The 3rd Symposium on Nuclear Physics in Guangdong-Hong Kong -Macao Area, 15-18 November 2024, Shenzhen, Guangdong

Shape evolution and shape coexistence in the superheavy isotopes with Z = 117 − 120

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Outline

- Introduction
- Ground-state properties
- Shell structure
- Summary

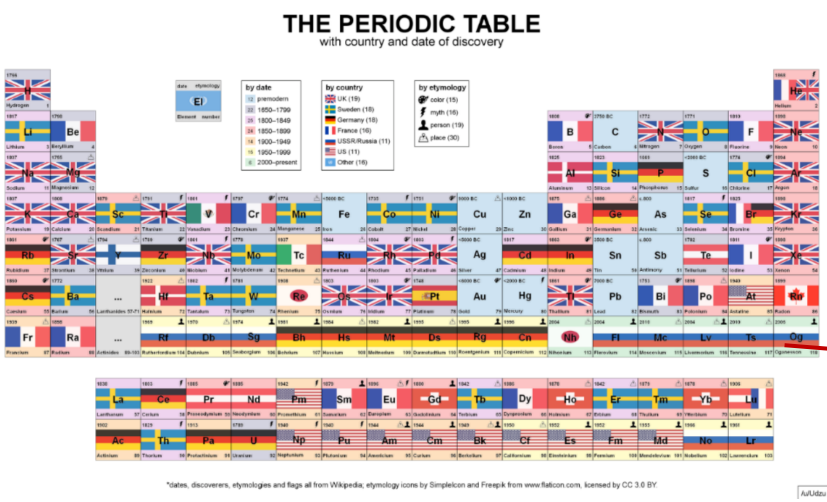
Introduction

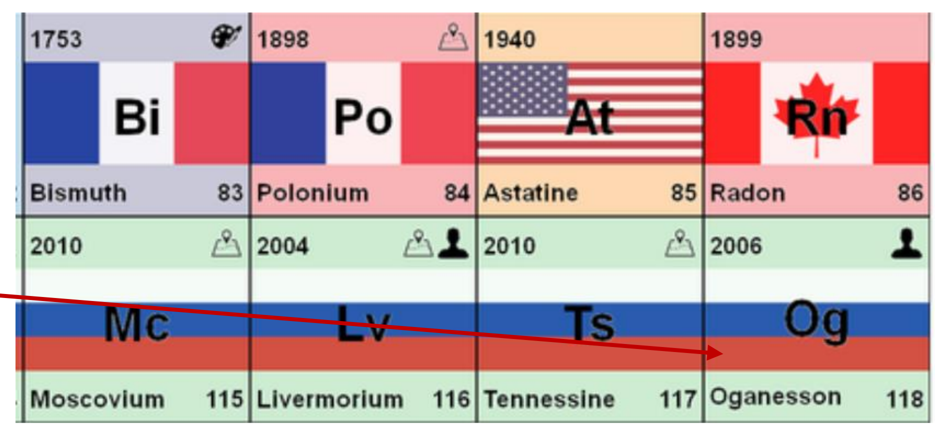
- The study of superheavy nuclei helps answer the fundamental questions on the limits of the existence of the heaviest elements and the borders of the nuclear chart.

Smits, ,et al., Nat. Rev. Phys. 6, 86 (2024).

- The synthesis of superheavy nuclei and exploration of their structural properties have been at the forefront of nuclear physics.

