Development of deformation and “smart” valence spaces

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Lecture 2

Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data

Shell model and deformation

Can the shell model describe deformed structures?

In the last two decades the improvement in computing power together with the development of powerful shell model methods and codes has allowed to describe well deformed nuclear states, provided the number of degrees of freedom (number of valence particles and the model space are not too large.

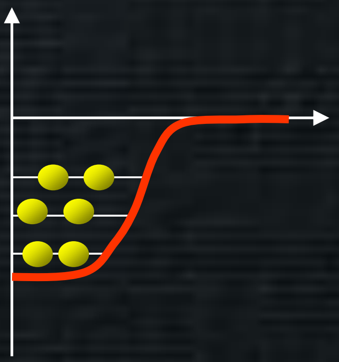
For this purpose it is essential to identify the smallest valence space that includes the relevant degrees of freedom

The effective interaction

A multipole expansion

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

monopole Multipole



V_m

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

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

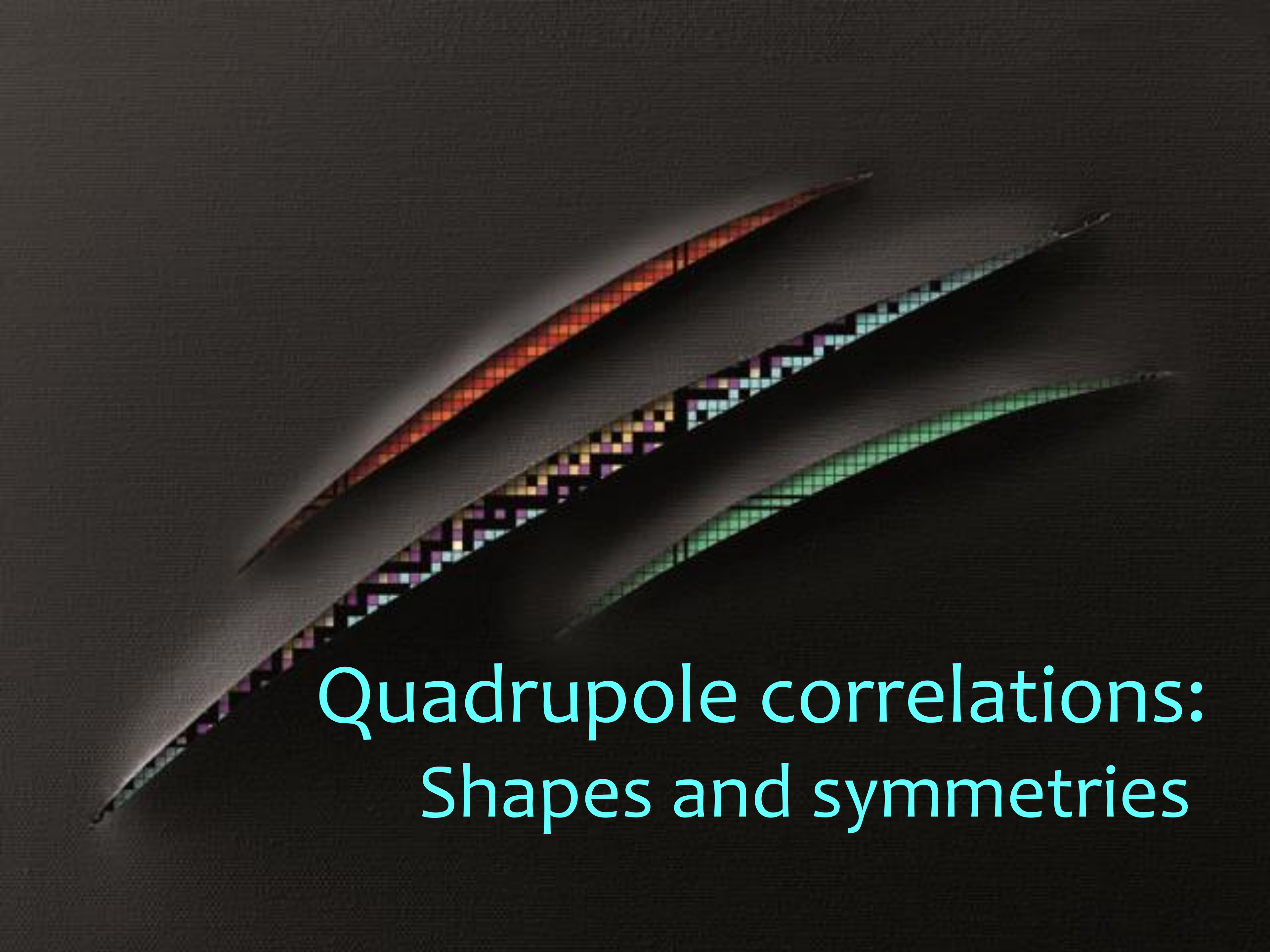
When quadrupole correlations dominate → deformation

Interplay: Monopole and Multipole

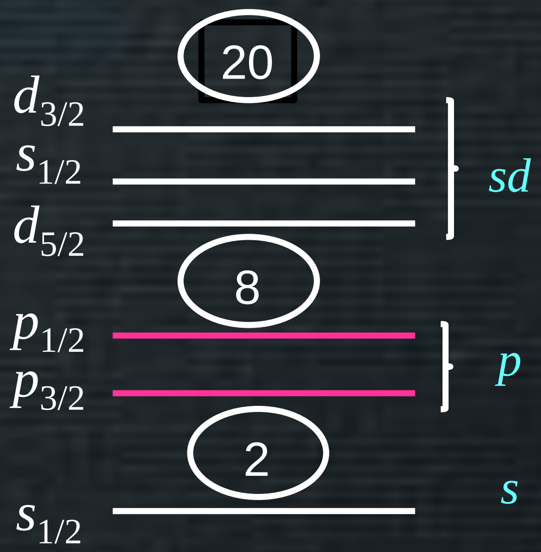
The interplay of the monopole with the multipole terms, like pairing and quadrupole, determines the different phenomena we observe.

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

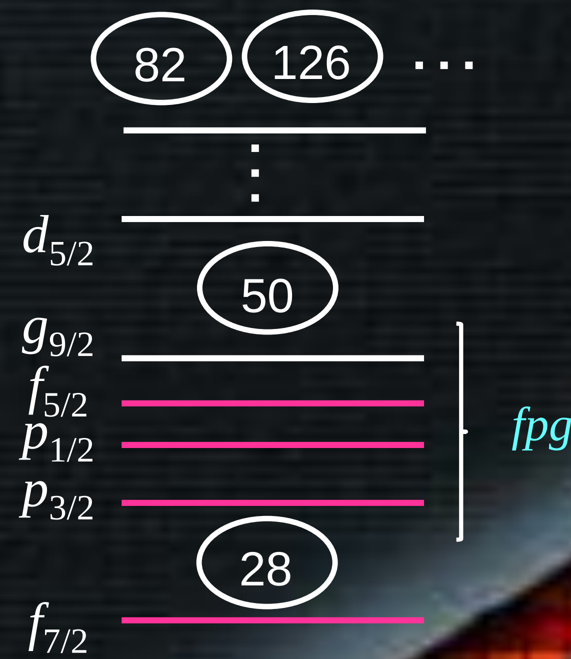
- islands of inversion
- shape phase transitions
- shape coexistence
- haloes, etc.


