Isospin Symmetric Island of Inversion at the N=Z line

Duy Duc Dao, Frédéric Nowacki

The 12th International Conference on Direct Reactions with Exotic Beams DREB2024

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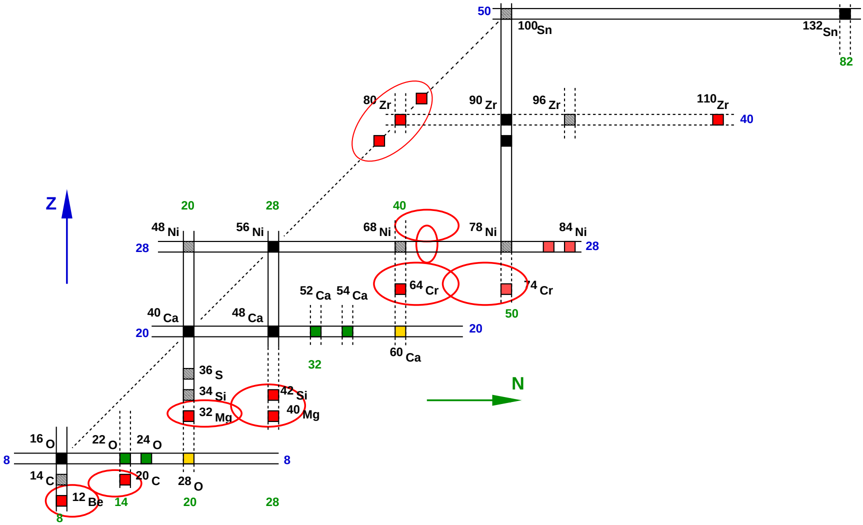
Landscape of medium mass nuclei



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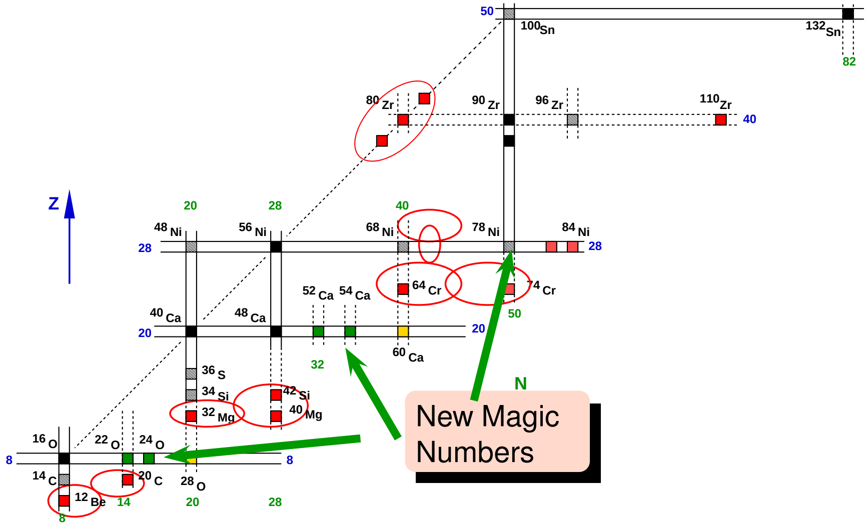

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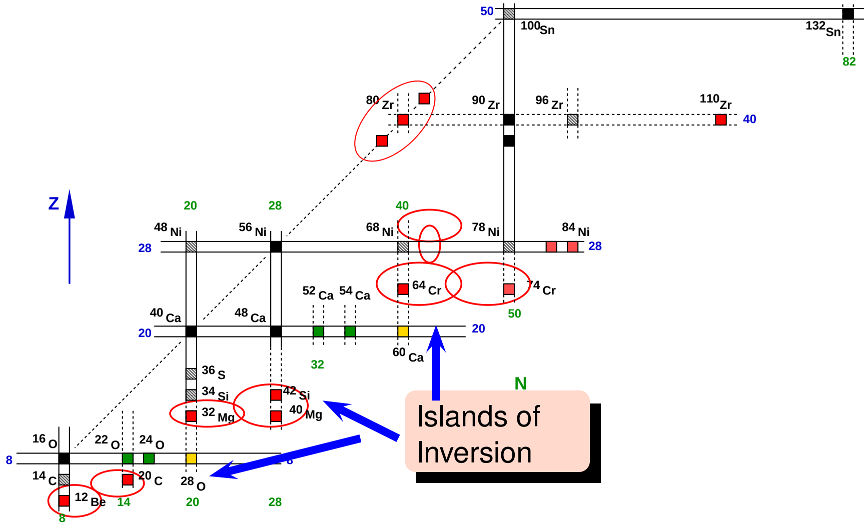