A. Sobiczewski and K. Pomorski, Prog. Part. Nucl. Phys. 58,292 (2007).
Hamilton ,et al., Rev.Nucl. Part. Sci. 63, 383 (2013).
Giuliani, et al., Rev. Mod. Phys. 91, 011001 (2019)





Theoretical models

☐Microscopic-macroscopic model:

Smits, ,et al., Nucl. Phys. A 131, 1 (1969)
Z. Patyk and A. Sobiczewski, Nucl. Phys. A 533, 132 (1991)
P. Möller and J. R. Nix, Nucl. Phys. A 549, 84 (1992)
N. Wang, M. Liu, X. Wu, and J. Meng, Phys. Lett. B 734, 215(2014) Rev. Phys. 6, 86 (2024)

☐Self-consistent mean-field approaches:

- Skyrme-Hartree-Fock (SHF) approach

S. Cwiok, J. Dobaczewski, P. H. Heenen, P. Magierski, andW. Nazarewicz, Nucl. Phys. A 611, 211 (1996)

S. ´Cwiok, P.-H. Heenen, and W. Nazarewicz, Nature 433, 705(2005)

- The relativistic mean-field (RMF) model

G. A. Lalazissis, M. M. Sharma, P. Ring, and Y. K. Gambhir,Nucl. Phys. A 608, 202 (1996)

A. V. Afanasjev, T. L. Khoo, S. Frauendorf, G. A. Lalazissis,and I. Ahmad, Phys. Rev. C 67, 024309 (2003)

B. V. Prassa, T. Niksic, G. A. Lalazissis, and D. Vretenar, Phys.Rev. C 86, 024317 (2012)

J. J. Li, W. H. Long, J. Margueron, and N. Van Giai, Phys. Lett.B 732, 169 (2014)

A. S. E. Agbemava, A. V. Afanasjev, T. Nakatsukasa, and P. Ring,Phys. Rev. C 92, 054310 (2015)

Deformed Relativistic Hartree-Bogoliubov theory in continuum(DRHBc) model：

Simultaneously takes into account the effects of deformation, pairing correlations and continuum

Zhou, Meng, Ring, and Zhao, Phys. Rev. C 82, 011301 (2010)
Li, Meng, Ring, Zhao, and Zhou, Phys. Rev. C 85, 024312 (2012)

The DRHBc mass table collaboration

- To construct the relativistic nuclear mass table with the deformation and continuum effects by the DRHBc theory, the DRHBc Mass Table Collaboration was established.

The DRHBc theory

- The mean fields and pairing correlations can be treated self-consistently by relativistic Hartree-Bogoliubov (RHB) equation

$$\begin{pmatrix} h_D - \lambda_{\tau_3} & \Delta \\ -\Delta^* & -h_D + \lambda_{\tau_3} \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

where h_D is Dirac Hamiltonian; Δ is pairing potential; $\lambda_{\tau 3}$ is Fermi energy; U_k, V_k are quasiparticle wavefunctions; E_k is quasiparticle energy.

- In coordinate space, Dirac Hamiltonian reads:

$$h_D(\boldsymbol{r}) = \boldsymbol{\alpha} \cdot \boldsymbol{p} + V(\boldsymbol{r}) + \beta(M + S(\boldsymbol{r})),$$

- where $S(r)$ and $V(r)$ denote scalar and vector potentials,

$$\begin{aligned} S(\boldsymbol{r}) &= \alpha_S \rho_S + \beta_S \rho_S^2 + \gamma_S \rho_S^3 + \delta_S \Delta \rho_S, \\ V(\boldsymbol{r}) &= \alpha_V \rho_V + \gamma_V \rho_V^3 + \delta_V \Delta \rho_V + e \frac{1 - \tau_3}{2} A_0 \\ &\quad + \alpha_{TV} \tau_3 \rho_{TV} + \delta_{TV} \tau_3 \Delta \rho_{TV}, \end{aligned}$$

$$\begin{aligned} \rho_S(\boldsymbol{r}) &= \sum_{k>0} V_k^\dagger(\boldsymbol{r}) \gamma_0 V_k(\boldsymbol{r}), \\ \rho_V(\boldsymbol{r}) &= \sum_{k>0} V_k^\dagger(\boldsymbol{r}) V_k(\boldsymbol{r}), \\ \rho_{TV}(\boldsymbol{r}) &= \sum_{k>0} V_k^\dagger(\boldsymbol{r}) \tau_3 V_k(\boldsymbol{r}). \end{aligned}$$