Quadrupole correlations:
Shapes and symmetries

The usual model spaces



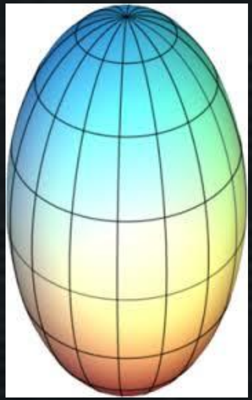
One is used to think that light and medium nuclei can be described in a single major HO shell



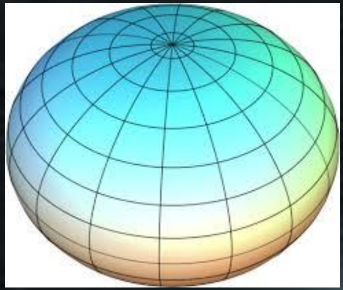
For heavier nuclei, the spin-orbit (SO) on top of the HO takes over and new boundaries appear

Quadrupole deformation: a simple model

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



In the limit of degeneracy of the single-particle energies of a major harmonic 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

The single-particle quadrupole moment is:

$$q_0 = (2n_z - n_x - n_y)$$

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

Example in the sd shell

In the *sd* shell *N* = 2

$$N = (n_x + n_y + nz)$$

there are 6 possibilities:

(2,0,0) (0,2,0) (0,0,2)

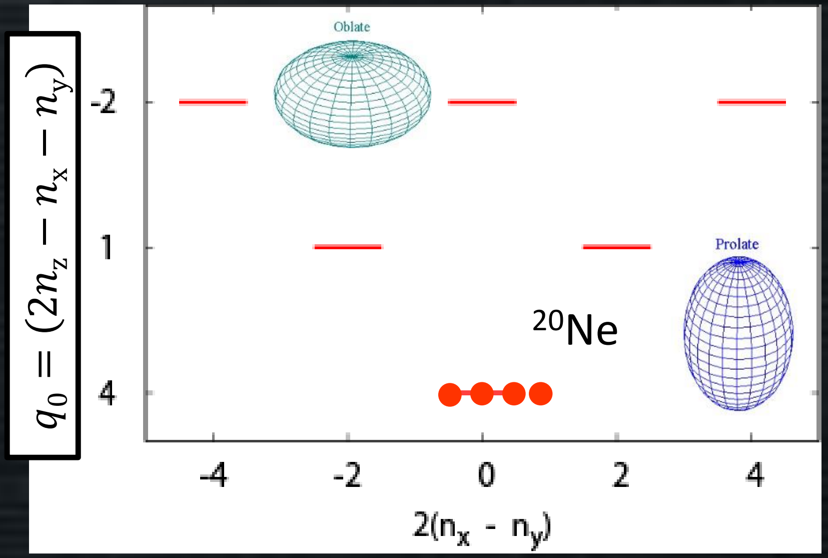
(1,1,0)(1,0,1)(0,1,1)

$$q_0 = (2n_z - n_x - n_y)$$

$$\boxed{q_0 = 4, 1, -2}$$

Intrinsic states are the Slater "determinants" obtained by filling these fourfold (2p + 2n) degenerate "orbits" along the N=Z line

The "intrinsic orbits" in SU3



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

Elliott's SU3 works well in the sd shell but fails for upper shells where the SO interaction introduces large energy shifts

SU3 approximate symmetries

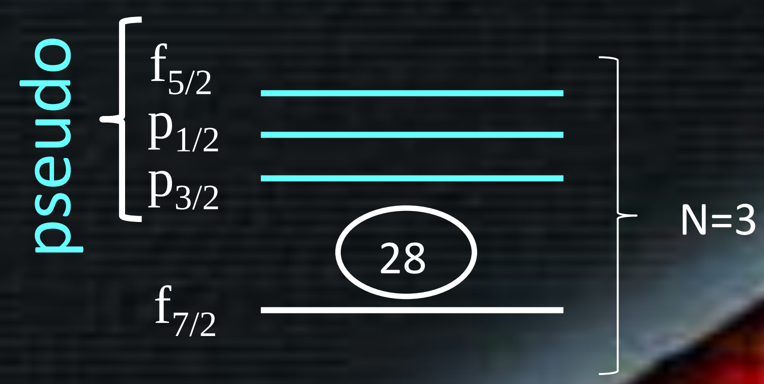
Two variants of SU3 apply in specific spaces

