SHELL-MODEL : RECENT ADVANCES FROM RARE-EARTH TO SUPERHEAVY ELEMENTS

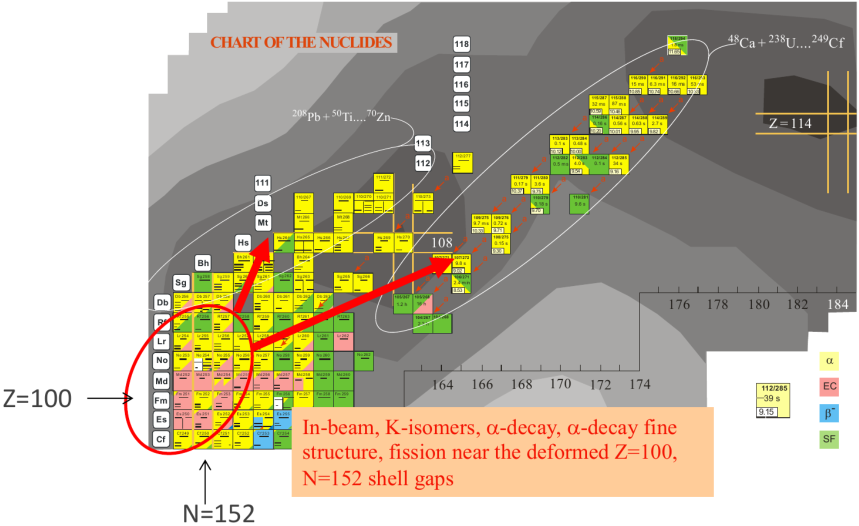
Duy-Duc Dao, F. Nowacki

CNRS IN2P3 Les deux infinis

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

UNIVERSITÉ DE STRASBOURG

Landscape of superheavy nuclei



In-beam, K-isomers, α-decay, α-decay fine structure, fission near the deformed Z=100, N=152 shell gaps

(From Seweryniak (SSNET 2024)

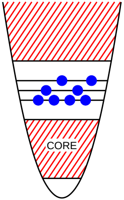
SM-CI approaches through the nuclear chart

◇ Nuclear Shell Model (SM) :

$$H_{\text{exact}}|\Psi_{\text{exact}}\rangle = E|\Psi_{\text{exact}}\rangle$$

$$\Updownarrow$$

$$H_{\text{eff}}|\Psi_{\text{eff}}\rangle = E|\Psi_{\text{eff}}\rangle$$



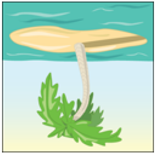
◇ Three Pillars of the Shell Model :

- A relevant valence space
- An associated effective interaction
- A "shell-model" code

(E. Caurier et al. Rev. Mod. Phys. 77, 427 (2005))

◇ Nuclear structure far from stability

- Deformation, Superdeformation
- Superfluidity, Dipole resonances
- Emergence of magic numbers
- Vanishing of shell closures

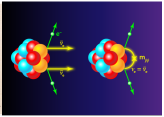


◇ Weak processes

- β decay
- double $\beta\beta$ decay

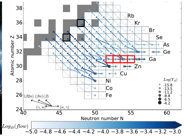
$$[T^{0\nu}_{1/2}(0^+ \to 0^+)]^{-1} = G_{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$$

(nature of neutrinos)



◇ Astrophysics and nucleosynthesis

- rp-process
- r-process



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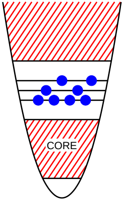

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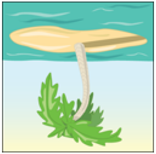

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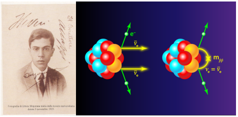

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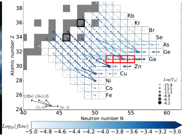


Diagonalization versus Variational Methods

Shell Model Exact Diagonalization

- Exponential growth of basis dimensions :

$$D \sim \begin{pmatrix} d_\pi \\ p \end{pmatrix} \cdot \begin{pmatrix} d_\nu \\ n \end{pmatrix}$$

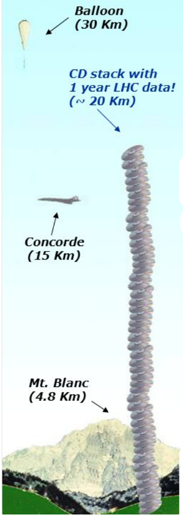
In *pf* shell :

^{48}Cr **1,963,461**

^{56}Ni **1,087,455,228**

In *pf-sdg* space :

^{78}Ni **210,046,691,518**



ANTOINE CODE (1989)

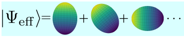
- Actual limits in giant diagonalizations :
  $\sim 10^{12}$, $\sim 10^{15}$ $\neq 0$ matrix elements
- Some of the largest diagonalizations ever are performed in Strasbourg with relatively modest computationnal ressources :
  E. Caurier et al., Rev. Mod. Phys. 77 (2005) 427

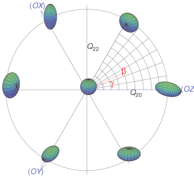
• m-scheme	ANTOINE code
	BIGSTICK
	KSHELL
• coupled scheme	NATHAN code

Variational Approximation

$$\mathcal{H}_{\text{eff}} |\Psi_\alpha^{JM}\rangle = E_\alpha^{(J)} |\Psi_\alpha^{JM}\rangle \rightarrow \delta \frac{\langle \Psi_\alpha^{JM} | \mathcal{H}_{\text{eff}} | \Psi_\alpha^{JM} \rangle}{\langle \Psi_\alpha^{JM} | \Psi_\alpha^{JM} \rangle} = 0$$

- **Mixing of shapes :**





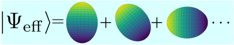
- **Restoration of the rotational symmetry**
- **Degree of freedom**
  - Multipole: β, γ, Q_{30}, ...
  - Cranking: J_x, J_z
  - Pairing constraints
  - Variation-After-Projection
- **Different implementations**

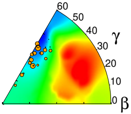
• MCSM	Tokyo group
• DNO-SM	Strasbourg group
• PGCM	Madrid group

Discrete Non-Orthogonal Shell Model (DNO-SM)

◇ Hill-Wheeler-Griffin Generator Coordinate Method :

- $\langle J_z \rangle$, (β, γ) (cranking, axial and triaxial)
- Selection of (β, γ) : Caurier technique
- Rotational symmetry restoration



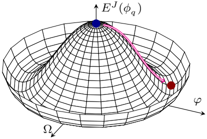


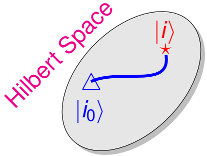
$$P_\alpha^{(J)}(q) = \sum_K |M_\alpha^{(J)}(q, K)|^2$$

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

◇ Variation after Projection :

