Nuclear structure far from stability and the effective NN interaction

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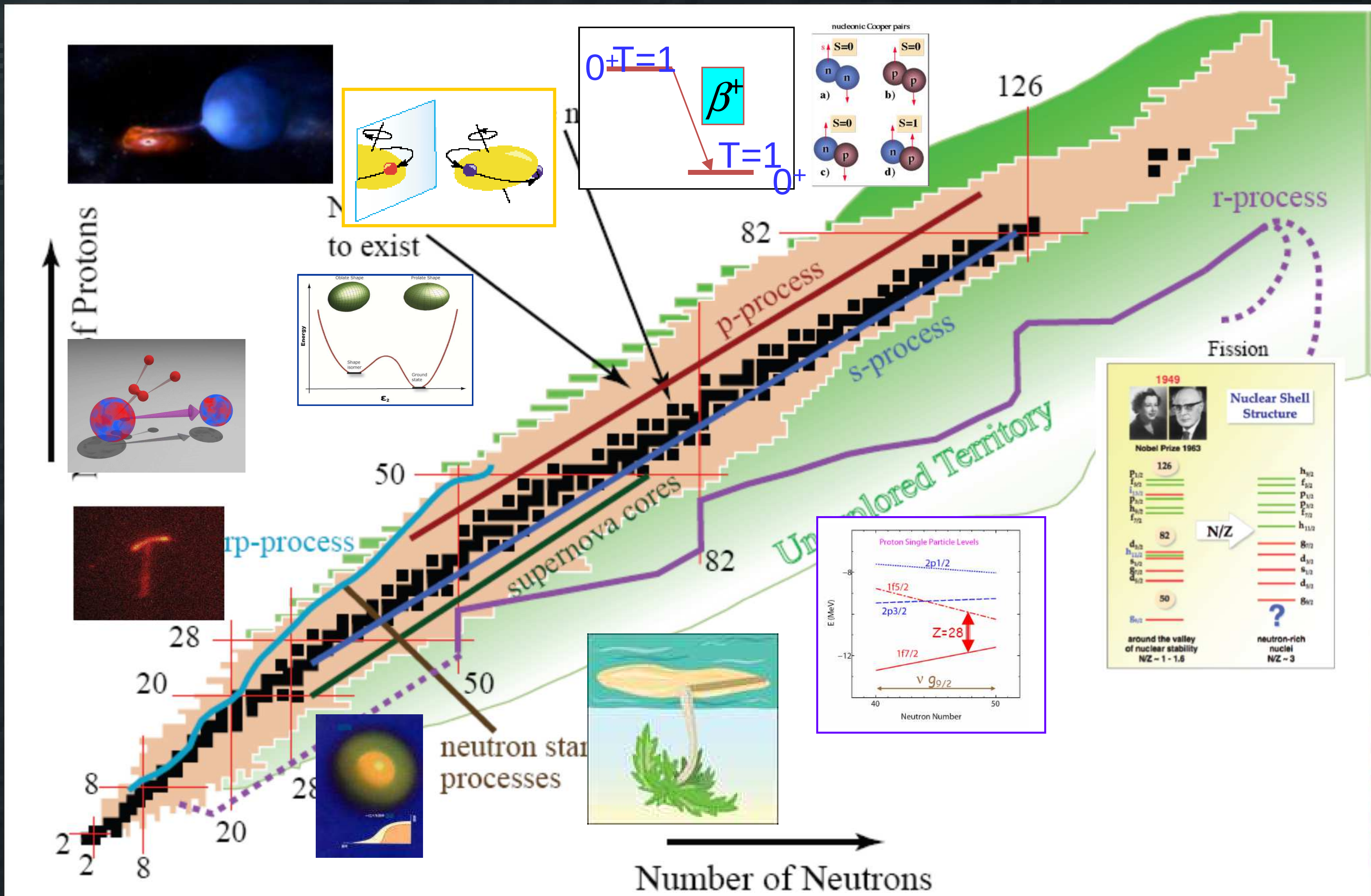
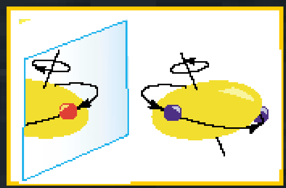
New phenomena far from stability



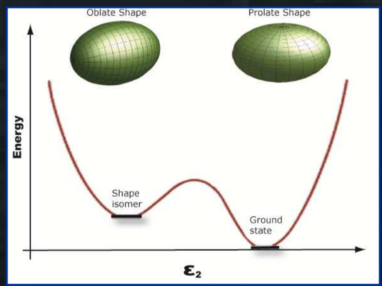
Shell structure far from stability

The proton-rich side

Isospin symmetry breaking

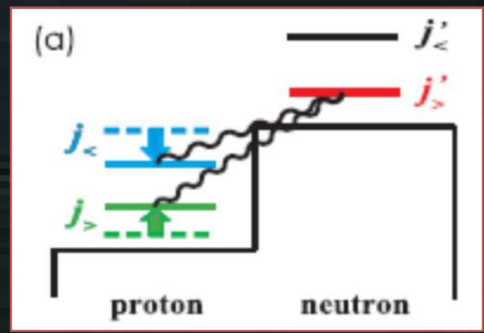


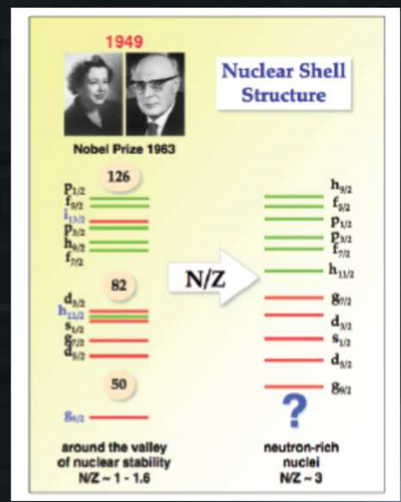
shape coexistence



The neutron-rich side

Shell evolution far from stability



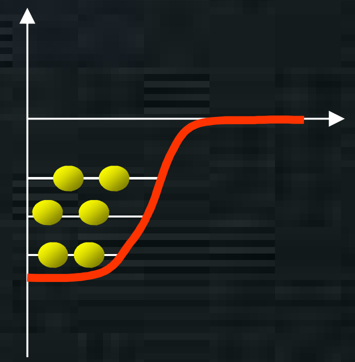


The effective interaction

A multipole expansion

$$\boxed{V = V_m + V_M}$$

monopole　　Multipole



$\boxed{V_m}$

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

$\boxed{V_M}$

- correlations
- energy gains

Deformation

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.

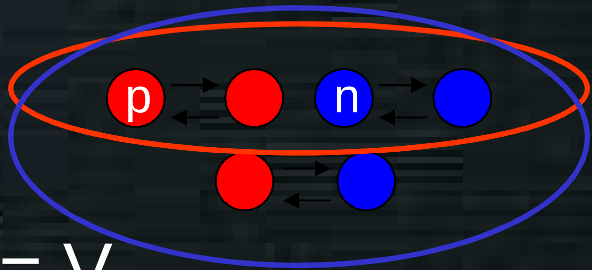
The proton-rich side

- Which components of the NN interaction break the isospin symmetry?
- How does isospin symmetry work with shape coexistence?
- Will new decay modes be observed far from stability?
- Do we understand the interplay of T=0 and T=1 pairing?
- Do proton skins / halos exist?
- Connection with other fields: Astrophysics, Standard Model

Neutron-proton exchange symmetry

Charge symmetry : $V_{pp} = V_{nn}$

Nuclear force slightly asymmetric
e.g. scattering lengths
Machleidt and Muther, PRC 58(2001)1393

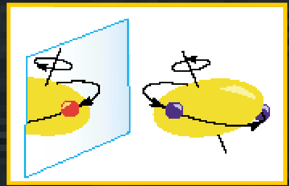


Charge independence: $(V_{pp} + V_{nn})/2= V_{np}$

some charge dependence exists
González Trotter et al., PRL 83 (1999)3788

Deviations are small

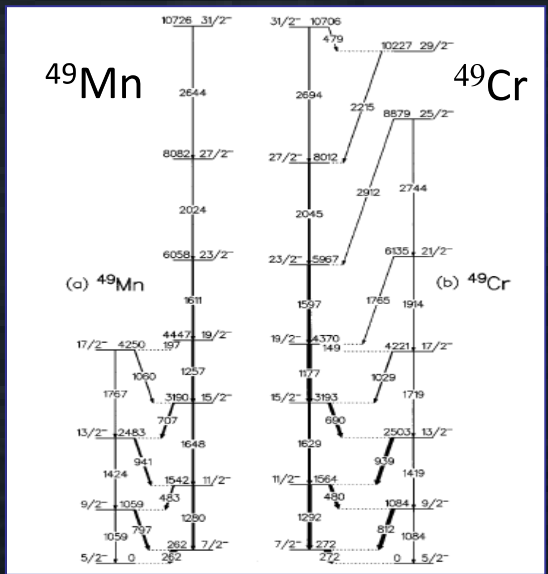
Mirror energy differences

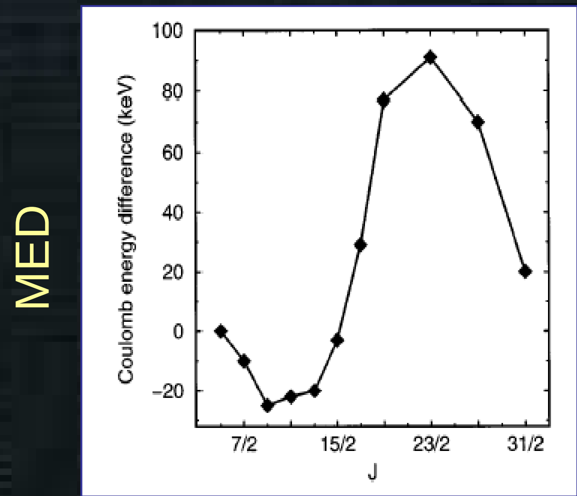


difference in excitation energies

$$\mathrm{MED}_J = \mathrm{E}^*_{J,T_z=-T} - \mathrm{E}^*_{J,T_z=T}$$

Test the charge symmetry of the interaction





Measuring the Isospin Symmetry Breaking

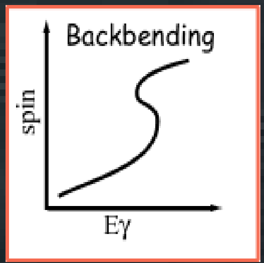
Can we reproduce such small energy differences?
What can we learn from them?

Interestingly they contain a richness of information
about spin-dependent structural phenomena

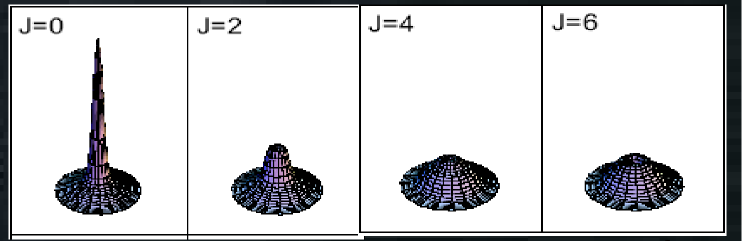
We measure **nuclear** structure features:

- How the nucleus generates its angular momentum
- Evolution of the radii (deformation) along a rotational band
- Learn about the configuration of the states
- Isospin non-conserving terms in the nuclear interaction

