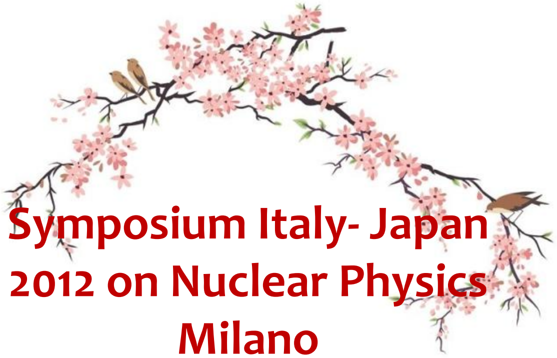
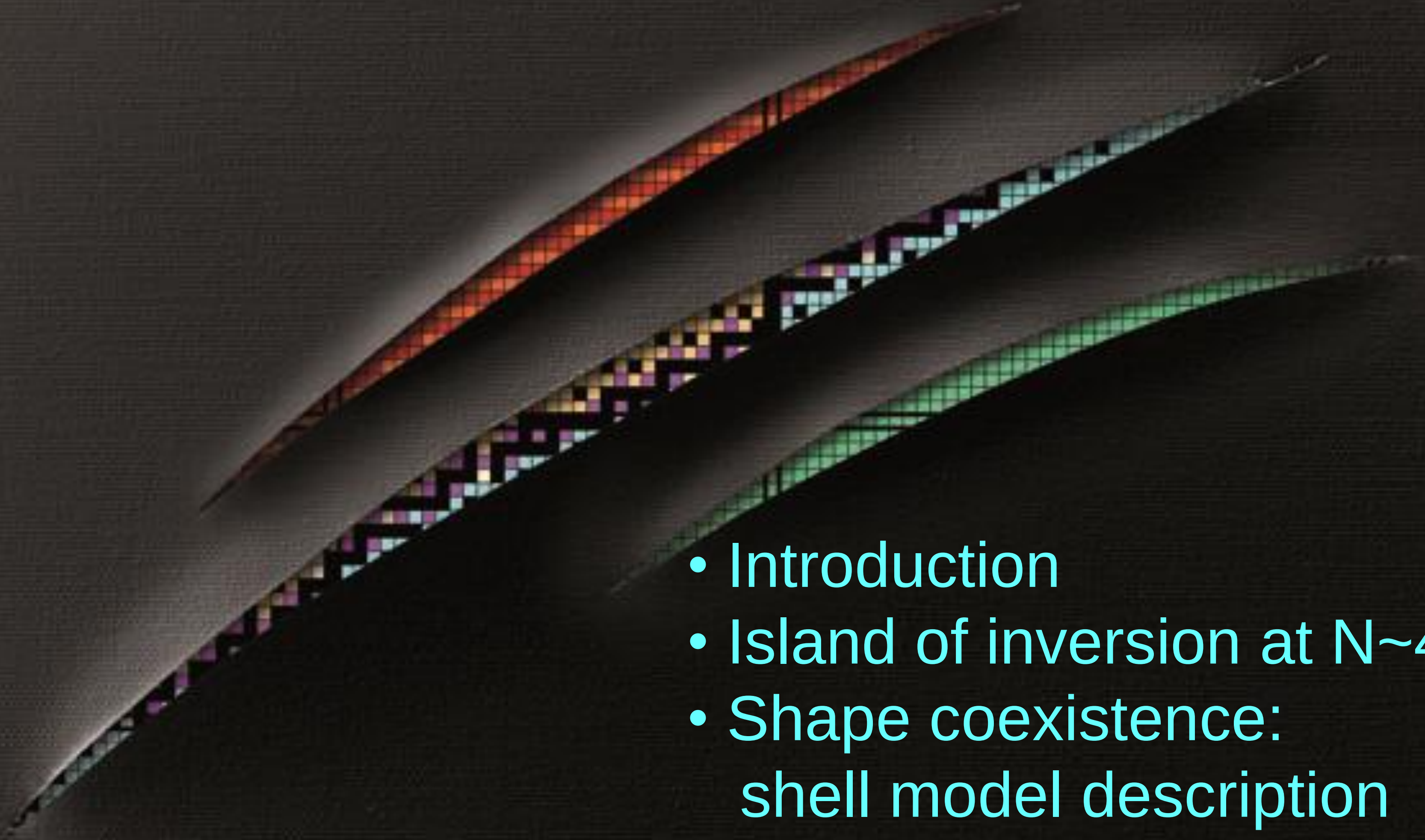
Nuclear structure far from stability



Symposium Italy- Japan 2012 on Nuclear Physics Milano

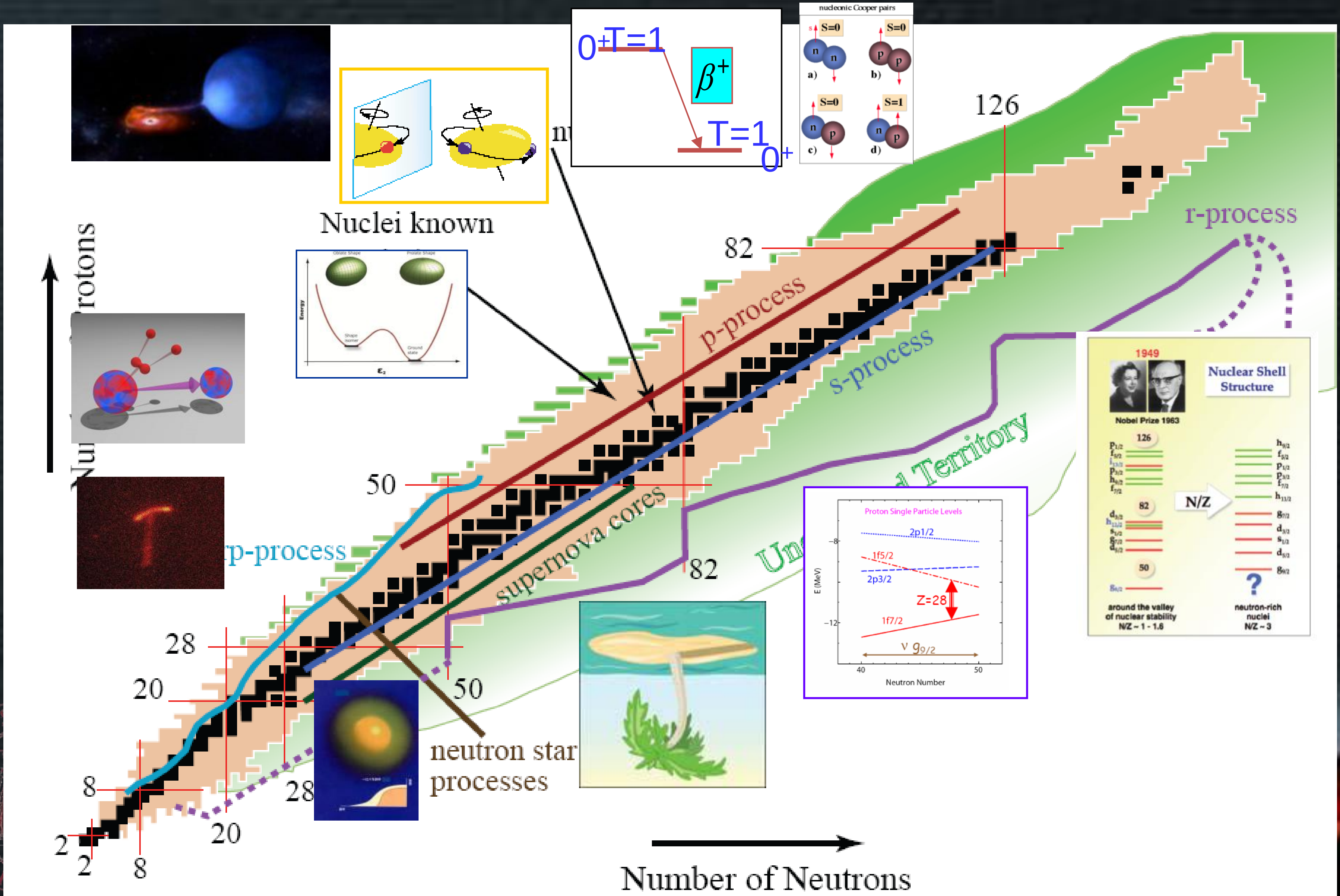
Silvia M. Lenzi
Department of Physics and Astronomy "Galileo Galilei"
University of Padua and INFN

Outline



- Introduction
- Island of inversion at N~40
- Shape coexistence: shell model description
- Beyond Z=28, N=40
- Conclusions

New phenomena far from stability

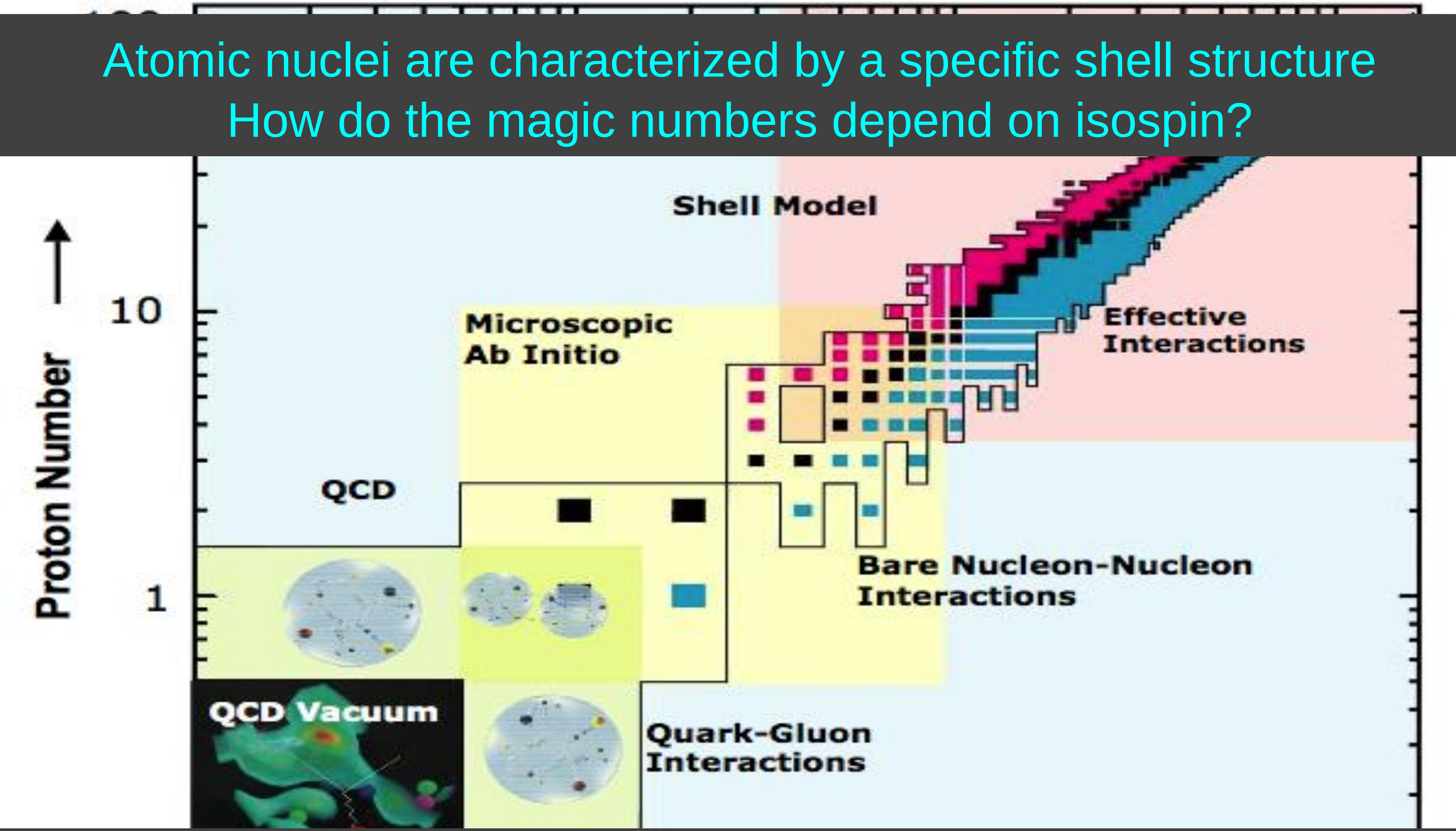


The neutron-rich side

- How does the shell structure change far from stability?
- How do new regions of deformation develop at “magic” numbers?
- How does the effective interaction describe shape evolution and shape coexistence?
- Will new excitation/decay modes be observed far from stability?
- New dynamical symmetries or new shapes?
- Connection with Astrophysics

Nuclear forces and shell evolution

Atomic nuclei are characterized by a specific shell structure
How do the magic numbers depend on isospin?



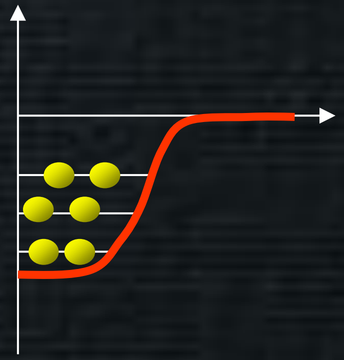
Data on exotic nuclei put in evidence the role of specific terms of the nuclear interaction and demand an improved modelling

The effective interaction

A multipole expansion

$$V = V_m + V_M$$

monopole Multipole

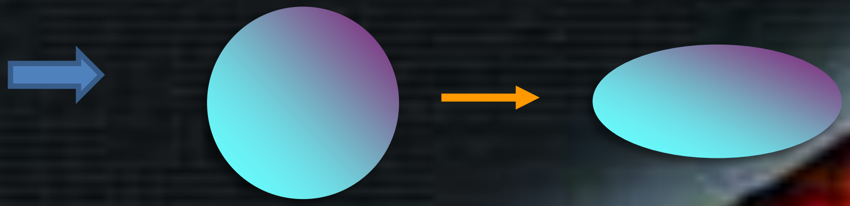


$$V_m$$

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

$$V_M$$

- correlations
- energy gains


Deformation

Understanding monopole effects

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

$$V^{T}_{jj'} = \frac{\sum_J (2J+1)\langle jj'|V|jj'\rangle_{JT}}{\sum_J (2J+1)}$$

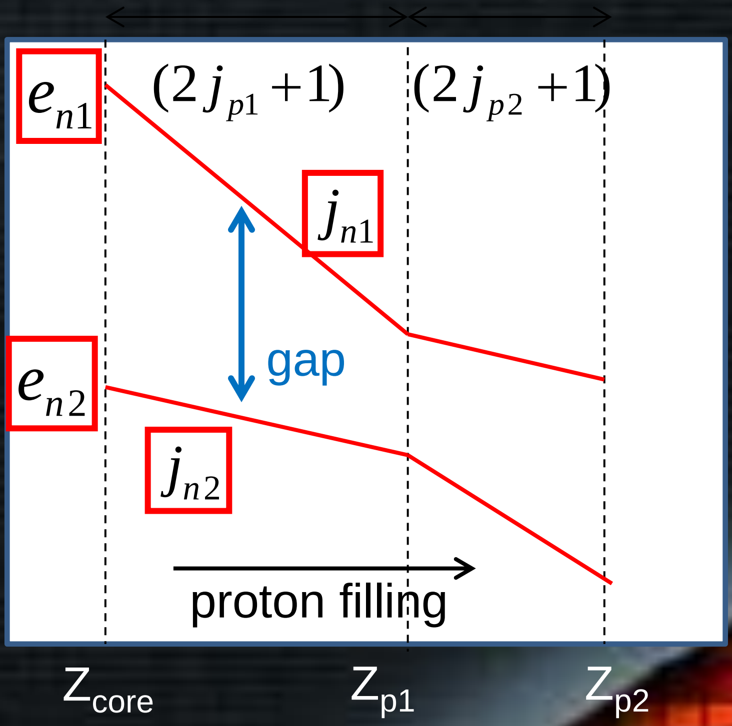
→ **Averaged over possible orientations**

As the orbit *j'* becomes occupied, the single-particle energy of an orbit *j*, e_j changes linearly:

$$\boxed{\Delta e_j = V_{jj'} n_{j'}}$$

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

O. Sorlin and M.G. Porquet
PPNP 61 (2008) 602-673

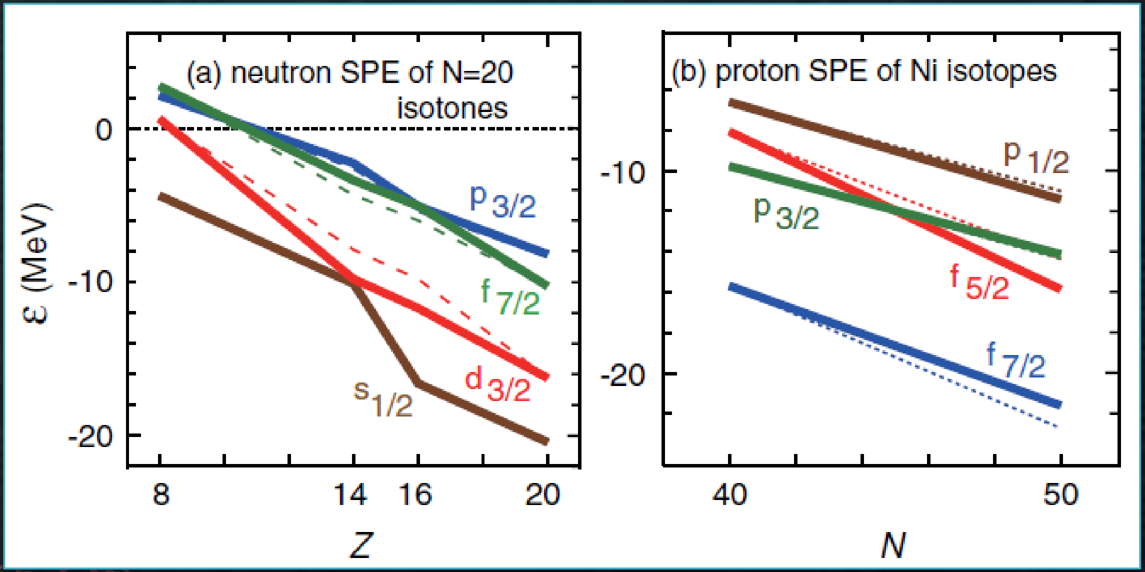


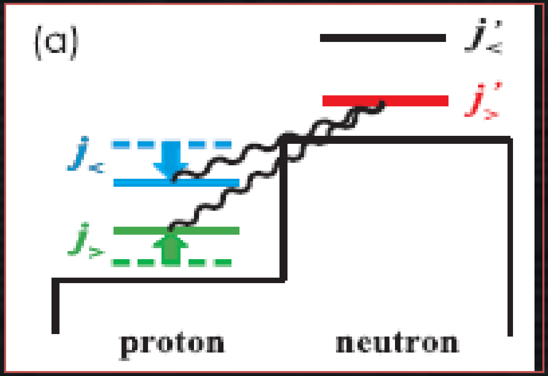
The monopole tensor force and the spe

Central part: global variation of the single-particle energies
Tensor part: characteristic behavior of spin–orbit partners, etc.