Quasi SU3

applies to the lowest Δj = 2, Δℓ = 2 orbits in a major HO shell

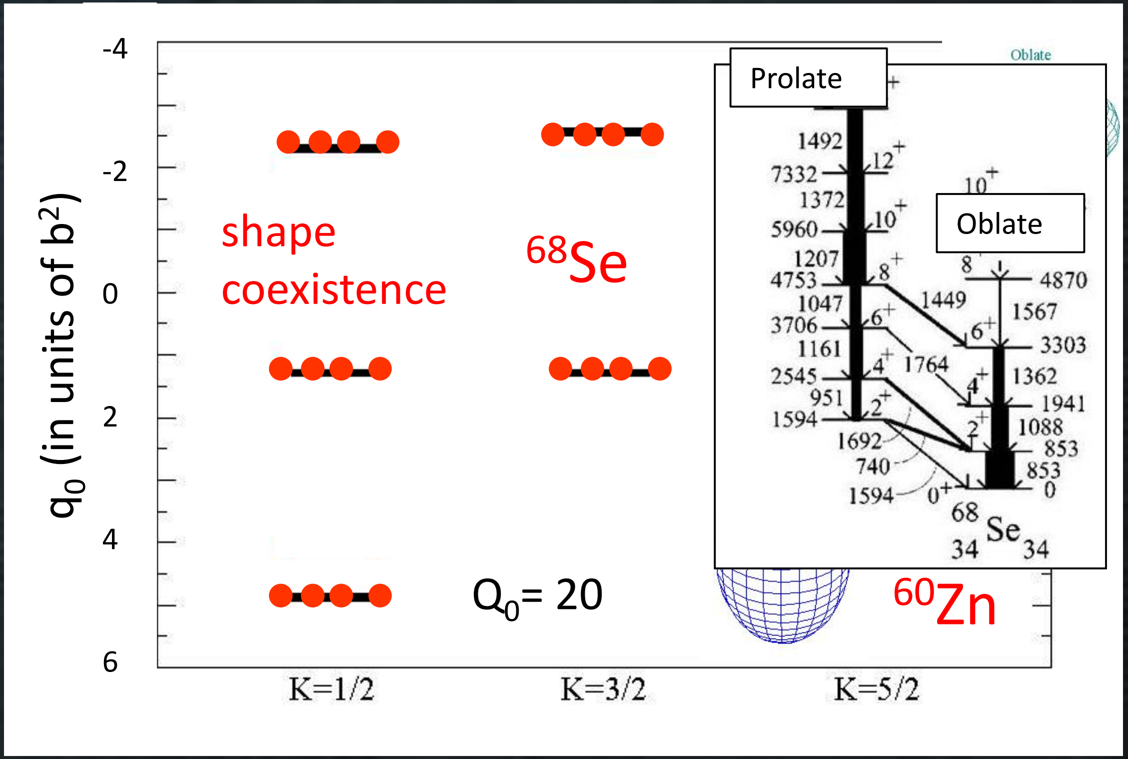
Pseudo SU3

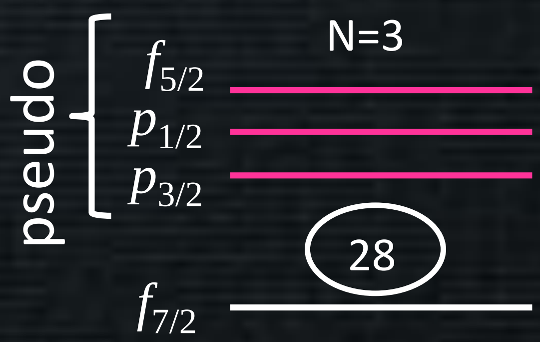
applies to a HO space where the largest *j* orbit has been removed.



A.P. Zuker et al., PRC 52, R1741 (1995).
Zuker, Poves, Nowacki, Lenzi, PRC 92, 024320 (2015)

Quadrupole moments in Pseudo SU3

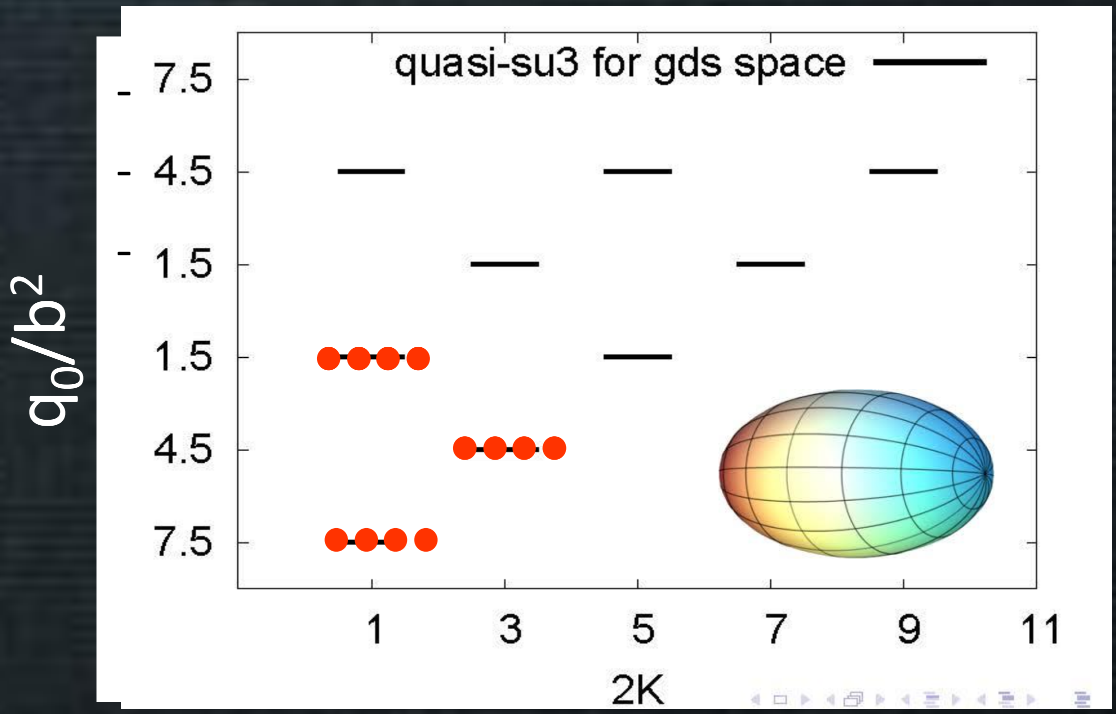


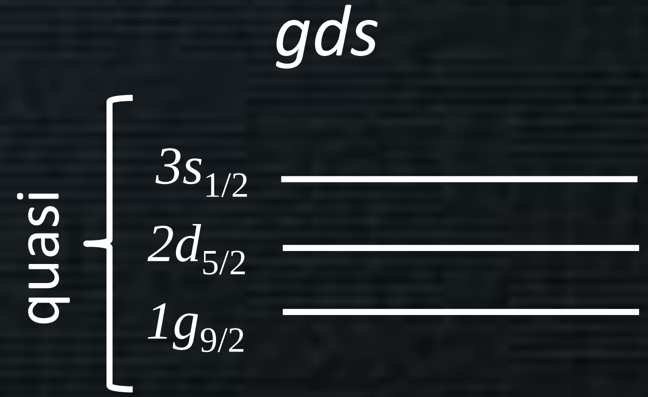


We obtain Q_0 by summing those of the single particles/holes in each "orbit"