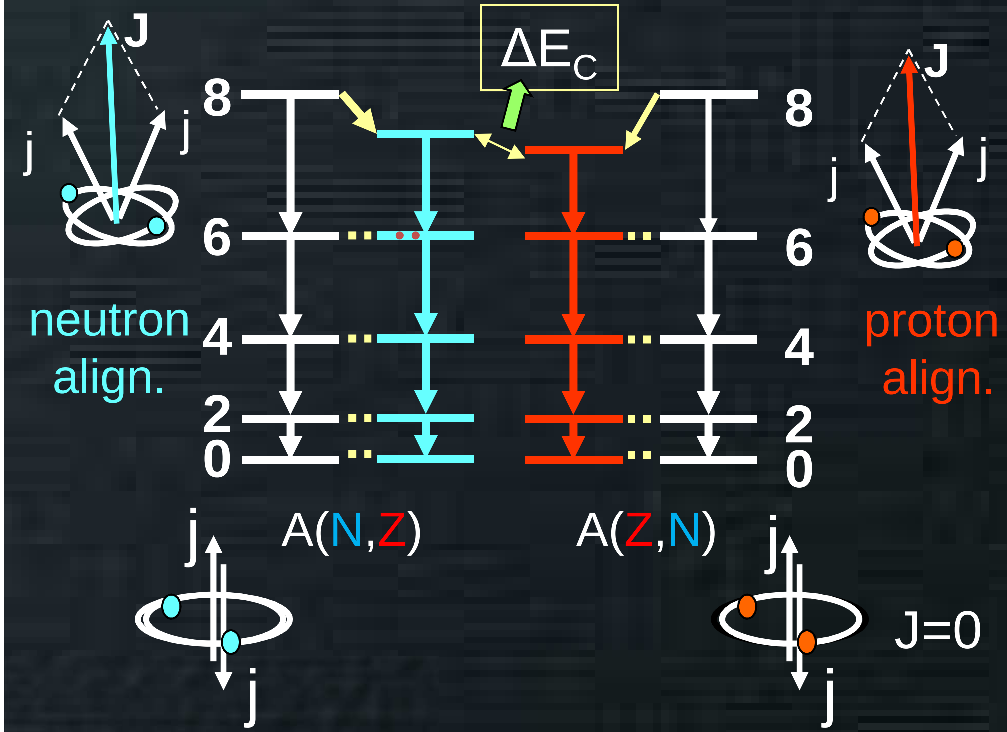
MED and nucleon spatial correlations

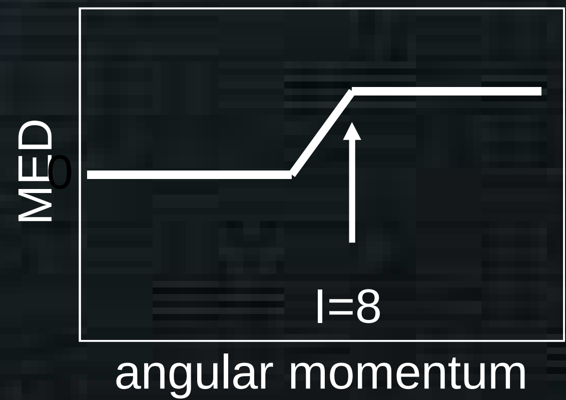


probability distribution for the relative distance of two like particles in the $f_{7/2}$ shell



courtesy P. Van Isacker

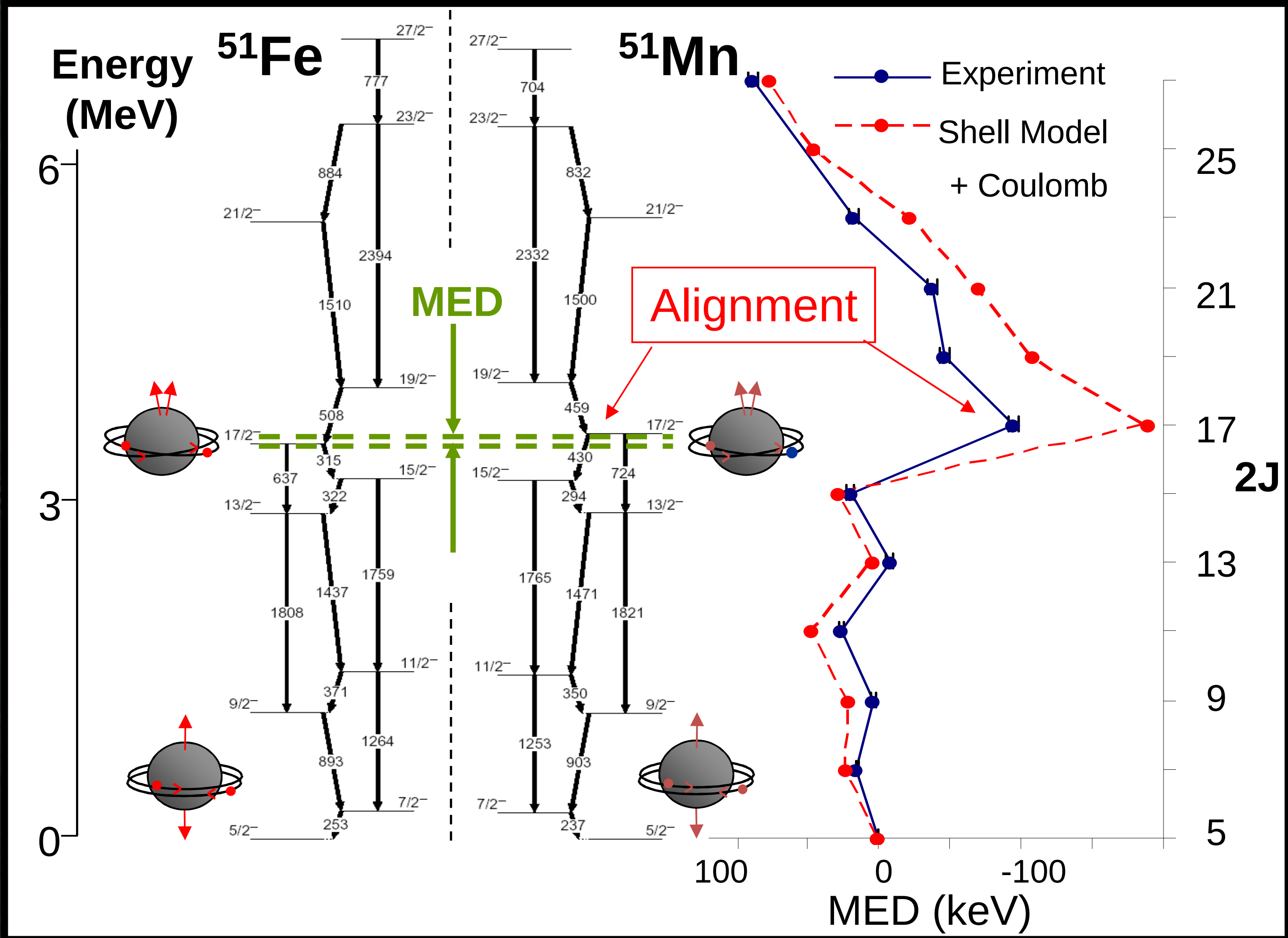




Shifts between the excitation energies of the mirror pair at the backbending indicate the type of nucleons that are aligning

MED and nucleon alignment

D.D. Warner, M.A. Bentley and P. Van Isacker., Nature Physics 2 (2006) 311

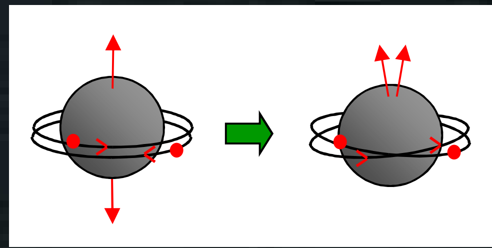


Improving the description of Coulomb effects

Can we do better?

$$\boxed{V_C = V_{CM} + V_{Cm}}$$

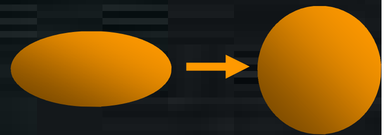
V_{CM} Multipole part of the Coulomb energy: → Between valence protons only



V_{cm} Monopole part of the Coulomb energy:

$$E_{Cr} = \frac{3}{5}\frac{e^2 Z(Z-1)}{R}$$

radial effect: radius changes with J



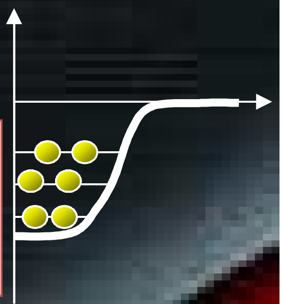
L^2 term to account for shell effects

$$E_{Cll} = \frac{-4.5 Z_{cs}^{13/12}[2l(l+1) - N(N+3)]}{A^{1/3}(N+3/2)} keV$$

electromagnetic LS term

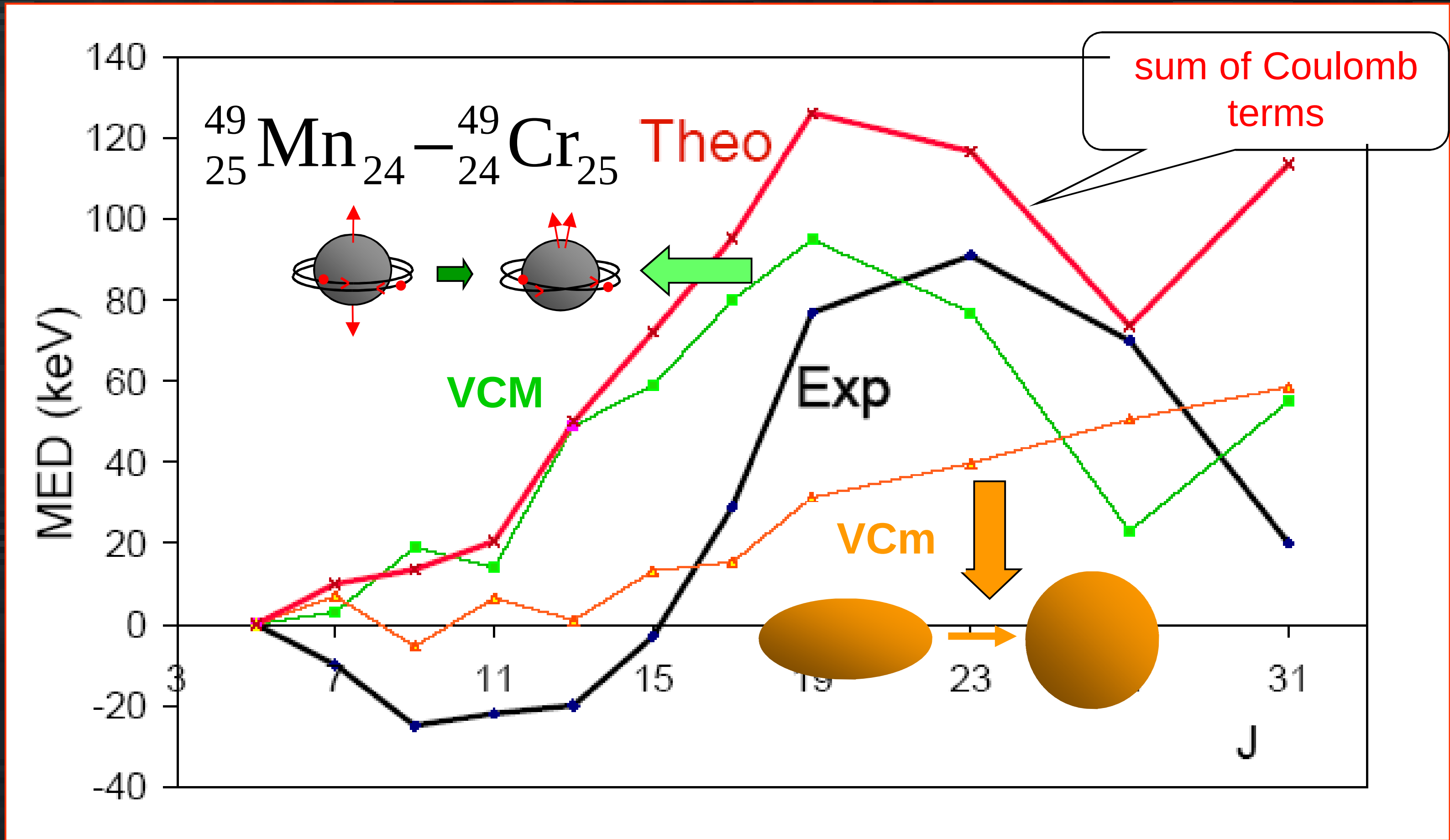
$$E_{Cls} = (g_s - g_l)\frac{1}{4m_N^2 c^2}\left(\frac{1}{r}\frac{dV_C}{dr}\right)\mathbf{l.s}$$

change the single-particle energies



A.P. Zuker

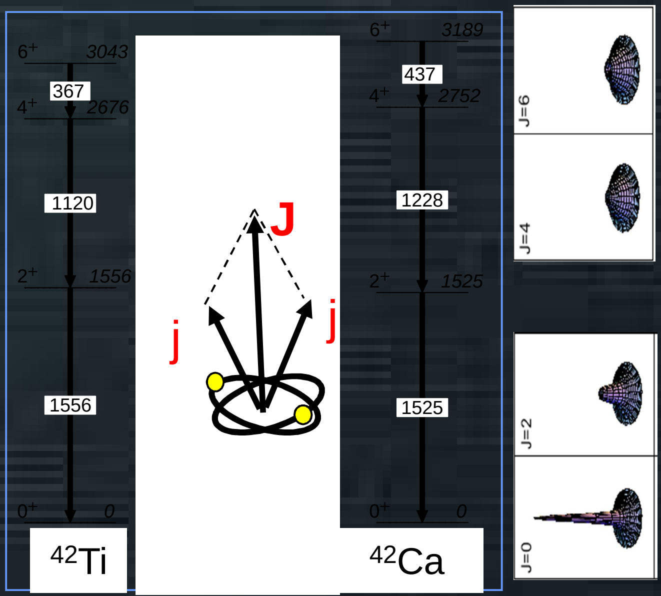
Are Coulomb corrections enough?



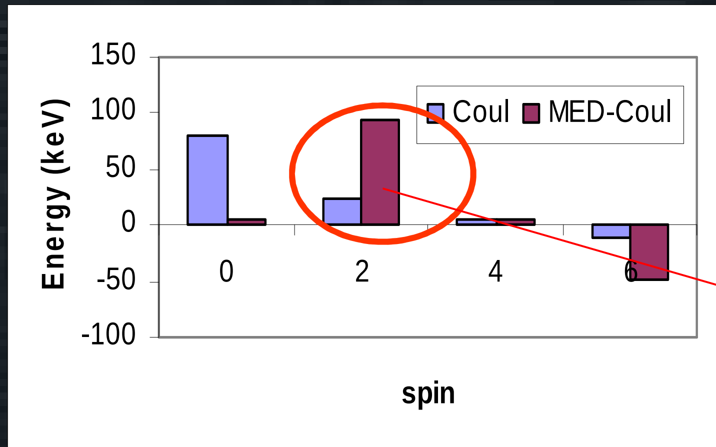
Another term of <u>nuclear (?) nature</u> is needed, but it has to be big!

