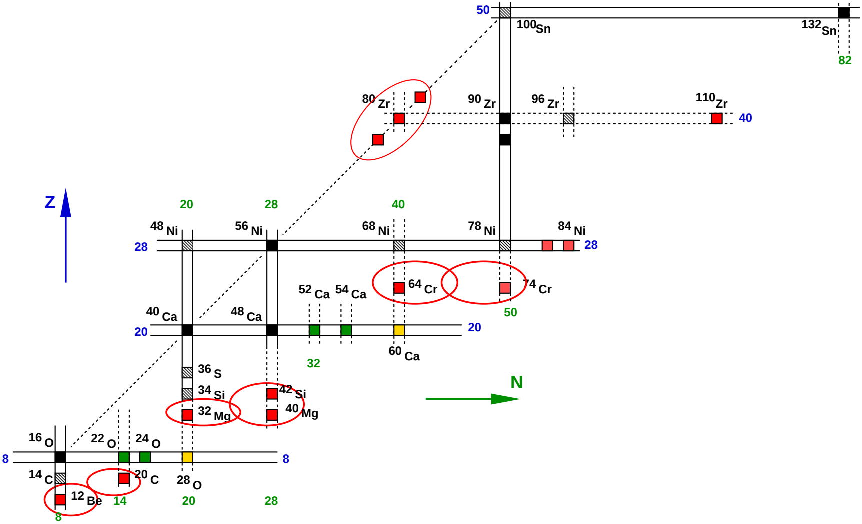
# Three body forces revealed in strongly deformed nuclei

Frédéric Nowacki

Kickoff meeting of the CNRS-MSU International Research Laboratory on Nuclear Physics and Nuclear Astrophysics

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

# Landscape of medium mass nuclei



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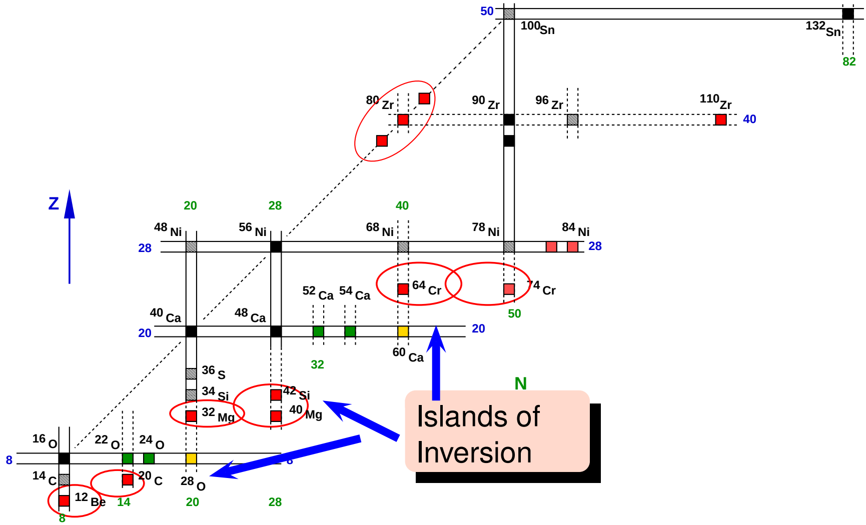

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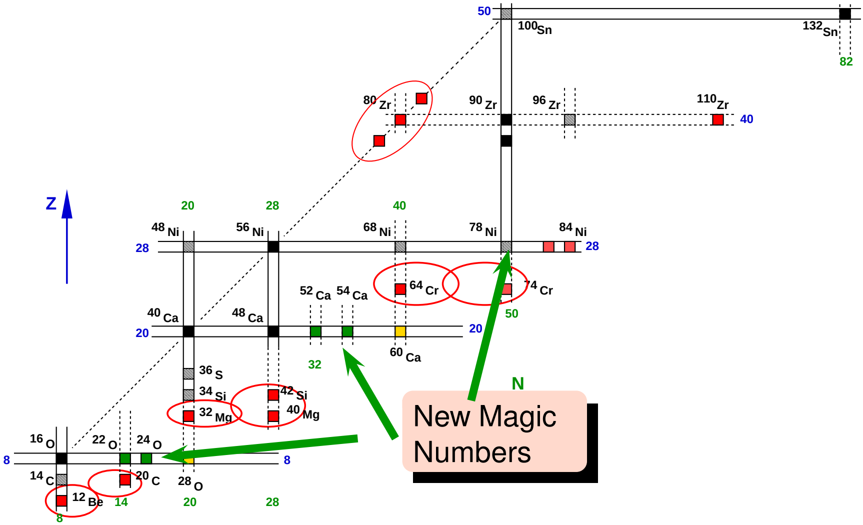


