4th NuSTRAP Workshop, 26/05/2026, UoA Athens, Greece

Measurements in Yb, Er and Dy isotopes: Deformation evolution and isomerism

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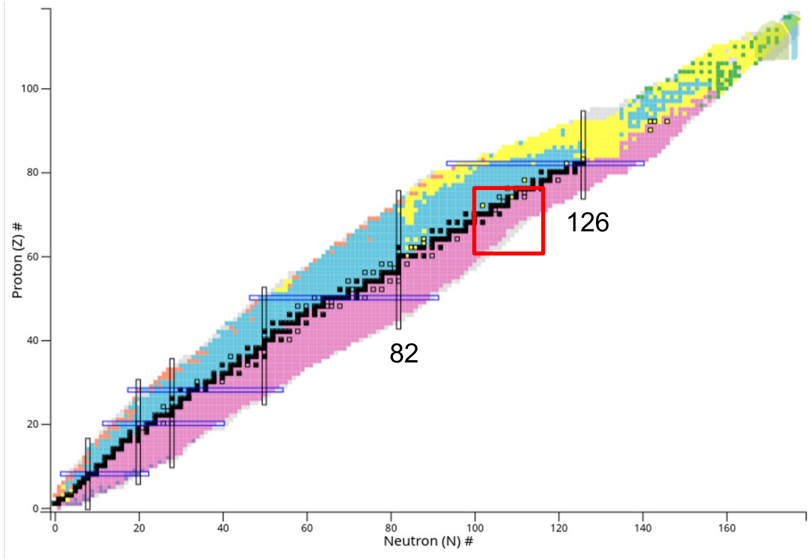
[6] Institute of Nuclear and Particle Physics, NCSR Demokritos, Athens, Greece

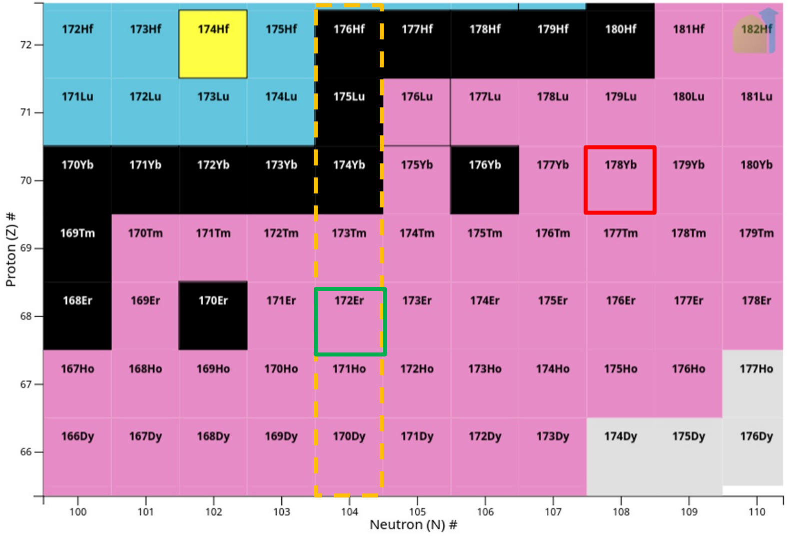
Outlook

- YbEr project: ^{178}Yb and ^{172}Er
- Upcoming measurements in ^{150}Dy

Evolution of deformation in neutron-rich Yb and Er isotopes

…by investigating, experimentally and theoretically, the well deformed ^{178}Yb (N=108) and ^{172}Er (N=104) isotopes

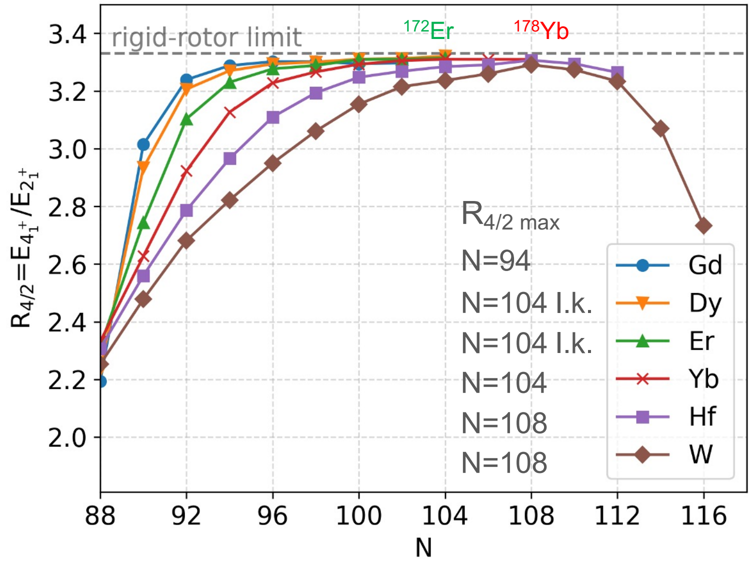


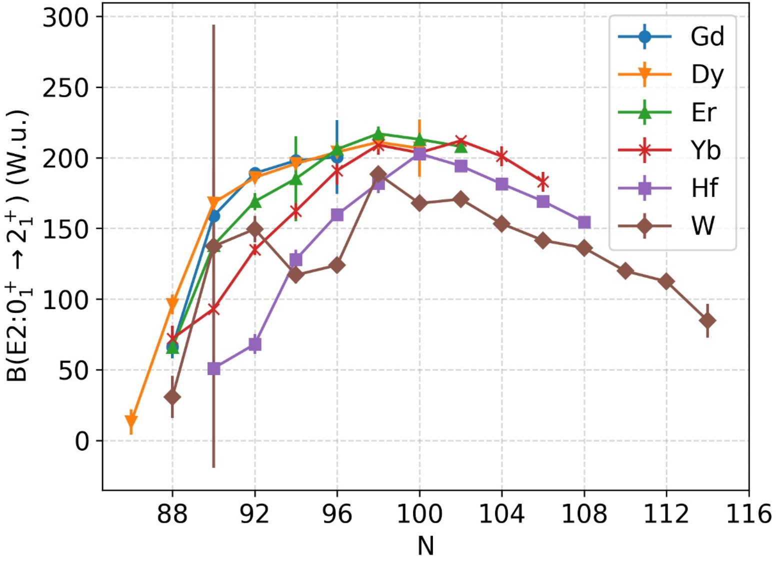


N=104 mid-shell

Systematics of the rare-earth isotopes A~170

All rare-earth isotopes in the N=104 mid-shell closure region with atomic number 64≤Z≤74 and neutron number 94≤N≤116 are known to **present some deformation**





J. Zhang et al. Phys. Rev. C 73 (2006), p. 037301

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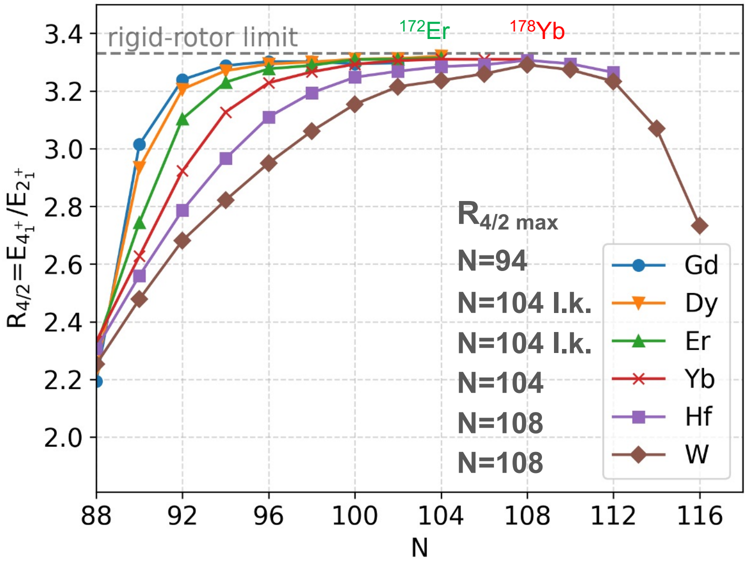