- $\dfrac{\delta E^J}{\delta \phi_q^*} = \dfrac{\delta}{\delta \phi_q^*} \sum_{KK'} f_q^{*J}(K) f_{q'}^J(K') \langle \phi_q | \hat{H} P_{KK'}^J | \phi_{q'} \rangle$
- $|\phi_q\rangle$: Slater or Bogoliubov wavefunctions
- $J_\alpha^\pi = 0_1^+, 2_1^-, \ldots$
- Intrinsic states generated consistent with the symmetries : rotation, particle number





◇ Interplay of deformation/pairing correlations

- Missing correlations energies
- Rotational spectra
- Reduction of collectivity

LNPS effective interaction

^{62}Cr	(β, γ)	DNO-SM(VAP)	SM
E(0_1^+) (MeV)	−212.426	−214.138	−214.138
E*(2_1^+) (MeV)	0.288	0.555	0.544
B(E2,$2_1^+ \rightarrow 0_1^+$) (e^2fm^4)	458	378	362

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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
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)

PHYSICAL REVIEW C **114**, 014327 (2026)

Editors' Suggestion

Exact solutions of the nuclear shell-model secular problem: Discrete nonorthogonal shell model within a variation-after-projection approach

Duy Duc Dao* and Frédéric Nowacki

(e^2fm^4)

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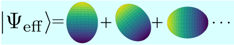

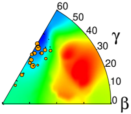

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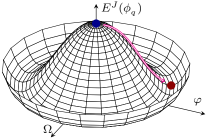

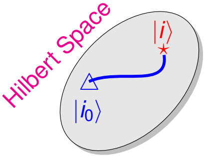

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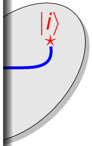

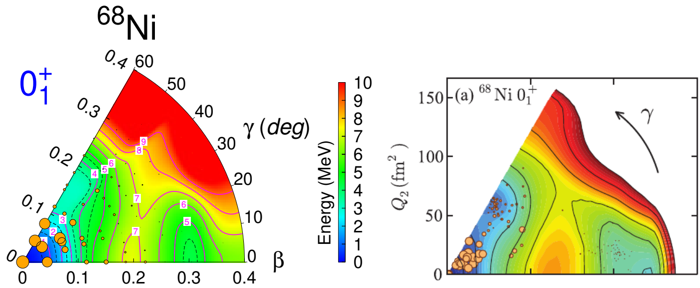

DNO-SM vs MCSM

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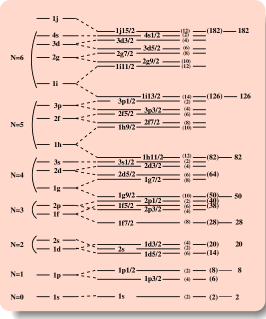
Multipole expansion : $\mathcal{H} = \mathcal{H}_{monopole} + \mathcal{H}_{Multipole}$

$\mathcal{H}_{monopole}$:

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

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



$\mathcal{H}_{multipole}$:

- *Correlations*
- *Energy gains*

- *Pairing (SU2)* — semi-magic (n-n) (p-p)
- *Quadrupole (SU3/pSU3/qSU3)* — p-n in H.O. or Δj = 2

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

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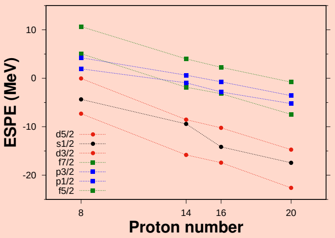

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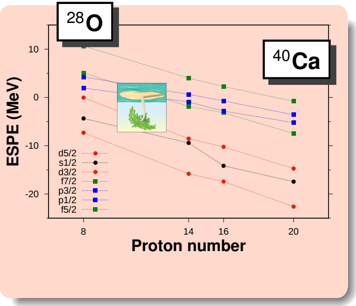

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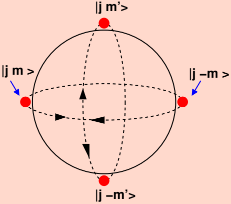
Multipo

- **Pairing regime : spherical nuclei**

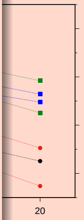
  ground state = pairs of like-particles coupled at J=0 (seniority v=0)

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

  superfluid nucleus :



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

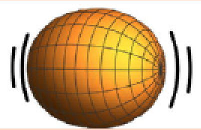


$\mathcal{H}_{monopole}$:

A. Poves an

- **Quadrupole regime : deformed nuclei**

  prolate nucleus :



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

$\mathcal{H}_{multipole}$:

- *Pai*
- *Qu*

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

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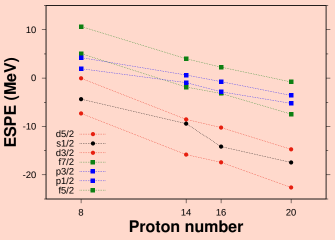

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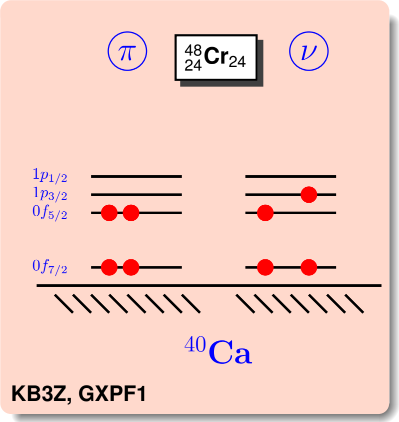
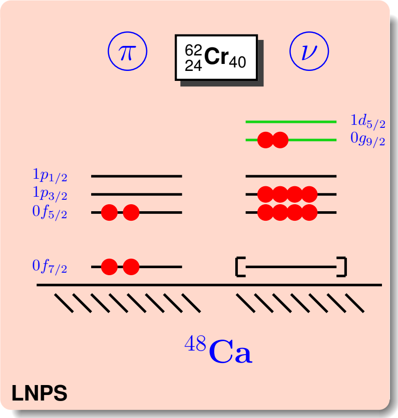
M. Dufour and A. Zuker (PRC 54 1996 1641)

Choice of valence space

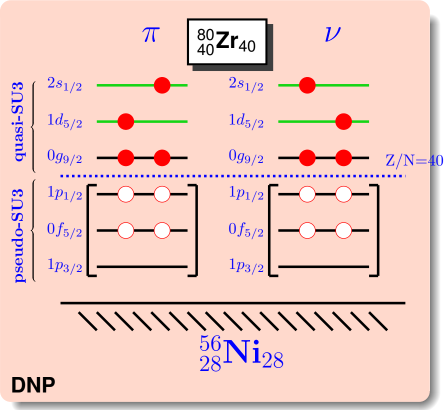
- Classical $0\hbar\omega$ model spaces like *sd* or *pf*-shell are successfull for the description of a low lying states of nuclei, their transition rates and weak-decays.
- Neutron rich systems invoke asymmetric proton and neutron spaces

