A new region of deformation for neutron-rich nuclei at N~40

Silvia M. Lenzi
University of Padua and INFN

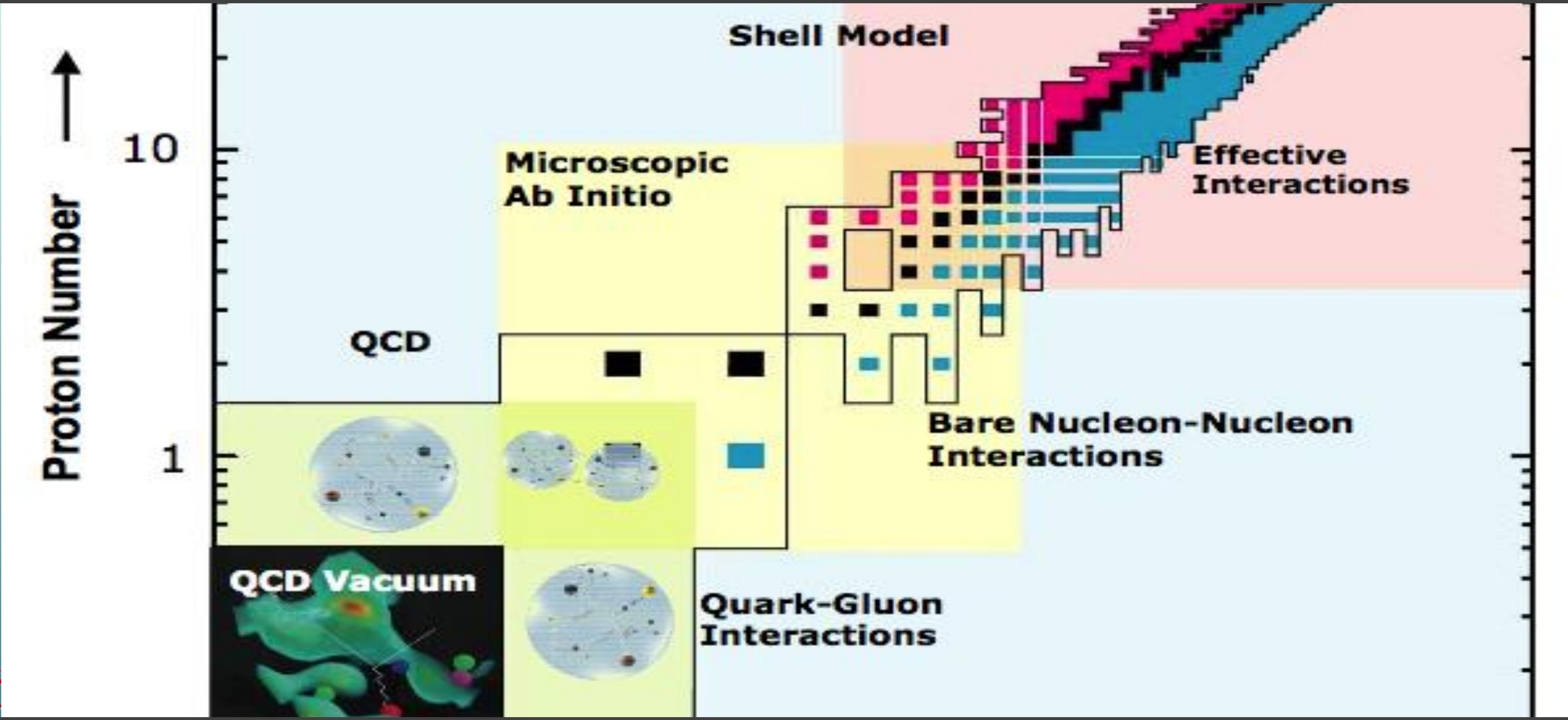
JAPAN-ITALY EFES Workshop
Torino, 6-8 September 2010

Outline

- Introduction
- Evidence of deformation at N~40
- Shell model description
- Conclusions

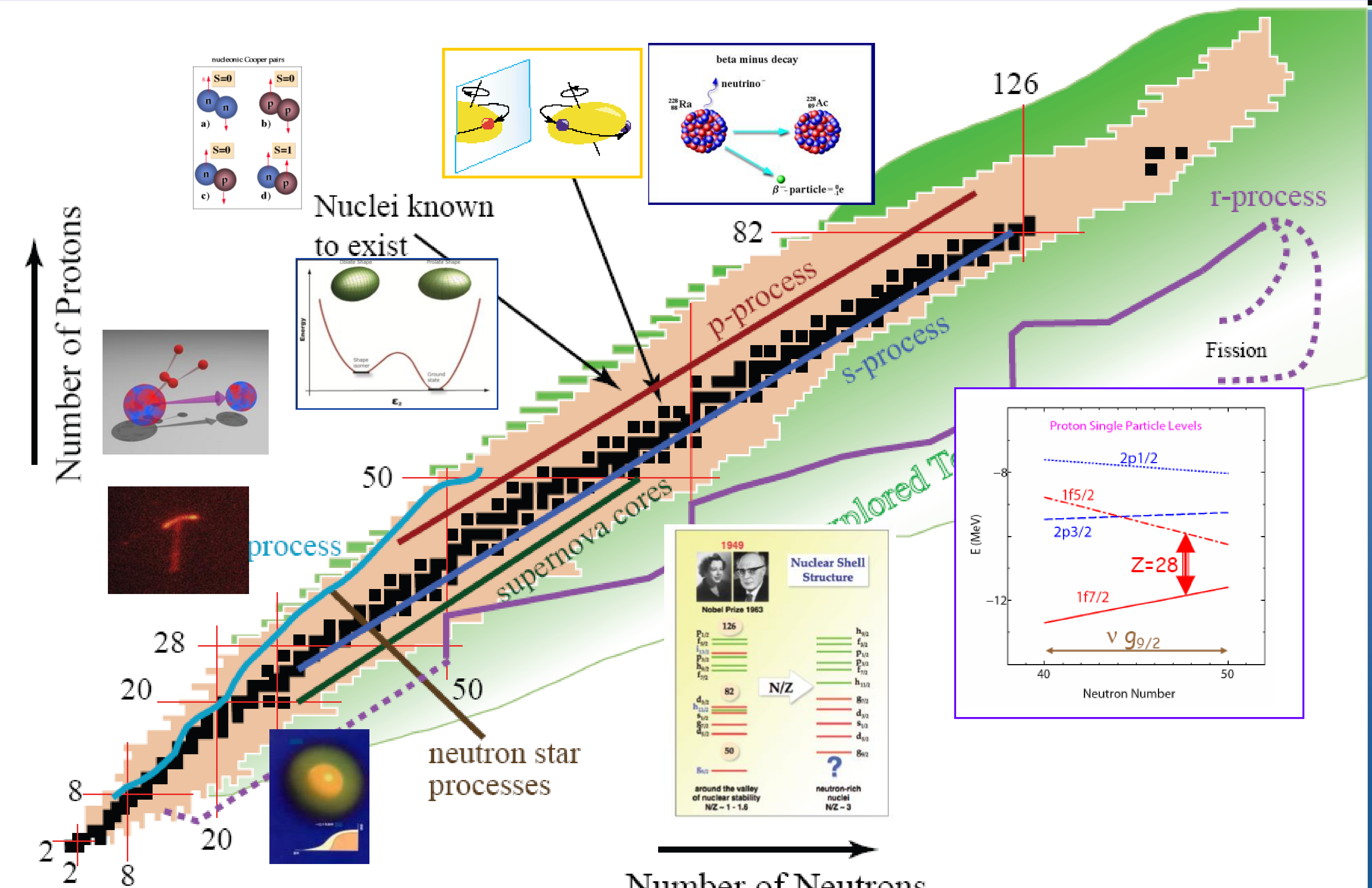
Open questions

- How does the nuclear force depend on isospin?
- What are the limits of existence for bound nuclei?



- Which are the properties of exotic nuclei at the limits of binding?
- What's new? collective motion, shapes, decay modes?

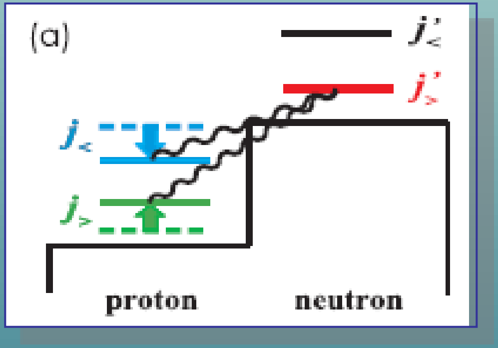
Shell evolution far from stability



Origin of monopole drifts

Explaining, reproducing and predicting shell structure far from stability

- proton-neutron spin-flip interaction $V_{\sigma\tau} = \tau \cdot \tau \sigma \cdot \sigma f_{\sigma\tau}(r)$
- tensor force $V_T = \tau \cdot \tau \left([\sigma \cdot \sigma]^{(2)} \cdot Y^{(2)} \right) f(r)$
- three-body forces



T. Otsuka et al., PRL 95 (2005) 232502

The effective interaction

A schematic (simplified) view

$$H = H_m + H_M$$

monopole   Multipole

H_m

- "unperturbed" energy of the different configurations in which the valence nucleons are distributed
- determines the single particle energies or ESPE
- dominant role far from stability

H_M

- correlations
- mixing of configurations
- coherence
- energy gains

Understanding monopole effects

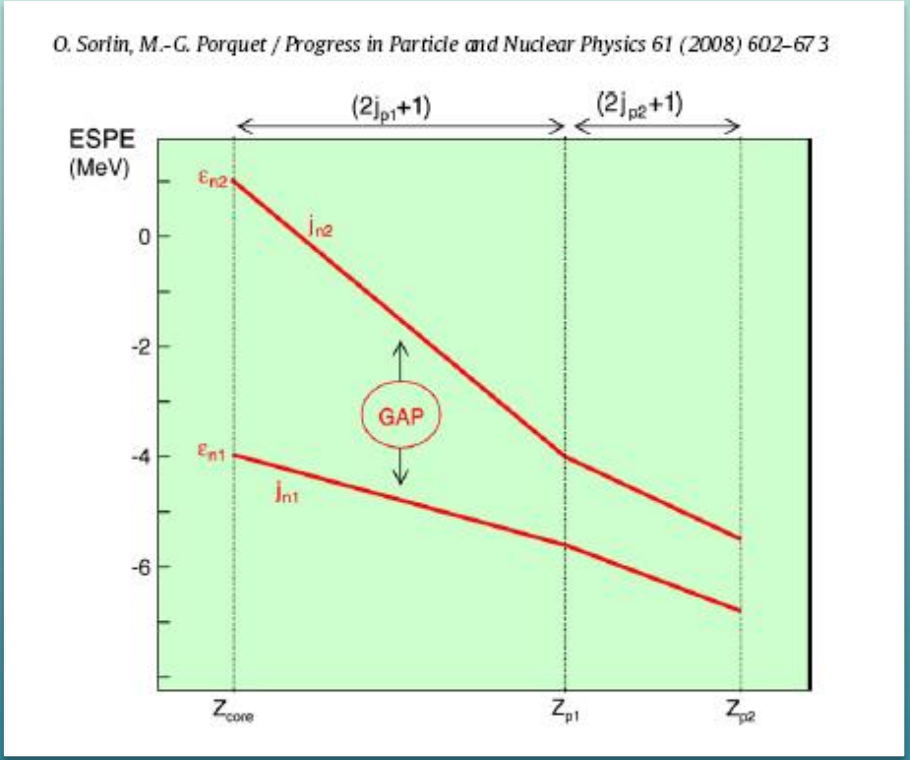
The monopole matrix element of an operator *V* can be written as

$$v_{j,j'} = \frac{\sum_{m,m'} \langle j_p m \; j_n m' | V | j m j' m' \rangle}{\sum_{m,m'} \mathbf{1}}$$

