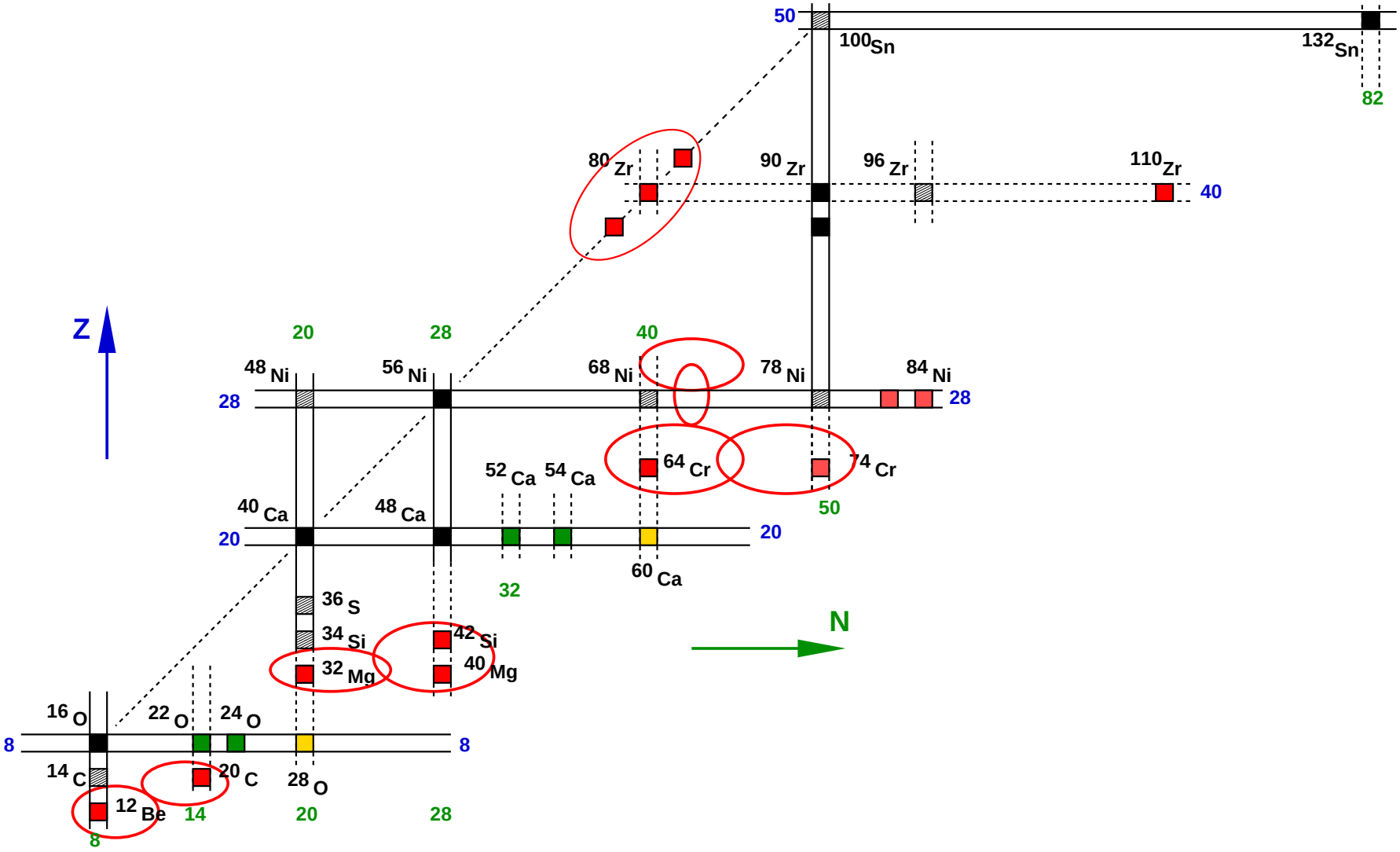
Three body forces revealed in strongly deformed nuclei

Frédéric Nowacki

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

Landscape of medium mass nuclei



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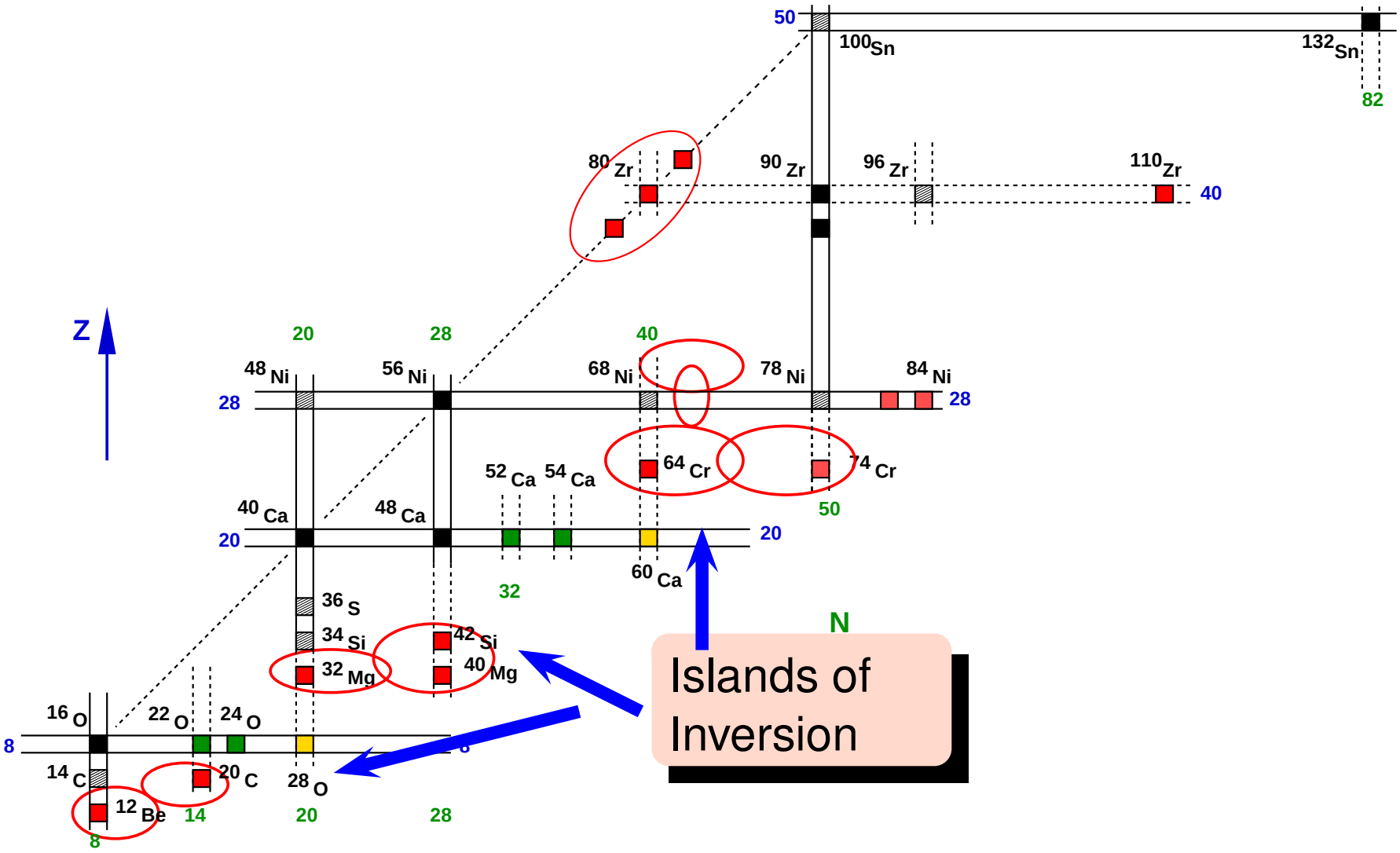

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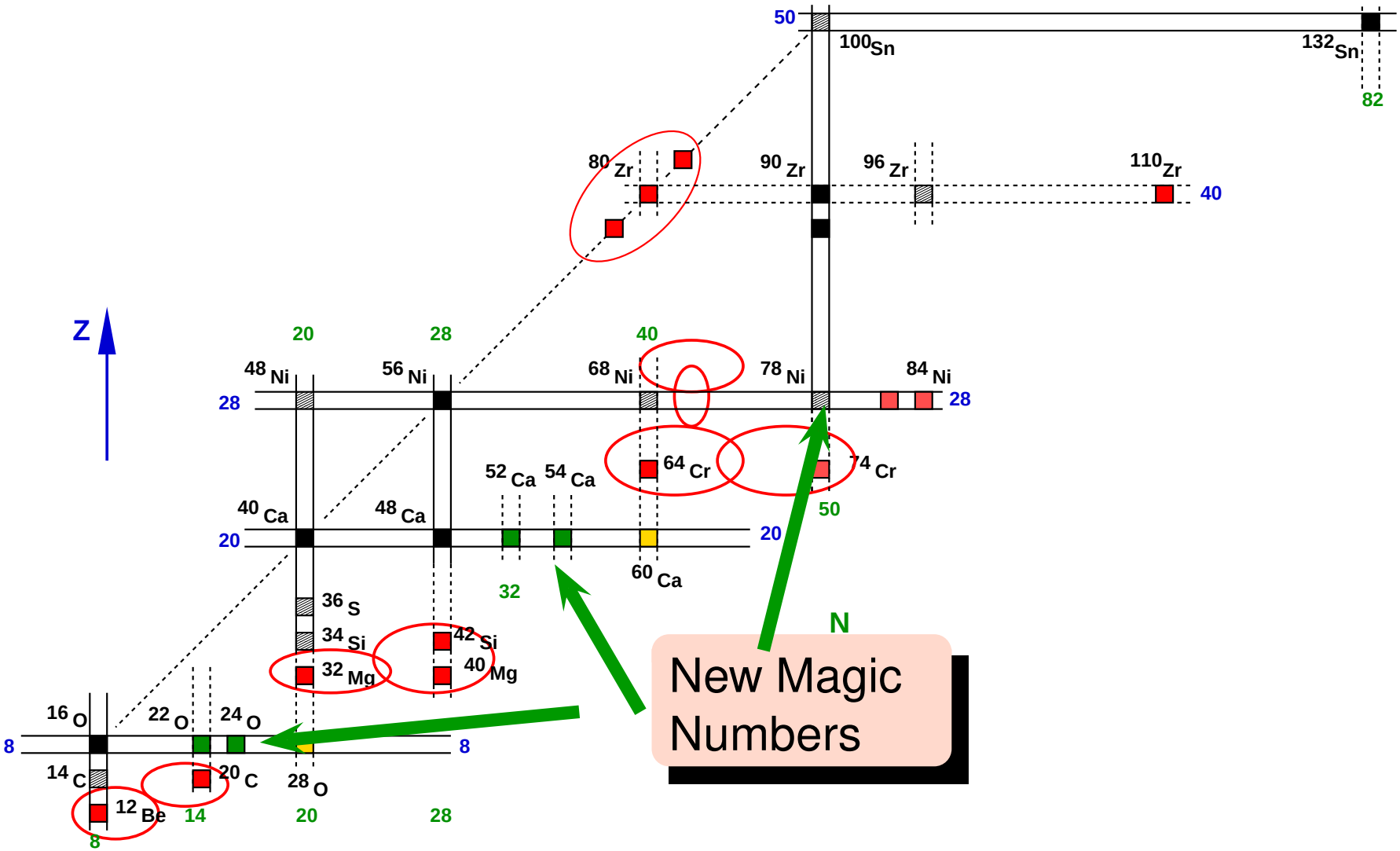

3N forces in light nuclei

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*

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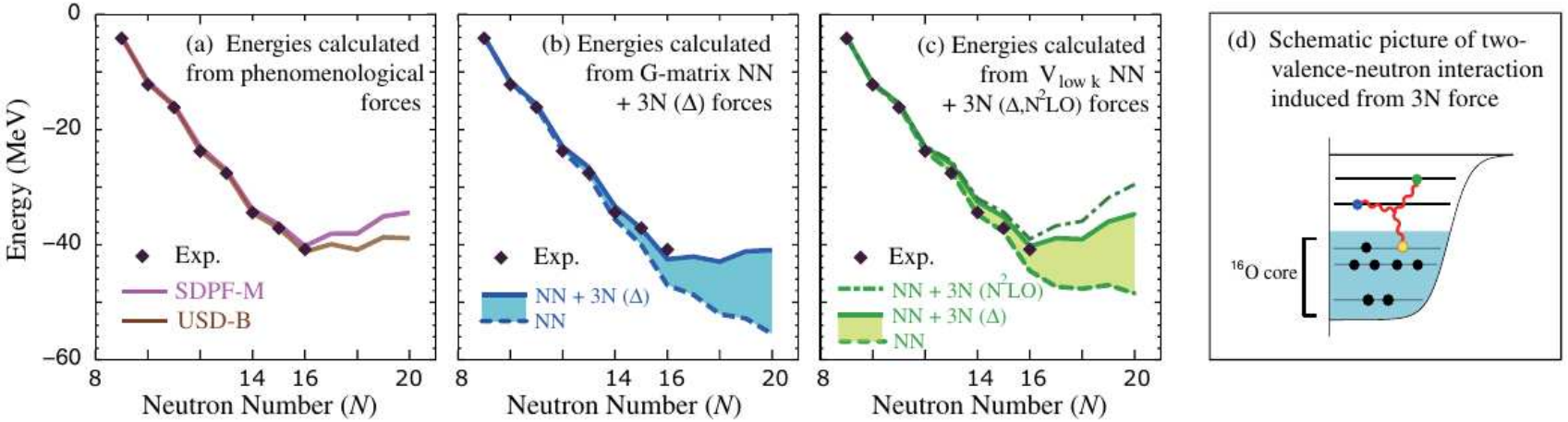