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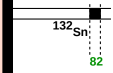


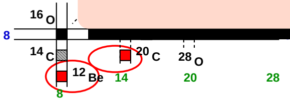
UNDERSTANDING REGULARITIES
for both SPHERICAL and DEFORMED systems

- 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, ...)

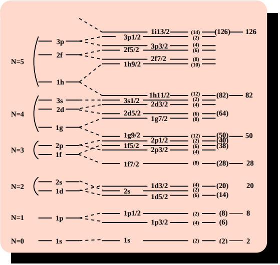


Multipole expansion:

$$H = {\color{red}H_{monopole}} + {\color{blue}H_{multipole}}$$

$H_{monopole}$:
- *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

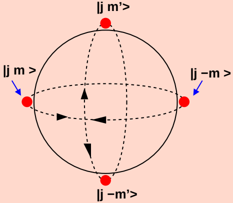
$H_{multipole}$:

- *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

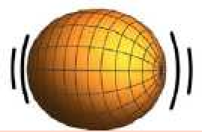
superfluid nucleus:



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

- **Quadrupole regime: deformed nuclei**

prolate nucleus:

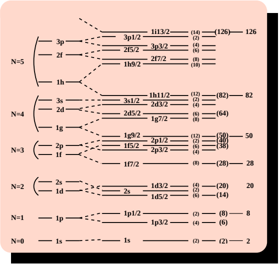


Typical example: **open shell N=Z nuclei**

Effective Hamiltonian
Monopole and multipole

Multipole expansion:

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



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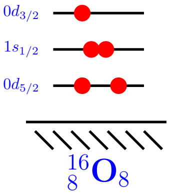
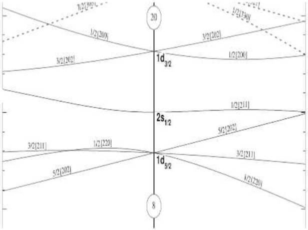
Nilsson-SU3 estimates

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

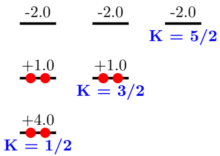
Nilsson-SU3 self-consistency in heavy $N = Z$ nuclei

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





s. p. quadrupole moments



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

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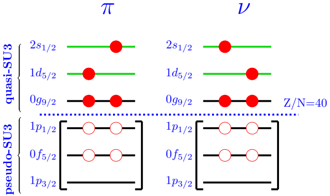


R.D.O. Llewellyn *et al.*, PRL **124**, 152501 (2020)

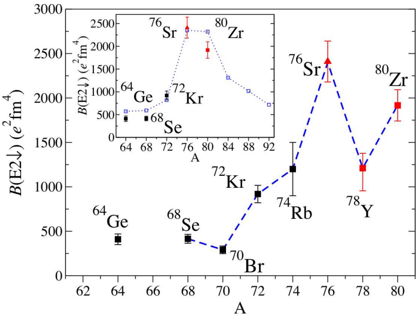


FIG. 3. Schematics of the $B(E2\downarrow)$ values for the $N = Z$ nuclei

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

- New effective interactions:
  - Realistic TBME + Monopole "3N" constraints"
  - ab-initio N3LO (2N) interaction
  - ongoing ab-initio N3LO (2N) + 3N (lnl) interaction

- SM + DNO-SM for most deformed cases

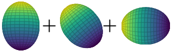
Discrete Non-Orthogonal Shell Model

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

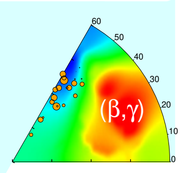
3) Mixing of shapes:

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

Intrinsic/Laboratory Description

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

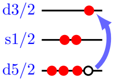
$$M_{\alpha}^{(J)}(q, K) = \sum_{q',K'} [\hat{N}^{1/2}]^{(J)}_{K'K}(q', q)\, f_{\alpha}^{(J)}(q', K')$$



