N=40 : from lol to lol

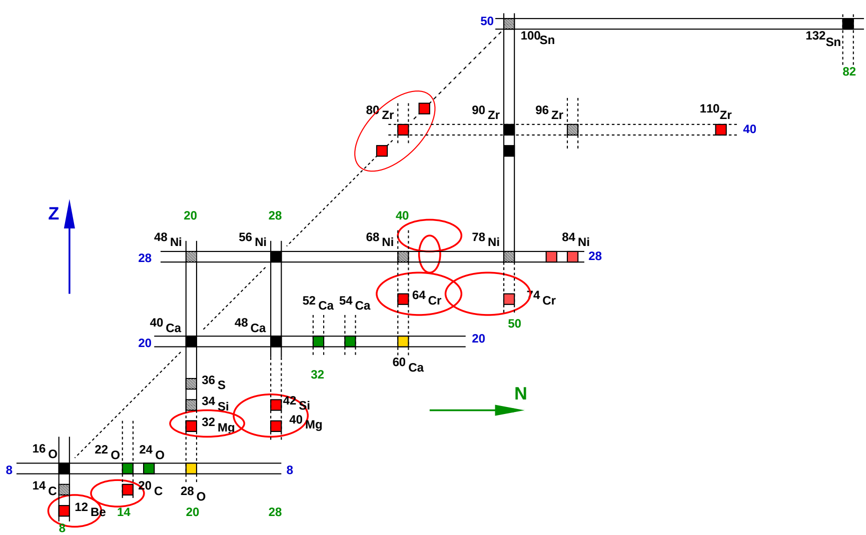
Frédéric Nowacki

ISOL-France Workshop VI

27–29 mai 2024
IPHC
Fuseau horaire Europe/Paris

CNRS IN2P3 Les deux infinis
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG
UNIVERSITÉ DE STRASBOURG

Landscape of medium mass nuclei



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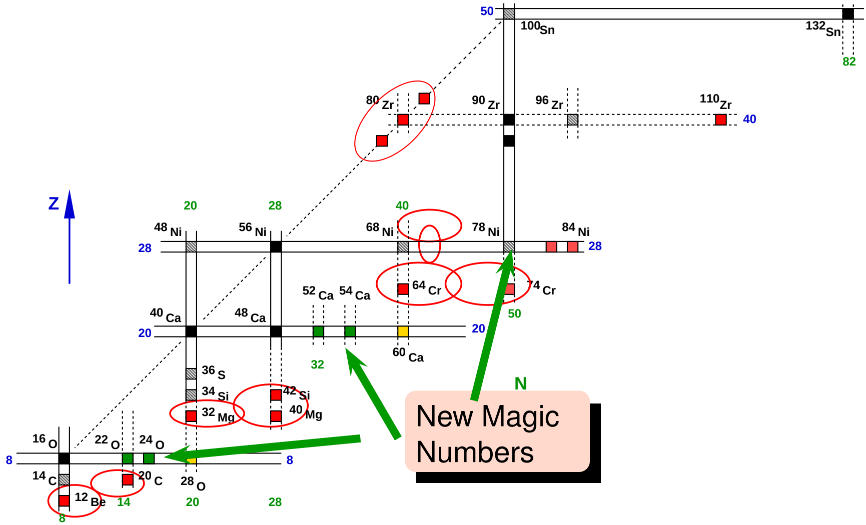

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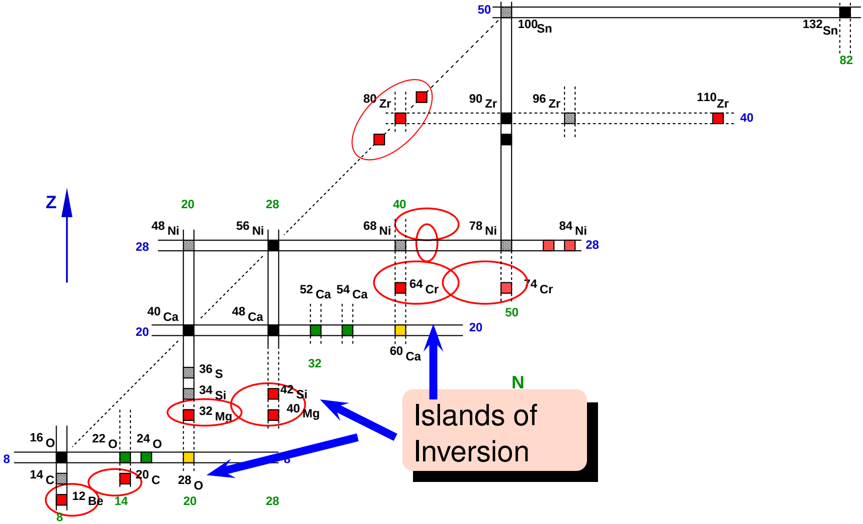

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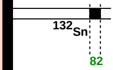
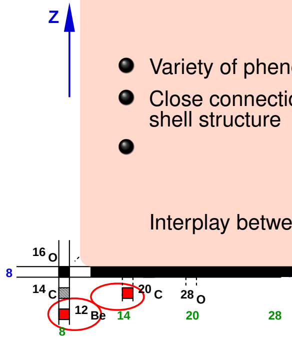


UNDERSTANDING REGULARITIES
for both SPHERICAL and DEFORMED systems

- New Magic Numbers: ^{24}O, ^{48}Ni, ^{54}Ca, ^{78}Ni, ^{100}Sn
- Vanishing of shell closures: ^{12}Be, ^{32}Mg, ^{42}Si, ^{64}Cr, ^{80}Zr ...
- Island of deformation around A$\sim$ 32, A$\sim$ 64
- Low-lying dipole excitations in Ne, Ni isotopes

- Variety of phenomena dictated by shell structure
- Close connection between collective behaviour and underlying shell structure
- $$\mathcal{H} = \mathcal{H}_m + \mathcal{H}_{\mathcal{M}}$$

  Interplay between
  - Monopole field (spherical mean field)
  - Multipole correlations (pairing, Q.Q, ...)



Separation of the effective Hamiltonian

Monopole and multipole

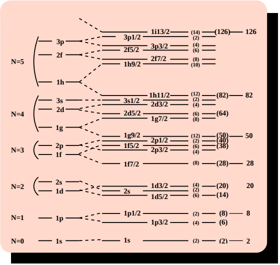
Multipole expansion:

$$H = H_{monopole} + H_{multipole}$$

$H_{monopole}$:

- *Spherical mean-field*
- *Evolution of the spherical single particle levels*

A. Poves and A. Zuker (Phys. Report 70, 235 (1981))



$H_{multipole}$:

- *Correlations*
- *Energy gains*

- *Pairing (SU2)* semi-magic (n-n) (p-p)
- *Quadrupole (SU3/p-SU3/q-SU3)* p-n in H.O. or Δj = 2

M. Dufour and A. Zuker (PRC 54 1996 1641)

Multipole expansion:

$H_{monopole}$:

A. Poves an

$H_{multipole}$:

- *Pai*
- *Qu*

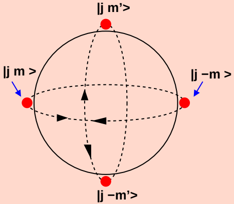
M. Dufour a

- **Pairing regime: spherical nuclei**

  ground state = pairs of like-particles coupled at J=0 (seniority v=0)