# 3N forces in light nuclei

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*

(Received 17 August 2009; published 13 July 2010)

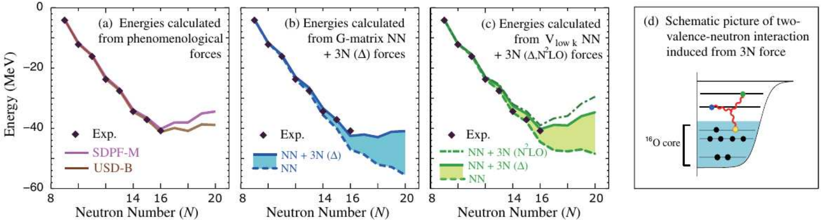
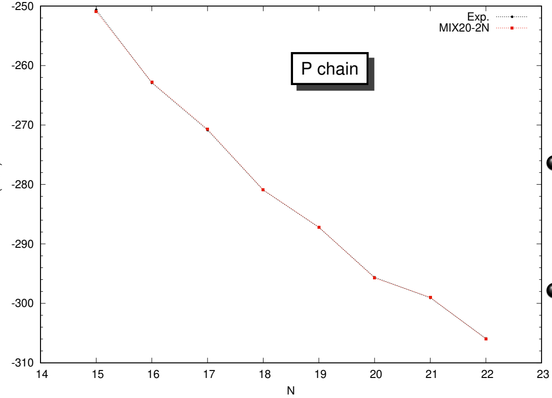



FIG. 4 (color online). Ground-state energies of oxygen isotopes measured from $^{16}$O, including experimental values of the bound 16–24 O. Energies obtained from (a) phenomenological forces SDPF-M [13] and USD-B [14], (b) a $G$ matrix and including FM $3N$ forces due to $\Delta$ excitations, and (c) from low-momentum interactions $V_{\mathrm{low}\,k}$ and including chiral EFT $3N$ interactions at N$^2$LO as well as only due to $\Delta$ excitations [25]. The changes due to $3N$ forces based on $\Delta$ 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.

# At the drip line




Duflo-Zuker master term:

$$BE \sim N\epsilon + \frac{N(N-1)}{2} V_{NN}$$

Nowacki/Poves 2023

- At the neutron drip line, the ESPE's of $^{28}$O are completely at variance with those of $^{40}$Ca at the stability valley. The change from the standard ESPE's of $^{16}$O to the anomalous ones in $^{28}$O is totally due to the interactions of *sd* shell neutrons among themselves

- Notice that the *sd* shell orbits remain always below th *pf* shell with the $\nu 0f_{\frac{7}{2}}$ and $\nu 0p_{\frac{3}{2}} - 0p_{\frac{1}{2}}$ orbitals DO get inverted

- The monopole part of the neutron-proton interaction restores the N=20 shell gap when the valley of stability is approached

- **New $^{28}$O data from NeuLAND-SAMOURAI collaboration (Kondo et al., NATURE 620, 965 (2023))**

- **New $^{30}$F data from NeuLAND-SAMOURAI collaboration (J. Kahlbow phD work, submitted)**

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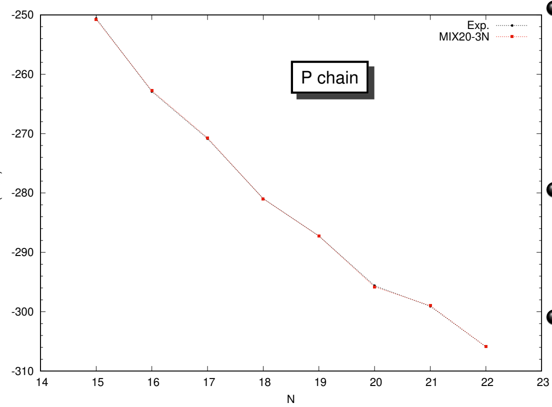


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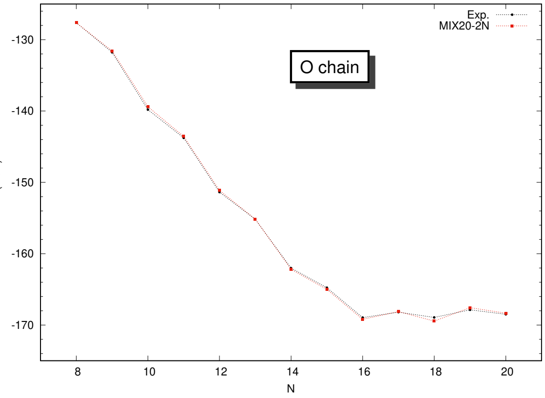