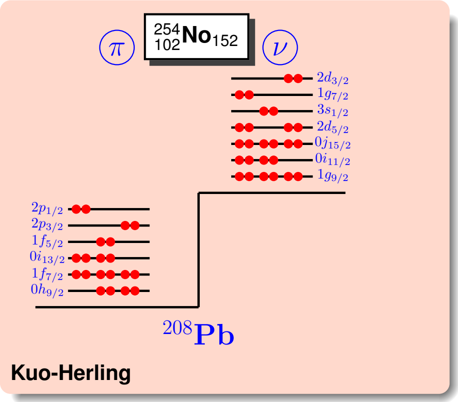




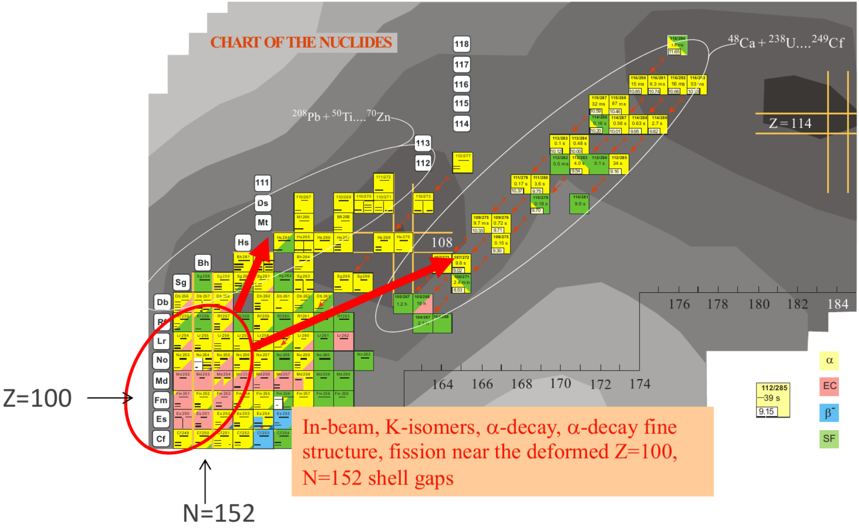
Choice of valence space

- Deformation/Superdeformation require enlarged valences spaces driven by underlying algrebraic symmetries
  (Duc's talk on Monday)
- Rare-earth region, Superheavy systems invoke also asymmetric proton and neutron and algebraic symmetries driven valence spaces
  (Waely's talk on Tuesday)





Landscape of superheavy nuclei



In-beam, K-isomers, α-decay, α-decay fine structure, fission near the deformed Z=100, N=152 shell gaps

(From Seweryniak (SSNET 2024))

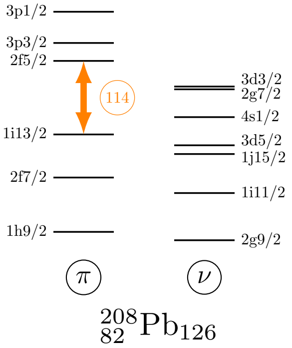
Applications to superheavy nuclei

Kuo-Herling interaction :

- $^{208}_{82}Pb_{126}$ core, realistic TBMEs
- $82 \leq Z \leq 126$ shells for proton and $126 \leq N \leq 184$ for neutrons
- monopole corrections (3N force)

E. Caurier and F. Nowacki,

*PRL **87** (2001),072511*

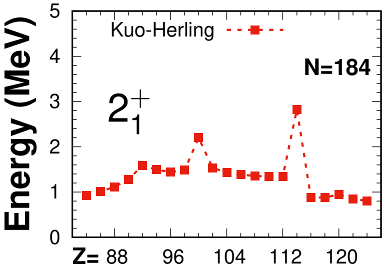


Calculations : NATHAN & CARINA codes

◇ Diagonalization within the seniority scheme along the chains of $N = 126$ and $N = 184$

◇ Variation After Projection calculations : $^{253,254,255}Es$, $^{249,251,253}Cf$, $^{253,254}No$, ^{256}Fm

◇ Comparison of spectra and electromagnetic moments



Yrast systematics : odd-even $^{251}_{98}\mathrm{Cf}_{153}$

PHYSICAL REVIEW C **114**, L021302 (2026)

Letter

First complete shell-model description of low-lying spectroscopy in ^{254}No

Duy Duc Dao * and Frédéric Nowacki †
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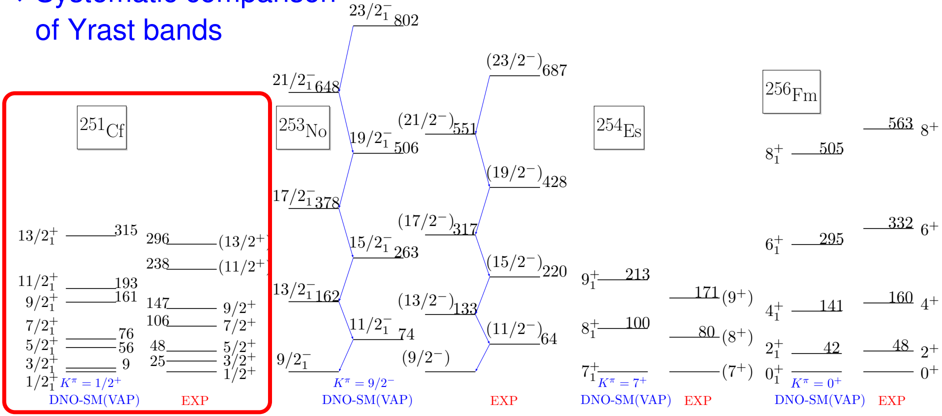
(Received 24 September 2024; revised 26 May 2026; accepted 15 July 2026; published 13 August 2026)

◇ Systematic comparison of Yrast bands



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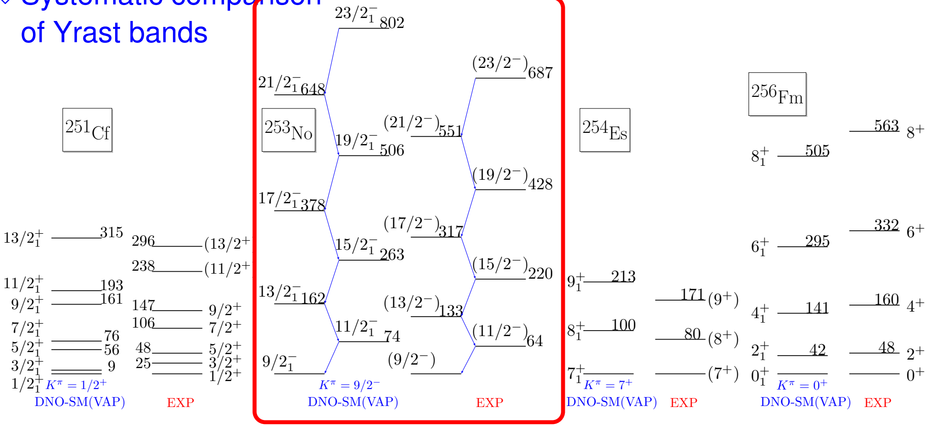

PHYSICAL REVIEW C **114**, L021302 (2026)

Letter

First complete shell-model description of low-lying spectroscopy in ^{254}No

Duy Duc Dao* and Frédéric Nowacki†
Université de Strasbourg, CNRS, IPHC UMR7178, 23 Rue du Loess, F-67000 Strasbourg, France