Looking for an empirical interaction

Yrast spectra of the T=1 ^{42}Ti and ^{42}Ca



We assume that the configurations of these states are pure $(f_{7/2})^2$



Coul: calculated
MED: measured
(monopole subtracted)

J=2 anomaly

This suggests that the role of the isospin non conserving nuclear force is at least as important as the Coulomb potential in the observed MED

Simple ansatz
for the application to
nuclei in the pf shell:

$$V_B\left[\pi f_{7/2}^{2}\right]^{J=2} = 100\,\mathrm{keV}$$

A. P. Zuker et al., PRL 89, 142502 (2002)

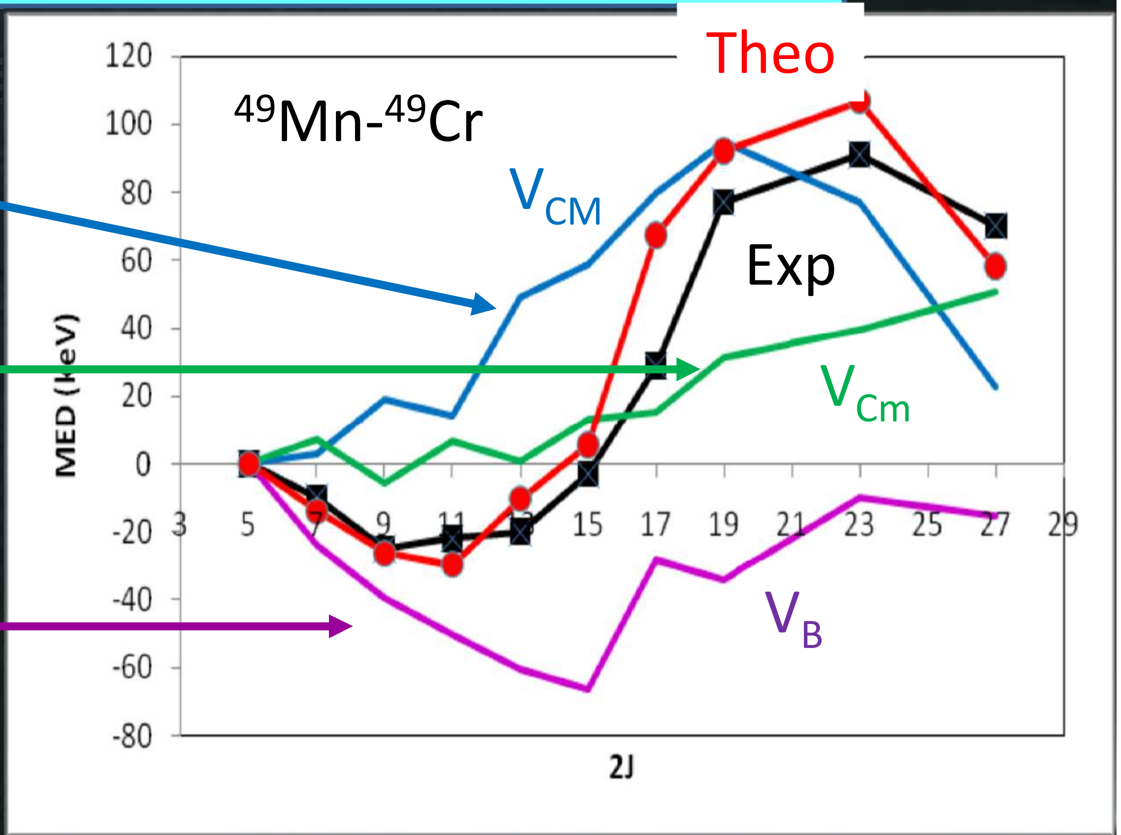
Calculating the MED with SM

$$MED_J = <VCM>_J + <VCm>_J + <VB>_J$$

VCM: gives information on the nucleon alignment or recoupling

VCm: gives information on changes in the nuclear radius

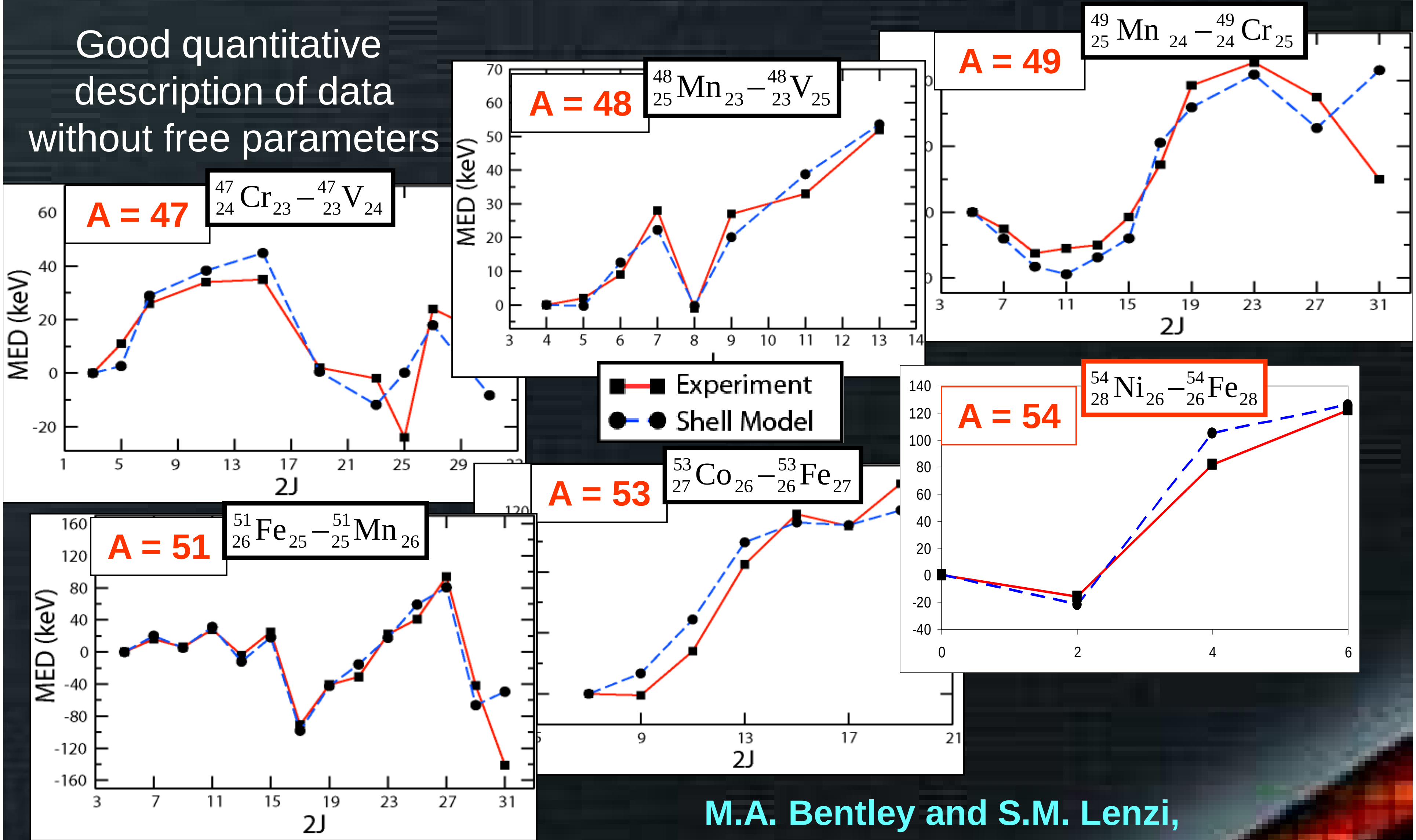
Important contribution from the VB term: $V(\pi[f_{7/2}f_{7/2}]_2)$=100 keV of the same order as the Coulomb contributions!



A. P. Zuker et al., PRL 89, 142502 (2002)

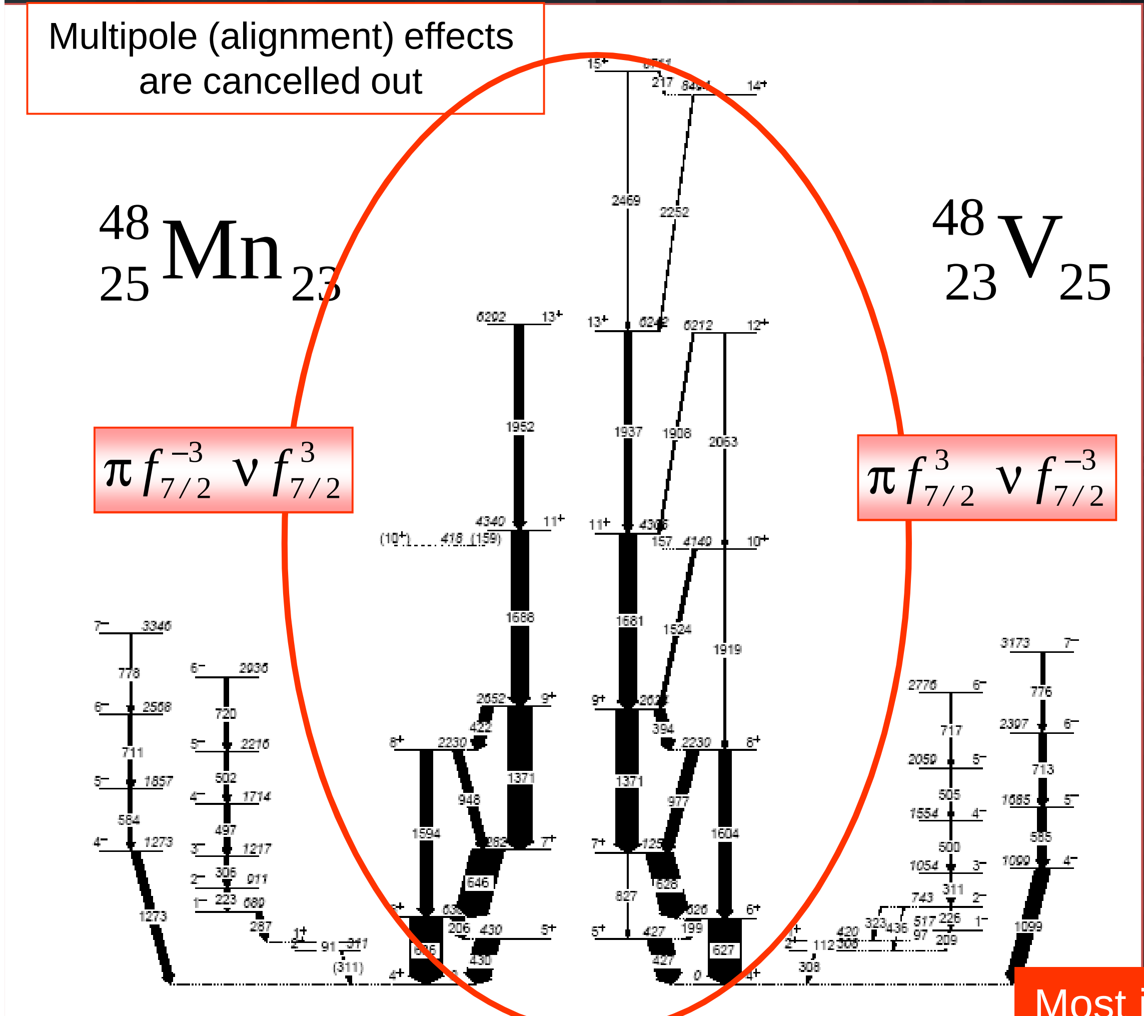
MED in the shell model framework

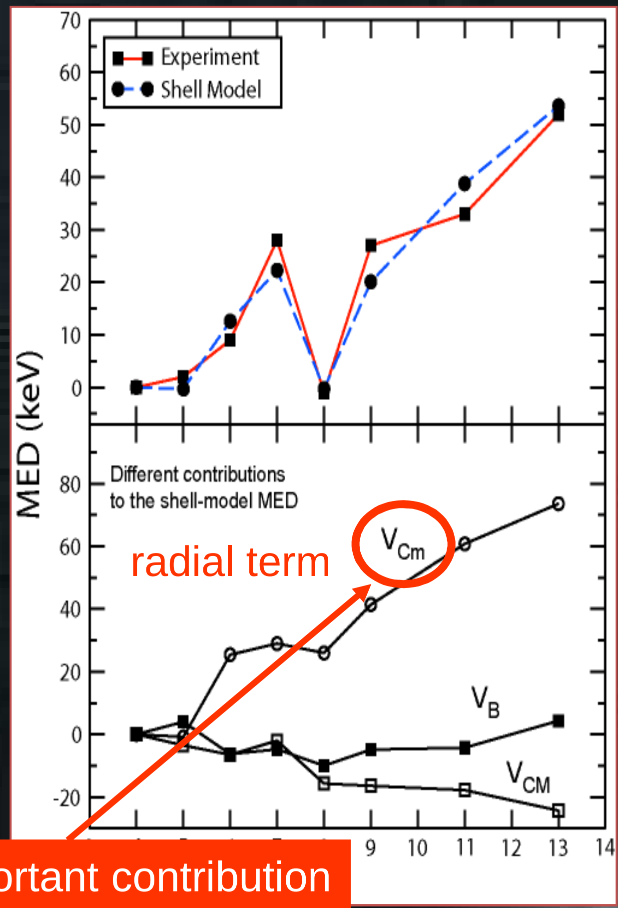
Good quantitative description of data without free parameters