- Pairing potential reads

$$\Delta(\boldsymbol{r}_1, \boldsymbol{r}_2) = V^{pp}(\boldsymbol{r}_1, \boldsymbol{r}_2) \kappa(\boldsymbol{r}_1, \boldsymbol{r}_2)$$

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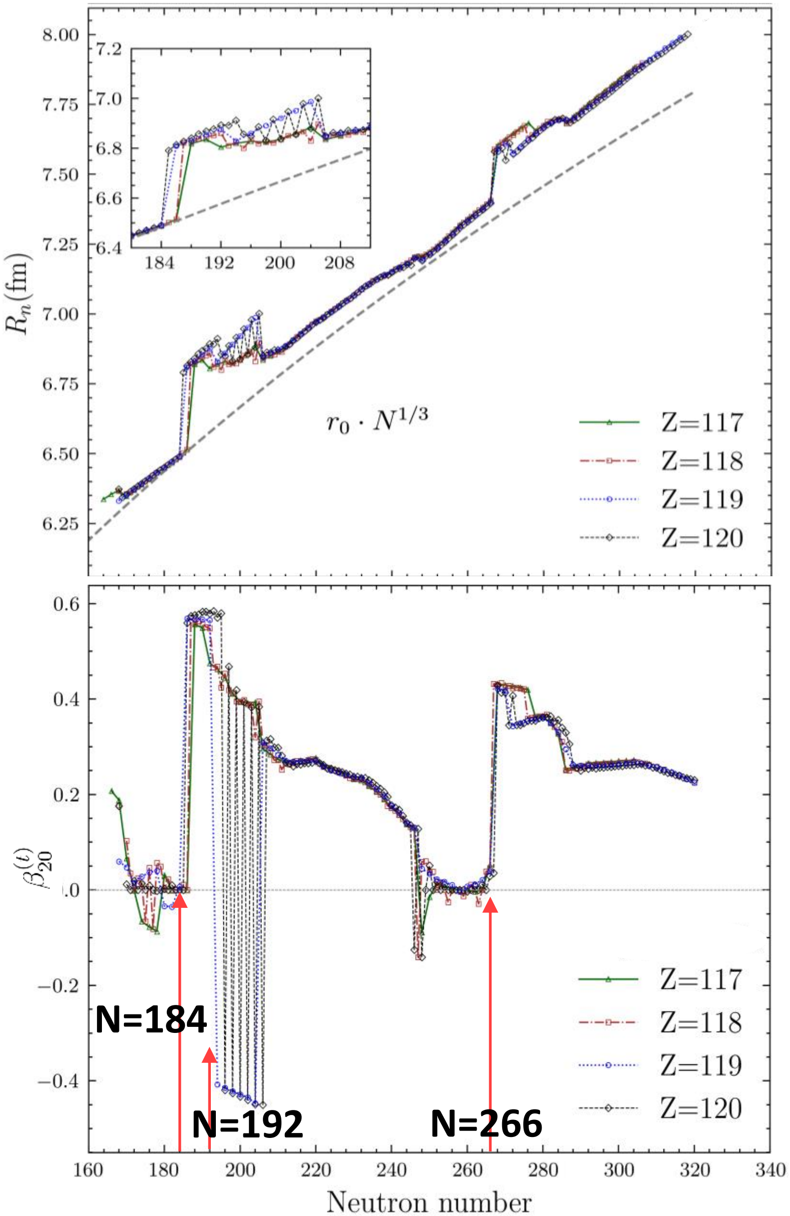
Rms radius and quadrupole deformation