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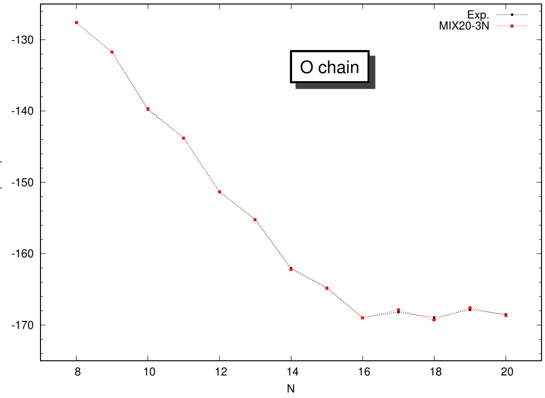


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Nowacki/Poves 2023

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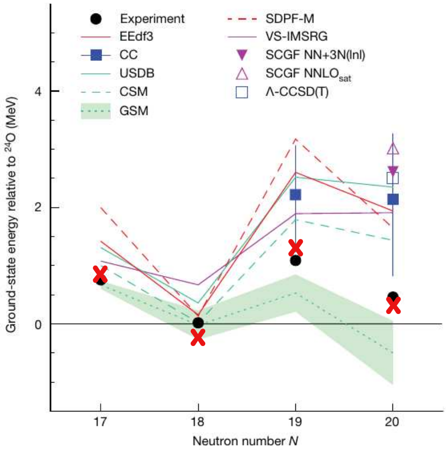


Nowacki/Poves 2023

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# 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)

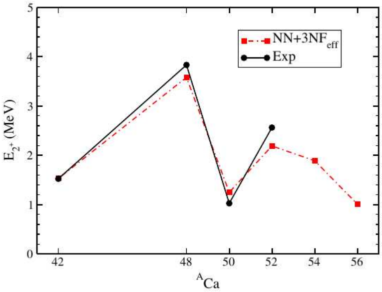



FIG. 2 (color online). (Excitation energies of $J^\pi = 2^+$ states in the isotopes $^{42,48,50,52,54,56}$Ca (experiment: black circles, theory: red squares)

# 3N forces in light nuclei

PHYSICAL REVIEW C **101**, 021303(R) (2020)

Rapid Communications

**Testing *ab initio* nuclear structure in neutron-rich nuclei: Lifetime measurements of second $2^+$ state in $^{16}C$ and $^{20}O$**

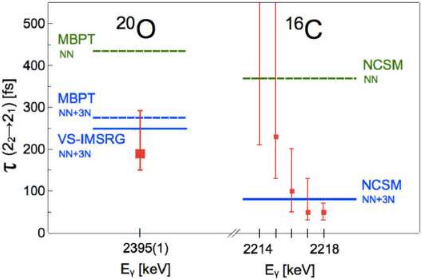
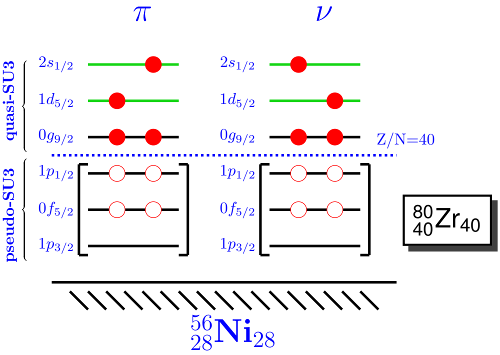



FIG. 4. Partial lifetime for $2_2^+ \to 2_1^+$ decays. Left: $^{20}O$, experiment (symbol) compared to MBPT (dashed lines, with and without 3N interactions), and *ab initio* VS-IMSRG (solid line) results. Right: $^{16}C$, experiment (symbols) for assumed $E_\gamma$ energies [see Fig. 3(j) and 3(k)], including the uncertainty from a $\leqslant 13\%$ branching ratio. The solid (dashed) lines show *ab initio* NCSM predictions with (without) 3N interactions. The MBPT results

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



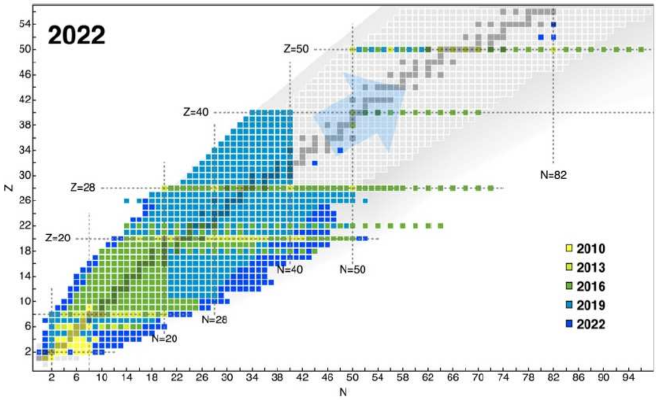

- p shell: $^{16}$O spherical/doubly magic
- sd shell: $^{40}$Ca spherical/doubly magic
- pf shell: $^{80}$Zr deformed nucleus

- 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: ???