◇ Probability of a configuration (β, γ):

$$P_{\alpha}^{(J)}(q) = \sum_K |M_{\alpha}^{(J)}(q, K)|^2$$

- **particle-hole interpretation**:



M-scheme

- ***K*–quantum numbers**:

$$P_{\alpha}^{(J)}(K) = \sum_q |M_{\alpha}^{(J)}(q, K)|^2$$

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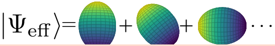

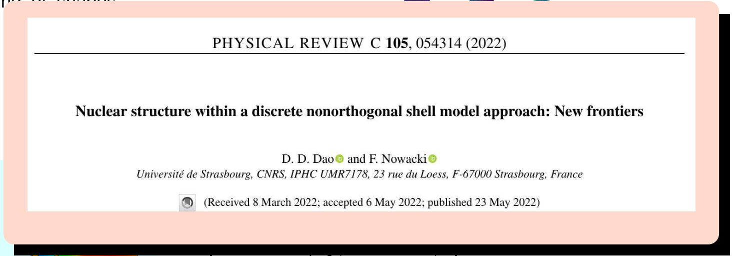

PHYSICAL REVIEW C **105**, 054314 (2022)

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

D. D. Dao and F. Nowacki

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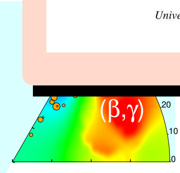
(Received 8 March 2022; accepted 6 May 2022; published 23 May 2022)



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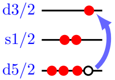


M-**scheme**

- ***K*–quantum numbers**:

$$P_\alpha^{(J)}(K) = \sum_q \left|M_\alpha^{(J)}(q,K)\right|^2$$

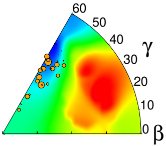
Recent developments of the DNO shell model

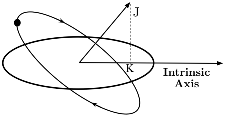
◇ Variation-After-Projection DNO-SM approach

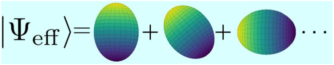
$$\mathcal{H}_{\rm eff}|\Psi_\alpha^{JM}\rangle = E_\alpha^{(J)}|\Psi_\alpha^{JM}\rangle \Longrightarrow \delta\frac{\langle\Psi_\alpha^{JM}|\mathcal{H}_{\rm eff}|\Psi_\alpha^{JM}\rangle}{\langle\Psi_\alpha^{JM}|\Psi_\alpha^{JM}\rangle} = 0, \quad |\Psi_\alpha^{JM}\rangle = \sum_{q,K} \boxed{f_\alpha^{(J)}(q,K)}\,\mathcal{P}^J_{MK}\boxed{|\Phi(q)\rangle}$$

Double variation AFTER Angular Momentum Projection: Mixing coefficient — Slater state

◇ DNO-SM(β,γ)



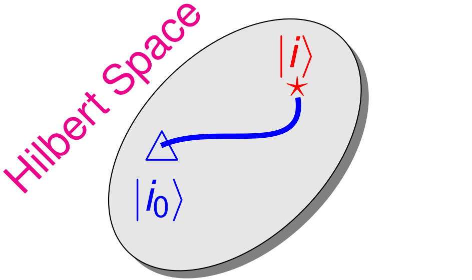




(D.D. Dao and F. Nowacki, PRC 105, 054314 (2022))

◇ DNO-SM(VAP)

- $q = 1, 2, 3, \ldots$
- $J^\pi_\alpha = 0^+_1, \ldots$
- Best energy-favoring Slater states



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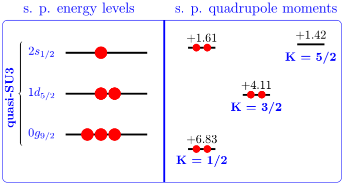