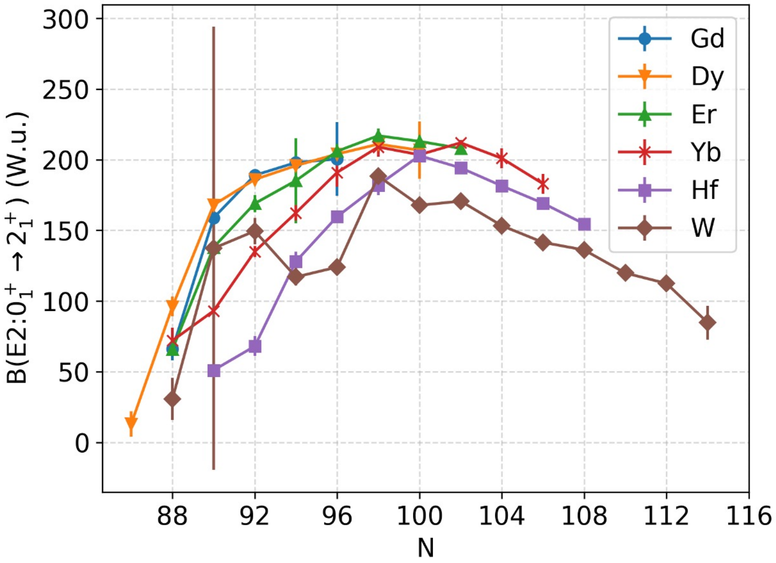

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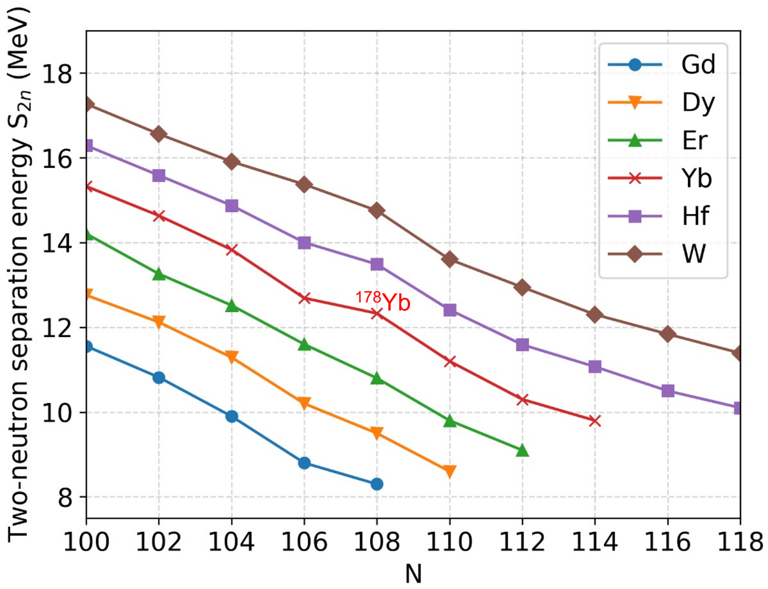
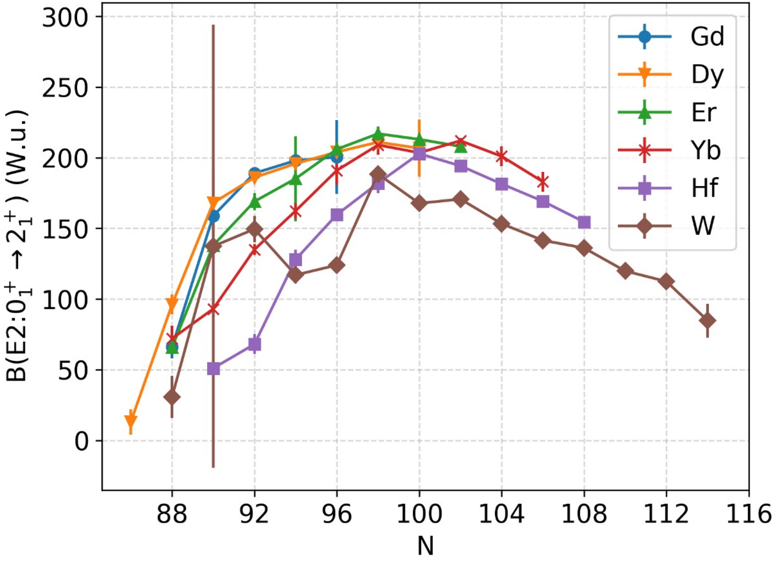
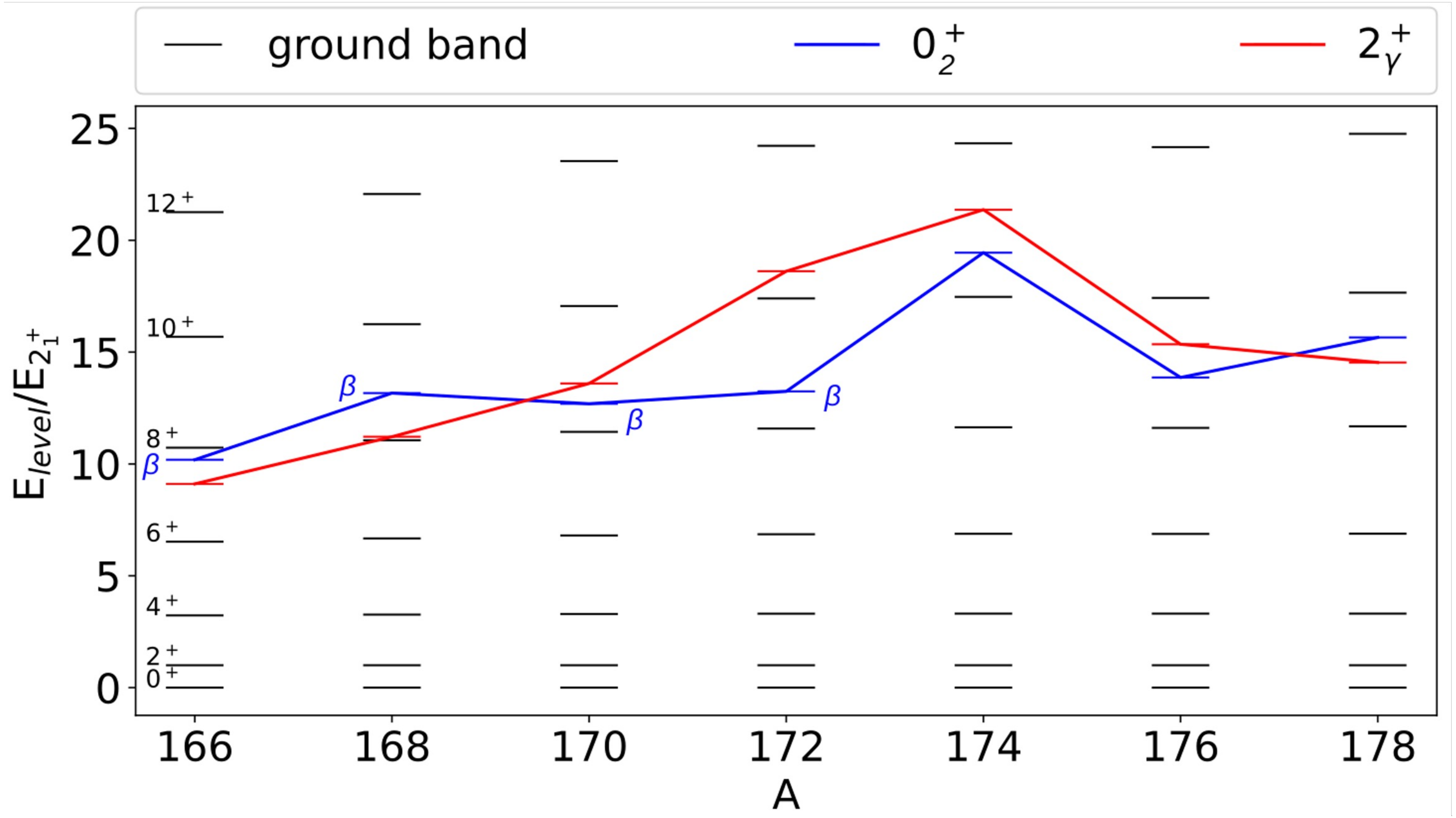


R. B. Cakirli et al. Phys. Rev. Lett. 96 (2006), p. 132501



J. Zhang et al. Phys. Rev. C 73 (2006), p. 037301

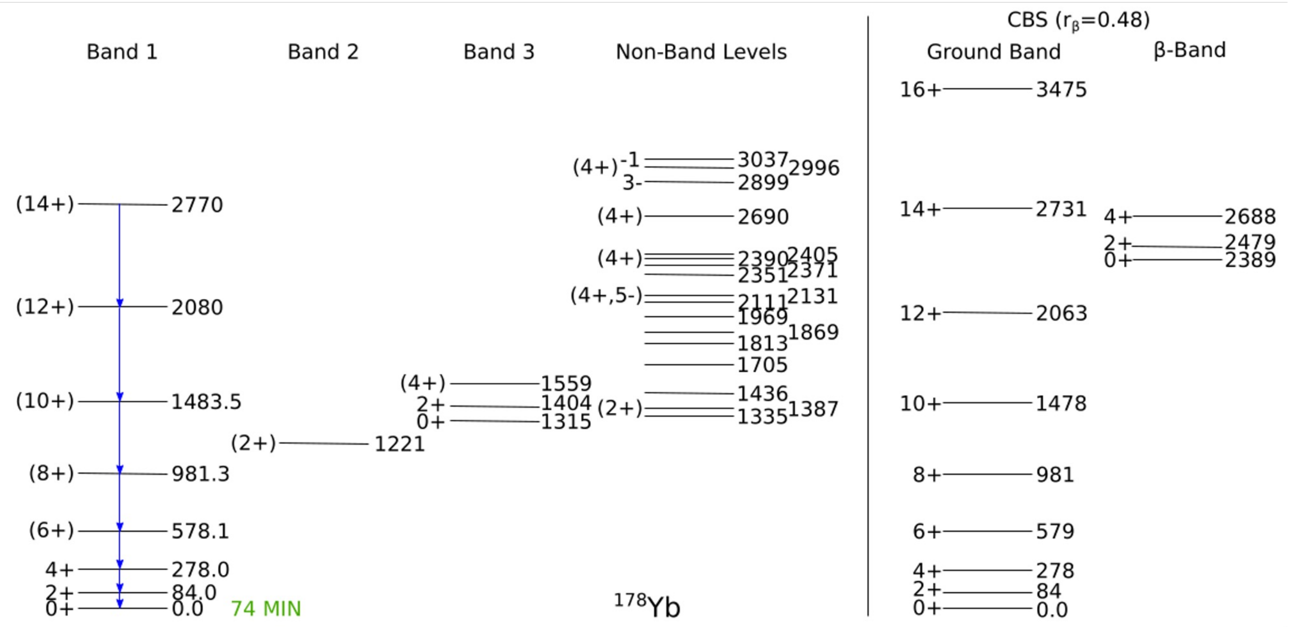
Levels systematics in the Yb isotopic chain