M.A. Bentley and S.M. Lenzi, Prog. Part. Nucl. Phys. 59, 497-561 (2007)

Evidence of the monopole radial effect



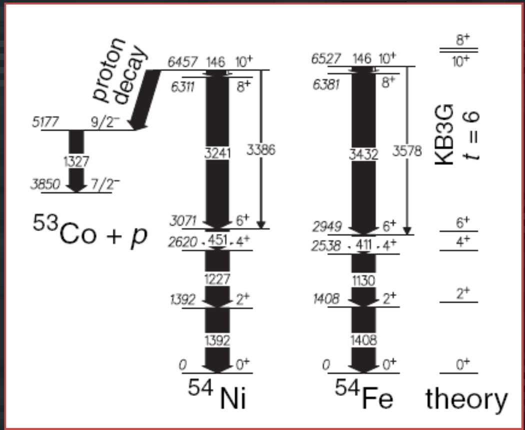


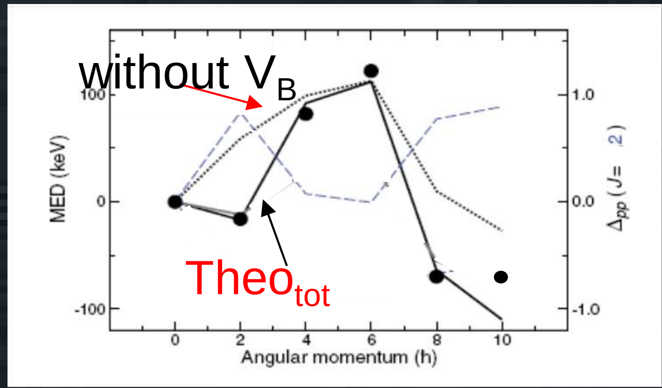
M.A. Bentley et al., PRL 97, 132501 (2006)

The nucleus changes shape towards band termination

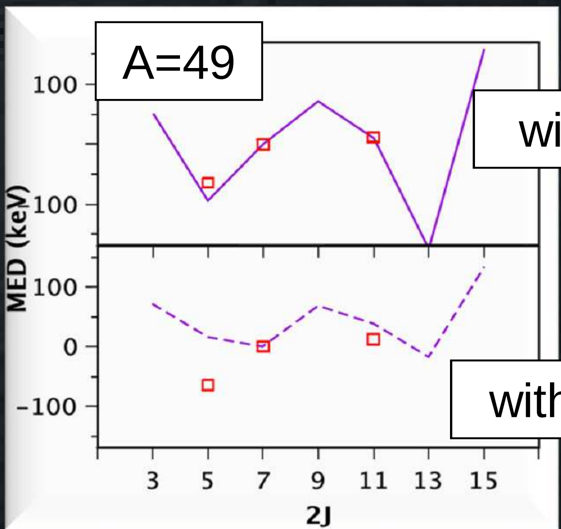
VB in the T=1 and T=3/2 mirrors

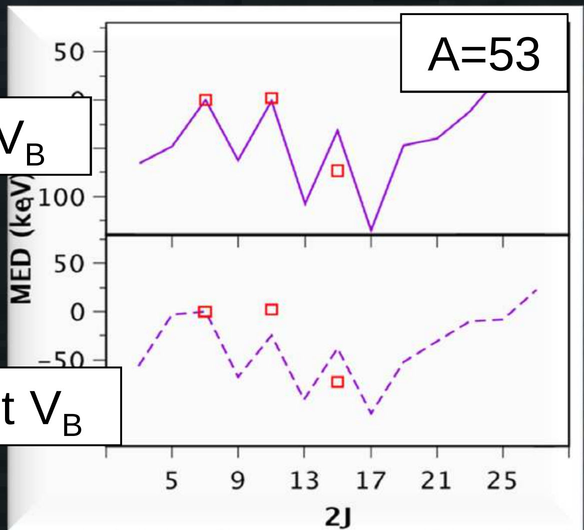
J=2 anomaly



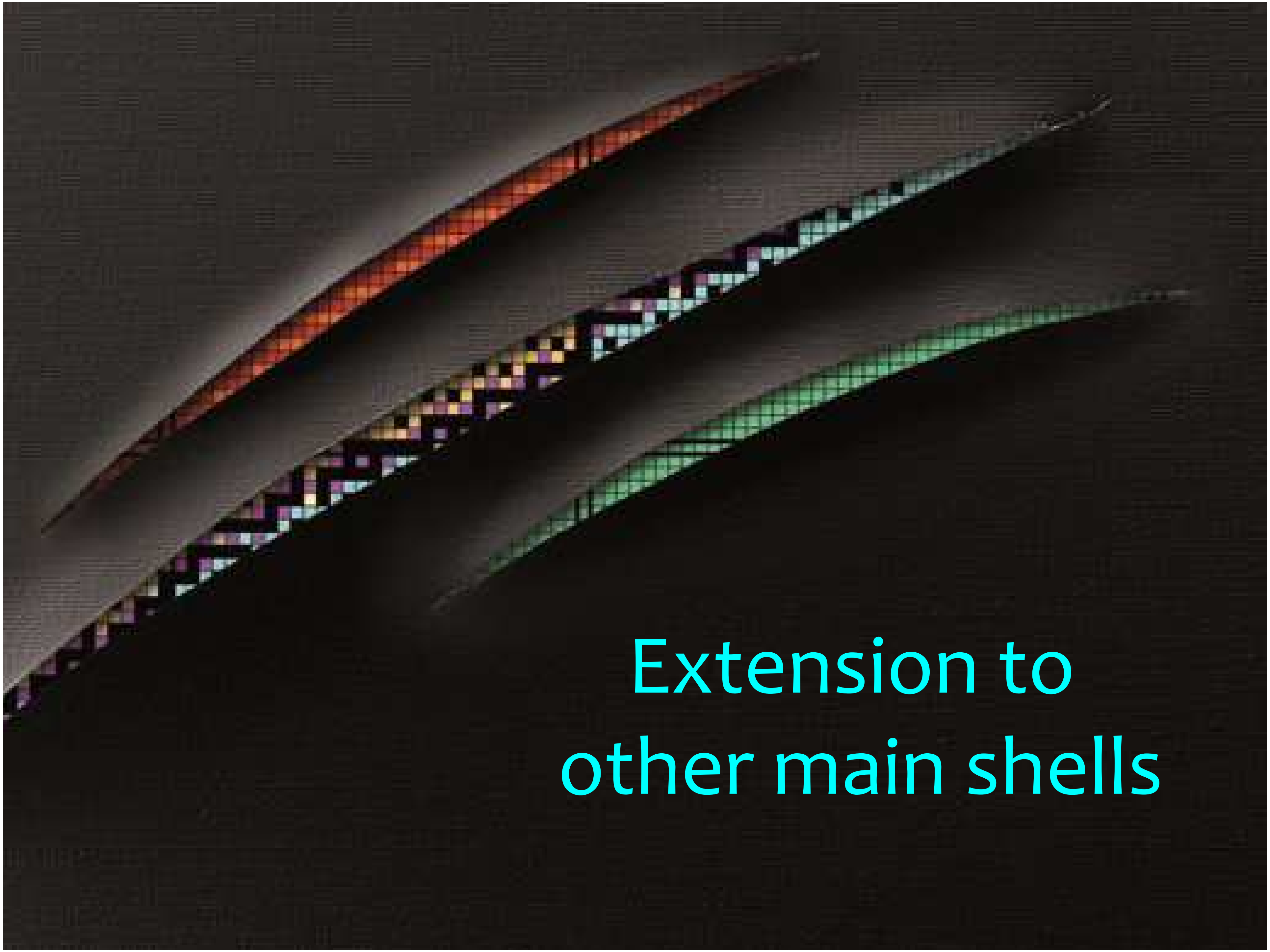


A.Gadea et al., PRL 97, 152501 (2006)
D. Rudolph et al., PRC **78**, 021301(R) (2008)





J.R. Brown et al.
PRC 80, 011306(R) 2009



Extension to other main shells

Understanding the ISB term VB

Can we understand the origin of this term from the N-N interaction?

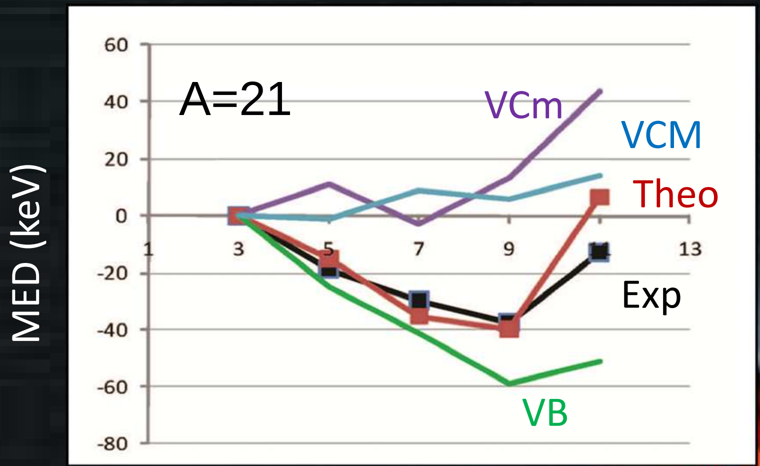
Is the ISB term a general feature or is it just confined to the $f_{7/2}$ shell?

Necessary conditions for such studies:

- good amount of data
- good shell model description of the structure

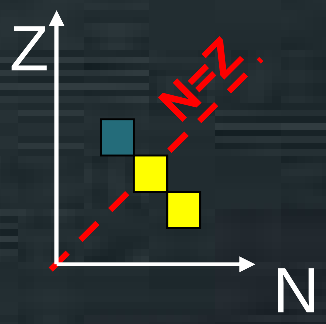
A similar VB term as in the $f_{7/2}$ shell is needed to reproduce these data in the sd shell

This suggests that the ISB term has a general character



S.M.L. et al., to be published

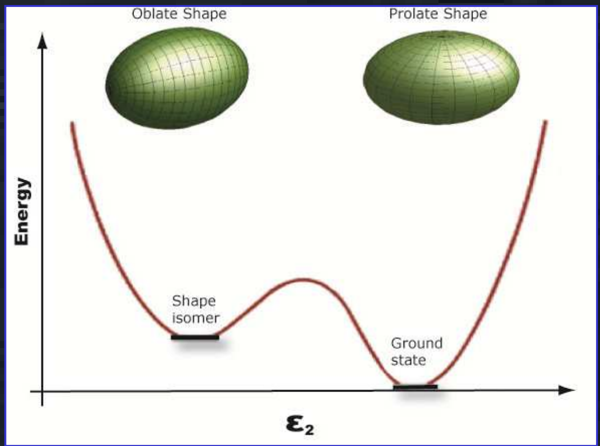
Isospin symmetry and shape coexistence

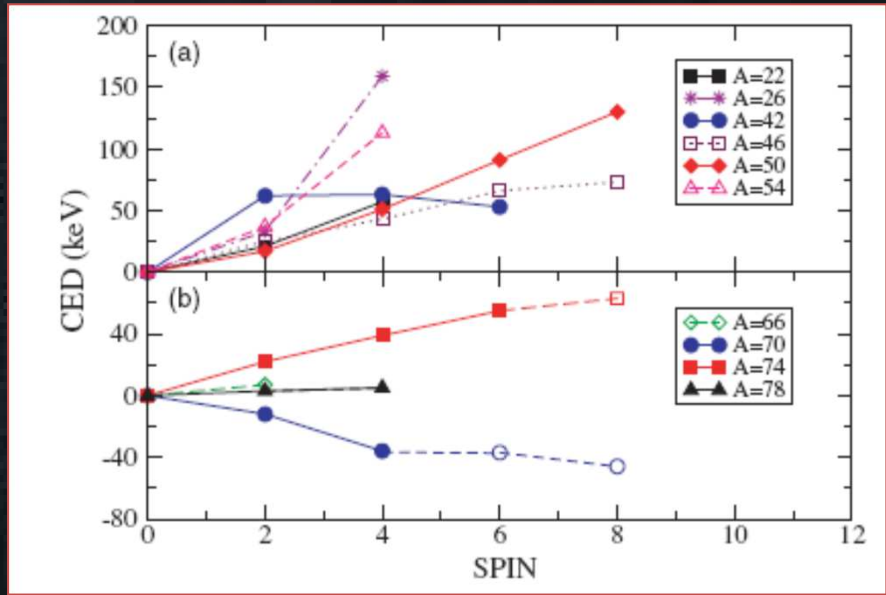


CED(J)=E_J(N=Z)-E_J (N=Z+2)

fpg shell

Large shell gaps exist at both oblate *and* prolate shape for *N* = *Z* = 34 and 36





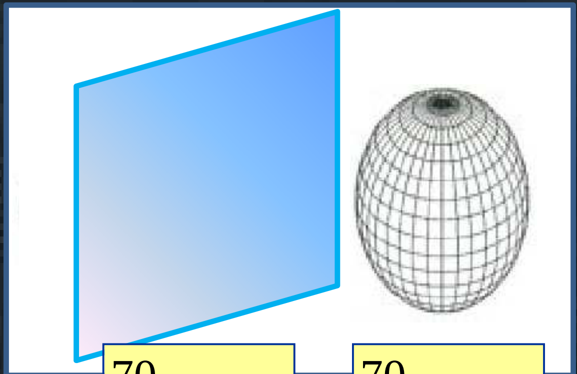
Negative values of the CED are associated to changes in the Coulomb energy due to shape changes as a function of J

CED and shape coexistence: The case of the non-identical twins?