As the orbit j’ is occupied, the single-particle energy of an orbit j, $\boldsymbol{e_j}$, is changed linearly by

$$e_j = v_{j,j'} n_{j'}$$

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

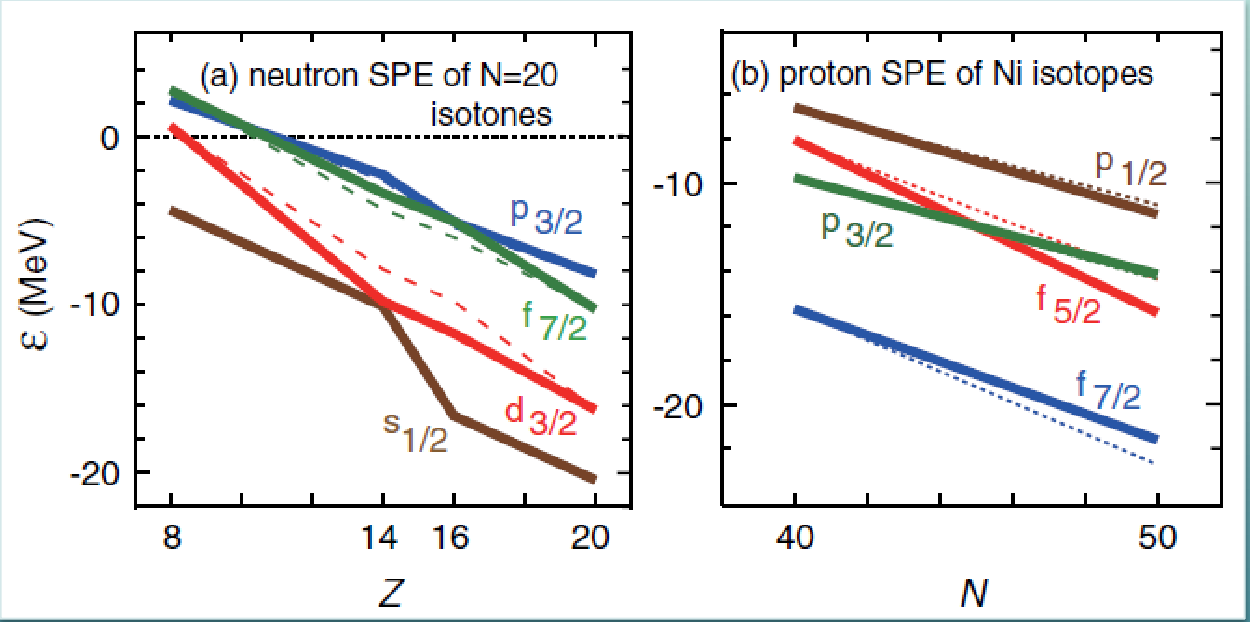


Effects of the tensor force on the spe

Shell model calculations using a schematical potential V_{MU}

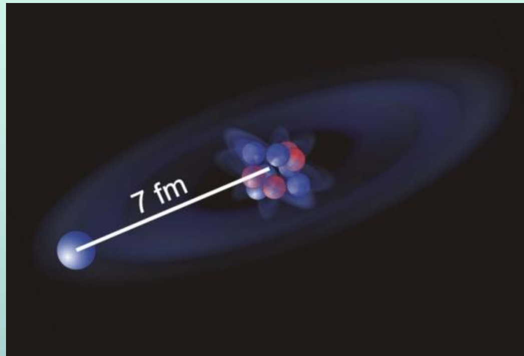
-------- only central

——— central + tensor



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

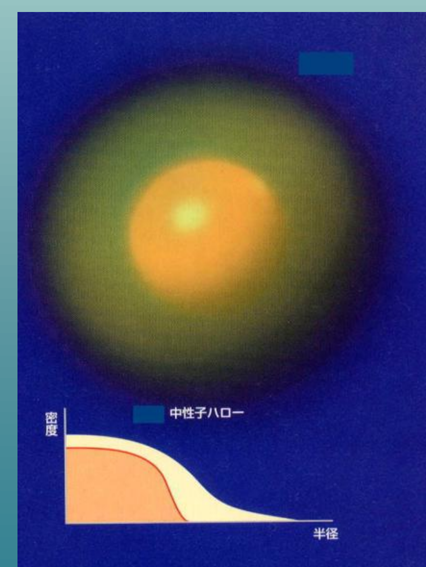
The islands of inversion (N=8)



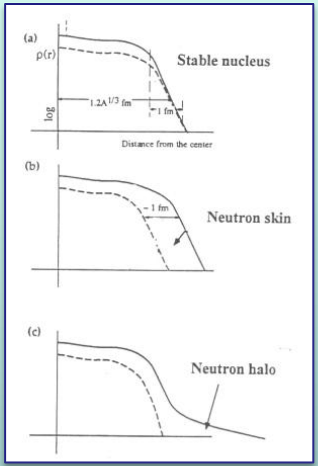
At N=8 the shell gap vanishes for very neutron rich nuclei.

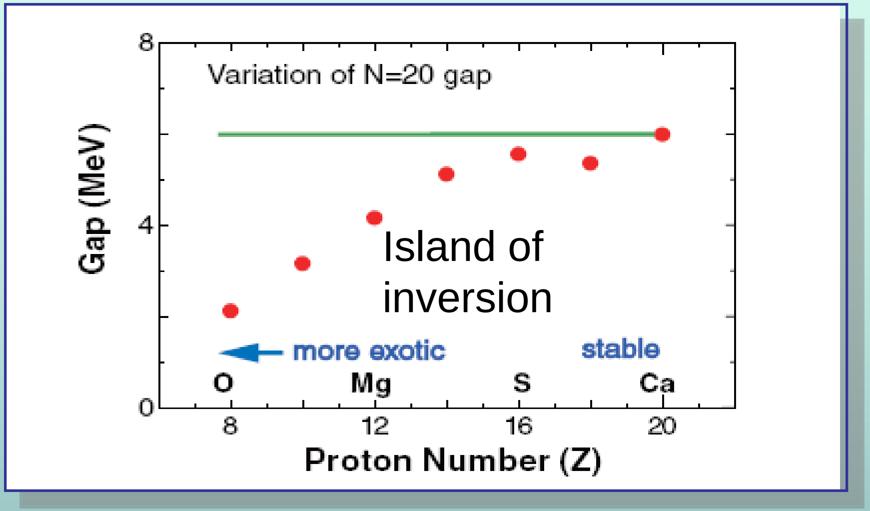
The ground state of ^{11}Be is the "intruder" $1/2^+$, the "normal" negative parity state lies at ~300 keV.

The weakly bound neutron/s occupy a low ℓ orbit, giving rise to the halo



The islands of inversion (N=20)





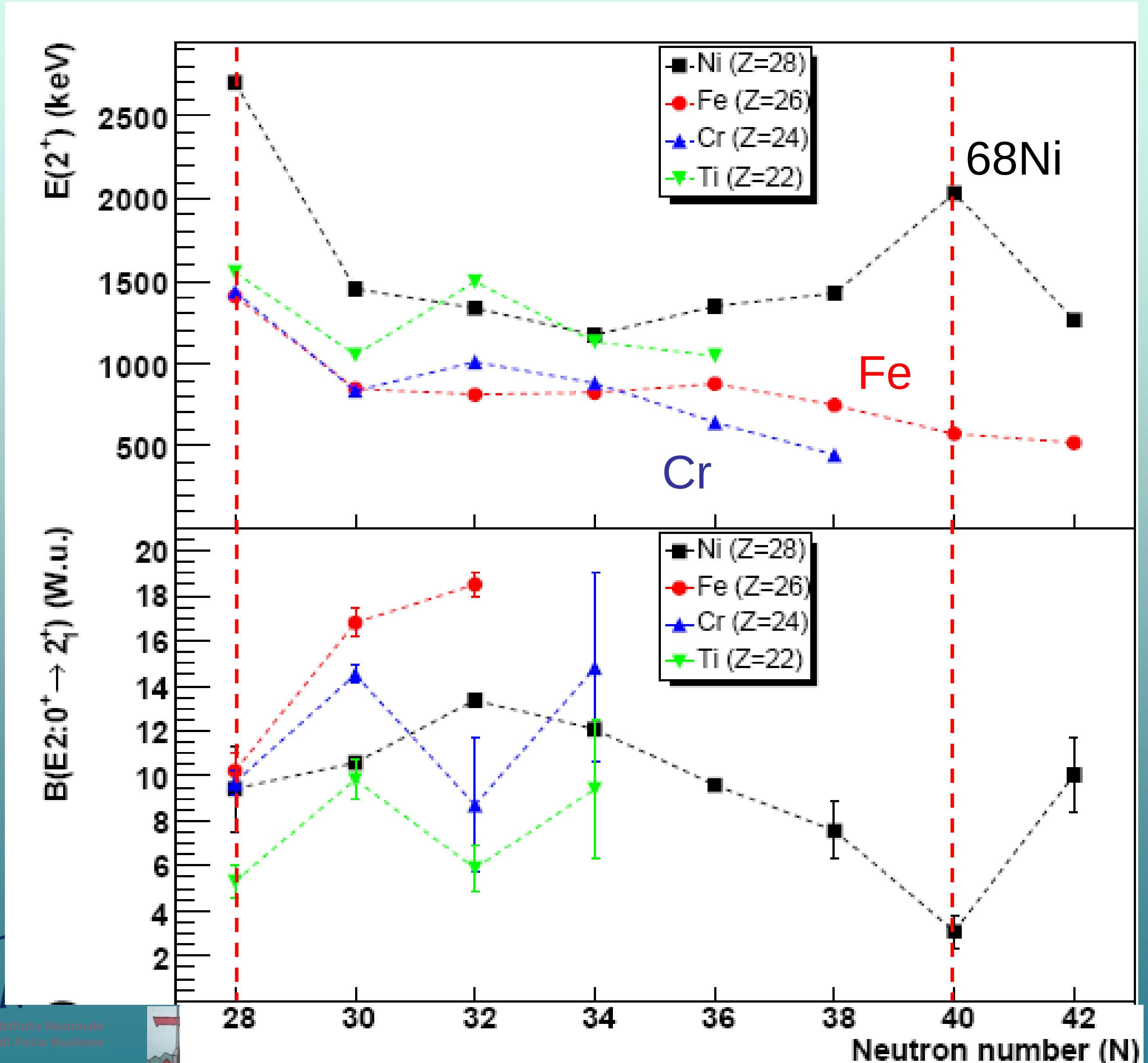
RIBF @ RIKEN
^{31}Ne the heaviest neutron halo system

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

The last neutron occupies probably the $2p_{3/2}$ ($S_n \leq$ 800 keV)
It is suggested to form a halo

T. Nakamura et al., Phys. Rev. Lett. 103, 262501 (2009)

The islands of inversion (N=40?)