  2^+ state (break of pair; v=2) at high energy

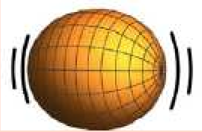
  superfluid nucleus:



Typical example: **semi-magic Tin isotopes**

- **Quadrupole regime: deformed nuclei**

  prolate nucleus:



Typical example: **open shell N=Z nuclei**

Separation of the effective Hamiltonian

Monopole and multipole

Multipole expansion:

$$H = H_{monopole} + H_{PP} + H_{QQ}$$

$H_{monopole}$:

- *Spherical mean-field*
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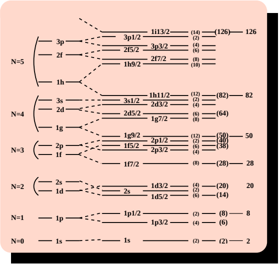
A. Poves and A. Zuker (Phys. Report 70, 235 (1981))



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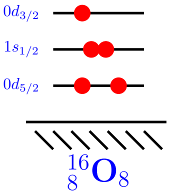
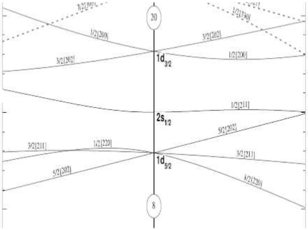
Nilsson-SU3 estimates

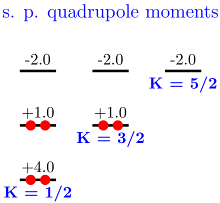
PHYSICAL REVIEW C **92**, 024320 (2015)

Nilsson-SU3 self-consistency in heavy $N = Z$ nuclei

A. P. Zuker,[1] A. Poves,[2,3] F. Nowacki,[1] and S. M. Lenzi[4]







$$Q_0 = 2q^{20} = (2n_z - n_x - n - y)$$

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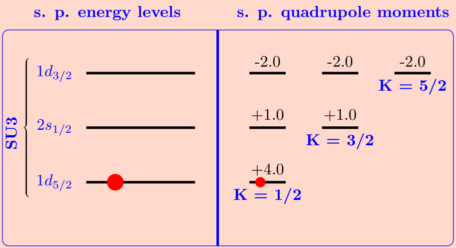

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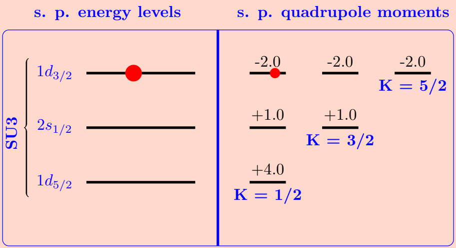

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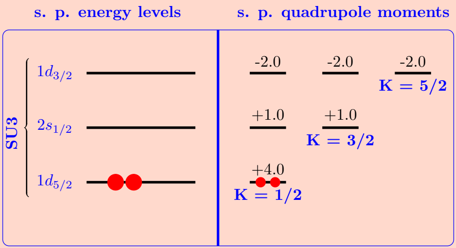

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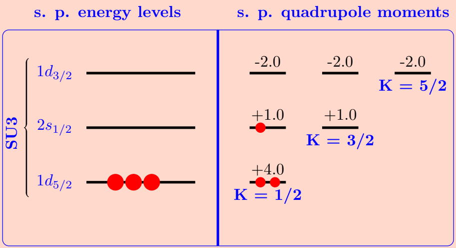

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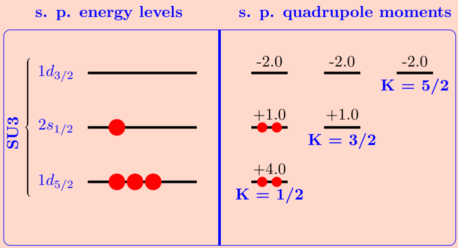

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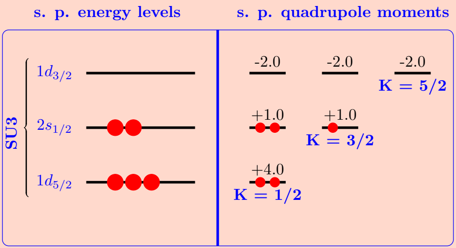

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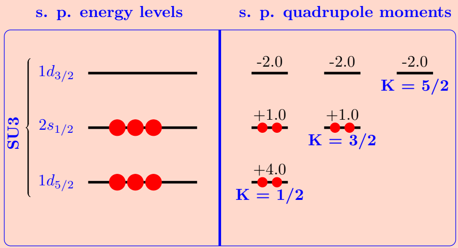

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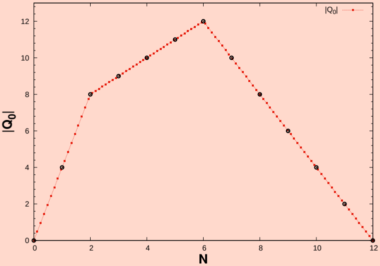
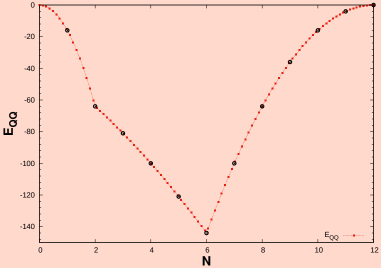
ments

2.0

$= 5/2$





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Development of deformation at N=8,20,40,70

F. Nowacki, A. Obertelli and A. Poves

Progress in Particle and Nuclear Physics 120 (2021) 103866

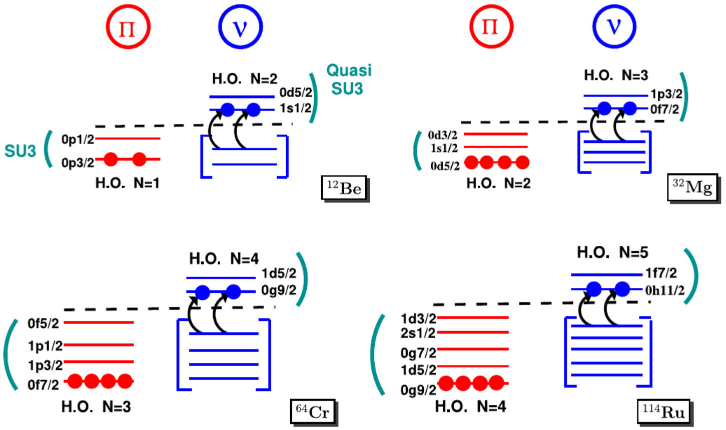
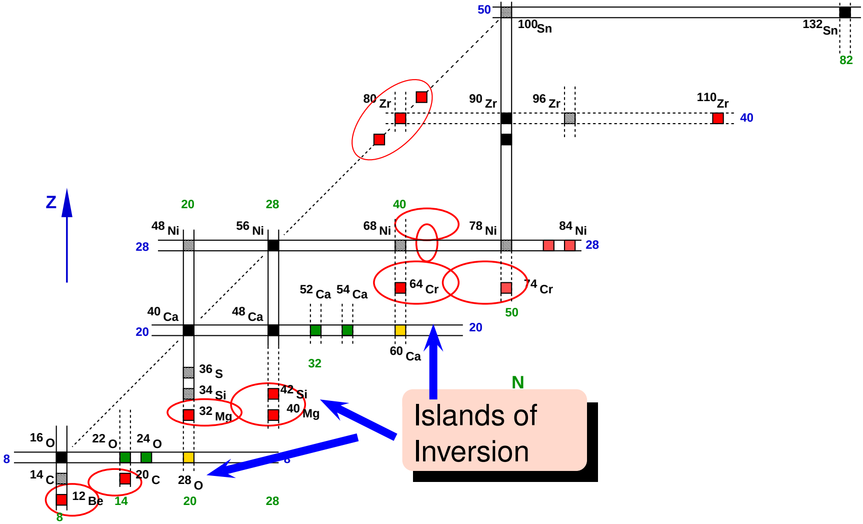


Fig. 40. Schematic view of the valence spaces at N = 8, 20, 40 and 70. The intruder configurations that develop quadrupole collectivity are highlighted.