FIG. 4 (color online). Ground-state energies of oxygen isotopes measured from ^{16}O, including experimental values of the bound 16–24 O. Energies obtained from (a) phenomenological forces SDPF-M [13] and USD-B [14], (b) a G matrix and including FM 3N forces due to Δ excitations, and (c) from low-momentum 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*

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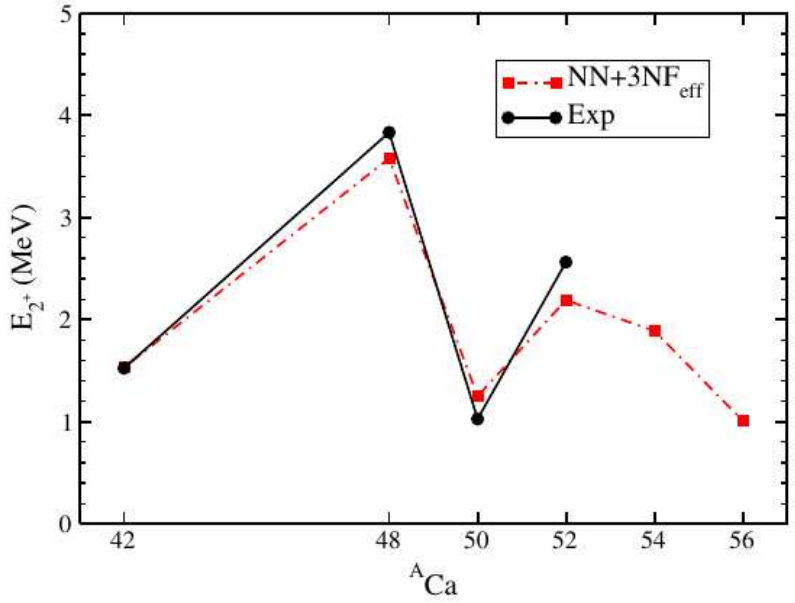


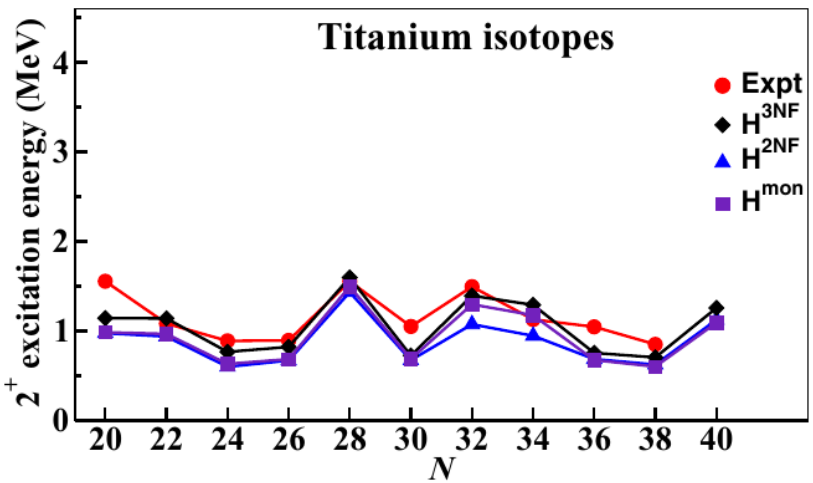
FIG. 2 (color online). (Excitation energies of $J^\pi = 2^+$ states in the isotopes ^{42,48,50,52,54,56}Ca (experiment: black circles, theory: red squares)

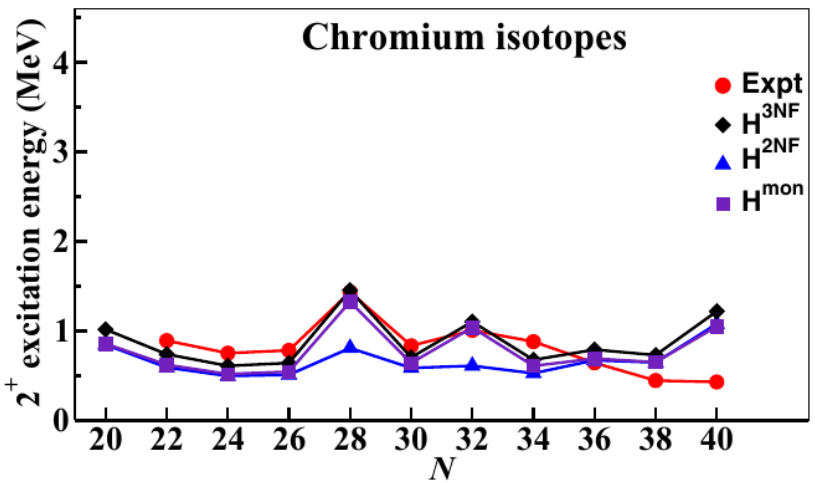
3N forces in light nuclei

PHYSICAL REVIEW C **100**, 034324 (2019)

Contribution of chiral three-body forces to the monopole component of the effective shell-model Hamiltonian

Y. Z. Ma,[1] L. Coraggio,[2] L. De Angelis,[2] T. Fukui,[2] A. Gargano,[2] N. Itaco,[2,3] and F. R. Xu[1]





3N forces in light nuclei

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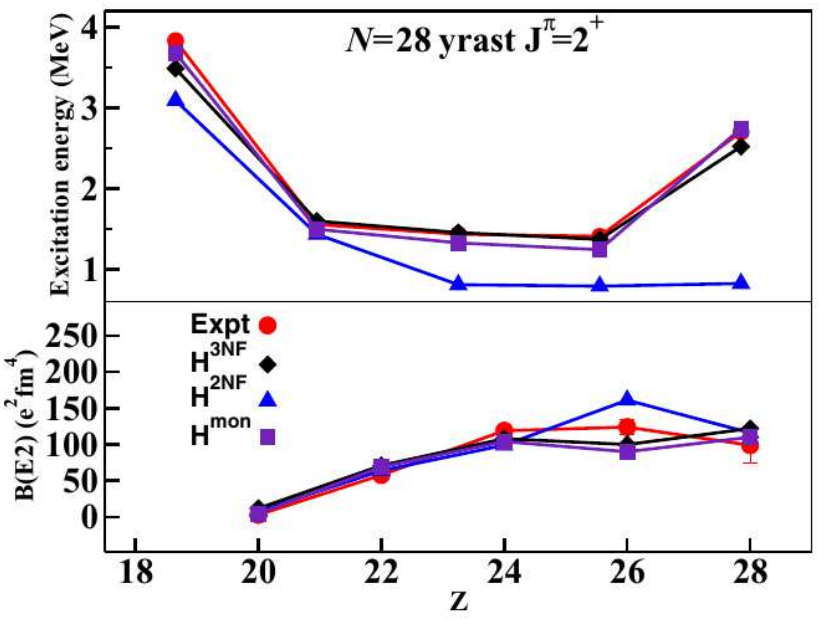
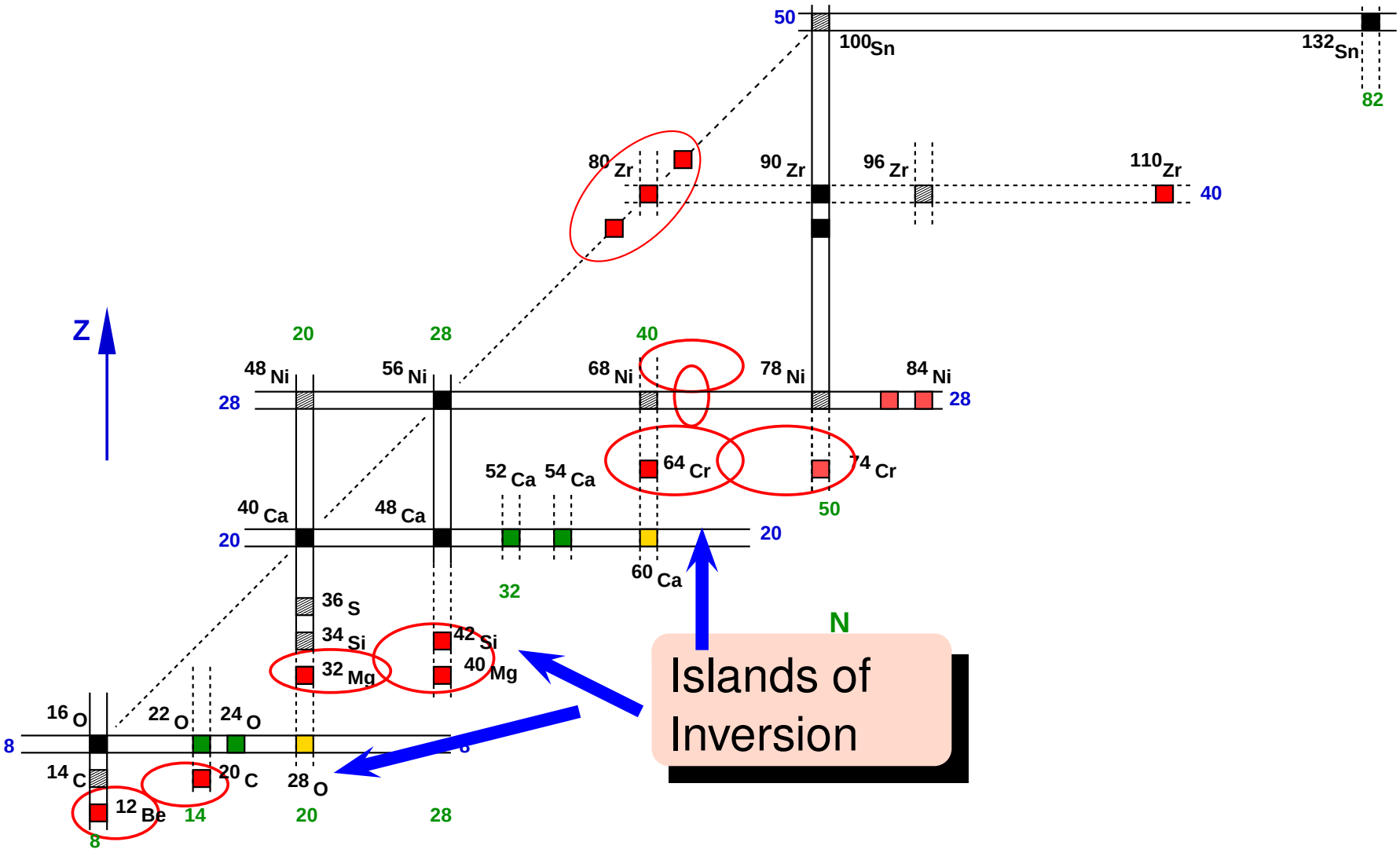
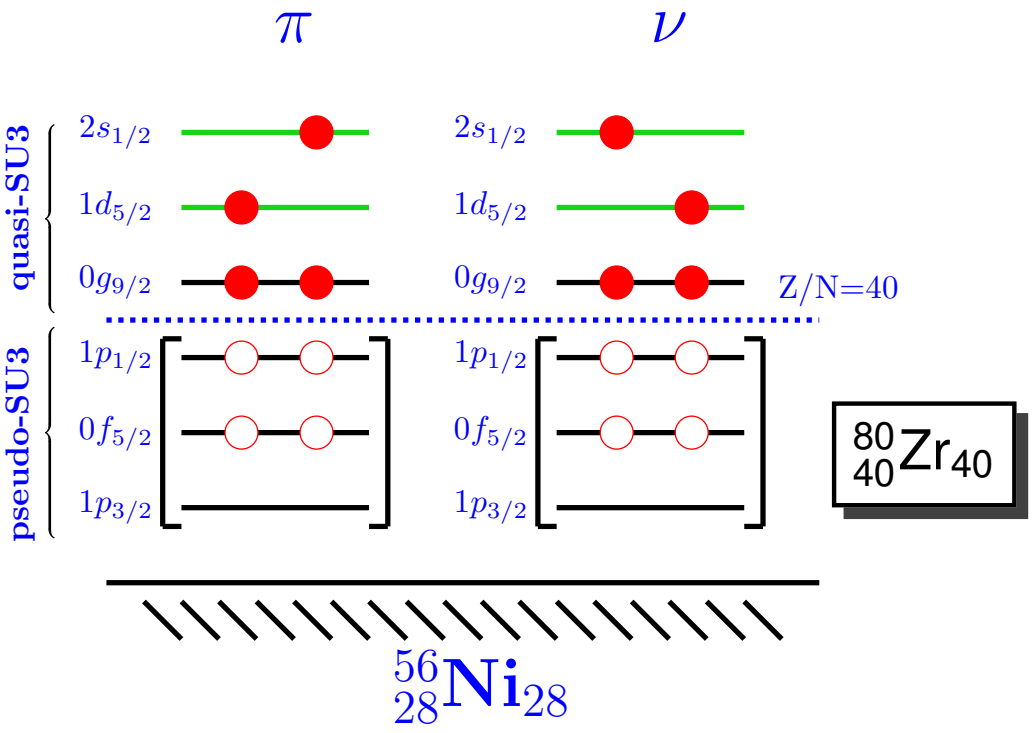


FIG. 22. Experimental and calculated excitation energies of the yrast $J^\pi = 2^+$ states and $B(E2; 2_1^+ \rightarrow 0_1^+)$ transition rates for the $N = 28$ isotones. See text for details.