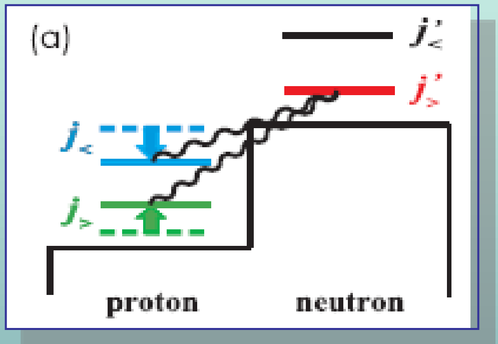


The new region of deformation at N~40:

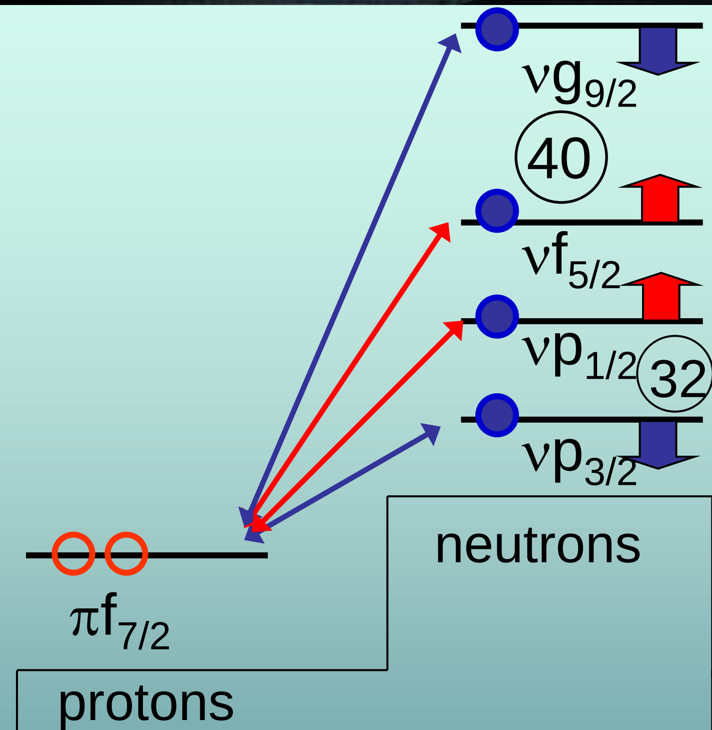
Cr, Fe and Co isotopic chains

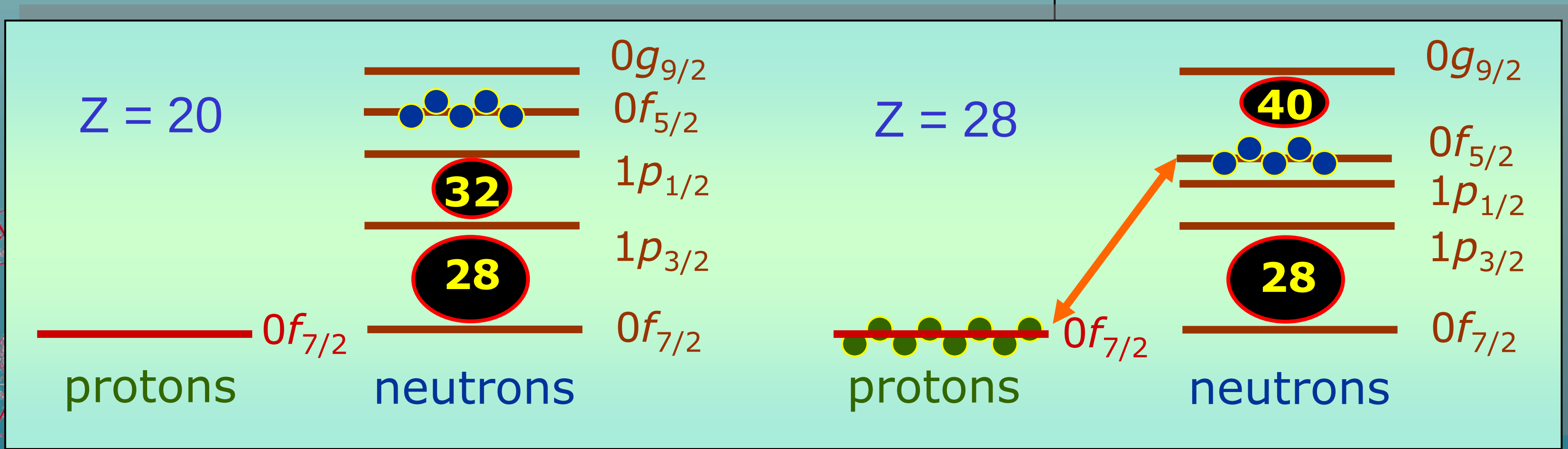
Neutron excess and shell migration

$$V_T = \tau\cdot\tau\left(\left[\sigma\cdot\sigma\right]^{(2)}\cdot Y^{(2)}\right)f(r)$$

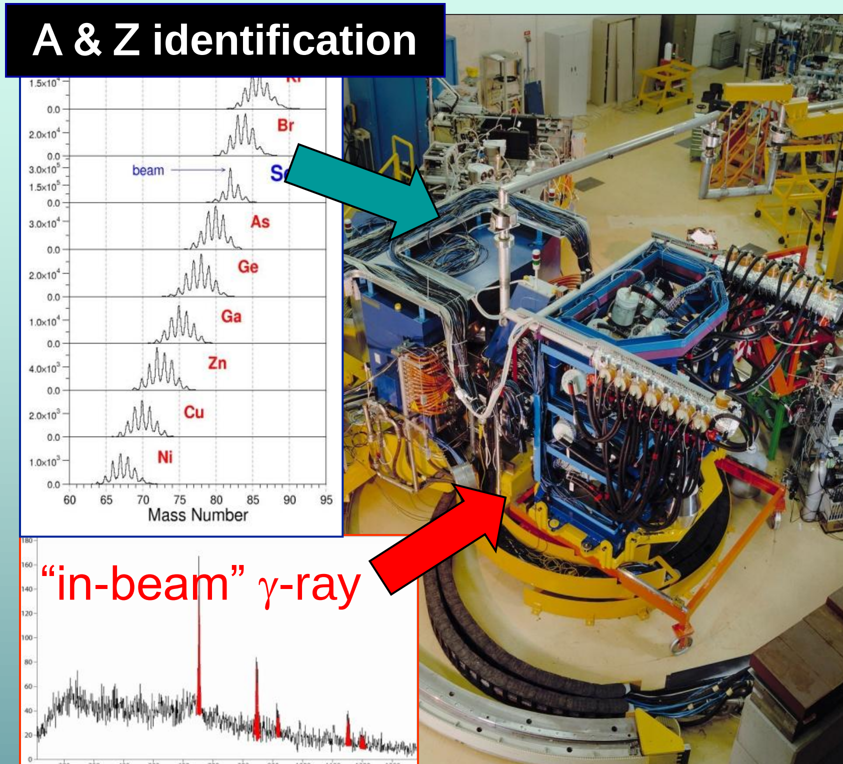


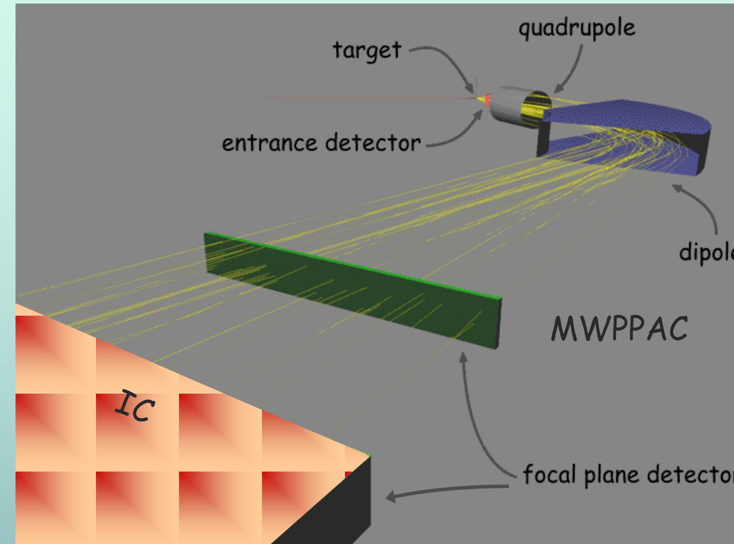
T. Otsuka et al., PRL 95 (2005) 232502



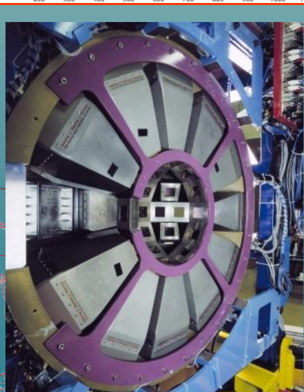


Studying the shape evolution

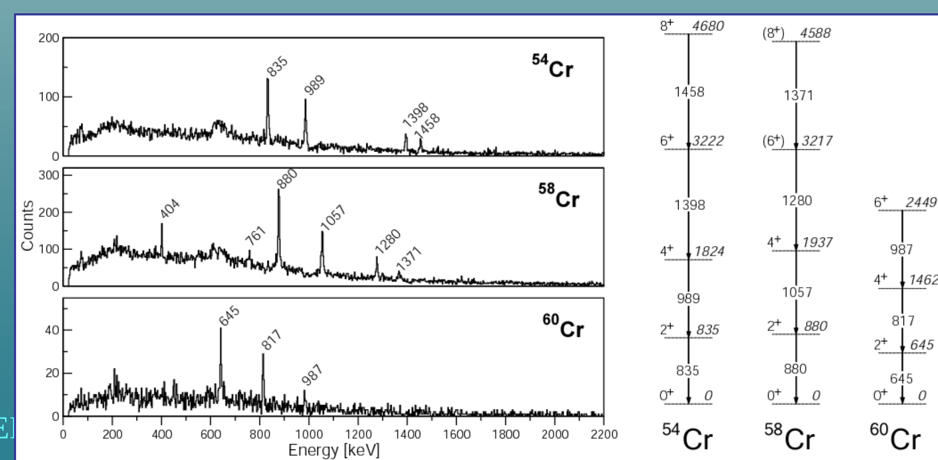




CLARA+PRISMA @ Legnaro



25 Euroball Clover detectors
for Eγ= 1.3MeV
Efficiency ~ 3 %
Peak/Total ~ 45 %
FWHM ~ 10 keV
(at v/c = 10 %)



^{58}Cr and the shape phase transition critical point

VOLUME 85, NUMBER 17 PHYSICAL REVIEW LETTERS 23 OCTOBER 2000

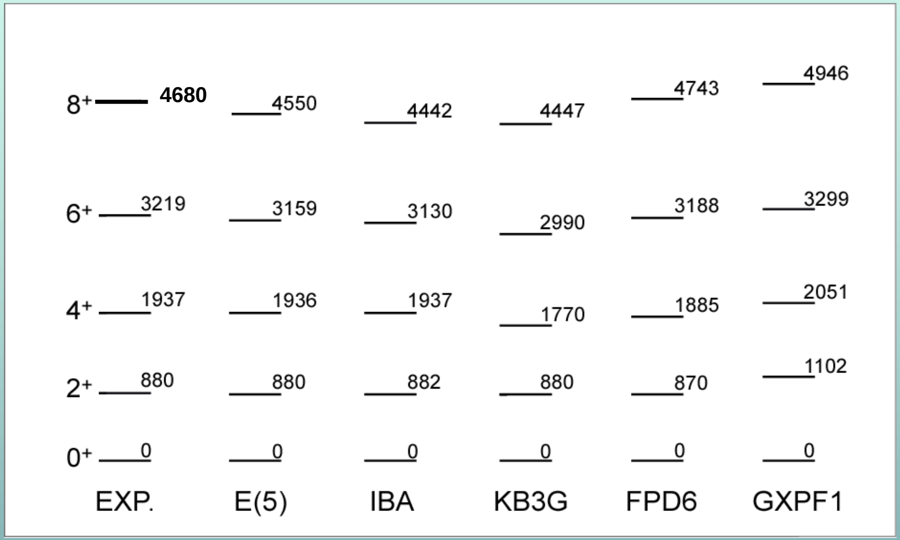
Dynamic Symmetries at the Critical Point

F. Iachello
Center for Theoretical Physics, Sloane Laboratory, Yale University, New Haven, Connecticut 06520-8120
(Received 8 May 2000)

TABLE 1. Excitation energies of the E(5) symmetry.