^{178}Yb experimental data and theory

Literature data
- no lifetime known
- no inter-band transitions have been seen yet

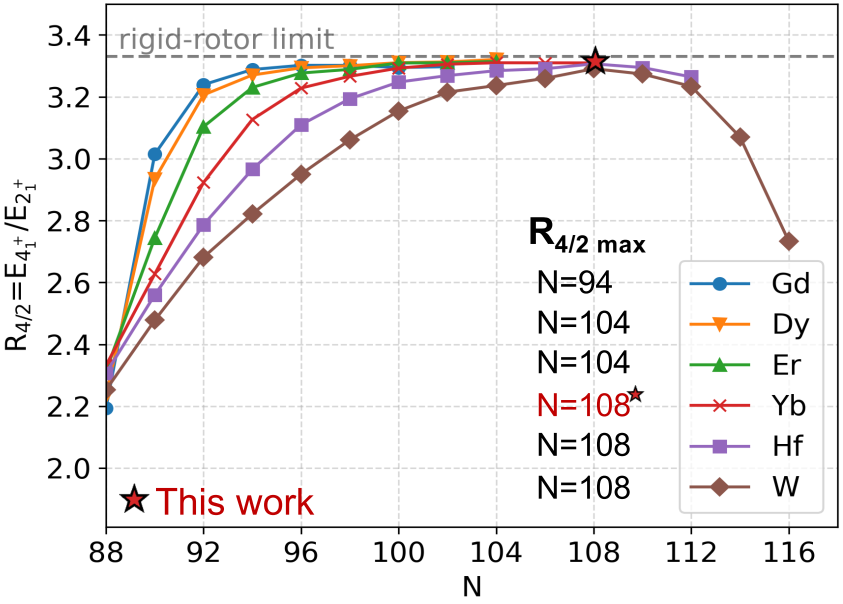
Theoretical investigation
- Collective models
  - “confined β-soft” (CBS) rotor model
  - Interacting Boson Model
- Microscopic models
  - Proxy-SU(3)
  - relativistic/covariant energy density functionals framework

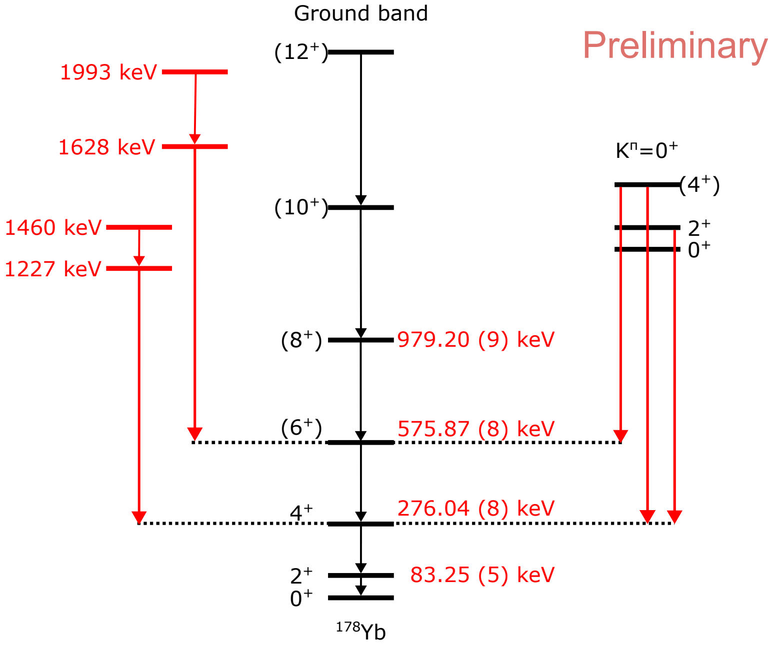


D. Bonatsos, Phys. Rev. C 95 (2017) 064325
D. Bonatsos et al., Symmetry 16 (2024) 1625
T. Nikšić, D. Vretenar, and P. Ring, Progress in Particle and Nuclear Physics 66, 519 (2011)

N. Pietralla et al. Phys. Rev. C 70 (2004) p. 011304
M. Reese, CBS model program (2011)

Gamma-spectroscopy on ^{178}Yb at IKP Cologne (May 2025)

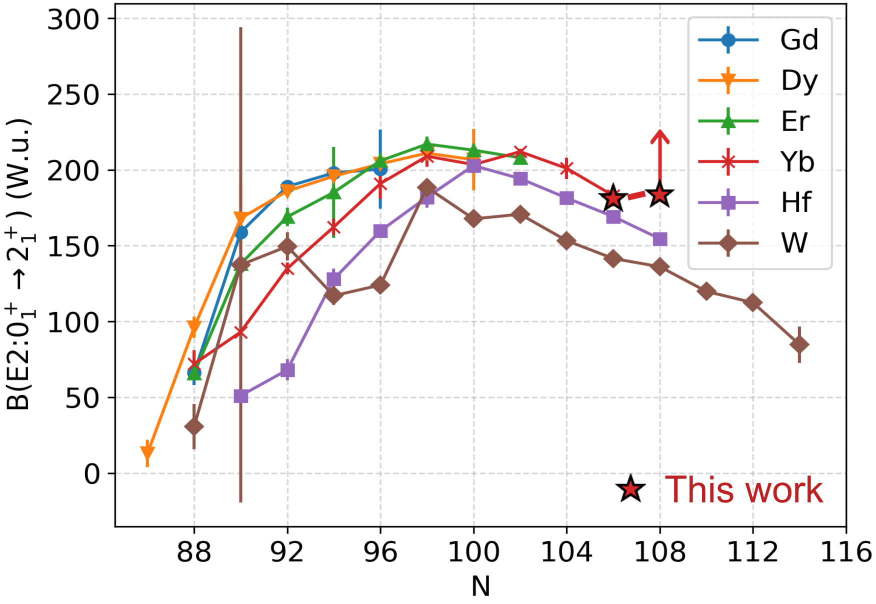




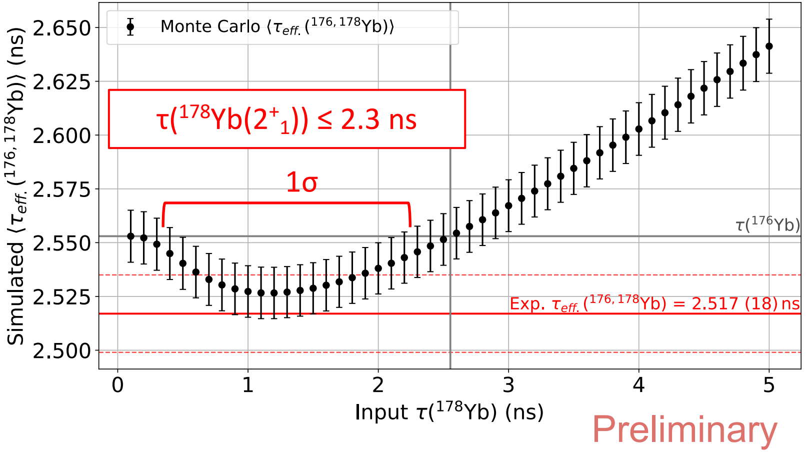
- The γ-spectroscopy findings indicate that **^{178}Yb is the most rigid-rotor-like isotope** of the isotopic chain, with the $R_{4/2}$ ratio maximizing at N=108

- New energies for the 2^+_1 and 4^+_1 decaying γ-rays were measured, resulting on new energies for the levels and the $R_{2/4}$ ratio, setting ^{178}Yb the most rigid-rotor-like isotope of the Yb isotopic chain
- New transitions and new levels have been found
- For the first-time inter-band transition has been identified

Lifetime measurements on ^{178}Yb at IKP Cologne (May 2025)



Monte Carlo simulations for extracting $\tau(^{178}Yb(2^+_1))$	
Input parameters	Relative intensity ratio of ^{178}Yb/^{176}Yb
	Measured $\tau(^{176}Yb(2^+_1))$ lifetime and precision
	Variable trial values for $\tau(^{178}Yb(2^+_1))$
Output	The simulated effective lifetime: $\tau_{eff.}(^{176,178}Yb(2^+_1))$
Goal	Compare simulated $\tau_{eff.}(^{176,178}Yb(2^+_1))$ with the experimentally measured value to determine $\tau(^{178}Yb(2^+_1))$