Landscape of medium mass nuclei



H.O. vs Spin-Orbit shell closure at N=Z



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

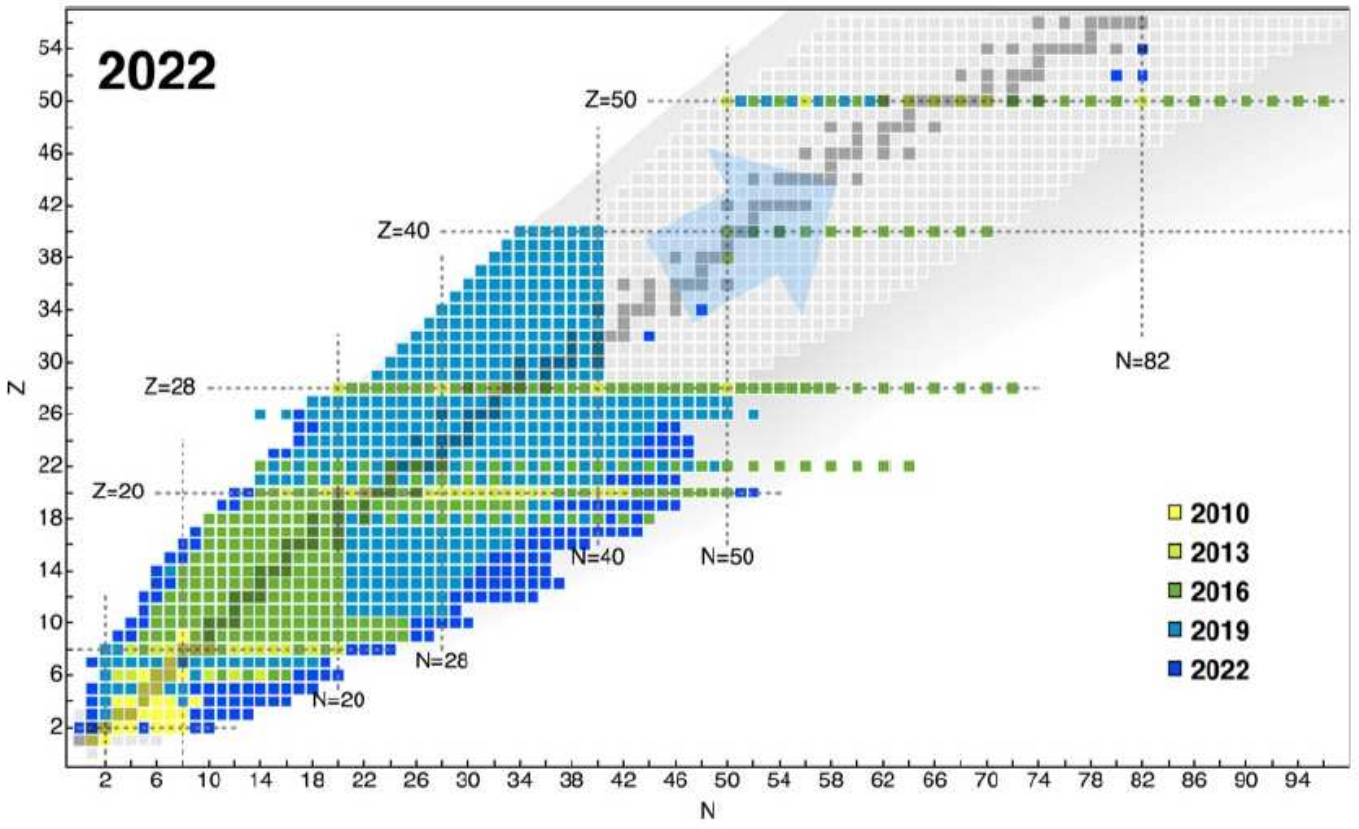
- Low-lying states in H.O. N=Z=8: **CS** , 4p4h, 8p8h
- Low-lying states in H.O. N=Z=20: **CS** , 4p4h,8p8h
- Low-lying states in H.O. N=Z=40: 4p4h ? 8p8h ? 12p12h ?

Ab-initio predictions ?

TRIUMF

Ab Initio Progress: How Heavy Can We Go?

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



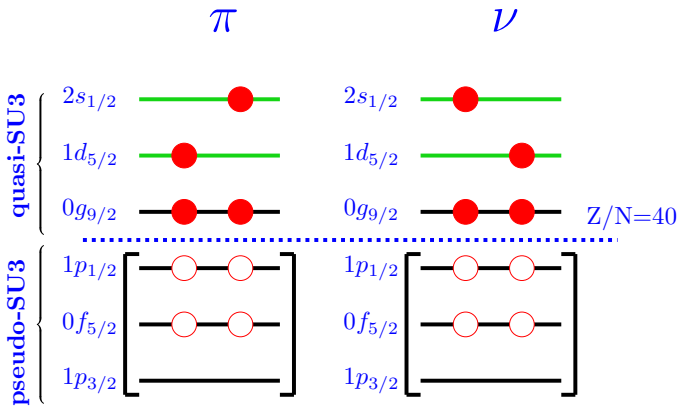
Jason Holt 2023

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.*, Phys. Rev. Lett. **124**, 152501

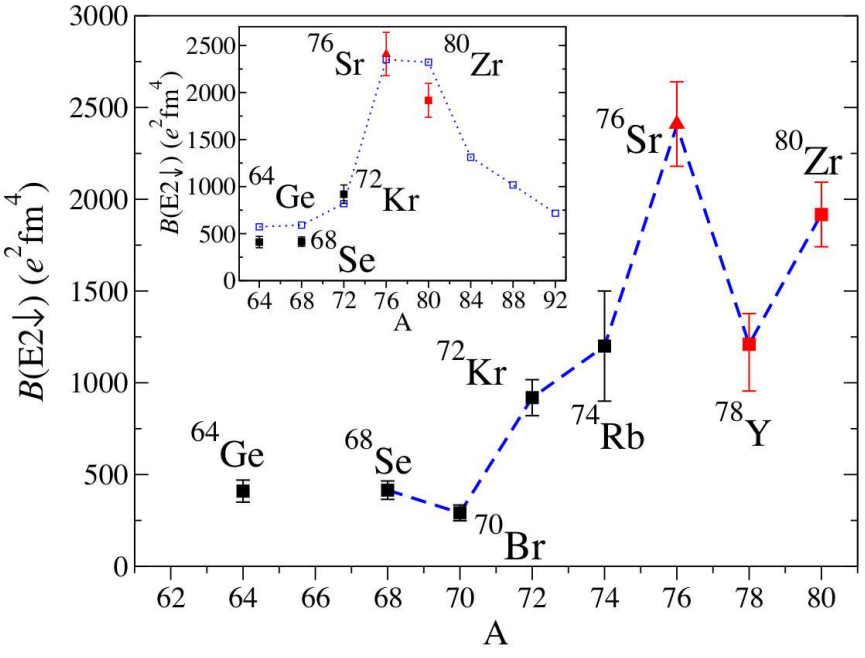


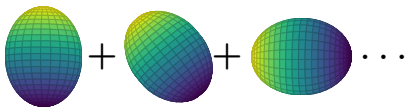
FIG. 3. Schematics of the $B(E2\downarrow)$ values for the $N = Z$ nuclei

- 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

Discrete Non-Orthogonal Shell Model

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

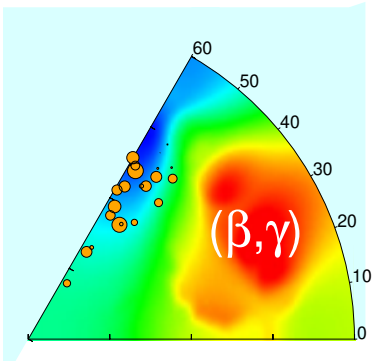
1) Deformed Hartree-Fock (HF) Slater determinants
2) Restoration of rotational symmetry
3) Mixing of shapes:

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

Intrinsic/Laboratory Description

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

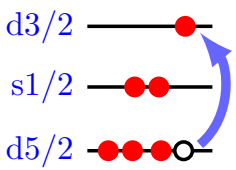
$$M^{(J)}_\alpha(q, K) = \sum_{q', K'} [\hat{N}^{1/2}]^{(J)}_{K'K}(q', q)\, f^{(J)}_\alpha(q', K')$$



◇ Probability of a configuration (β, γ):

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

- **particle-hole interpretation**:

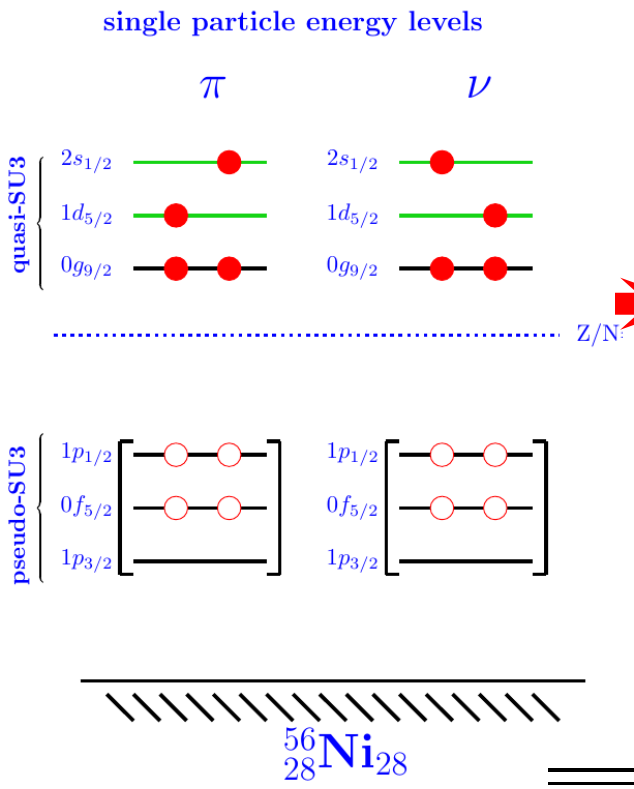


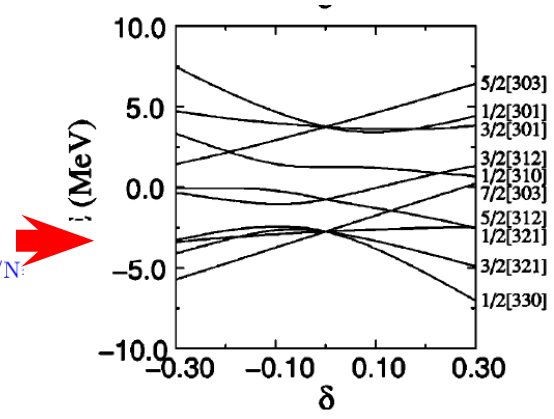
M-scheme

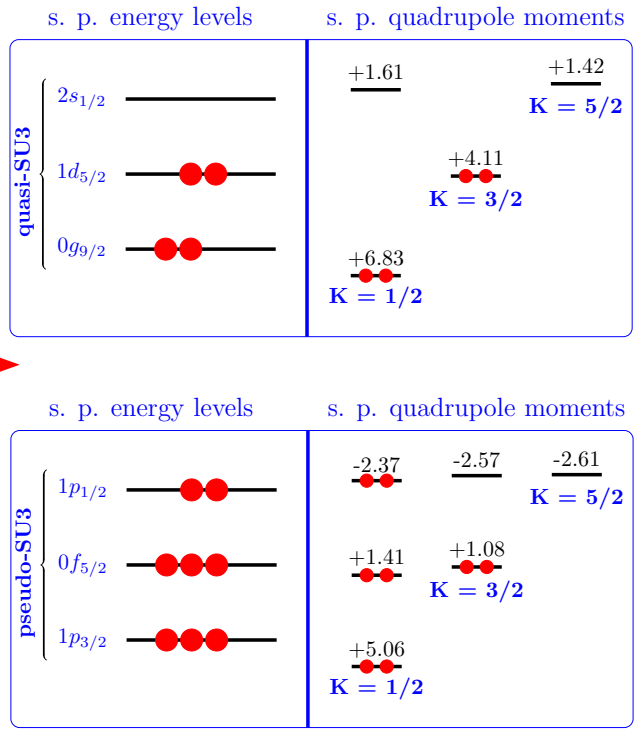
- K**–quantum numbers**:

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

Nilsson-SU3 estimates







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	8p-8h	2189	2101		
	12p-12h	2316	2300		
^{80}Zr	4p-4h	587	637	1910(180)	2325
	8p-8h	1713	1509		
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Nilsson-SU3 estimates

quasi-SU3

pseudo-SU3

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

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

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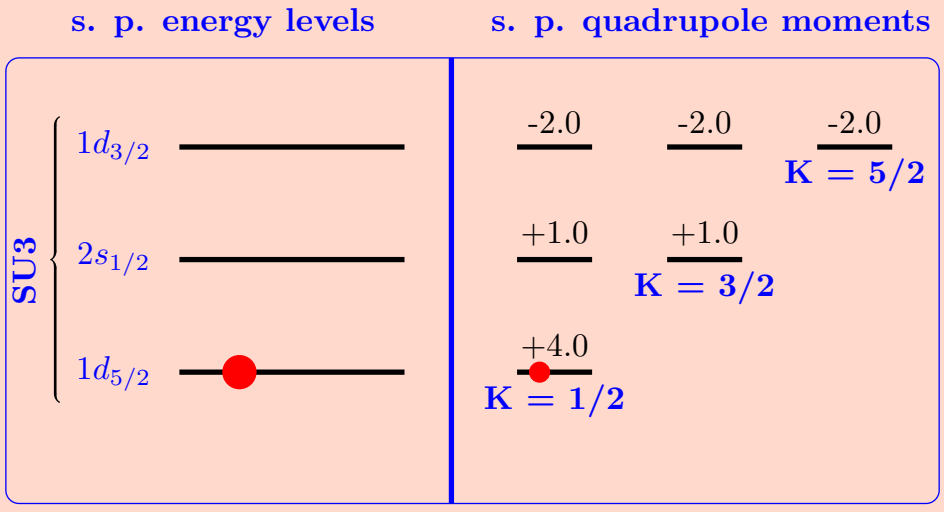

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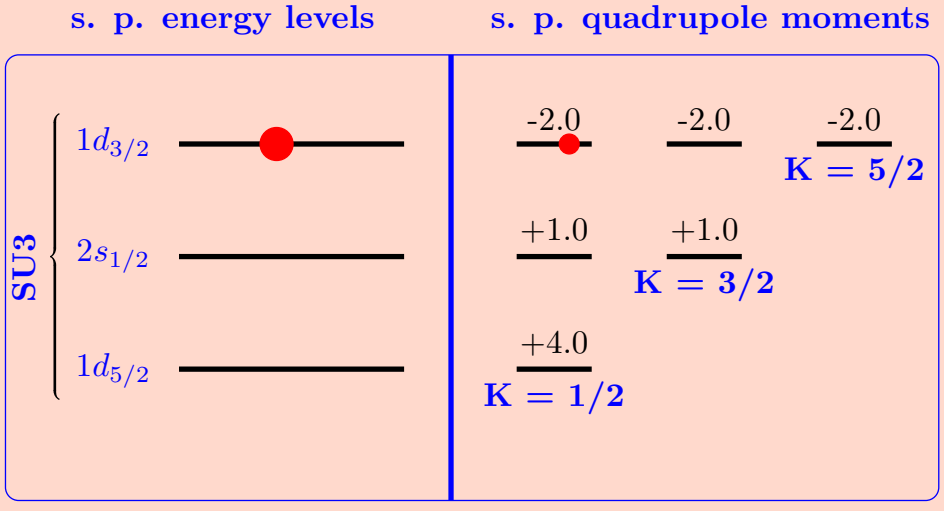

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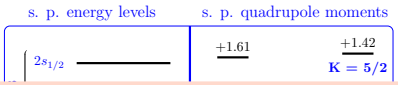

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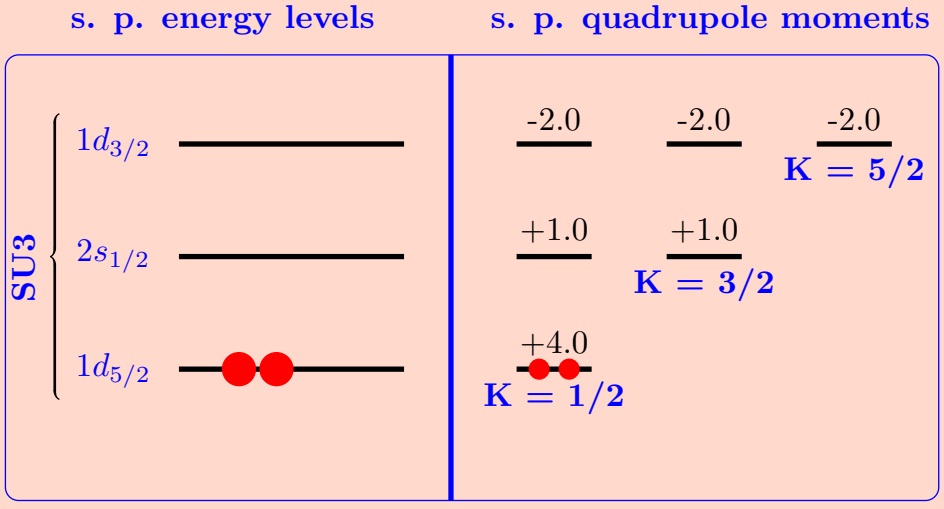

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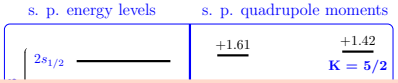

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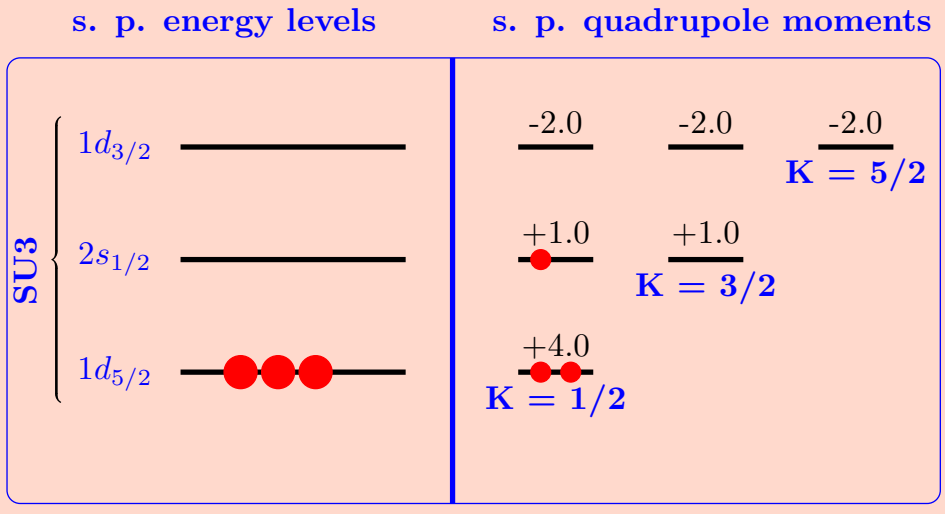

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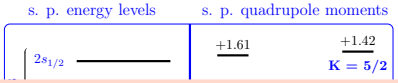

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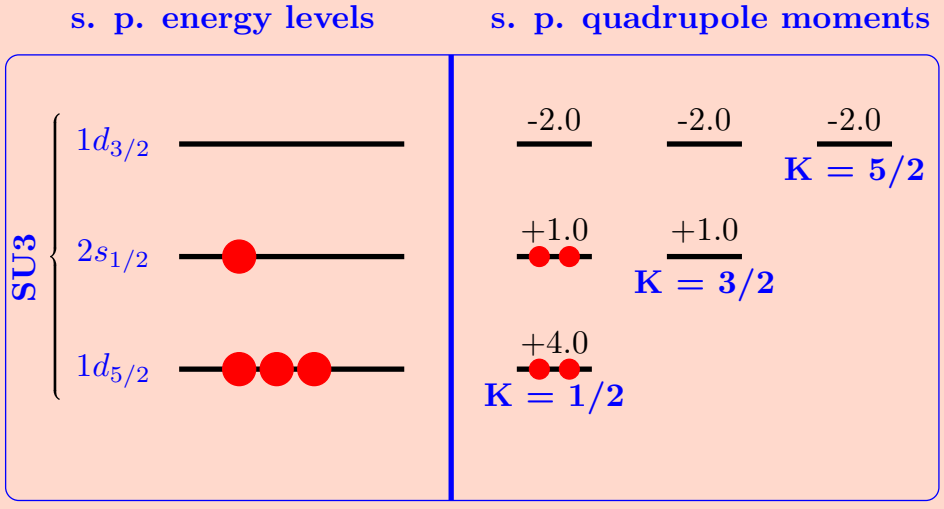

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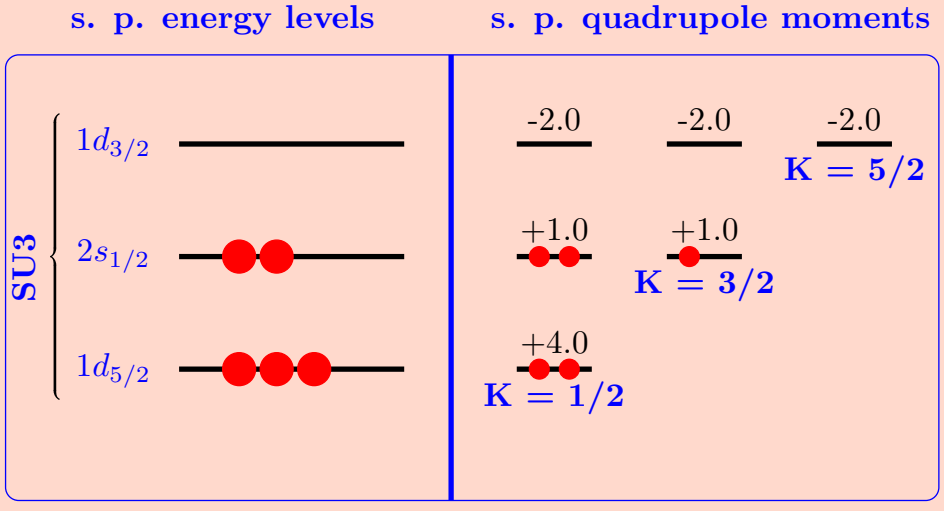

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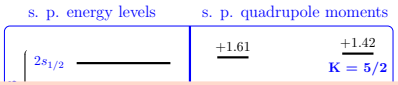

quasi-SU3

pseudo-SU3

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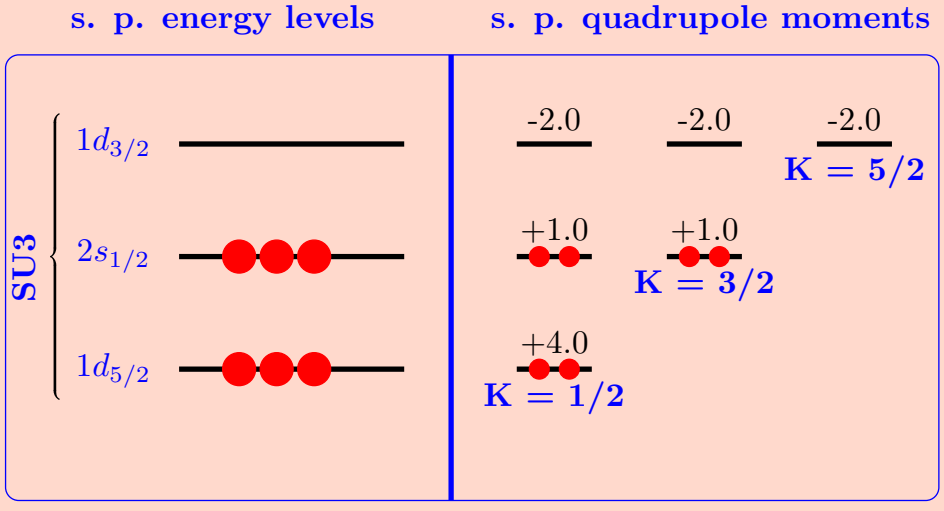

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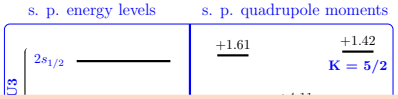
Nilsson-SU3 estimates

single particle energy levels

quasi-SU3

pseudo-SU3



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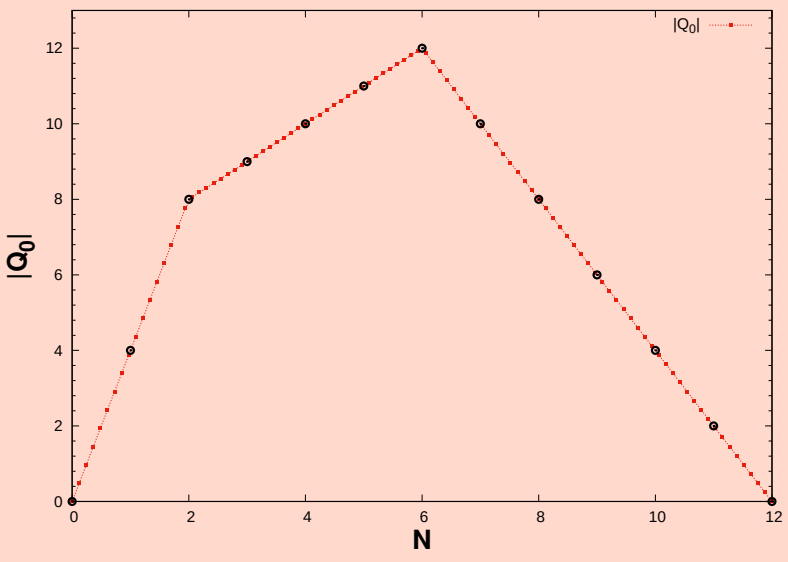