╍╍╍╍╍╍╍╍ only central
━━━━━━━━ central + tensor

$$j_> = l + \tfrac{1}{2}$$
$$j_< = l - \tfrac{1}{2}$$





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

Interplay: Monopole and Multipole

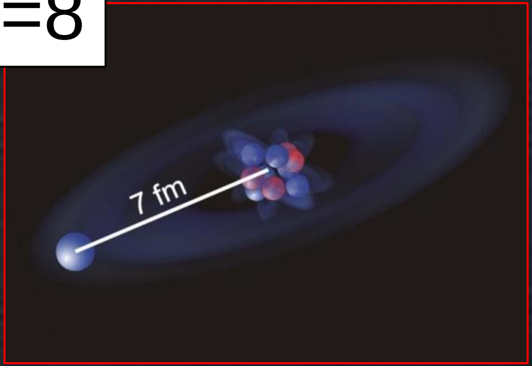
The interplay of the monopole with multipole terms, like pairing and quadrupole, determines the different phenomena we observe.

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

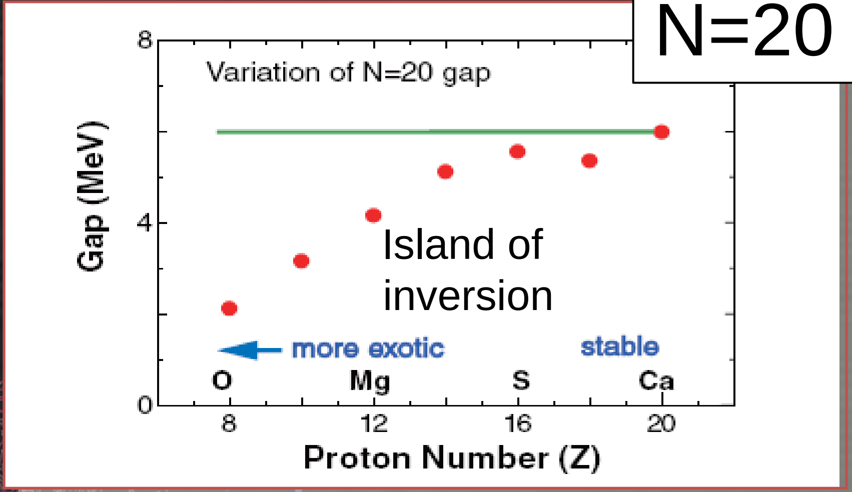
At N=8 and N=20 the h.o. shell gap vanishes for very neutron rich nuclei.

N=8



Deformed intruder configurations fall below the spherical ones

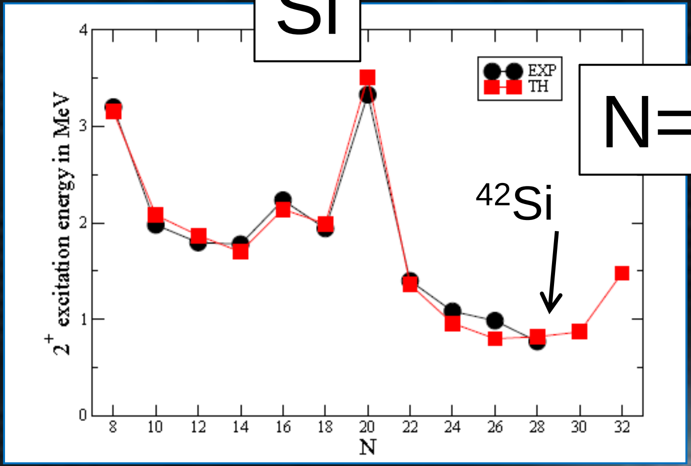
N=20



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

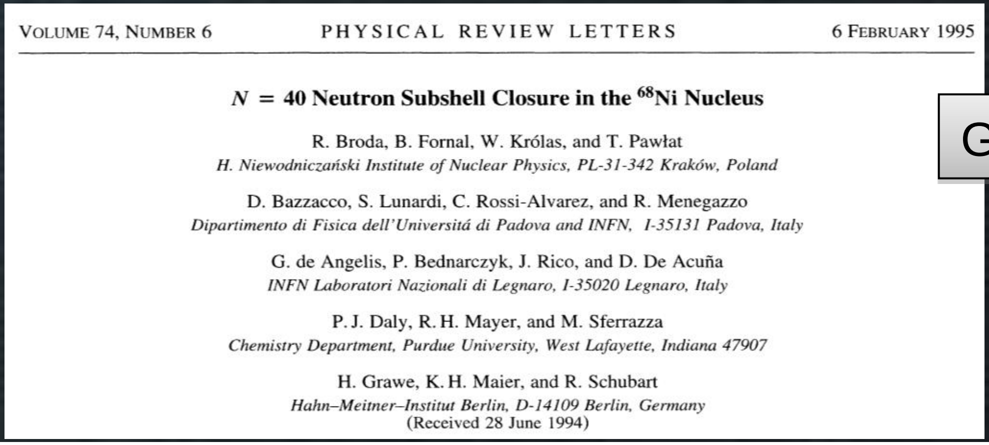
Si

N=28



A. Poves, 2011

Subshell closure at N=40



VOLUME 74, NUMBER 6 PHYSICAL REVIEW LETTERS 6 FEBRUARY 1995

N = 40 Neutron Subshell Closure in the ^{68}Ni Nucleus

R. Broda, B. Fornal, W. Królas, and T. Pawłat
H. Niewodniczański Institute of Nuclear Physics, PL-31-342 Kraków, Poland

D. Bazzacco, S. Lunardi, C. Rossi-Alvarez, and R. Menegazzo
Dipartimento di Fisica dell'Universitá di Padova and INFN, I-35131 Padova, Italy

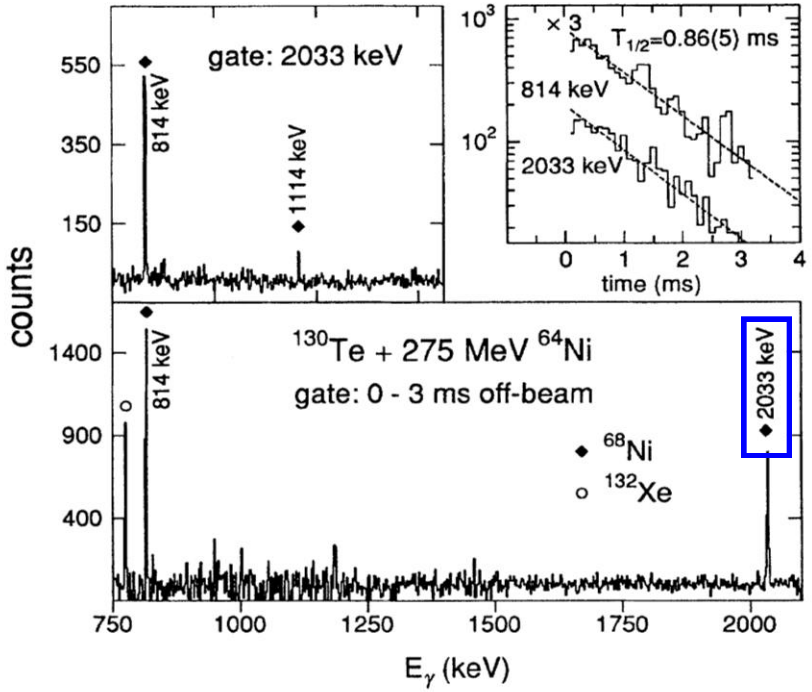
G. de Angelis, P. Bednarczyk, J. Rico, and D. De Acuña
INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy

P. J. Daly, R. H. Mayer, and M. Sferrazza
Chemistry Department, Purdue University, West Lafayette, Indiana 47907

H. Grawe, K. H. Maier, and R. Schubart
Hahn–Meitner–Institut Berlin, D-14109 Berlin, Germany
(Received 28 June 1994)

GASP (Legnaro) 1995

The increase of the ^{68}Ni 2$^+$ excitation energy indicates a significant shell closure at N=40



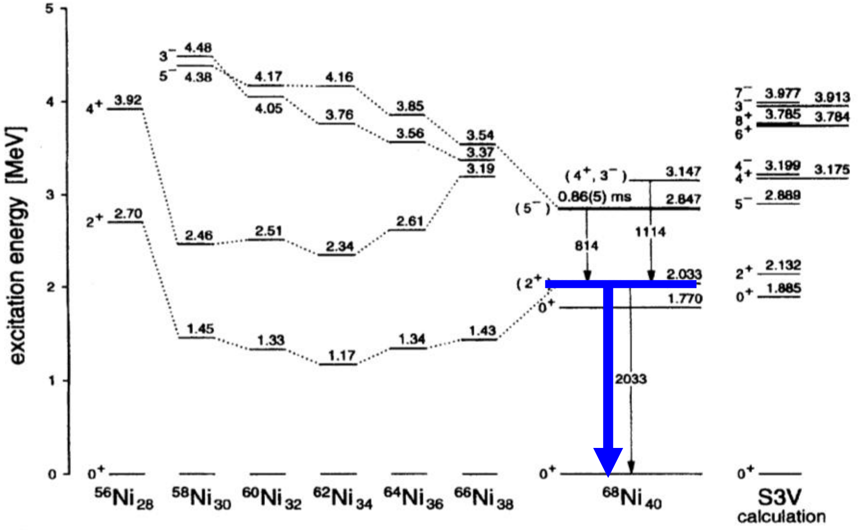
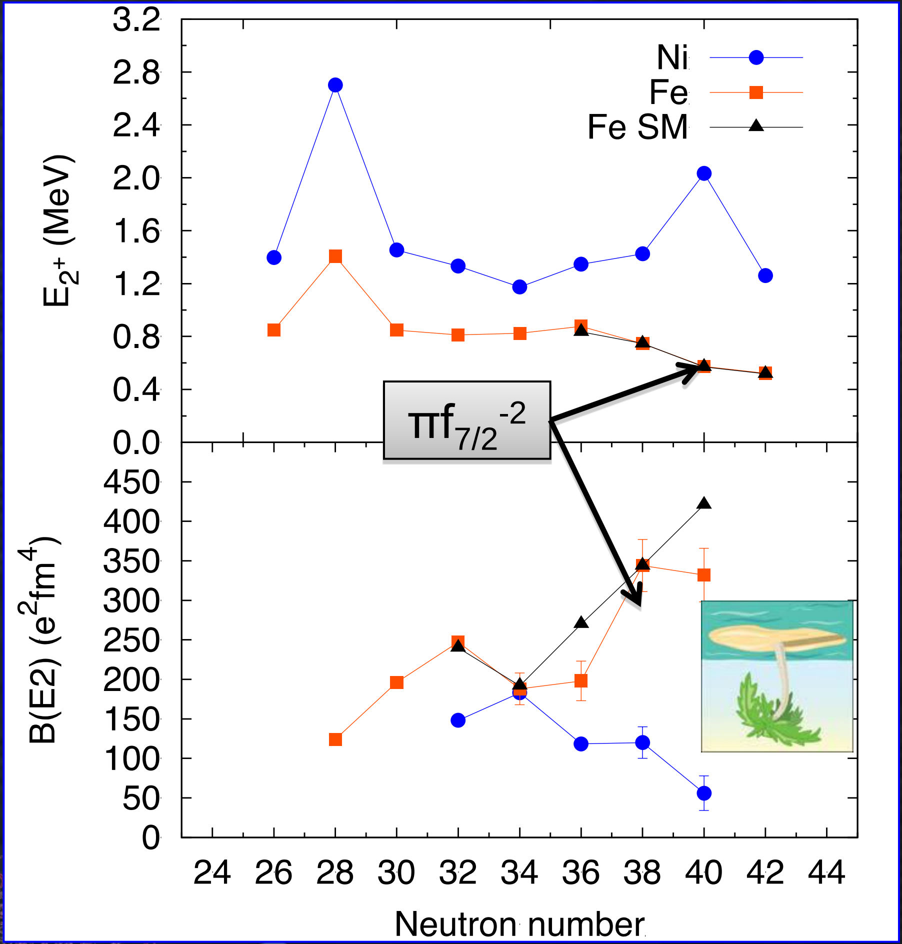
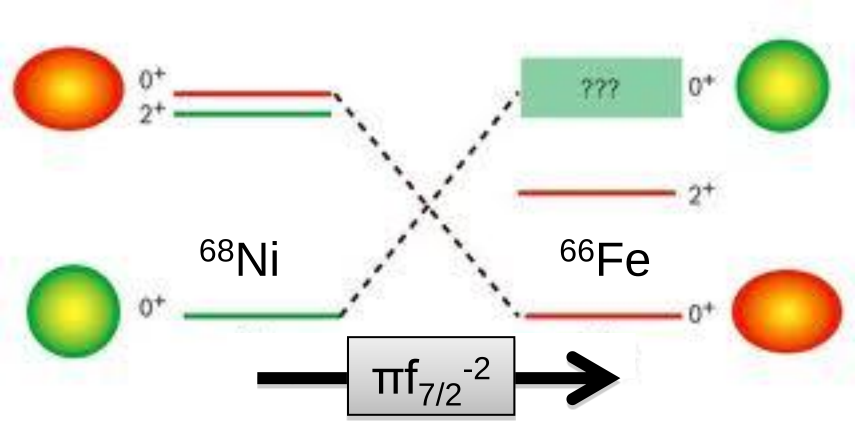


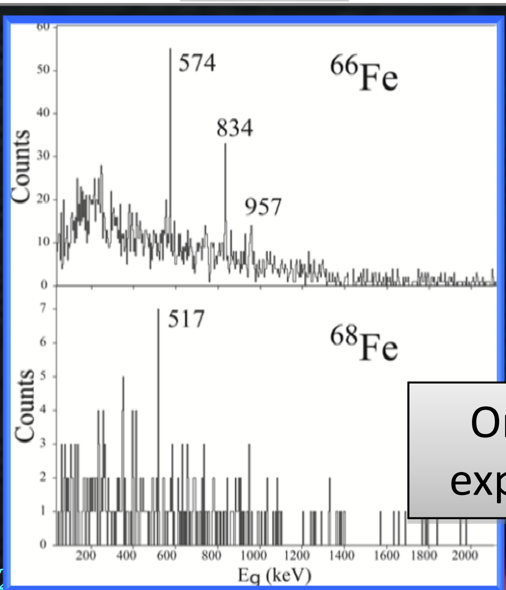
FIG. 3. Systematics of selected states in even Ni isotopes. The ^{68}Ni results are prominently displayed and compared with the S3V shell model calculations (see text).

New island of inversion at N=40



CLARA-PRISMA (Legnaro) 2007



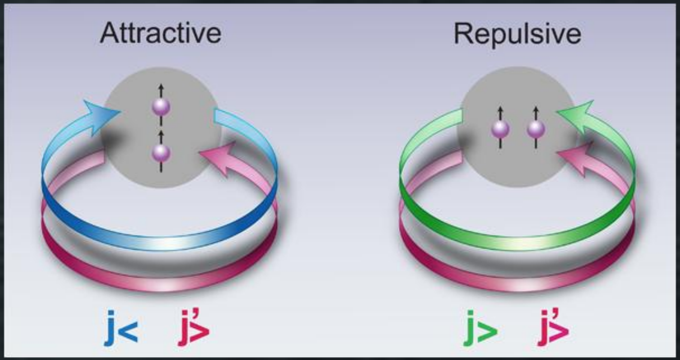


One week experiment.