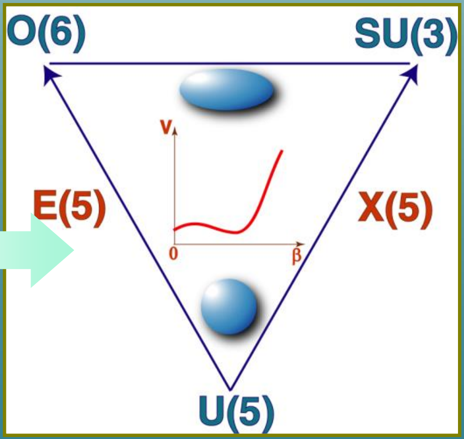
	$\xi = 1$	$\xi = 2$	$\xi = 3$	$\xi = 4$
$\tau = 0$	0	[illegible]	7.58	13.64
$\tau = 1$	1	[illegible]	[illegible]11	16.93
$\tau = 2$	2.20	[illegible]	[illegible]86	20.44
$\tau = 3$	3.59	[illegible]	[illegible]81	24.16
$\tau = 4$	5.17			

^{58}Cr:
$E_{4+}/E_{2+} = 2.20$
$E_{6+}/E_{2+} = 3.65$
$E_{8+}/E_{2+} = 5.31$



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

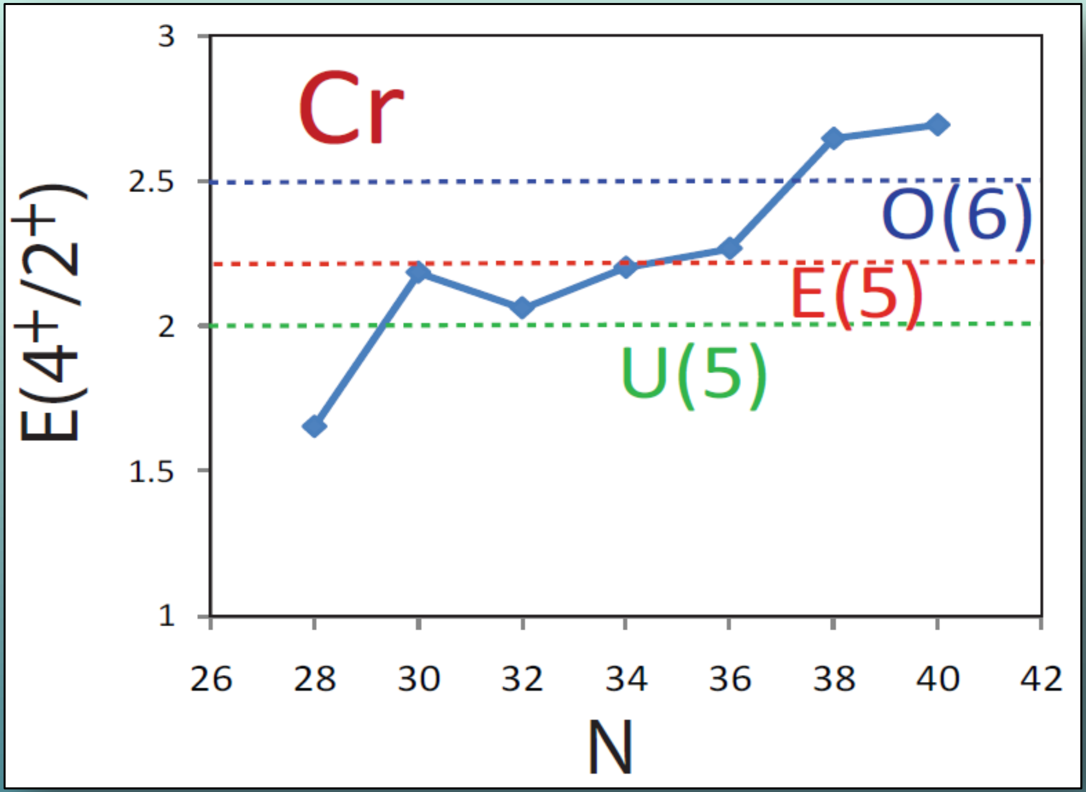
^{58}Cr



A possible bridge between shell model, algebraic and analytical approaches

Need to measure transition probabilities

Evolution of Cr isotopes



Cr isotopic chain: data

beta decay @ GANIL

Eur. Phys. J. A 16, 55–61 (2003)
DOI 10.1140/epja/i2002-10069-9
The European Physical Journal A

New region of deformation in the neutron-rich $^{60}_{24}Cr_{36}$ and $^{62}_{24}Cr_{38}$

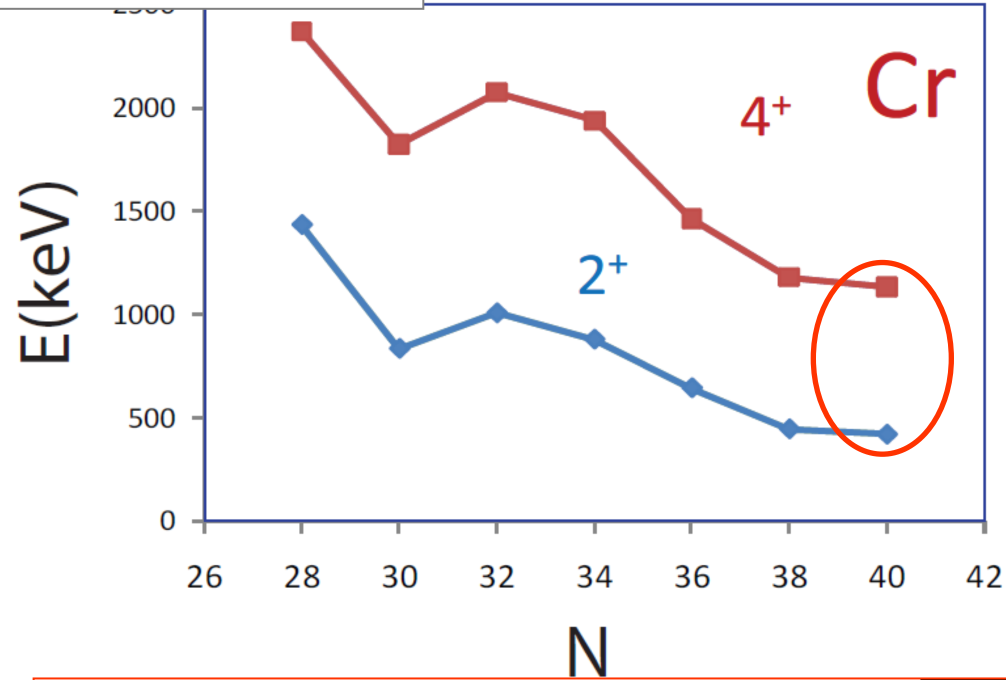
O. Sorlin[1,a], C. Donzaud[1], F. Nowacki[2], J.C. Angélique[3], F. Azaiez[1], C. Bourgeois[1], V. Chiste[1], Z. Dlouhy[4], S. Grévy[3], D. Guillemaud-Mueller[1], F. Ibrahim[1], K.-L Kratz[5], M. Lewitowicz[6], S.M. Lukyanov[7], J. Mrasek[4], Yu.-E. Penionzhkevich[7], F. de Oliveira Santos[6], B. Pfeiffer[5], F. Pougheon[1], A. Poves[8], M.G. Saint-Laurent[6], and M. Stanoiu[6]

PRL 102, 012502 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

Development of Large Deformation in ^{62}Cr

N. Aoi,[1] E. Takeshita,[1,2] H. Suzuki,[3] S. Takeuchi,[1] S. Ota,[4] H. Baba,[1] S. Bishop,[1] T. Fukui,[4] Y. Hashimoto,[5] H. J. Ong,[6] E. Ideguchi,[7] K. Ieki,[2] N. Imai,[8] M. Ishihara,[1] H. Iwasaki,[6] S. Kanno,[2] Y. Kondo,[5] T. Kubo,[1] K. Kurita,[2] K. Kusaka,[1] T. Minemura,[8] T. Motobayashi,[1] T. Nakabayashi,[5] T. Nakamura,[5] T. Nakao,[6] M. Niikura,[7] T. Okumura,[5] T. K. Ohnishi,[6] H. Sakurai,[6] S. Shimoura,[7] R. Sugo,[2] D. Suzuki,[6] M. K. Suzuki,[6] M. Tamaki,[7] K. Tanaka,[1] Y. Togano,[2] and K. Yamada[1]

(p,p’) @ RIKEN



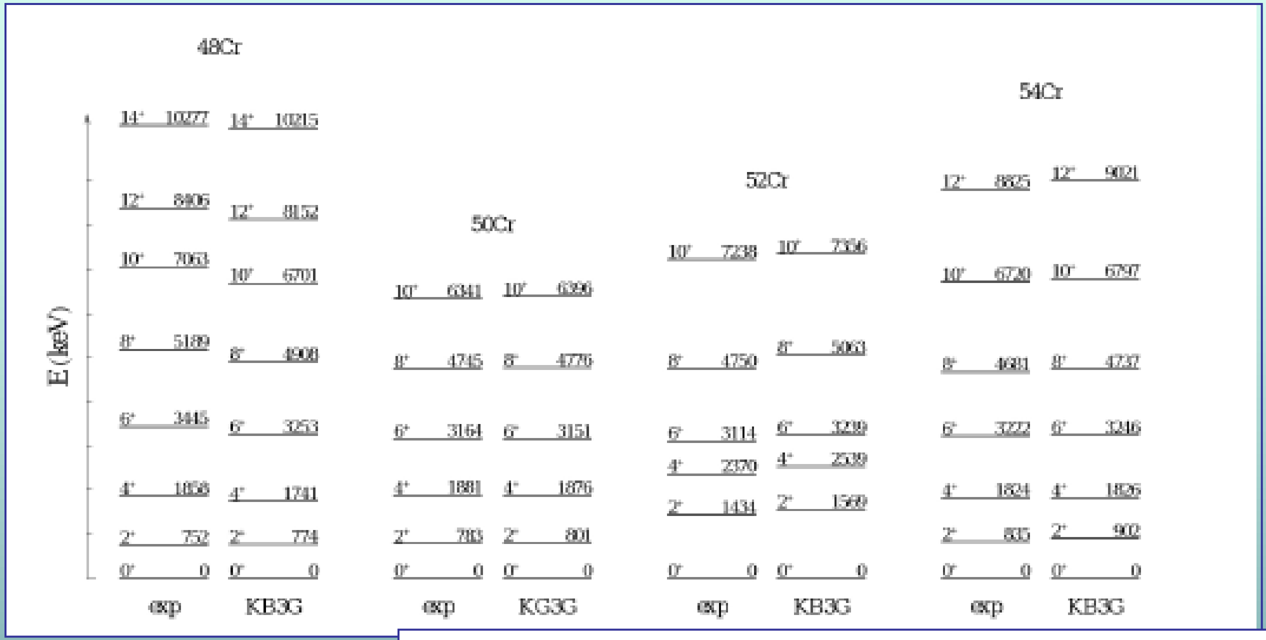
inelastic scattering
@ NSCL (MSU)

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

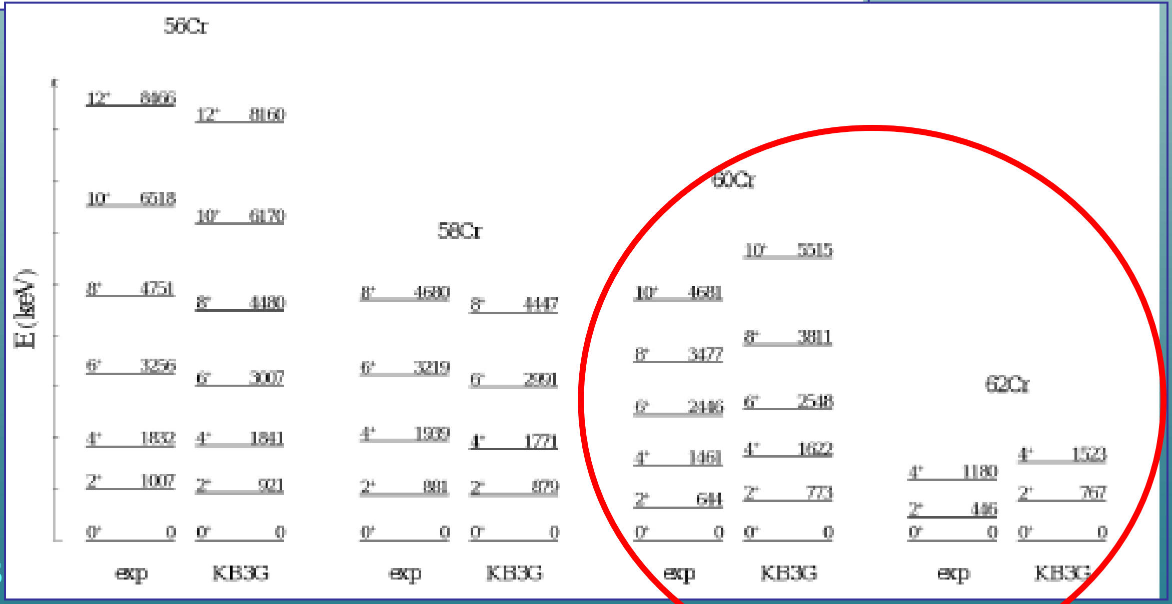
Collectivity at $N = 40$ in neutron-rich ^{64}Cr

