The region of deformation south of ^{68}Ni

Silvia M. Lenzi
University of Padua and INFN

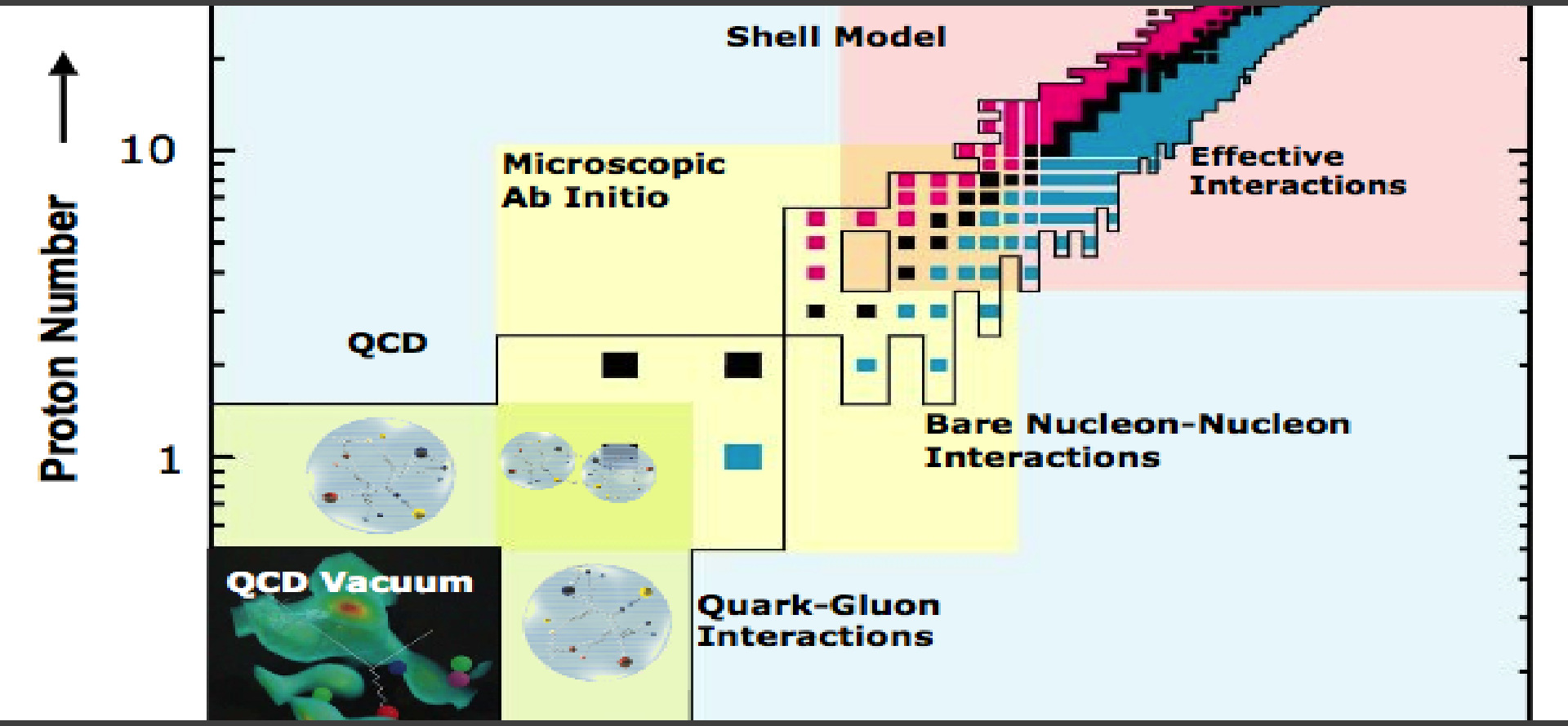
IV LEA-Colliga Meeting
Legnaro, 18-19 November 2010

Outline

- Introduction
- Evidence of deformation at N~40:
  data obtained with Clara+Prisma at LNL
- Shell model description: SML, F. Nowacki, A. Poves and K. Sieja, PRC 82, 054301 (2010)
- Conclusions

Some open questions

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

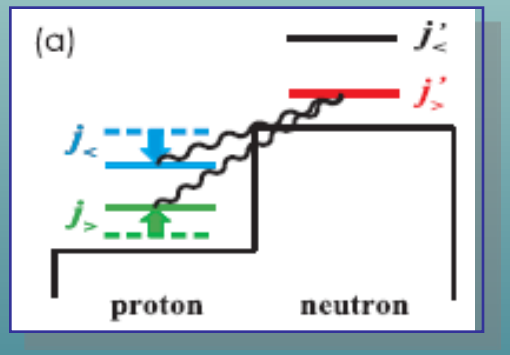


- Which are the properties of exotic nuclei at the limits of binding?
- What's new? collective motion, shapes, decay modes?

Explaining monopole drifts

Attempts to explain, reproduce and predict 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



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

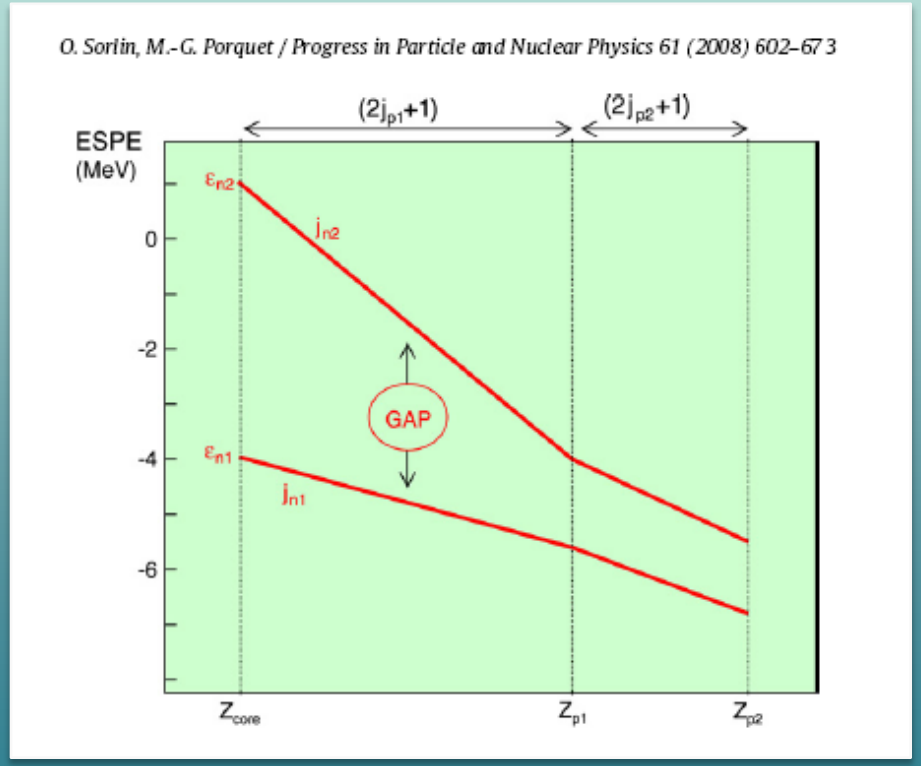
The monopole matrix element of an operator *V* can be written as

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

As the orbit j' is occupied, the single-particle energy of an orbit j, e_j, is changed linearly by

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

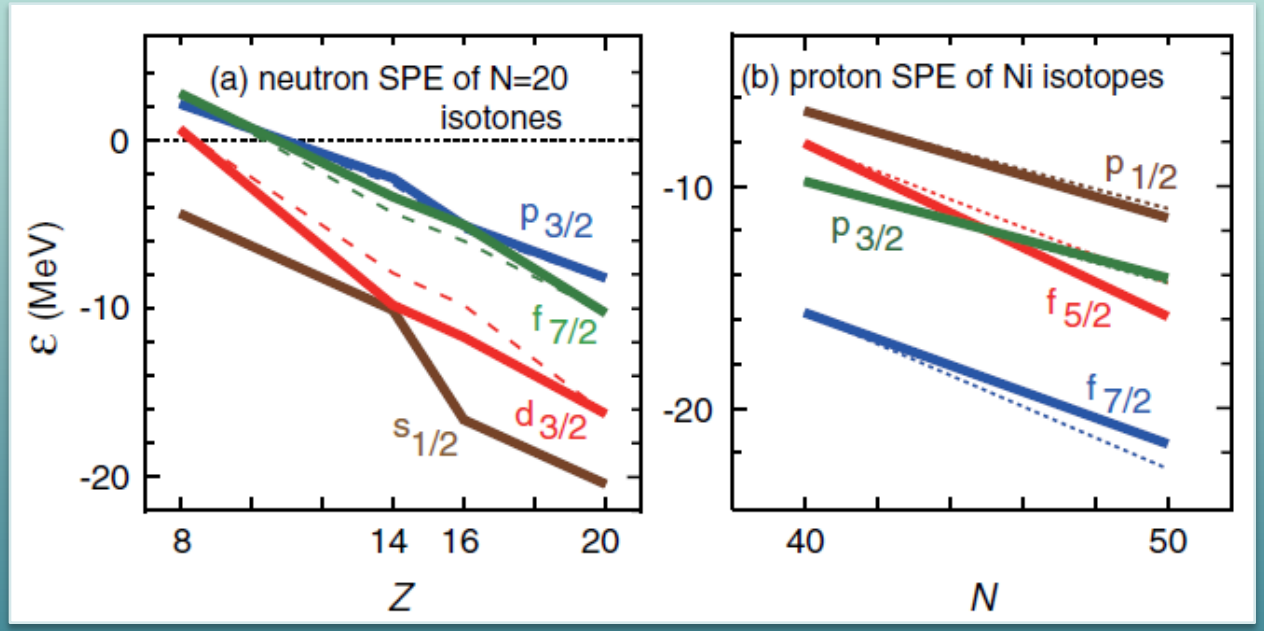
T. Otsuka et al.,
PRL 104, 012501 (2010)



Effects of the tensor force on the spe

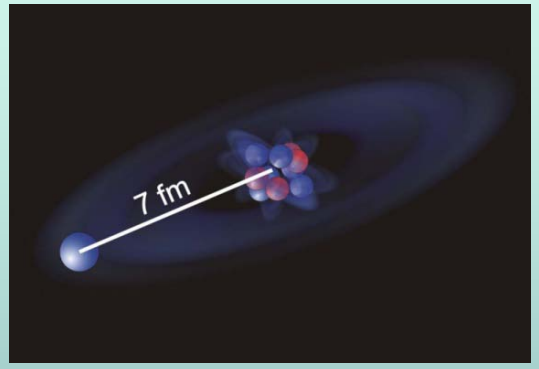
Shell model calculations V_{MU}

only central central + tensor



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

The islands of inversion (N=8)

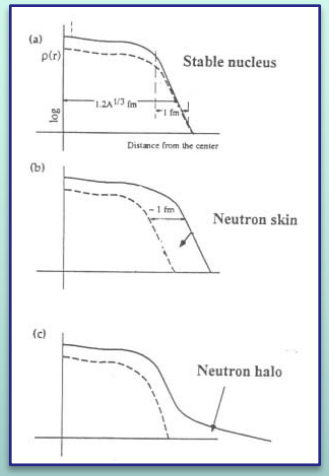


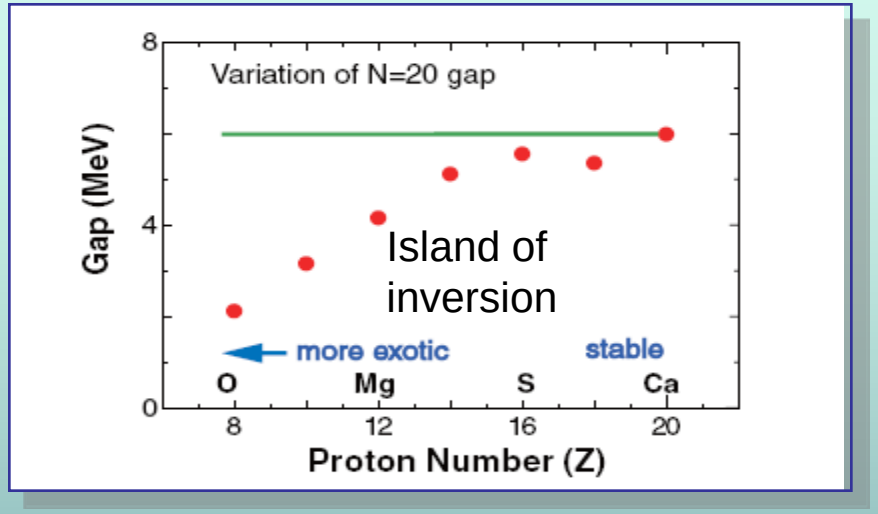
At N=8 the shell gap vanishes for very neutron rich nuclei.