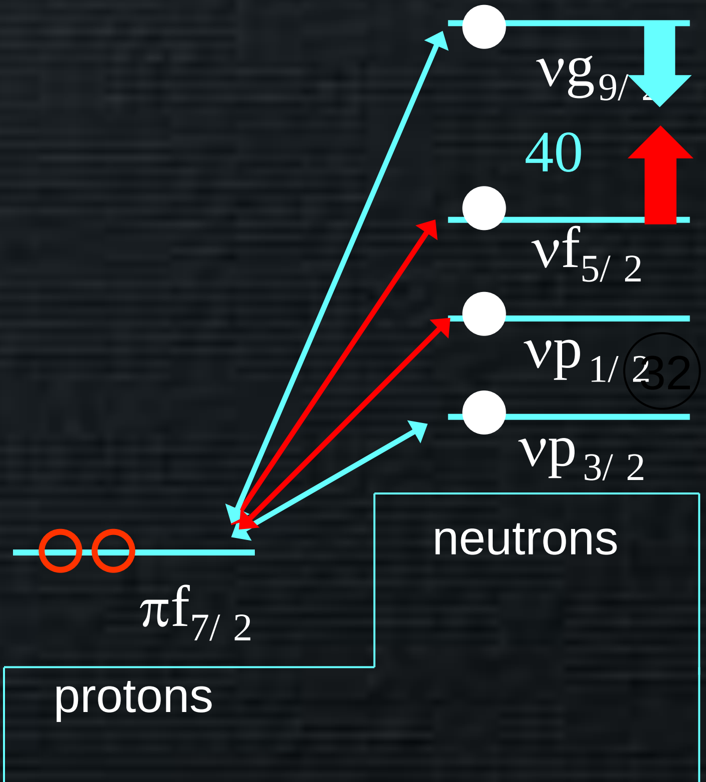
S. Lunardi et al., PRC**76**, 034303 (2007).
S. M. Lenzi et al., PRC**82**, 054301 (2010).
W. Rother et al., PRL106, 022502 (2011).

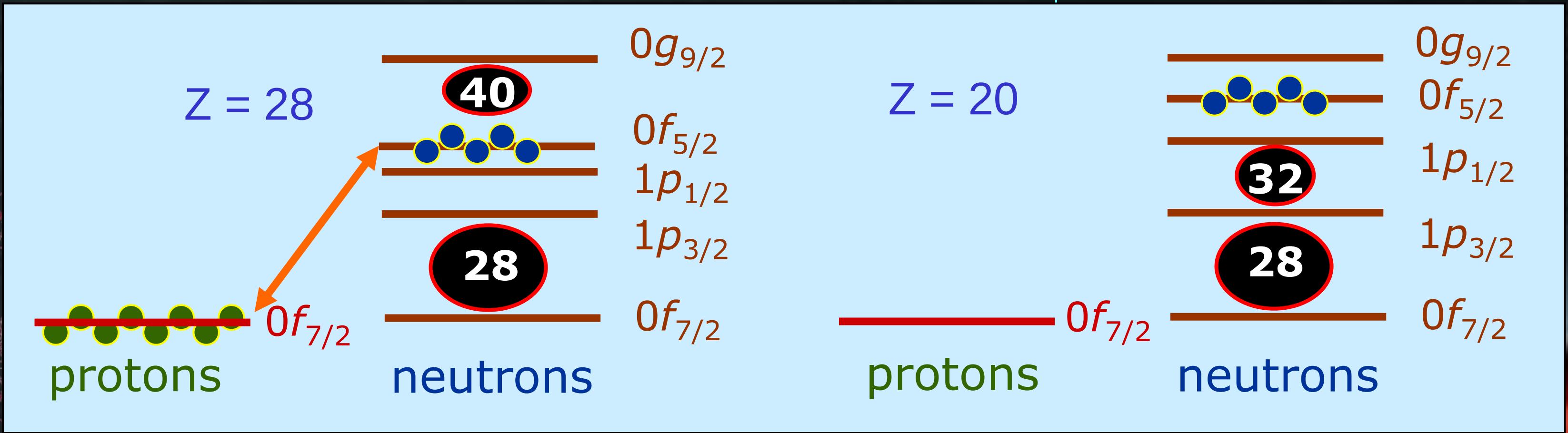
Neutron excess and shell migration

Monopole shifts



T. Otsuka

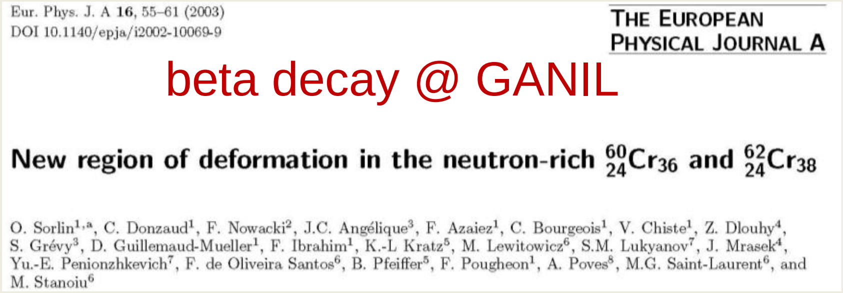




The island of inversion at N~40:

Cr and Fe isotopic chains

Cr isotopic chain: data



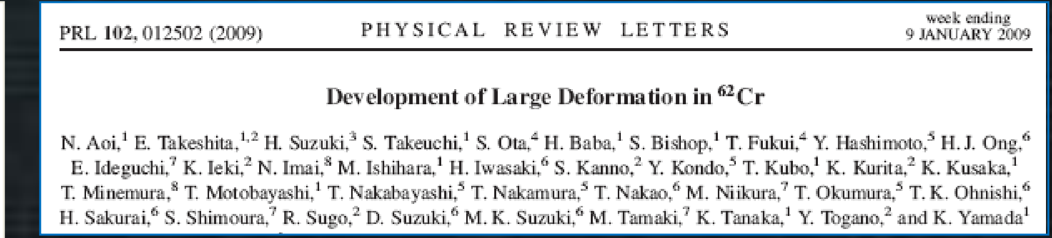
Eur. Phys. J. A **16**, 55–61 (2003)
DOI 10.1140/epja/i2002-10069-9

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]



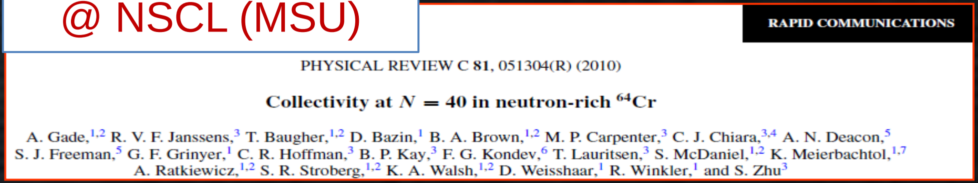
PRL **102,** 012502 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

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,[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)

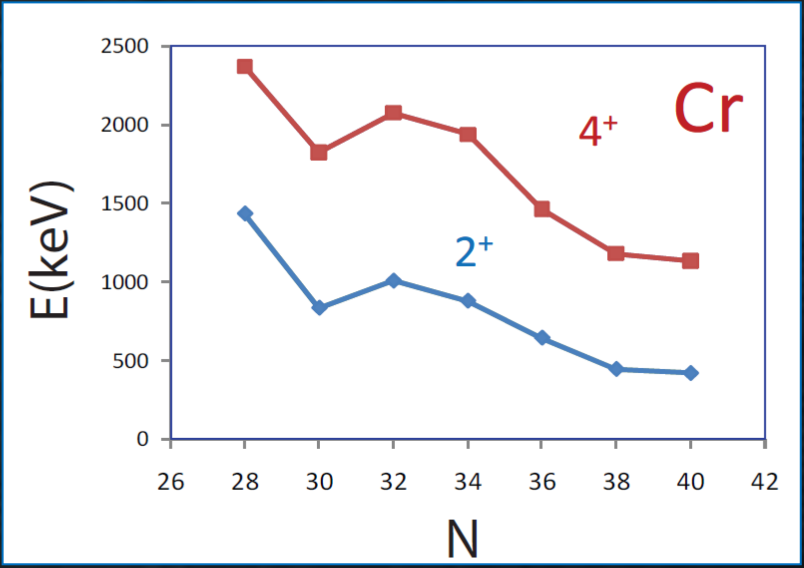


RAPID COMMUNICATIONS

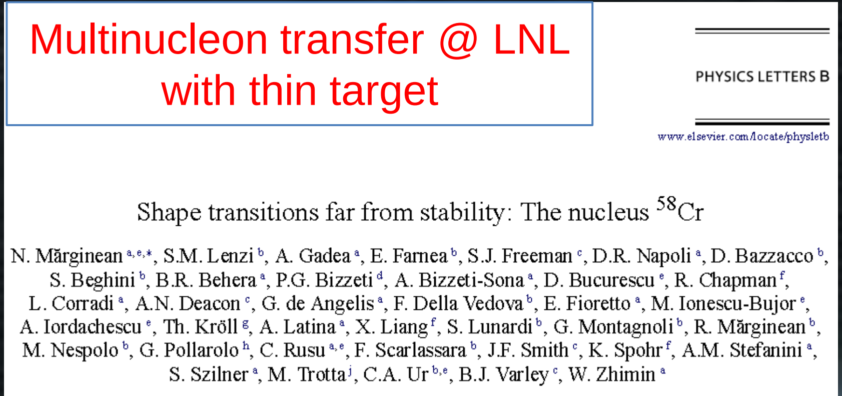
PHYSICAL REVIEW C **81**, 051304(R) (2010)

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]



Multinucleon transfer @ LNL with thin target



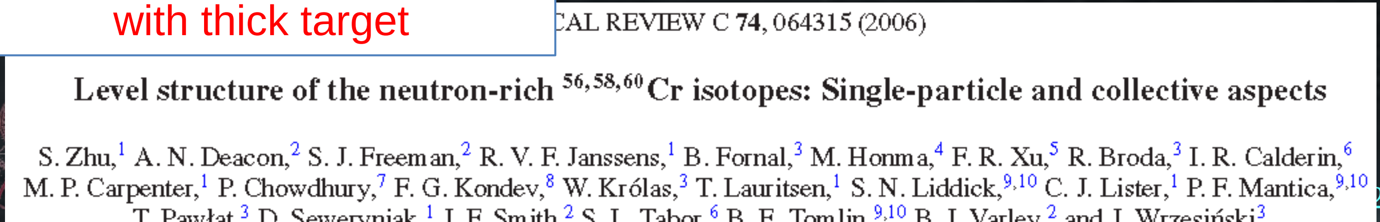
PHYSICS LETTERS B

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]

Multinucleon transfer @ ANL with thick target

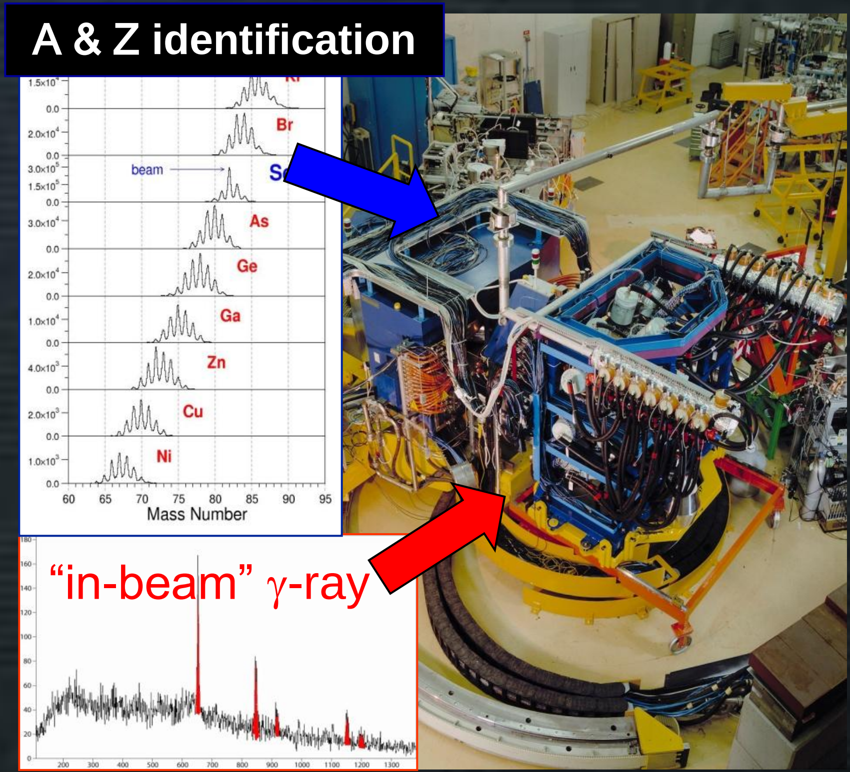


CAL REVIEW C **74**, 064315 (2006)

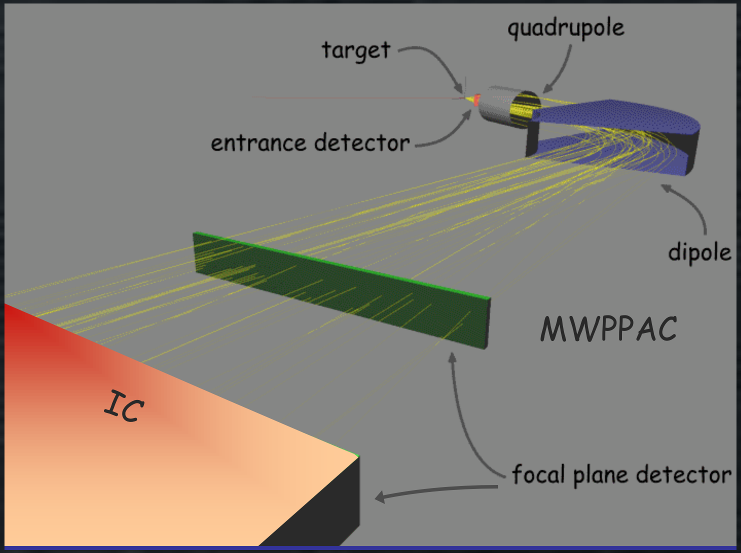
Level structure of the neutron-rich ^{56,58,60}Cr isotopes: Single-particle and collective aspects

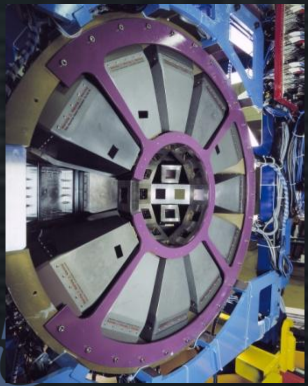
S. Zhu,[1] A. N. Deacon,[2] S. J. Freeman,[2] R. V. F. Janssens,[1] B. Fornal,[3] M. Honma,[4] F. R. Xu,[5] R. Broda,[3] I. R. Calderin,[6] M. P. Carpenter,[1] P. Chowdhury,[7] F. G. Kondev,[8] W. Królas,[3] T. Lauritsen,[1] S. N. Liddick,[9,10] C. J. Lister,[1] P. F. Mantica,[9,10] T. Pawłat,[3] D.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

The CLARA+PRISMA setup at Legnaro


A & Z identification

“in-beam” γ-ray





25 Euroball Clover detectors

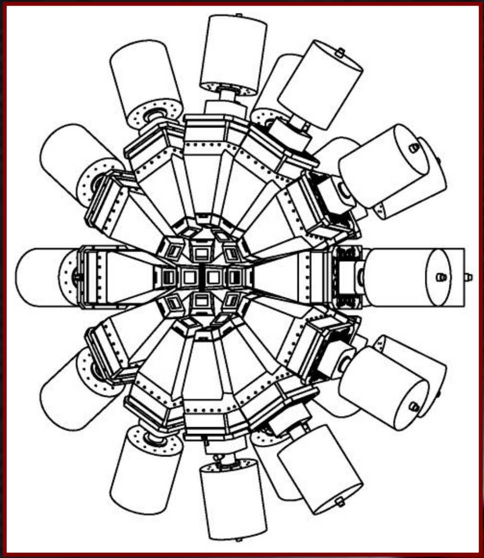
for Eγ= 1.3MeV

Efficiency ~ 3 %

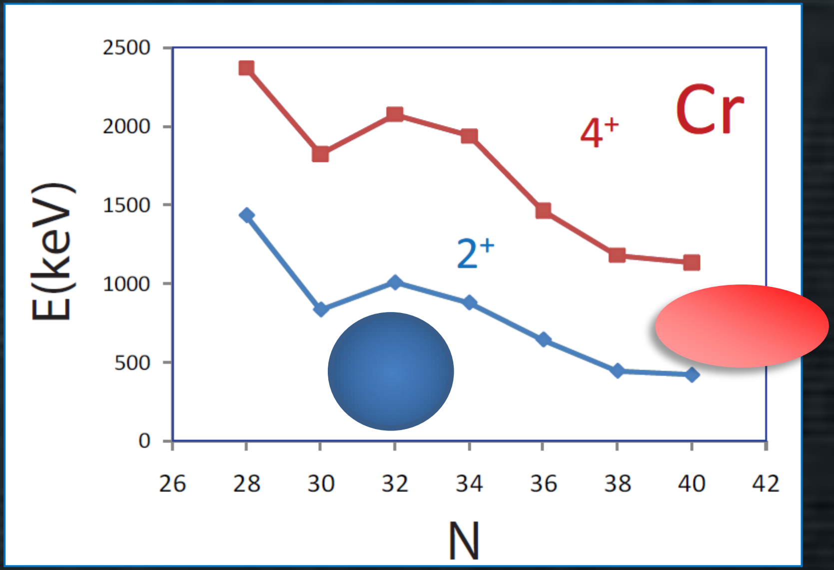
Peak/Total ~ 45 %

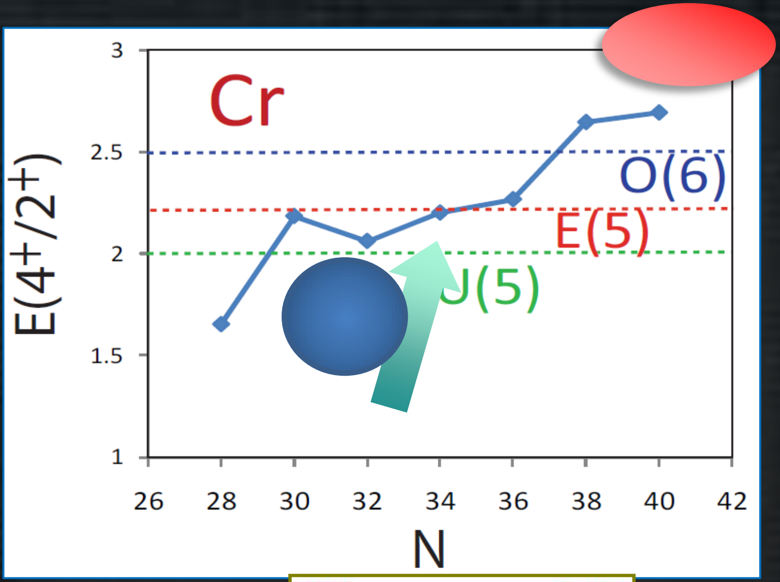
FWHM ~ 10 keV

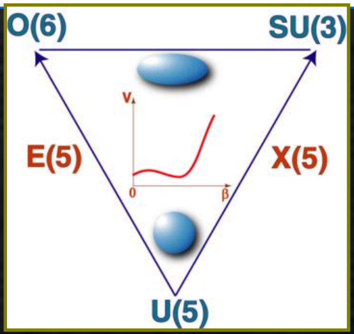
(at v/c = 10 %)



Cr isotopic chain







^{58}Cr

at the shape phase transition critical point?