Landscape of medium mass nuclei



Island of inversion at N=40, an old story: 1996

The Physics around the doubly-magic ^{78}Ni Nucleus

Leuven, Belgium
November 4-5, 1996

A. Poves

^{64}Cr

$$g(0ph - 2ph) = 5.70$$
$$g(0ph - 4ph) = 8.30$$

$Q = -9.0\ b^2$

$BE2 = 19.8\ b^4$

$CS < 1\%$

$n(d_{5/2}) = 1.1$

$$\frac{E(4^+)}{E(2^+)} = 2.7$$

$$\left[\frac{E(4^+)}{E(2^+)} = (3.2)(3.4) \right]$$

in the intruder configurations.

A SITUATION THAT REMINDS WHAT IS KNOWN AT N=20 FFS.

More recent experimental information

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]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **81**, 061301(R) (2010)

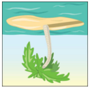
Onset of collectivity in neutron-rich Fe isotopes: Toward a new island of inversion?

J. Ljungvall,[1,2,3] A. Görgen,[1] A. Obertelli,[1] W. Korten,[1] E. Clément,[2] G. de France,[2] A. Bürger,[4] J.-P. Delaroche,[5] A. Dewald,[6] A. Gadea,[7] L. Gaudefroy,[5] M. Girod,[5] M. Hackstein,[6] J. Libert,[8] D. Mengoni,[9] F. Nowacki,[10] T. Pissulla,[6] A. Poves,[11] F. Recchia,[12] M. Rejmund,[2] W. Rother,[6] E. Sahin,[12] C. Schmitt,[2] A. Shrivastava,[2] K. Sieja,[10] J. J. Valiente-Dobón,[12] K. O. Zell,[6] and M. Zielińska[13]

[1]*CEA Saclay, IRFU, Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France*

[2]*GANIL, CEA/DSM-CNRS/IN2P3, Bd Henri Becquerel, BP 55027, F-14076 Caen, France*

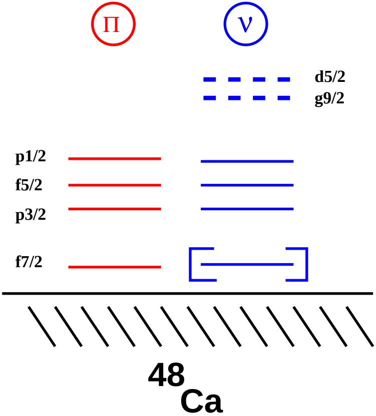
SM framework



Island of inversion around ^{64}Cr

S. Lenzi, F. Nowacki, A. Poves and K. Sieja

Phys. Rev. C82, 054301, 2010



LNPS interaction:

- based on realistic TBME
- new fit of the pf shell (KB3GR, E. Caurier)
- monopole corrections
- $g_{9/2}$-$d_{5/2}$ gap now constrained to 2.5 Mev in ^{68}Ni

Calculations:

- Up to $14\hbar\omega$ excitations across Z=28 and N=40 gaps
- Matrix diagonalizations up to 2.10^{10}
- m-scheme code ANTOINE (non public parallel version)
- DNO-SM for most deformed cases (D. D. Dao Strasbourg)

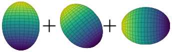
Discrete Non-Orthogonal Shell Model

Generator Coordinate Method: $|\Psi_{\rm eff}\rangle = \sum_i f_i |\Phi_i\rangle$

1) Deformed Hartree-Fock (HF) Slater determinants

2) Restoration of rotational symmetry

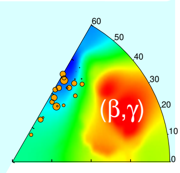
3) Mixing of shapes:

$|\Psi_{\rm eff}\rangle =$  $\cdots$

Intrinsic/Laboratory Description

- **Deformation structure of nuclear states**: $\{J^\pi_\alpha\}, \;\; q = (\beta, \gamma)$

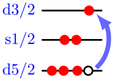
$$M^{(J)}_\alpha(q,K) = \sum_{q',K'} [\hat{N}^{1/2}]^{(J)}_{K'K}(q',q)\, f^{(J)}_\alpha(q',K')$$



◇ Probability of a configuration (β,γ):

$$P^{(J)}_\alpha(q) = \sum_K |M^{(J)}_\alpha(q,K)|^2$$

- **particle-hole interpretation**:



M**-scheme**

- K**–quantum numbers**:

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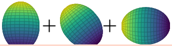
$|\Psi_{\text{eff}}\rangle =$  $\cdots$

3) Mixing of shapes:

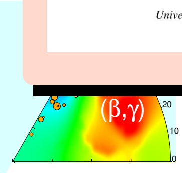
•

PHYSICAL REVIEW C **105**, 054314 (2022)

Nuclear structure within a discrete nonorthogonal shell model approach: New frontiers

D. D. Dao and F. Nowacki
Université de Strasbourg, CNRS, IPHC UMR7178, 23 rue du Loess, F-67000 Strasbourg, France

(Received 8 March 2022; accepted 6 May 2022; published 23 May 2022)



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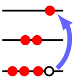

M-**scheme**

• ***K*–quantum numbers**:

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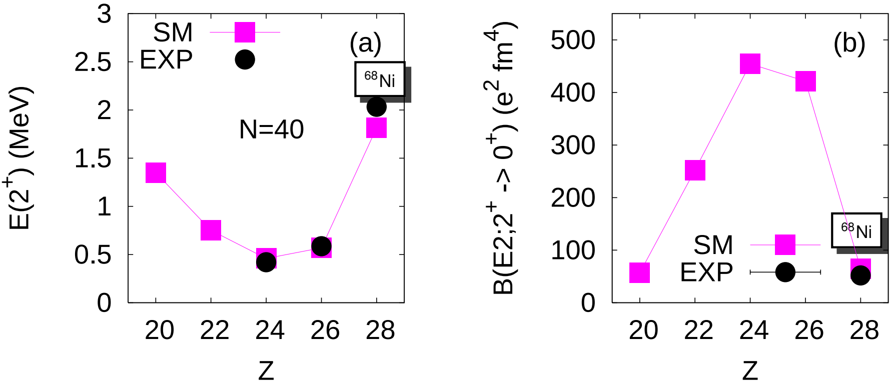
Shape transition at N=40



Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	configuration
^{68}Ni	0.98	0.10	0p0h(51%)
^{66}Fe	3.17	0.46	4p4h(60%)
^{64}Cr	3.41	0.76	4p4h(70%)
^{62}Ti	3.17	1.09	4p4h(48%)

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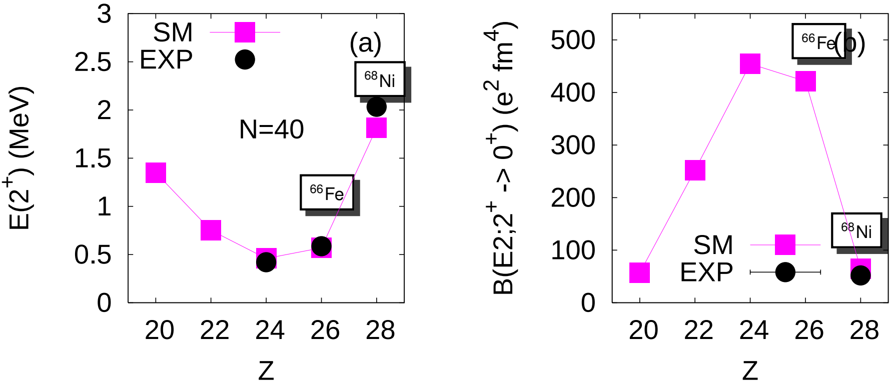

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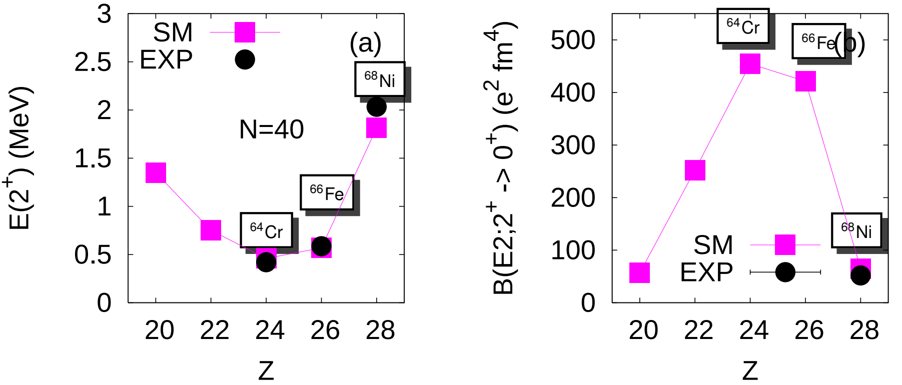

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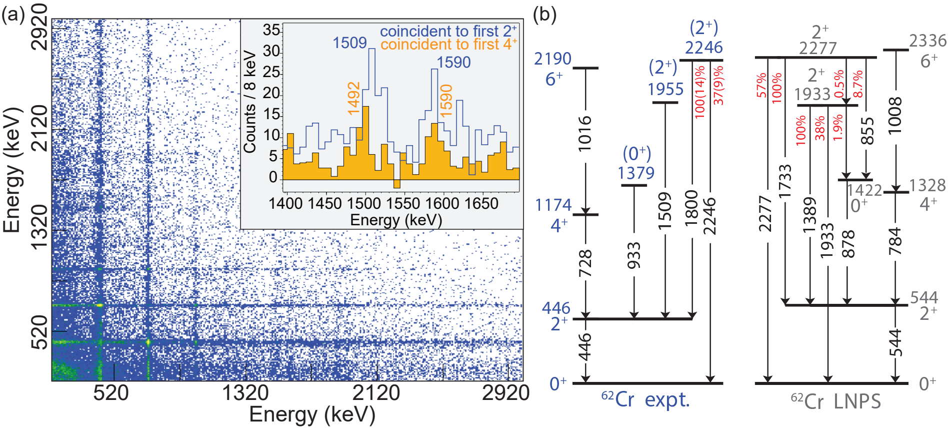
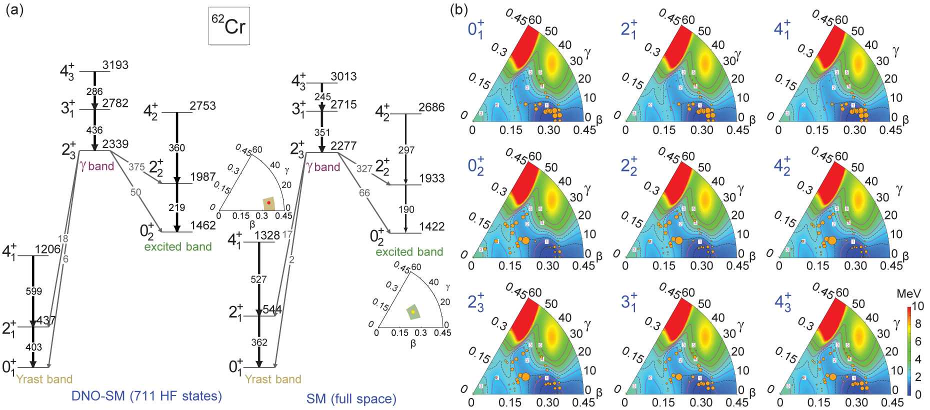
Triple-band observation in ^{62}Cr



FRIB/MSU/GRETINA Experiment

Triple-band observation in ^{62}Cr



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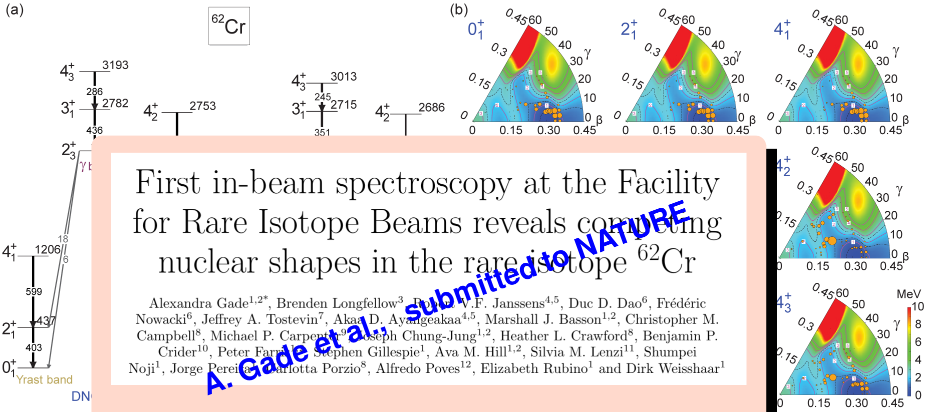


First in-beam spectroscopy at the Facility for Rare Isotope Beams reveals competing nuclear shapes in the rare isotope ^{62}Cr