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

Island of inversion: the region of nuclei where the strong quadrupole correlations overcome the spherical mean-field gaps, favoring energetically the deformed intruders, which often become ground states.

The islands of inversion (N=20)





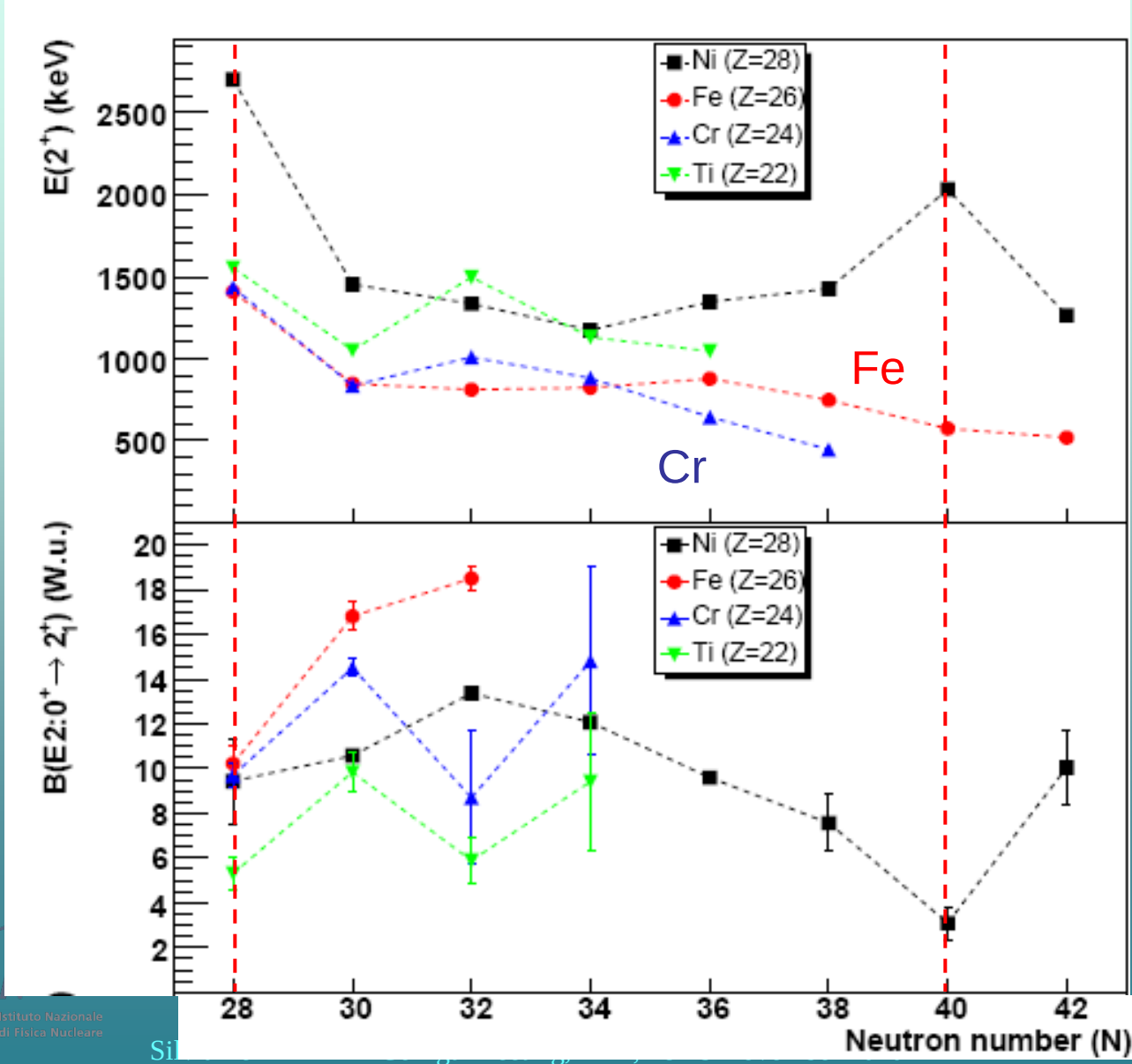
RIBF @ RIKEN
Coulomb excitation of ^{31}Ne
230 A MeV

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)

Ni and the Z<28 isotopic chains

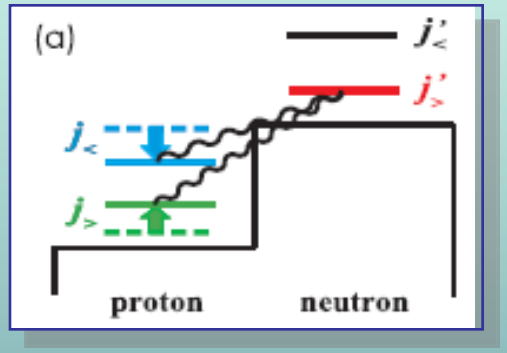


The new region of deformation at N~40:

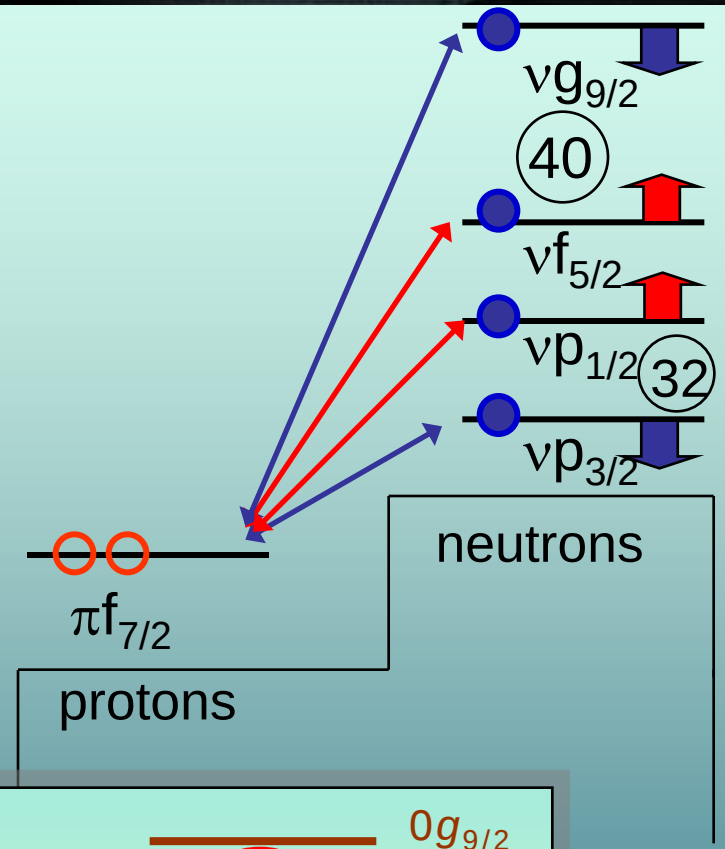
Cr, Fe and Co isotopic chains

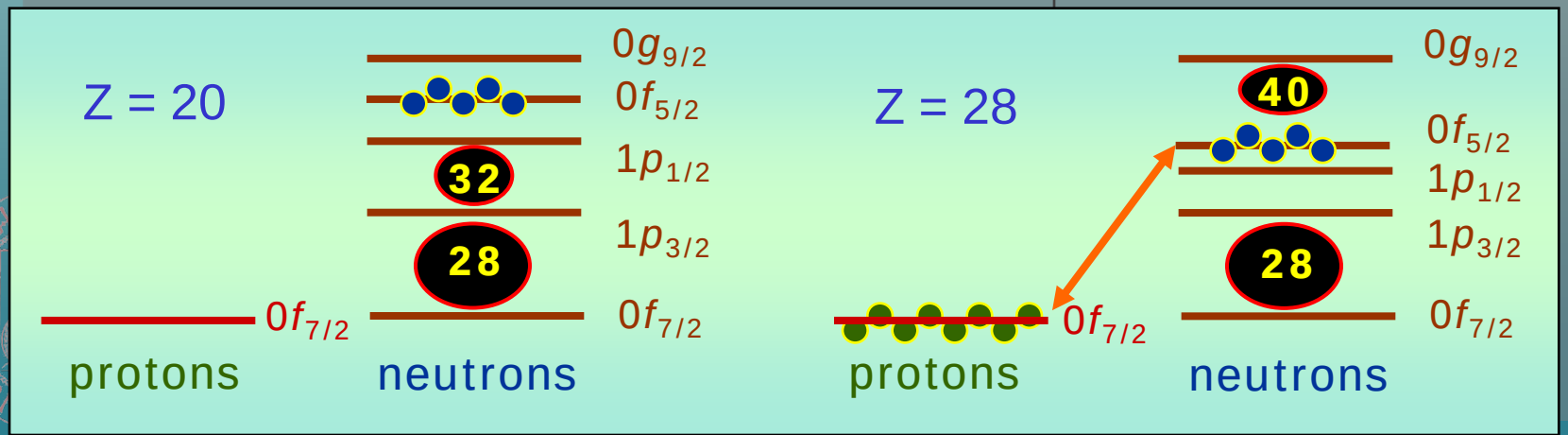
Neutron excess and shell migration

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

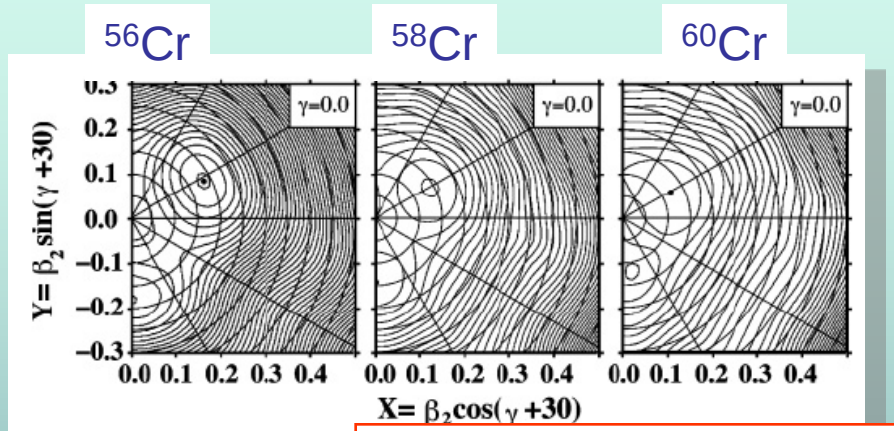


T. Otsuka et al., PRL 95 (2005) 232502





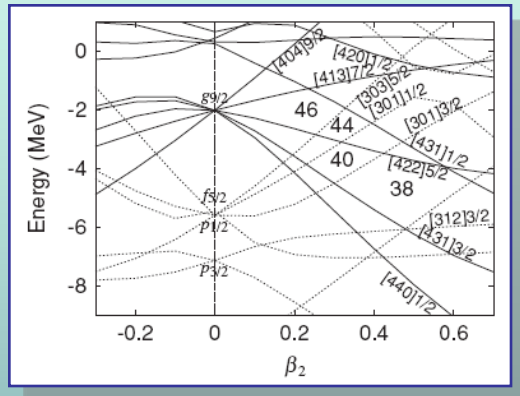
Collectivity at N~40, Z<28



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

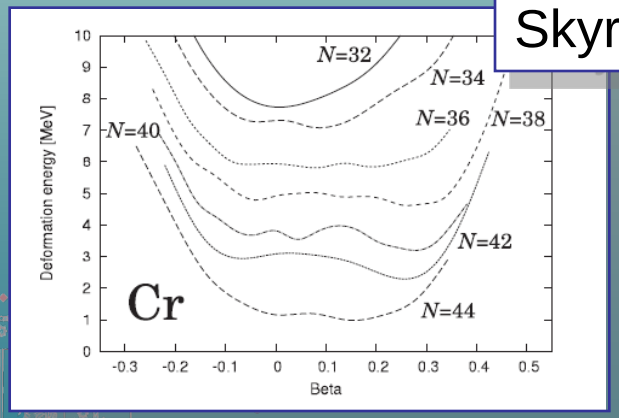
Ground-state potential energy surfaces (TRS) Cr isotope seem to exhibit γ softness for large N values