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

The Chromium Isotopic chain



Calculations in the fp shell only



Shell model for heavier Cr isotopes

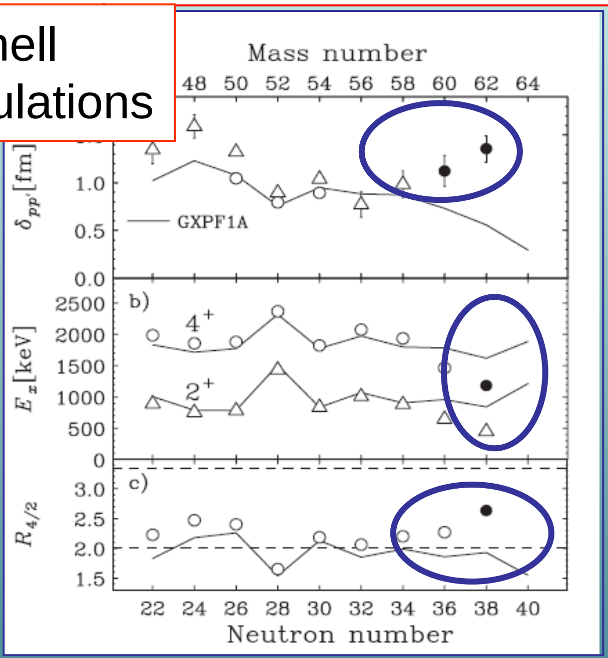
Proton inelastic scattering in inverse kinematics

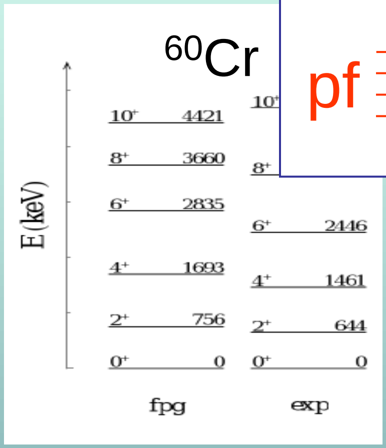
PRL 102, 012502 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

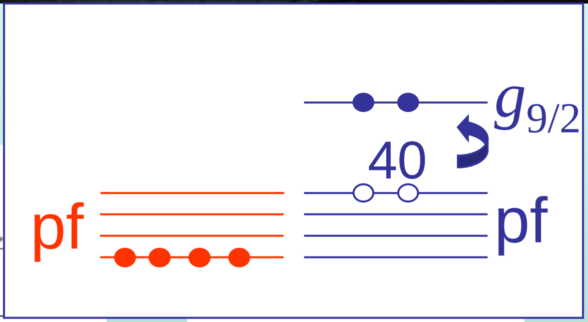
Development of Large Deformation in ^{62}Cr

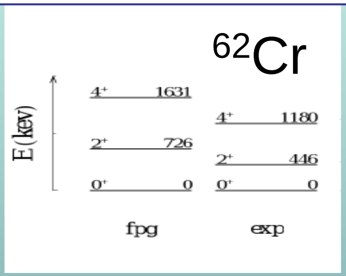
N. Aoi,[1] E. Takeshita,[1,2] H. Suzuki,[3] S. Takeuchi,[1] S. Ota,[4] H. Baba,[1] S. Bishop,[1] T. Fukui,[4] Y. Hashimoto,[5] H. J. Ong,[6] E. Ideguchi,[7] K. Ieki,[2] N. Imai,[8] M. Ishihara,[1] H. Iwasaki,[6] S. Kanno,[2] Y. Kondo,[5] T. Kubo,[1] K. Kurita,[2] K. Kusaka,[1] T. Minemura,[8] T. Motobayashi,[1] T. Nakabayashi,[5] T. Nakamura,[5] T. Nakao,[6] M. Niikura,[7] T. Okumura,[5] T. K. Ohnishi,[6] H. Sakurai,[6] S. Shimoura,[7] R. Sugo,[2] D. Suzuki,[6] M. K. Suzuki,[6] M. Tamaki,[7] K. Tanaka,[1] Y. Togano,[2] and K. Yamada[1]

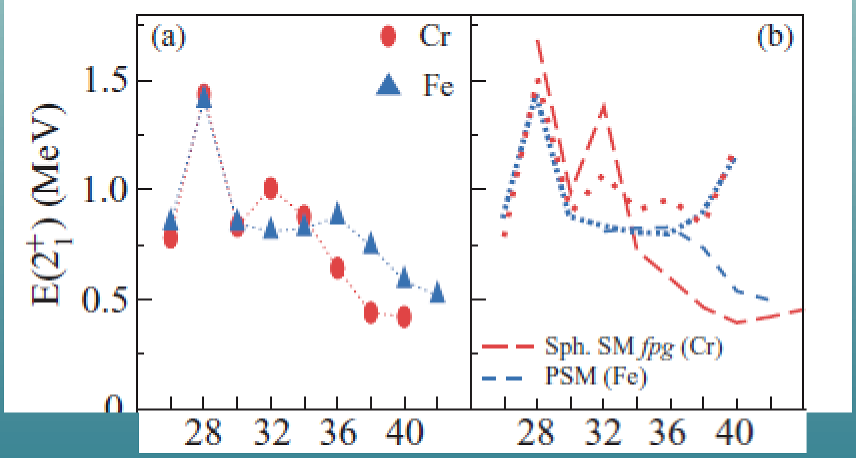
pf-shell calculations







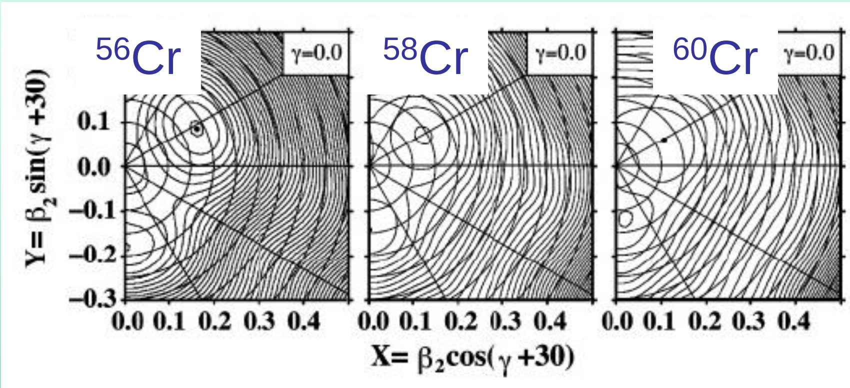




The energy levels at N=40 cannot be described within the *pf* or *fpg* space

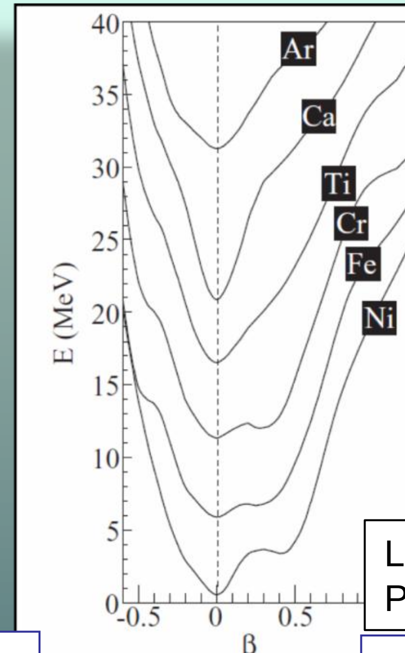
A.Gade et al., PRC 81, 051304(R) (2010)

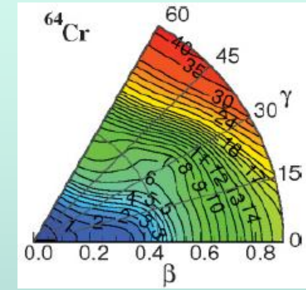
Collectivity at N~40, Z<28



S. Zhu et al., PRC 74, 064315 (2006)

Ground-state potential energy surfaces (TRS). Cr isotope seem to exhibit γ softness for large N values

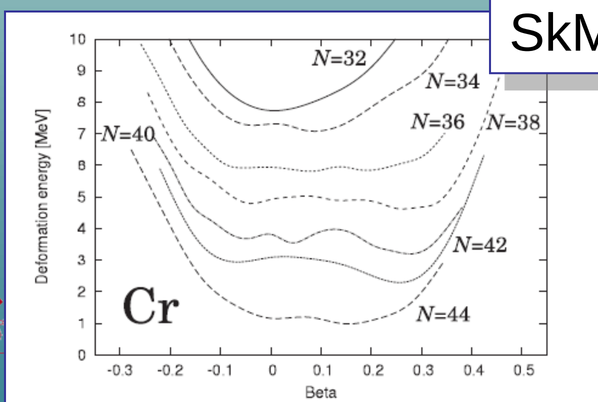




N=40 isotones
HFB+GCM
Gogny force

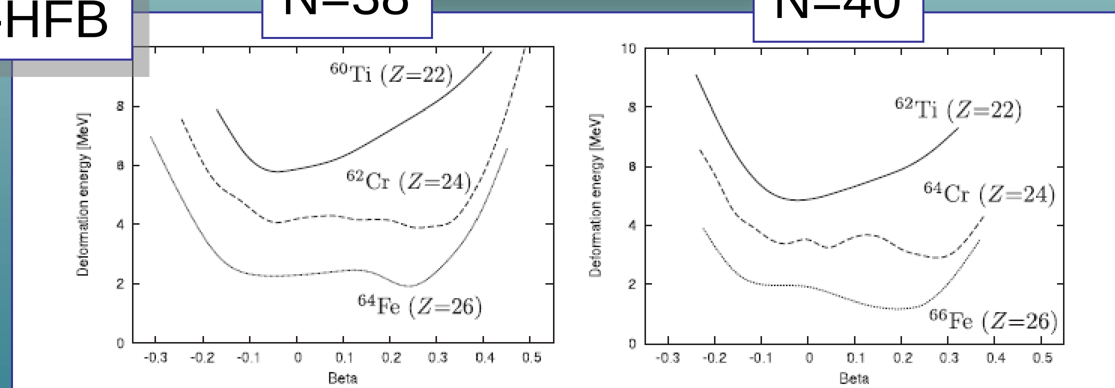
L. Gaudefroy et al., PRC 80 064313(2009)