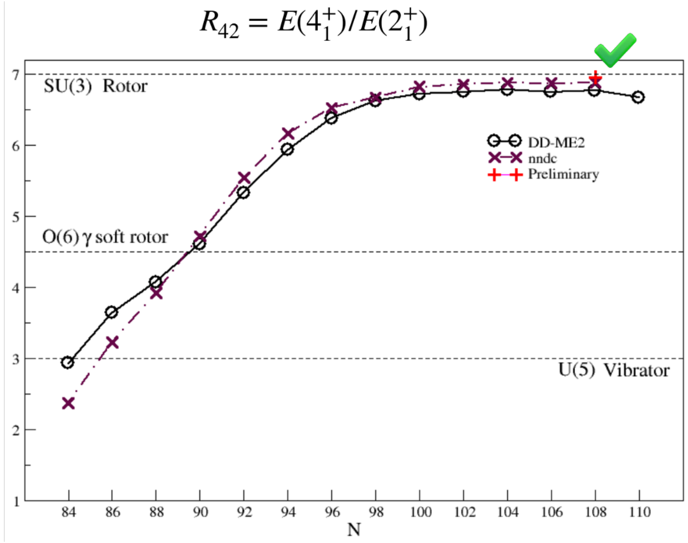


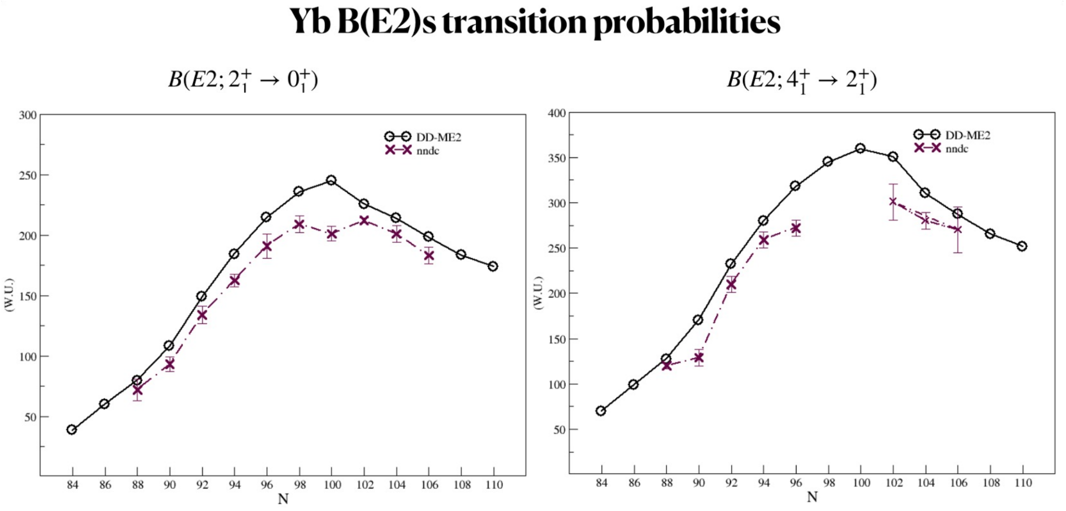
- The **lifetime of the 2^+_1 state in ^{178}Yb was measured for the first time**, allowing the calculation of a **lower limit for the B(E2)** value at N = 108
- Local minimum at N=106 in **trend of the B(E2)** values, not visible at the neighboring Hf and W isotopic chains

Microscopic calculations

Shape transitions and collective behaviour of Yb isotopes based on **relativistic energy density functional theory**

- **Relativistic Hartree Bogoliubov Theory to get the Potential Energy Surface**
- **Beyond mean-field: 5D Collective Hamiltonian of rotational vibrational model to get the Low-energy collective states & transition probabilities**

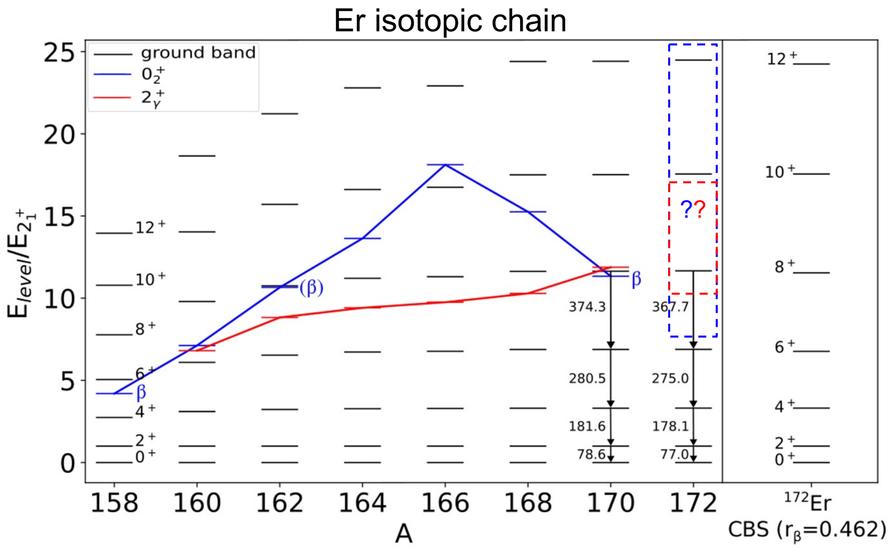


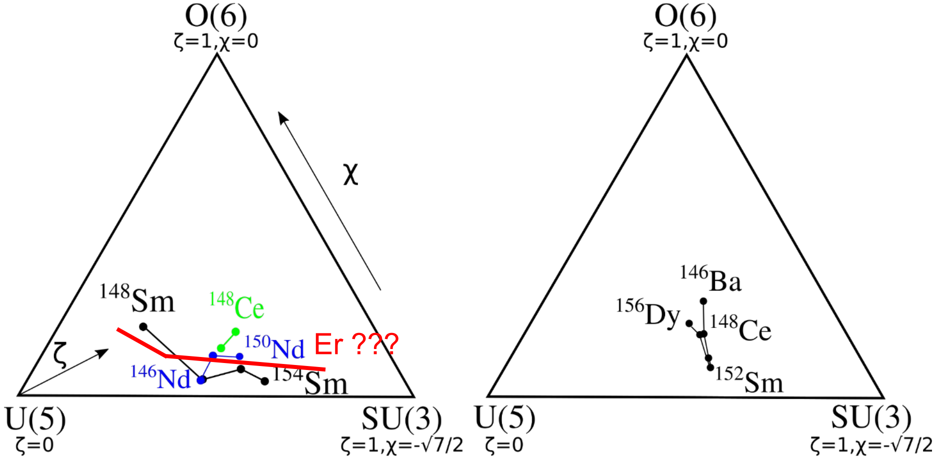


T. Nikšić, D. Vretenar, and P. Ring, Progress in Particle and Nuclear Physics 66, 519 (2011)
D. Vretenar, A. Afanasjev, G. Lalazissis, and P. Ring, Physics Reports 409, 101 (2005)
P. Ring and P. Schuck, The Nuclear Many-Body Problem (Springer-Verlag, Berlin, 1980)
K. E. Karakatsanis and K. Nomura, Phys. Rev. C 105, 064310 (2022)

Courtesy of K. E. Karakatsanis

Levels systematics and theoretical models





$$R_{4/2} = E(4_1^+)/E(2_1^+) \qquad R_{0\gamma} = \frac{E(0_2^+) - E(2_\gamma^+)}{E(2_1^+)}$$

The theoretical interpretation of the findings can be done through:

- the “confined β-soft” (CBS) rotor model
- the Interacting Boson Model (IBM)
- the proxy-SU(3) model

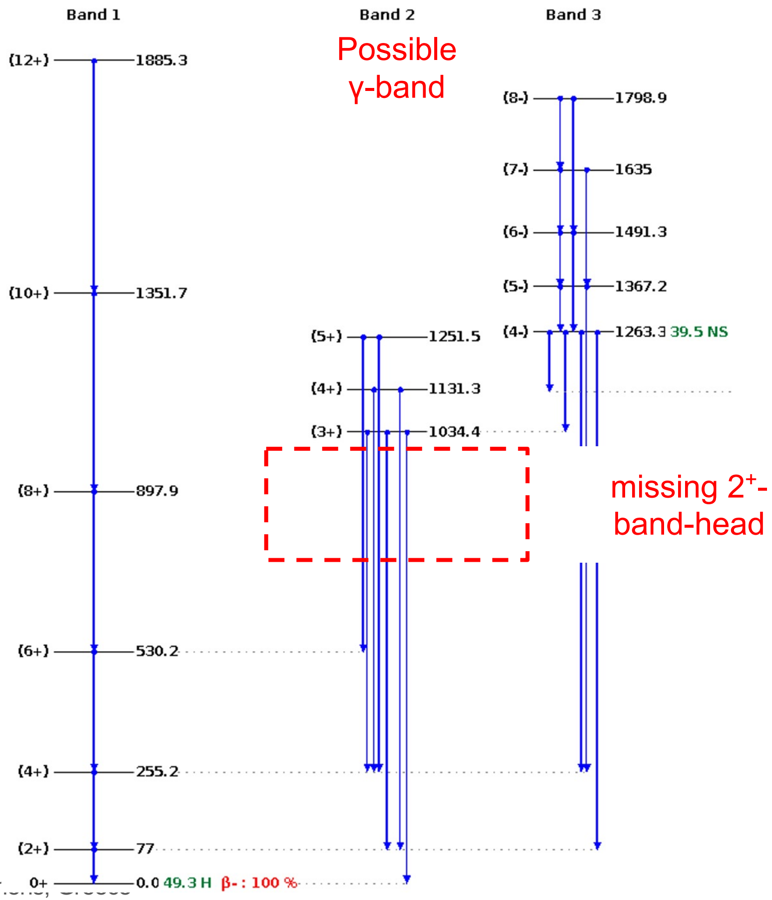
N. Pietralla et al. Phys. Rev. C 70 (2004), p. 011304.
A. Arima et al. Phys. Rev. Lett. 35 (1975), p. 1069.
P. Koseoglou et al. Phys. Rev. C 101 (2020), p. 014303.
Dennis Bonatsos et al. Phys. Rev. C 95 (2017), p. 064326.