single particle energies in a deformed WS potential

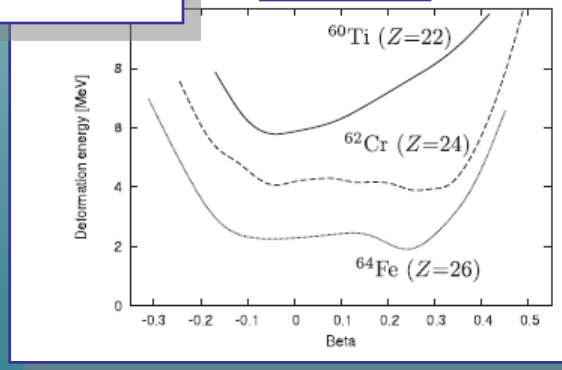


K. Yoshida and M. Yamagami, PRC 77, 044312 (2008)

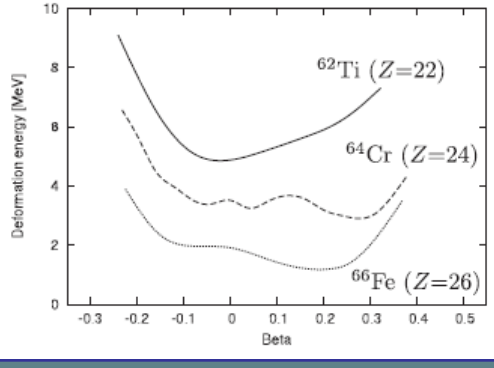
Skyrme-HFB



N=38



N=40



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

The Cr isotopic chain: data

Eur. Phys. J. A 16, 55–61 (2003)
DOI 10.1140/epja/i2002-10069-9
THE EUROPEAN PHYSICAL JOURNAL A

beta decay @ GANIL

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

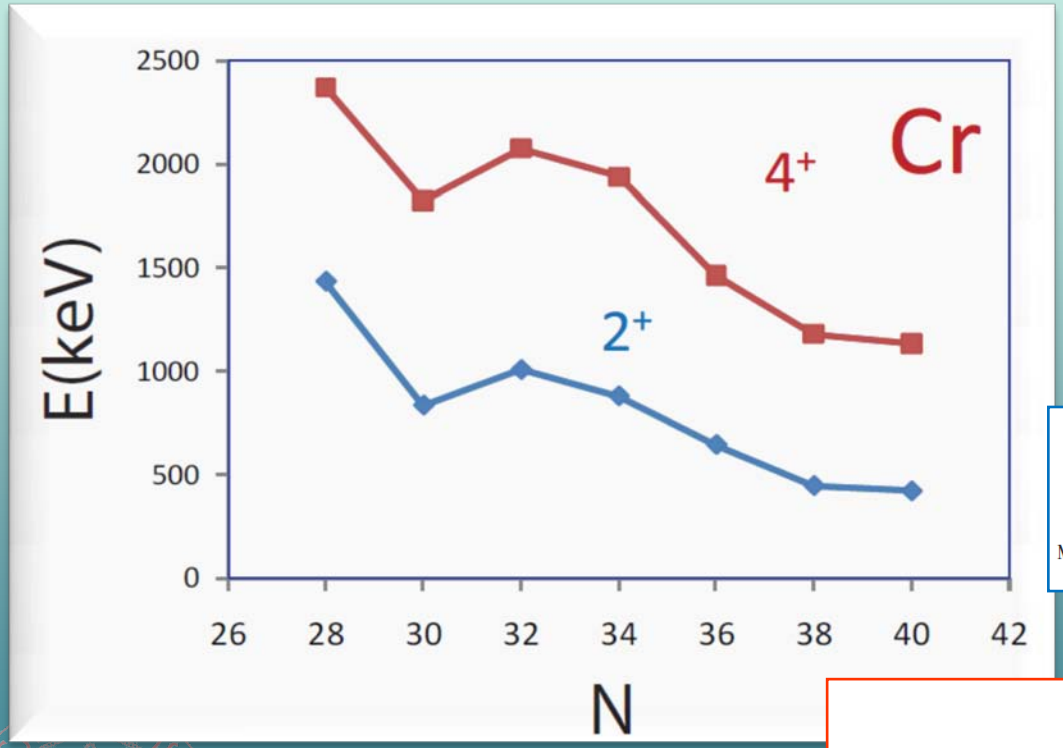
O. Sorlin[1,a], C. Donzaud[1], F. Nowacki[2], J.C. Angélique[3], F. Azaiez[1], C. Bourgeois[1], V. Chiste[1], Z. Dlouhy[4], S. Grévy[3], D. Guillemaud-Mueller[1], F. Ibrahim[1], K.-L Kratz[5], M. Lewitowicz[6], S.M. Lukyanov[7], J. Mrasek[4], Yu.-E. Penionzhkevich[7], F. de Oliveira Santos[6], B. Pfeiffer[5], 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, T. Minemura,[8] T. Motobayashi,[1] T. Nakabayashi,[5] T. Nakamura,[5] T. Na H. Sakurai,[6] S. Shimoura,[7] R. Sugo,[2] D. Suzuki,[6] M. K. Suzuki,[6] M. Ta

(p,p') @ RIKEN



Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Physics Letters B 633 (2006) 696–700
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Shape transitions far from stability: The nucleus ^{58}Cr

N. Mărginean[a,e,*], S.M. Lenzi[b], A. Gadea[a], E. Farnea[b], S.J. Freeman[c], D.R. Napoli[a], D. Bazzacco[b], S. Beghini[b], B.R. Behera[a], P.G. Bizzeti[d], A. Bizzeti-Sona[a], D. Bucurescu[e], R. Chapman[f], L. Corradi[a], A.N. Deacon[c], G. de Angelis[a], F. Della Vedova[b], E. Fioretto[a], M. Ionescu-Bujor[e], A. Iordachescu[e], Th. Kröll[g], A. Latina[a], X. Liang[f], S. Lunardi[b], G. Montagnoli[b], R. Mărginean[b], M. Nespolo[b], G. Pollarolo[h], C. Rusu[a,e], F. Scarlassara[b], J.F. Smith[c], K. Spohr[f], A.M. Stefanini[a], S. Szilner[a], M. Trotta[j], C.A. Ur[b,e], B.J. Varley[c], W. Zhimin[a]

PHYSICAL REVIEW C 74, 064315 (2006)

Level structure of the neutron-rich ^{56,58,60}Cr isotopes: Single-particle and collective aspects

S. Zhu,[1] A. N. Deacon,[2] S. J. Freeman,[2] R. V. F. Janssens,[1] B. Fornal,[3] M. Honma,[4] F. R. Xu,[5] R. Broda,[3] I. R. Calderin,[6] M. P. Carpenter,[1] P. Chowdhury,[7] F. G. Kondev,[8] W. Królas,[3] T. Lauritsen,[1] S. N. Liddick,[9,10] C. J. Lister,[1] P. F. Mantica,[9,10] T. Pawłat,[3] D. Seweryniak,[1] J. F. Smith,[2] S. L. Tabor,[6] B. E. Tomlin,[9,10] B. J. Varley,[2] and J. Wrzesiński[3]

RAPID COMMUNICATIONS

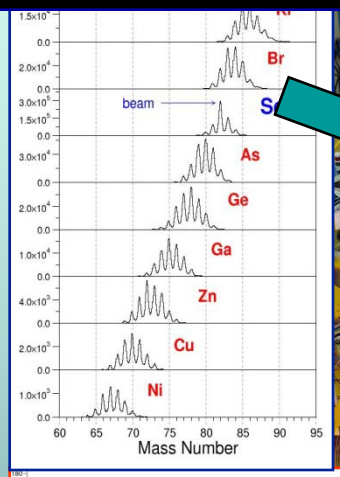
PHYSICAL REVIEW C 81, 051304(R) (2010)

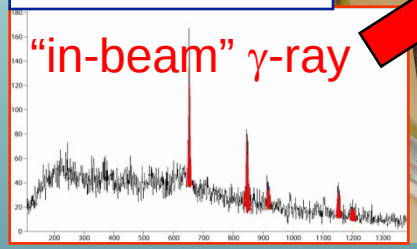
Collectivity at $N = 40$ in neutron-rich ^{64}Cr

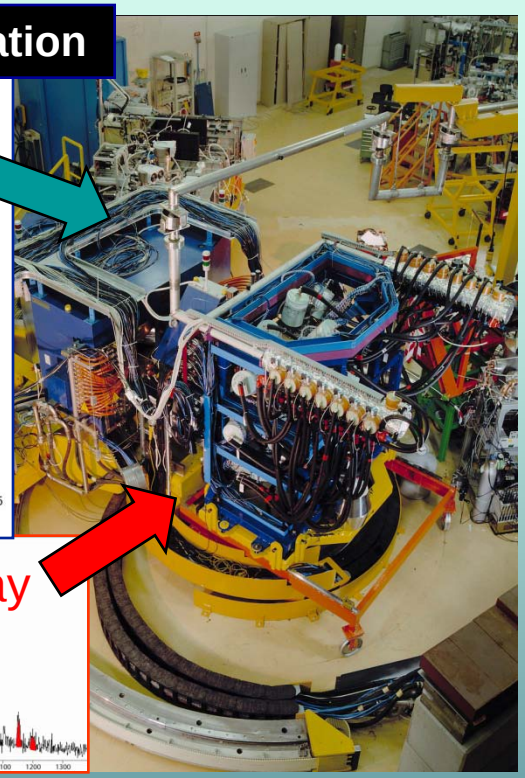
A. Gade,[1,2] R. V. F. Janssens,[3] T. Baugher,[1,2] D. Bazin,[1] B. A. Brown,[1,2] M. P. Carpenter,[3] C. J. Chiara,[3,4] A. N. Deacon,[5] S. J. Freeman,[5] G. F. Grinyer,[1] C. R. Hoffman,[3] B. P. Kay,[3] F. G. Kondev,[6] T. Lauritsen,[3] S. McDaniel,[1,2] K. Meierbachtol,[1,7] A. Ratkiewicz,[1,2]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