# 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
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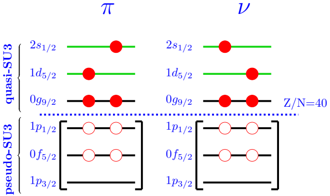



R.D.O. Llewellyn *et al.*, Phys. Rev. Lett. **124**, 152501 (2020)

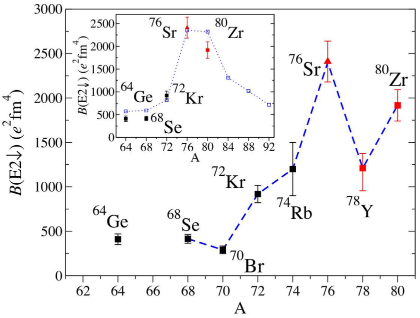



FIG. 3. Schematics of the $B(E2\downarrow)$ values for the $N = Z$ nuclei

- ZBM3 valence space:
  extension of JUN45
  to pseudo-SU3 + Quasi-SU3
- New effective interaction
  ( Realistic TBME
  + Monopole "3N" constraints")
- SM + DNO-SM for most deformed cases

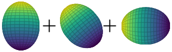
# Discrete Non-Orthogonal Shell Model

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

**1)** Deformed Hartree-Fock (HF) Slater determinants

**2)** Restoration of rotational symmetry

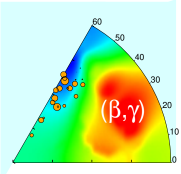
**3)** Mixing of shapes:

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

## Intrinsic/Laboratory Description

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

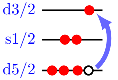
$$M^{(J)}_\alpha(q, K) = \sum_{q', K'} [\hat{N}^{1/2}]^{(J)}_{K'K}(q', q)\, f^{(J)}_\alpha(q', K')$$




◇ Probability of a configuration $(\beta, \gamma)$:

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

- **particle-hole interpretation**:

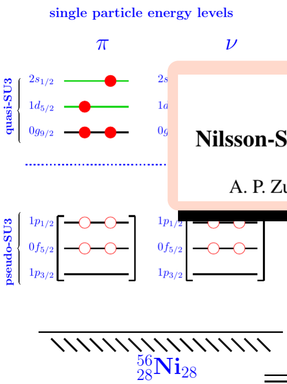


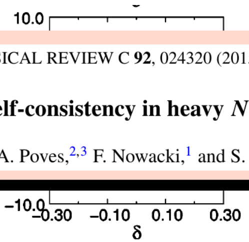

$M$**-scheme**

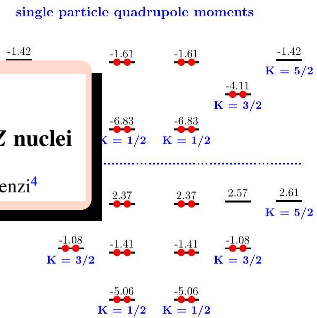
- $K$**–quantum numbers**:

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

# Nilsson-SU3 estimates



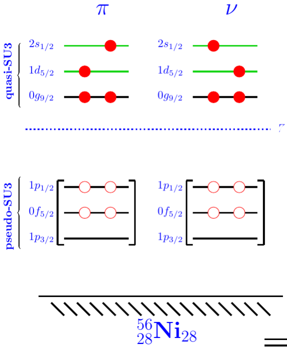

PHYSICAL REVIEW C **92**, 024320 (2015)

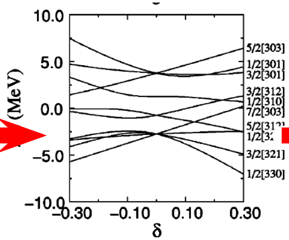
**Nilsson-SU3 self-consistency in heavy $N = Z$ nuclei**