What is known today experimentally on ^{172}Er

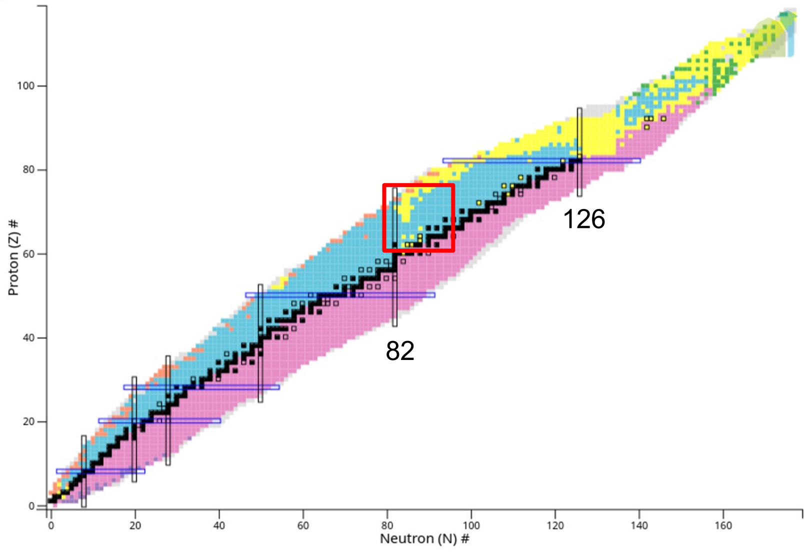
- no spin and parity assignment in the g.b. states
- no lifetime known in the g.b.
- no investigation through the 2n-transfer production mechanism

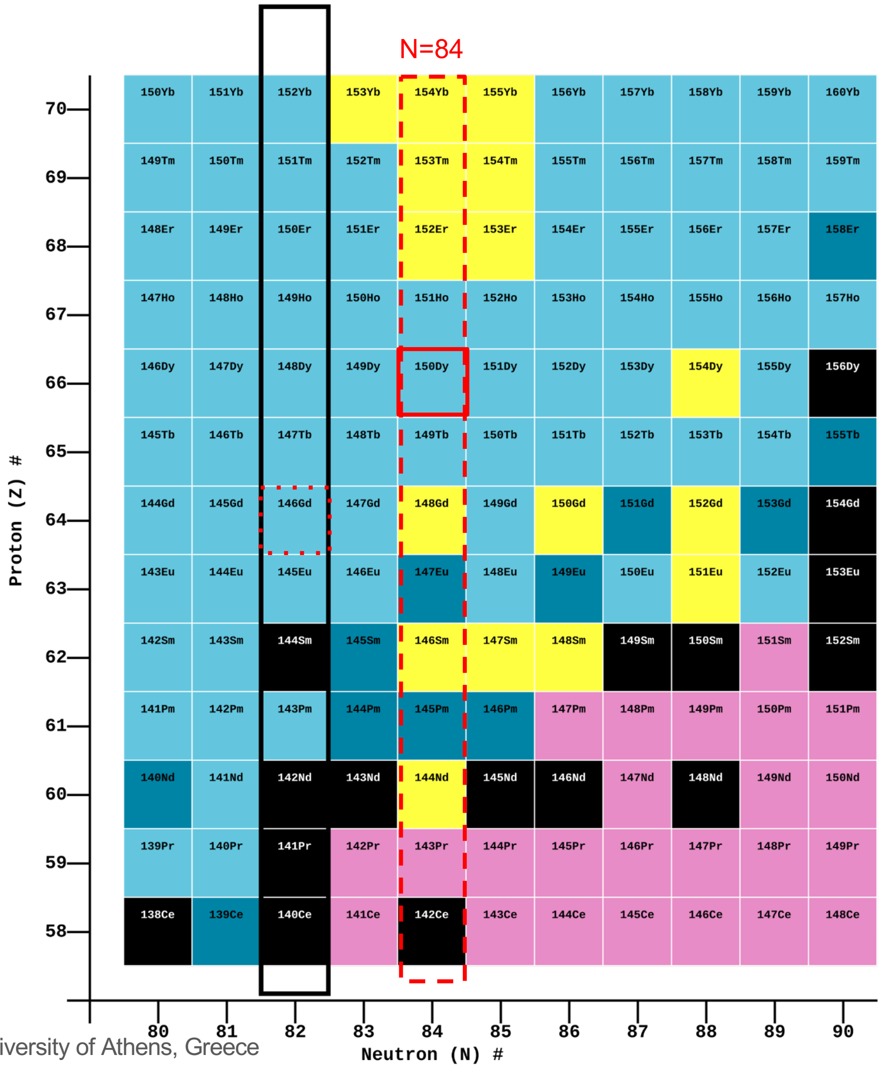
Gamma-spectroscopy on ^{172}Er to investigate the β- and γ-bands at IFIN, Magurele (Nov 2025)
➡️ ^{172}Er states successfully populated, analysis about to start

G. D. Dracoulis et al. Phys. Rev. C **81** (2010), p. 054313.

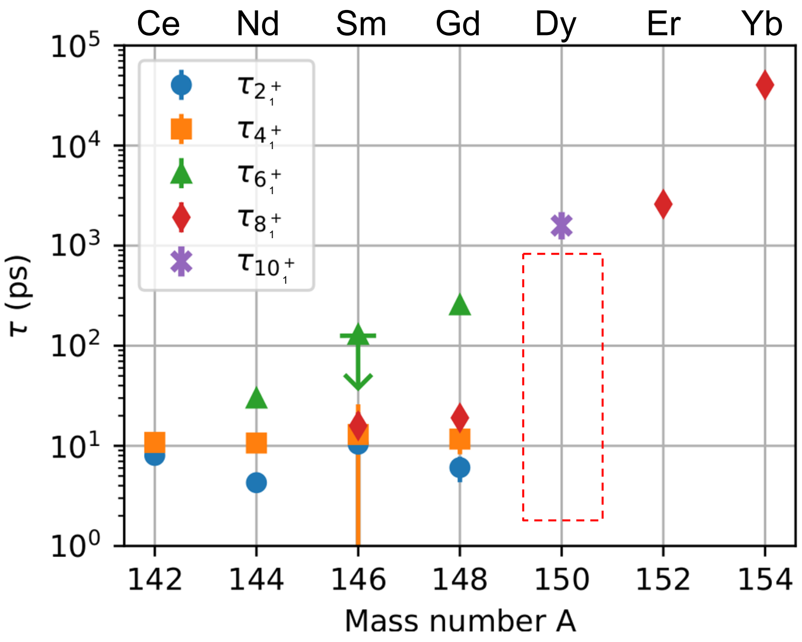


Upcoming measurements on ^{150}Dy at IFIN, Magurele

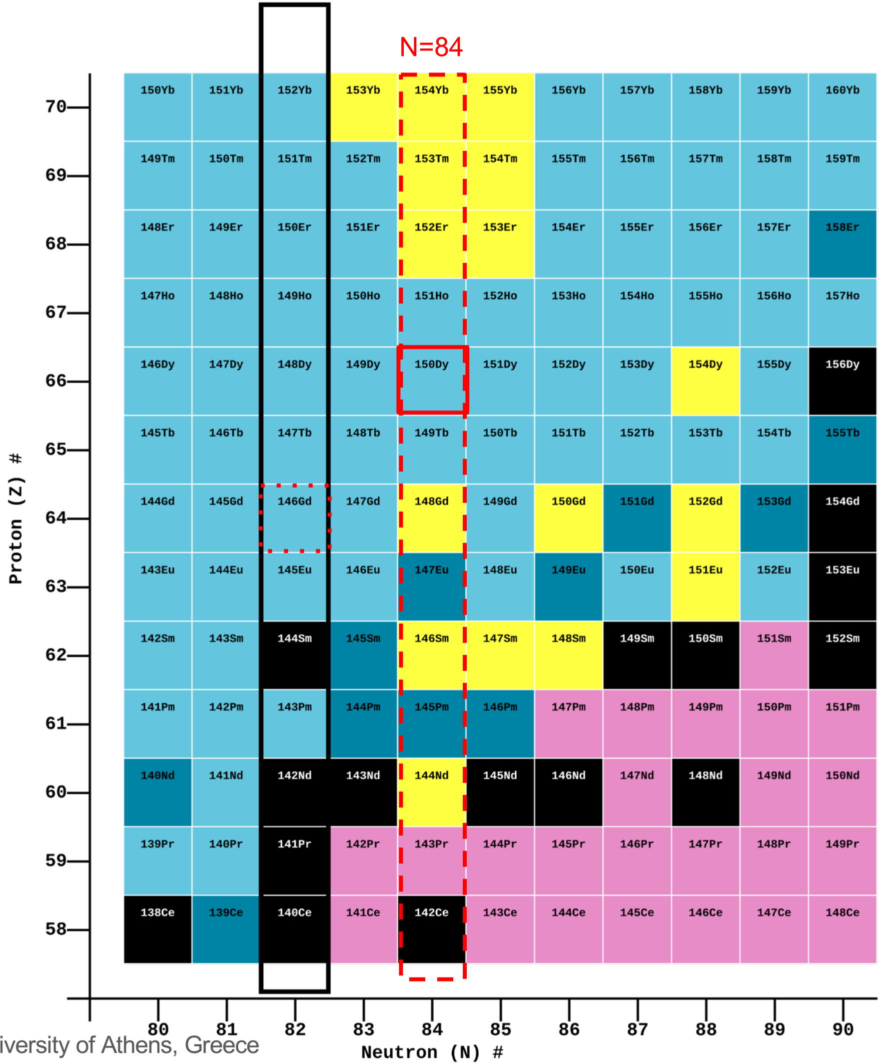




N=84 isotones - Systematics



National Nuclear Data Center (NNDC)