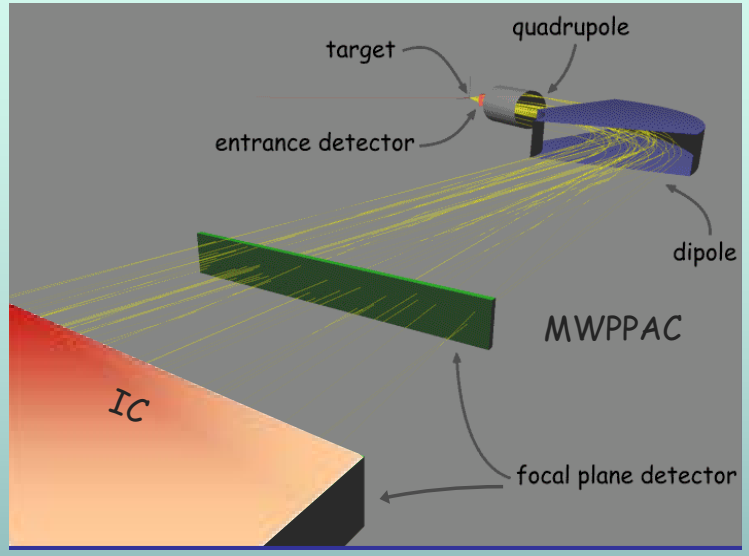
Studying the shape evolution

A & Z identification

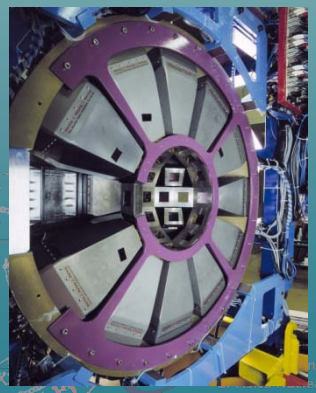




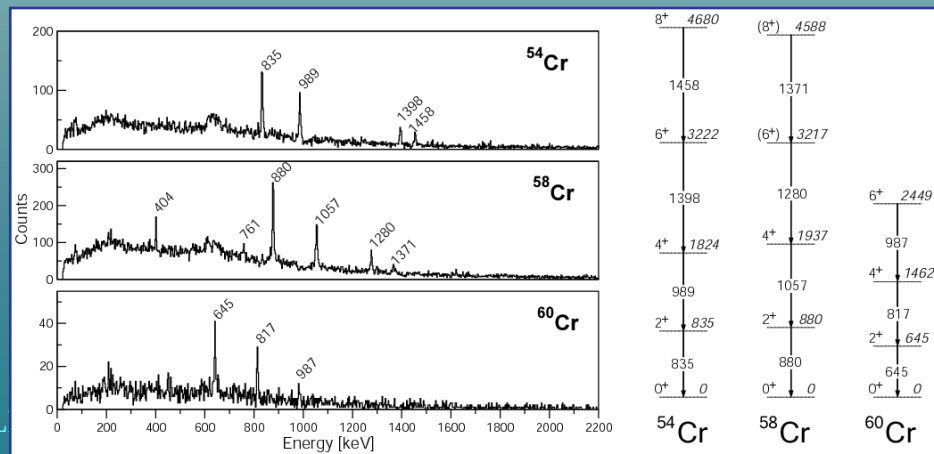




CLARA+PRISMA @ Legnaro



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

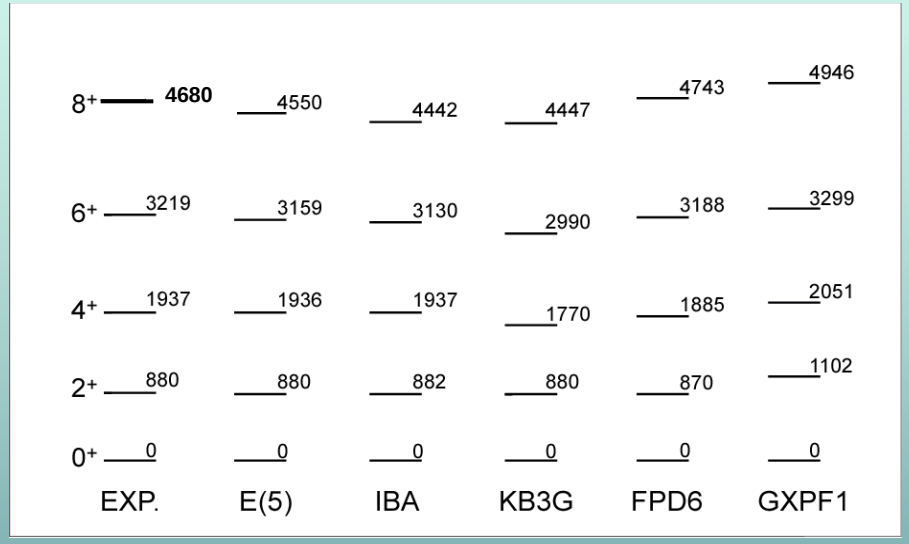
Dynamic Symmetries at the Critical Point

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.

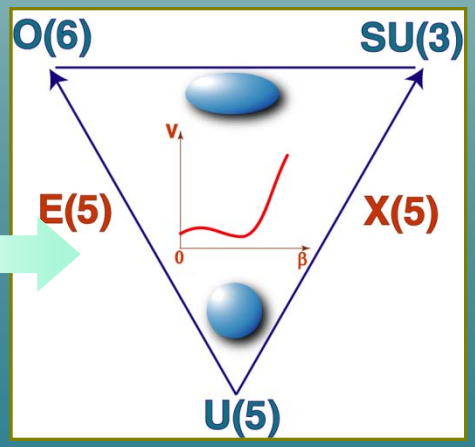
	$\xi = 1$	$\xi = 2$	$\xi = 3$	$\xi = 4$
$\tau = 0$	0	[illegible]	7.58	13.64
$\tau = 1$	1	[illegible]	11	16.93
$\tau = 2$	2.20	[illegible]	86	20.44
$\tau = 3$	3.59	[illegible]	81	24.16
$\tau = 4$	5.17			

^{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

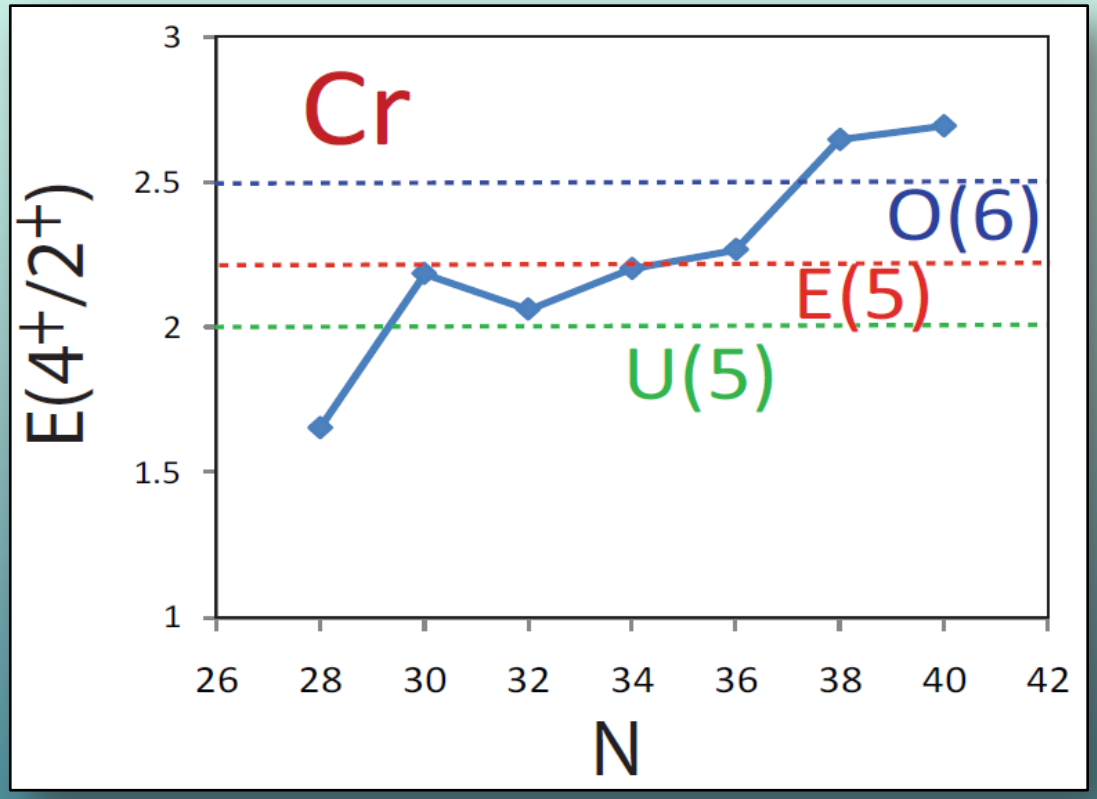
^{58}Cr



A possible bridge between shell model, algebraic and analytical approaches

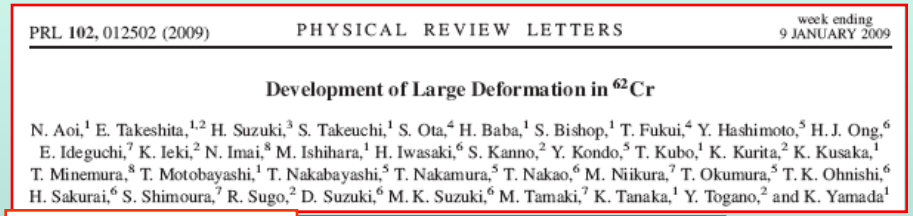
Need to measure transition probabilities

Evolution of Cr isotopes



Shell model: enlarging the space

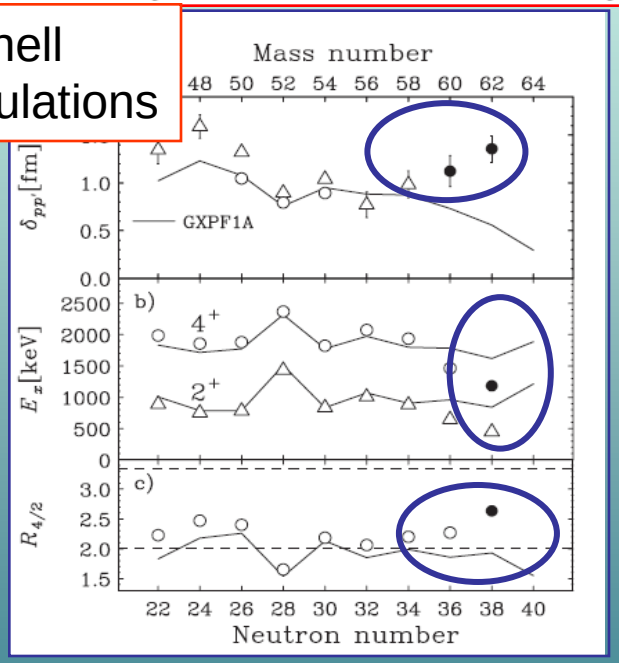
Proton inelastic scattering in inverse kinematics

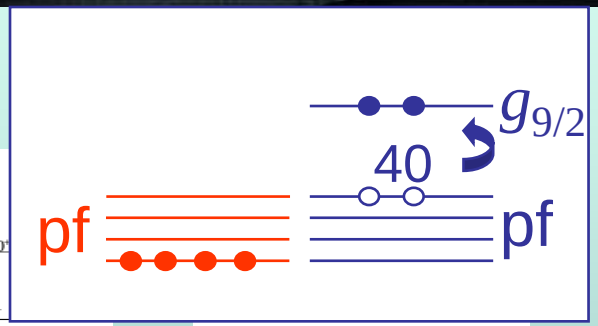

PRL 102, 012502 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

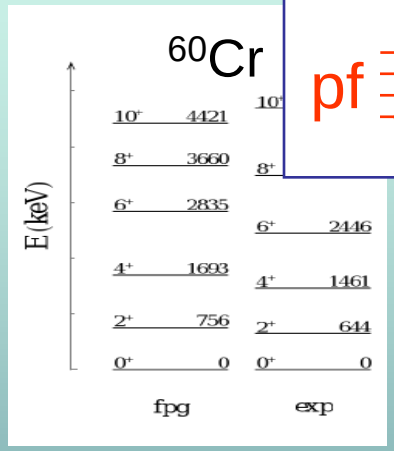
Development of Large Deformation in ^{62}Cr

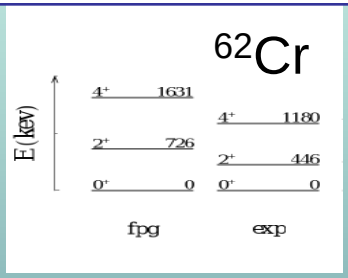
N. Aoi,[1] E. Takeshita,[1,2] H. Suzuki,[3] S. Takeuchi,[1] S. Ota,[4] H. Baba,[1] S. Bishop,[1] T. Fukui,[4] Y. Hashimoto,[5] H. J. Ong,[6] E. Ideguchi,[7] K. Ieki,[2] N. Imai,[8] M. Ishihara,[1] H. Iwasaki,[6] S. Kanno,[2] Y. Kondo,[5] T. Kubo,[1] K. Kurita,[2] K. Kusaka,[1] T. Minemura,[8] T. Motobayashi,[1] 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]

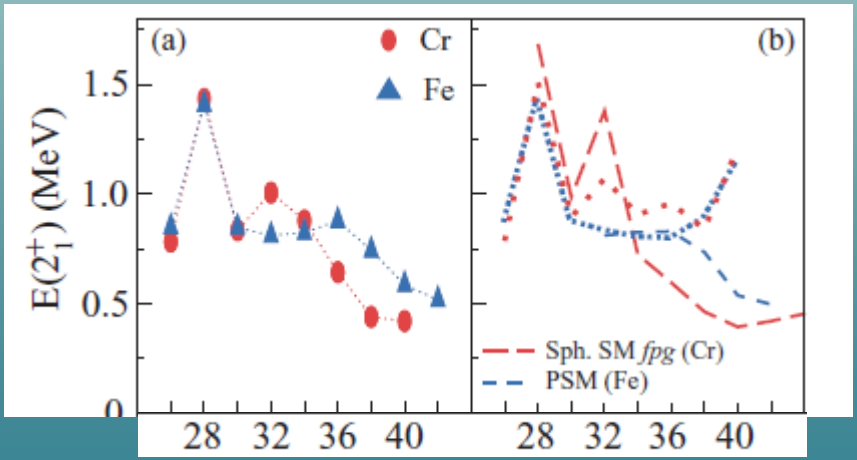
pf-shell calculations











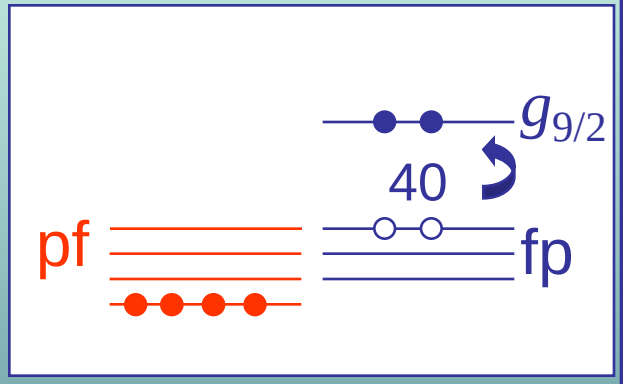
A.Gade et al., Phys. Rev. C 81, 051304(R) (2010)