^{70}Br: G.de Angelis et al., EPJ. A **12**, 51 (2001)
D.G.Jenkins *et al.*, PRC **65**, 064307 (2002)

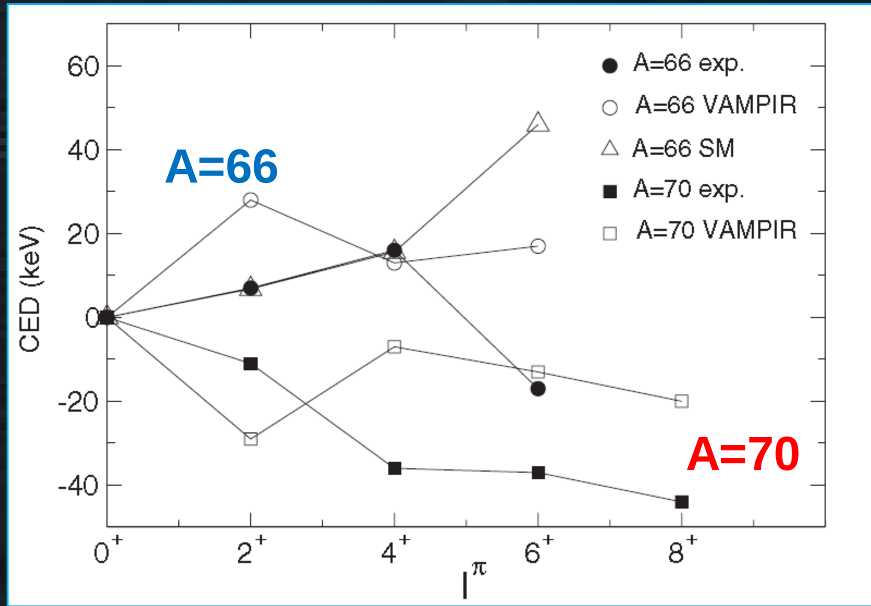
$$^{70}_{35}\mathrm{Br}_{35} - ^{70}_{34}\mathrm{Se}_{36}, T = 1$$

CED very sensitive to structural changes



$^{70}_{35}\mathrm{Se}_{35}$ $^{70}_{35}\mathrm{Br}_{35}$

J. Ljungvall et al., PRL 100, 102502 (2008)



$$^{66}_{33}\mathrm{As}_{33} - ^{66}_{32}\mathrm{Ge}_{34}, T = 1$$

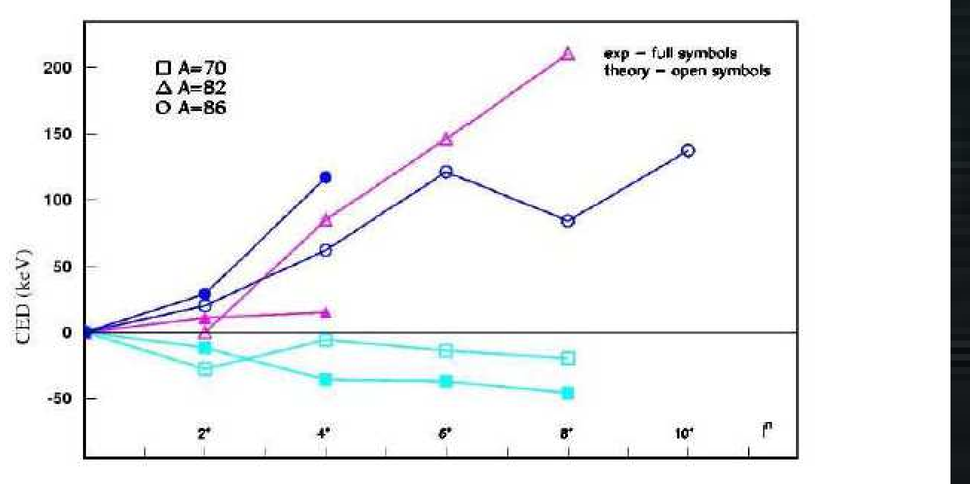
G. de Angelis et al., PRC 85, 034320 (2012)

Modifications in the Fermi surface induced by isospin-breaking interactions can cause rapid changes in the nuclear shape that may lead to different shapes in the ground-state configurations of nuclei belonging to the same isospin multiplet.

CED: BMF and SM: complementary approaches

Beyond mean field (Vampire) CED based on different shape mixing (axially symmetric) of the analog states.

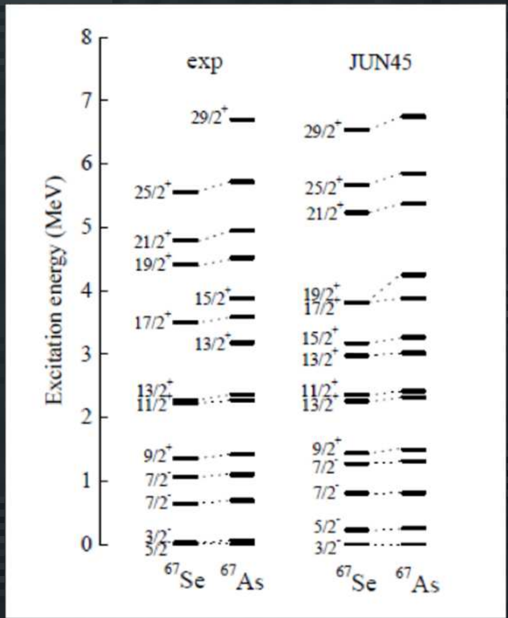
Need to measure the $T_z = -1$ member of the isobaric triplet, electromagnetic transition probabilities and precise quadrupole moments

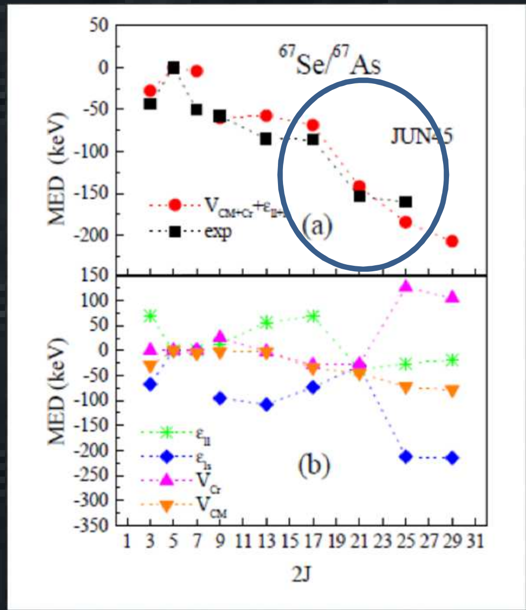


A. Petrovici, J. Phys.G: Nucl. Part. Phys 37 (2010) 064036

A new collaboration within SARFEN with A. Petrovici to perfom shell model calculations that are not constrained to axial deformation

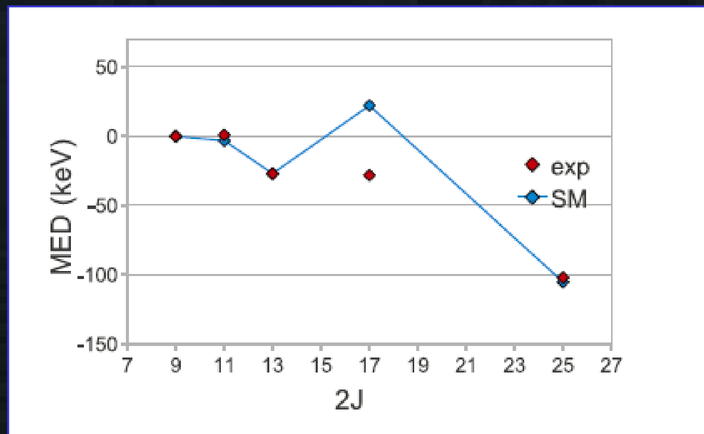
The mirror pair ^{67}Se – ^{67}As





Shape coexistence causes the crossing or mixing of levels of the same spin.
A careful look at the 21/2+ wfs show different structures in the IAS!
Important to have a good shell model description.

Data: R. Orlandi et al., PRL 103, 052501 (2009)
Calc. K. Kaneko et al., PRC 82, 061301, 2010



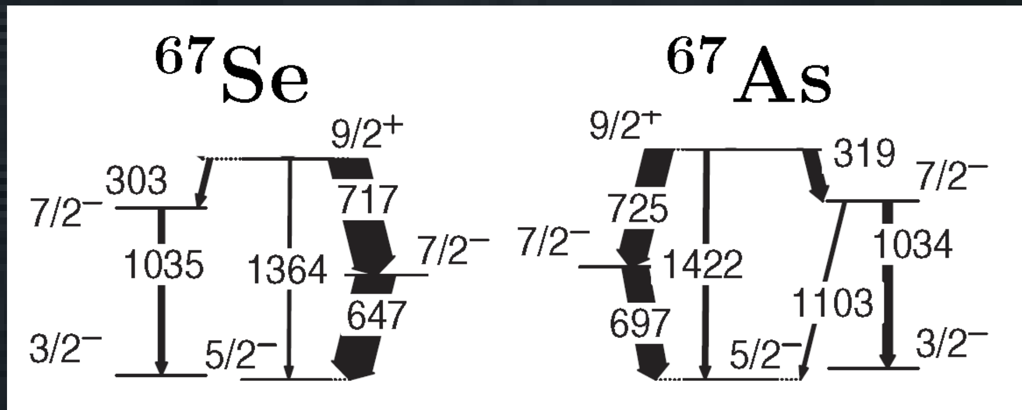
A. Boso, Thesis, Padova 2011

Isospin mixing in mirror pairs

Isospin Symmetry violation in mirror E1 transitions

Coherent contributions from Giant Isovector Monopole Resonance in ^{67}As – ^{67}Se

P.G. Bizzeti[1], G. de Angelis[2], S.M. Lenzi[3], and R. Orlandi[4]



The coherent effect of Coulomb-induced mixing with the high-lying Giant Isovector Monopole Resonance is proposed as the most probable process to produce large asymmetry in the E1 transitions, with comparatively small effect on the other properties of the parent and daughter level.

The proton-neutron interaction

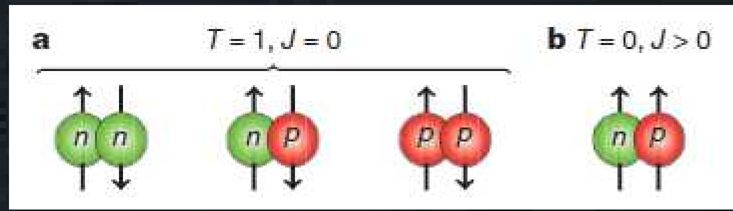
nature International weekly journal of science

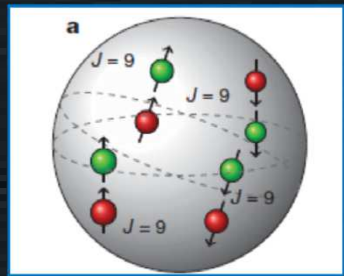
LETTER

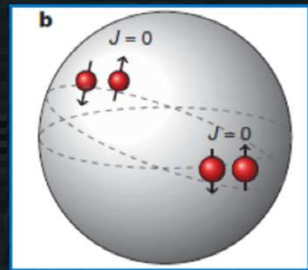
doi:10.1038/nature09644

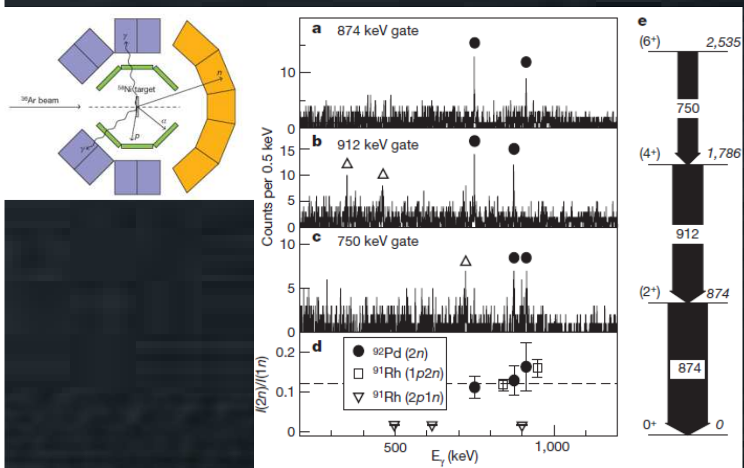
Evidence for a spin-aligned neutron–proton paired phase from the level structure of ^{92}Pd