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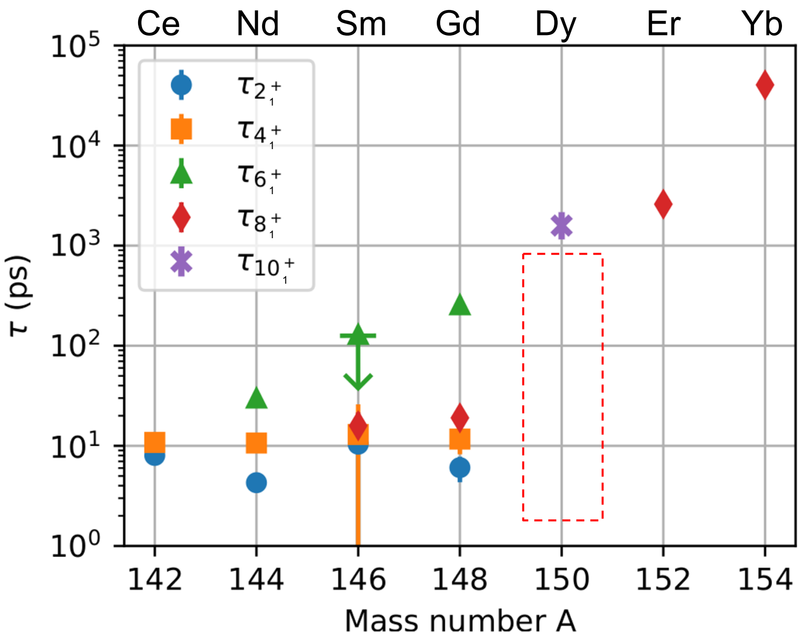
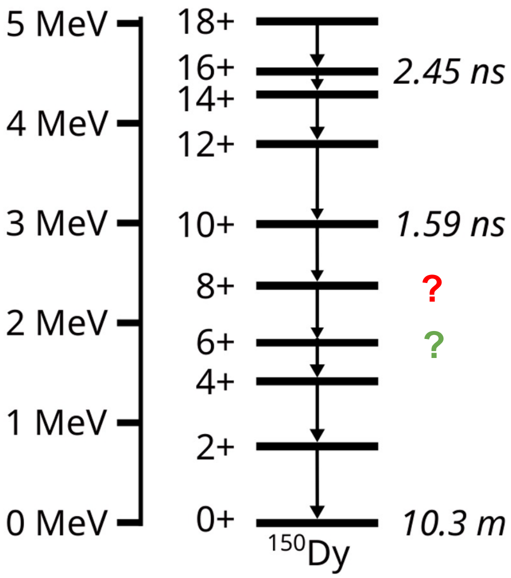
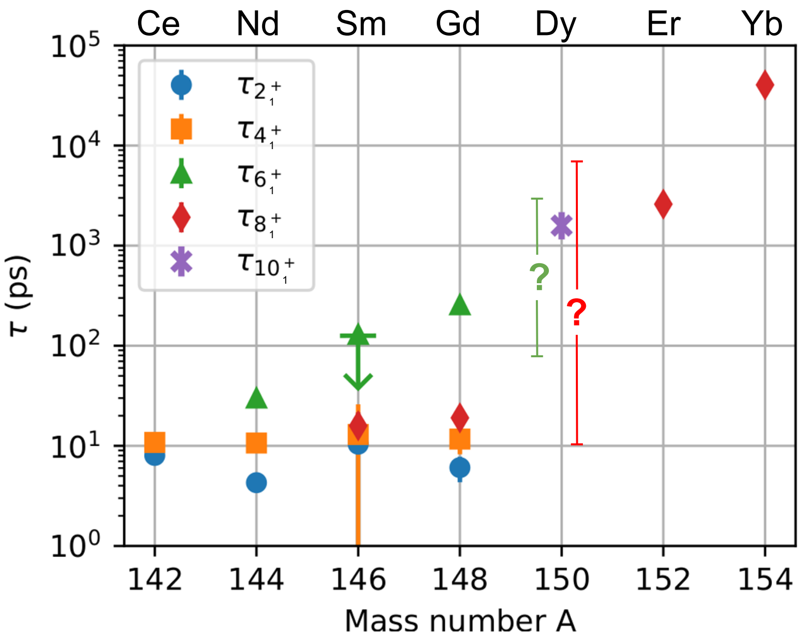




National Nuclear Data Center (NNDC)

N=84 isotones - Seniority isomers



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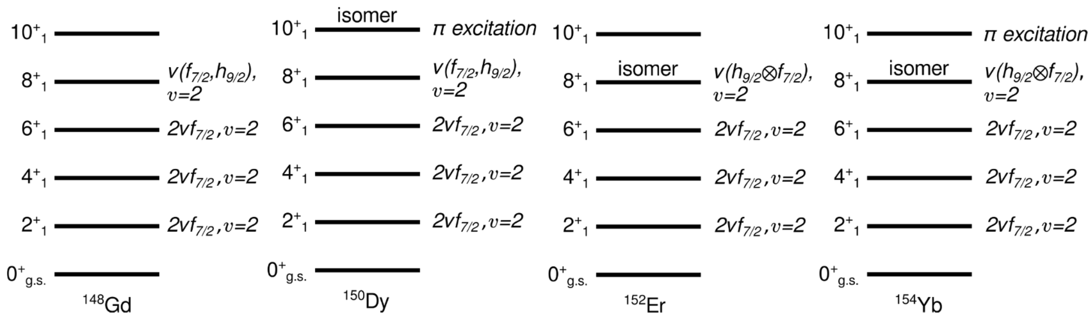
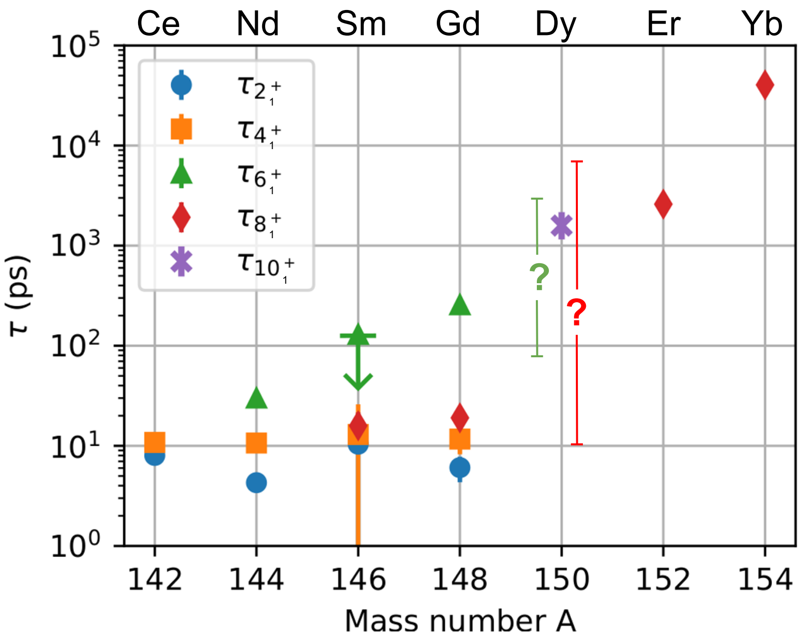
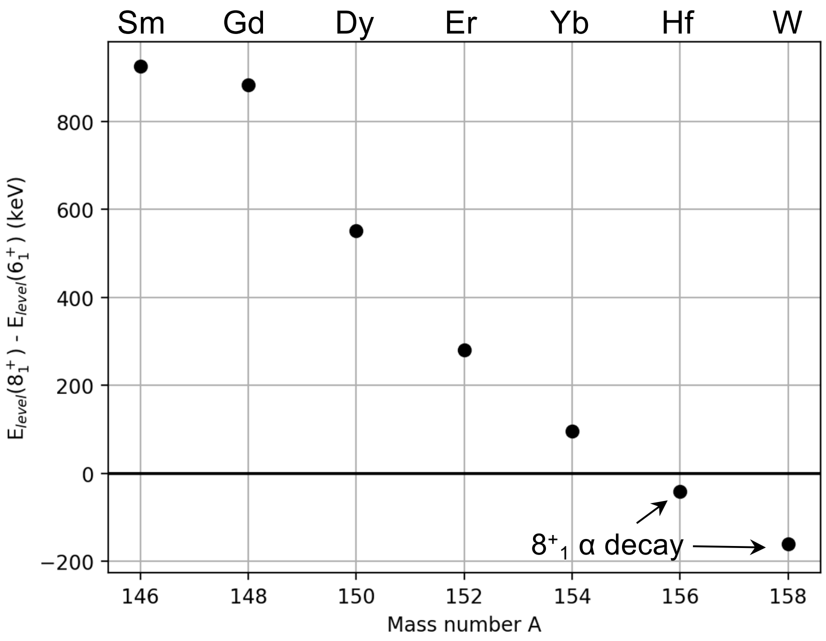


Definition:
Seniority isomers arise when states share the same seniority quantum number υ (the number of unpaired nucleons).