Alexandra Gade[1,2*], Brenden Longfellow[3], Robert V.F. Janssens[4,5], Duc D. Dao[6], Frédéric Nowacki[6], Jeffrey A. Tostevin[7], Akaa D. Ayangeakaa[4,5], Marshall J. Basson[1,2], Christopher M. Campbell[8], Michael P. Carpenter[9], Joseph Chung-Jung[1,2], Heather L. Crawford[8], Benjamin P. Crider[10], Peter Farris[1,2], Stephen Gillespie[1], Ava M. Hill[1,2], Silvia M. Lenzi[11], Shumpei Noji[1], Jorge Pereira[1], Carlotta Porzio[8], Alfredo Poves[12], Elizabeth Rubino[1] and Dirk Weisshaar[1]

A. Gade et al., submitted to NATURE

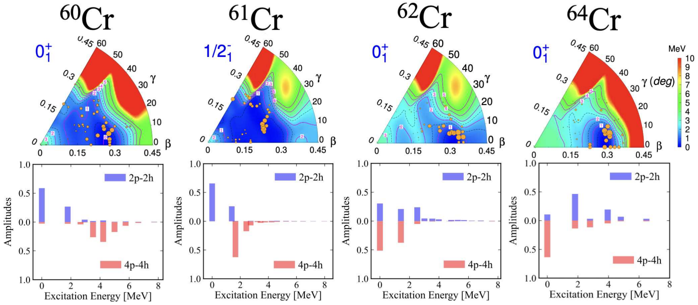
Spectroscopy and moments of ^{61}Cr

TABLE I. Top: spin-parity, excitation energy and magnetic moment of the ground and first two excited states of ^{61}Cr determined in this work from experiment (left) and from shell-model calculations (right, see text for details). Bottom: ground state proton and neutron occupations computed with our shell-model calculations.

Exp.			Th.		
I^π	E_x [keV]	μ [μ_N]	I^π	E_x [keV]	μ [μ_N]
$1/2^-$	0	+0.540(13)	$1/2^-$	0	+0.558
$(3/2^-)$	70.8(9.3)[a]	-	$3/2^-$	283	+1.27
$(5/2)^-$	97.7(24.9)[a]	-	$5/2^-$	397	+0.342

^{61}Cr *g.s.*	$f_{7/2}$	$p_{3/2}$	$f_{5/2}$	$p_{1/2}$	$g_{9/2}$	$d_{5/2}$
Proton	3.33	0.29	0.33	0.04	-	-
Neutron	8.0	3.78	2.49	1.07	1.46	0.19

[a] Value from Ref. [36]



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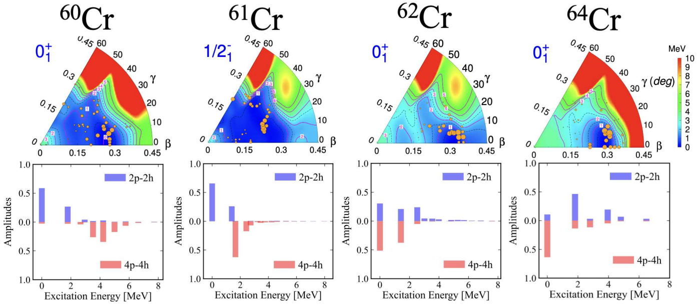
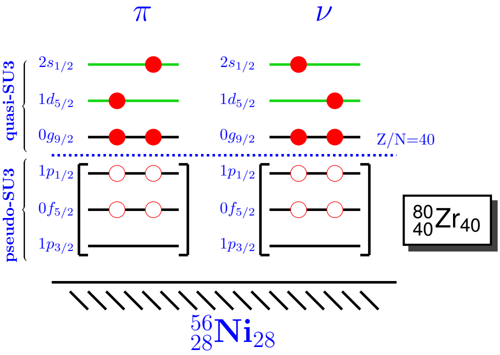
CRIS Collab./ISOLDE Experiment



N=40 at N=Z



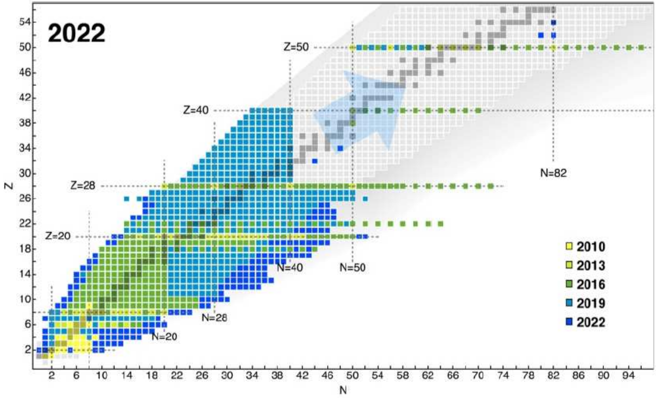
- p shell: ^{16}O spherical/doubly magic
- sd shell: ^{40}Ca spherical/doubly magic
- pf shell: ^{80}Zr deformed nucleus

- Low-lying states in H.O. N=Z=8: **CS** , 4p4h, 8p8h
- Low-lying states in H.O. N=Z=20: **CS** , 4p4h,8p8h
- Low-lying states in H.O. N=Z=40: 4p4h ? 8p8h ? 12p12h ?

Ab-initio predictions ?

TRIUMF **Ab Initio Progress: How Heavy Can We Go?**

Tremendous progress in ab initio reach, largely due to polynomially scaling methods!

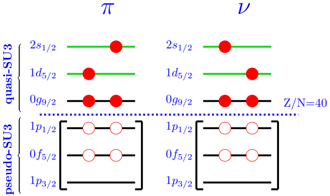


Jason Holt 2023

Island of Inversion at the N=Z line

◇ Strongly deformed states at $N = Z$:

- Configuration mixing in ^{72}Kr
- Most deformed cases for ^{76}Sr, ^{80}Zr
- Shape transition between ^{84}Mo and ^{86}Mo
  NSCL/GRETINA Experiment



R.D.O. Llewellyn *et al.*, PRL **124**, 152501 (2020)

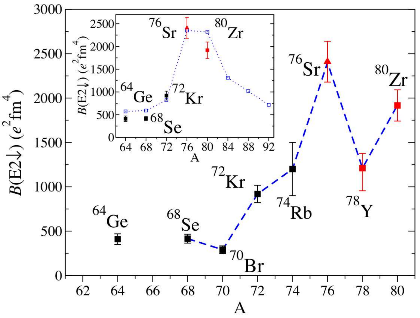


FIG. 3. Schematics of the B(E2↓) values for the $N = Z$ nuclei

- ZBM3 valence space:
  extension of JUN45
  to pseudo-SU3 + Quasi-SU3

- New effective interactions:
  - Realistic TBME + Monopole “3N” constraints”
  - ab-initio N3LO (2N) interaction

- SM + DNO-SM for most deformed cases

Island of Inversion at the N=Z line

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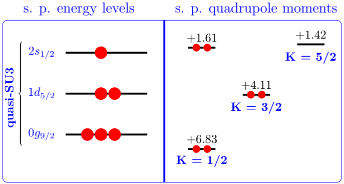