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

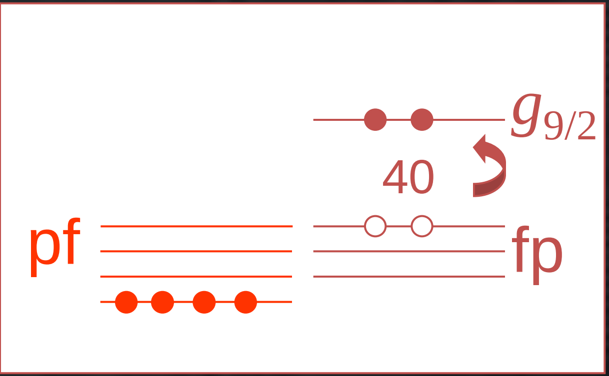
Recent plunger experiment at MSU to measure the lifetimes and test the E(5).

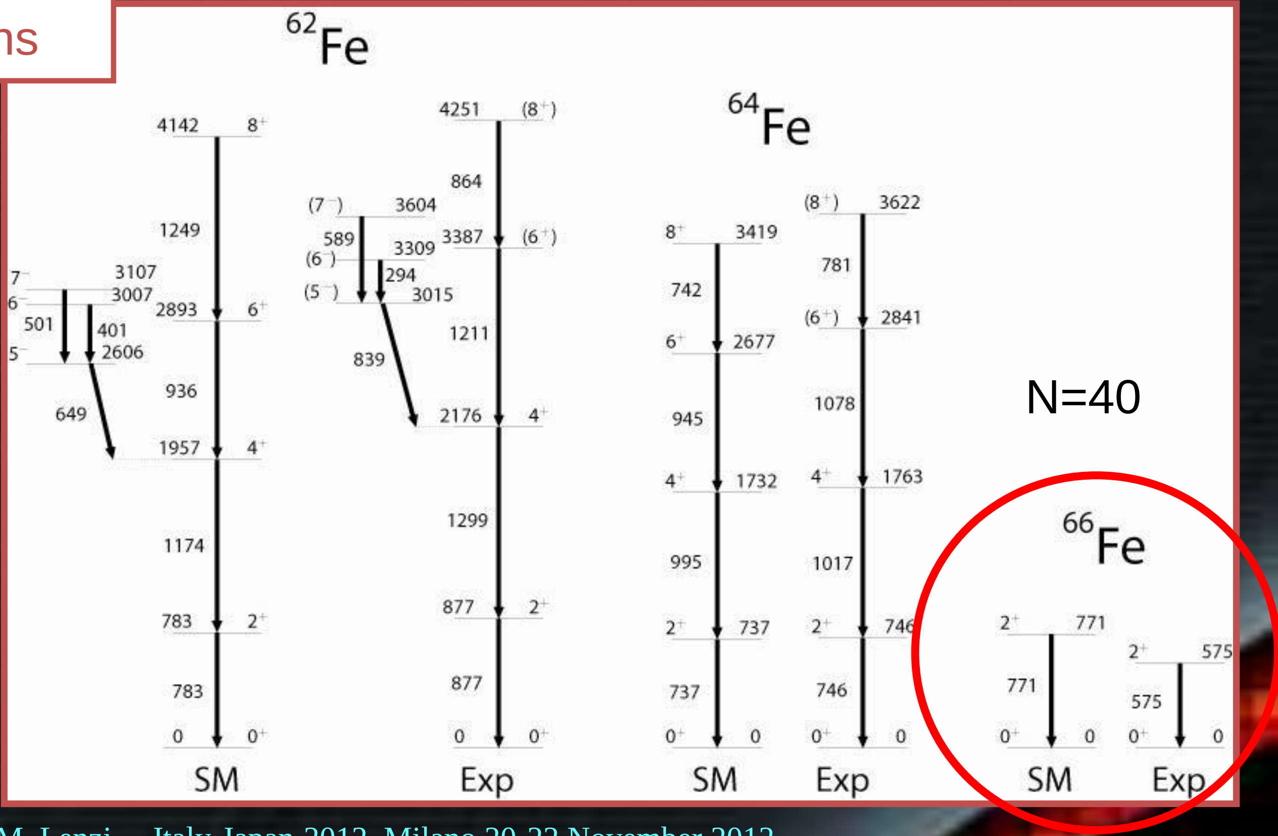
Fe isotopes and the shell model

Approaching N=40, Fe and Cr isotopes become deformed

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

The inclusion of the $g_{9/2}$ orbital is not enough to allow a good theoretical description of ^{66}Fe

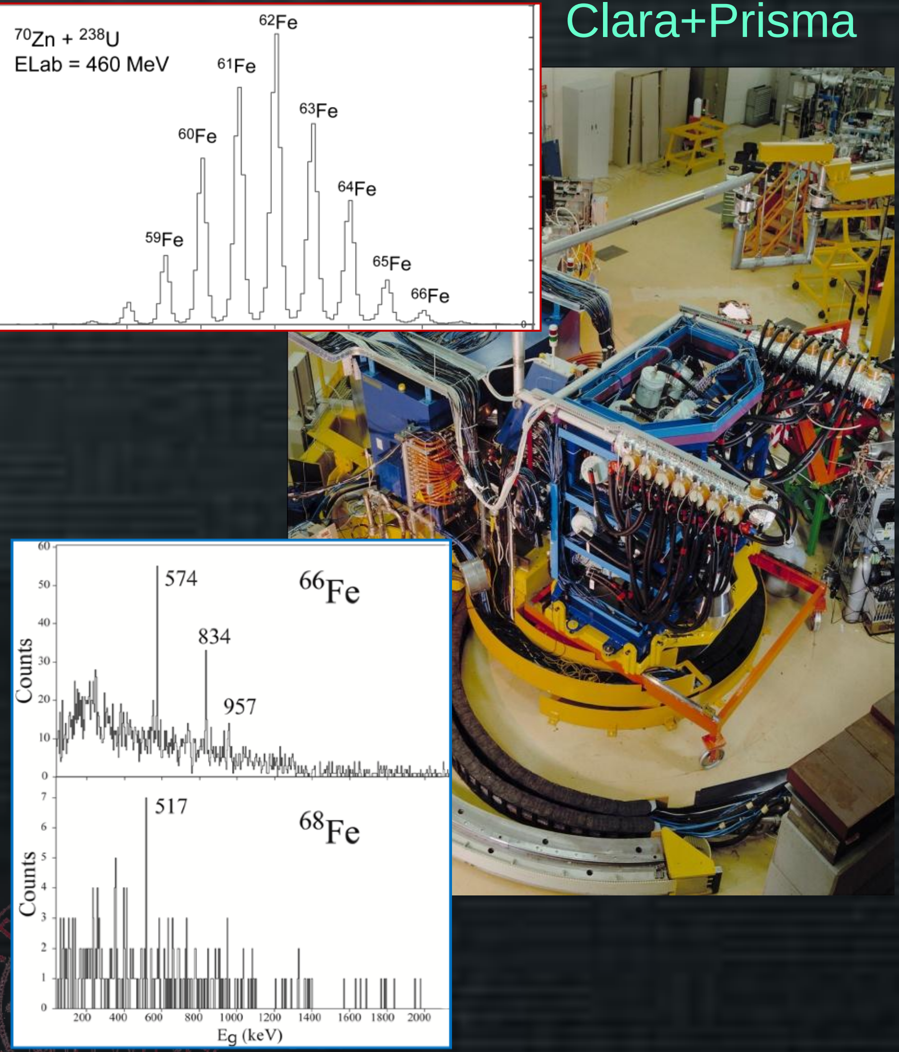


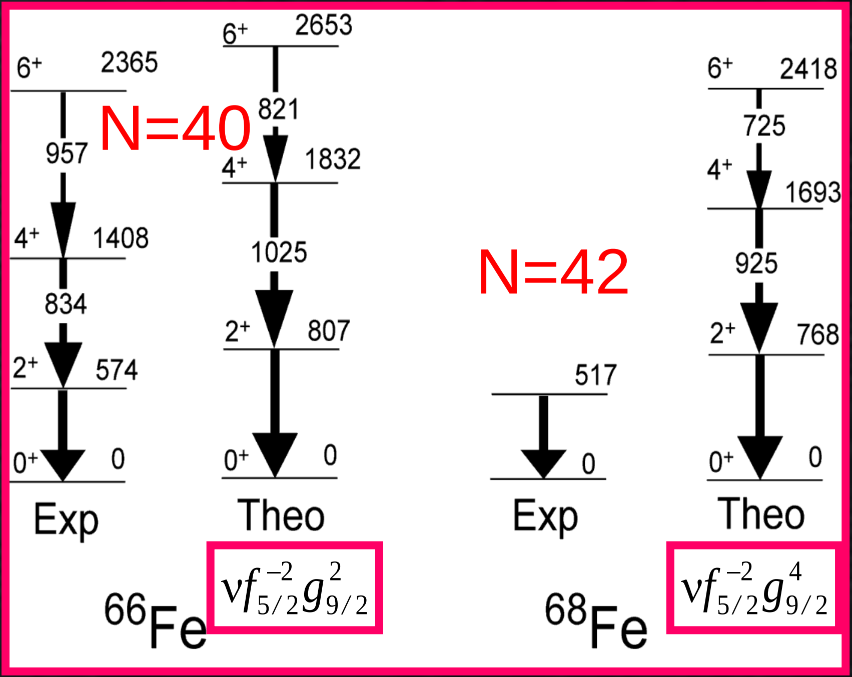


S. Lunardi *et al.*,
PRC **76**, 034303 (2007)

At and beyond N=40

Clara+Prisma

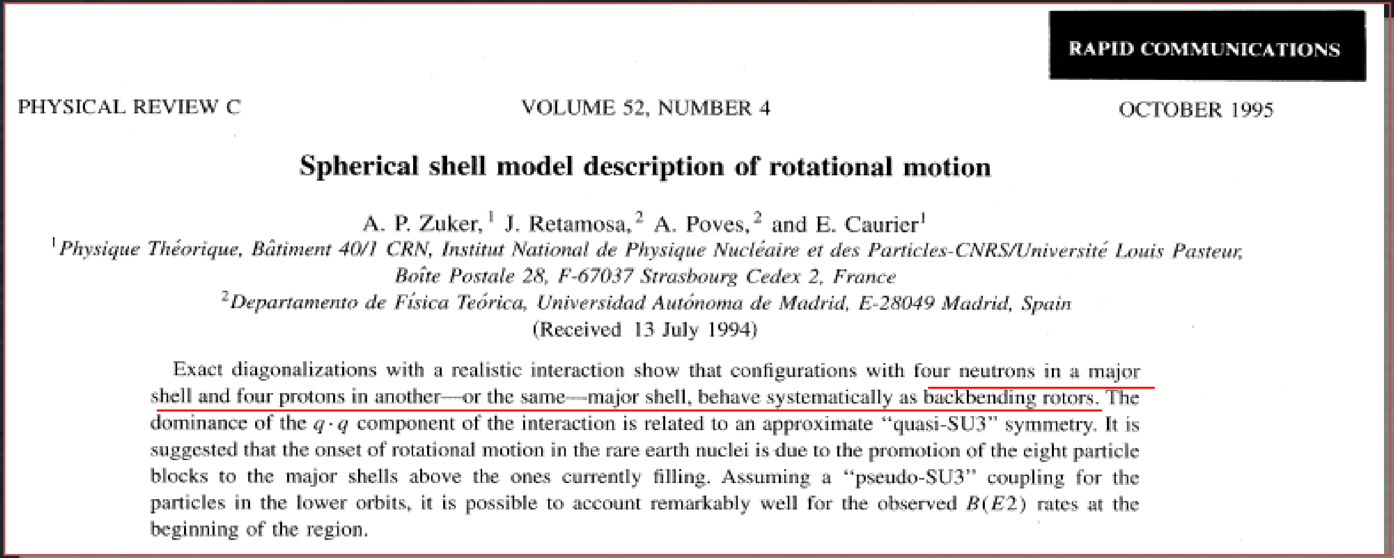




SML et al.,
LNL Ann. Rep. 2008

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

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]

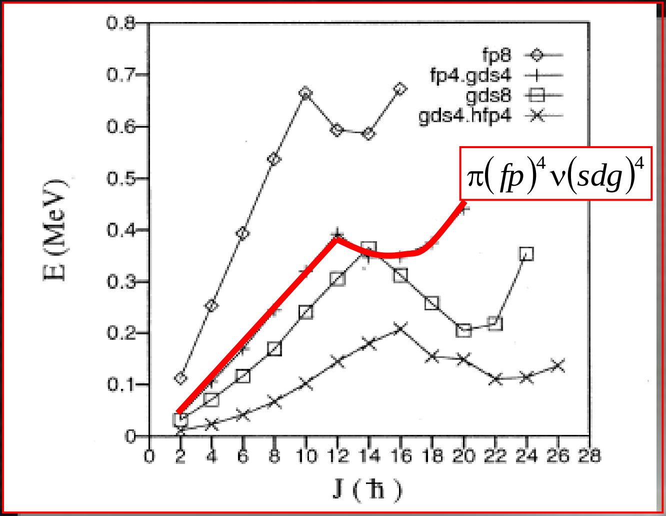
[1]*Physique Théorique, Bâtiment 40/1 CRN, Institut National de Physique Nucléaire et des Particles-CNRS/Université Louis Pasteur, Boîte Postale 28, F-67037 Strasbourg Cedex 2, France*

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

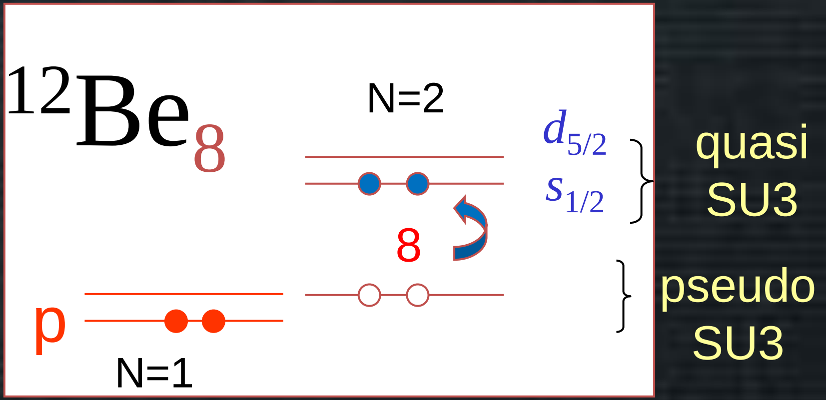
(Received 13 July 1994)

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.

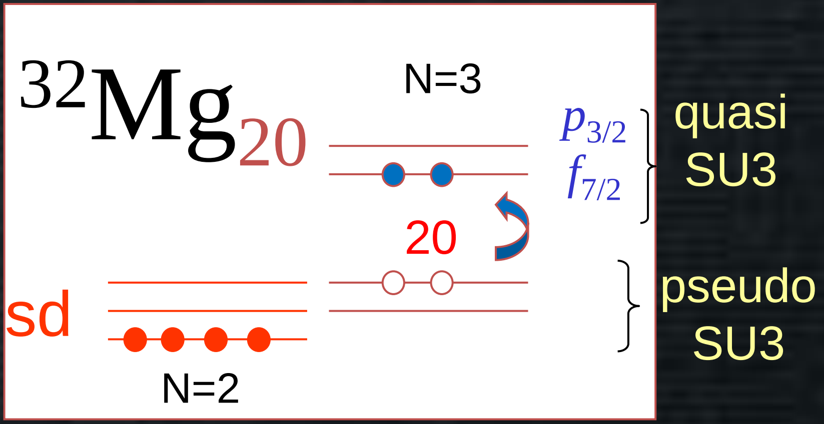
Rotational features are determined by the interplay of the quadrupole force with the central field in the subspace spanned by a sequence of Δj = 2 orbits that come lowest by the spin-orbit splitting.