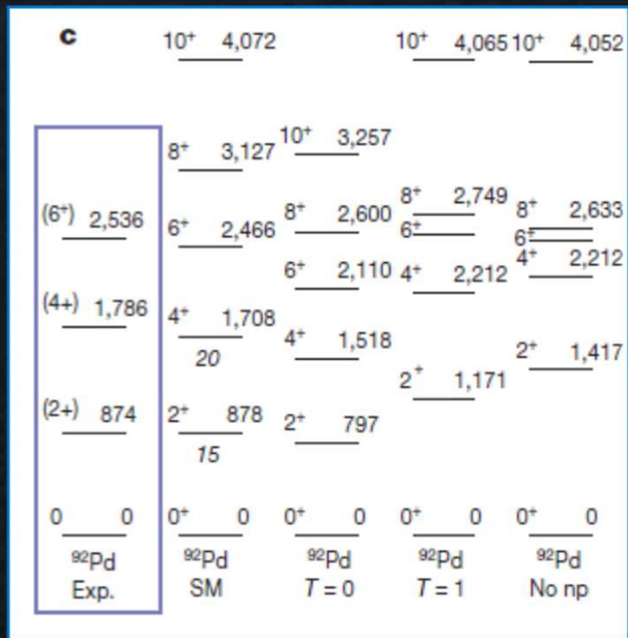
B. Cederwall[1], F. Ghazi Moradi[1], T. Bäck[1], A. Johnson[1], J. Blomqvist[1], E. Clément[2], G. de France[2], R. Wadsworth[3], K. Andgren[1], K. Lagergren[1,4], A. Dijon[2], G. Jaworski[5,6], R. Liotta[1], C. Qi[1], B. M. Nyakó[7], J. Nyberg[8], M. Palacz[5], H. Al-Azri[3], A. Algora[9], G. de Angelis[10], A. Ataç[11], S. Bhattacharyya[2]†, T. Brock[3], J. R. Brown[3], P. Davies[3], A. Di Nitto[12], Zs. Dombrádi[7], A. Gadea[9], J. Gál[7], B. Hadinia[1], F. Johnston-Theasby[3], P. Joshi[3], K. Juhász[13], R. Julin[14], A. Jungclaus[15], G. Kalinka[7], S. O. Kara[11], A. Khaplanov[1], J. Kownacki[5], G. La Rana[12], S. M. Lenzi[16], J. Molnár[7], R. Moro[12], D. R. Napoli[10], B. S. Nara Singh[3], A. Persson[1], F. Recchia[16], M. Sandzelius[1]†, J.-N. Scheurer[17], G. Sletten[18], D. Sohler[7], P.-A. Söderström[8], M. J. Taylor[3], J. Timár[7], J. J. Valiente-Dobón[10], E. Vardaci[12] & S. Williams[19]

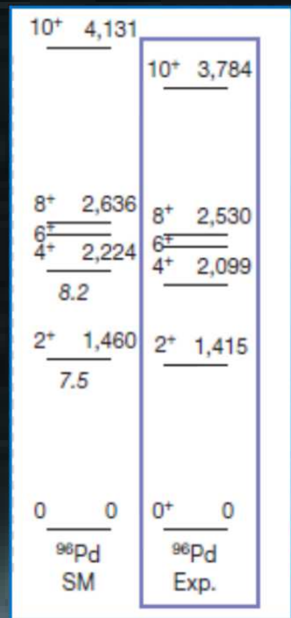






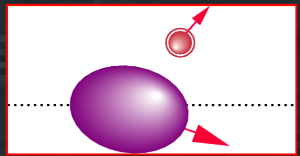




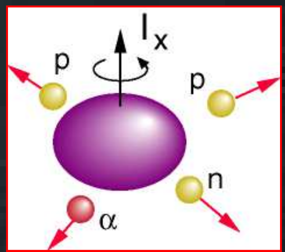


Techniques for proton-rich spectroscopy

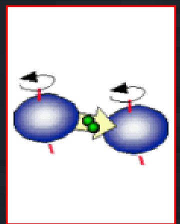
The basic techniques for selecting proton-rich systems



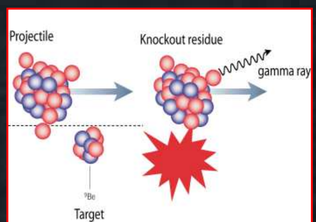
Fusion-evaporation 1: Gamma-ray array + recoil mass spectrometer + focal plane detectors - identify A,Z of recoiling nucleus $\rightarrow$ tag emitted gamma-rays



Fusion-evaporation 2: Gamma-ray array + clean identification of all emitted particles from reaction - needs a high efficiency & high granularity charged-particle detector (p, α) + neutron detector array



Multinucleon transfer: Gamma-ray array + identify cleanly the recoiling nuclei - needs identify A,Z of recoiling nucleus $\rightarrow$ tag emitted gamma-rays



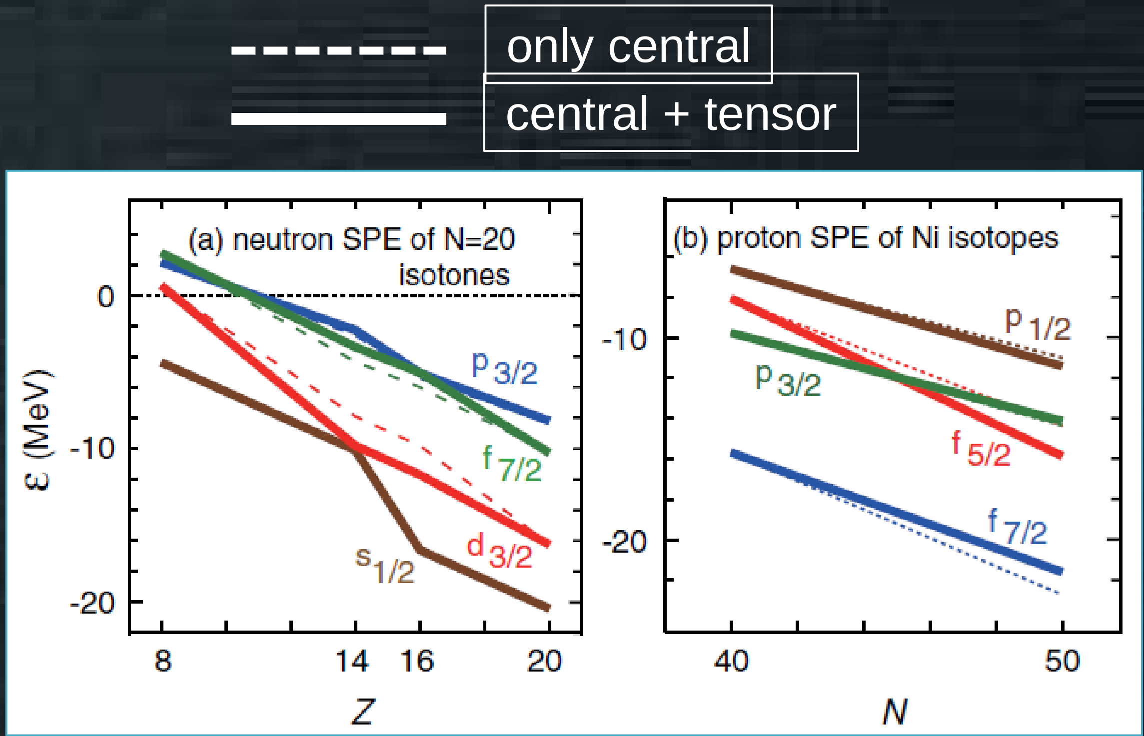
Fragmentation and knockout: high efficiency gamma-ray array (limited to relatively low spins)

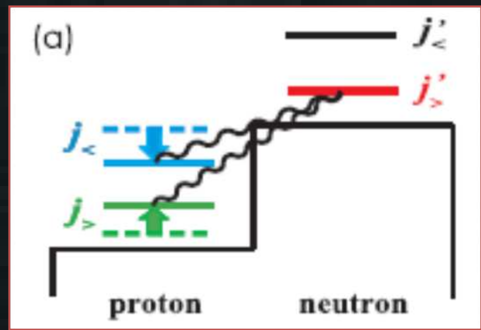
The neutron-rich side

- 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

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.