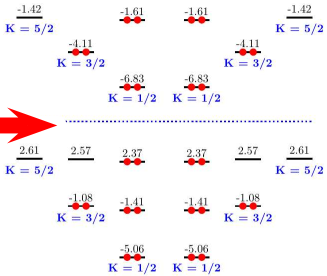
A. P. Zuker,[1] A. Poves,[2,3] F. Nowacki,[1] and S. M. Lenzi[4]

| | | 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 | | |

# Nilsson-SU3 estimates

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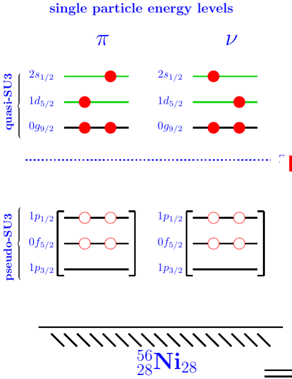


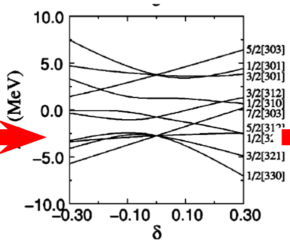


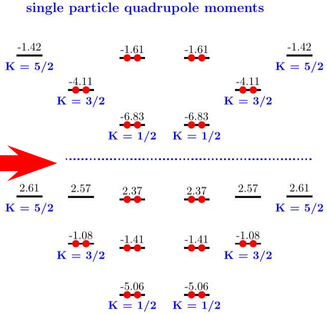


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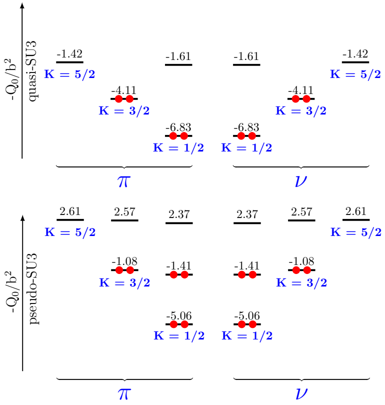


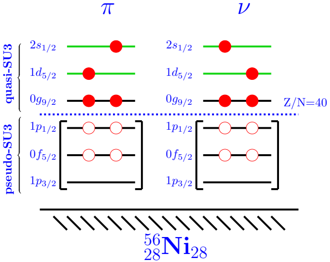


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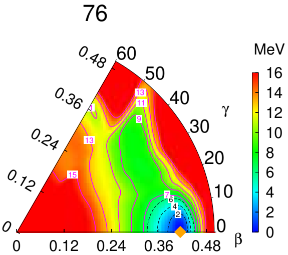


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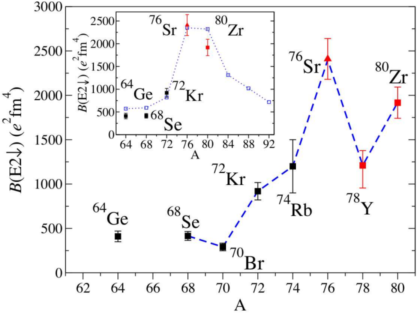


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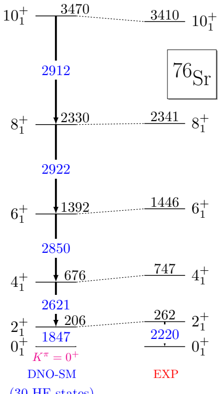

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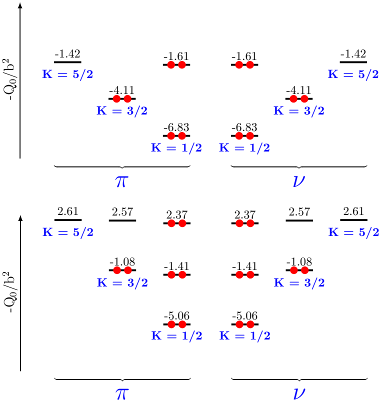


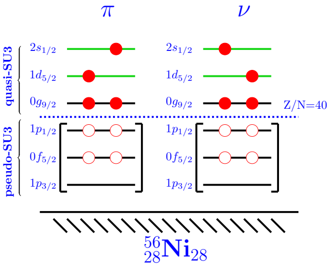


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|---|---|---|---|---|---|---|
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| | 8p-8h | 1891 | 1732 | | | |
| $^{86}$Mo | 0p-0h | 542 | 196 | **707(71)** | 1184 | 731 |
| | 2p-2h | 1030 | 871 | | | |
| | 4p-4h | 1416 | 1179 | | | |
| | 6p-6h | 1858 | 1655 | | | |