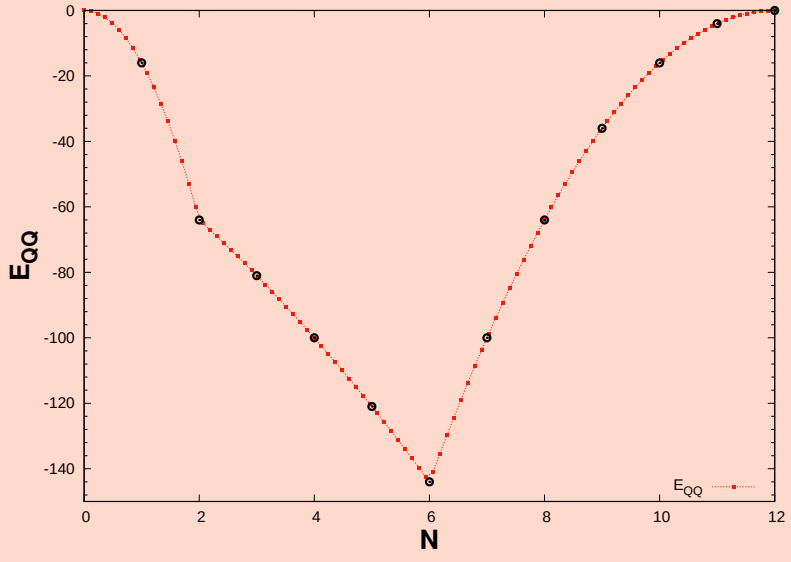

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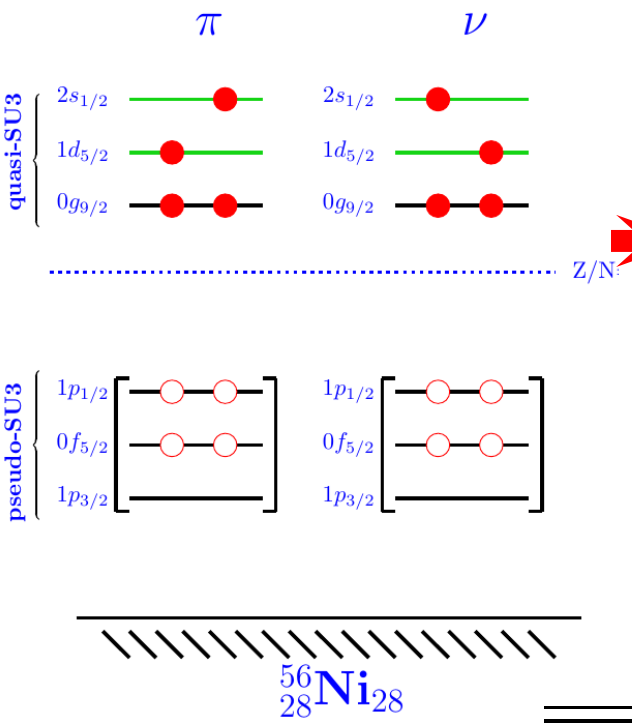

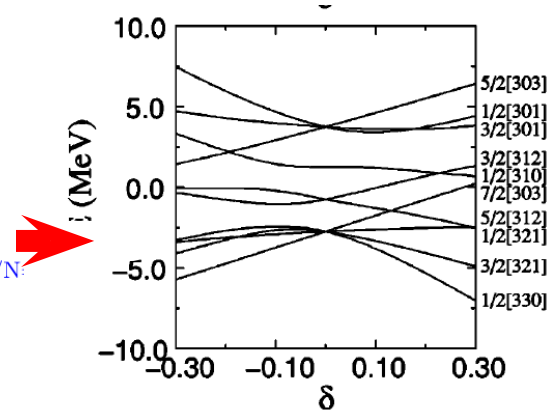

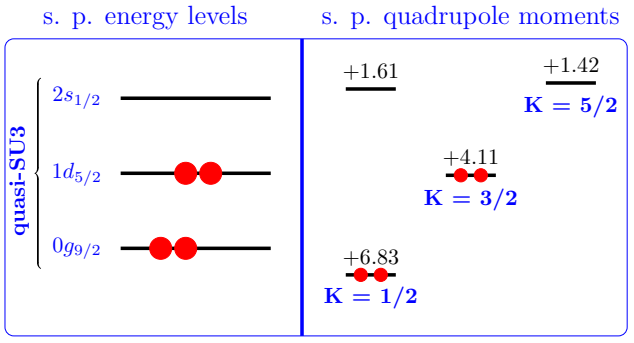

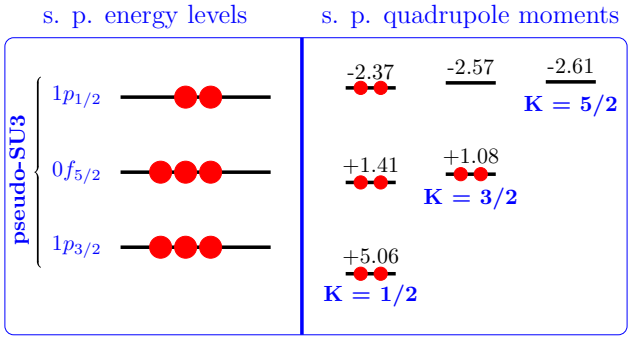

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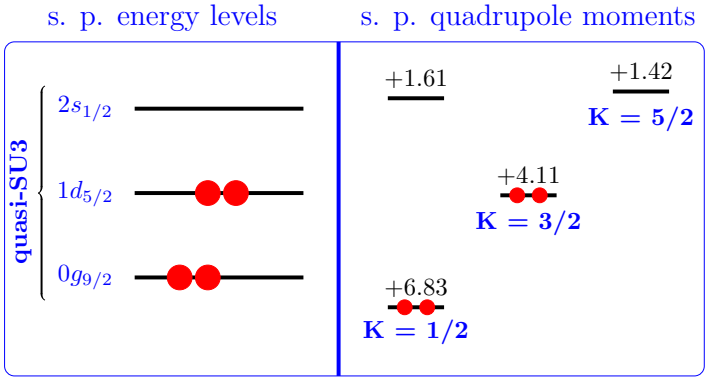

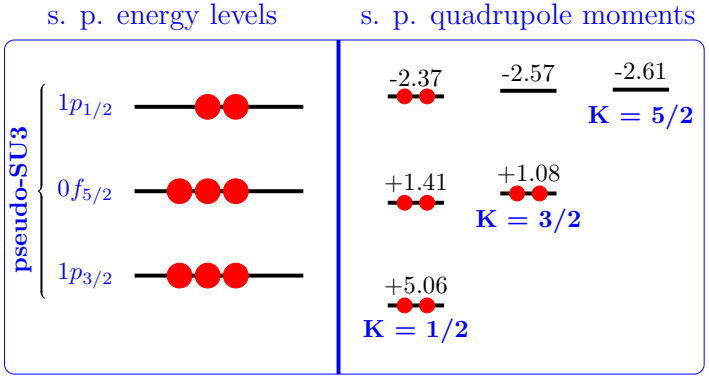

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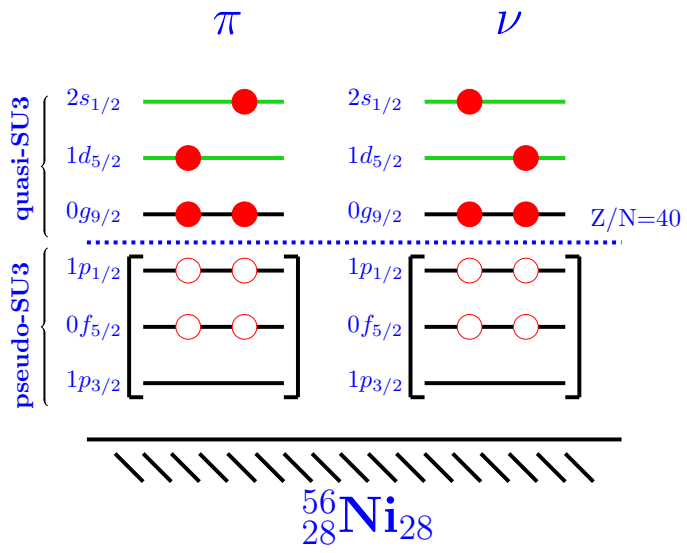

				B(E2)(e^2.fm^4)	
nucleus	NpNh*	ZRP	PHF	**Exp.**	DNO-SM
^{76}Sr	4p-4h	924	806	**2390(240)**	1847
	8p-8h	2189	2101		
	12p-12h	2316	2300		
^{80}Zr	4p-4h	587	637	**1910(180)**	2325
	8p-8h	1713	1509		
	12p-12h	2663	2396		

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
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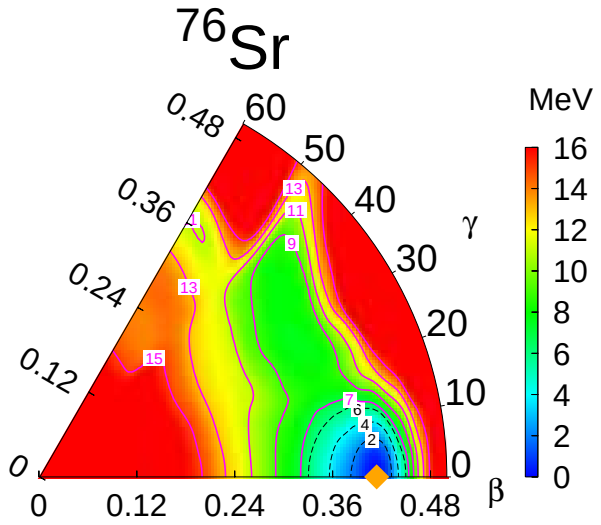
NSCL/GRETINA Experiment



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

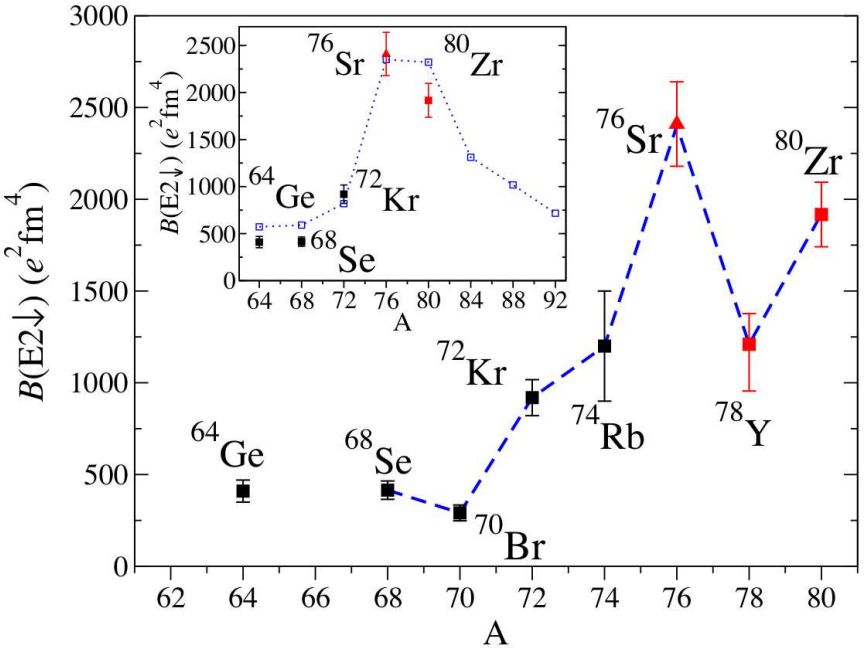
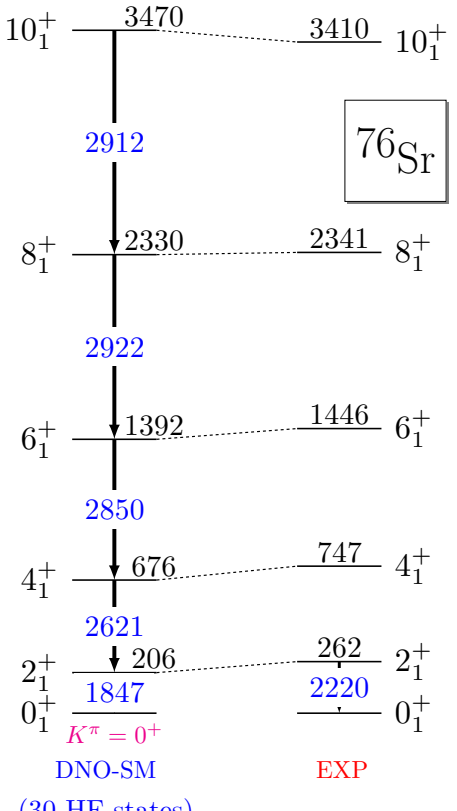


FIG. 3. Schematics of the $B(\mathrm{E2}\downarrow)$ values for the $N = Z$ nuclei