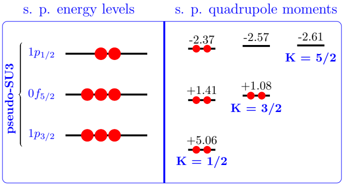

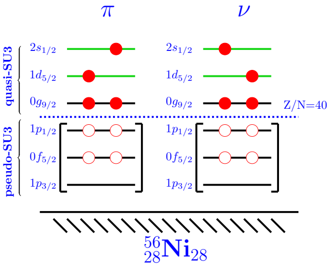

				B(E2)(e^2.fm^4)		
nucleus	Np-Nh*	ZRP	PHF	Exp.	DNO-SM*	SM
^{84}Mo	4p-4h	1104	1193	**1740^{+580}_{-430}**	1765	-
	8p-8h	1891	1732			
^{86}Mo	0p-0h	542	196	**707(71)**	980	731
	2p-2h	1030	871			
	4p-4h	1416	1179			
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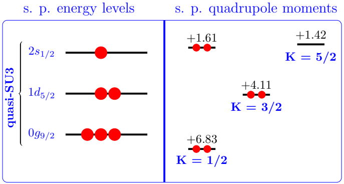

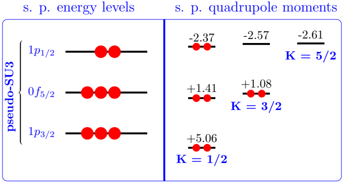

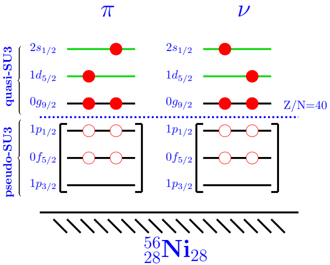

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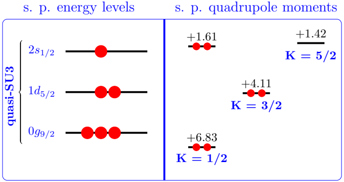

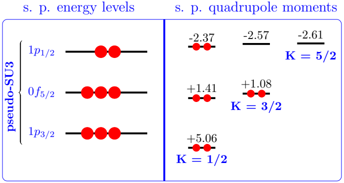

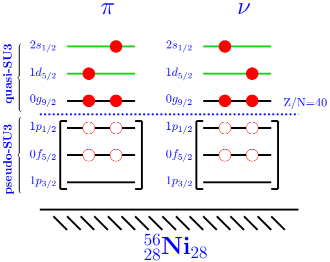

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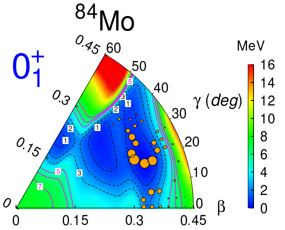

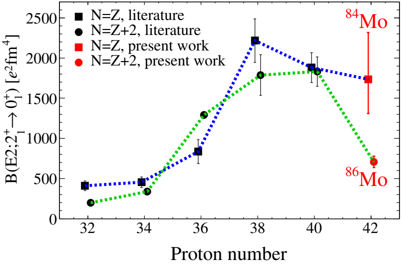

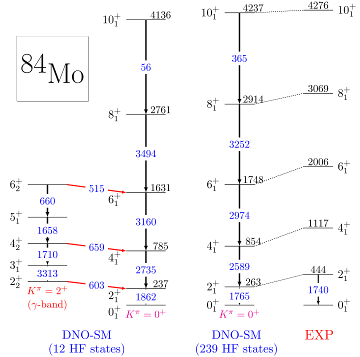

J. Ha, F. Recchia *et al.*, submitted to NATURE

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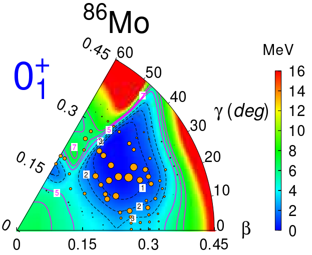

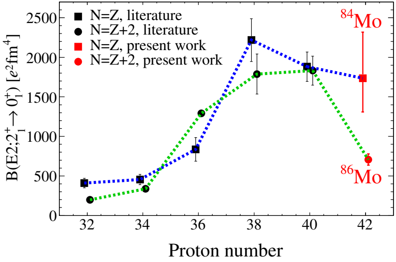

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J. Ha, F. Recchia *et al.*, submitted to NATURE

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]

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(Received 17 August 2009; published 13 July 2010)