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

Quadrupole moments in Quasi SU3





We obtain Q_0 by summing those
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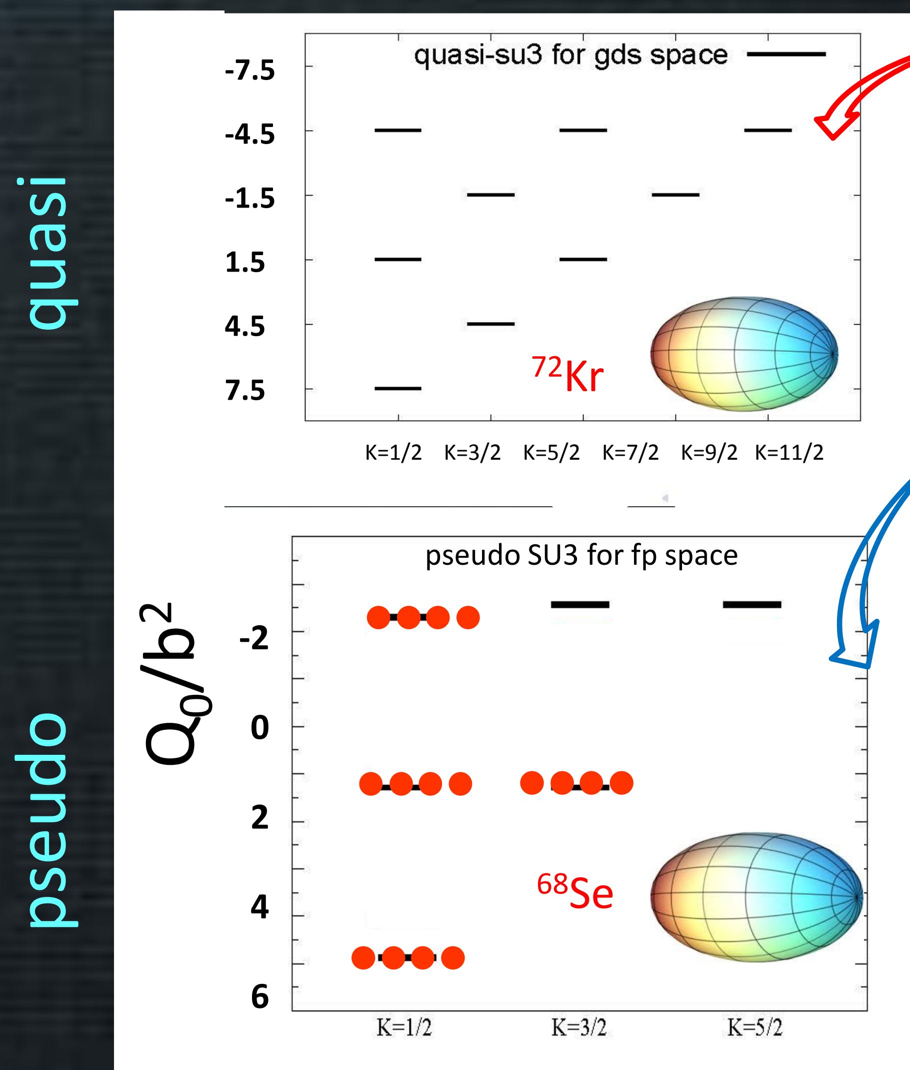
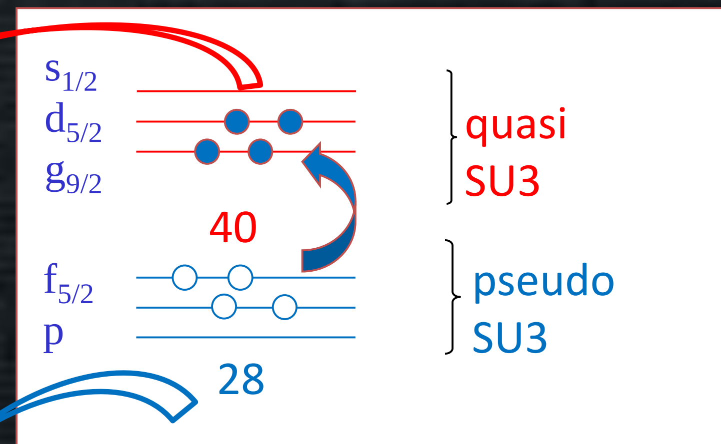
A.P. Zuker et al., PRC 92, 024320 (2015)

Maximizing quadrupole correlations





Particle-hole excitations in the pseudo + quasi space maximize the quadrupole moment.

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

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

Quadrupole moments in N=Z nuclei

Quadrupole moments can be obtained from this simple schemes for different *np-nh* configurations between pseudo and quasi SU3 spaces.

B(E2) values can be deduced and compared to experiment.

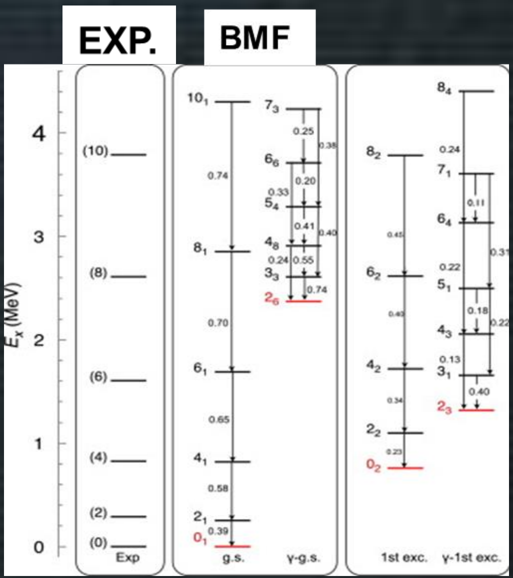
$B(E2: 2^+ \rightarrow 0^+) = Q_0^2/50.3$

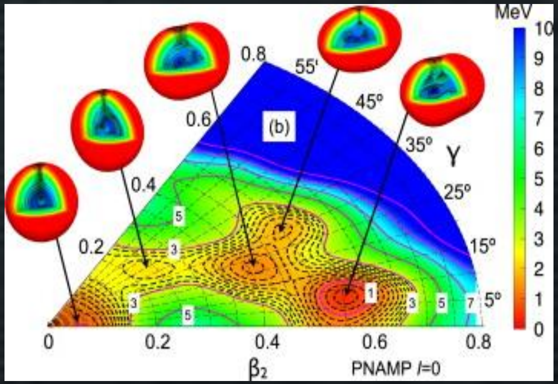
$B(E2: 4^+ \rightarrow 2^+) = Q_0^2/35.17$

Non-degenerate single-particle energies erode slightly the quadrupole collectivity.