SkM*-HFB



N=38

N=40

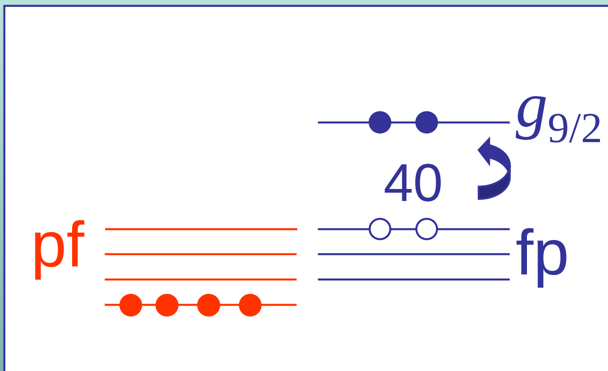


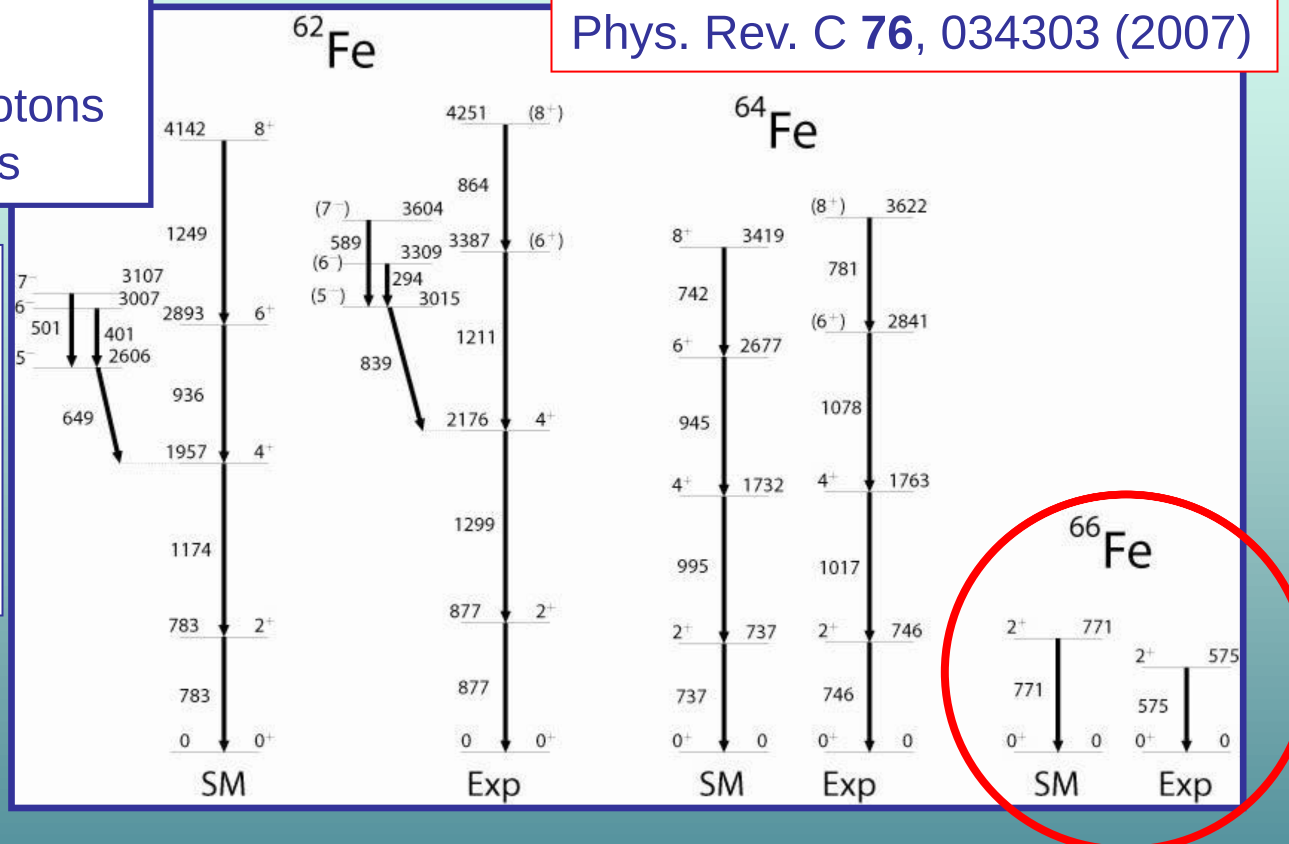
H. Oba and M. Matsuo, Prog. Theo. Phys. 120, 143 (2008)

Fe isotopes and the shell model

Shell model calculations
Core ^{48}Ca
valence space: full *fp* for protons
$p_{3/2}, f_{5/2}, p_{1/2}, g_{9/2}$ for neutrons

S. Lunardi *et al.*,
Phys. Rev. C **76**, 034303 (2007)

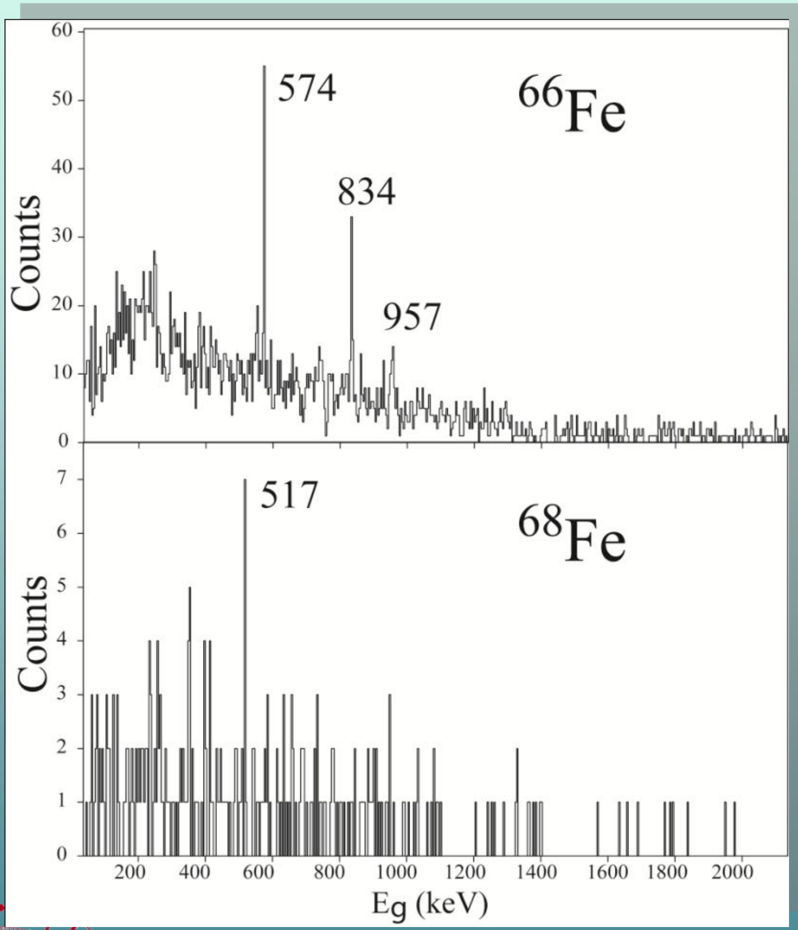




fpg Interaction described in O. Sorlin *et al.*, PRL **88**, 092501 (2002).

These calculations fail to describe the collectivity in the N=40 ^{66}Fe isotope

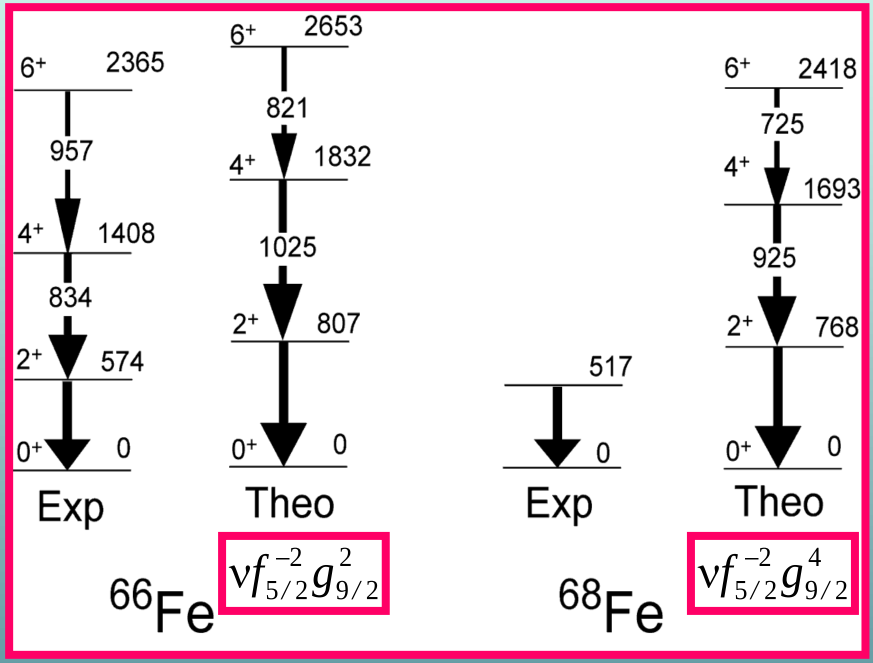
Beyond N=40



SML et al.,
LNL Ann. Rep. 2008

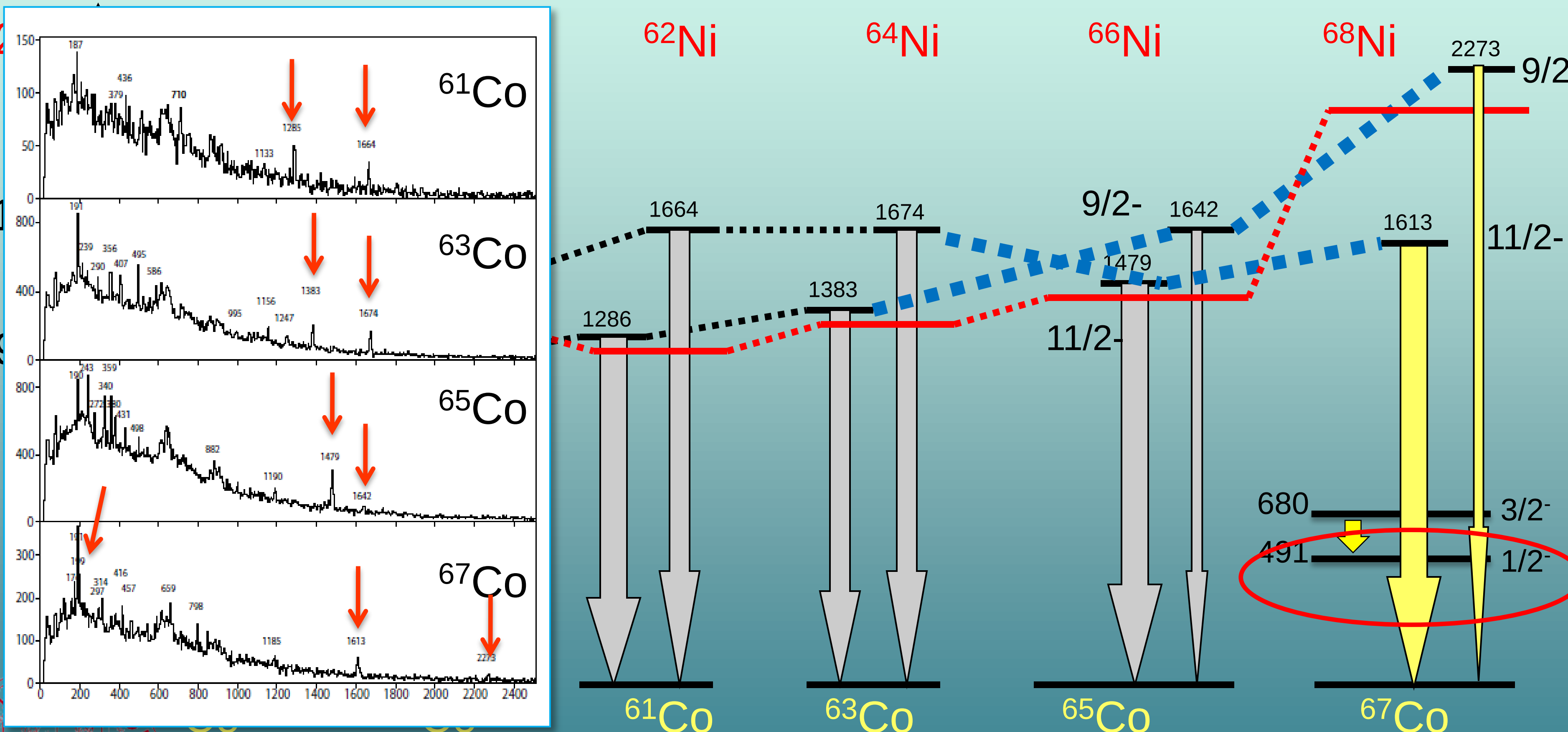
N=40

N=42



Shell model calculations
Core ^{48}Ca
valence space: full *fp* for protons
$p_{3/2}, f_{5/2}, p_{1/2}, g_{9/2}$ for neutrons