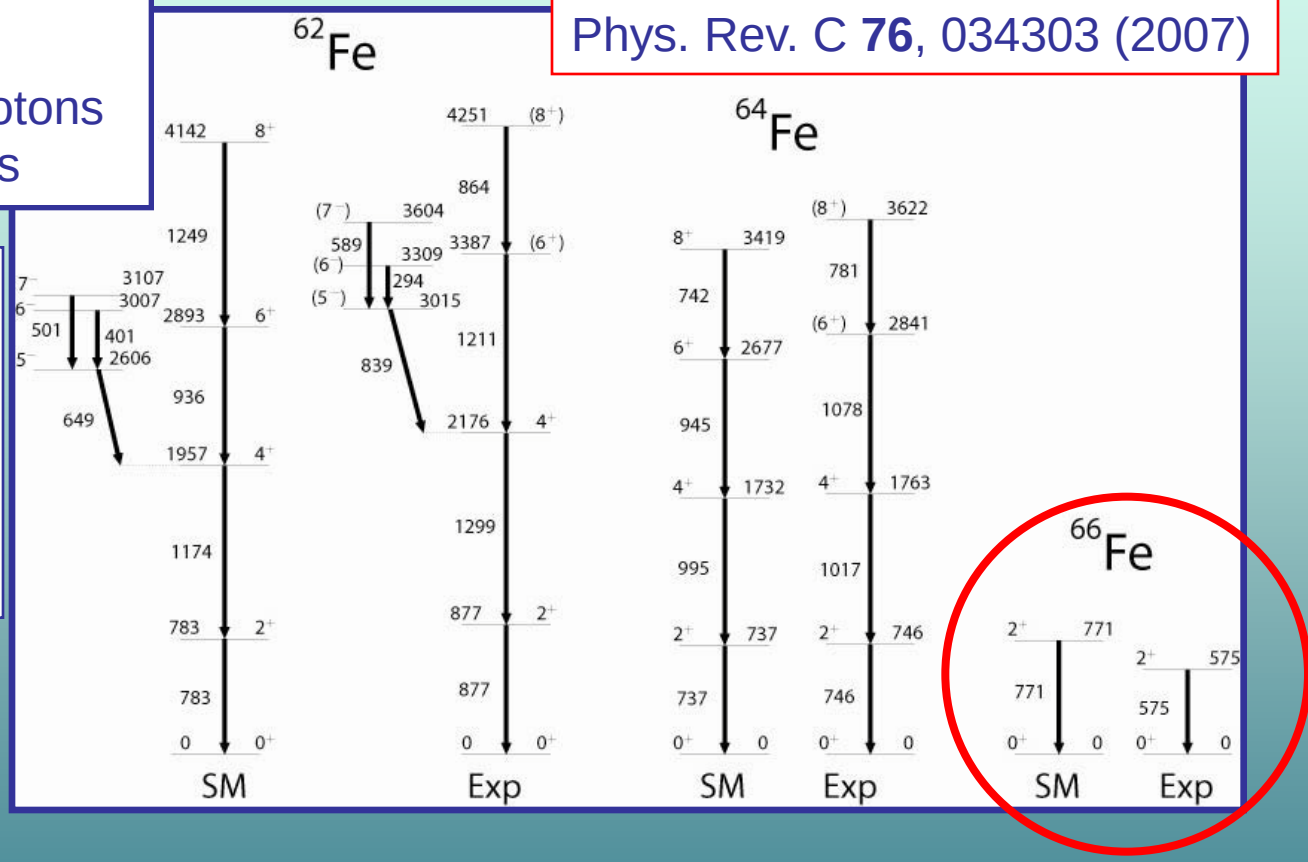
The energy levels at N=40 cannot be described within the *pf* or *fpg* space

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

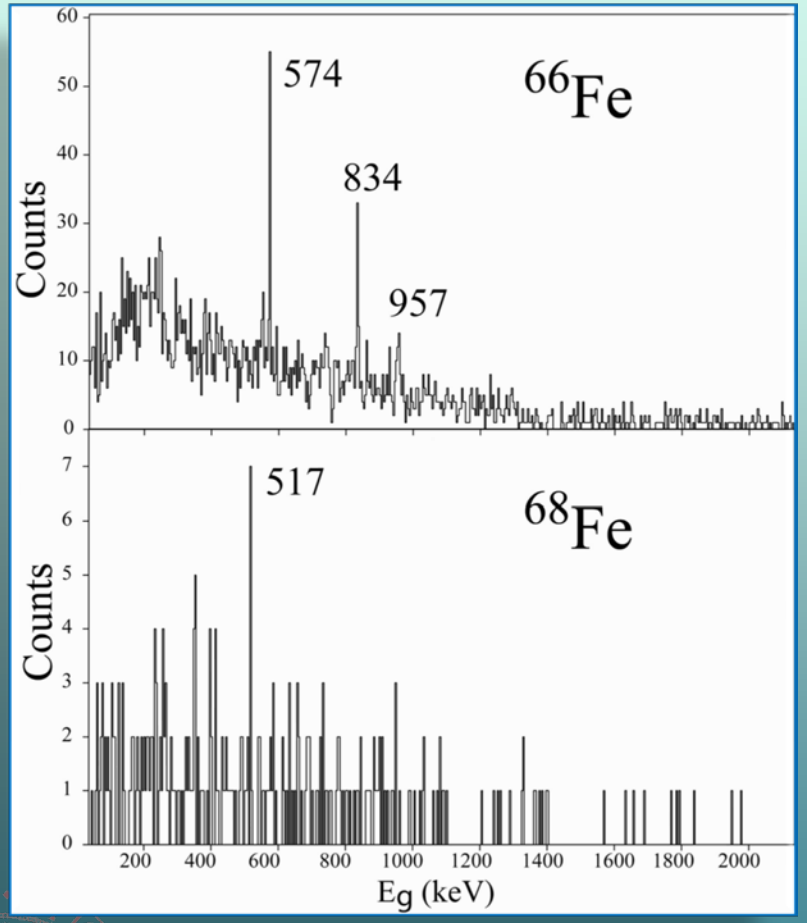
S. Lunardi *et al.*,
Phys. Rev. C **76**, 034303 (2007)

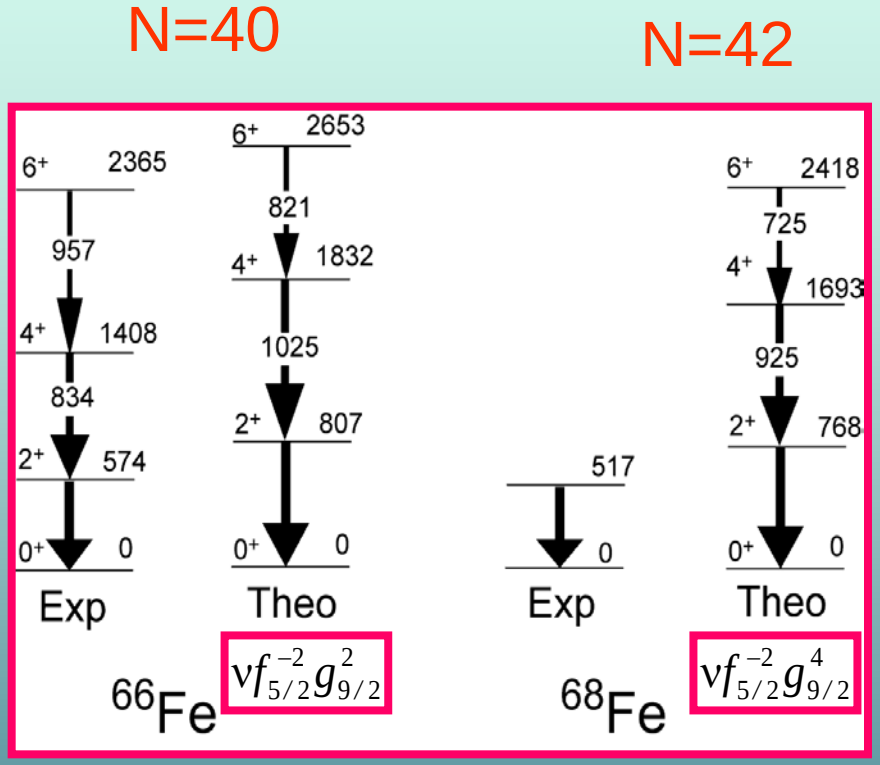




fpg Interaction described in
O. Sorlin *et al.*, PRL **88**, 092501 (2002).