(Received 24 September 2024; revised 26 May 2026; accepted 15 July 2026; published 13 August 2026)

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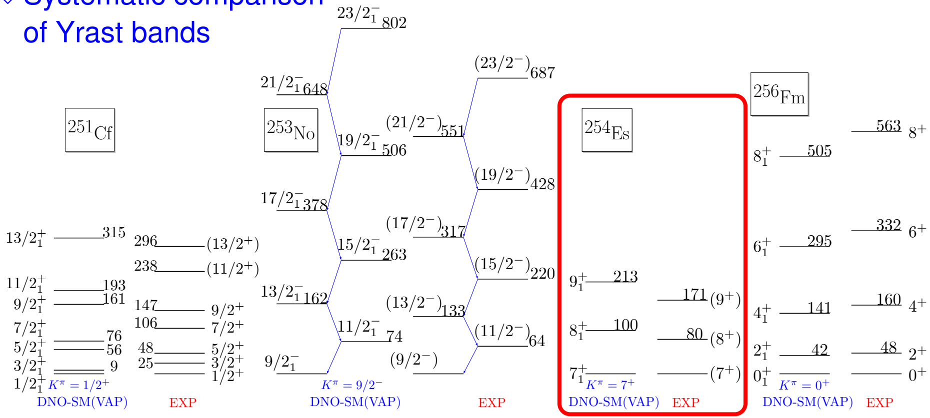

Yrast systematics : even-even $^{256}_{100}Fm_{156}$

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Letter

First complete shell-model description of low-lying spectroscopy in ^{254}No

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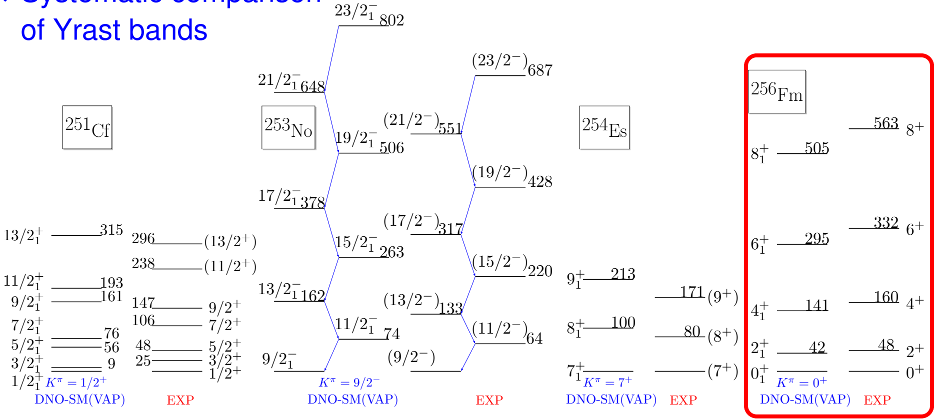

Applications to superheavy nuclei : Electromagnetic moments

PHYSICAL REVIEW C **114**, L021302 (2026)

Letter

First complete shell-model description of low-lying spectroscopy in ^{254}No

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(Received 24 September 2024; revised 26 May 2026; accepted 15 July 2026; published 13 August 2026)

◇ Comparison of magnetic and quadrupole moments

Effective charges : e_p = 1.72, e_n = 0.75

J^π_{gs}		E (MeV)		$\mu(\mu_N)$			Q_s (eb)		
		PHF	VAP	PHF	VAP	EXP	PHF	VAP	EXP
^{253}No	$9/2^-$	−241.818	−242.816	+0.591	−0.493	−0.527(33)(75)	−3.5	+7.2	+5.9(1.4)(0.9)
^{253}Cf	$7/2^+$	−253.402	−253.818	−0.677	−0.556	−0.731(35)	+5.77	+5.78	+5.53(51)
^{251}Cf	$1/2^+$	−241.321	−241.724	−0.727	−0.610	−0.571(24)	-	-	-
^{249}Cf	$9/2^-$	−229.021	−229.381	−0.480	−0.461	−0.395(17)	+6.62	+6.63	+6.27(33)
^{255}Es	$7/2^+$	−263.512	−264.695	−1.10	+3.94	+4.14(10)	+6.0	+5.8	+5.1(1.7)
^{254}Es	7^+	−257.492	−258.441	+0.778	+3.36	+3.42(7)	+1.8	+8.4	+9.6(1.2)
^{253}Es	$7/2^+$	−251.837	−252.280	+3.63	+3.93	+4.10(7)	+5.87	+5.9	+6.7(8)
^{256}Fm	0^+	−268.999	−269.717	+0.87	+0.89	-	−3.57	−3.60	-
^{254}No	0^+	−249.568	−250.187	+0.87	+0.91	-	−3.78	−3.75	-

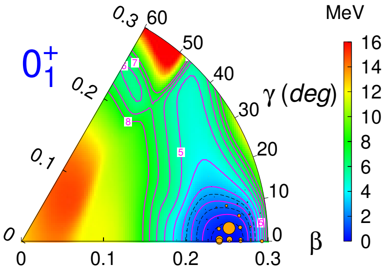
Applications to superheavy nuclei : $^{254}_{102}\mathrm{No}_{152}$

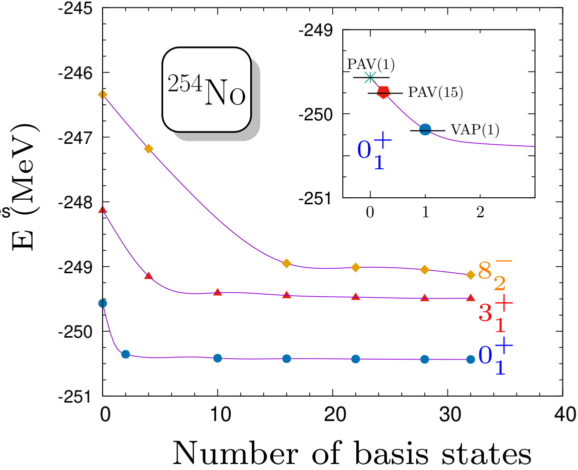
Known spectrospcopy :

- Axially well-deformed nucleus
- Ground-state rotational band
- Several isomeric states $(8^-, 3^+, 10^+)$

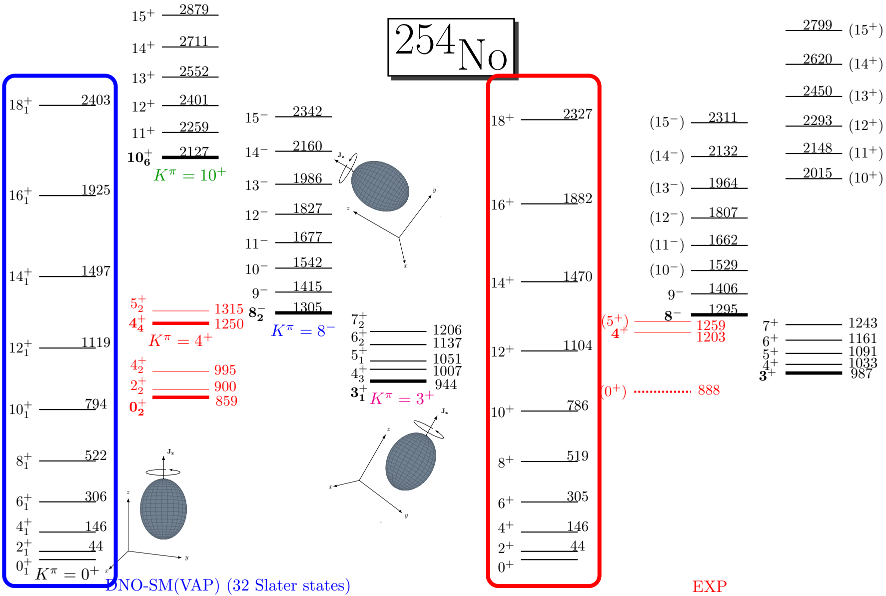
Calculations :