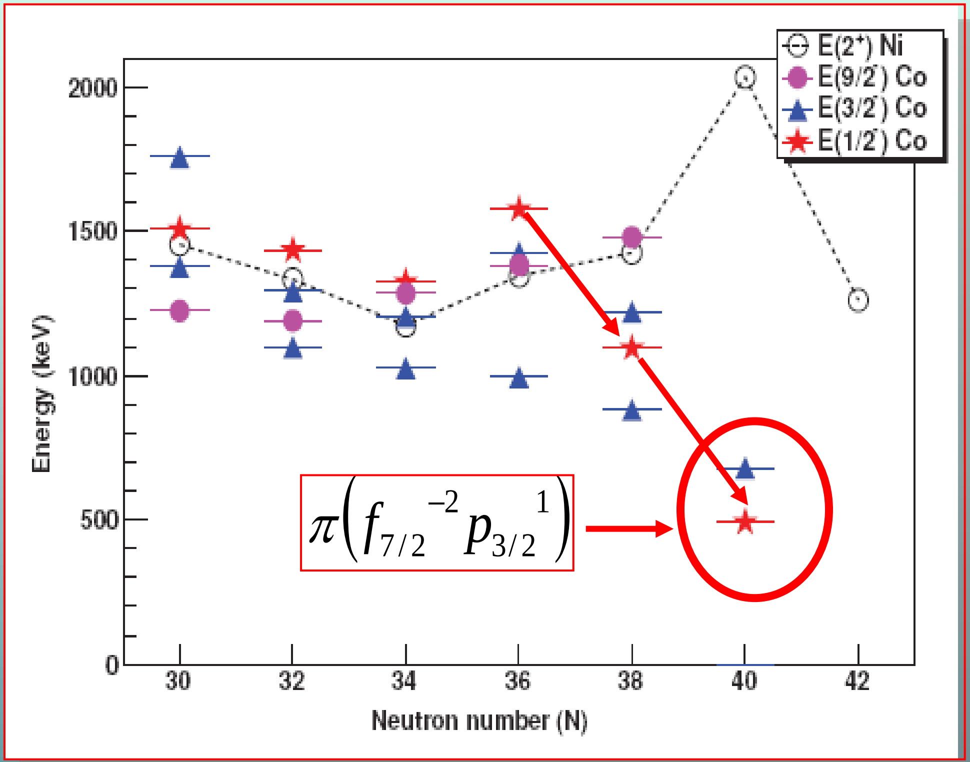
Evolution of yrast levels in Co isotopes

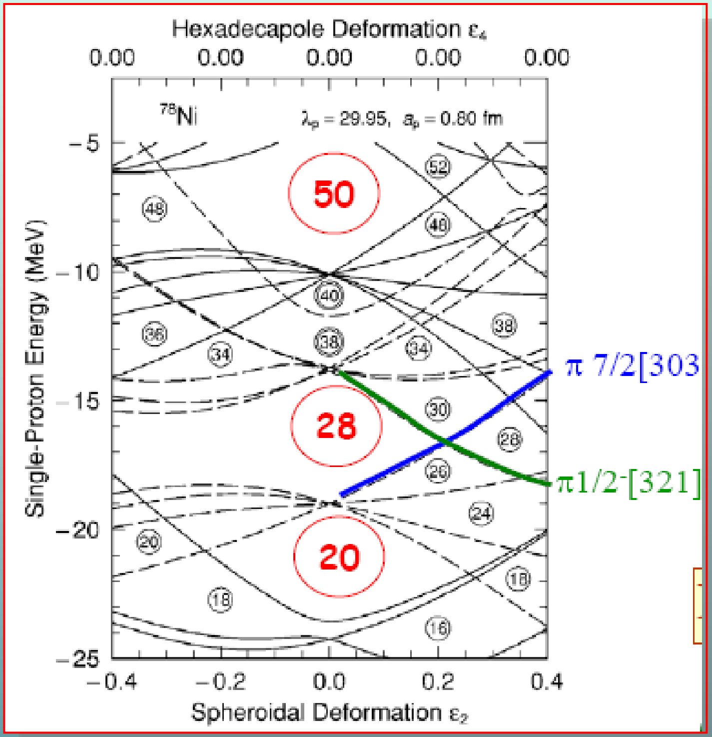


65Co: D.Pawels et al., Phys. Rev. C 79, 044309 (2009)

65-67Co: F. Recchia et al., In preparation

Proton intruder states and shape coexistence in ^{67}Co





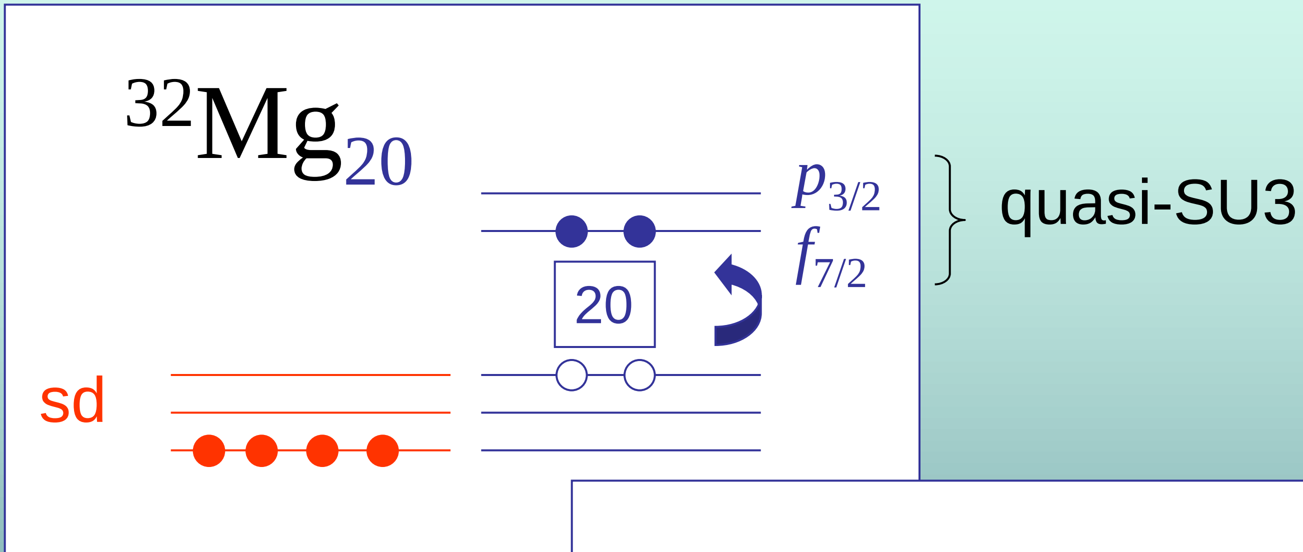
The 1/2$^-$ state lowers due to deformation increase at Z<28 N=40

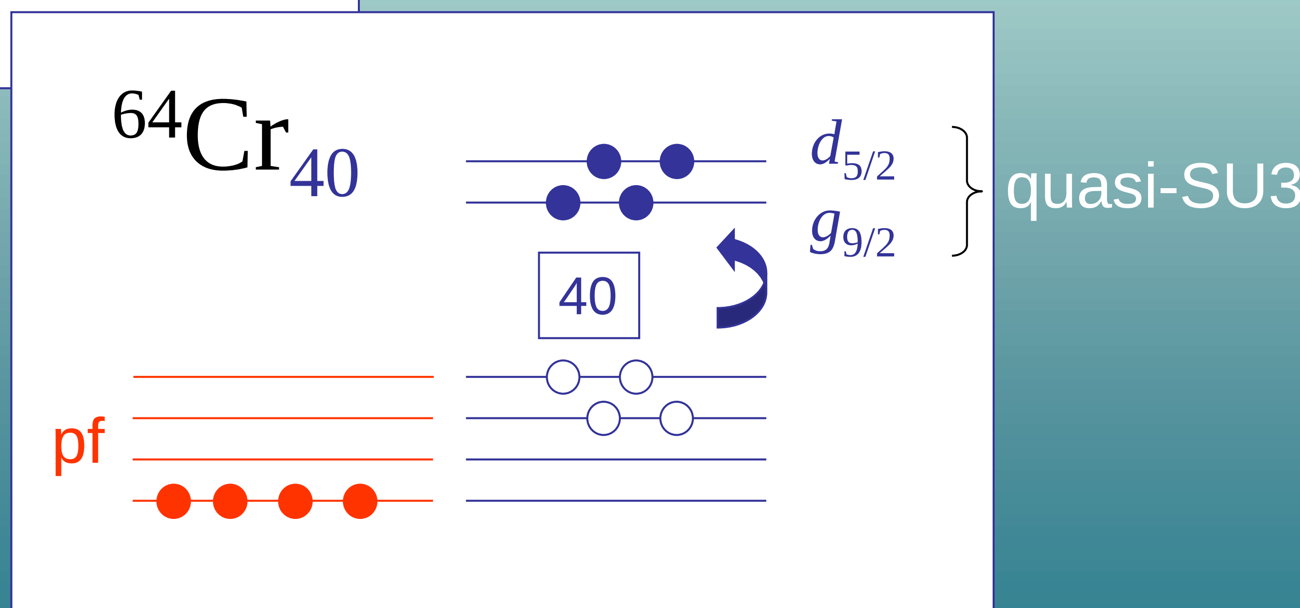
D. Pauwels et al., PRC 78, 041307 (2008) and PRC 79, 044309 (2009)

Courtesy D. Pauwels and P. Van Duppen

Shell model description: the LNPS interaction

Islands of inversion





Building quadrupole collectivity

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 52, NUMBER 4 OCTOBER 1995

Spherical shell model description of rotational motion

A. P. Zuker,[1] J. Retamosa,[2] A. Poves,[2] and E. Caurier[1]

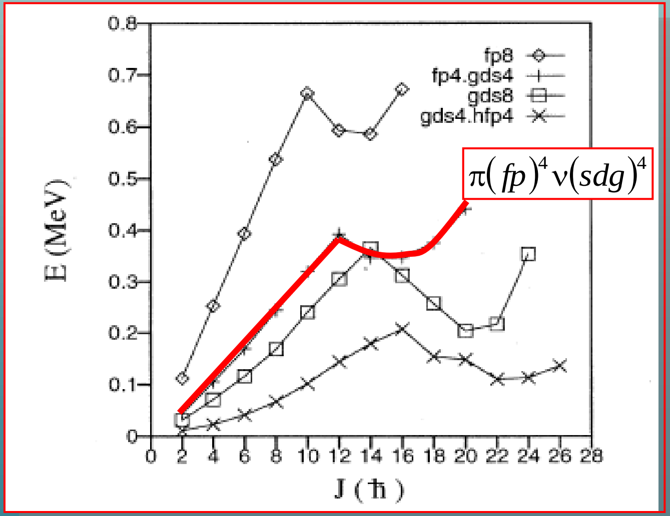
[1] *Physique Théorique, Bâtiment 40/1 CRN, Institut National de Physique Nucléaire et des Particles-CNRS/Université Louis Pasteur, Boîte Postale 28, F-67037 Strasbourg Cedex 2, France*

[2] *Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*

(Received 13 July 1994)

Exact diagonalizations with a realistic interaction show that configurations with four neutrons in a major shell and four protons in another—or the same—major shell, behave systematically as backbending rotors. The dominance of the $q \cdot q$ component of the interaction is related to an approximate "quasi-SU3" symmetry. It is suggested that the onset of rotational motion in the rare earth nuclei is due to the promotion of the eight particle blocks to the major shells above the ones currently filling. Assuming a "pseudo-SU3" coupling for the particles in the lower orbits, it is possible to account remarkably well for the observed $B(E2)$ rates at the beginning of the region.

Rotational features are determined by the interplay of the quadrupole force with the central field in the subspace spanned by a sequence of $\Delta j = 2$ orbits that come lowest by the spin-orbit splitting.