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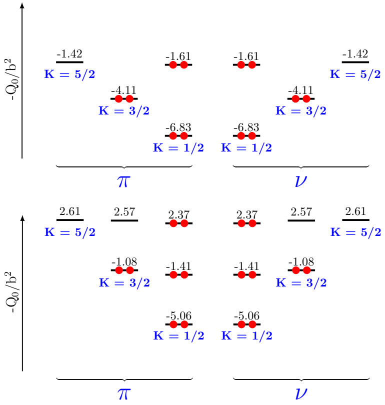


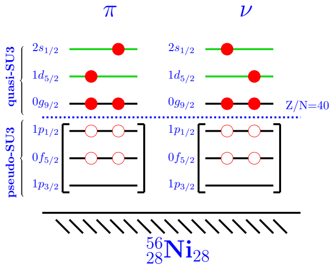


| nucleus | Np-Nh* | ZRP | PHF | B(E2)(e$^2$.fm$^4$) Exp. | DNO-SM* | SM |
|---|---|---|---|---|---|---|
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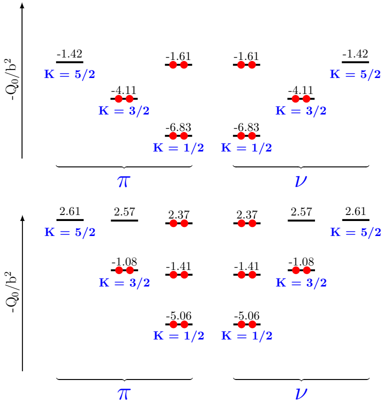


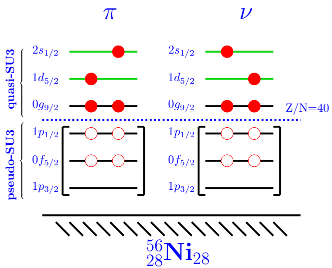


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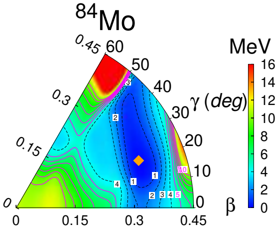


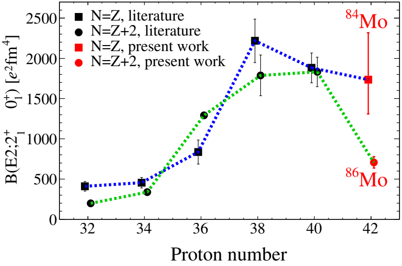


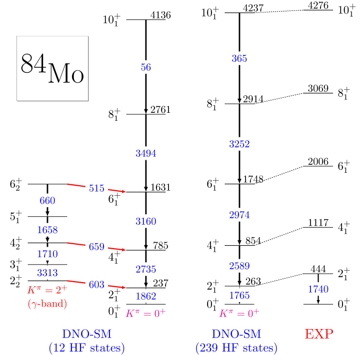


**J. Ha, F. Recchia *et al.*, to be submitted**

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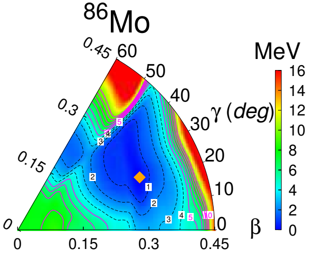


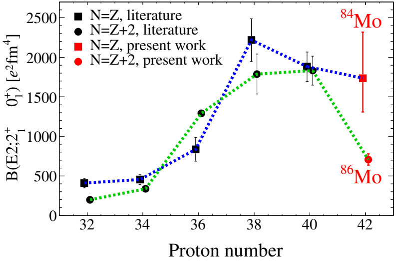


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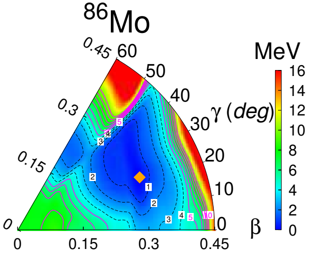


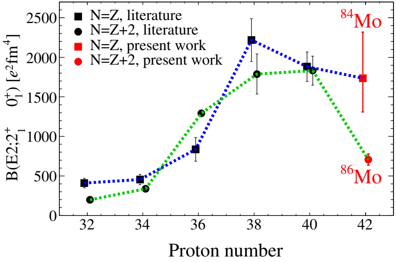


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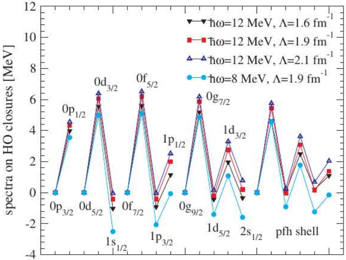
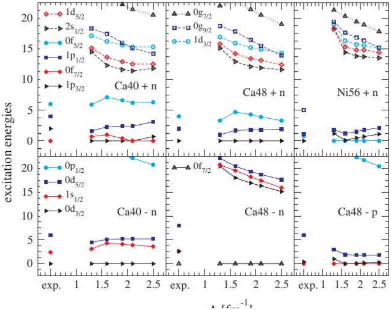
# Shell closures and 2N forces only