B. Maheshwari and K. Nomura, Symmetry 14.12 (2022). doi: 10.3390/sym14122680
G. Racah, Phys. Rev. 63 (1943), doi: 10.1103/PhysRev.63.367
Zs. Podolyák et al. , EPJ A 17.1 (2003), doi: 10.1140/epja/i2002-10144-3
S. Lunardi et al., Proceedings of XVIII Winter School, Bielsko - Biała , Poland (1980)
G. Bastin et al., NPA 345.1 (1980), doi: 10.1016/0375-9474(80)90426-1
C.T. Zhang et al., Physik A - Hadrons and Nuclei 345 (1993), doi: 10.1007/BF01280841

Level energy differences in the N=84 isotones





National Nuclear Data Center (NNDC)

Low- and medium-spin states in ^{150}Dy

Valence nucleons outside the ^{146}Gd-core occupy high-j orbitals drive the **low- and medium-spin excitations**:

- Protons: $h_{11/2}$
- Neutrons: $f_{7/2}$, $h_{9/2}$, $i_{13/2}$

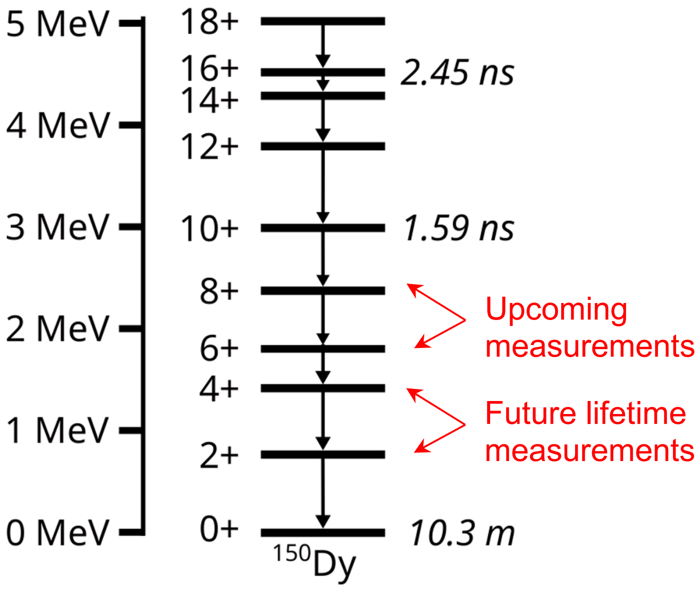
Reaction to populate the states of interest:

^{144}Sm(^{9}Be, 3n)^{150}Dy

The ^{9}Be beam generates lower angular momentum in the compound nucleus

- Suppresses population of high-spin states
- Study of the population of the low- and medium-spin states by bypassing the long-lived states

- **Additional goal:** γ-spectroscopy in the low- and medium-spin states in ^{150}Dy
  - the population of the shorter-lived states will be investigated



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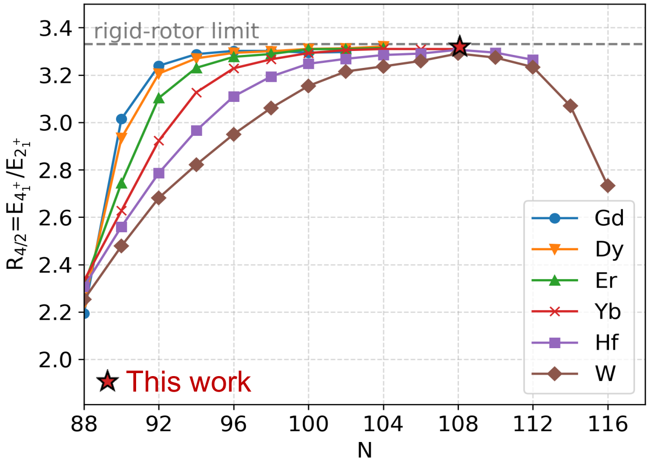

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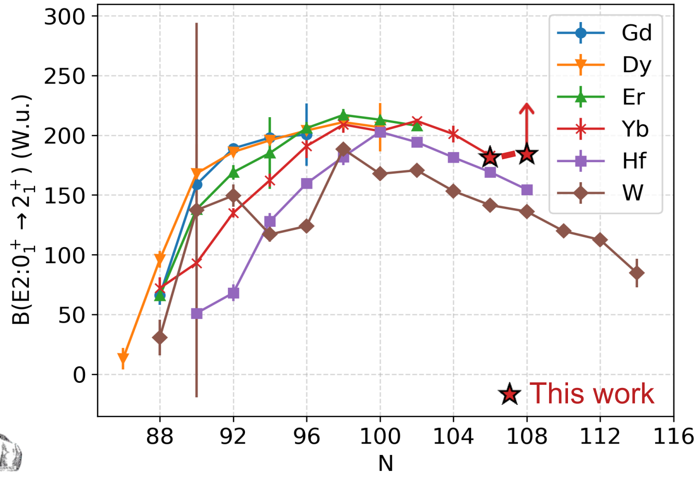

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DFG Deutsche Forschungsgemeinschaft German Research Foundation

Walter Benjamin-Programm DFG

National and Kapodistrian University of Athens

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^{178}Yb experimental data and theory

Literature data

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Theoretical investigation

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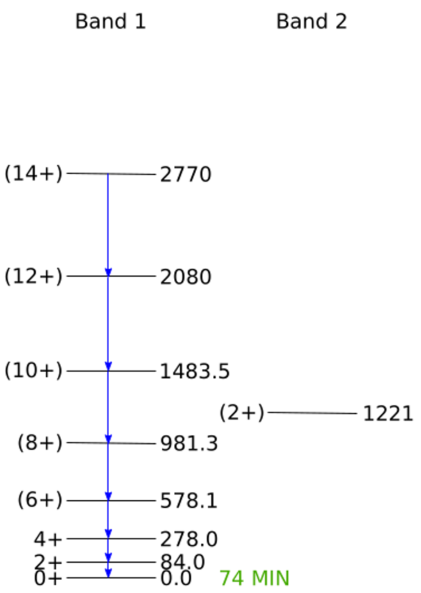
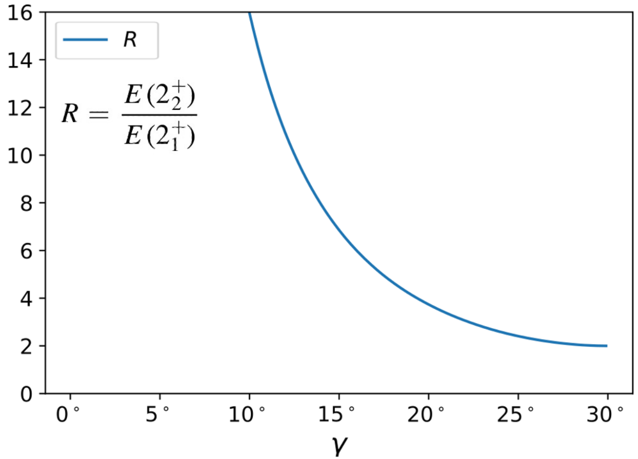
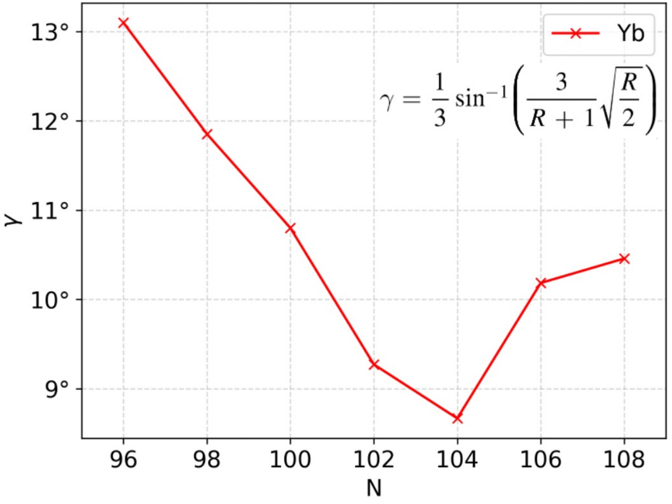
  - Interacting Boson Model
- Microscopic models
  - **Proxy-SU(3)**







D. Bonatsos et al., Phys. Rev. C 95 (2017), p. 064326
D. Bonatsos et al., Symmetry 16 (2024) 1625
D. Bonatsos et al., J. Phys. G: Nucl. Part. Phys. 52 (2025) 015102

