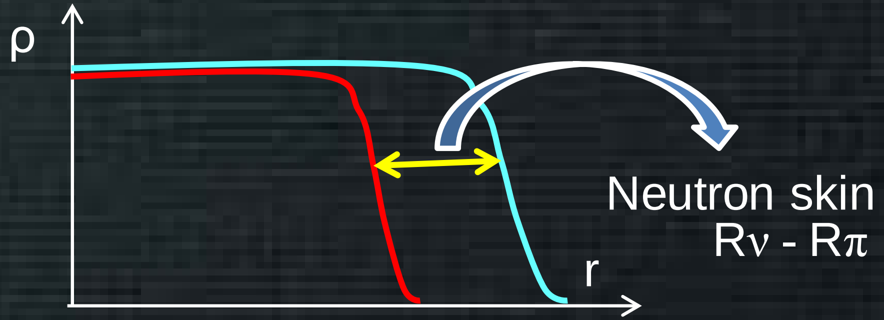
Low ℓ orbits and halo character

In the sd shell the difference between rms radii of s and d orbits reaches 1.6 fm!

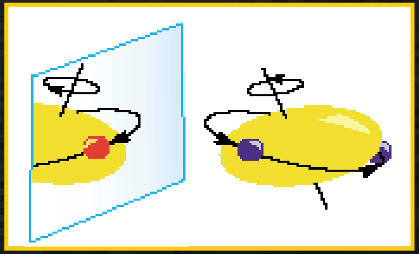


J. Bonnard et al.,
arXiv:1606.03345v1 (2016)
No-core shell model calculations with chiral realistic interaction.

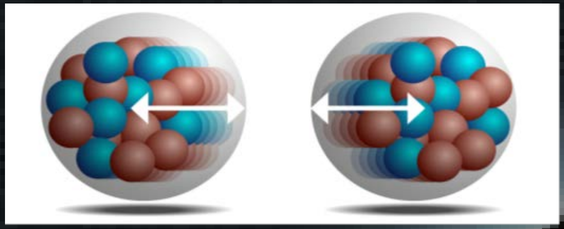
These investigations have a large impact also in the estimate of neutron skins…



…mirror symmetry and Coulomb energy differences



…development of pygmy resonances



Conclusions and perspectives

The structure of exotic nuclei presents a richness of phenomena that put in evidence the effects of subtle terms of the effective interaction

Dynamical symmetries help to interpret the development of deformation and the Islands of Inversion near “traditional” magic numbers.
They indicate the “smart” model spaces to be considered by SM calculations.

The position and evolution of single-particle energies give information on the existence and development of shell closures.

Different theoretical models, based on EFT interactions, EDF, ab initio are becoming available in some mass regions.

SPES beams will allow to perform detailed spectroscopy to achieve a much deeper understanding of the underlying nuclear force