Beyond N=40

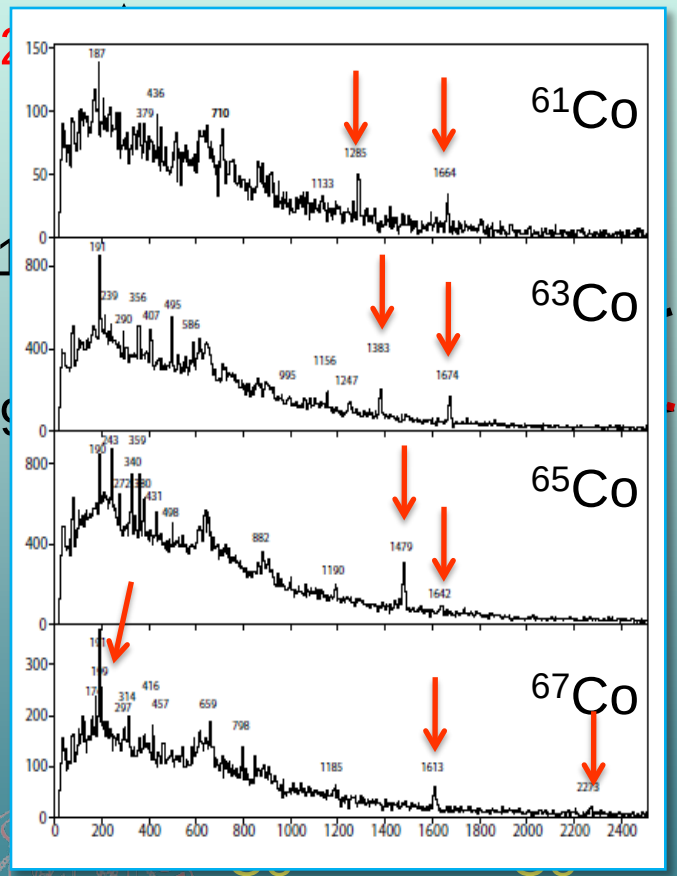


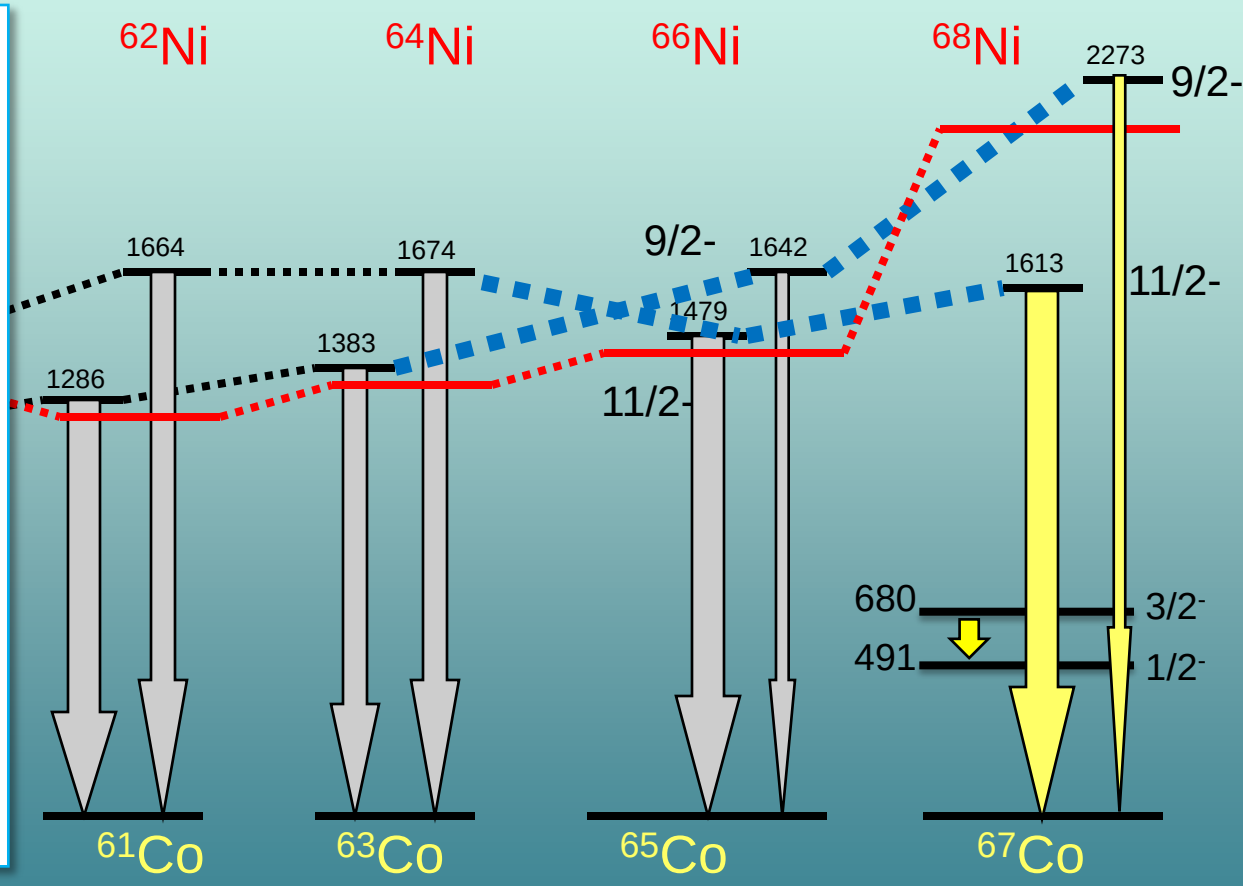


Clara+Prisma data

SML et al.,
LNL Ann. Rep. 2008

Evolution of yrast levels in Co isotopes

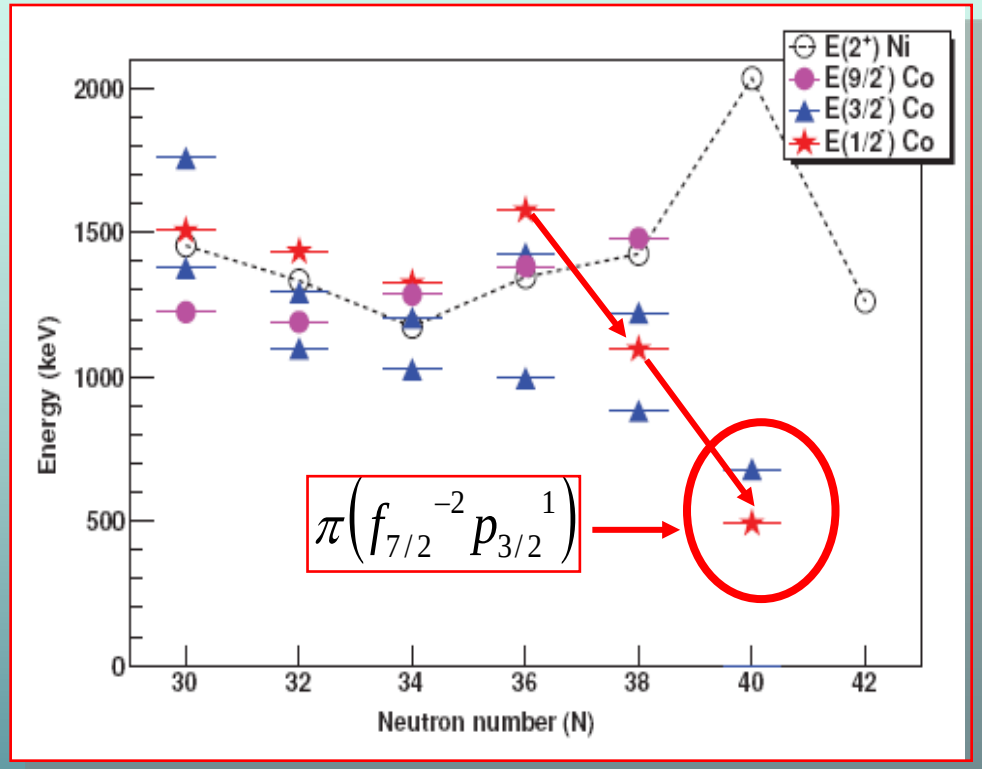


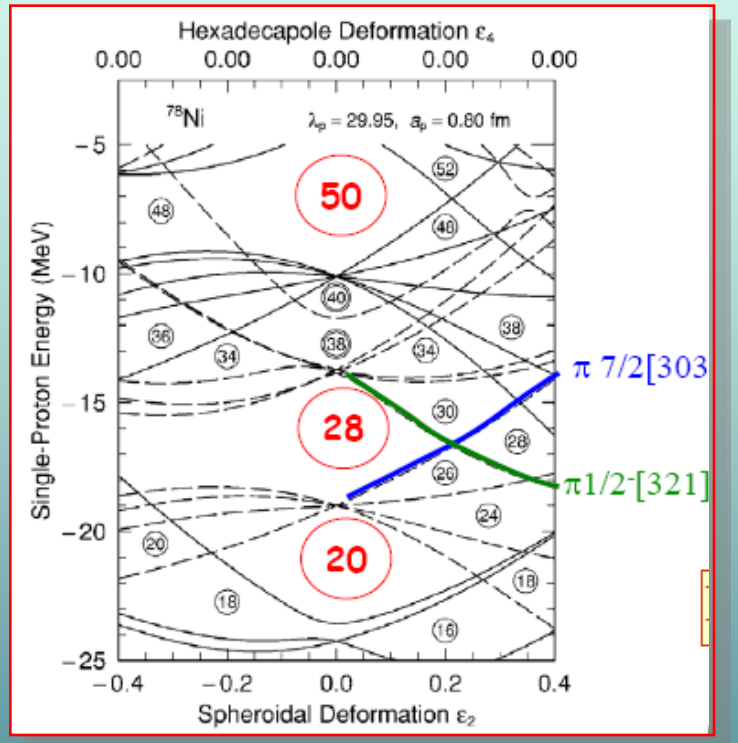


65Co: D.Pawels et al., Phys. Rev. C 79, 044309 (2009)

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

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]

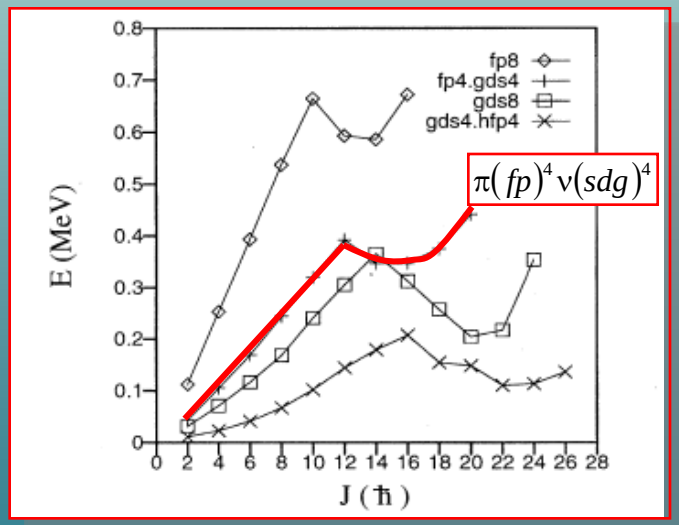
[1]*Physique Théorique, Bâtiment 40/1 CRN, Institut National de Physique Nucléaire et des Particles-CNRS/Université Louis Pasteur, Boîte Postale 28, F-67037 Strasbourg Cedex 2, France*

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

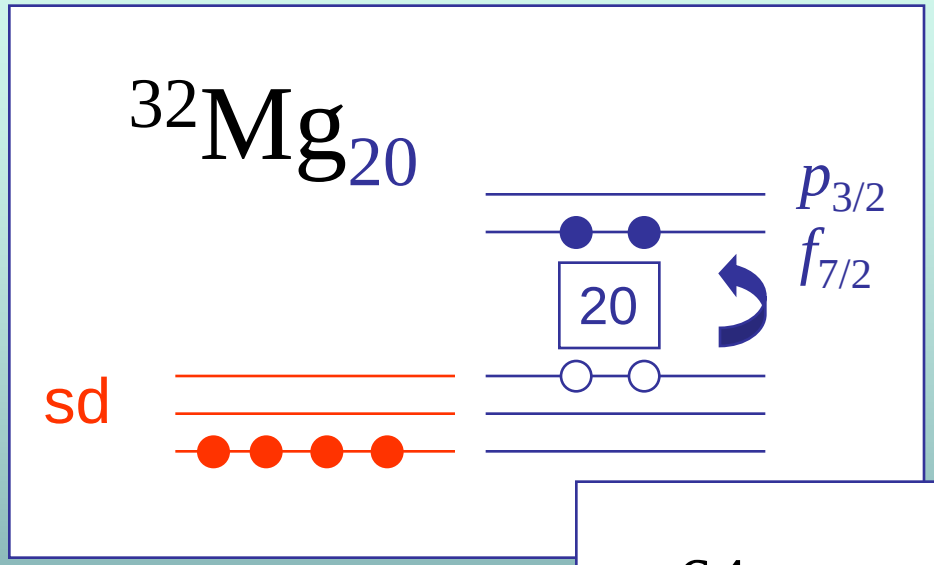
(Received 13 July 1994)

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.

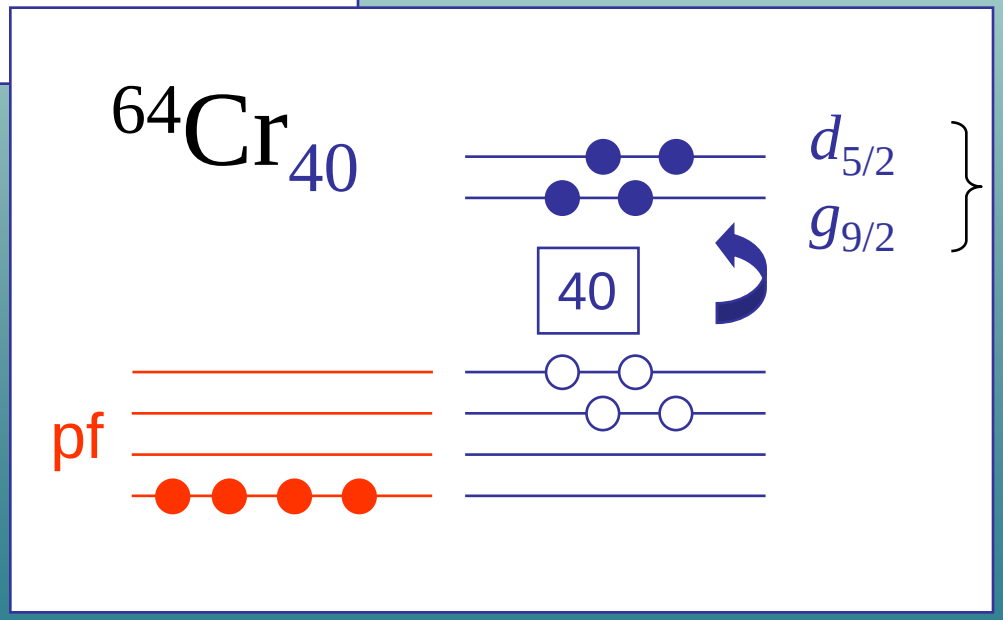
Rotational features are determined by the interplay of the quadrupole force with the central field in the subspace spanned by a sequence of $\Delta j = 2$ orbits that come lowest by the spin-orbit splitting.