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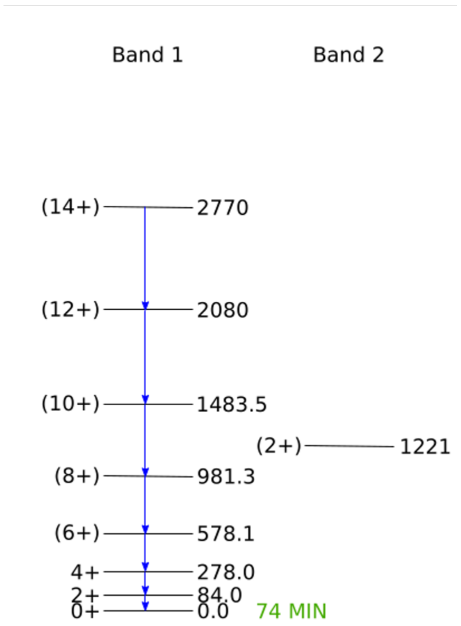

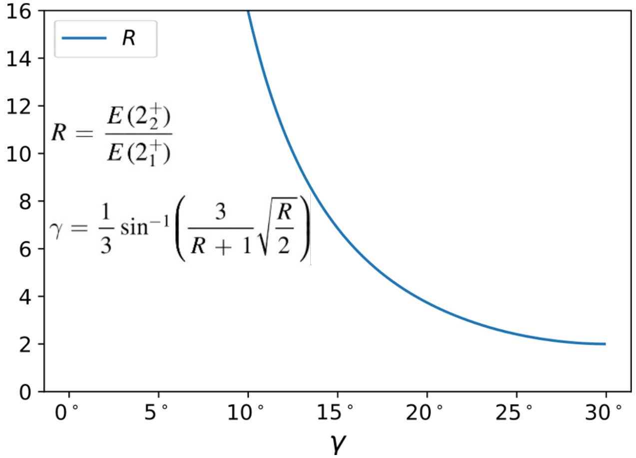

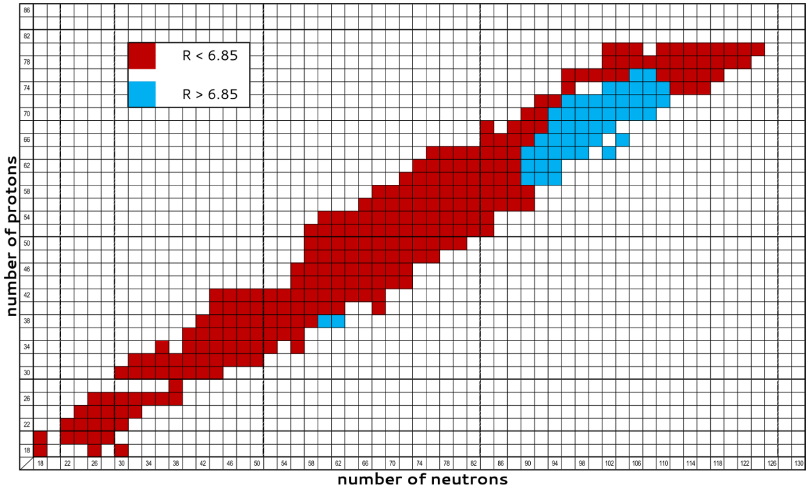

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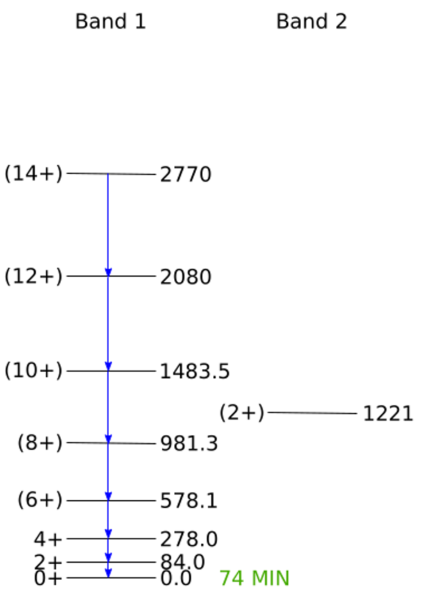

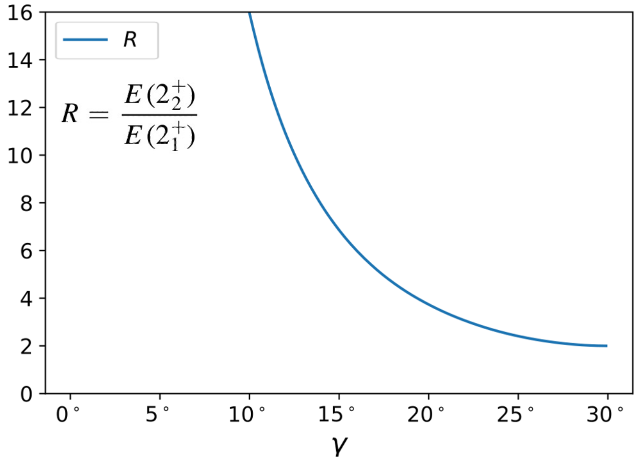

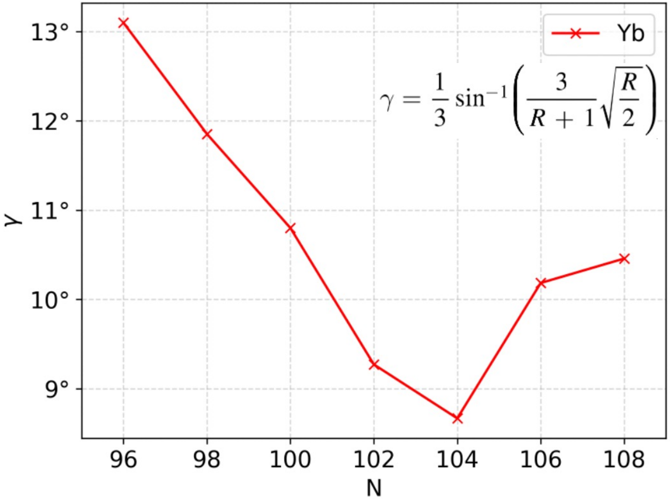

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Microscopic calculations by K. E. Karakatsanis

Shape transitions and collective behaviour of Er and Yb isotopes based on **relativistic energy density functional theory**

Relativistic Hartree-Bogoliubov Theory

Unified framwork of long range p-h and short range p-p pairing interactions

- Basic concept: quasiparticles with creation operators $\alpha_k^+ = \sum_n U_{nk} c_n^+ + V_{nk} c_n$
- Ground state is the quasiparticle vacuum $a_k |\Phi\rangle = 0$ for $E_k > 0$ or $|\Phi_0\rangle = \prod_{E_k>0} a_k | - \rangle$
- Aside the normal density - an abnormal density or pairing tensor

$$\hat{\rho}_{nn'} = \langle \Phi | c_{n'}^\dagger c_n | \Phi \rangle \Big/ \hat{\kappa}_{nn'} = \langle \Phi | c_{n'} c_n | \Phi \rangle \longrightarrow E_{\mathrm{RHB}}[\hat{\rho}, \hat{\kappa}] = E_{\mathrm{RMF}}[\hat{\rho}] + E_{\mathrm{pair}}[\hat{\kappa}]$$

- E_{pair} determined by pairing interaction $E_{\mathrm{pair}}[\hat{\kappa}] = \frac{1}{4} \sum_{n_1 n_1'} \sum_{n_2 n_2'} \hat{\kappa}^*_{n_1 n_1'} \langle n_1 n_1' | V^{pp} | n_2 n_2' \rangle \hat{\kappa}_{n_2 n_2'}$
- RHB equations, U & V Bogoliubov wavefunctions

$$\begin{pmatrix} \hat{h}_D - \lambda & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{h}_D^* + \lambda \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

Dirac field $\hat{h}_D = \frac{\delta E}{\delta \hat{\rho}}$, Pairing field $\hat{\Delta} = \frac{\delta E}{\delta \hat{\kappa}}$

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Potential Energy Surface

Beyond mean-field

5D Collective Hamiltonian of rotational vibrational model

- Use the microscopic PES to build a collective Hamiltonian with quadrupole rotations and vibrations included with the restoration of the broken symmetries at the MF level.
  Calculate excitation spectra and transition probabilities

$$H_{coll} = T_{vib}(\beta, \gamma) + T_{rot}(\beta, \gamma, \Omega) + V_{coll}(\beta, \gamma)$$

vibrational kinetic energy $T_{vib} = \frac{1}{2} B_{\beta\beta} \dot{\beta}^2 + \beta B_{\beta\gamma} \dot{\beta} \dot{\gamma} + \frac{1}{2} \beta^2 B_{\gamma\gamma} \dot{\gamma}^2$

Rotational kinetic energy $T_{rot} = \frac{1}{2} \sum_{k=1}^{3} I_k \omega_k^2$

Collective potential term $V_{coll}(\beta, \gamma) = E_{rot}(\beta, \gamma) - \Delta V_{vib}(\beta, \gamma) - \Delta V_{rot}(\beta, \gamma)$

- The entire dynamics of the collective Hamiltonian governed by seven functions of the intrinsic deformations β,γ and Ω: the three **mass parameters**: $B_{\beta\beta}$, $B_{\beta\gamma}$, $B_{\gamma\gamma}$, the three **moments of inertia I_k**, and the **collective potential**
- **Mass parameters** are calculated in the cranking approximation.
- **Moments of inertia** are calculated using the *Inglis-Belyaev* formula

★ [*Usually much lower than empirical values. Readjustement with experimental data applied*]

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Low-energy collective states & transition probabilities