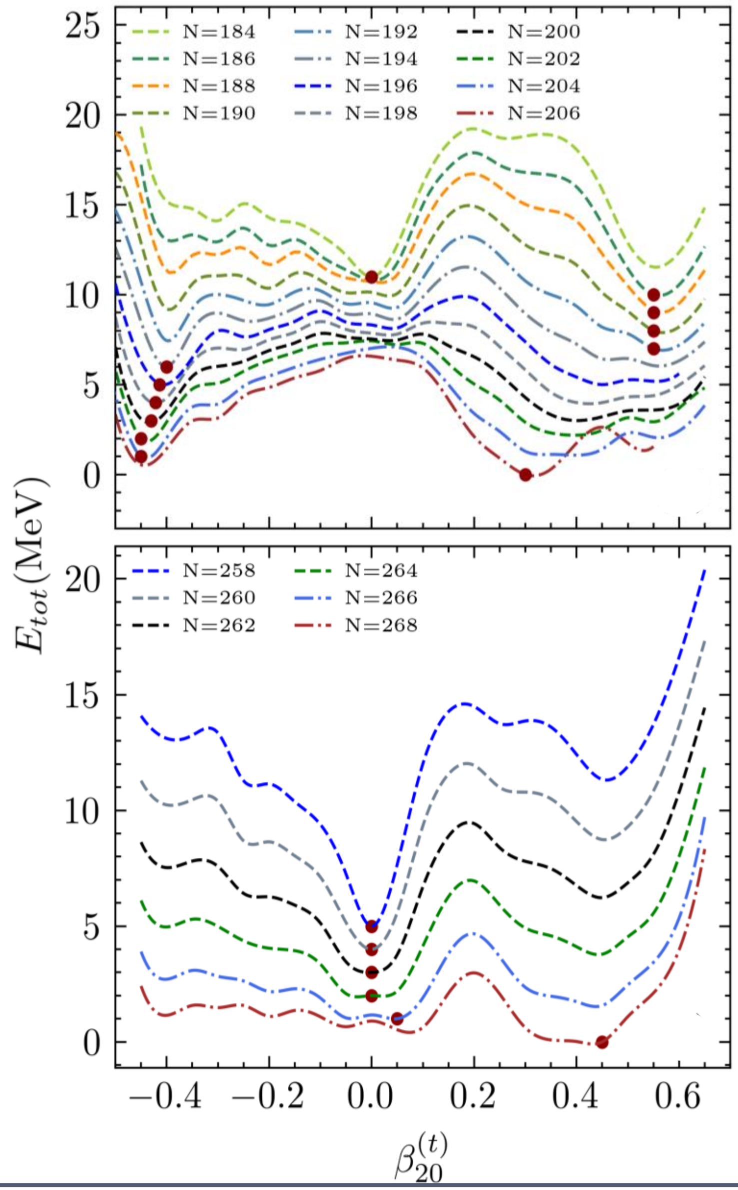
✓ The sudden shape evolution from spherical to large prolate shape deformation near N=184 and N=266.

✓ The sudden increases of rms radii correspond to the drastic deformation changes.

✓ The evolution of deformation can be understood with the help of potential energy curves.

•Y.X. Zhang, B.R. Liu, K.Y. Zhang, J.M. Yao, Phys.Rev.C 110, 024302 (2024)

Potential energy curves for Z = 119 isotopes



- ✓ The competition between minima can be found near N = 184 and N = 266.
- ✓ The shape coexistence is responsible for the observed sudden shape transitions.
- ✓ The evolution of the minima can be understood with shell structure.