Islands of inversion



quasi-SU3

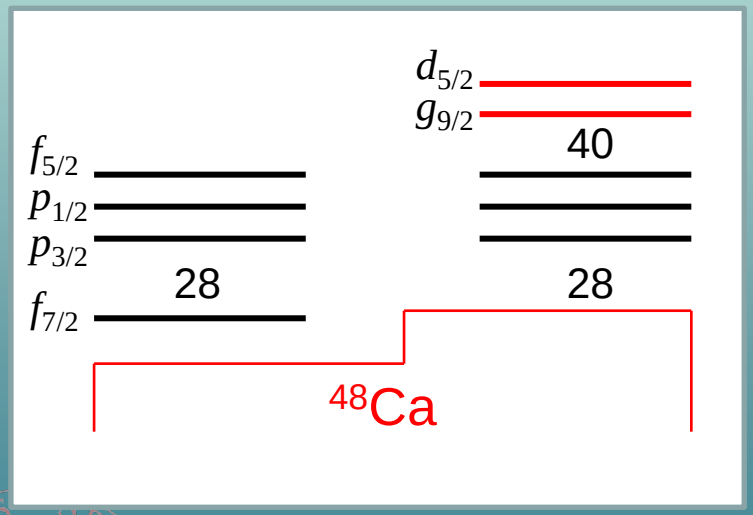


quasi-SU3

The new LNPS interaction

LNPS interaction: renormalized realistic interaction
+ monopole corrections

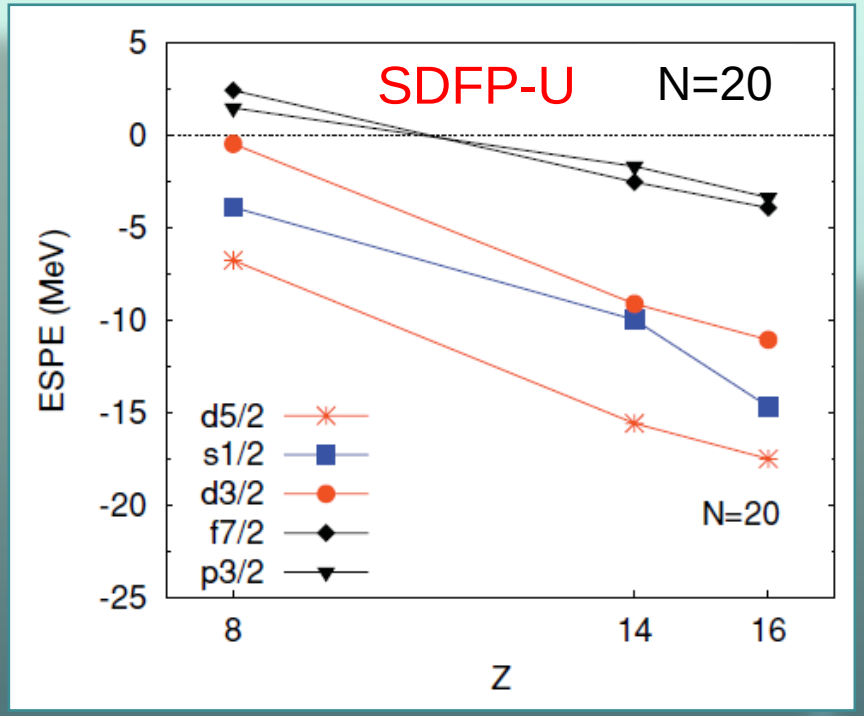
^{48}Ca core
protons: full pf shell
neutrons: $p_{3/2}$,$f_{5/2}$, $p_{1/2}$, $g_{9/2}$, $d_{5/2}$

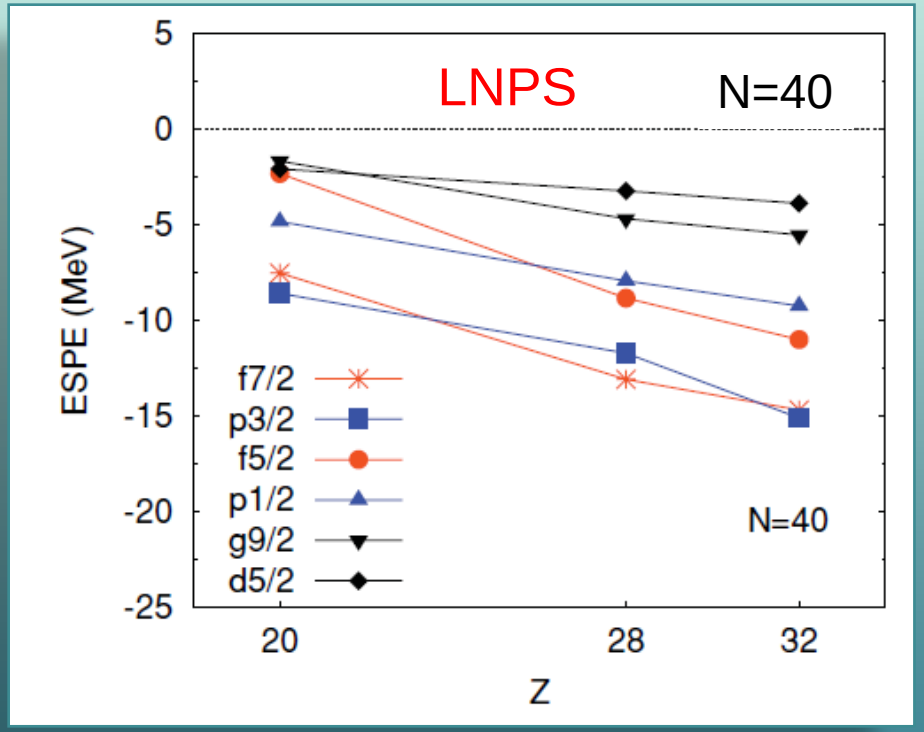


- KB3gr for the pf-shell;
- renormalized G-matrix with monopole corrections for the remaining matrix elements involving the p3/2, p1/2, f5/2 and g9/2 neutron orbits;
- the G-matrix based on the Kahana-Lee-Scott potential for the matrix elements involving the d5/2 orbit;
- monopole corrections to reproduce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

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

ESPE in N=20 and N=40

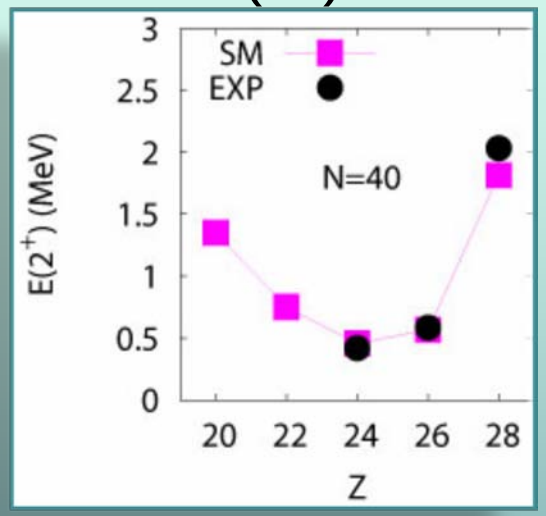




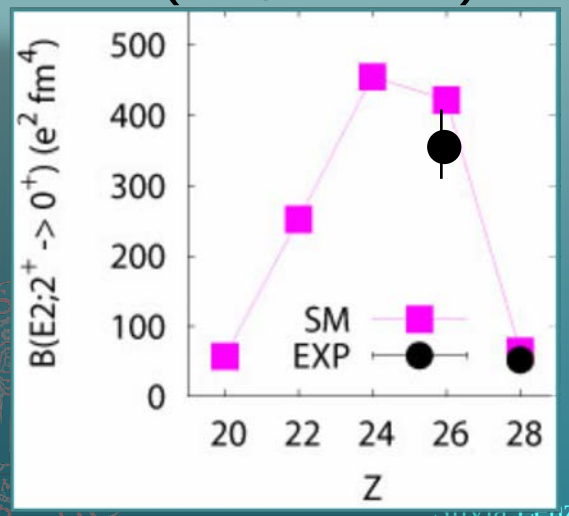
Note: the ground-state deformation properties result from the total balance between the monopole and the correlation energies

The N=40 isotones

E (2^+)



B($E2;2^+ \rightarrow 0^+$)



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

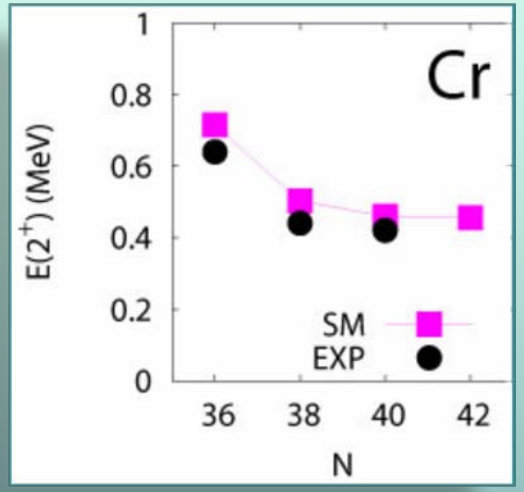
Occupation of intruder orbitals and percentage of p-h configurations

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

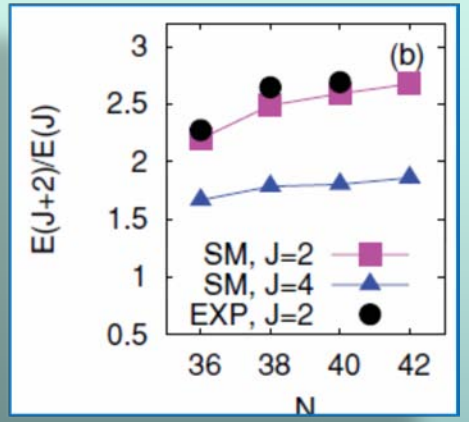
SML, F. Nowacki, A. Poves and K. Sieja, PRC 82, 054301 (2010)

Cr isotopes

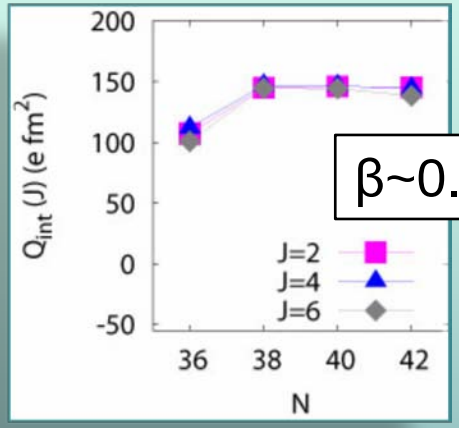
E (2^+)



E(J+2)/E(J)



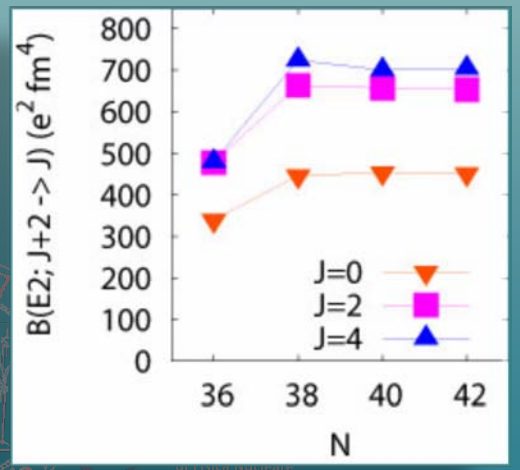
$Q_{int}(J)$



β~0.35

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

B(E2)



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

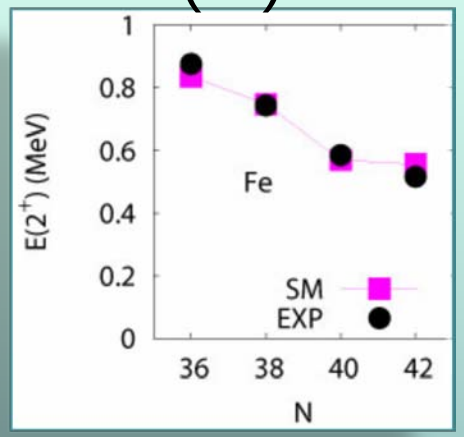
$K \neq \frac{1}{2}, 1.$

The deformation stabilizes at N=38.
The intrinsic quadrupole moment obtained from the B(E2) and Q_{spec} coincide.