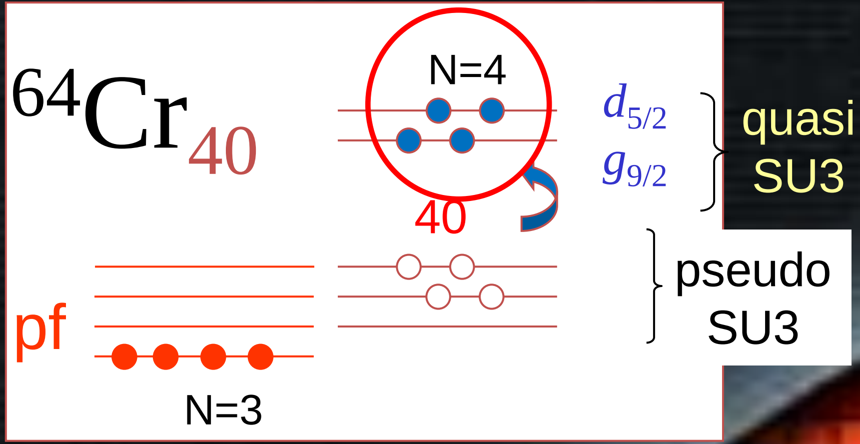


Islands of inversion and symmetries



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



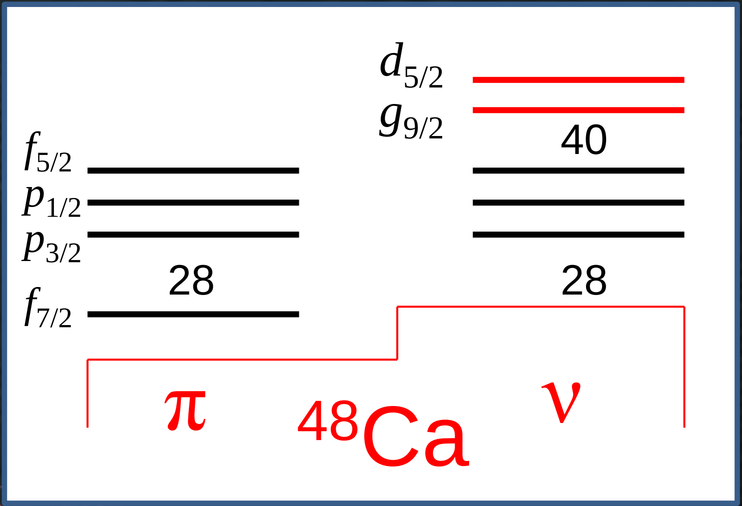


A.P. Zuker et al., PRC 52 (1995)

The new interaction in the fpgd space

LNPS interaction: renormalized realistic interaction
+ monopole corrections

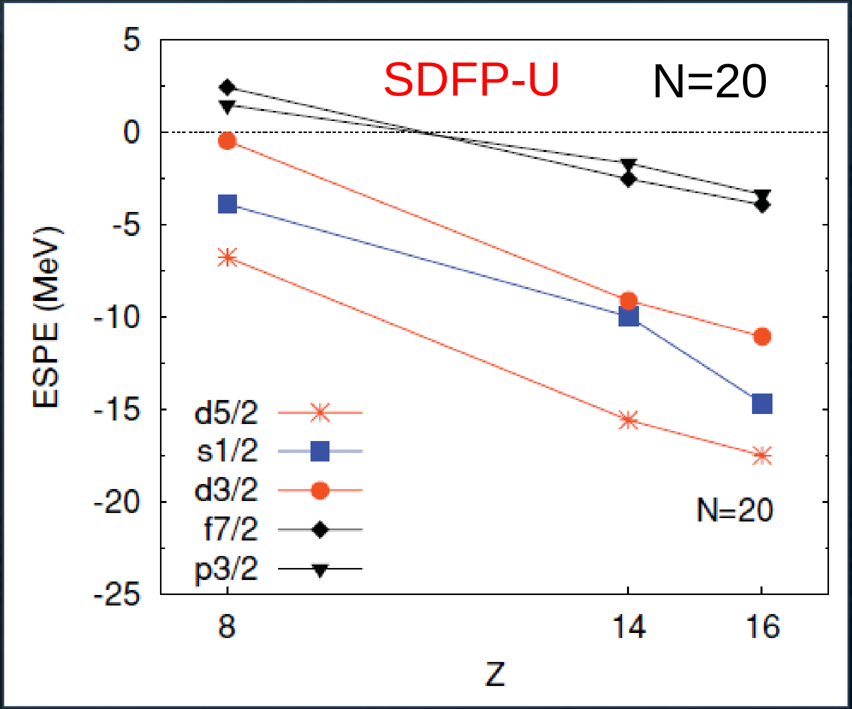
^{48}Ca core
protons: full pf shell
neutrons: $p_{3/2}$,$f_{5/2}$, $p_{1/2}$, $g_{9/2}$, $d_{5/2}$

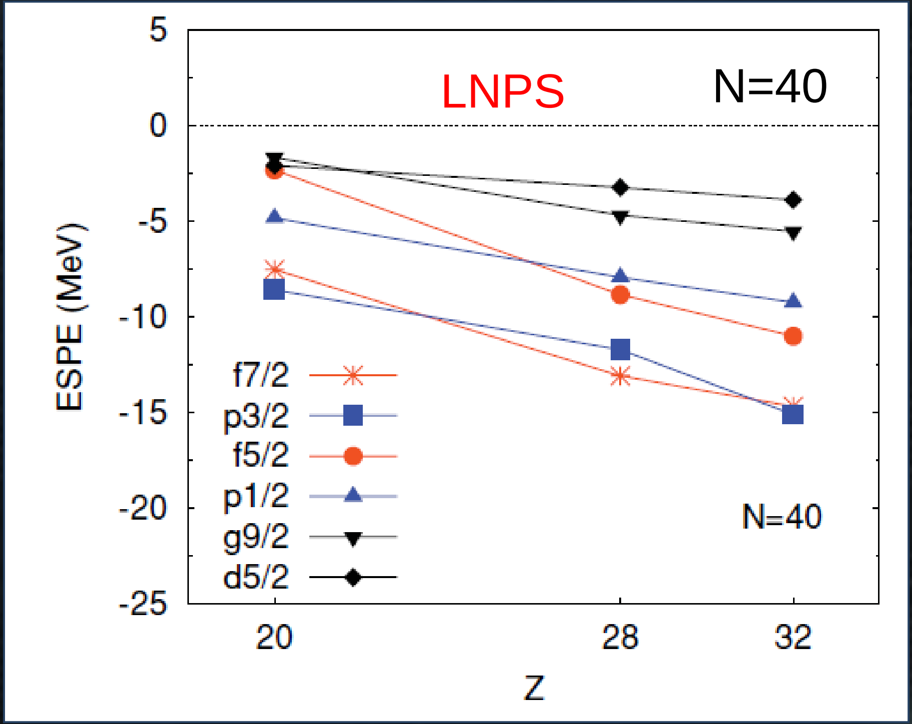


- KB3gr for the pf-shell
- renormalized G-matrix with monopole corrections for the remaining matrix elements involving the p3/2, p1/2, f5/2 and g9/2 neutron orbits
- the G-matrix based on the Kahana-Lee-Scott potential for the matrix elements involving the d5/2 orbit
- monopole corrections to reproduce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

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

ESPE in N=20 and N=40



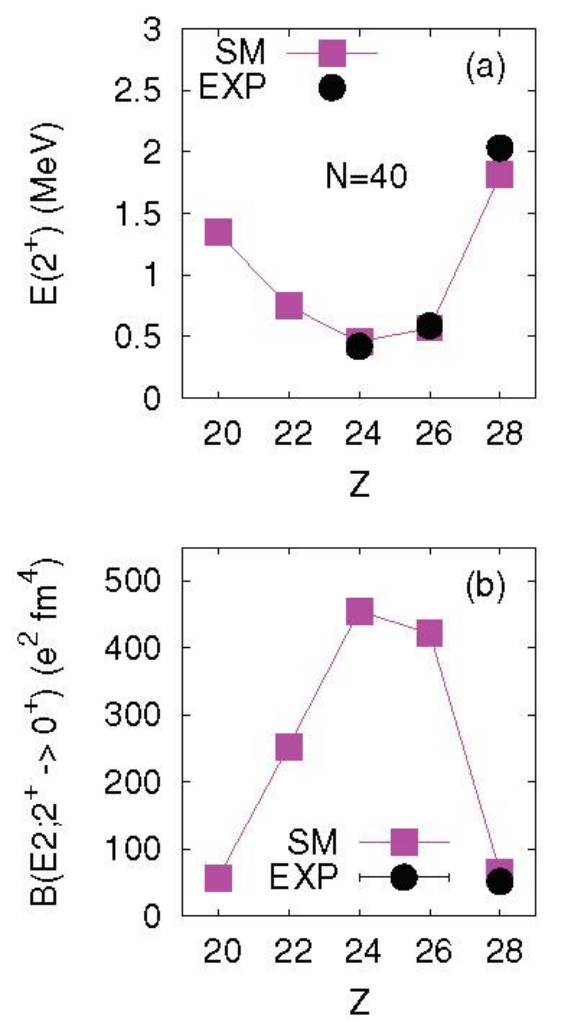


Note: the ground-state deformation properties result from the total balance between the monopole and the correlation energies

LNPS, PRC 82, 054301 (2010)

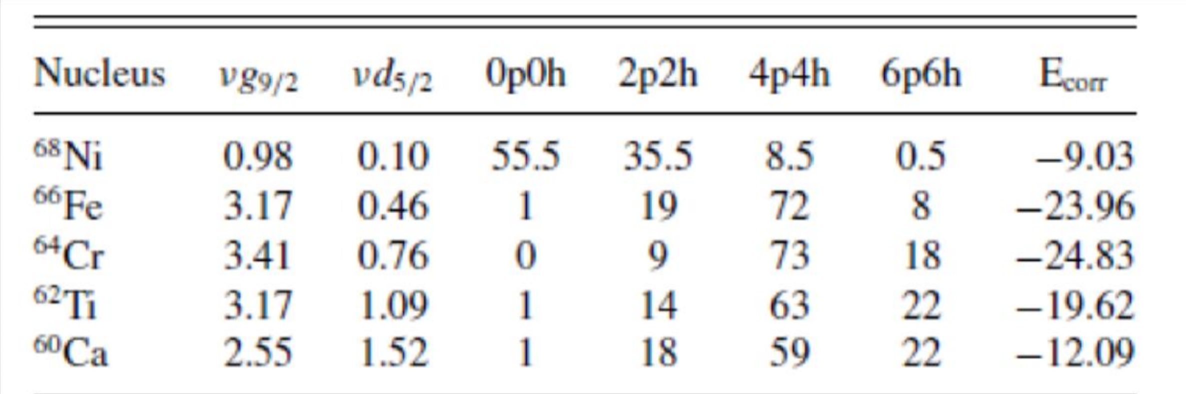
The N=40 isotones

E (2^+)



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



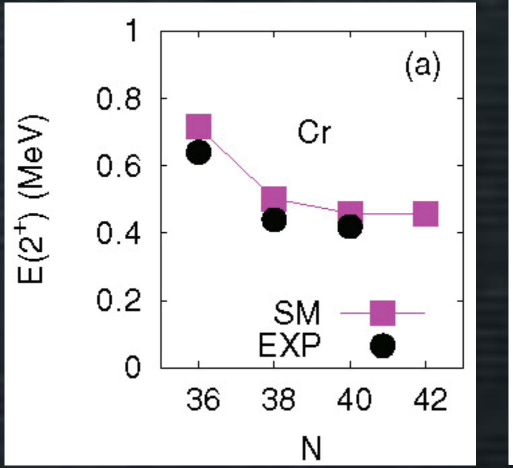
Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	0p0h	2p2h	4p4h	6p6h	E_{corr}
^{68}Ni	0.98	0.10	55.5	35.5	8.5	0.5	−9.03
^{66}Fe	3.17	0.46	1	19	72	8	−23.96
^{64}Cr	3.41	0.76	0	9	73	18	−24.83
^{62}Ti	3.17	1.09	1	14	63	22	−19.62
^{60}Ca	2.55	1.52	1	18	59	22	−12.09

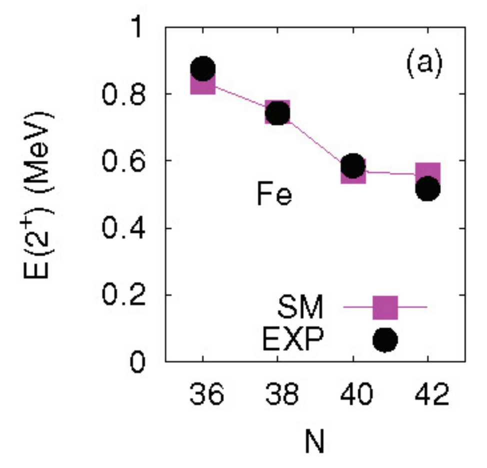
LNPS, PRC 82, 054301 (2010)

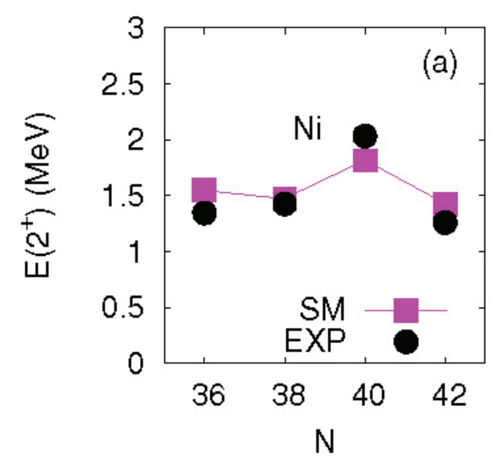
Cr, Fe and Ni isotopic chains

Cr Fe Ni

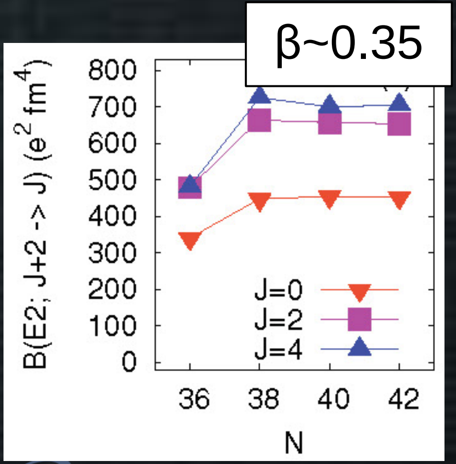
E (2^+)



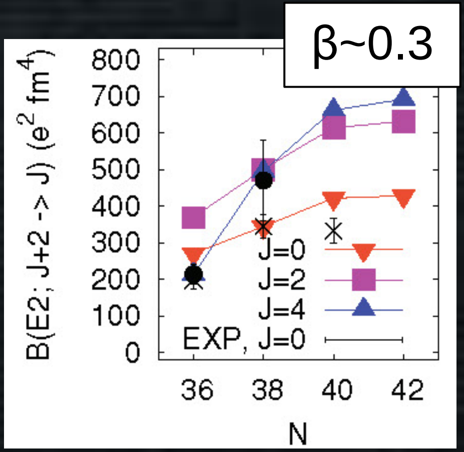




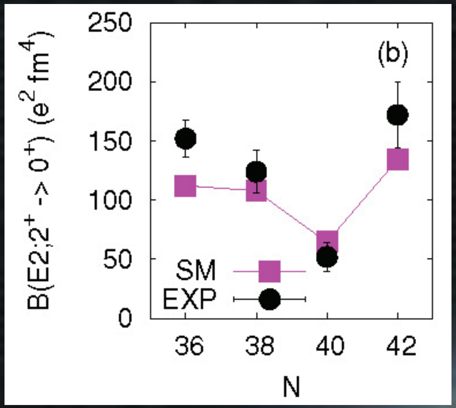
B(E2)



β~0.35

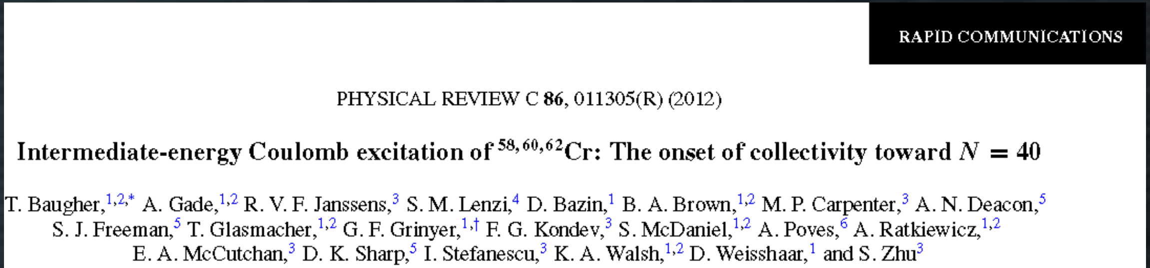


β~0.3



LNPS, PRC 82, 054301 (2010)

The choice of the effective charges



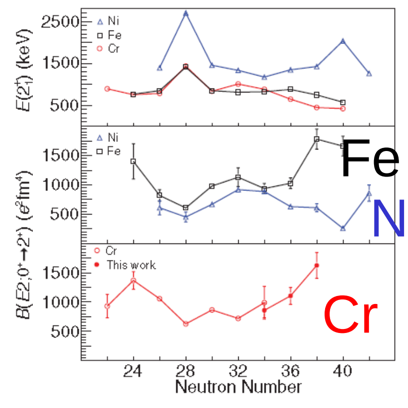
RAPID COMMUNICATIONS

PHYSICAL REVIEW C **86**, 011305(R) (2012)

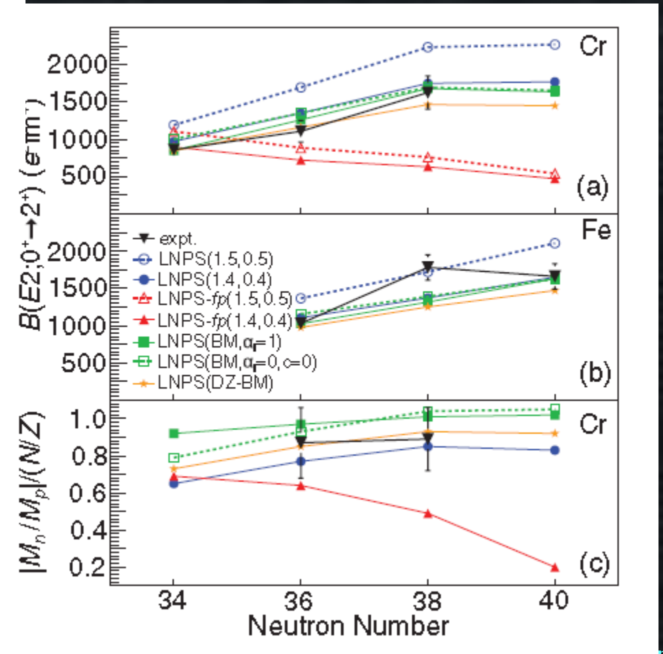
Intermediate-energy Coulomb excitation of ^{58,60,62}Cr: The onset of collectivity toward $N = 40$