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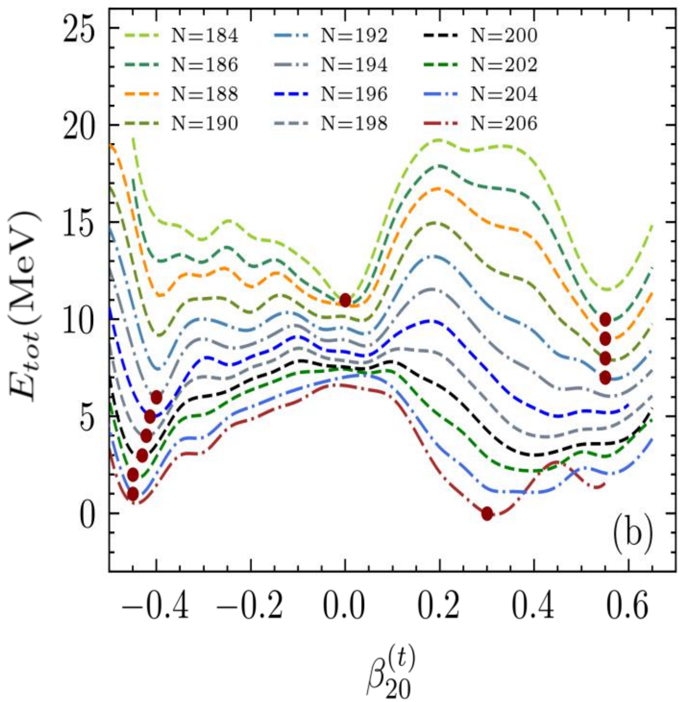
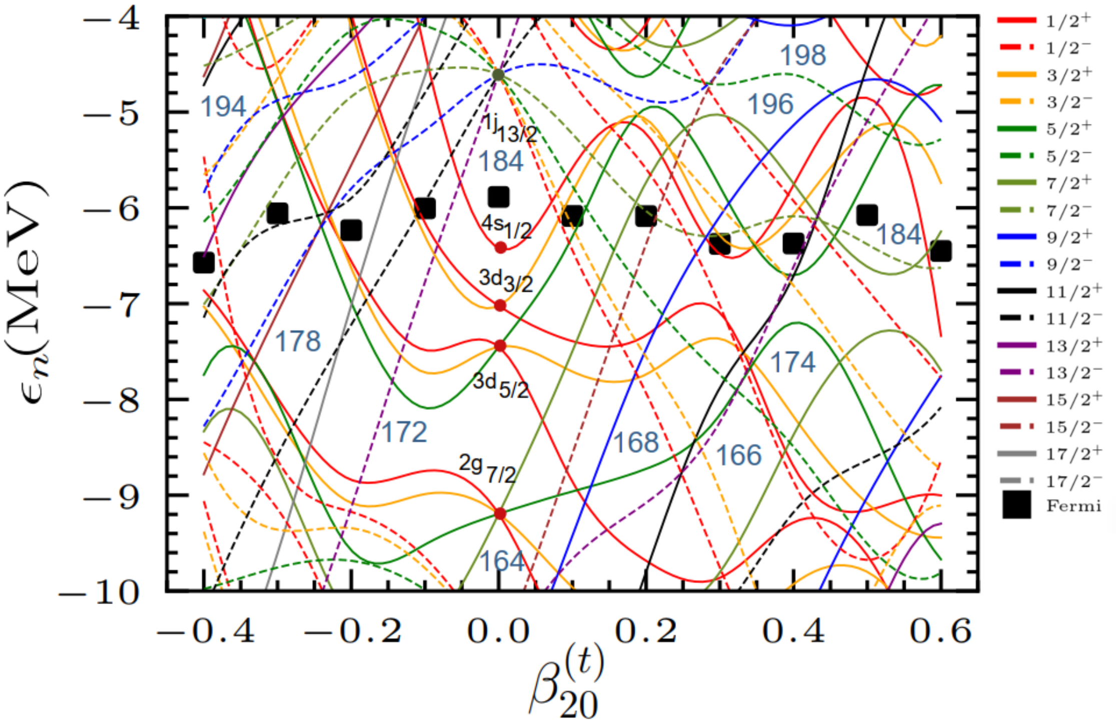
Single-particle orbitals and shell gap