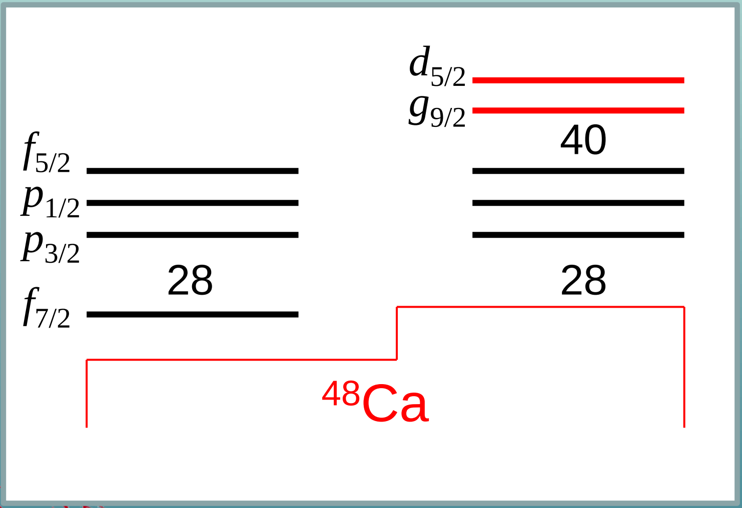
The new LNPS interaction

LNPS interaction: renormalized realistic interaction + monopole corrections

^{48}Ca core

protons: full pf shell

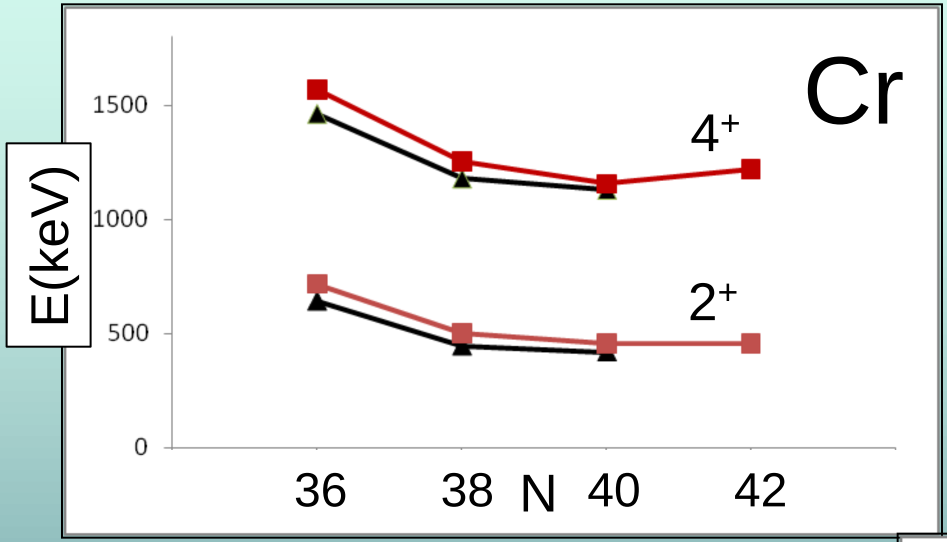
neutrons: $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, $d_{5/2}$

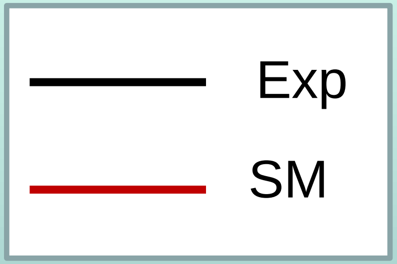


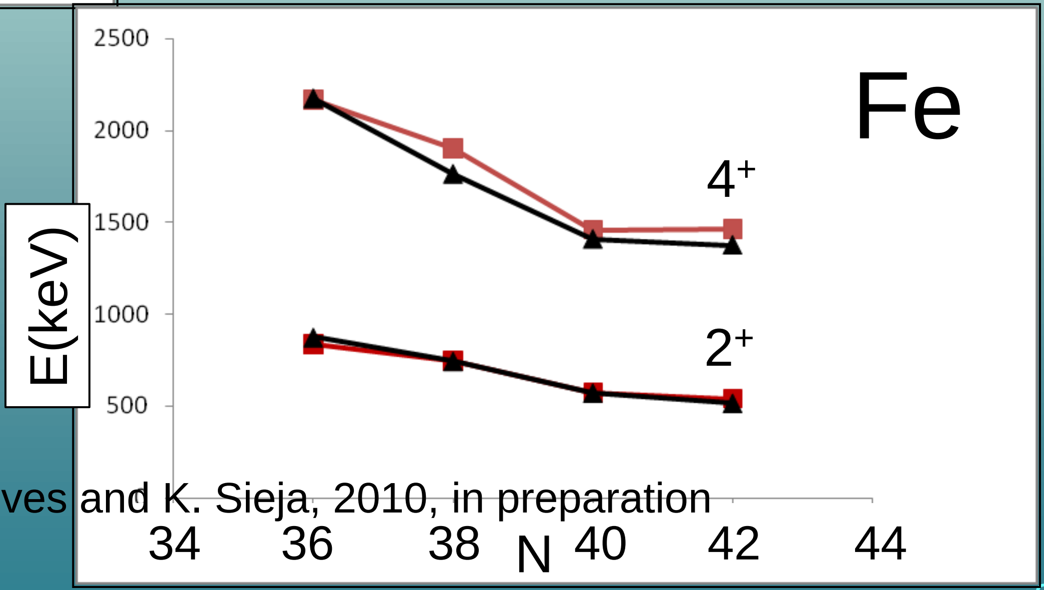
- KB3gr for the pf-shell;
- renormalized G-matrix with monopole corrections for the remaining matrix elements involving the p3/2, p1/2, f5/2 and g9/2 neutron orbits;
- the G-matrix based on the Kahana-Lee-Scott potential for the matrix elements involving the d5/2 orbit;
- monopole corrections to reproduce the Z=28 and N=50 gaps in 78Ni based on data of neighboring nuclei

SML, F. Nowacki, A. Poves and K. Sieja, 2010, in preparation

Description of Cr an Fe around N=40







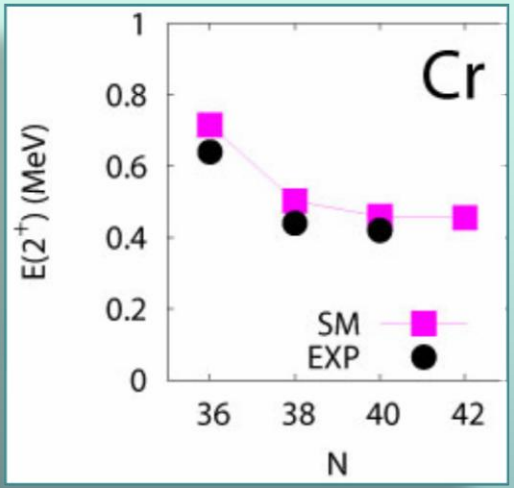
Calculations with the LNPS interaction and the code Antoine:

- up to 14p-14h excitations.
- matrix dimensions up to 10^{10}

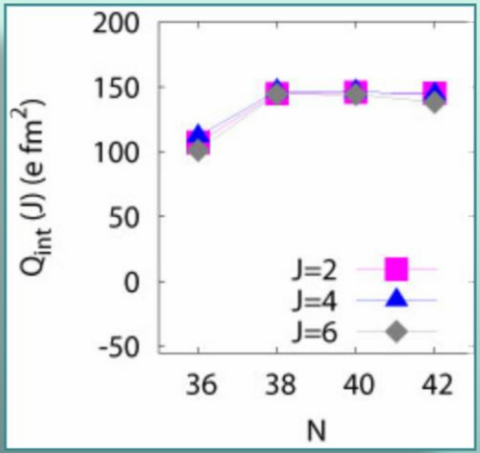
SML, F. Nowacki, A. Poves and K. Sieja, 2010, in preparation

Cr isotopes

E (2$^+$)

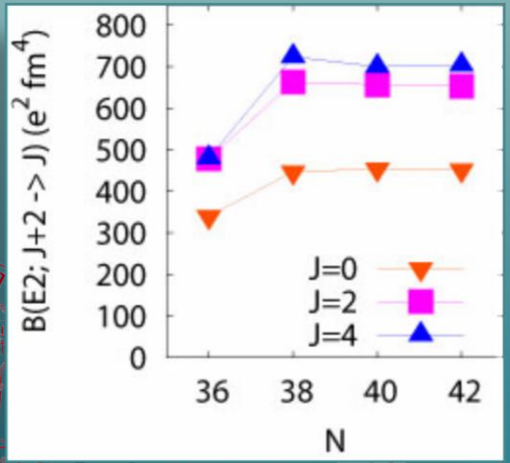


$Q_{int}(J)$



β ~ 0.35

B(E2;2$^+$→0$^+$)



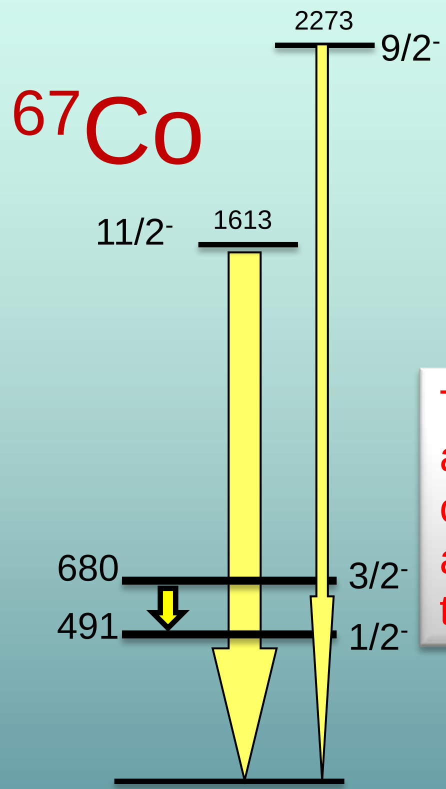
Relation between Laboratory and Intrinsic frames

$$Q_{int} = \frac{(J+1)(2J+3)}{3K^2 - J(J+1)} Q_{spec}(J), \quad K \neq 1,$$

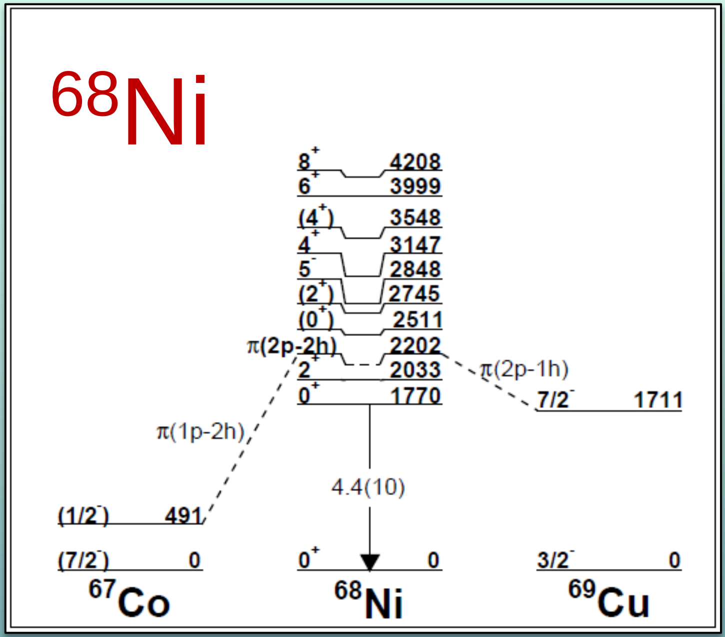
$$B(E2, J \to J-2) = \frac{5}{16} e^2 |\langle JK20|J-2, K\rangle|^2 Q_{int}^2 \quad K \neq \tfrac{1}{2},\ 1$$

SML, F. Nowacki, A. Poves and K. Sieja, 2010, in preparation

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



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



D. Pauwels et al., arXiv:1005.4602v1 [nucl-ex] 25 May 2010

67Co: F. Recchia et al., to be published

The LNPS interaction reproduces the shape coexistence in ^{67}Co and ^{68}Ni

Conclusions

The mass region studied shows a development of collectivity (deformation) towards N=40 with rapid changes of shape along the isotopic chains.

The LNPS effective interaction: built up using sets of realistic TBME and monopole corrections. Large scale shell model calculations for Ca, Ti, Cr, Fe, Co and Ni near N=40 (dim ~ 10^{10}) have been presented.

The maximum of collectivity is found in Cr isotopes, where stable deformation starts at N=38. Iron isotopes become well deformed at N=40.

The LNPS effective interaction in the fpgd space is able to describe shape coexistence in this third island of inversion.

Collaboration

Theory:

F. Nowacki, A. Poves, K. Sieja

Experiments:

F. Recchia, S. Lunardi, E. Farnea, A. Gadea,
J.J. Valiente-Dobon, D.R. Napoli, N. Marginean,
D. Bazzacco, M. Ionescu-Bujor,
A. Iordachescu, S. J. Freeman, R. Chapman,
D. Mengoni, R. Orlandi, A. Bracco, G. Benzoni,
S. Leoni, B. Million, O. Wieland, R. Broda, B. Fornal,
J. Wrzesinski *et al.*