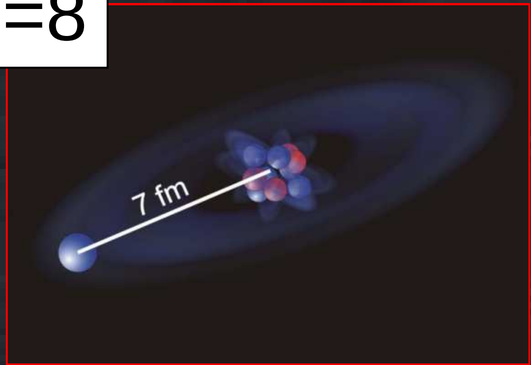




T. Otsuka et al., PRL 104, 012501 (2010)
N. A. Smirnova et al., PLB 686, 109 (2010)

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

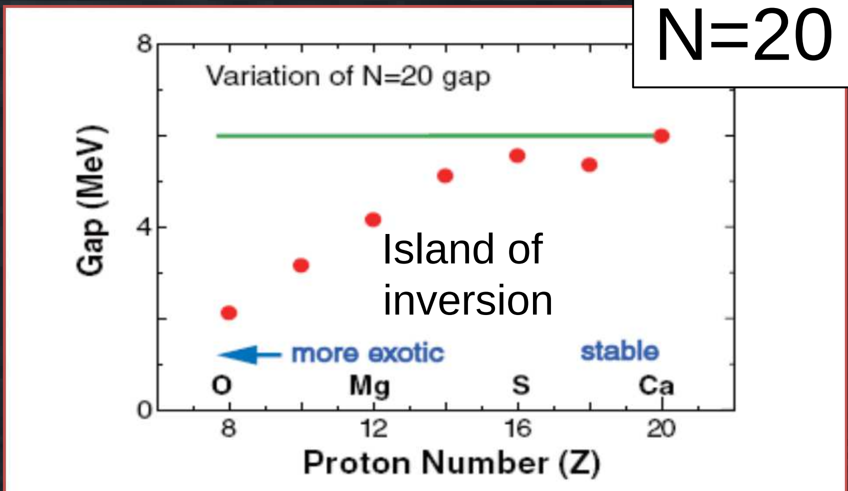
N=8



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

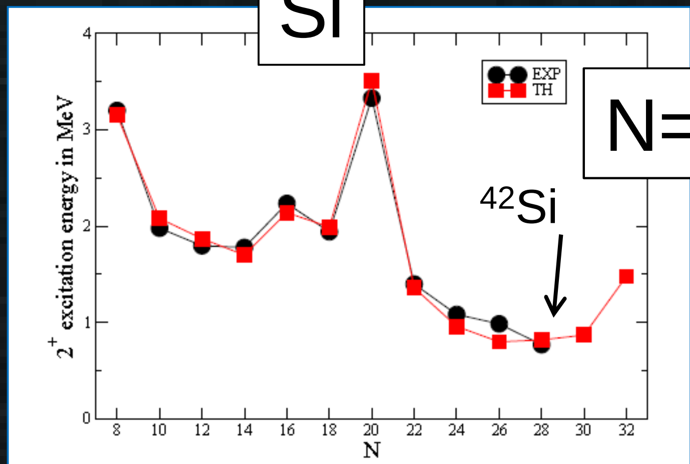
N=20



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

Si

N=28

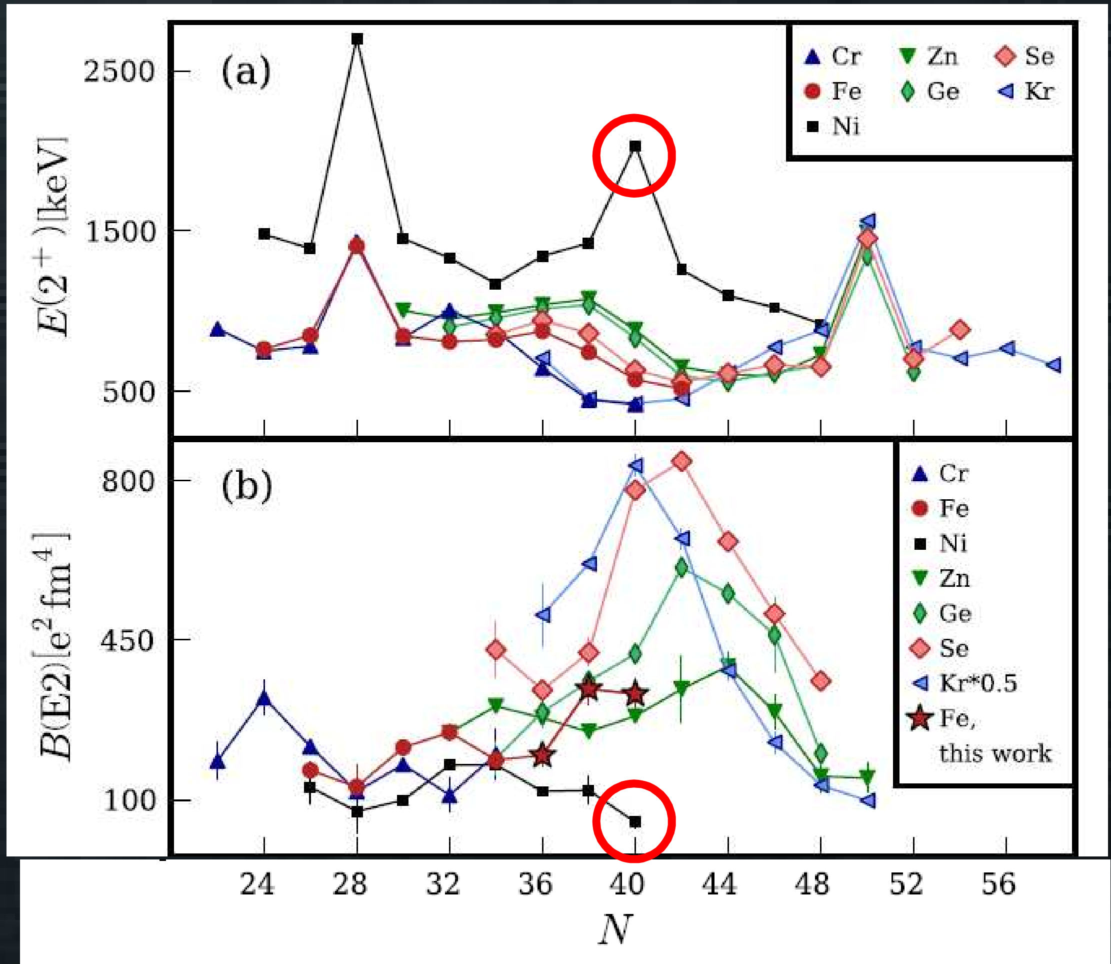


A. Poves, 2011

Island of Inversion in N=40

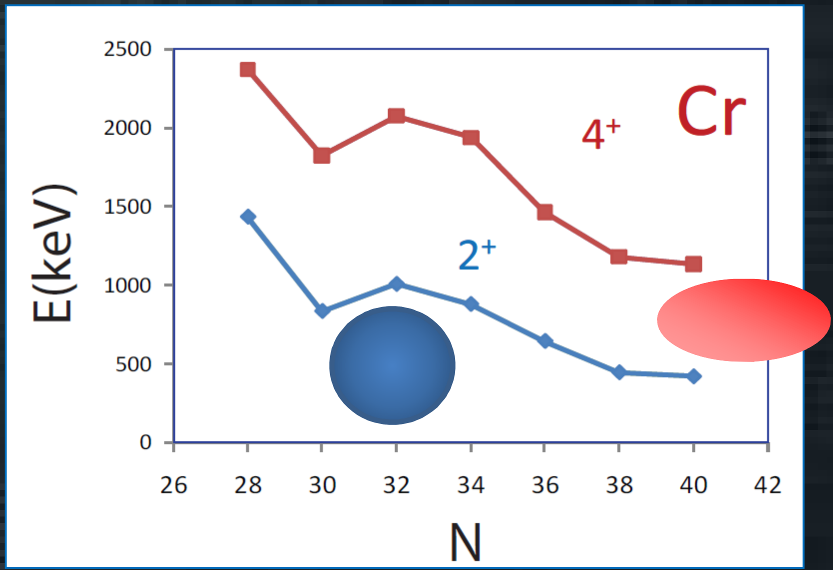
E(2^+)

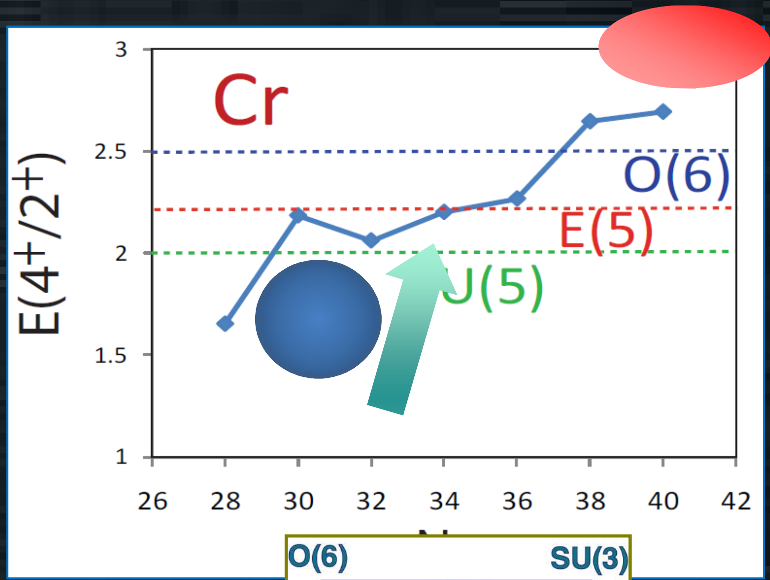
B(E2)

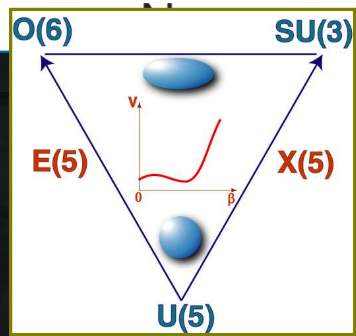


W. Rother et al., PRL 106, 022502 (2011)

Cr isotopic chain







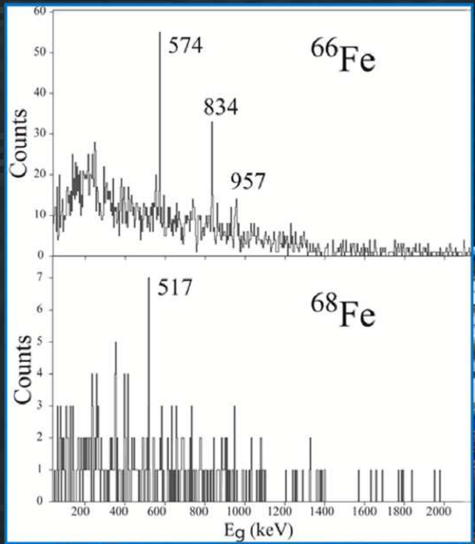
^{58}Cr

at the shape phase transition critical point?

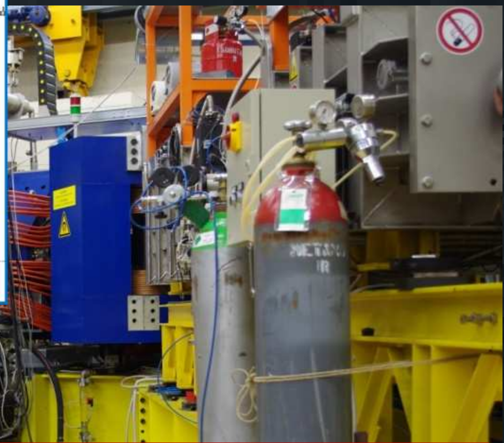
Marginean et al.
Phys. Lett. B 633 (2006) 696.

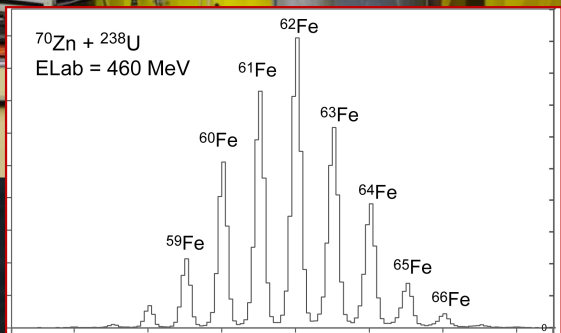
Recent plunger experiment at MSU to measure the lifetimes and test the E(5).

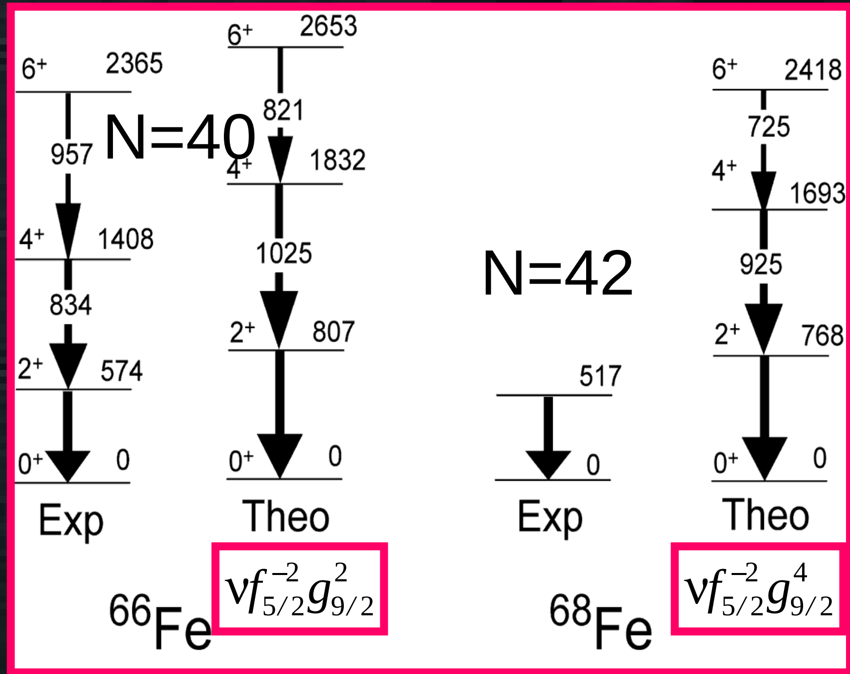
Deep-inelastic and multi-nucleon transfer reactions



Clara+Prisma



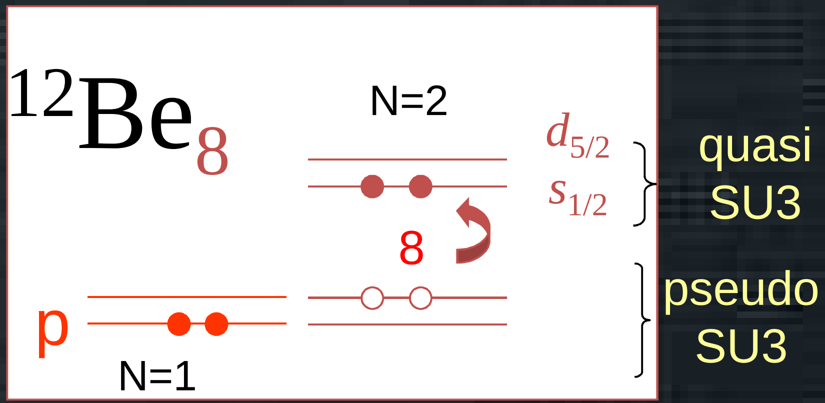




SML et al.,
LNL Ann. Rep. 2008

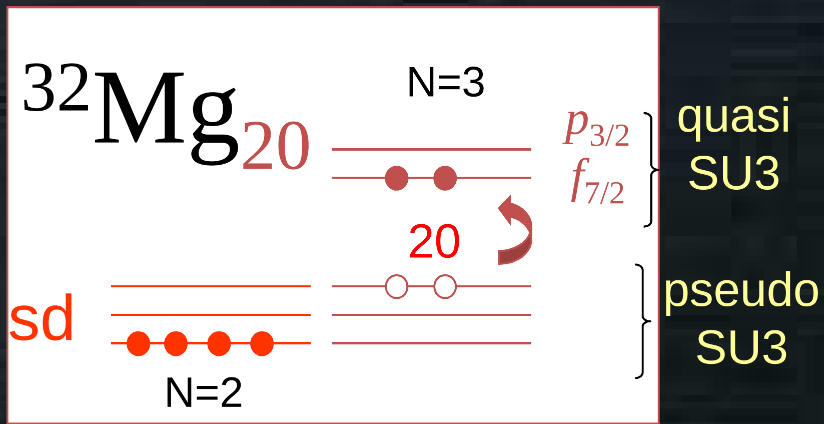
The fpg model space is not able to reproduce the increase of collectivity of Cr and Fe isotopes approaching N=40

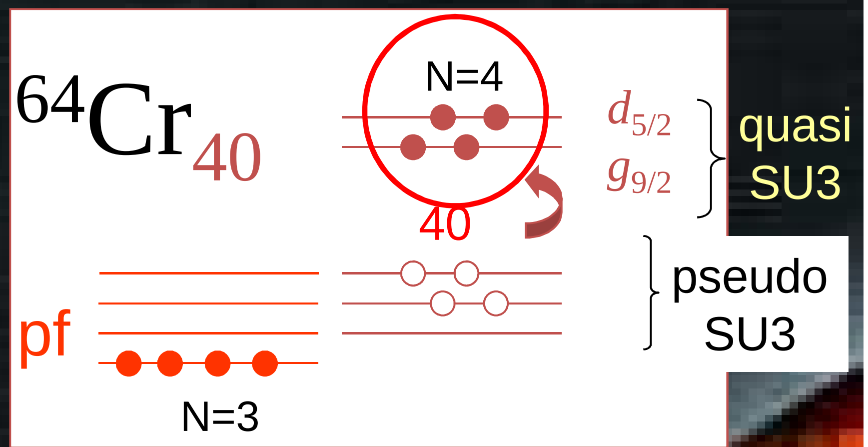
Islands of inversion and symmetries



Islands of Inversion at the magic numbers.

Can be understood in terms of symmetries.