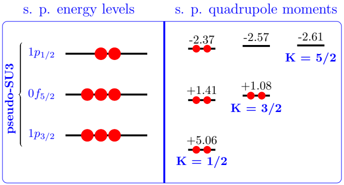

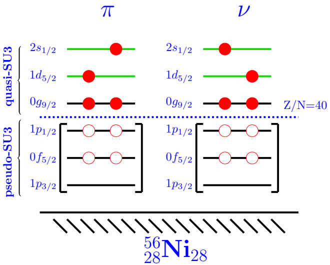

				B(E2)(e^2.fm^4)		
nucleus	Np-Nh*	ZRP	PHF	Exp.	DNO-SM*	SM
^{84}Mo	4p-4h	1104	1193	**1740^{+580}_{-430}**	1765	-
	8p-8h	1891	1732			
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	2p-2h	1030	871			
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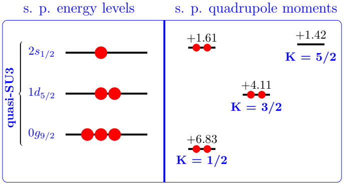

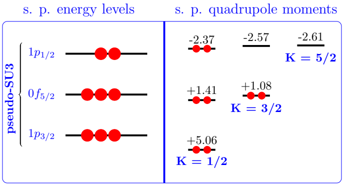

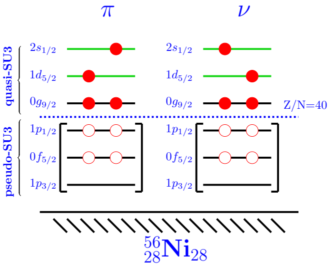

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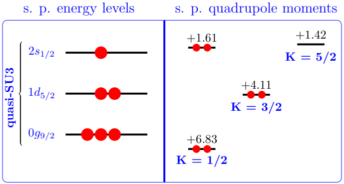

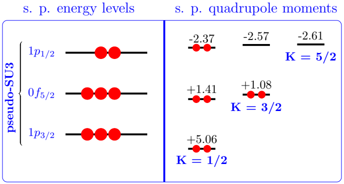

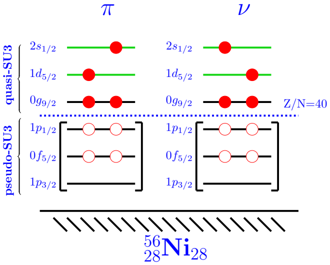

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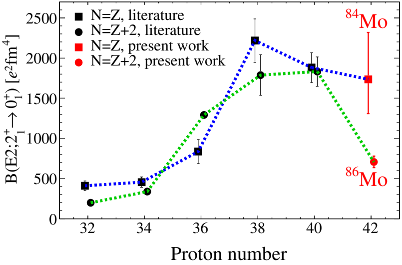

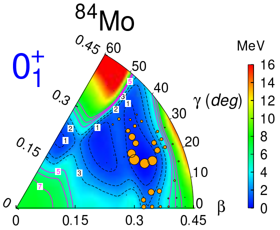

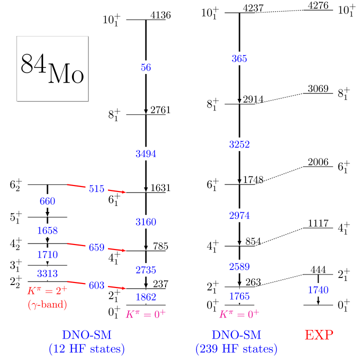

J. Ha, F. Recchia *et al.*, submitted to NATURE

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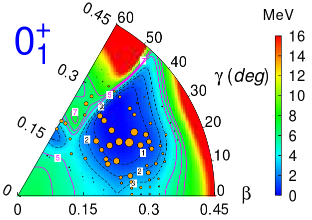

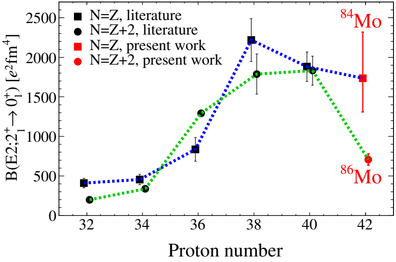

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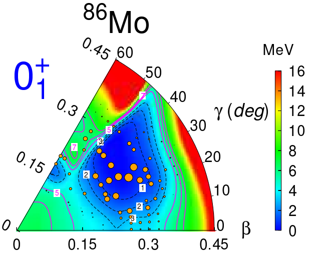

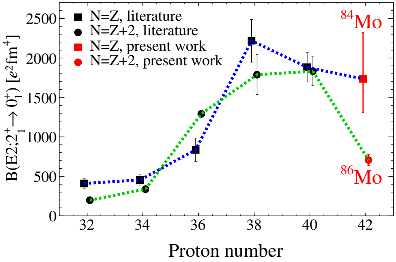

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J. Ha, F. Recchia *et al.*, submitted to NATURE

3N forces in light nuclei

PRL 105, 032501 (2010) PHYSICAL REVIEW LETTERS week ending 16 JULY 2010

Three-Body Forces and the Limit of Oxygen Isotopes

Takaharu Otsuka,[1,2,3] Toshio Suzuki,[4] Jason D. Holt,[5] Achim Schwenk,[5] and Yoshinori Akaishi[6]
[1]*Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan*
[2]*Center for Nuclear Study, University of Tokyo, Hongo, Tokyo 113-0033, Japan*
[3]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan, 48824, USA*
[4]*Department of Physics, College of Humanities and Sciences, Nihon University, Sakurajosui 3, Tokyo 156-8550, Japan*
[5]*TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada*
[6]*RIKEN Nishina Center, Hirosawa, Wako-shi, Saitama 351-0198, Japan*
(Received 17 August 2009; published 13 July 2010)

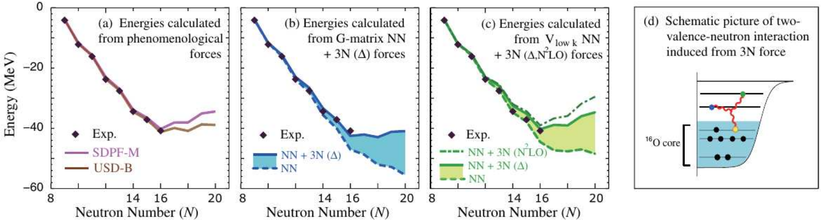


FIG. 4 (color online). Ground-state energies of oxygen isotopes measured from ^{16}O, including experimental values of the bound 16–24 O. Energies obtained from (a) phenomenological forces SDPF-M [13] and USD-B [14], (b) a G matrix and including FM $3N$ forces due to Δ excitations, and (c) from low-momentum interactions $V_{\mathrm{low}\,k}$ and including chiral EFT $3N$ interactions at N^{2}LO as well as only due to Δ excitations [25]. The changes due to $3N$ forces based on Δ excitations are highlighted by the shaded areas. (d) Schematic illustration of a two-valence-neutron interaction generated by $3N$ forces with a nucleon in the ^{16}O core.

3N forces in light nuclei

PRL 109, 032502 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 2012

Evolution of Shell Structure in Neutron-Rich Calcium Isotopes

G. Hagen,[1,2] M. Hjorth-Jensen,[3,4] G. R. Jansen,[3] R. Machleidt,[5] and T. Papenbrock[1,2]
[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[3]*Department of Physics and Center of Mathematics for Applications, University of Oslo, N-0316 Oslo, Norway*
[4]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics, University of Idaho, Moscow, Idaho 83844, USA*
(Received 16 April 2012; published 17 July 2012)

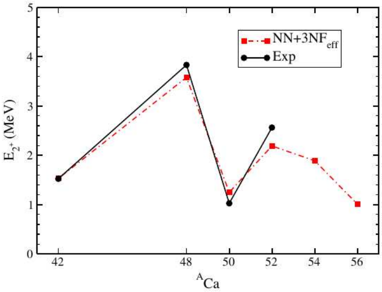


FIG. 2 (color online). (Excitation energies of $J^\pi = 2^+$ states in the isotopes ^{42,48,50,52,54,56}Ca (experiment: black circles, theory: red squares).