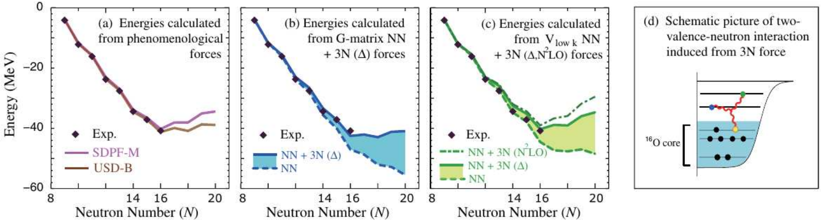

FIG. 4 (color online). Ground-state energies of oxygen isotopes measured from ^{16}O, including experimental values of the bound 16–24 O. Energies obtained from (a) phenomenological forces SDPF-M [13] and USD-B [14], (b) a G matrix and including FM $3N$ forces due to Δ excitations, and (c) from low-momentum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

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[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*

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(Received 16 April 2012; published 17 July 2012)

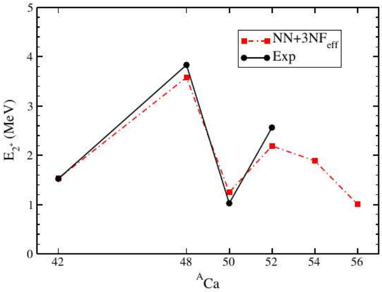

FIG. 2 (color online). (Excitation energies of $J^\pi = 2^+$ states in the isotopes ^{42,48,50,52,54,56}Ca (experiment: black circles, theory: red squares).

Shell closures and 2N forces only

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

Shell-model phenomenology of low-momentum interactions

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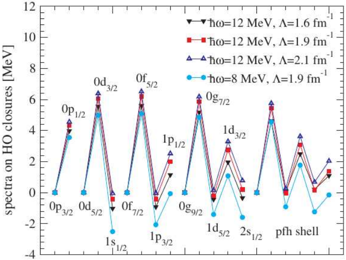
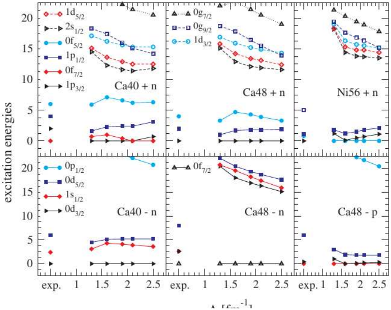
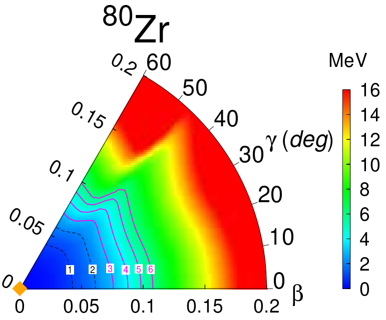
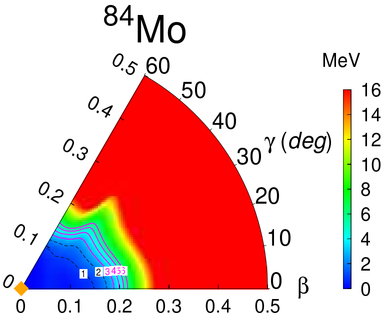




- no Spin-orbite shell closures in ^{12}C, ^{22}O, ^{48}Ca, ^{56}Ni
- too strong H. O. shell closures ^{16}O, ^{40}Ca, ... and ^{80}Zr !!!