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

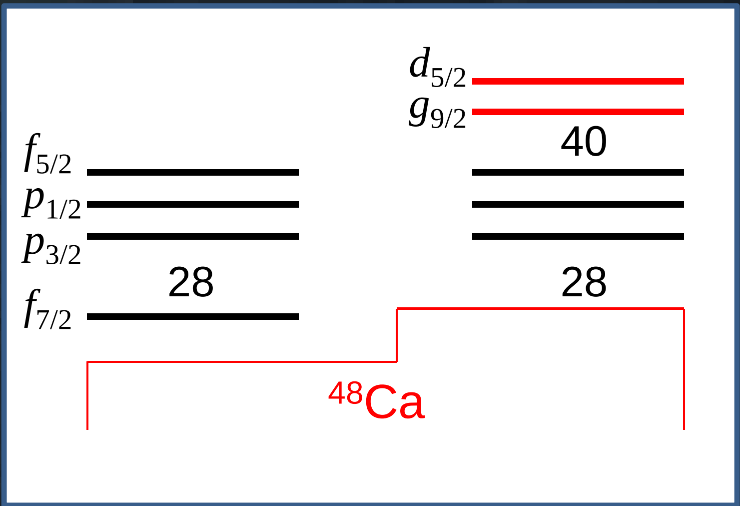
The new interaction in the fpgd space

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, PRC 82, 054301 (2010)

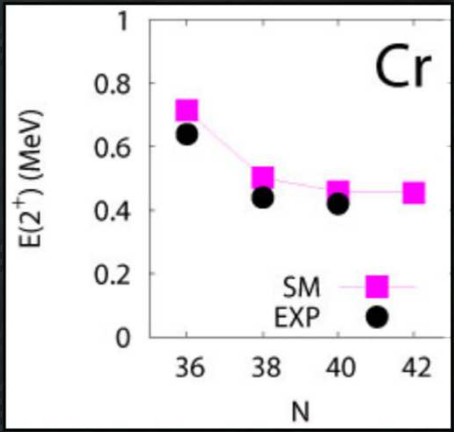
Cr-Fe isotopes and the N=40 isotones

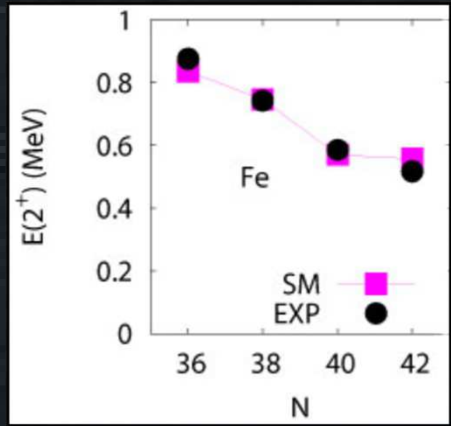
Cr

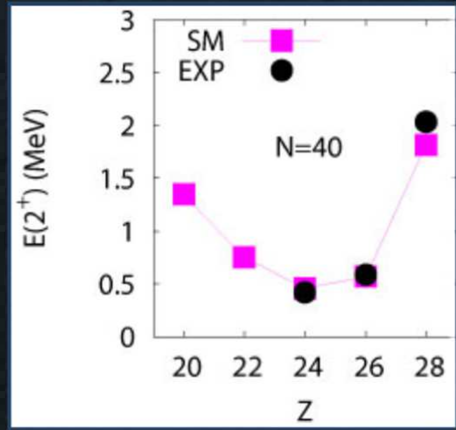
Fe

N=40 isotones

E (2^+)

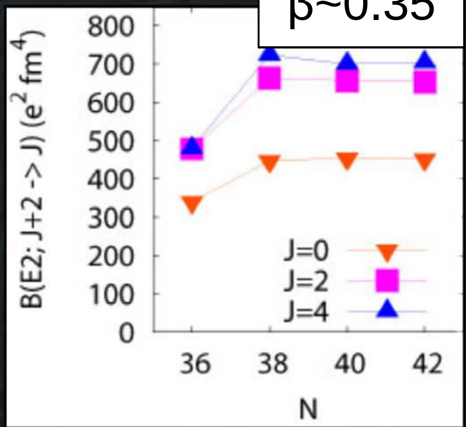




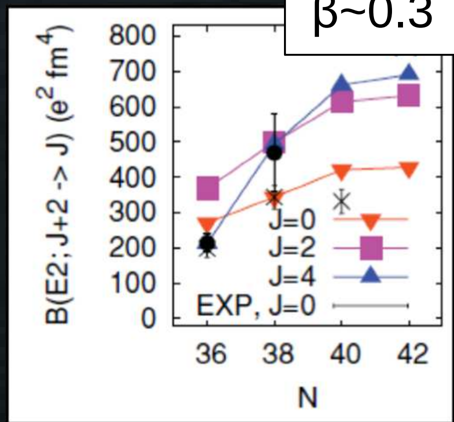


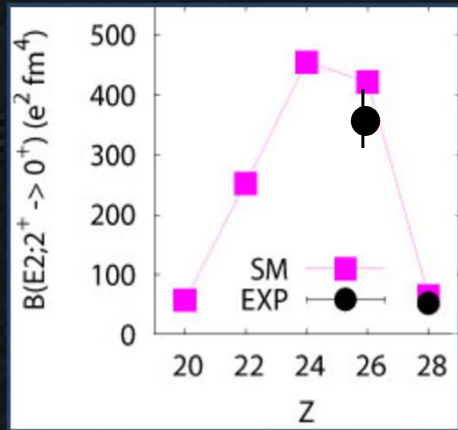
B(E2)

β~0.35



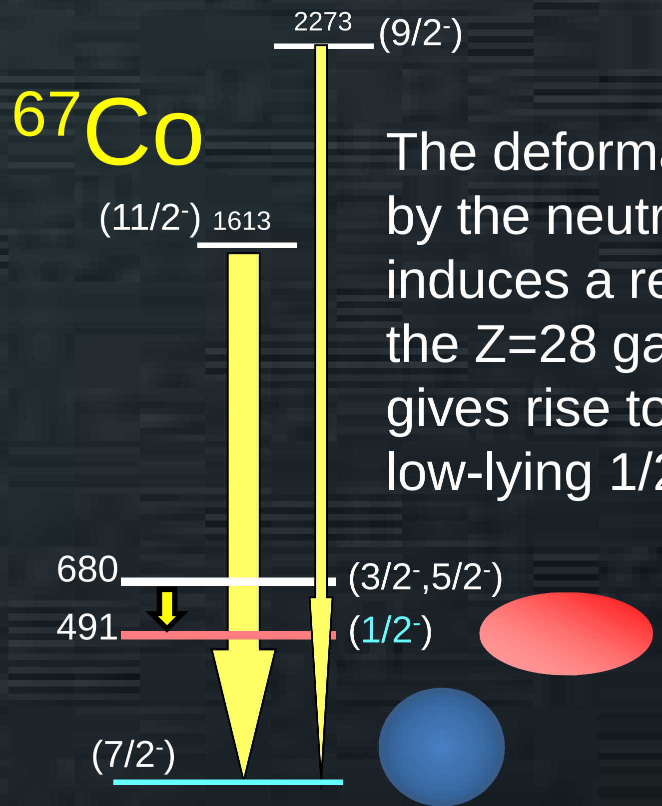
β~0.3





LNPS, PRC 82, 054301 (2010)

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

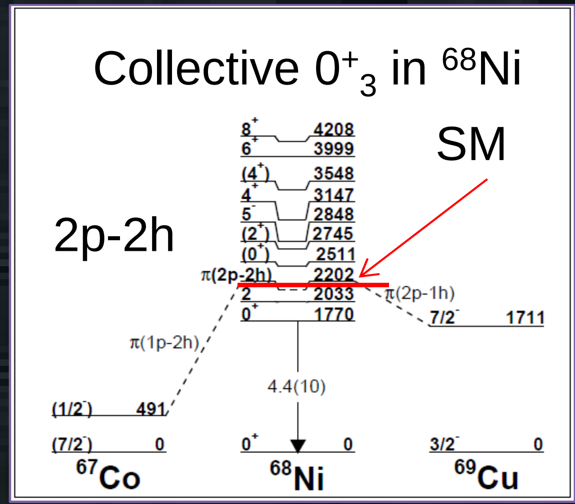


The deformation driven by the neutrons induces a reduction of the Z=28 gap and gives rise to a deformed low-lying 1/2- state

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

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

^{68}Ni

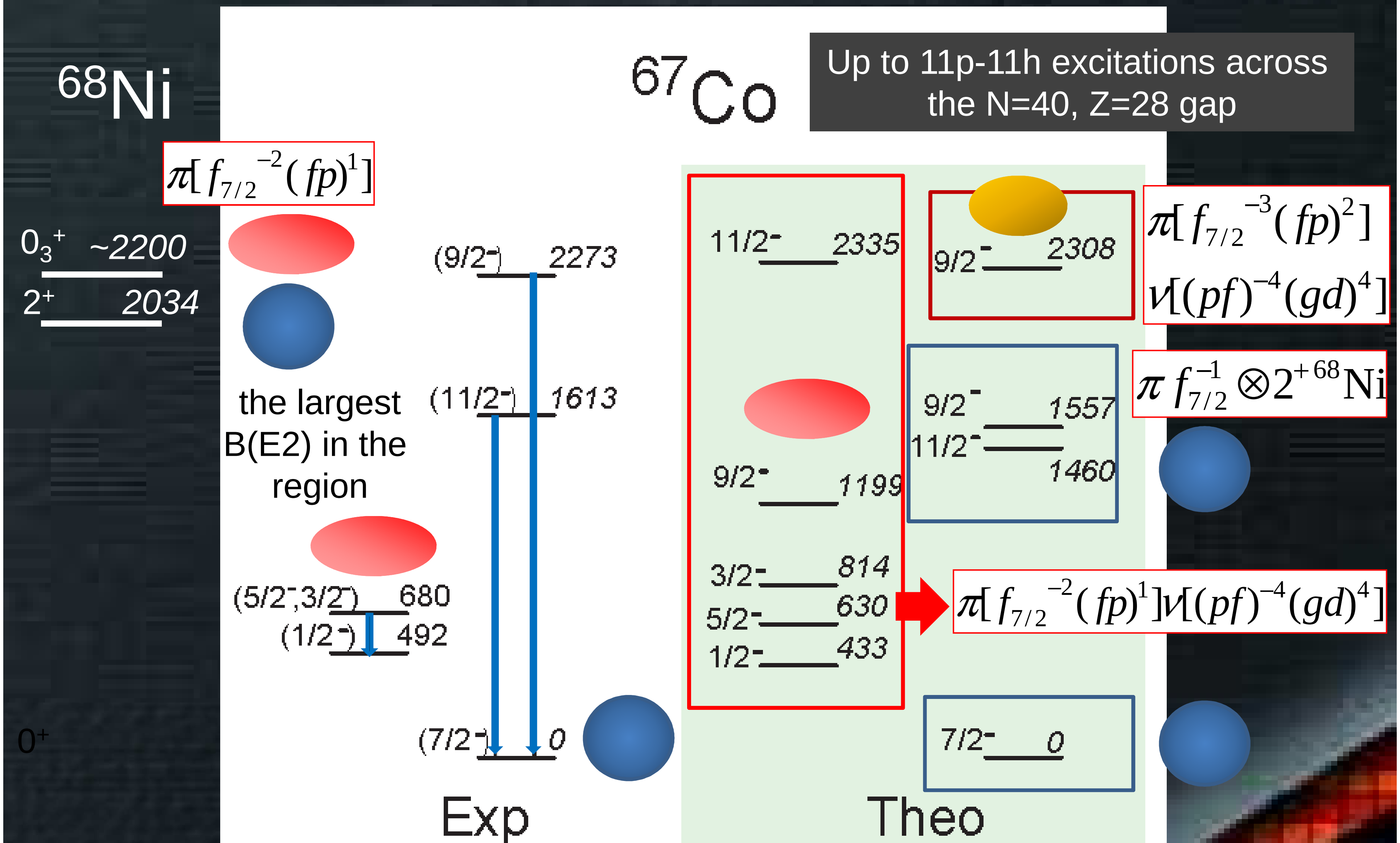


Prediction: D. Pauwels et al.,
Phys.Rev. C 82, 027304 (2010)
Data: A. Dijon et al., PRC 85, 031301 (2012)

The LNPS interaction is able to reproduce these structures

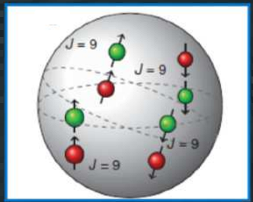
The 1/2$^-$ state gains a total of ~ 8 MeV of correlation energy and ~ 5 MeV relative to the ground state

Shape coexistence in ^{67}Co



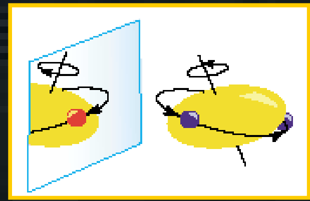
F. Recchia et al., PRC 85, 064305 (2012)

Conclusions



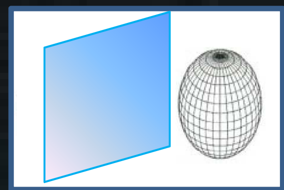
Proton-rich nuclei present several interesting properties and phenomena that can give information on specific terms of the nuclear interaction:

- charge symmetry and independence
- proton-neutron pairing



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.

In both cases the phenomenon of shape coexistence can give information on the proton-neutron correlations that drive the nucleus towards different competing deformations.



Moving the frontier

With high intensity stable beams

Move to higher spins and masses
- to probe the ISB terms in other shell model spaces in PRN
- to better study NRN (γ-γ, shape evolution along isobaric chains)

Measure $T_z < 0$ members of the multiplets and study MED and Triplet energy differences.

Measure transition probabilities and electromagnetic moments to probe shape coexistence and dynamical symmetries

Move to other "magic numbers" in both proton and neutron-rich sides