- Deformed Axial Minimum at $\beta = 0.25$
- Mixing of triaxial configurations (β, γ) (PAV(15))
- VAP calculations for band-head structures

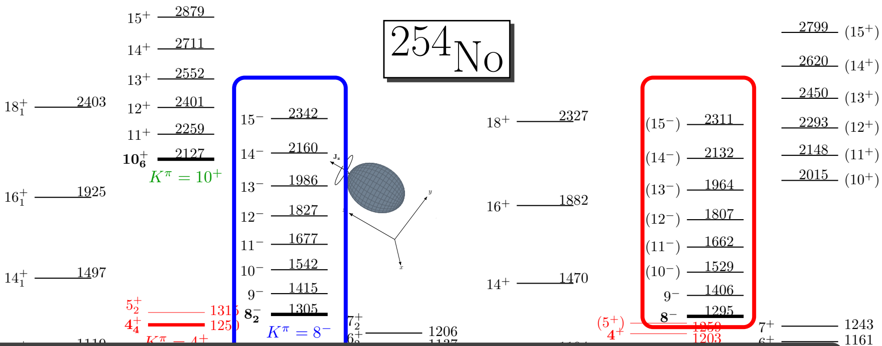




Reproduction of spectra : Yrast rotational band



Isomeric $8^-(K = 8)$ band



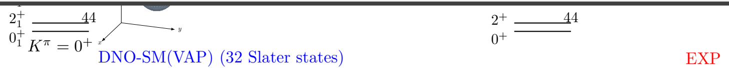
8_2^-	Calc.	EXP.
E^* (keV)	1305	1295[a]

([a] M. Forge *et al.*, Phys. Rev. C114, 0243024 (2026))

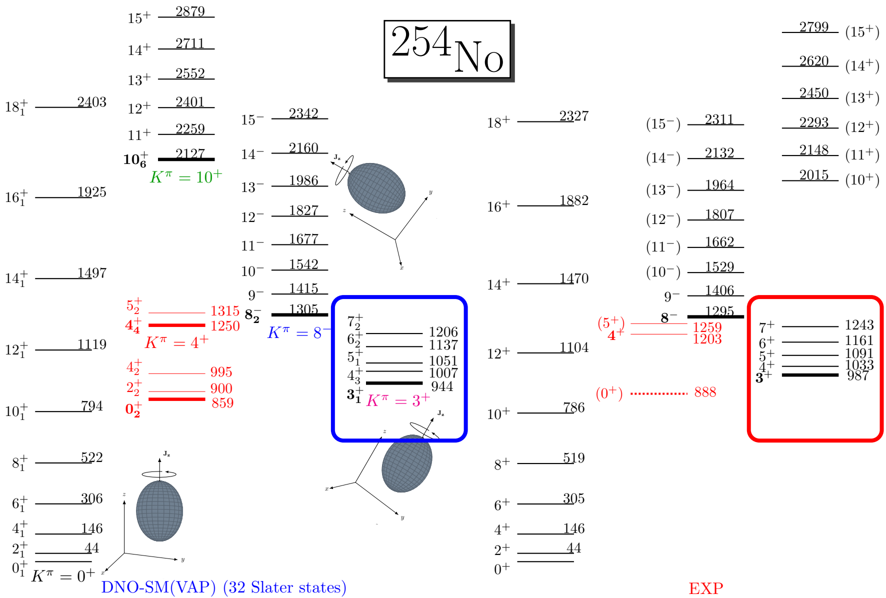
Single-particle configurations :

$\sim$ Two-neutron excitations

$\nu j15/2 \otimes \nu g9/2$



Isomeric $3^+(K=3)$ band



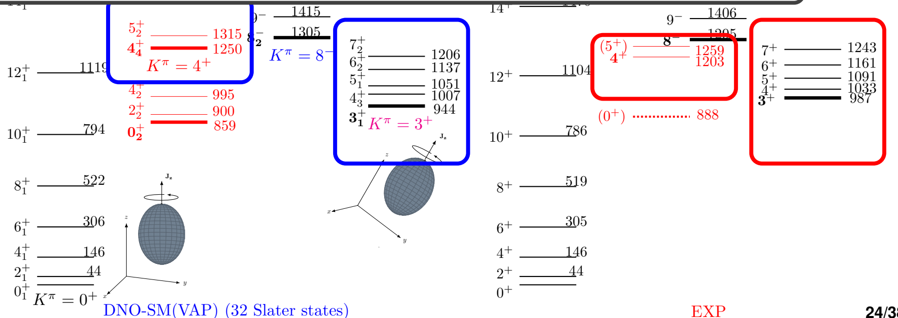
Isomeric $3^+(K=3)$ band : Gallagher-Moszkowski partner $4^+(K=4)$

^{254}No	Calc.	EXP.
$E^*(3^+)$ (keV)	944	987[a]
$E^*(4^+)$ (keV)	1250	1203[a]
$\Delta E_{GM} = E_{\uparrow\downarrow} - E_{\uparrow\uparrow}$	306	216[a]

([a] M. Forge *et al.*, Phys. Rev. C114, 024324 (2026))

$$K = |\Omega_n \pm \Omega_p|$$

$K=3$ (spin-aligned) lies lower than $K=4$ (spin-anti-aligned)



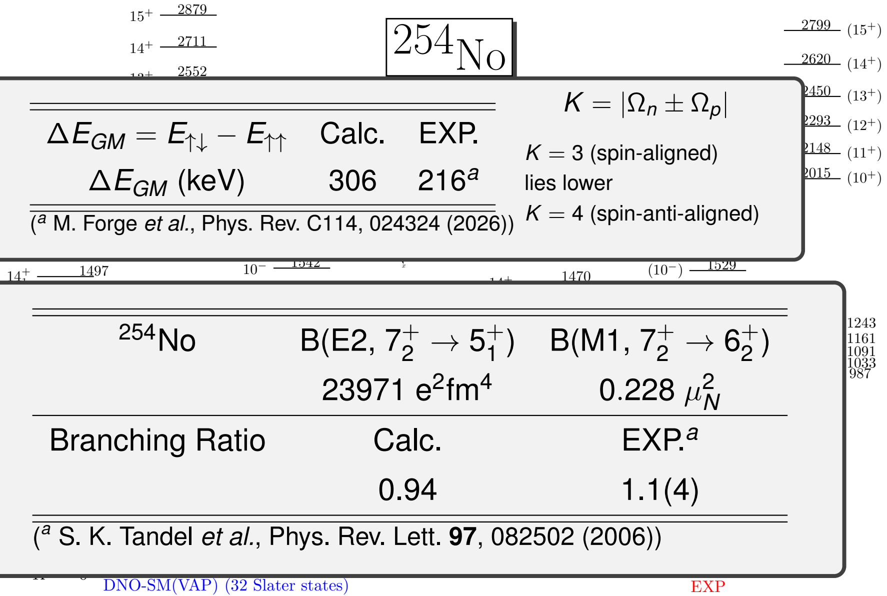
Single-particle Occupations : $3^+(K=3)$, $4^+(K=4)$