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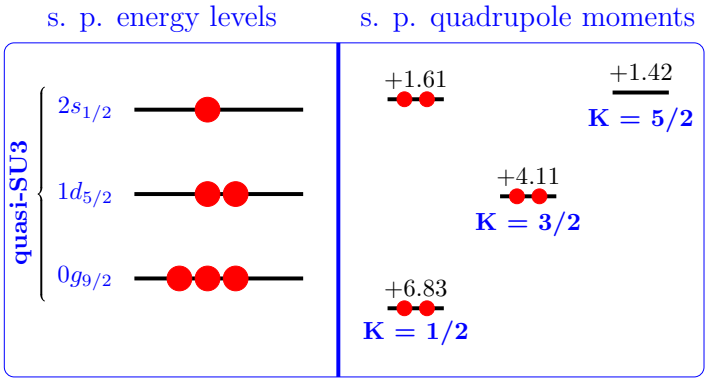

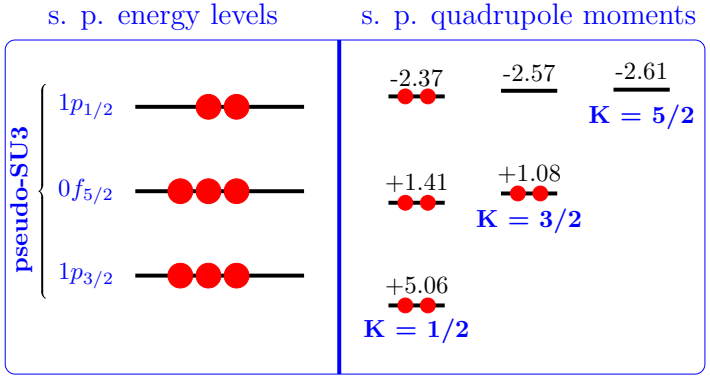

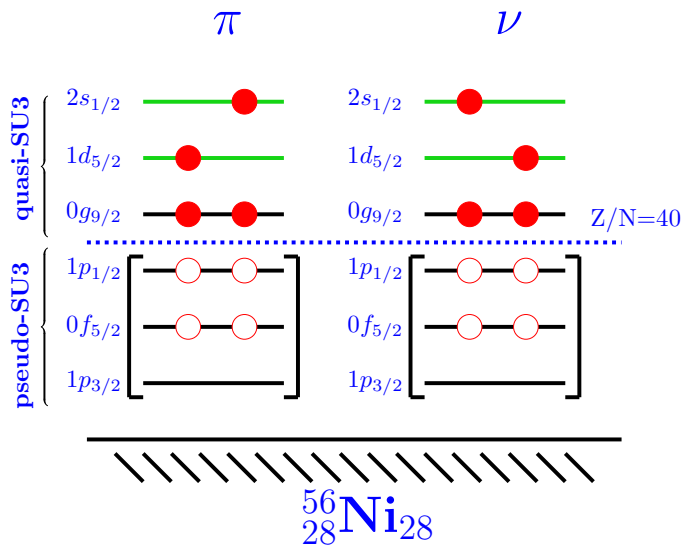

				B(E2)(e^2.fm^4)		
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^{84}Mo	4p-4h	1104	1193	1740^{+580}_{-430}	1765	-
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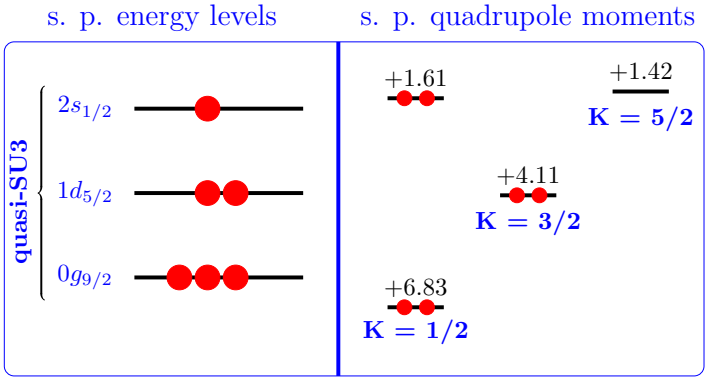

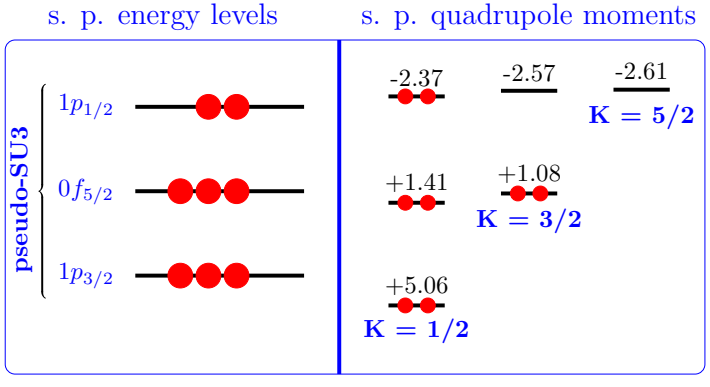

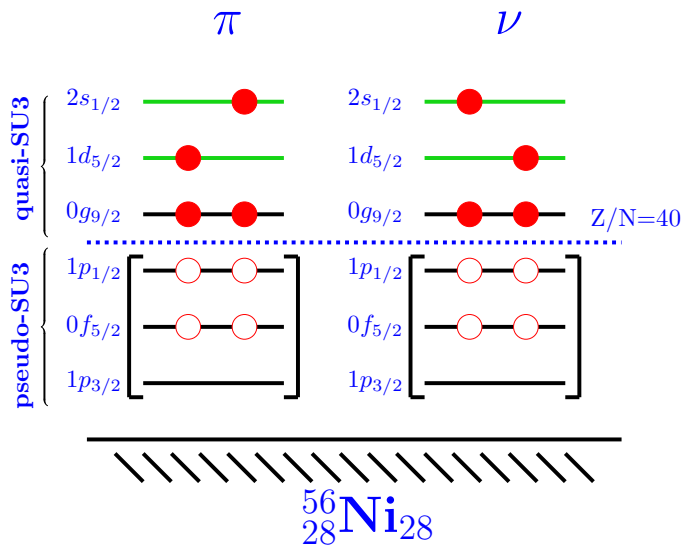

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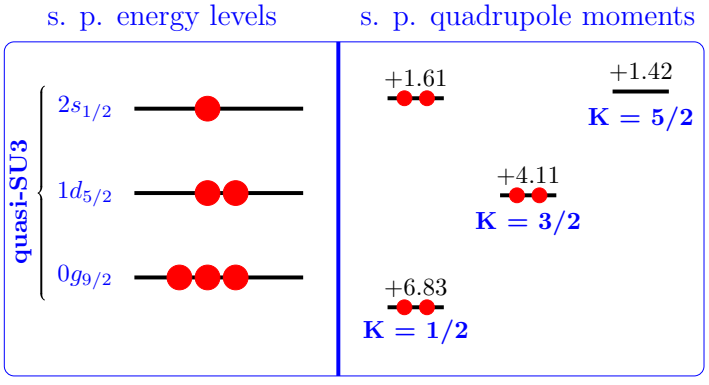

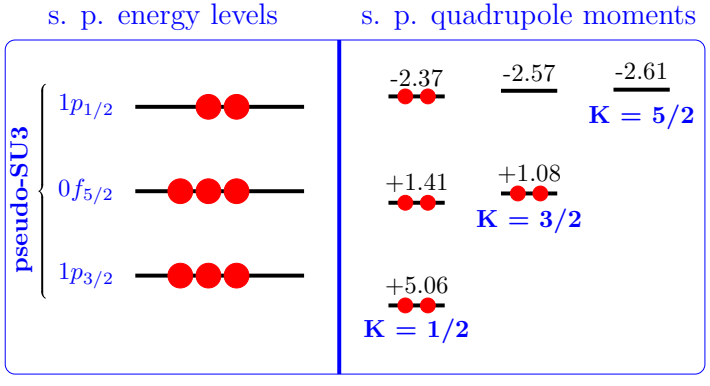

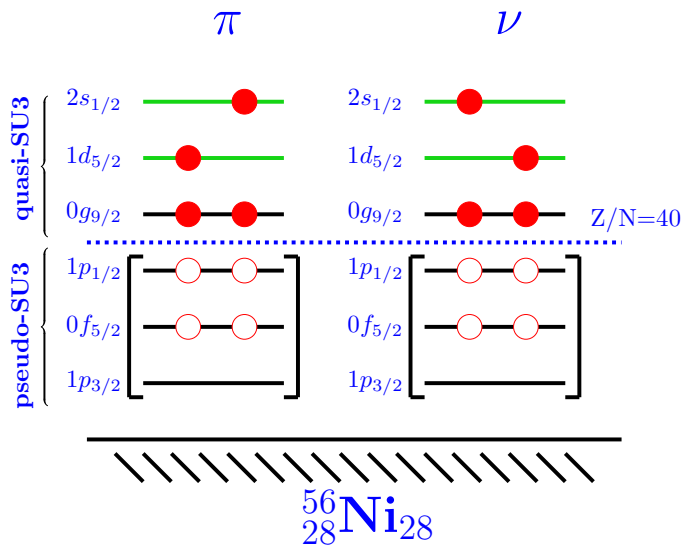

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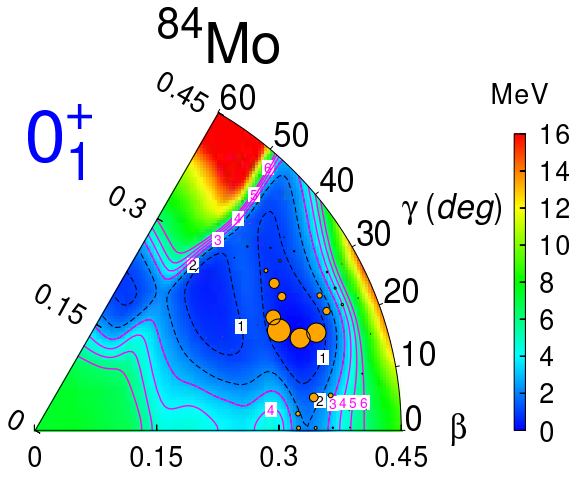

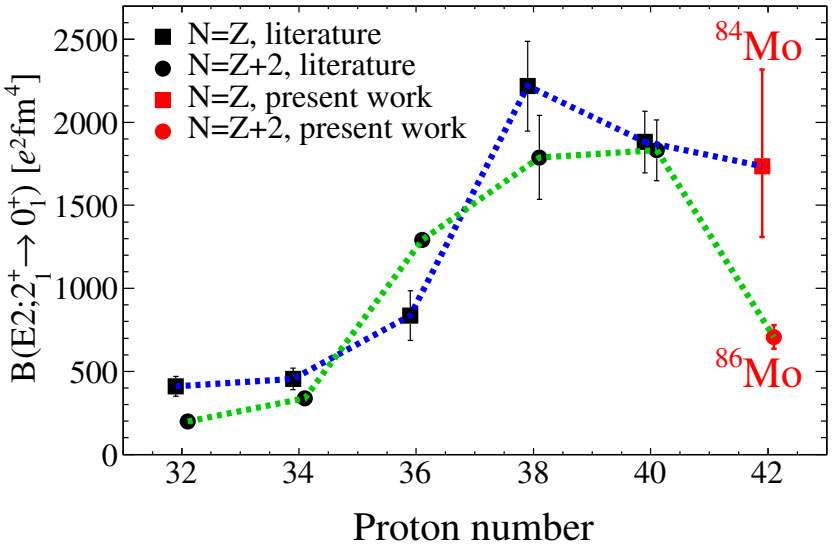

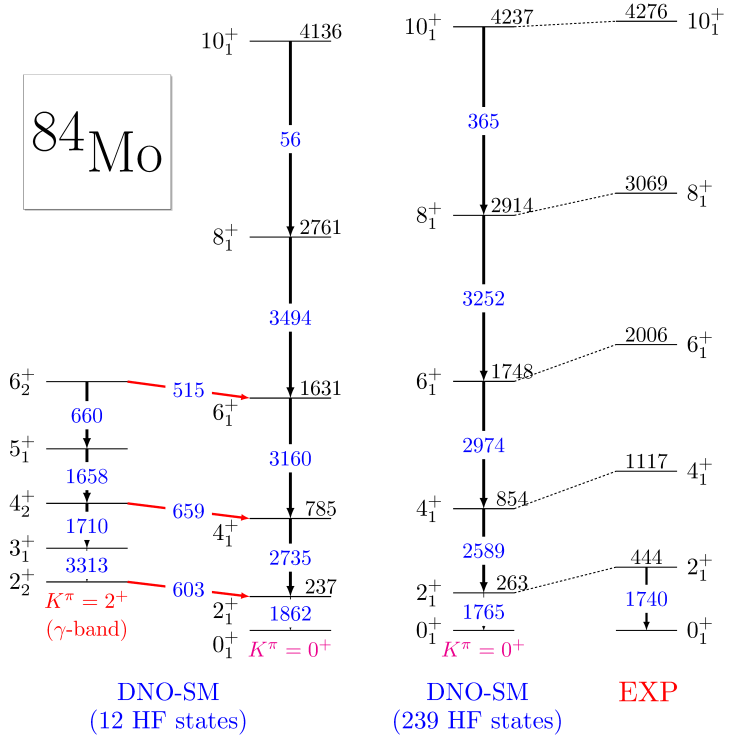

J. Ha, F. Recchia *et al.*, to be submitted

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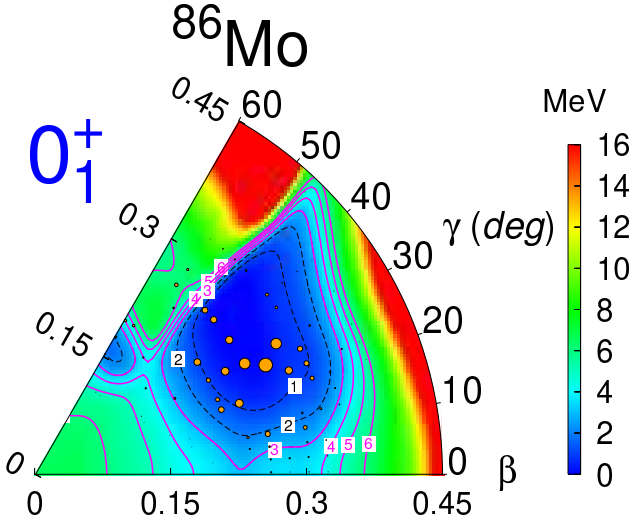