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

Shape coexistence in ^{80}Zr

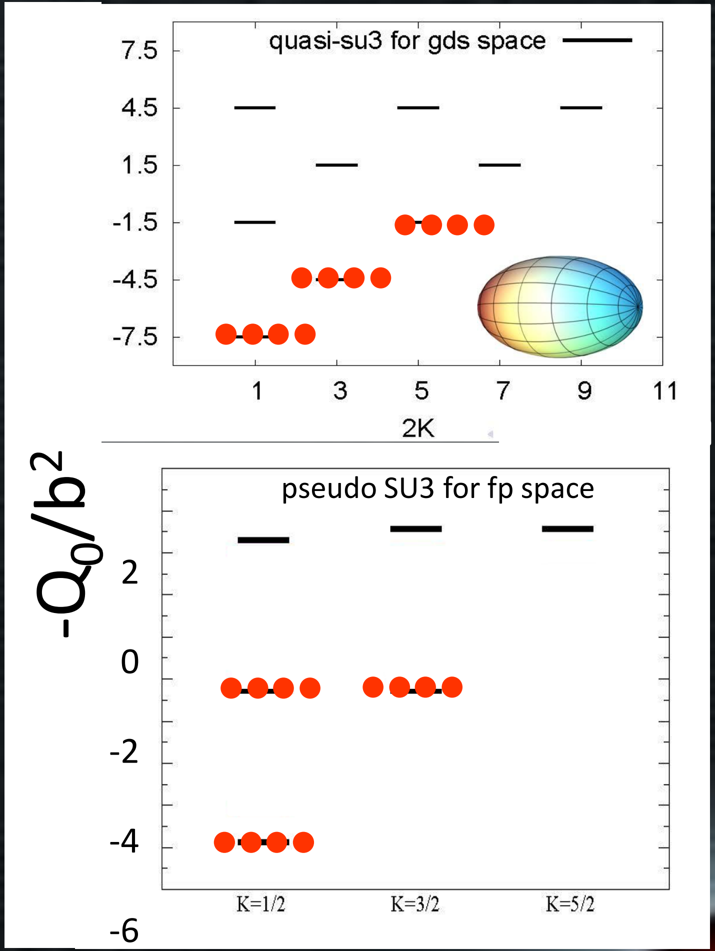




T.R.Rodríguez & J.L. Egido, PLB 705, 255 (2011)

quasi

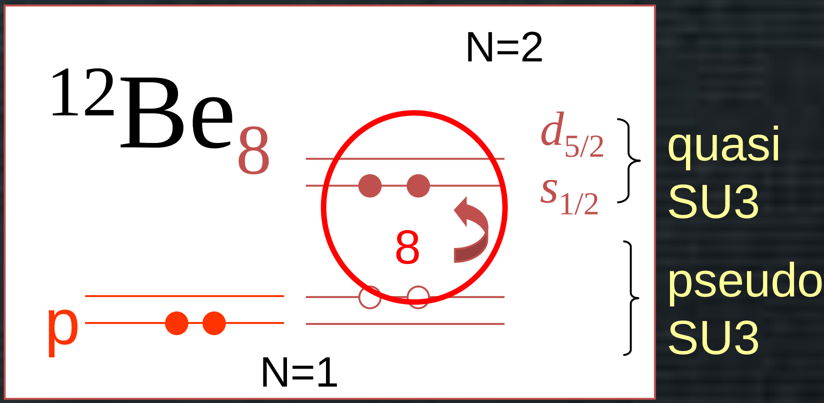
pseudo



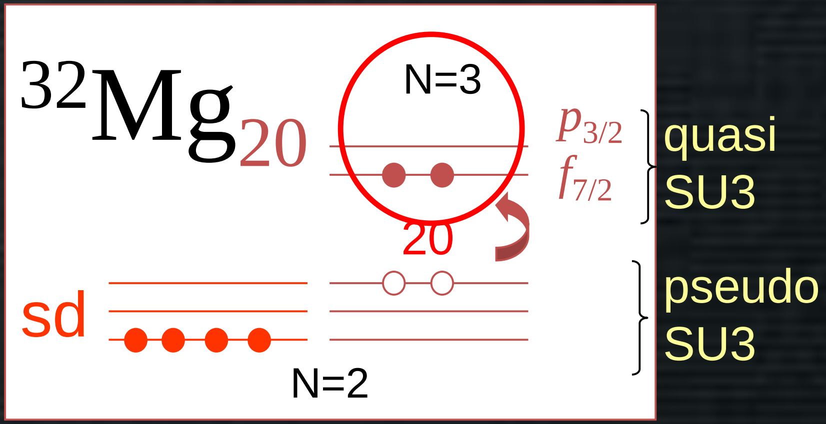
Our scheme predicts a gamma band due to the two platforms available in the quasi SU3 space

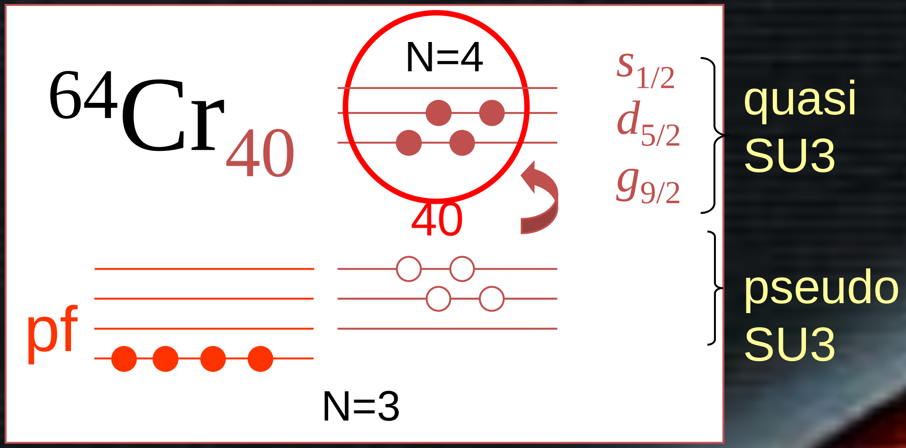
A.P. Zuker et al., PRC 92, 024320 (2015)