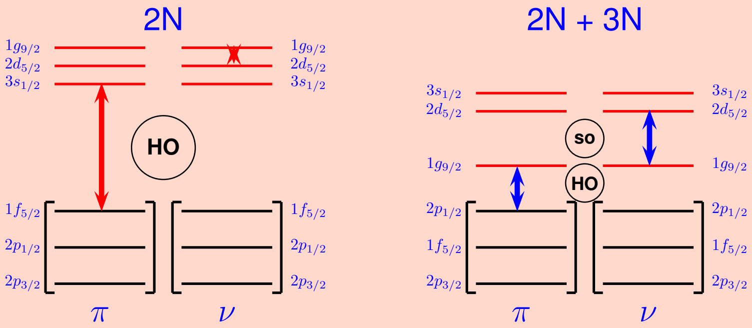
N3LO NN calculations





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



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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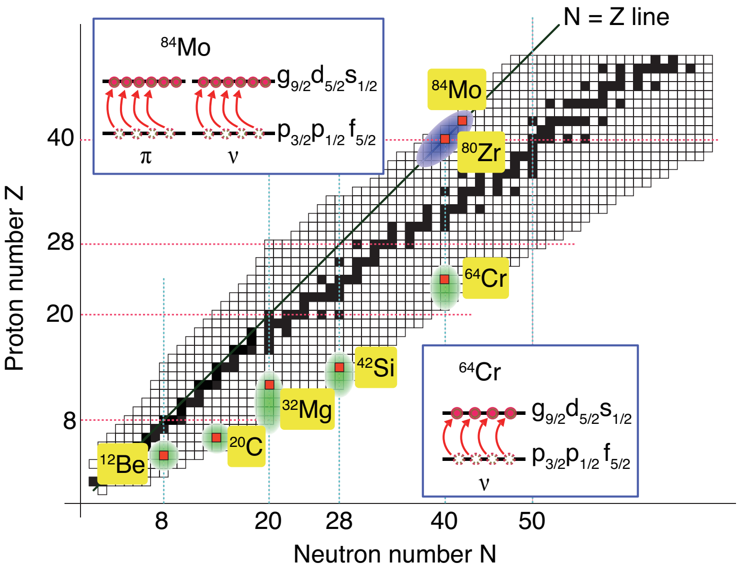
Isospin Symmetric Island of Inversion



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.

- New spectroscopy for ^{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:

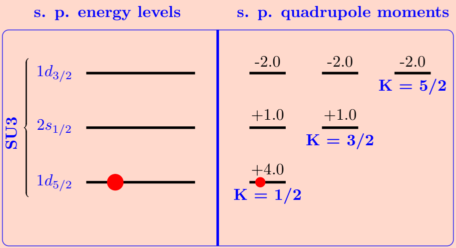
- D. D. Dao
- G. Martinez-Pinedo, A. Poves, S. Lenzi
- A. Gade, O. Sorlin, A. Obertelli

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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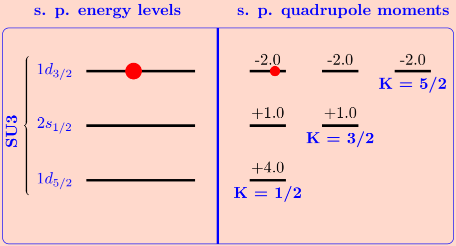

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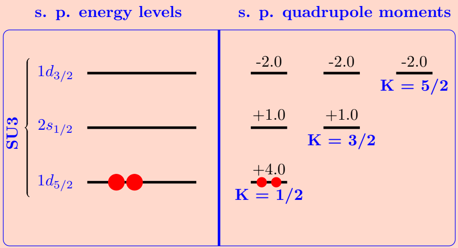

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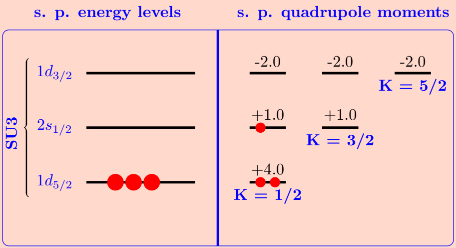

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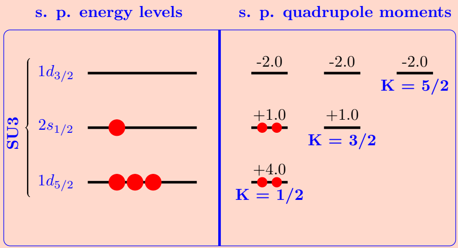

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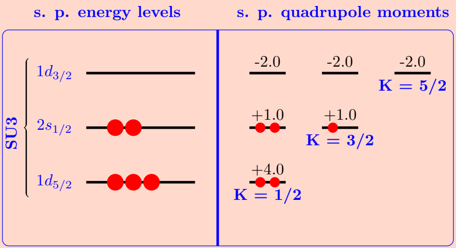

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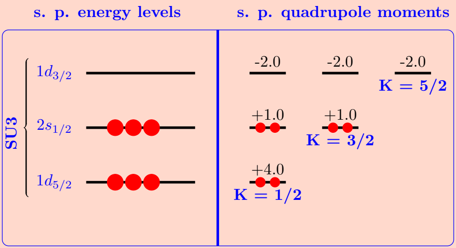