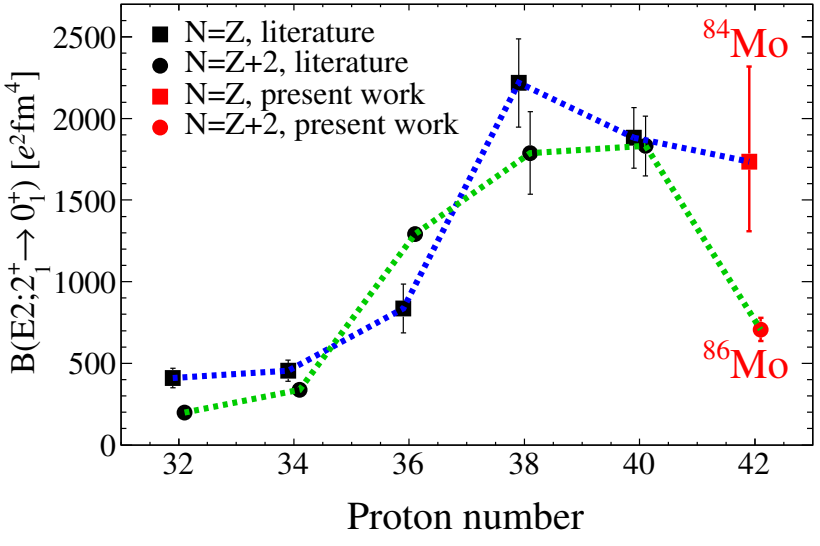

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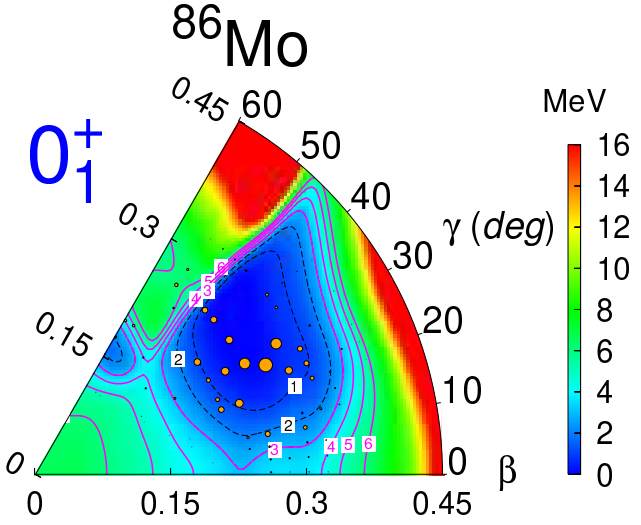

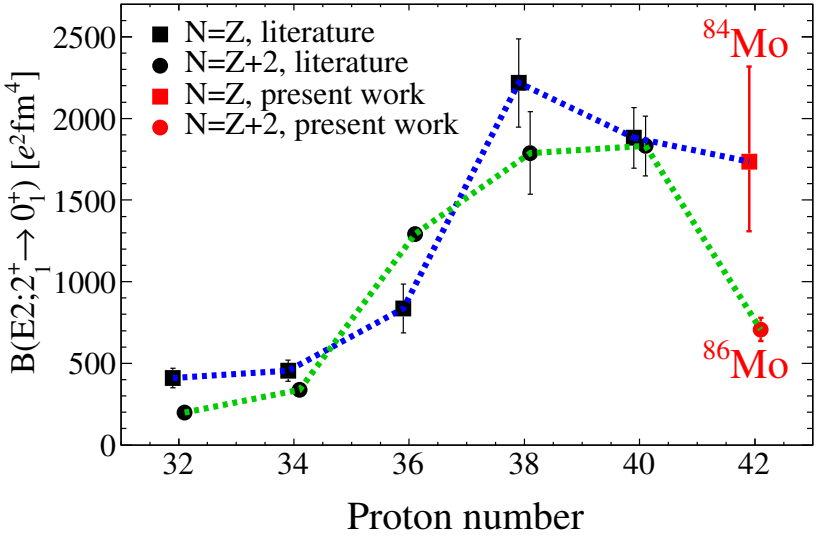

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Shell closures and 2N forces only

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

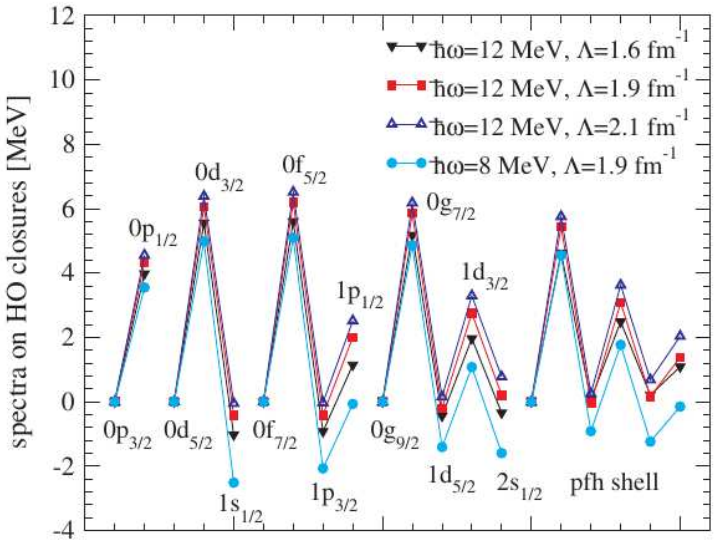
Shell-model phenomenology of low-momentum interactions

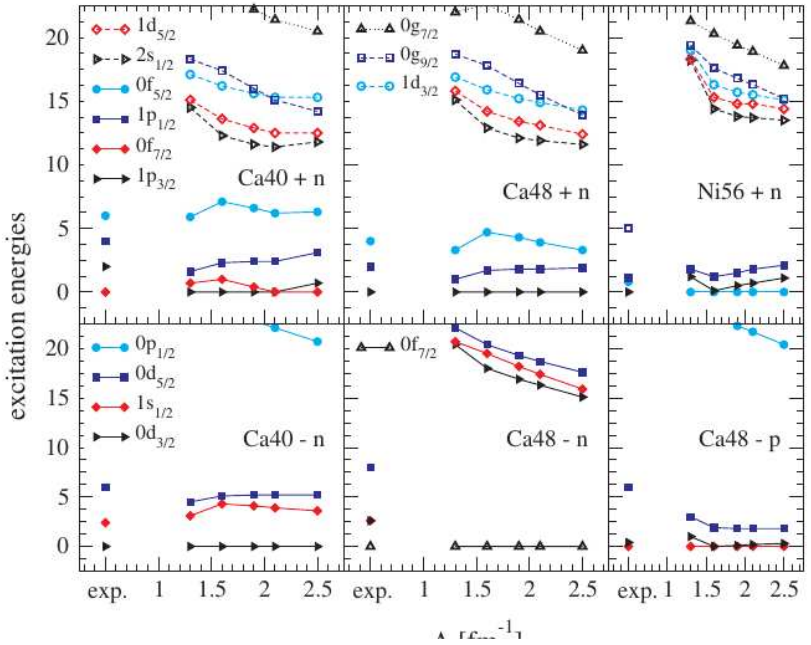
Achim Schwenk[1,*] and Andrés P. Zuker[2,†]

[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*

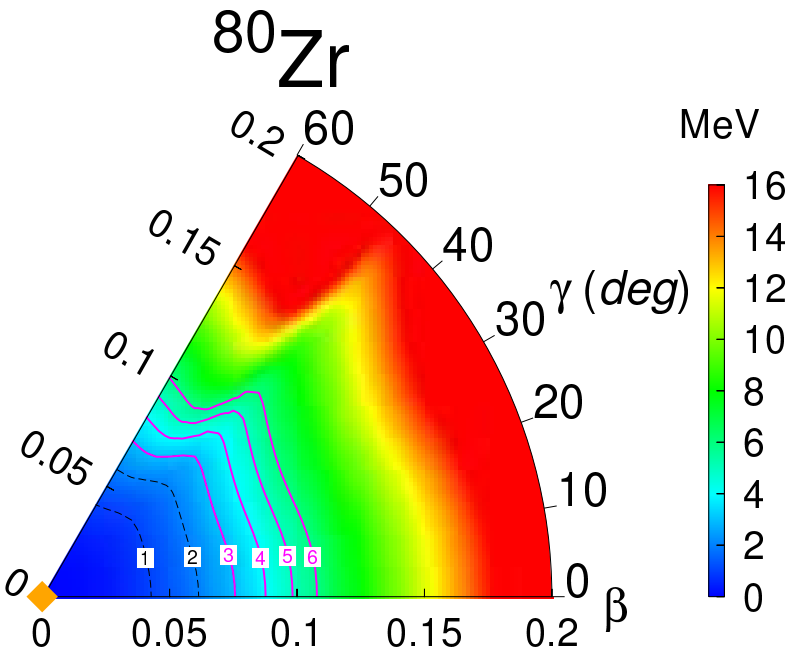
(Received 14 January 2005; revised manuscript received 20 September 2006; published 12 December 2006)

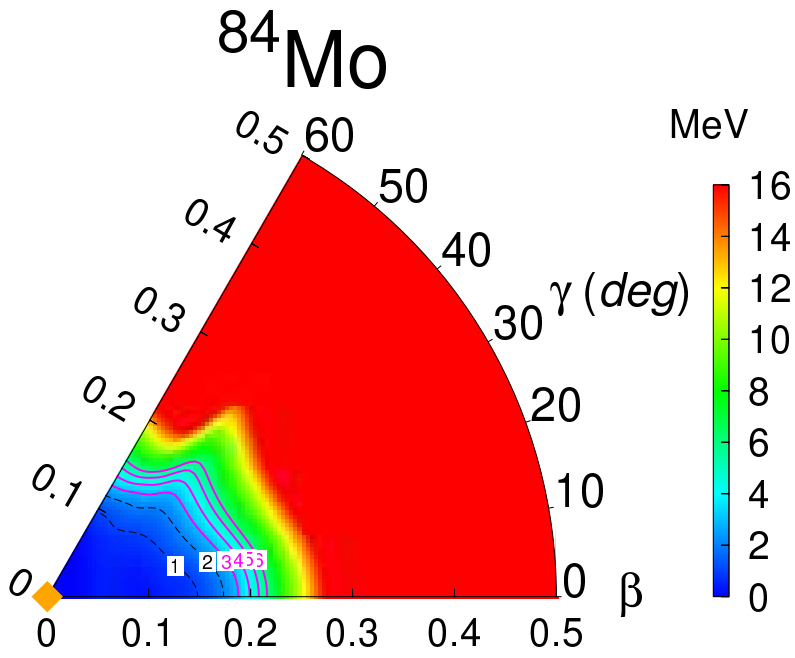




- no Spin-orbite shell closures in ^{12}C, ^{22}O, ^{48}Ca, ^{56}Ni
- too strong H. O. shell closures ^{16}O, ^{40}Ca, ... and ^{80}Zr !!!