Islands of inversion and symmetries



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





The region south of ^{68}Ni

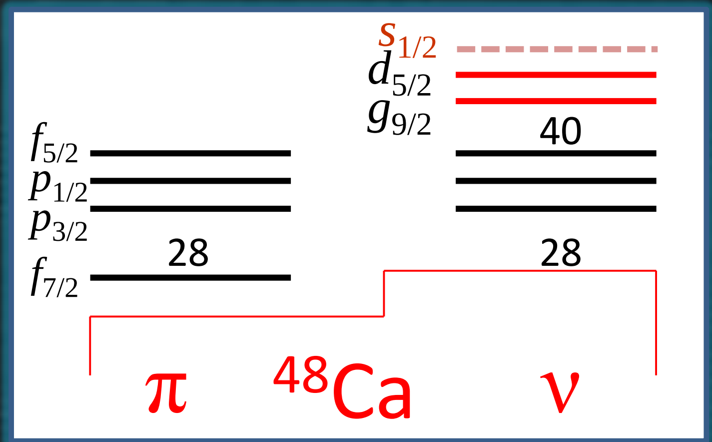
Deformation and SM in the fpgd space

LNPS interaction: renormalized realistic interaction
+ monopole corrections

^{48}Ca core

protons: full *pf* shell

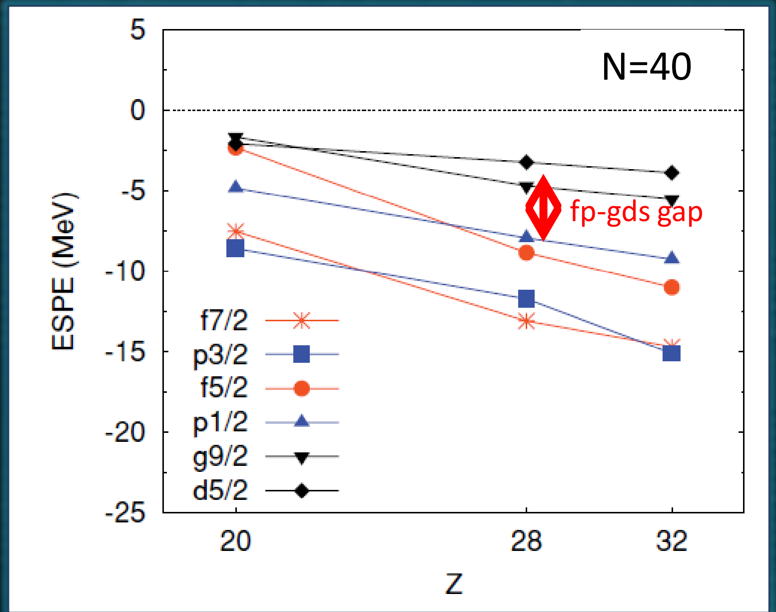
neutrons: $p_{3/2}, f_{5/2}, p_{1/2}, g_{9/2}, d_{5/2}$



quasi SU3

pseudo SU3

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

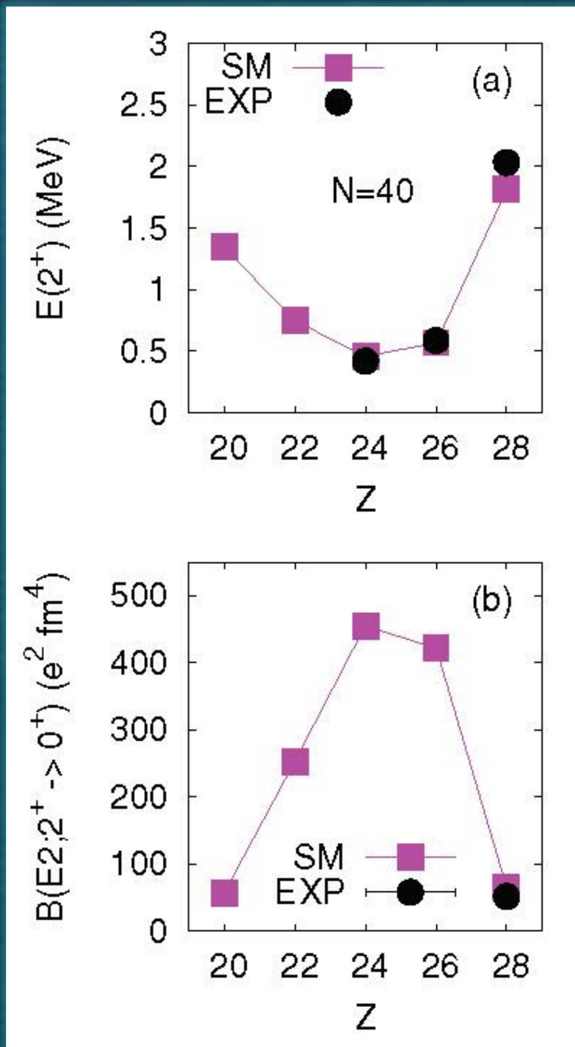


Other effective interactions:

$V_{low\ k}$: L. Coraggio et al., PRC 89, 024319 (2014).

A3DA: Tsunoda et al., PRC 89, 031301 (2014).

The N=40 isotones



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

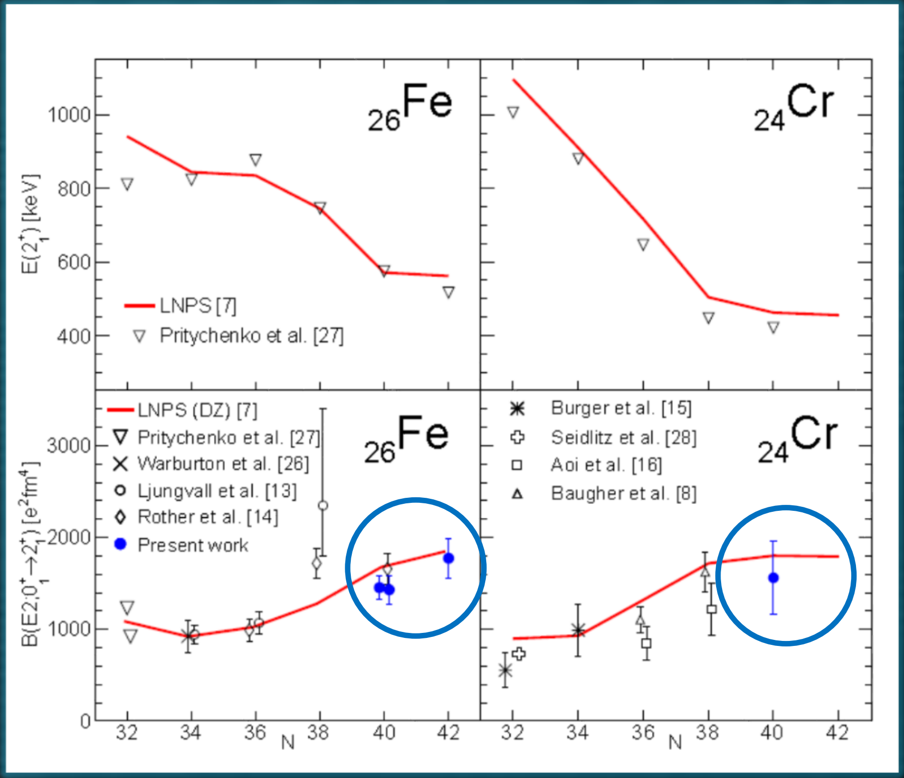
Occupation of intruder orbitals and percentage of p-h in g.s. configurations

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)

Measurement of deformation with radioactive beams

Intermediate-energy Coulomb excitation measurements at NSCL-MSU

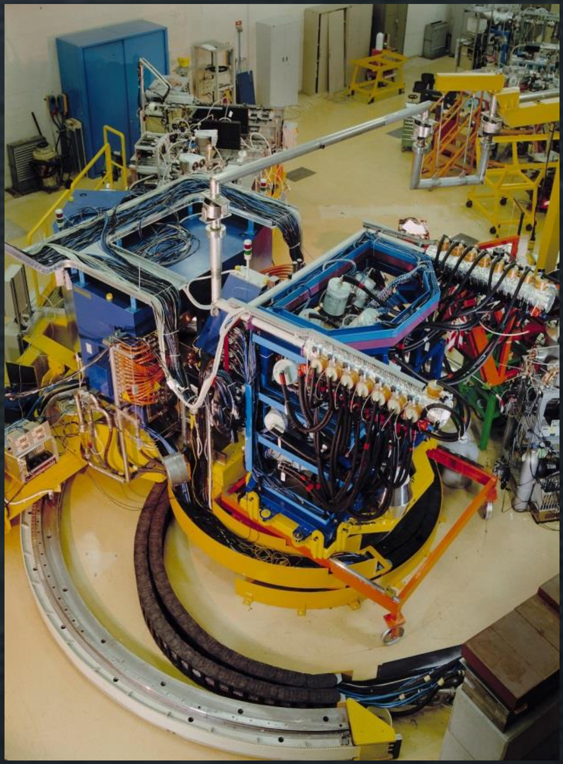


These data constitute a stringent test for the effective interaction and give direct information on the collectivity and deformation at N=40