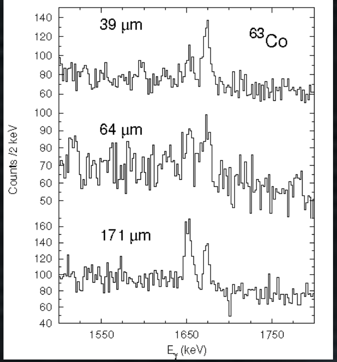
T. Baugher,[1,2,*] A. Gade,[1,2] R. V. F. Janssens,[3] S. M. Lenzi,[4] D. Bazin,[1] B. A. Brown,[1,2] M. P. Carpenter,[3] A. N. Deacon,[5] S. J. Freeman,[5] T. Glasmacher,[1,2] G. F. Grinyer,[1,†] F. G. Kondev,[3] S. McDaniel,[1,2] A. Poves,[6] A. Ratkiewicz,[1,2] E. A. McCutchan,[3] D. K. Sharp,[5] I. Stefanescu,[3] K. A. Walsh,[1,2] D. Weisshaar,[1] and S. Zhu[3]

It is suggested that the effective charges need to be reduced



By combining the results of cex and (p,p') (Aoi et al) the ratio of the neutron and proton transition matrix elements can be obtained and compared with the calculations → discriminate the best effective charges

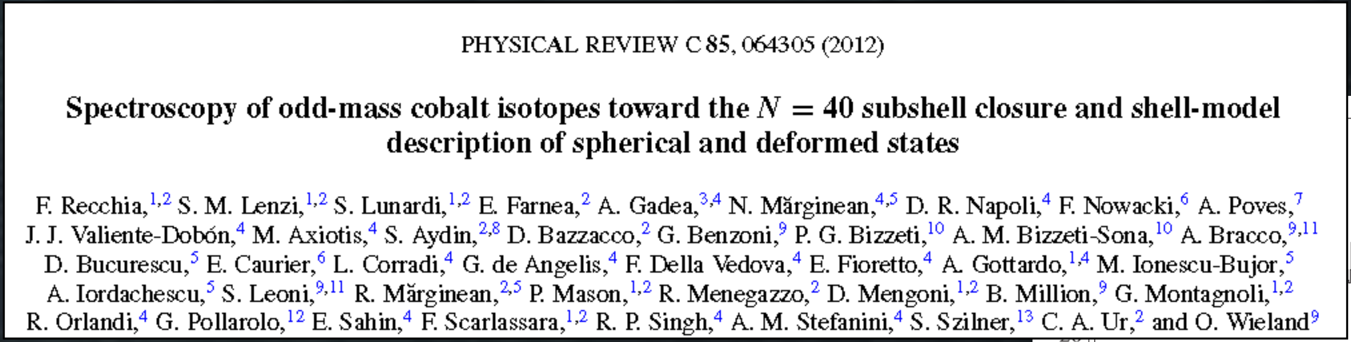




V. Modamio et al., AGATA lifetimes measurement. Confirms the reduction of the effective charges for 63-65Co

Shape coexistence: the Co isotopic chain

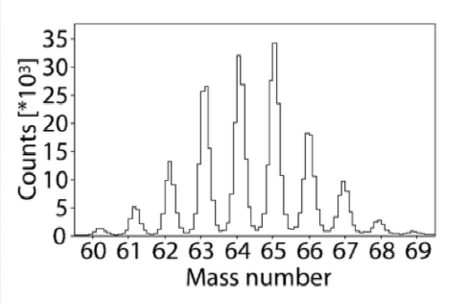
Co isotopes

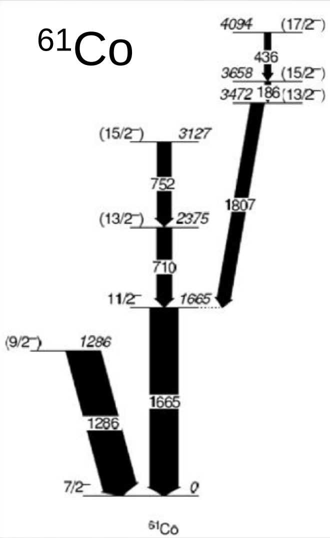


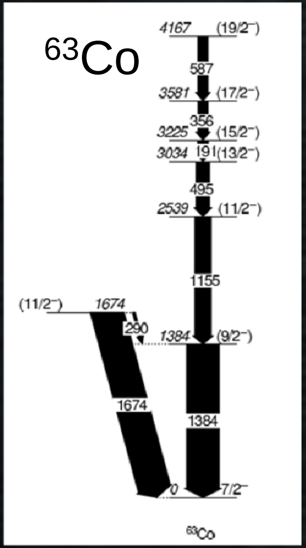
PHYSICAL REVIEW C 85, 064305 (2012)

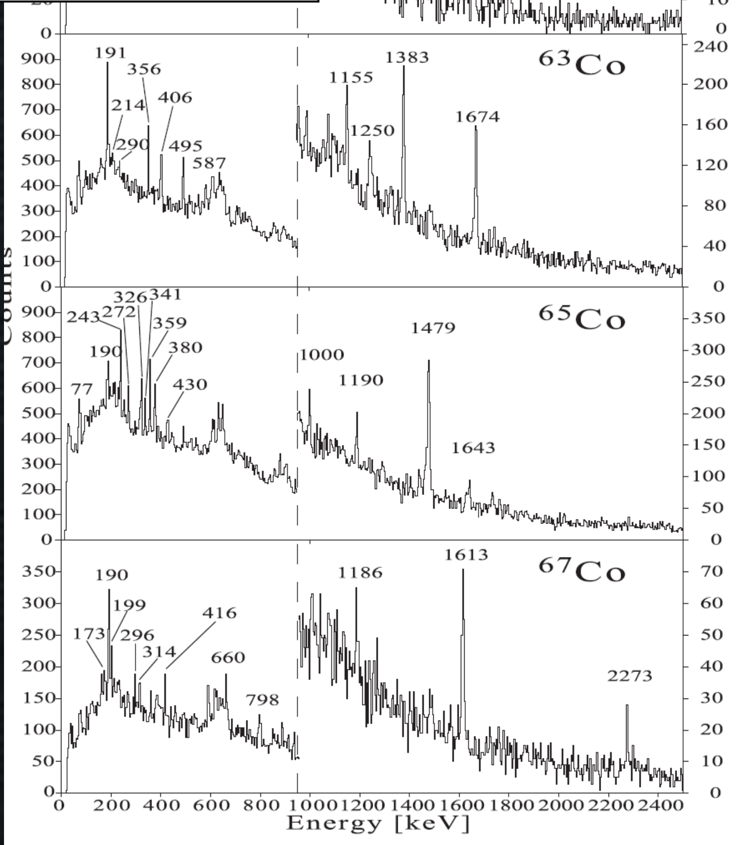
Spectroscopy of odd-mass cobalt isotopes toward the $N = 40$ subshell closure and shell-model description of spherical and deformed states

F. Recchia,[1,2] S. M. Lenzi,[1,2] S. Lunardi,[1,2] E. Farnea,[2] A. Gadea,[3,4] N. Mărginean,[4,5] D. R. Napoli,[4] F. Nowacki,[6] A. Poves,[7] J. J. Valiente-Dobón,[4] M. Axiotis,[4] S. Aydin,[2,8] D. Bazzacco,[2] G. Benzoni,[9] P. G. Bizzeti,[10] A. M. Bizzeti-Sona,[10] A. Bracco,[9,11] D. Bucurescu,[5] E. Caurier,[6] L. Corradi,[4] G. de Angelis,[4] F. Della Vedova,[4] E. Fioretto,[4] A. Gottardo,[1,4] M. Ionescu-Bujor,[5] A. Iordachescu,[5] S. Leoni,[9,11] R. Mărginean,[2,5] P. Mason,[1,2] R. Menegazzo,[2] D. Mengoni,[1,2] B. Million,[9] G. Montagnoli,[1,2] R. Orlandi,[4] G. Pollarolo,[12] E. Sahin,[4] F. Scarlassara,[1,2] R. P. Singh,[4] A. M. Stefanini,[4] S. Szilner,[13] C. A. Ur,[2] and O. Wieland[9]

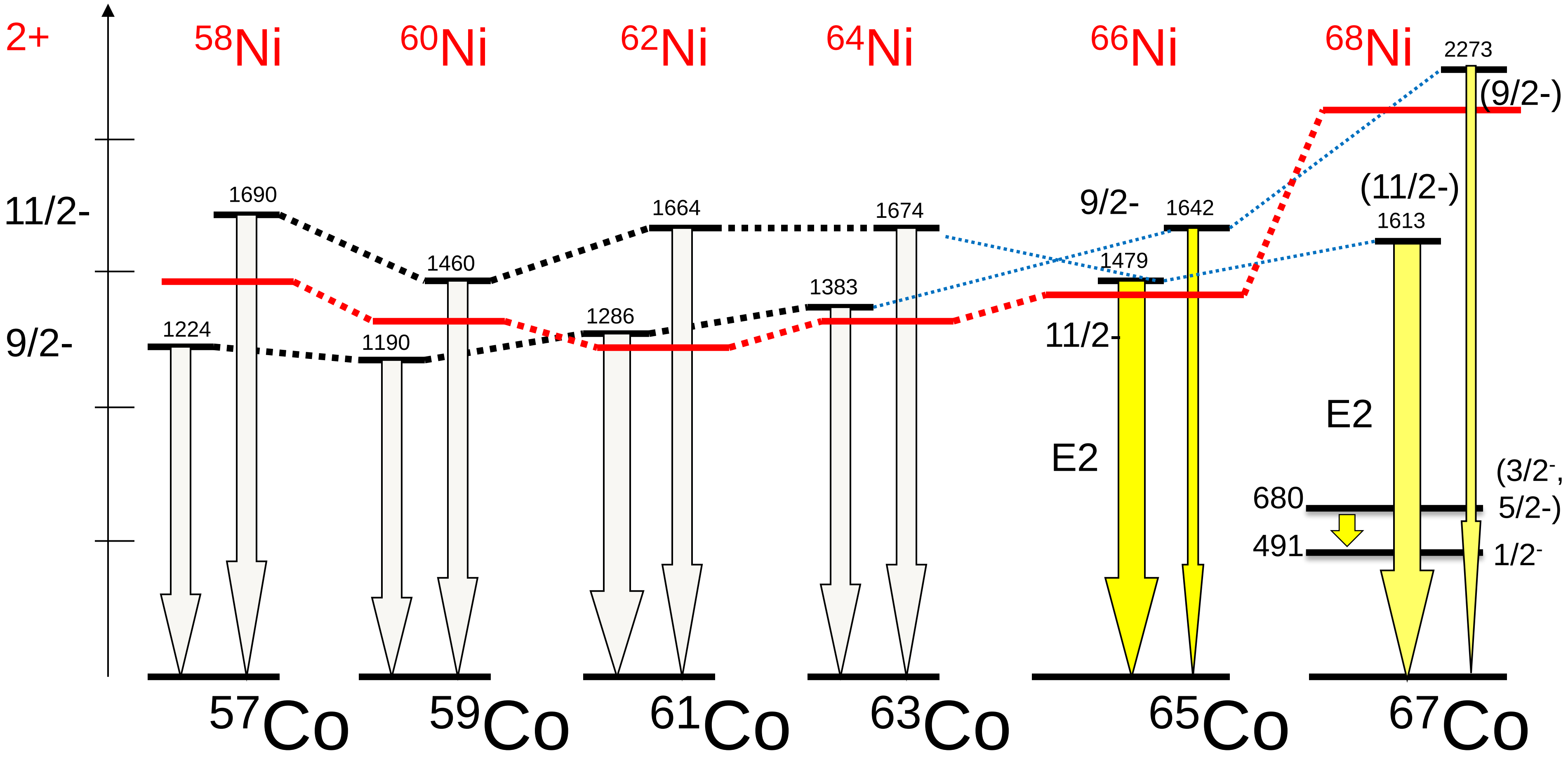








Evolution of yrast levels in Co isotopes



65Co
Phys. Rev

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

Inversions of the multiplets

In the weak coupling limit, the energy shifts between the states in the multiplet can be obtained

L. Trache et al., PRC54, 2361 (1996)

$$\Delta E = k_2 \langle L \parallel Q \parallel L \rangle \langle j \parallel q \parallel j \rangle (-)^{j+L+J} \begin{Bmatrix} L & j & J \\ j & L & 2 \end{Bmatrix}$$

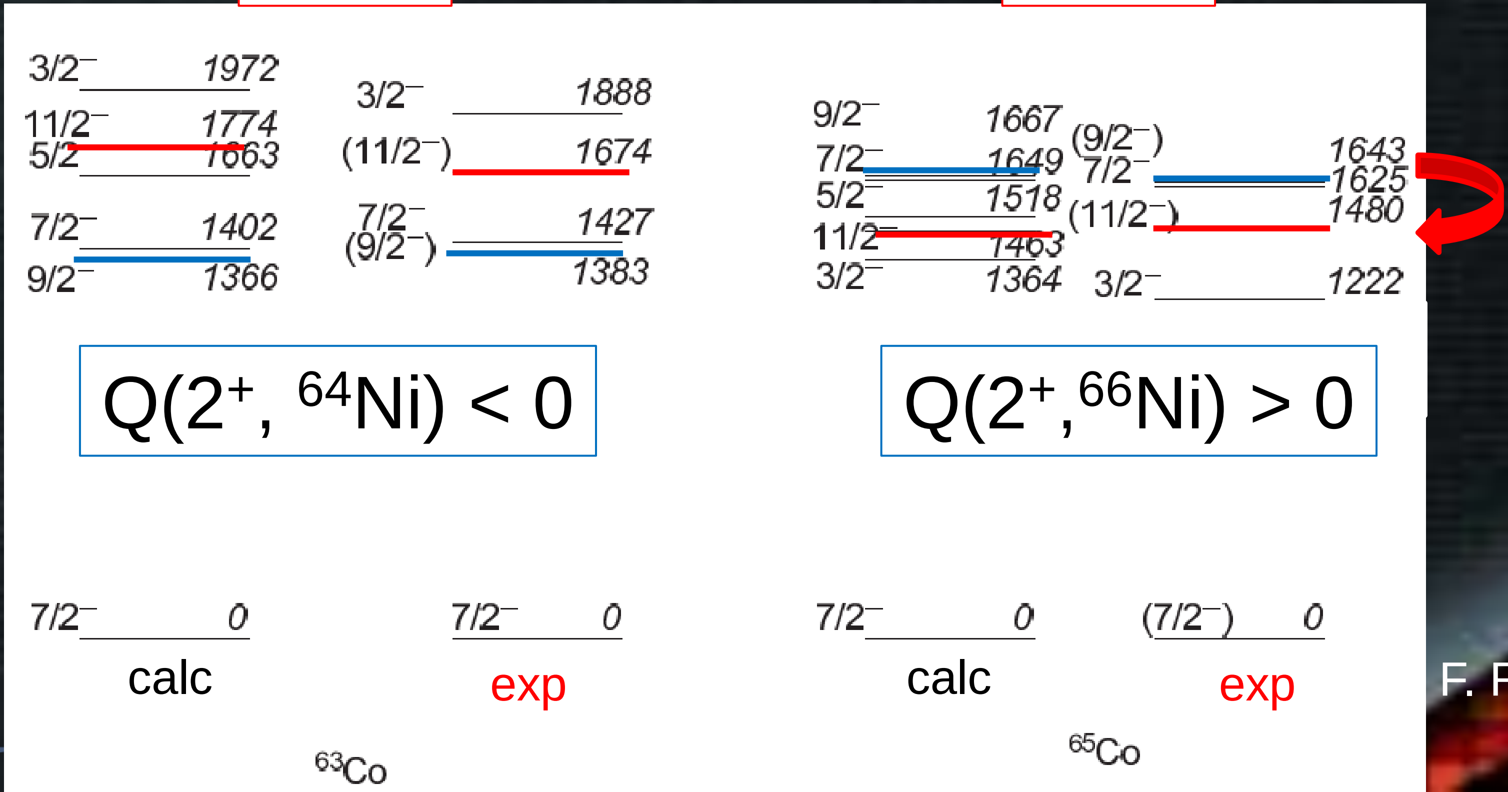
Q(Ni core)