N3LO NN calculations





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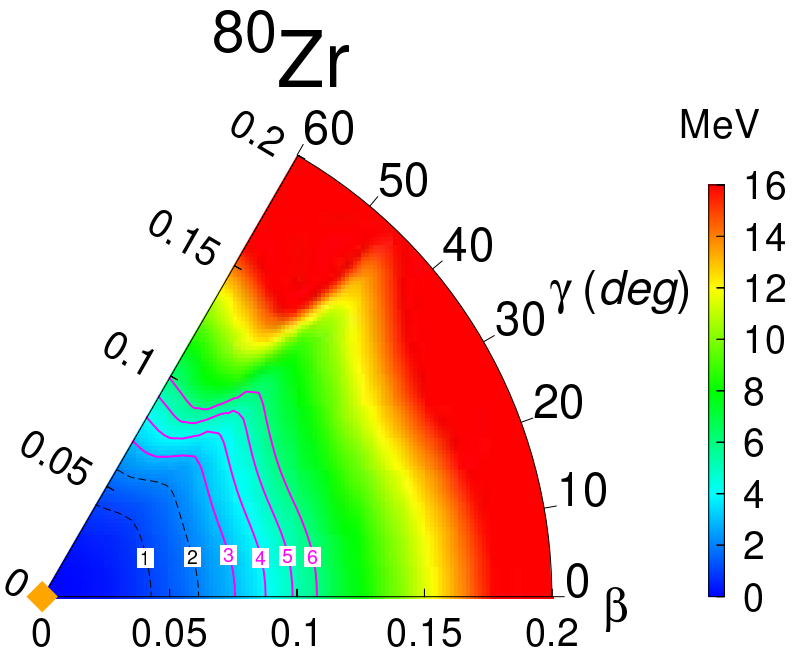
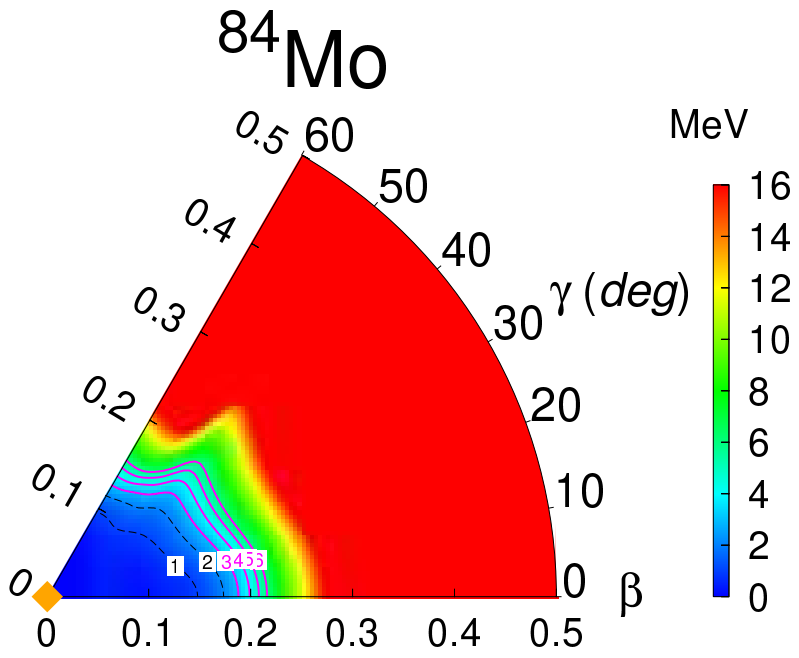
N3LO NN calculations





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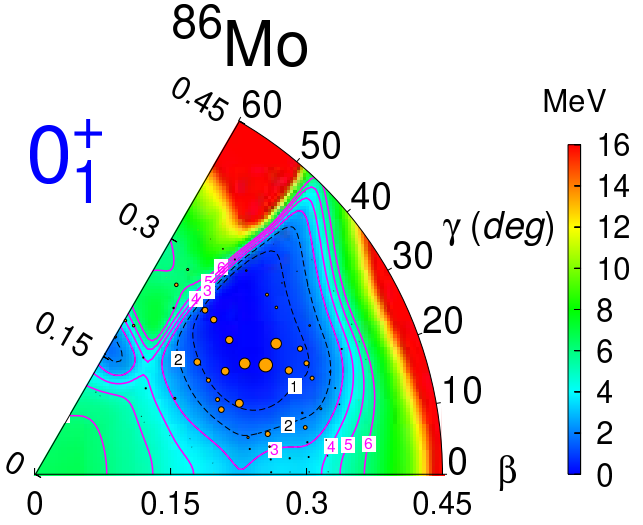

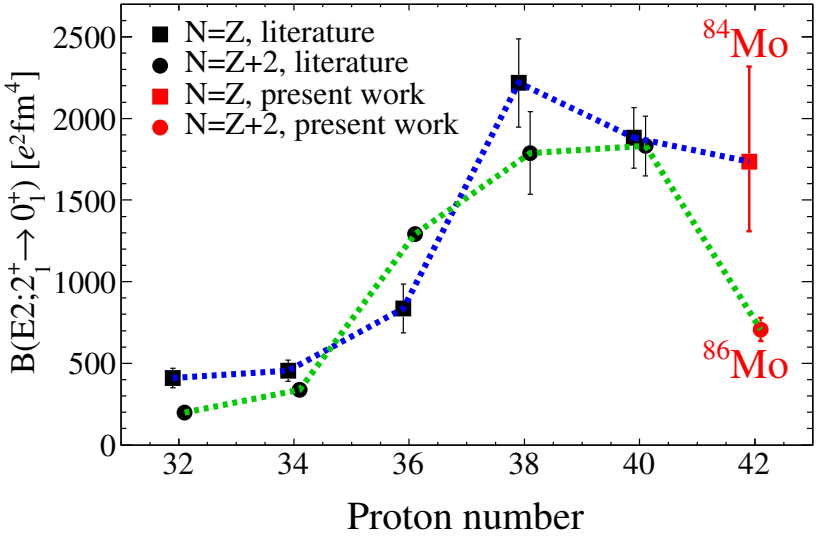

J. Ha, F. Recchia *et al.*, to be submitted

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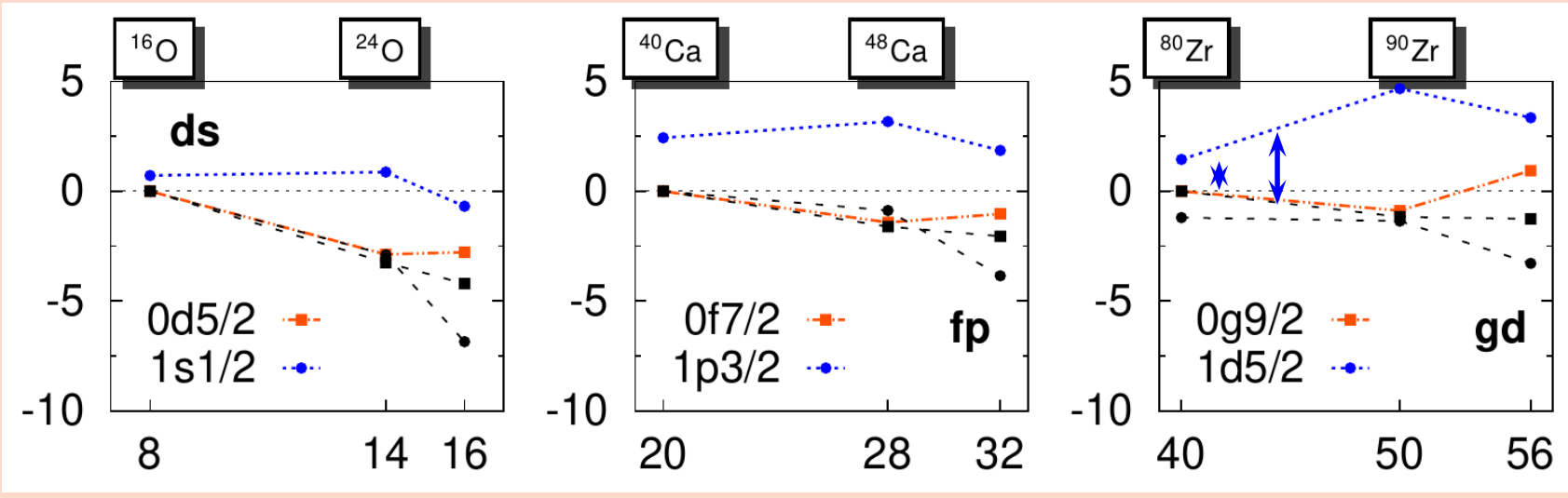
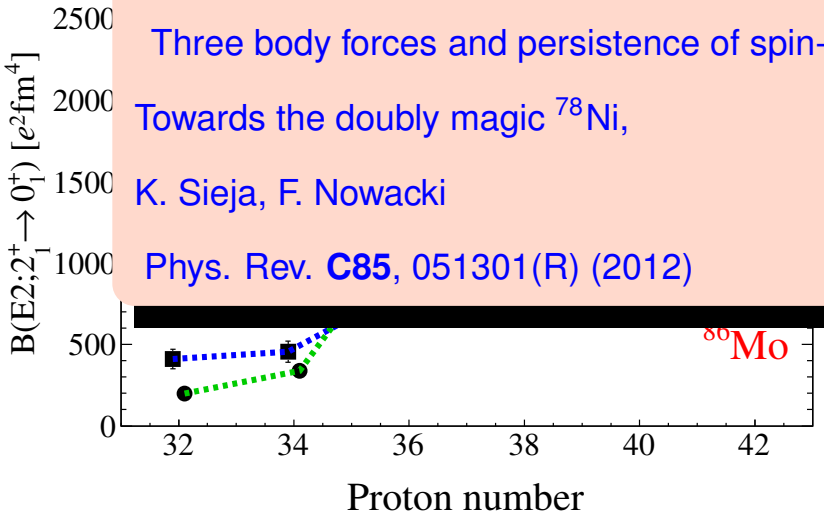


Three body forces and persistence of spin-orbit shell gaps in medium-mass nuclei:

Towards the doubly magic ^{78}Ni,

K. Sieja, F. Nowacki

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



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

^{86}Mo

0.45 60 MeV

^{86}Mo	2p-2h	1030	871	707(71)	1184	731
	4p-4h	1416	1179			
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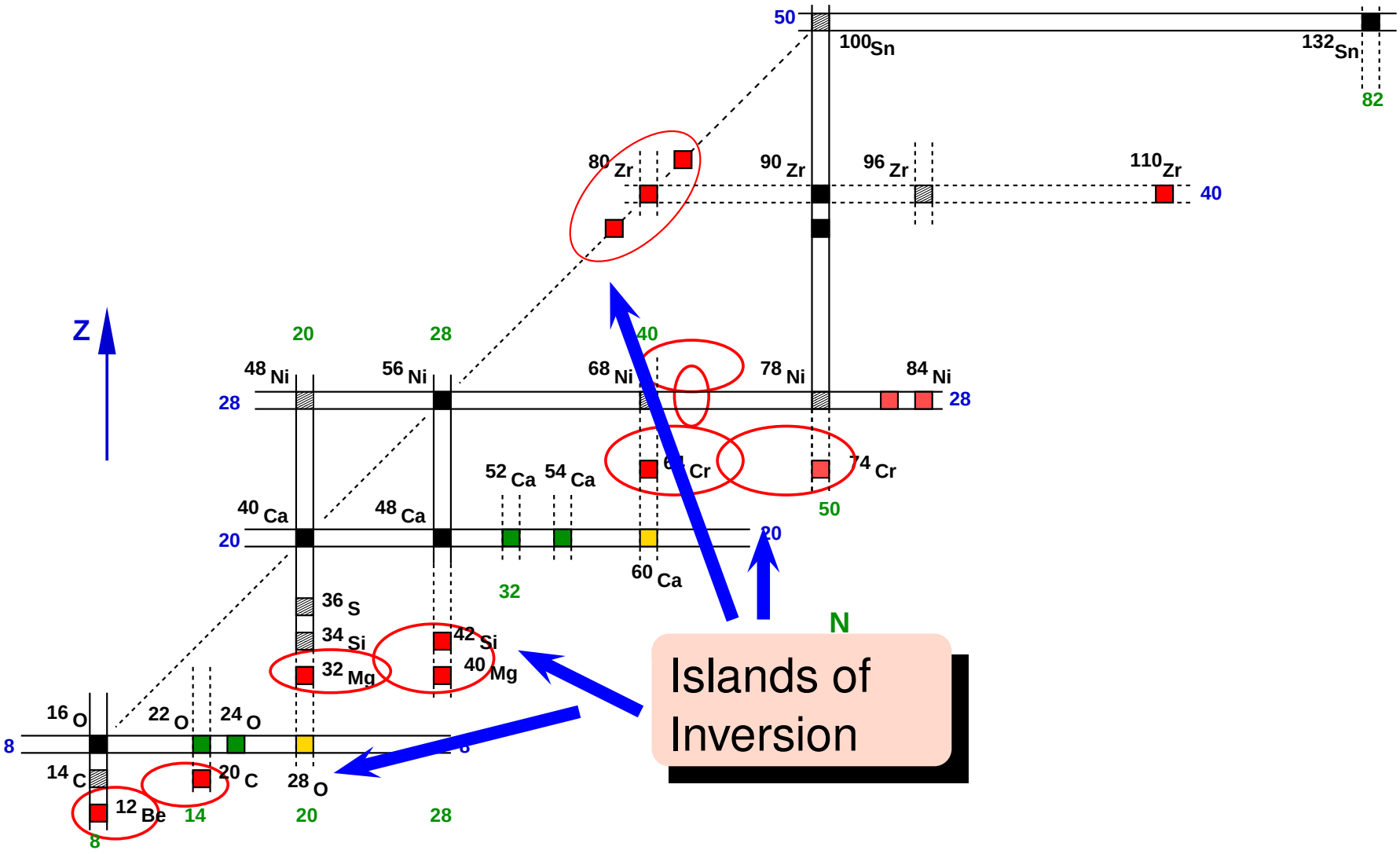
Landscape of medium mass nuclei



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.

Summary

Special thanks to:

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