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

## Shell-model phenomenology of low-momentum interactions

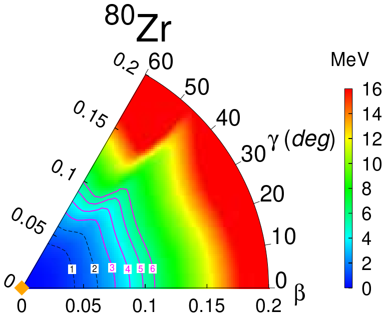
Achim Schwenk[1,*] and Andrés P. Zuker[2,†]
[1]*Nuclear Theory Center, Indiana University, 2401 Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*
[2]*Institut de Recherches Subatomiques, IN2P3-CNRS, Université Louis Pasteur, F-67037 Strasbourg, France*
(Received 14 January 2005; revised manuscript received 20 September 2006; published 12 December 2006)

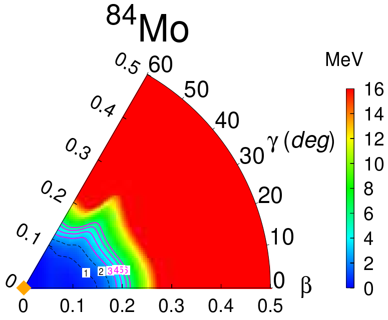



- no Spin-orbite shell closures in $^{12}$C, $^{22}$O, $^{48}$Ca, $^{56}$Ni
- too strong H. O. shell closures $^{16}$O, $^{40}$Ca, ... and $^{80}$Zr !!!

# N3LO NN calculations




| | | | | B(E2)($e^2.fm^4$) | | |
|---|---|---|---|---|---|---|
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| $^{80}$Zr | 4p-4h | 587 | 637 | | | |
| | 8p-8h | 1713 | 1509 | **1910(180)** | 2325 | 0.03 |
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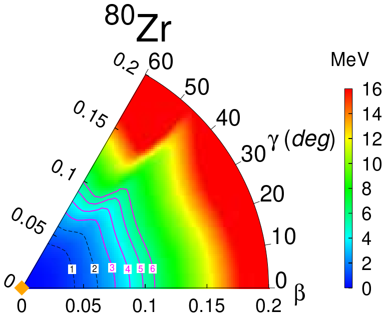
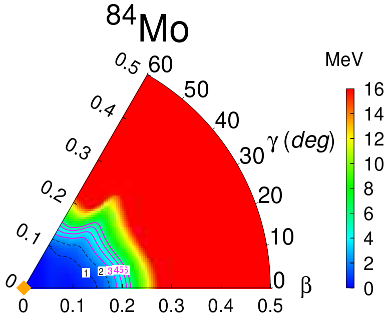
# N3LO NN calculations

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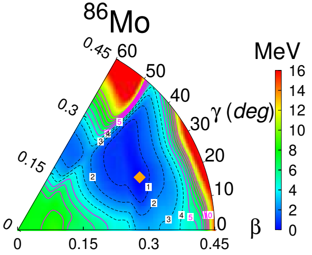


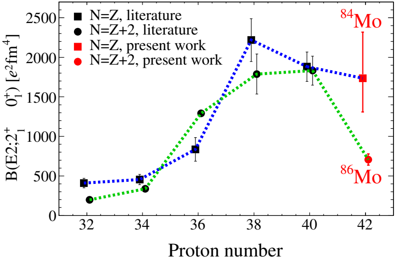


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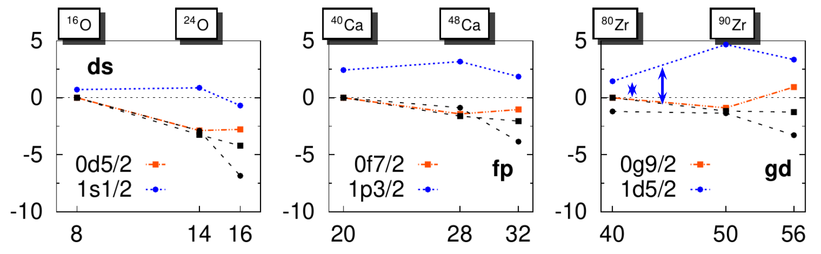
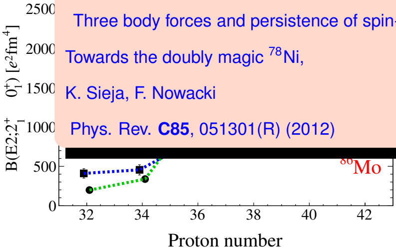