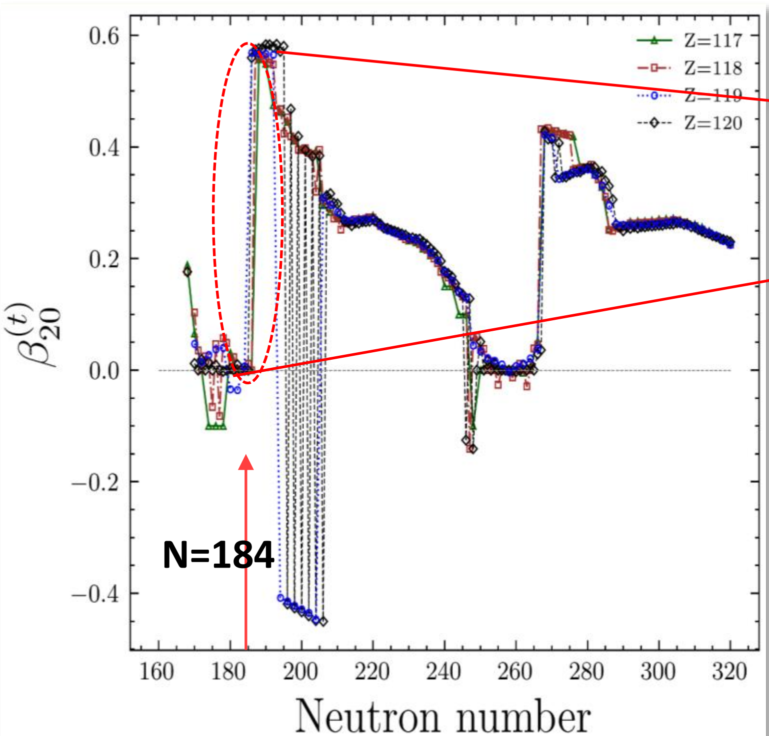


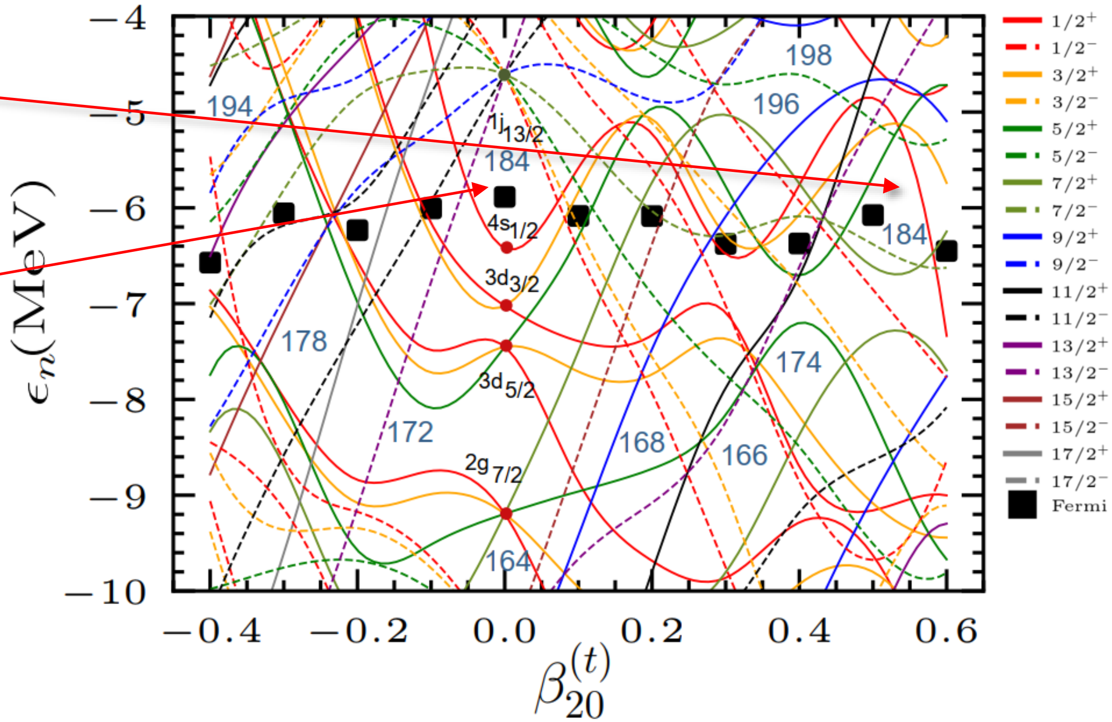


Nilsson diagrams obtained for N=184,Z=120.