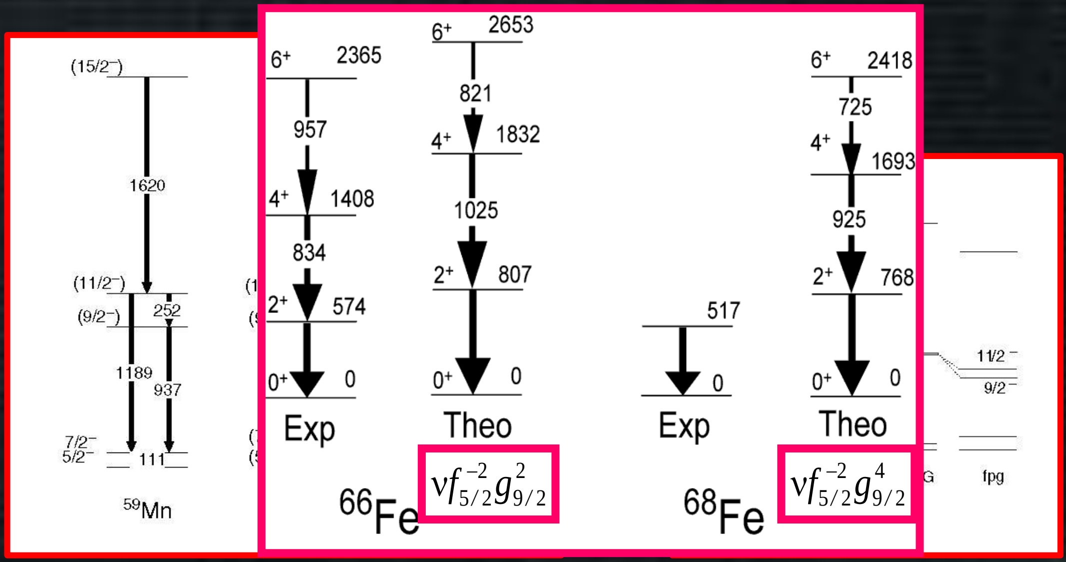
H. L. Crawford et al., PRL 110, 242701 (2013)
T. Baugher et al., PRC 86, 011305(R) (2012)

Spectroscopy of Mn isotopes

First level schemes from multi-nucleon transfer reactions using CLARA + PRISMA at LNL



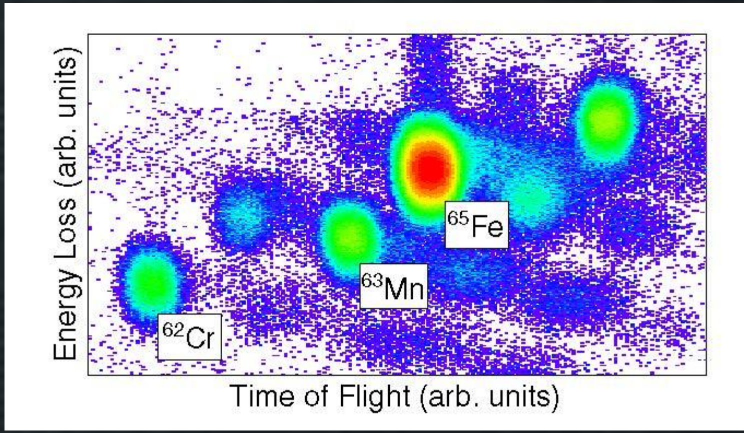
Calculations without the quasi-SU3 partners in the *gds* space were unable to reproduce the data for the neutron-rich isotopes

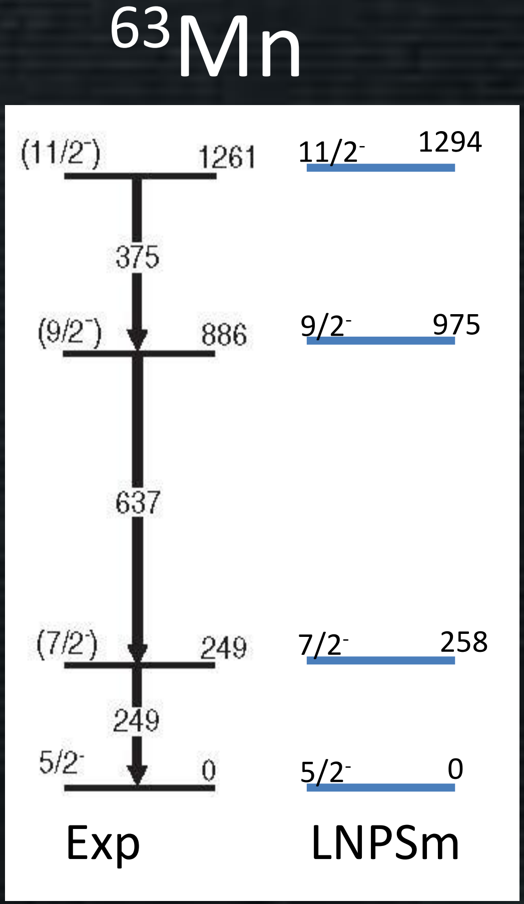


J.J. Valiente-Dobon et al., PRC **78**, 024302 (2008)

Spectroscopy with radioactive beams

Inelastic scattering following fragmentation with SEGA @ MSU



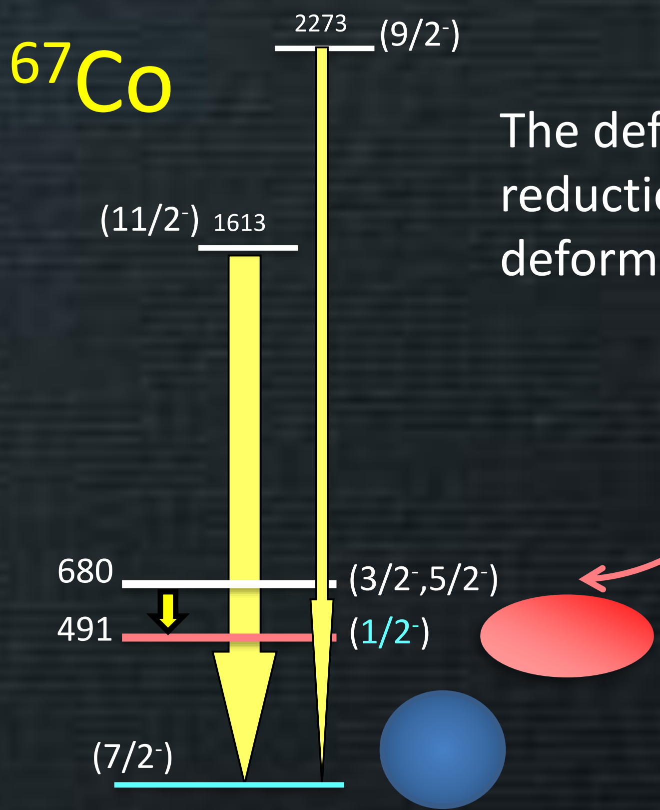


Excitation energy and lifetimes in agreement with data.