$\pi f_{7/2}^{-1} \otimes 2^{+\,64}\mathrm{Ni}$

^{63}Co

^{65}Co

$\pi f_{7/2}^{-1} \otimes 2^{+\,66}\mathrm{Ni}$

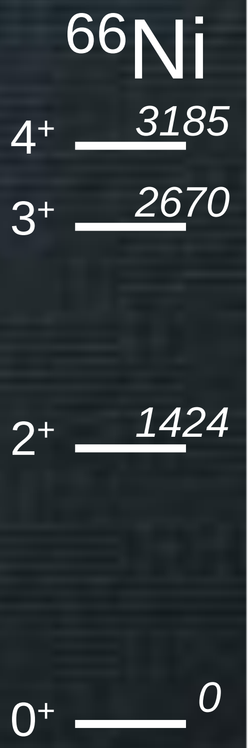


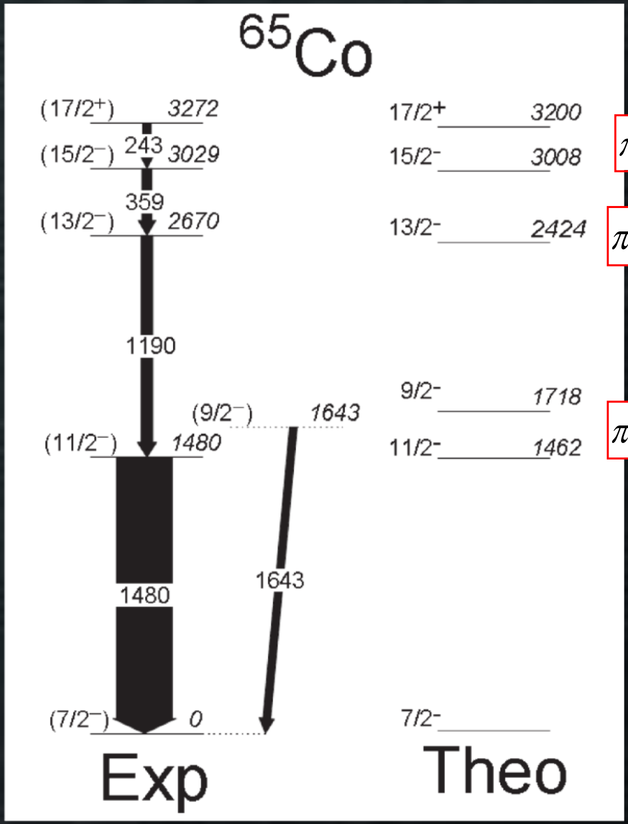
Q(2$^+$, ^{64}Ni) < 0

Q(2$^+$,^{66}Ni) > 0

F. Recchia

^{65}Co: weak coupling interpretation

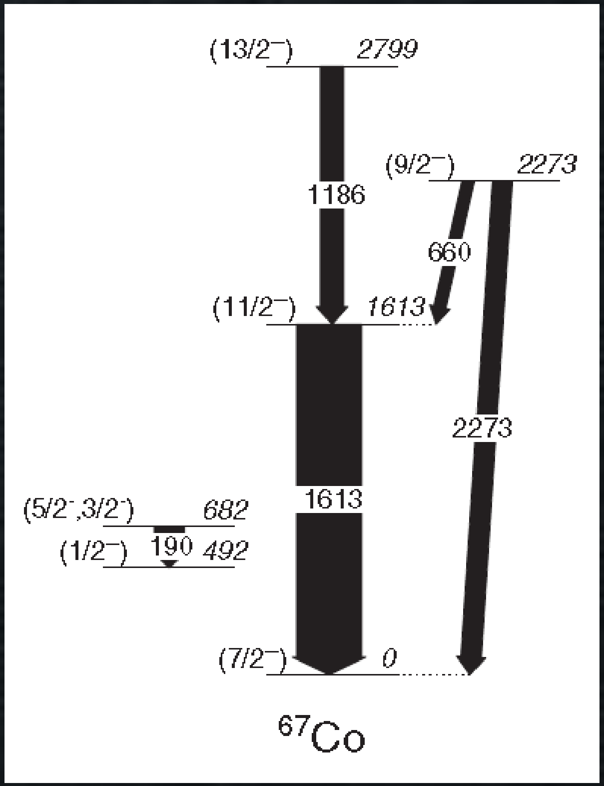




$\pi f_{7/2}^{-1} \otimes 4^{+}\,{}^{66}\mathrm{Ni}$

$\pi f_{7/2}^{-1} \otimes 3^{+}\,{}^{66}\mathrm{Ni}$

$\pi f_{7/2}^{-1} \otimes 2^{+}\,{}^{66}\mathrm{Ni}$

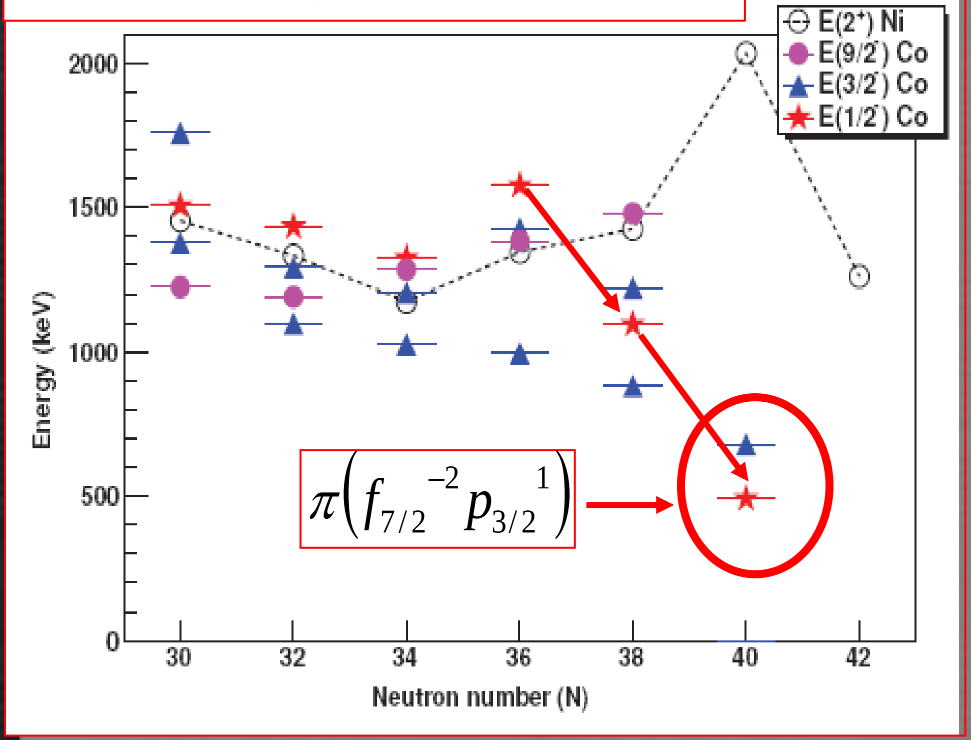


Can we explain ^{67}Co in a similar way?

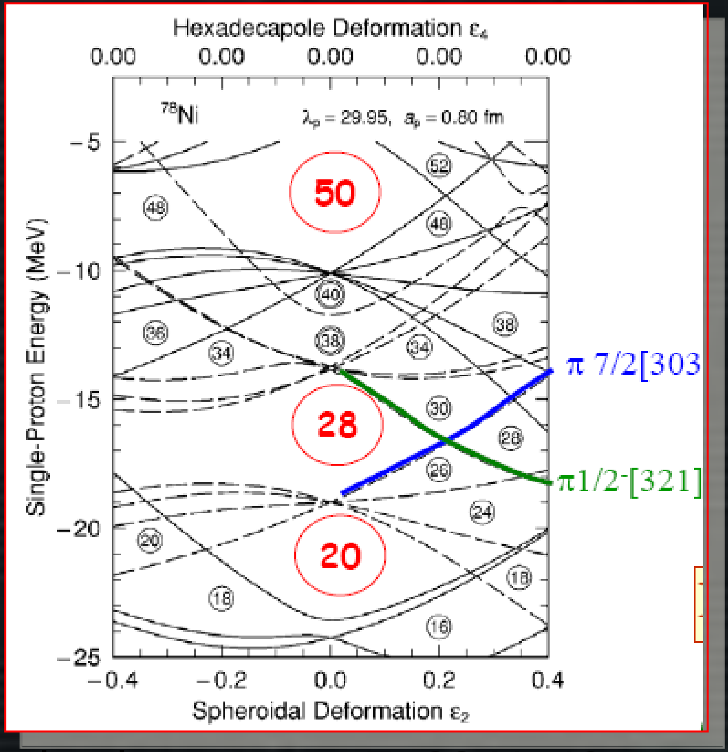
F. Recchia et al., PRC 85, 064305 (2012)

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

evolution of $1/2^-$ states in odd Co



$$\pi\left(f_{7/2}^{\ -2}\,p_{3/2}^{\ \ 1}\right)$$

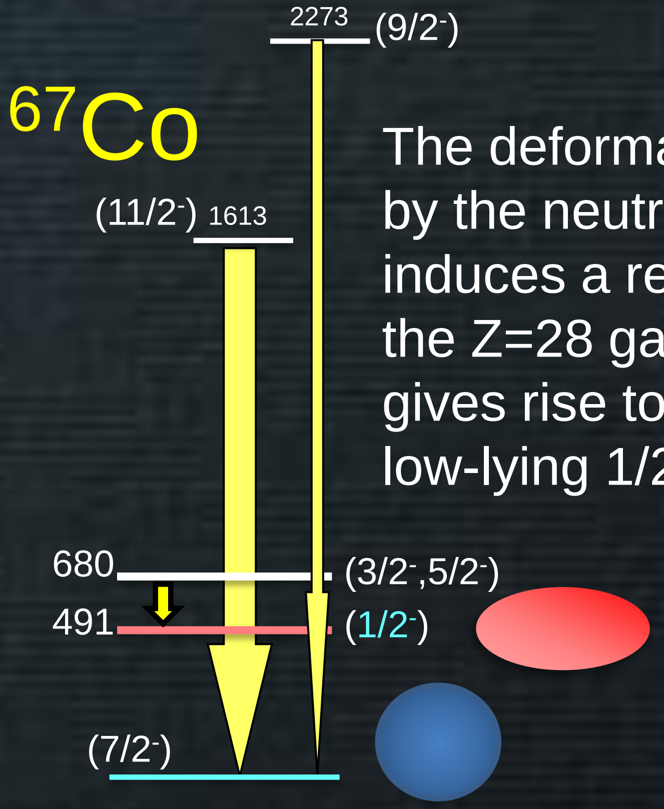


The $1/2^-$ state lowers due to deformation increase at $Z<28$ $N=40$

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

Courtesy D. Pauwels and P. Van Duppen

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

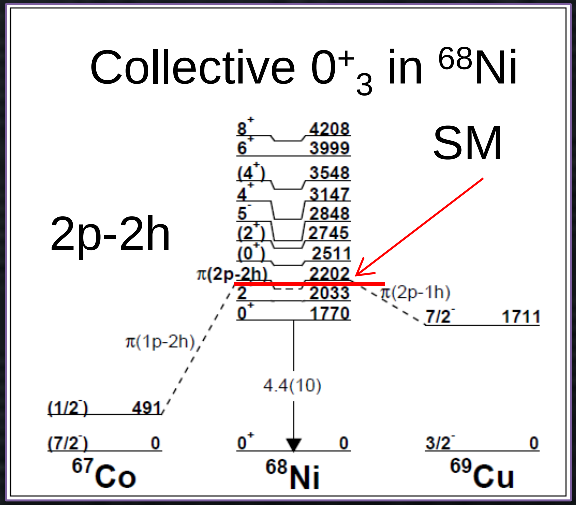


The deformation driven by the neutrons induces a reduction of the Z=28 gap and gives rise to a deformed low-lying 1/2- state

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

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

^{68}Ni

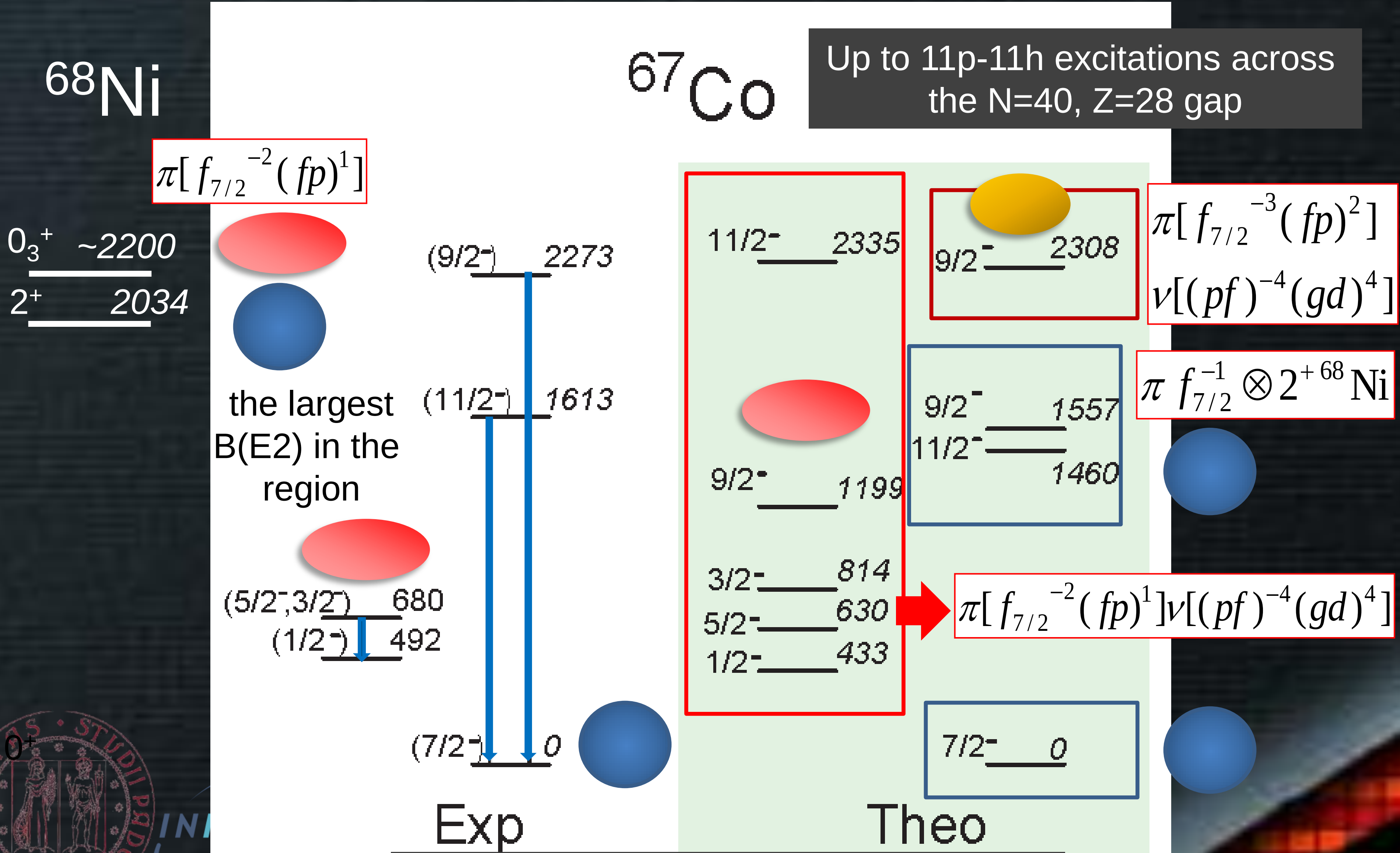


Prediction: D. Pauwels et al.,
Phys.Rev. C 82, 027304 (2010)

The 1/2$^-$ state in ^{67}Co gains a total of ~8 MeV of correlation energy and ~5 MeV relative to the ground state

The LNPS interaction is able to reproduce these structures

Shape coexistence in ^{67}Co



Up to 11p-11h excitations across the N=40, Z=28 gap

^{68}Ni

$\pi[f_{7/2}{}^{-2}(fp)^1]$

0_3^+ ~2200

2^+ 2034

0^+

the largest B(E2) in the region

$\pi[f_{7/2}{}^{-3}(fp)^2]$

$\nu[(pf)^{-4}(gd)^4]$

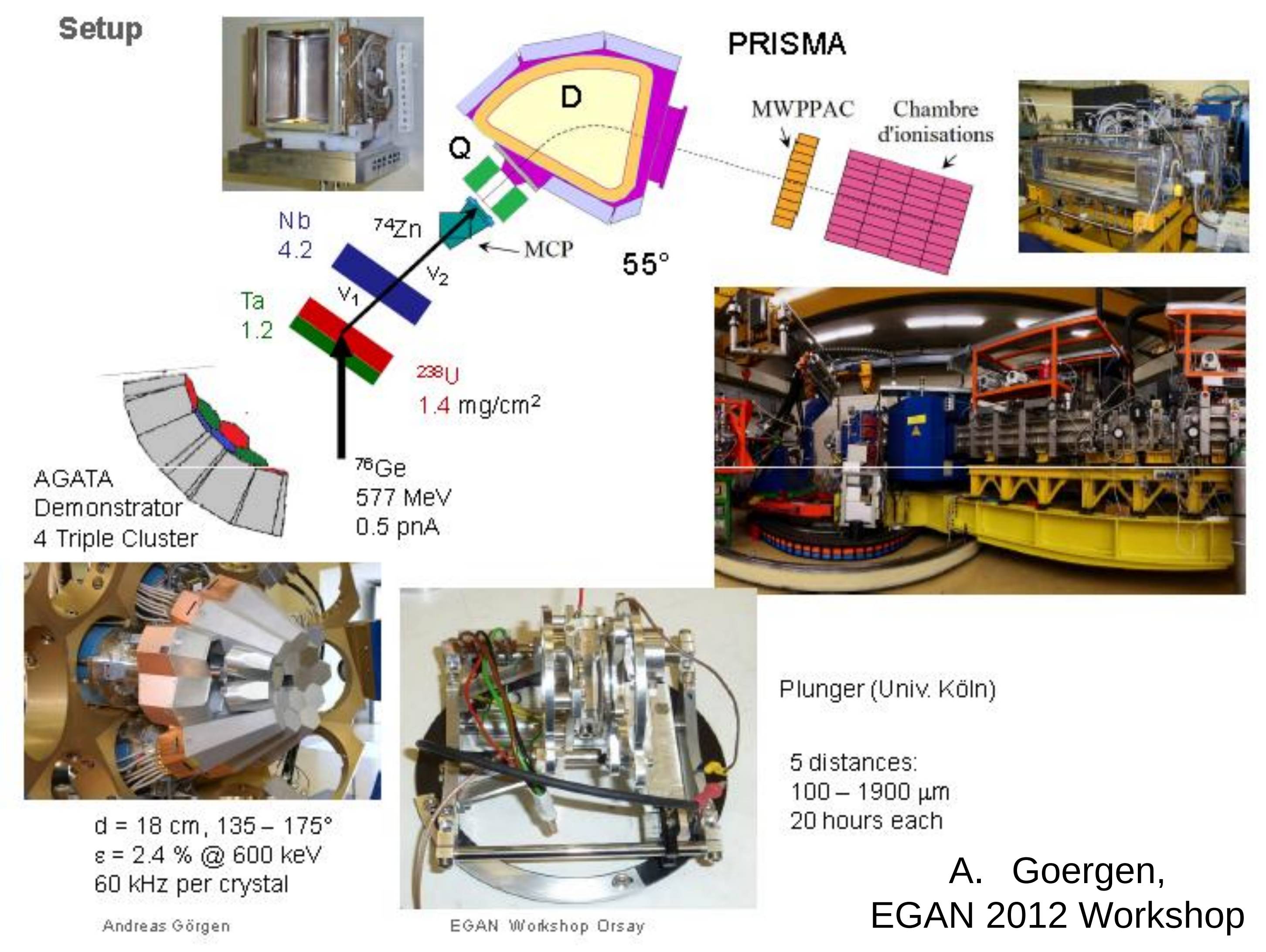
$\pi f_{7/2}^{-1} \otimes 2^{+\,68}\mathrm{Ni}$