Shell closures and 2N forces only

PHYSICAL REVIEW C **74**, 061302(R) (2006)

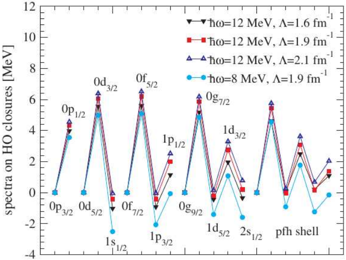
Shell-model phenomenology of low-momentum interactions

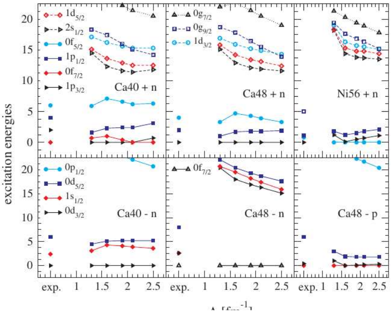
Achim Schwenk[1,*] and Andrés P. Zuker[2,†]

[1]*Nuclear Theory Center, Indiana University, 2401 Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*

[2]*Institut de Recherches Subatomiques, IN2P3-CNRS, Université Louis Pasteur, F-67037 Strasbourg, France*

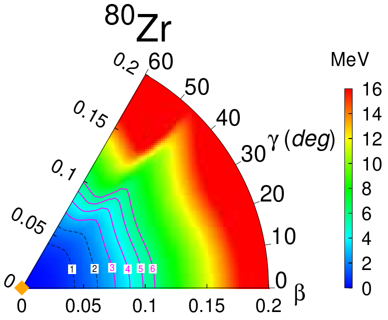
(Received 14 January 2005; revised manuscript received 20 September 2006; published 12 December 2006)

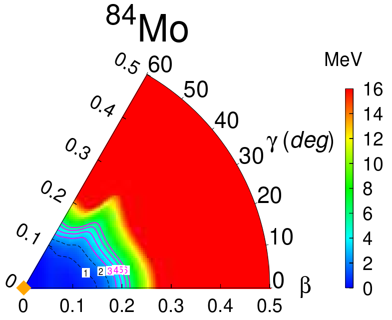




- no Spin-orbite shell closures in ^{12}C, ^{22}O, ^{48}Ca, ^{56}Ni
- too strong H. O. shell closures ^{16}O, ^{40}Ca, ... and ^{80}Zr !!!

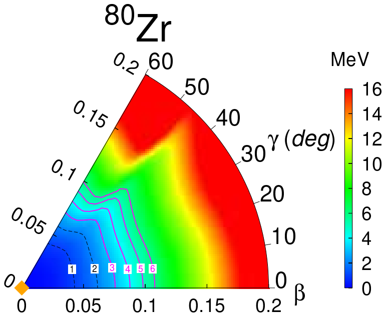
N3LO NN calculations

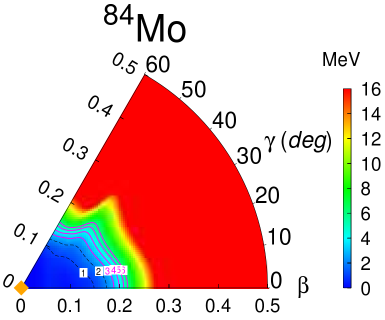




nucleus	NpNh*	ZRP	PHF	B(E2)($e^2.fm^4$) Exp.	DNO-SM	N3LO
^{80}Zr	4p-4h 8p-8h 12p-12h	587 1713 2663	637 1509 2396	**1910(180)**	2325	0.03
^{84}Mo	4p-4h 8p-8h	1104 1891	1193 1732	**1740^{+580}_{-430}**	1740	174

N3LO NN calculations





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	12p-12h	2663	2396			
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Island of Inversion at the N=Z line

◇ Strongly deformed states at $N = Z$

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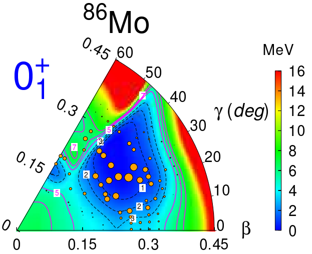

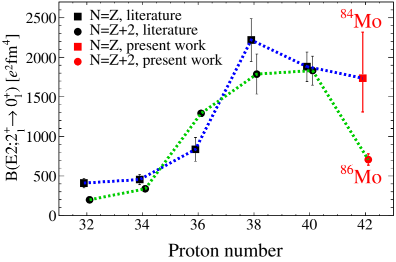

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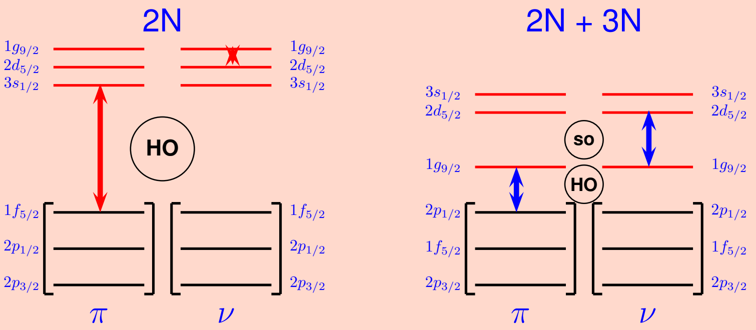
J. Ha, F. Recchia *et al.*, submitted to NATURE

Island of Inversion at the N=Z line

◇ Strongly deformed states at $N = Z$

^{86}Mo

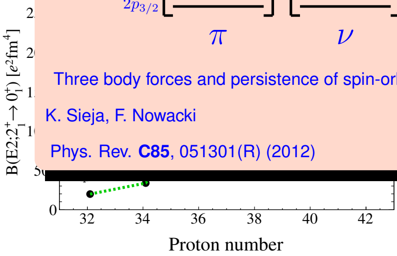
2N   2N + 3N



Three body forces and persistence of spin-orbit shell gaps in medium-mass nuclei: Towards the doubly magic ^{78}Ni,

K. Sieja, F. Nowacki

Phys. Rev. **C85**, 051301(R) (2012)