Three body forces and persistence of spin-orbit shell gaps in medium-mass nuclei:

Towards the doubly magic $^{78}$Ni,

K. Sieja, F. Nowacki

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

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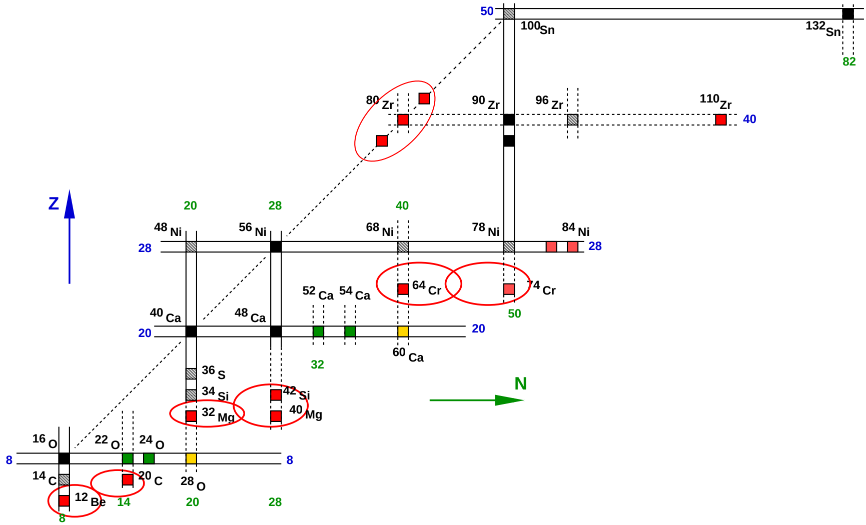
# Landscape of medium mass nuclei



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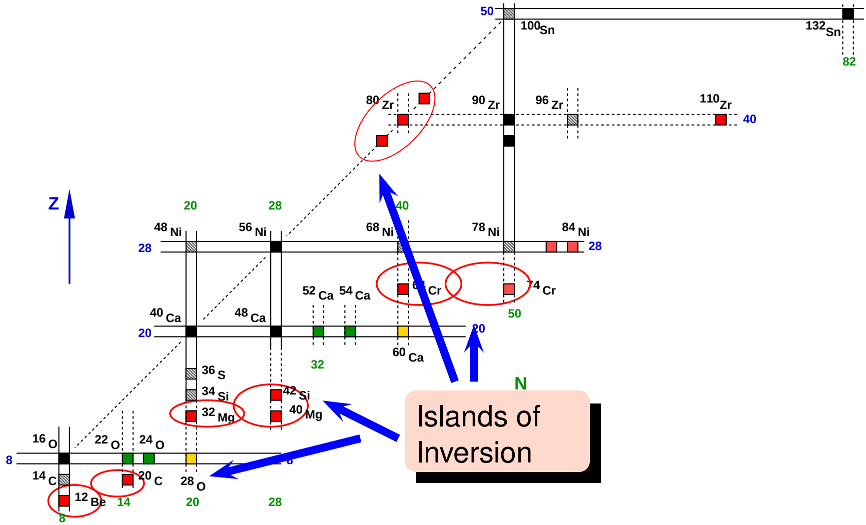

# Summary

- 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.

- First FRIB in-beam spectroscopy of $^{62}$Cr , A. Gade et al. to be submitted to NATURE
- Island of Inversion in $^{84,86}$Mo @GRETINA/MSU, F. Recchia et al. to be submitted to NATURE
- FRIB-TA topical prgram: Theoretical justifications for FRIB (May 2023)

# Open questions for the future

- Are Ab-initio approaches accurate enough to describe the whole chart of isotopes within the same framework (2N , 3N hamiltonian etc ...)? So far 34 “non-implausible”

- How to simplify such calculations ? (see N. Smirnova’s talk)
  3N effects mainly monopole 3N effects ?
  How to implement simple global monopole effects ?

- What are the data needed to better constrain theoretical models ?

- Better interplay between EDF and SM/CI expertises ?

- How to disentangle continuum effects from bound systems description ?

# Summary

Special thanks to:

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