- $3^+_1, 4^+_4$: similar structure involving a $\pi h9/2$ recoupled with others orbitals

Ground- and excited-states occupations

Proton orbits	$0h_{9/2}$	$0i_{13/2}$	$1f_{7/2}$	$1f_{5/2}$	$2p_{3/2}$	$2p_{1/2}$	
0^+_1	6.03	7.75	3.43	1.49	0.77	0.52	
0^+_2	7.08	7.91	3.23	0.89	0.69	0.21	
$3^+_1(K=3)$	6.47	7.98	3.34	1.15	0.72	0.34	
$4^+_4(K=4)$	6.50	7.83	3.41	1.18	0.72	0.36	
$8^-_2(K=8)$	6.48	7.90	3.36	1.19	0.70	0.37	
$10^+_6(K=10)$	6.55	7.03	3.48	1.56	0.79	0.58	
Neutron orbits	$0i_{11/2}$	$0j_{15/2}$	$1g_{9/2}$	$1g_{7/2}$	$2d_{5/2}$	$2d_{3/2}$	$3s_{1/2}$
0^+_1	7.30	9.91	5.43	1.00	1.09	0.84	0.43
0^+_2	7.36	9.95	5.45	0.96	1.05	0.80	0.42
$3^+_1(K=3)$	7.32	9.94	5.46	0.97	1.07	0.81	0.42
$4^+_4(K=4)$	7.34	9.79	5.48	1.03	1.11	0.81	0.44
$8^-_2(K=8)$	7.42	9.00	6.30	0.98	1.06	0.81	0.43
$10^+_6(K=10)$	7.23	8.89	5.72	1.40	1.34	0.97	0.45

Branching Ratio : $3^+(K=3)$ band



$\Delta E_{GM} = E_{\uparrow\downarrow} - E_{\uparrow\uparrow}$	Calc.	EXP.
ΔE_{GM} (keV)	306	216[a]

([a] M. Forge *et al.*, Phys. Rev. C114, 024324 (2026))

$K = |\Omega_n \pm \Omega_p|$

$K=3$ (spin-aligned) lies lower

$K=4$ (spin-anti-aligned)

^{254}No	$B(E2, 7_2^+ \to 5_1^+)$	$B(M1, 7_2^+ \to 6_2^+)$
	23971 e^2fm^4	0.228 μ_N^2
Branching Ratio	Calc.	EXP.[a]
	0.94	1.1(4)

([a] S. K. Tandel *et al.*, Phys. Rev. Lett. **97**, 082502 (2006))

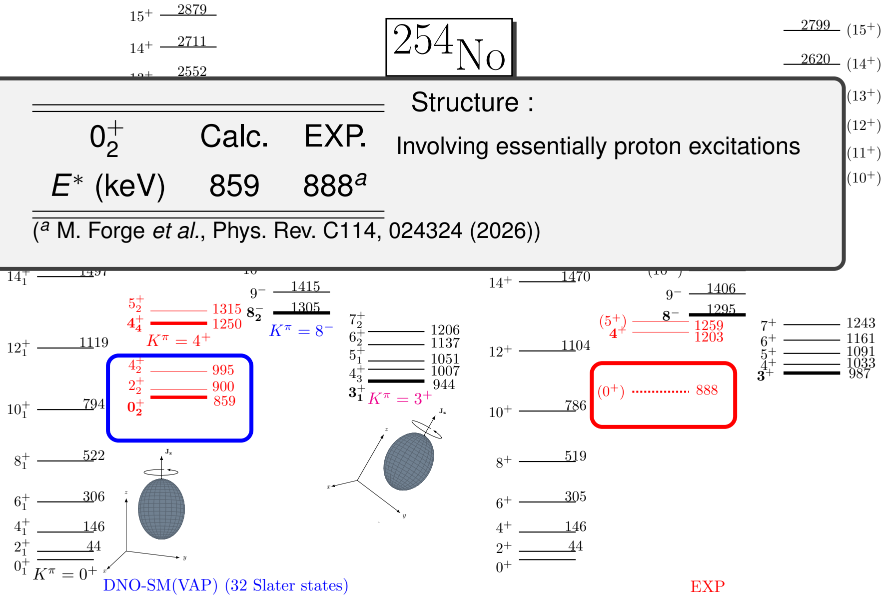
Low-lying excited 0_2^+ state

0_2^+	Calc.	EXP.
E^* (keV)	859	888[a]

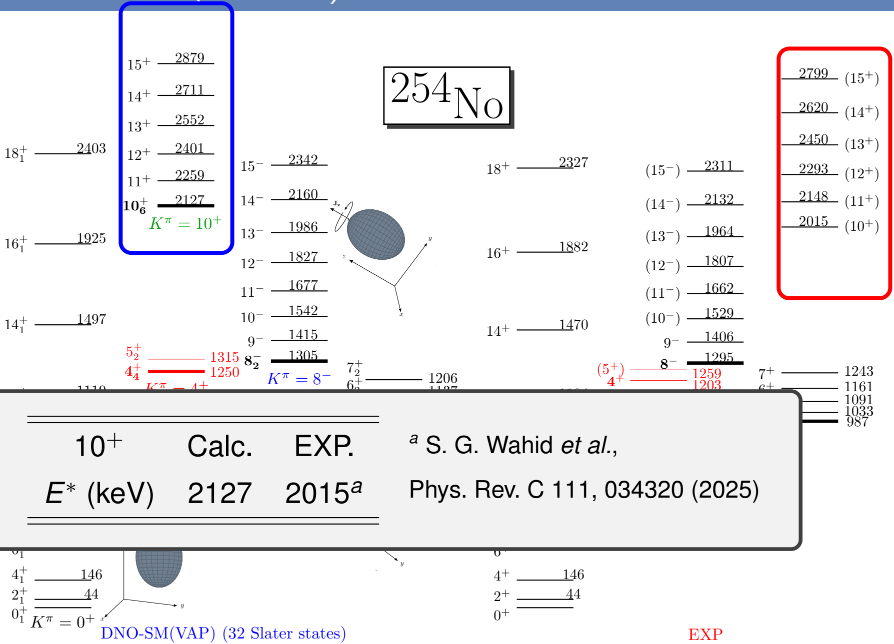
([a] M. Forge *et al.*, Phys. Rev. C114, 024324 (2026))

Structure :