- ✓ There are large shell gaps around N = 184 in the spherical side and prolate side with β ≃ 0.5.
- ✓ It explains the shape transition from spherical to a large prolate deformation in the ground state

Single-particle orbitals and shell gap

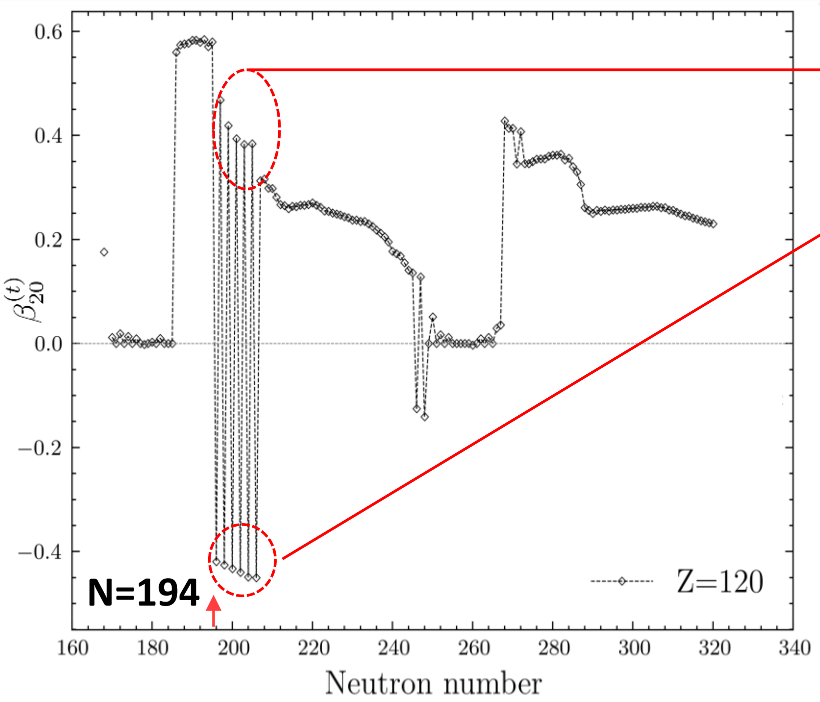


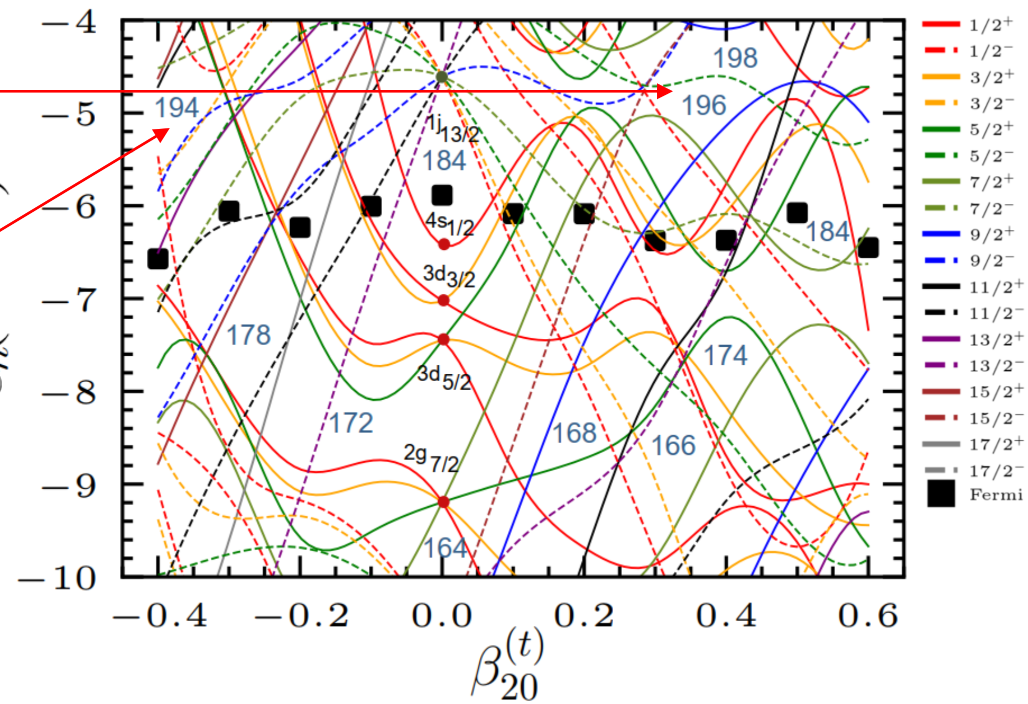


Nilsson diagrams obtained for N=184,Z=120.

- ✓ There are large shell gaps around N = 184 in the spherical side and prolate side with $\beta \simeq 0.5$.
- ✓ It explains the shape transition from spherical to a large prolate deformation in the ground state