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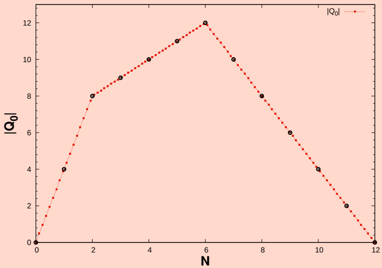

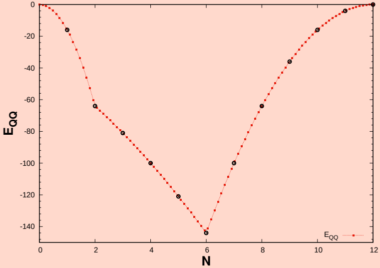

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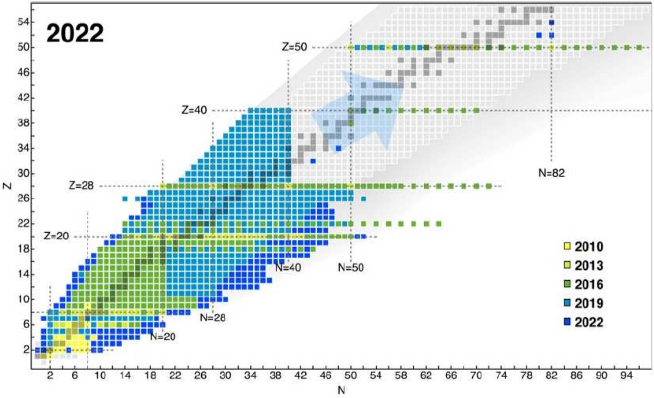
Ab-initio predictions ?

TRIUMF

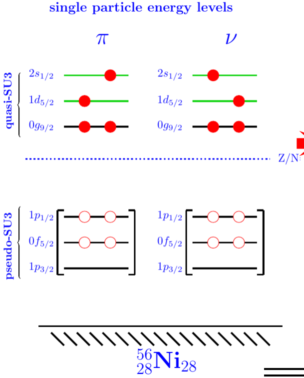
Ab Initio Progress: How Heavy Can We Go?

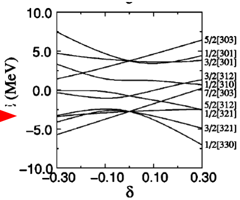
Tremendous progress in ab initio reach, largely due to polynomially scaling methods!

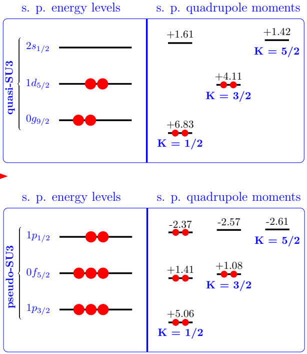


Jason Holt 2023

Nilsson-SU3 estimates







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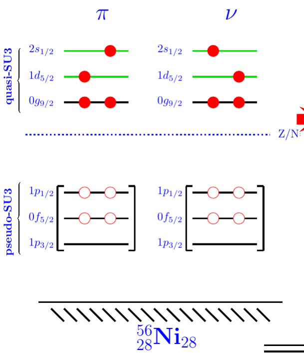

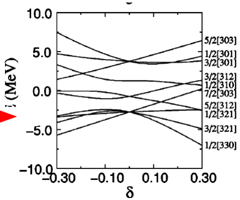

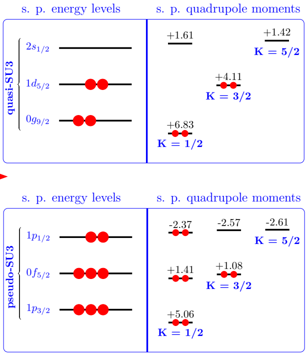

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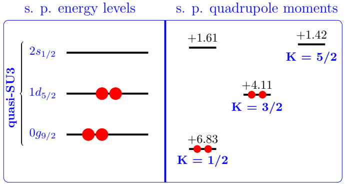
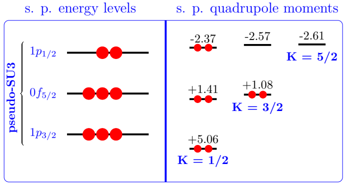
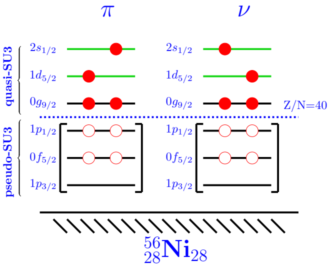
Island of Inversion at the N=Z line