Involving essentially proton excitations



Isomeric $10^+(K = 10)$ band



10^+	Calc.	EXP.
E^* (keV)	2127	2015[a]

[a] S. G. Wahid *et al.*, Phys. Rev. C 111, 034320 (2025)

Isomeric $10^+(K=10)$ band

15^+ 2879

2711

18^+_1

16^+_1

14^+_1

2799 (15^+)

2620 (14^+)

2450 (13^+)

2293 (12^+)

2148 (11^+)

2015 (10^+)

PHYSICAL REVIEW C **114**, L021302 (2026)

Letter

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Université de Strasbourg, CNRS, IPHC UMR7178, 23 Rue du Loess, F-67000 Strasbourg, France

(Received 24 September 2024; revised 26 May 2026; accepted 15 July 2026; published 13 August 2026)

PHYSICAL REVIEW C **114**, 024324 (2026)

First experimental measurement of spin splitting and evidence for a second 0^+ state in $^{254}_{102}\mathrm{No}_{152}$

M. Forge,[1] O. Dorvaux,[1] A. Lopez-Martens,[2] K. Kessaci,[1] B. J. P. Gall,[1] K. Hauschild,[2] D. D. Dao,[1] F. Nowacki,[1] S. Péru,[3] Z. Asfari,[1] R. Chakma,[2,*] A. V. Yeremin,[4,5] M. L. Chelnokov,[4] V. I. Chepigin,[4] A. V. Isaev,[4,5] I. N. Izosimov,[4] D. Katrasev,[4] A. A. Kuznetsova,[4] O. N. Malyshev,[4,5] R. Mukhin,[4] A. G. Popeko,[4,5] Yu. A. Popov,[4] B. Saylaubekov,[4] A. I. Svirikhin,[4,5] E. A. Sokol,[4] M. S. Tezekbayeva,[4] N. I. Zamyatin,[6] and J. Piot[7]

1243
1161
1091
1033
987

4^+_1 146
2^+_1 44
0^+_1
$K^\pi = 0^+$

DNO-SM(VAP) (32 Slater states)

4^+ 146
2^+ 44
0^+

EXP

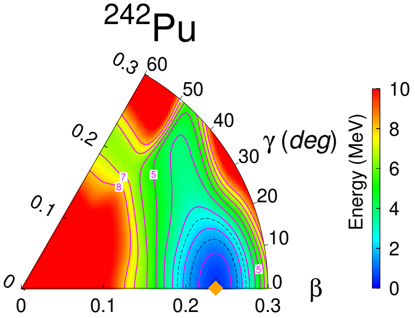
Dipole excitations in $^{242}_{94}\mathrm{Pu}_{148}$

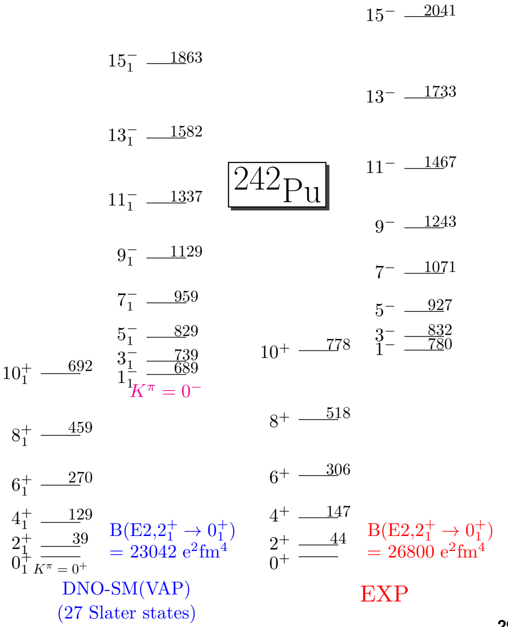
Known spectrospcopy :

- Axially well-deformed nucleus
- Ground-state rotational band
- Several side bands :
  $1^-(K=0), 3^-(K=3), 7^-$

Calculations :

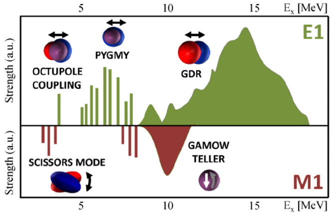
- Deformed Axial Minimum at $\beta = 0.24$
- VAP calculations for band-head structures



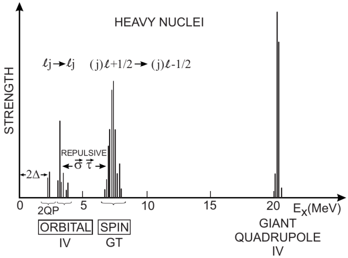


◇ Strength function description of *M*1, *E*1 :

- Scissors mode in deformed nuclei
- DNO-SM(VAP) : capture correlations



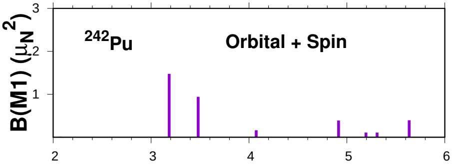
D. Budker *et al.*, Ann. Phys. **2022**, 534, 2100284.



K. Heyde *et al.*, Rev. Mod. Phys. **104**, 045801 (2021).

◇ Open questions :

- Generate easily structure function for many final states
- E1 transitions forbidden in the natural valence space
  ⟶ add QSU3 higher orbitals



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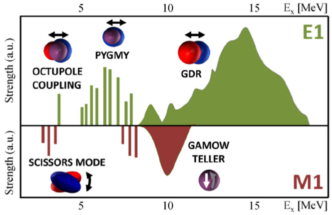

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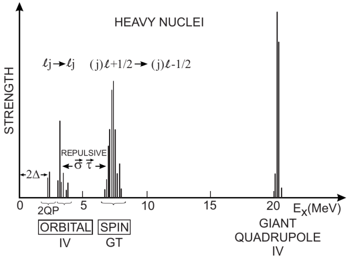

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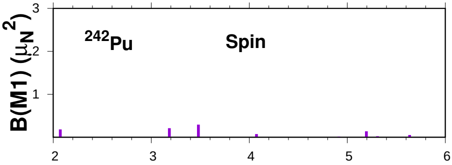

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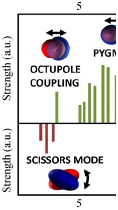
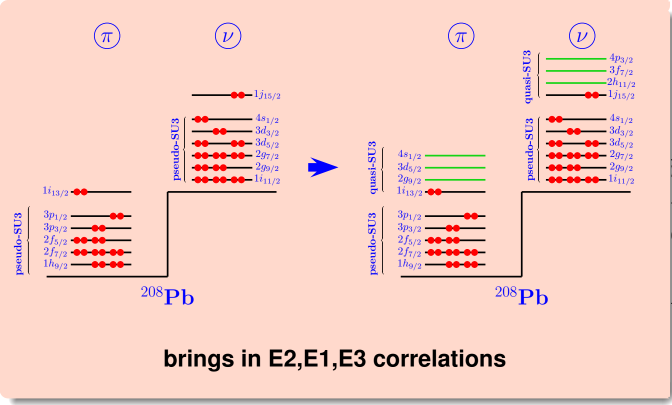
- Scissors mode in deformed nuclei
- DNO-SM(VAP) : capture correlations



D. Budker *et al.*,

01 (2021).