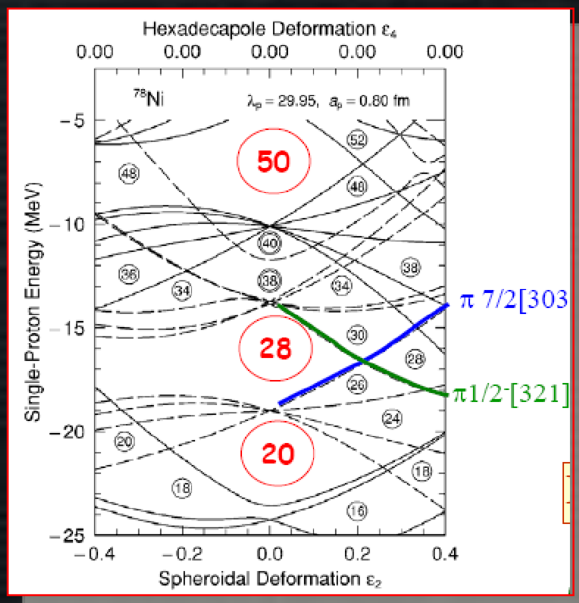
T. Baugher et al., PRC 93, 014313 (2016)

More data on heavier Mn isotopes coming soon from RIKEN

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

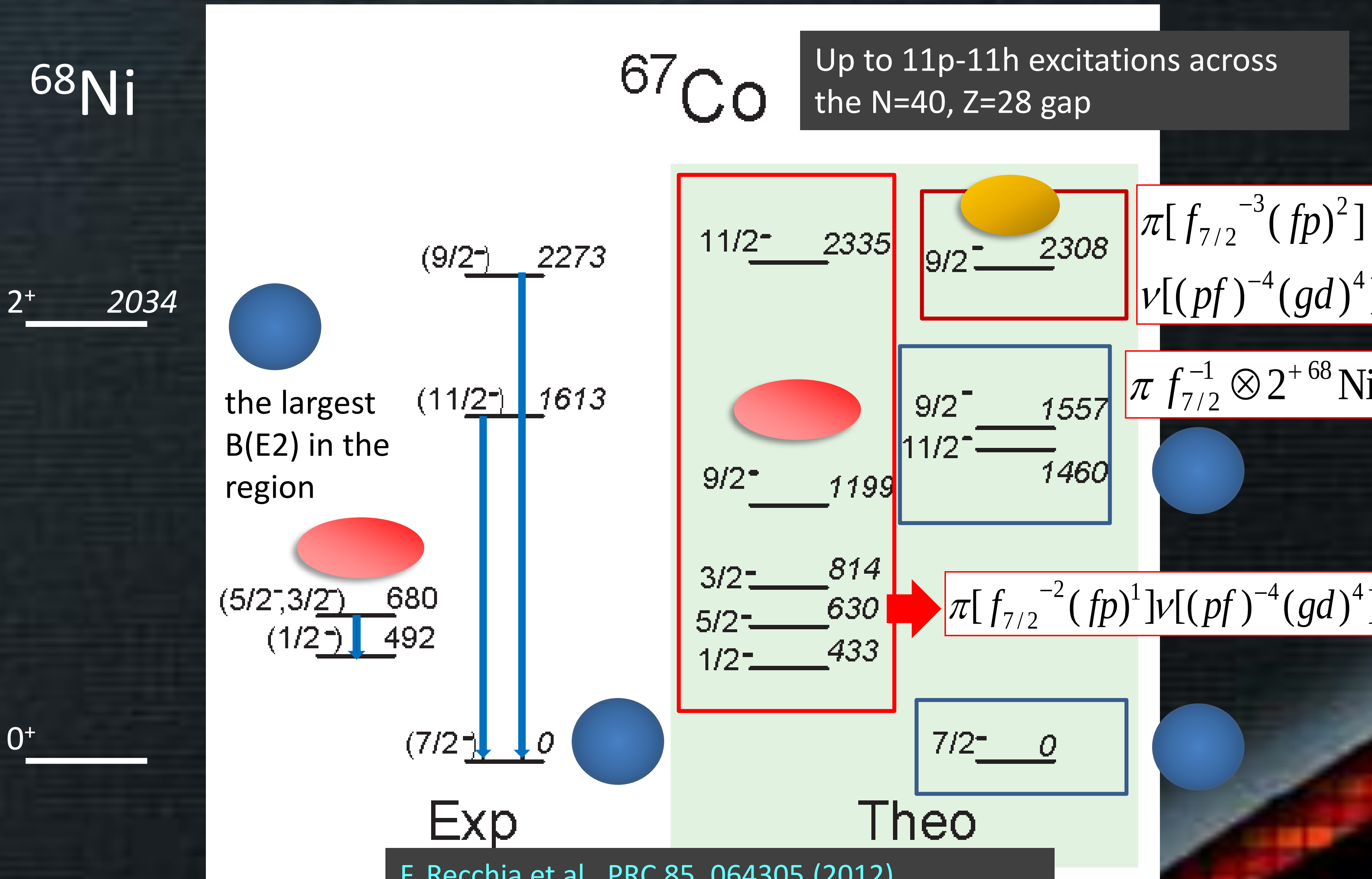


F. Recchia et al., PRC 85, 064305 (2012)

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



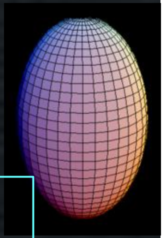
F. Recchia et al., PRC 85, 064305 (2012)

Triple shape coexistence in ^{68}Ni

F. Nowacki, LNPS calculations

In first approximation, ^{68}Ni has a doubly 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

See also: Y. Tsunoda et al., Phys.Rev.C 89, 024313(R) (2014), for ^{70}Ni, ^{70}Co: A.I. Morales et al., PLB 765 (2017) 328 and for ^{72}Ni, A.I. Morales et al., PRC 93, 034328 (2016)

More data on heavier Ni isotopes coming soon from RIKEN