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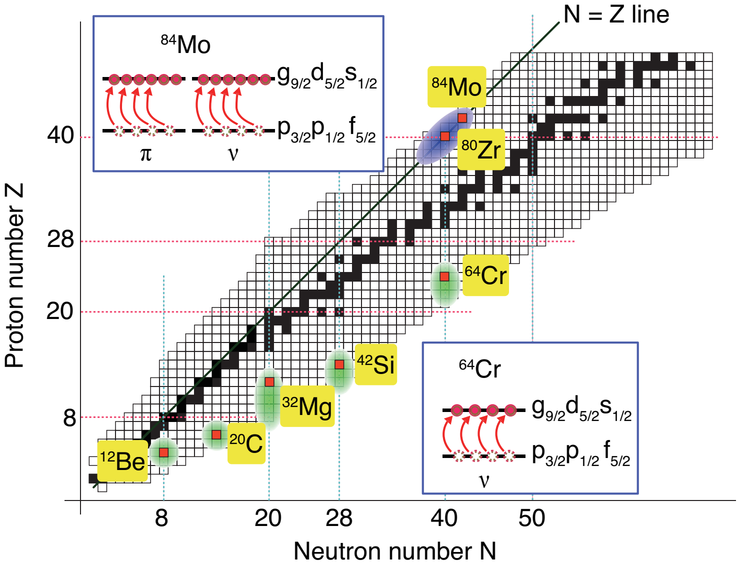
6p-6h   1858   1655

J. Ha, F. Recchia *et al.*, submitted to NATURE

Isospin Symmetric Island of Inversion



Summary

- Monopole drift develops in all regions but the Interplay between correlations (pairing + quadrupole) and spherical mean-field (monopole field) determines the physics.

- New “island of inversion” or “island of deformation” present for neutron-rich systems show up also at N=Z line with very deformed rotors dominated by Many-particles-Many-holes configurations.

- Shape transition between ^{84}Mo and ^{86}Mo and first fingerprint of 3N forces in deformed systems

- Around A$\sim$ 80, an “island of enhanced collectivity” show very deformed rotors dominated by Many-particles-Many-holes configurations.

- Ongoing NN + 3N(lnl) ab-initio calculations

Summary

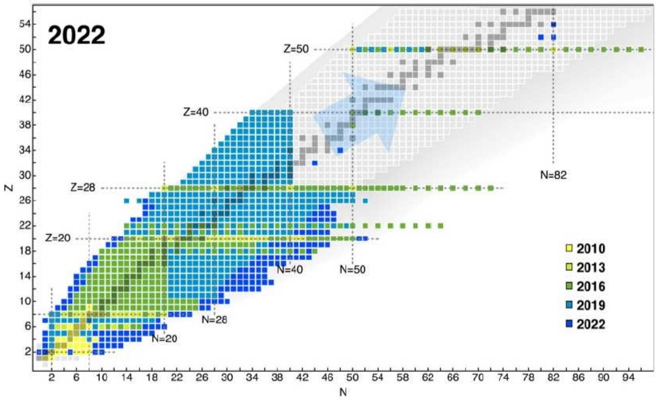
Special thanks to:

- D. D. Dao, K. Sieja
- G. Martinez-Pinedo, A. Poves, S. Lenzi
- A. Gade, O. Sorlin, A. Obertelli

Ab-initio predictions ?

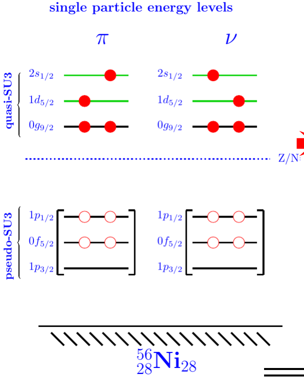
Ab Initio Progress: How Heavy Can We Go?

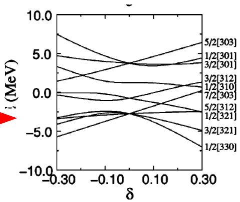
Tremendous progress in ab initio reach, largely due to polynomially scaling methods!

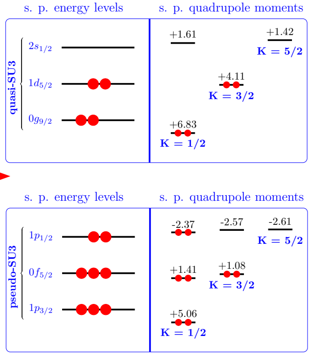


Jason Holt 2023

Nilsson-SU3 estimates

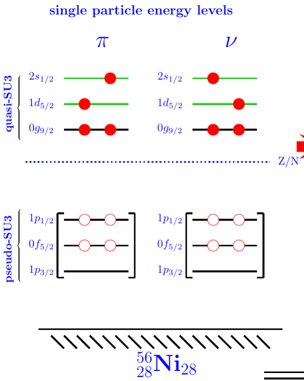


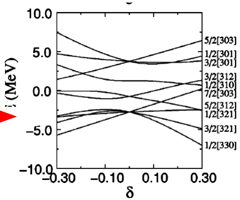


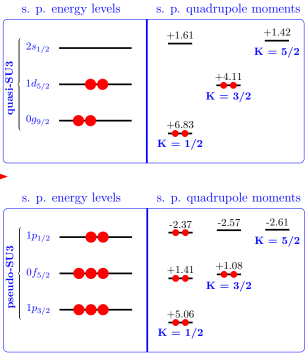


nucleus	NpNh*	ZRP	PHF	Exp.	DNO-SM
		B(E2)(e^2.fm^4)			
^{76}Sr	4p-4h	924	806	2390(240)	1847
	8p-8h	2189	2101		
	12p-12h	2316	2300		
^{80}Zr	4p-4h	587	637	1910(180)	2325
	8p-8h	1713	1509		
	12p-12h	2663	2396		

Nilsson-SU3 estimates







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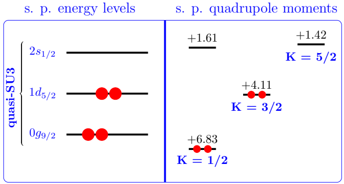
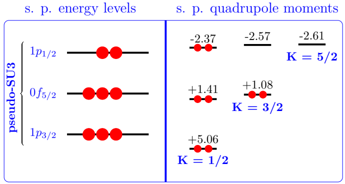
Island of Inversion at the N=Z line

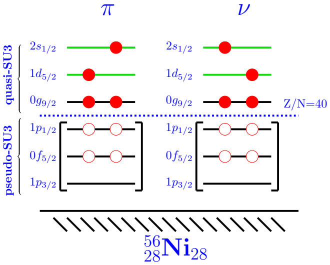
◇ Strongly deformed states at $N = Z$

- Configuration mixing in ^{72}Kr
- Most deformed cases for ^{76}Sr, ^{80}Zr
- Shape transition between ^{84}Mo and ^{86}Mo

NSCL/GRETINA Experiment







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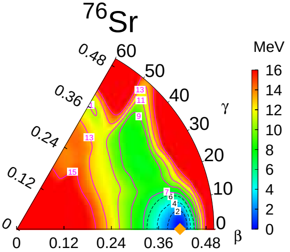

R.D.O. Llewellyn *et al.*, Phys. Rev. Lett. **124**, 152501 (2020)

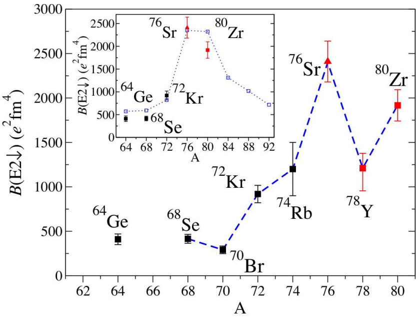

FIG. 3. Schematics of the $B(E2\downarrow)$ values for the $N = Z$ nuclei