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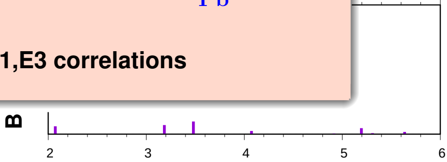
  for many
- E1 transit
  in the natural valence space
  ⟶ add QSU3 higher orbitals



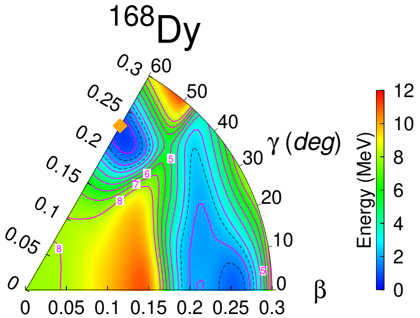
Spectroscopy in rare-earth region

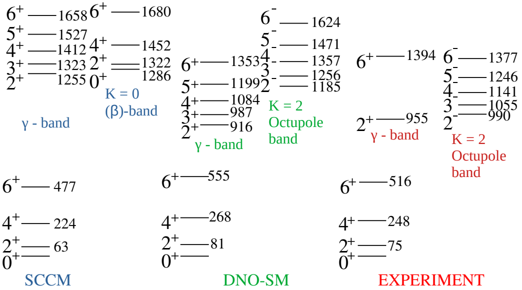
Few spectrospcopy :

- Well-deformed nucleus
- Ground-state rotational band
- few negative parity states bands : 3^-, 4^-

Calculations :

- realistic N3LO interaction for ^{132}Sn core and $\pi\ g_{\frac{7}{2}} d_{\frac{5}{2}} d_{\frac{3}{2}} s_{\frac{1}{2}} h_{\frac{11}{2}}$ $\nu\ h_{\frac{9}{2}} f_{\frac{7}{2}} f_{\frac{5}{2}} p_{\frac{3}{2}} p_{\frac{1}{2}} i_{\frac{13}{2}}$ orbitals
- Deformed Oblate minimum at $\beta = 0.23$
- VAP calculations for band-head structures





Level scheme for the ground state banf, the γ band, the $K^\pi = 0^+$ band and the $K^\pi = 2^-$ band in ^{168}Dy computed with the Symmetry-Conserving Configuration Mixing Model and DNO-SM, compared to experimental values

E. L. Larsson *et al.*, "Revealing the shapes of ^{168}Dy by first-time projectile-fragmentation of ^{170}Er", to be submitted

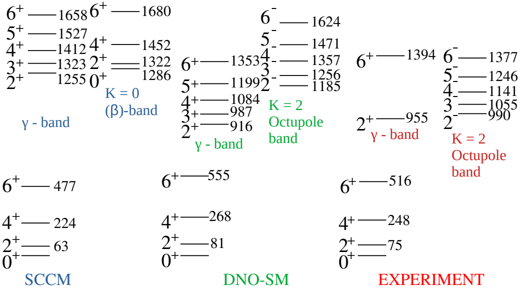
Octupole excitations in $^{168}_{66}\mathrm{Dy}_{102}$

Few spectrospcopy :

- Well-deformed nucleus
- Ground-state rotational band
- few negative parity states bands : 3^-, 4^-

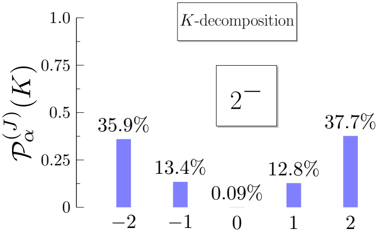
Calculations :

- realistic N3LO interaction for ^{132}Sn core and
  π $g_{\frac{7}{2}}\, d_{\frac{5}{2}}\, d_{\frac{3}{2}}\, s_{\frac{1}{2}}\, h_{\frac{11}{2}}$
  ν $h_{\frac{9}{2}}\, f_{\frac{7}{2}}\, f_{\frac{5}{2}}\, p_{\frac{3}{2}}\, p_{\frac{1}{2}}\, i_{\frac{13}{2}}$ orbitals
- Deformed Oblate minimum at $\beta = 0.23$
- VAP calculations for band-head structures



Level scheme for the ground state banf, the γ band, the $K^{\pi} = 0^{+}$ band and the $K^{\pi} = 2^{-}$ band in ^{168}Dy computed with the Symmetry-Conserving Configuration Mixing Model and DNO-SM, compared to experimental values

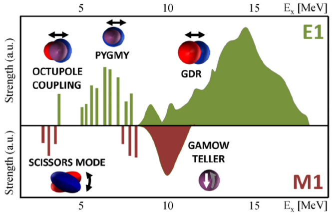
E. L. Larsson *et al.*, “Revealing the shapes of ^{168}Dy by first-time projectile-fragmentation of ^{170}Er”, to be submitted



Dipole excitations in Rare-Earth region

◇ Strength function description of *M*1, *E*1 :

- Scissors mode in deformed nuclei
- DNO-SM(VAP) : capture correlations



D. Budker *et al.*, Ann. Phys. **2022**, 534, 2100284.

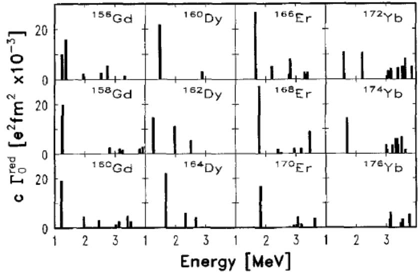


Fig. 1. Distribution of $\Delta K = 0$ dipole strengths in the rare earth nuclei $^{156, 158, 160}$Gd, $^{160, 162, 164}$Dy, $^{166, 168, 170}$Er and $^{172, 174, 176}$Yb. In case of negative parity the ordinate value can be identified with the $10^{-3} e^2\,\mathrm{fm}^2$, i.e. $c \cdot \Gamma_0^{red}(1^- \to 0^+) = B(E1,$ $866 \cdot 10^{-3} e^2\,\mathrm{fm}^2\,(\mathrm{meV})^{-1}$ and Γ_0^{red} is the in meV defined in (1)

A. Zilges *et al.*, Z. Phys. A **340**, 155 (1991).

◇ Open questions :

- Generate easily structure function for many final states
- E1 transitions forbidden in the natural valence space
  $\longrightarrow$ add QSU3 higher orbitals

Summary

- Non-Orthogonal Multi-Slater Determinants give an exact representation of shell-model wave functions
- Pairing correlations are fully captured by the variation after projection where the rotational symmetry is consistently restored
- Isospin symmetric Island of Inversion around A$\sim$ 80
- First shell-model description of superheavy nuclei : ^{253,254,255}Es, ^{249,251,253}Cf, ^{253,254}No, ^{256}Fm
- Complete reproduction of known spectroscopy of ^{254}No : yrast and excited isomeric structures
- Ongoing study of dipole excitations in ^{242}Pu
- Ongoing study of dipole/octupole excitations in ^{168}Dy