◇ Strongly deformed states at $N = Z$

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







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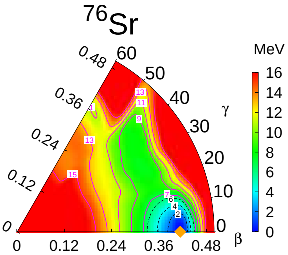


R.D.O. Llewellyn *et al.*, Phys. Rev. Lett. **124**, 152501 (2020)

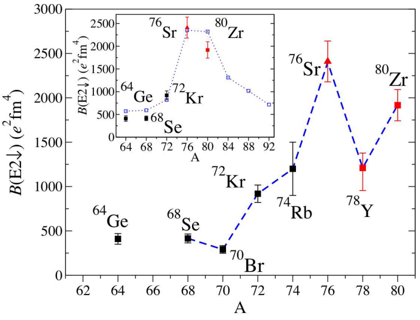
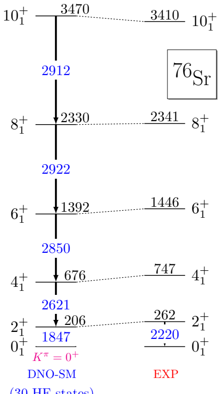


FIG. 3. Schematics of the $B(E2\downarrow)$ values for the $N = Z$ nuclei



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

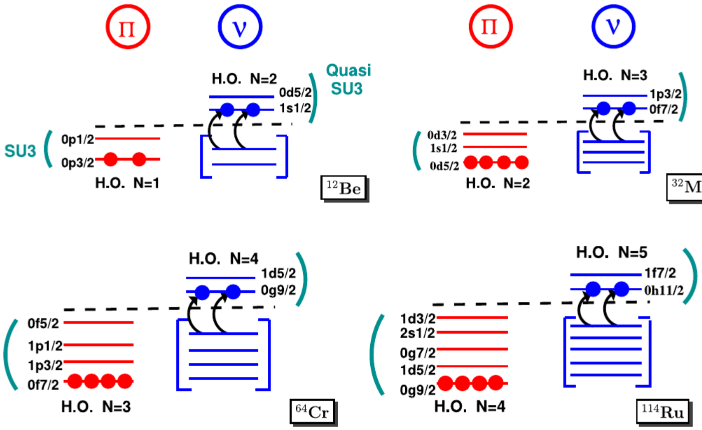
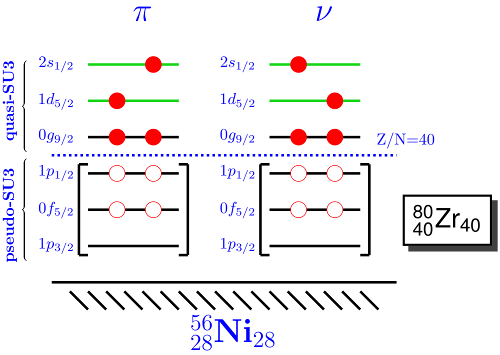


Fig. 40. Schematic view of the valence spaces at N = 8, 20, 40 and 70. The intruder configurations that develop quadrupole collectivity are highlighted.

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 ?

^{88}Ru: boundary of the N=Z island of inversion

^{88}Ru, DNP-ZBM3 effective interaction

	(β,γ)	(β,γ)+np-nh	DNO-SM(VAP)	SM
dimension	39	207	10	$\sim 2 \times 10^{12}$
$E(0^+_{gs})$ (MeV)	-416.465	-418.029	-418.244	-419.780
$E^*(2^+_1)$ (MeV)	0.25	–	0.30	0.49
BE(2) ($e^2.fm^4$)	1322		979	635

(D. D. Dao, F. Nowacki, A. Poves, *Isospin-symmetric island of inversion at the N=Z line*)