$\pi[f_{7/2}{}^{-2}(fp)^1]\nu[(pf)^{-4}(gd)^4]$

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

Beyond Z=28 and N=40

Transition probability measurements with AGATA at LNL



Setup

AGATA
Demonstrator
4 Triple Cluster

d = 18 cm, 135 – 175°
ε = 2.4 % @ 600 keV
60 kHz per crystal

Plunger (Univ. Köln)

5 distances:
100 – 1900 μm
20 hours each

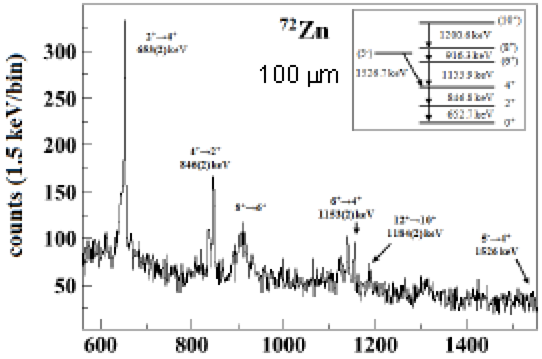
Andreas Görgen

EGAN Workshop Orsay

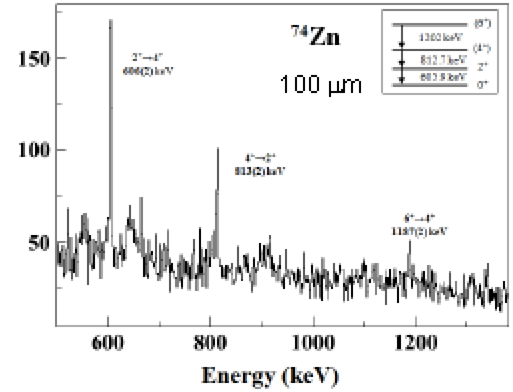
A. Goergen,
EGAN 2012 Workshop

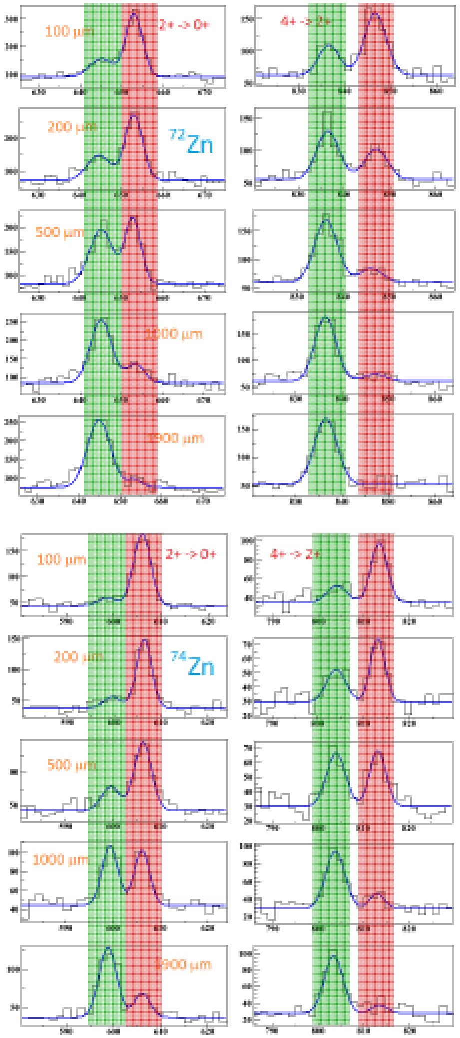
Lifetime measurements in Zn isotopes

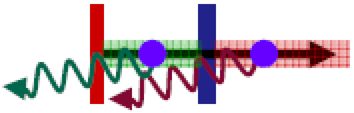
RDDS spectra



C. Louchart et al.
to be published





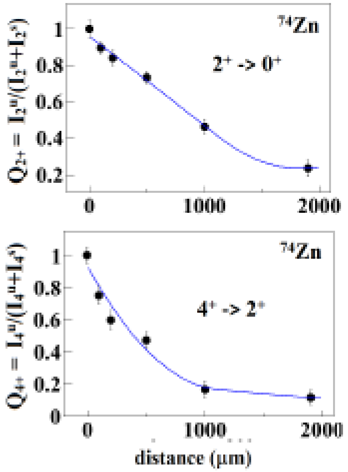


feeding transitions

$$\tau_i(x) = -\frac{Q_i(x) - \sum_k \alpha_k Q_k(x)}{v * \frac{dQ_i}{dx}(x)}$$

$$Q_i = \frac{I_i^u}{I_i}$$

$$I_i = I_i^u + I_i^s$$

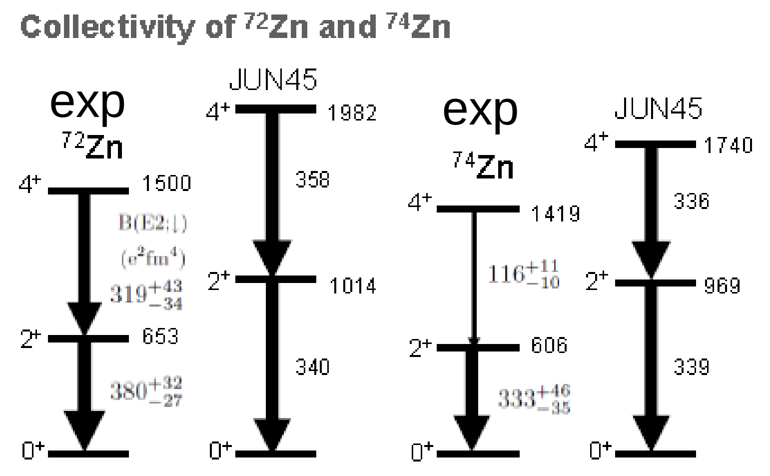


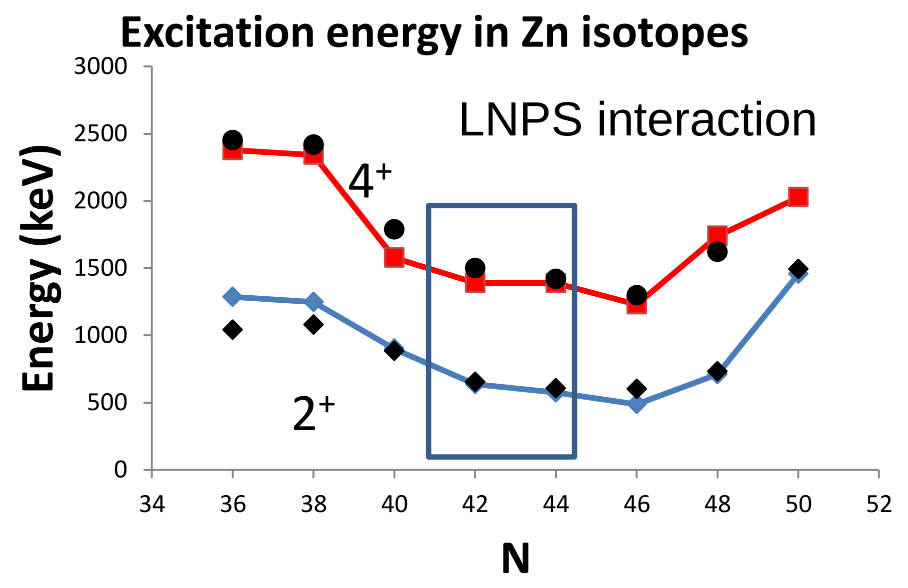
A. Goergen,
EGAN 2012 Workshop

Istituto Nazionale
di Fisica Nucleare

The Zn isotopic chain

JUN45: fpg model space



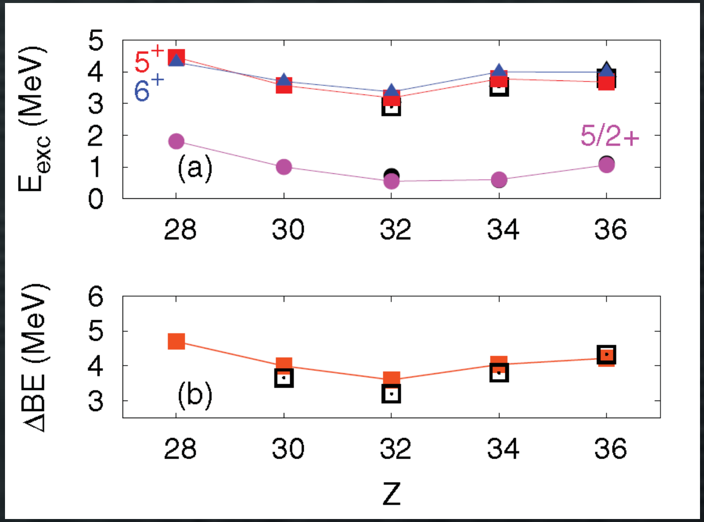


Calculations using the LNPS give good results for the excitation energy of Zn isotopes. New results for transition probabilities are needed.

The N=50 isotonic chain

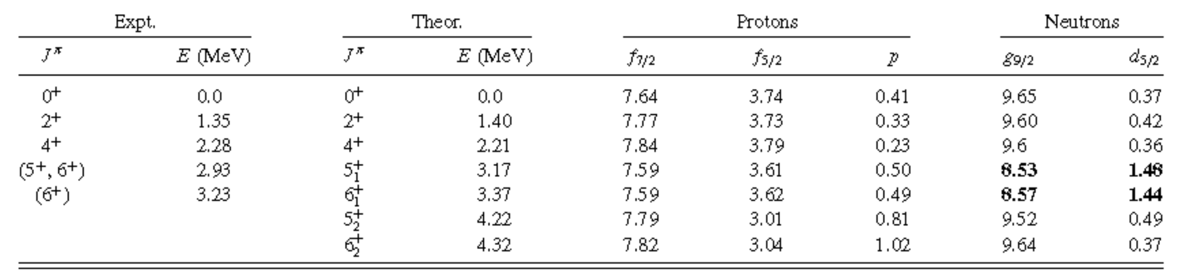
The LNPS interaction is able to reproduce the available data for N=50 isotones towards ^{78}Ni.

low-lying 1p-1h states

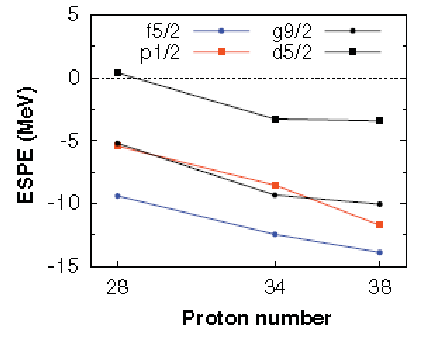


evolution of the *N = 50* gap calculated from masses

82Ge



Expt.		Theor.		Protons			Neutrons	
J^π	E (MeV)	J^π	E (MeV)	$f_{7/2}$	$f_{5/2}$	p	$g_{9/2}$	$d_{5/2}$
0^+	0.0	0^+	0.0	7.64	3.74	0.41	9.65	0.37
2^+	1.35	2^+	1.40	7.77	3.73	0.33	9.60	0.42
4^+	2.28	4^+	2.21	7.84	3.79	0.23	9.6	0.36
$(5^+, 6^+)$	2.93	5_1^+	3.17	7.59	3.61	0.50	**8.53**	**1.46**
(6^+)	3.23	6_1^+	3.37	7.59	3.62	0.49	**8.57**	**1.44**
		5_2^+	4.22	7.79	3.01	0.81	9.52	0.49
		6_2^+	4.32	7.82	3.04	1.02	9.64	0.37



N=50

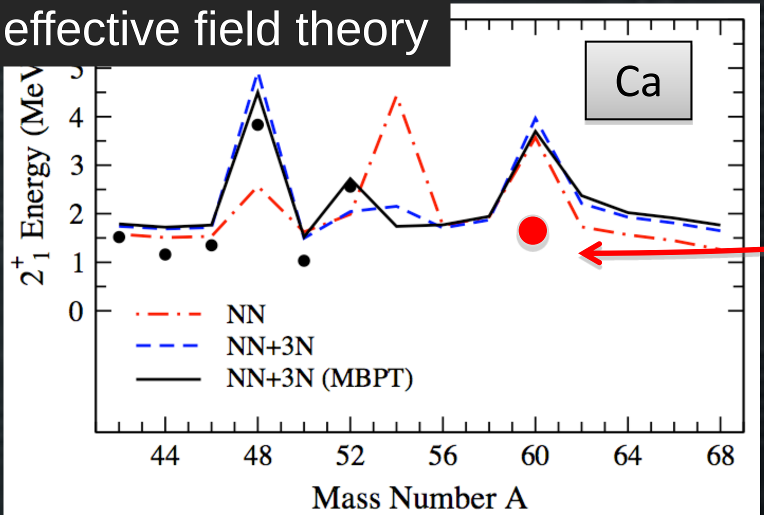
No reduction of the N=50 gap is predicted

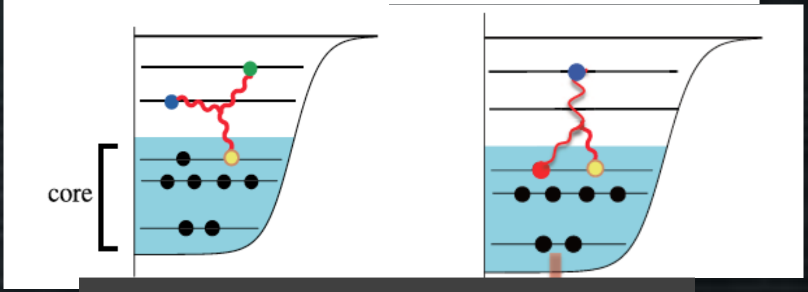
K. Sieja and F. Nowacki, PRC 85 (2012) 051301(R)

Three body forces

Theoretical efforts to include 3N forces in the Shell Model calculations. Need a clear signature.

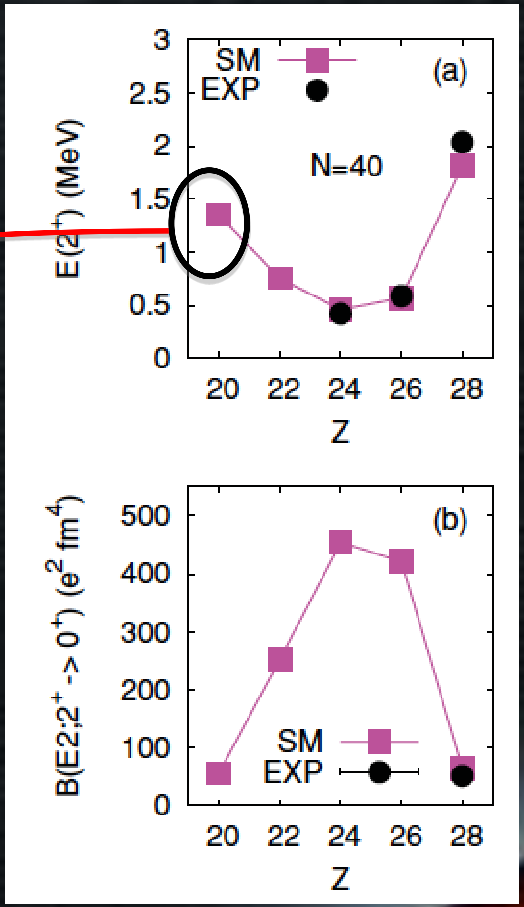
chiral effective field theory





T. Otsuka et al., PRL105, 032501 (2010)
J.D. Holt et al., in preparation

Realistic NN



S.M. Lenzi et al., PRC**82**, 054301 (2010)

Conclusions

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

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

^{67}Co shows very different shapes at low excitation energy. Gamma-gamma data needed to construct the level scheme, together with the measurement of transition probabilities to study the evolution of deformation → provide a stringent test for the effective interactions.

The model space and interaction are suitable for describing the structure of nuclei beyond Z=28, N=40, towards N=50. The effect of three body forces may be important. This needs experimental efforts to find clear signatures.