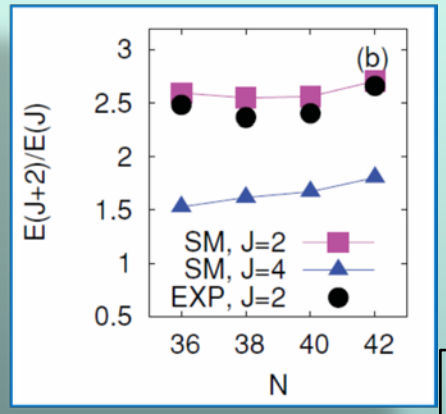
SML, F. Nowacki, A. Poves and K. Sieja, PRC 82, 054301 (2010)

Fe isotopes

$E(2^+)$

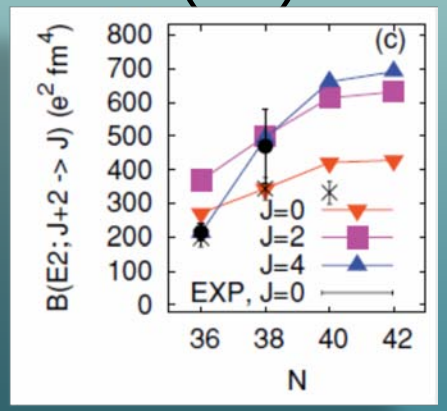


$E(J+2)/E(J)$

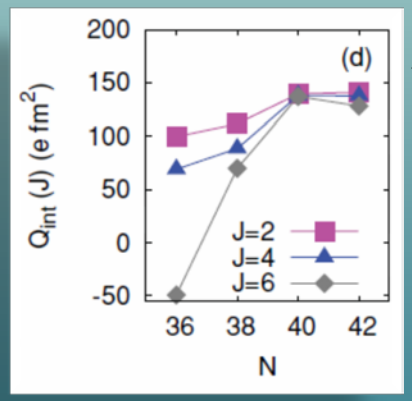


Good rotor behavior starts at N=40 in Fe

$B(E2)$



$Q_{int}(J)$

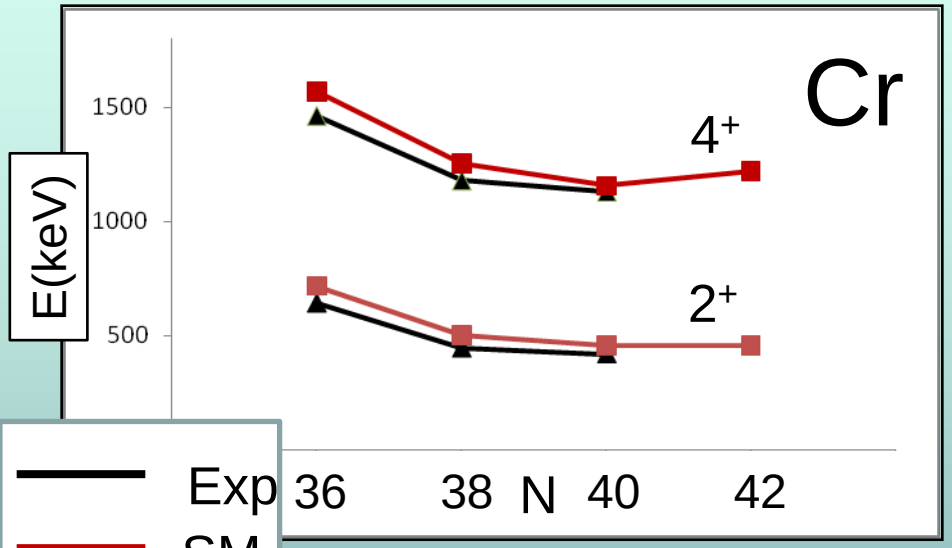


β~0.3

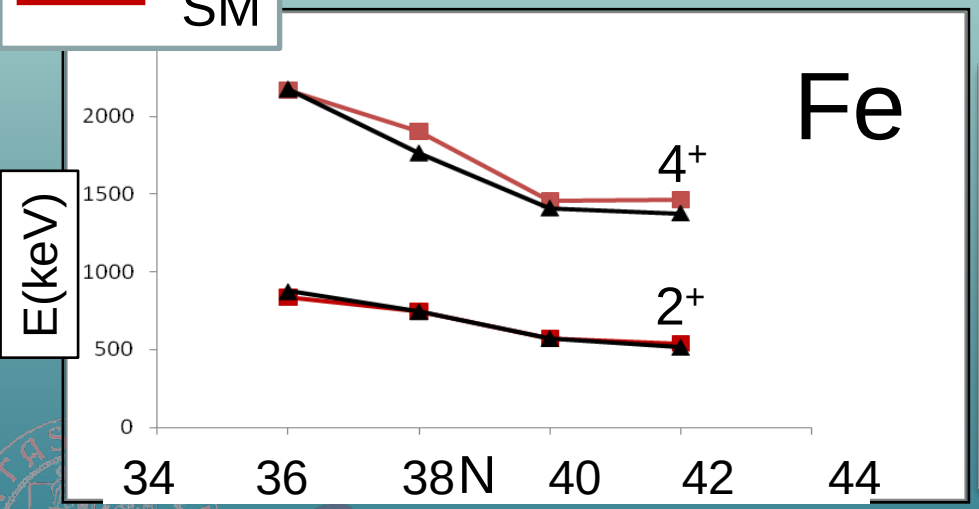
DATA:
J. Ljungvall et al., Phys. Rev. C 81, 061301 (2010).
W. Rother et al., arXiv:1006.5297.

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

Description of Cr an Fe around N=40



Exp
SM



Calculations with the LNPS interaction and the code Antoine:

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

The deformation stabilizes at N=38 in Cr and at N=40 in Fe

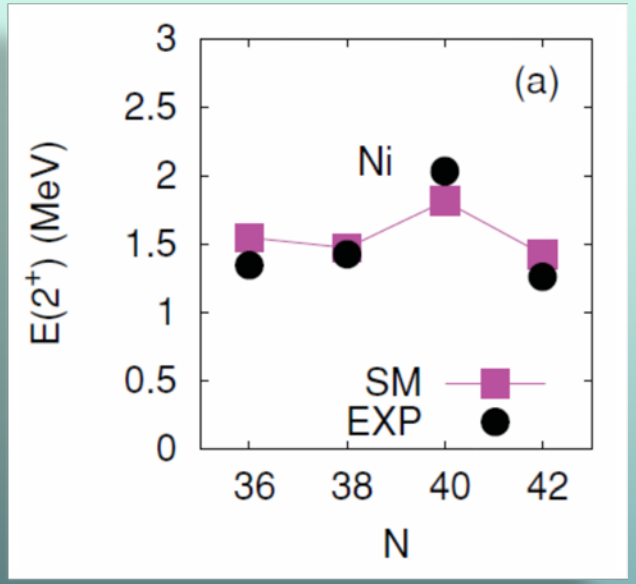
Occupation of intruder orbitals

Nucleus	N	$\nu 0g_{9/2}$	$\nu 1d_{5/2}$
^{62}Fe	36	0.95	0.12
^{64}Fe	38	2.0	0.27
^{66}Fe	40	3.22	0.51
^{68}Fe	42	2.30	0.62
^{60}Cr	36	1.55	0.31
^{62}Cr	38	2.77	0.66
^{64}Cr	40	3.41	0.76
^{66}Cr	42	2.28	0.90

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

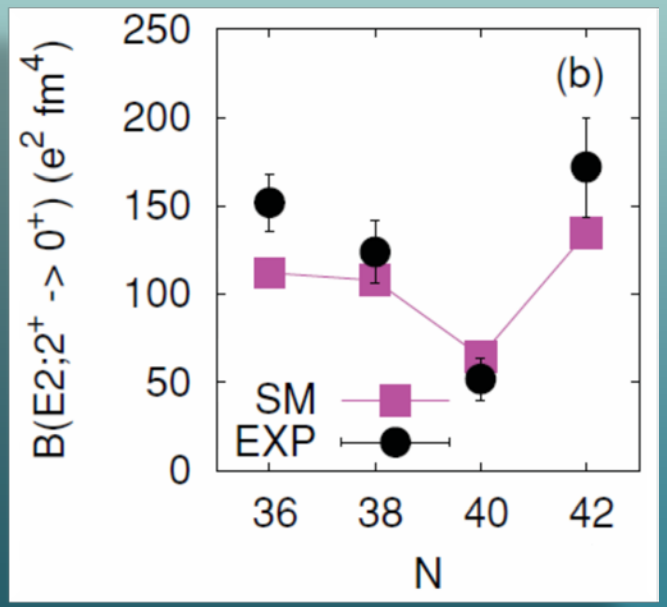
Ni isotopes

E(2$^+$)



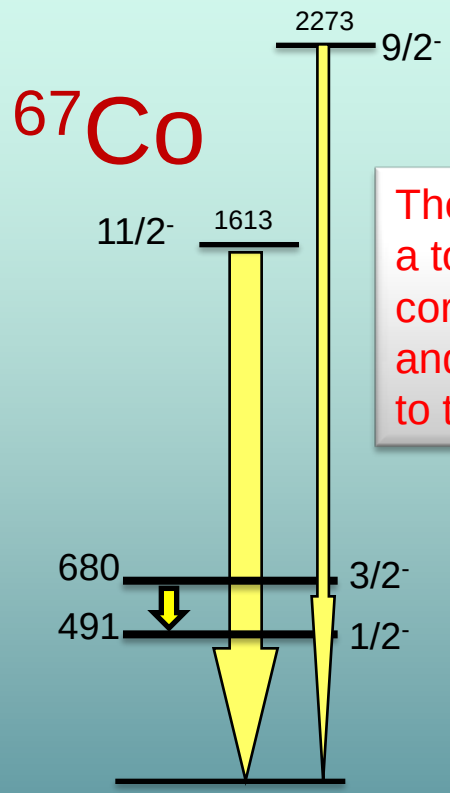
Energies and B(E2) trend are well reproduced

B(E2)

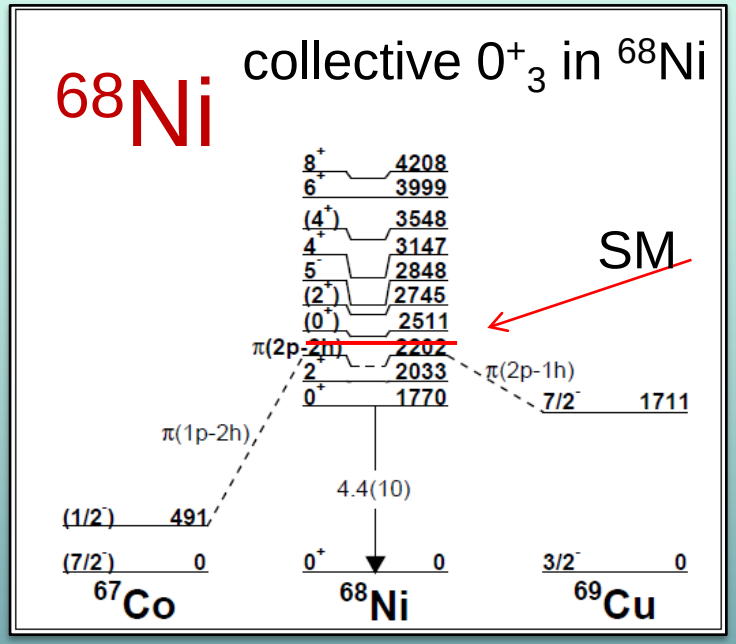


Better agreement with the experiment can be obtained in a full pf-shell calculation as the neutron excitations from the $0f_{7/2}$ orbital are here more important than those through the N = 50 gap.

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., Phys.Rev. C 82, 027304 (2010)

67Co: F. Recchia et al., in preparation

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.

Complementary experimental techniques are needed to construct the level schemes.

The LNPS effective interaction in the fpgd space accounts for the monopole migrations and is able to describe the rapid changes of structure, the development of quadrupole collectivity and shape coexistence phenomena in this third island of inversion.

The progress in algorithms and computer power have made it possible to achieve the largest shell-model diagonalizations in this region of nuclei up to date.

Measurement of transition probabilities is needed to study the evolution of deformation and will provide a stringent test for these theoretical predictions.

Collaboration

Theory:

F. Nowacki, A. Poves, K. Sieja

Experiments:

F. Recchia, S. Lunardi, D. Bazzacco, E. Farnea, J.J. Valiente-Dobon, D.R. Napoli, G. de Angelis, A. Gadea, N. Marginean, 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.*