Single-particle orbitals and shell gap



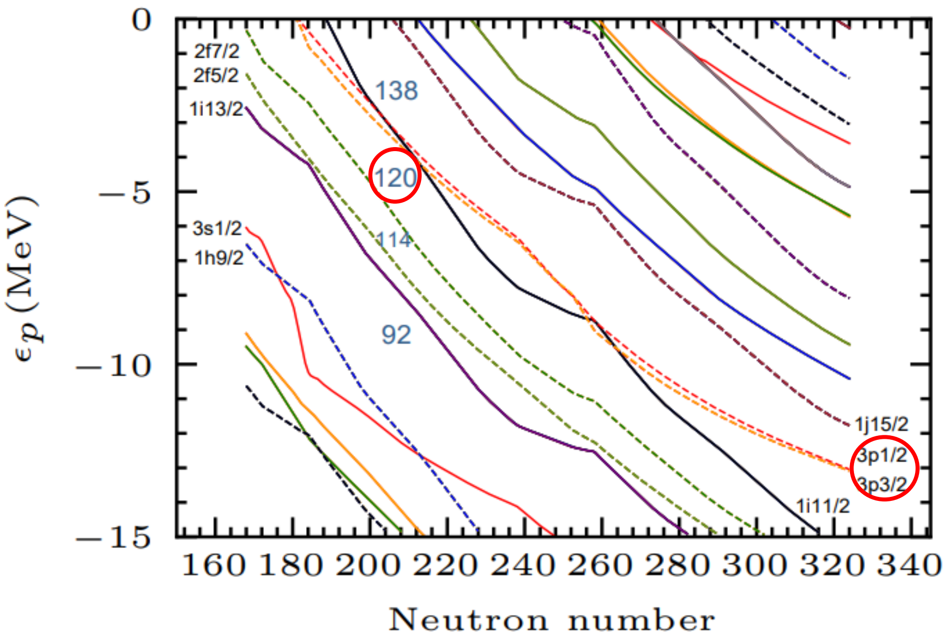


Nilsson diagrams obtained for N=184,Z=120.

- ✓ There are large shell gaps around N = 194 in the oblate side with $\beta \simeq -0.4$ and prolate side with $\beta \simeq 0.4$.
- ✓ It explains the development of competing prolate and oblate deformed energy minimum in the isotopes around N = 194.

The evolution of shell gaps

- ✓ The shell gap at Z = 120 decreases globally with the increase of neutron number due to the intruder orbital $1i_{11/2}$.
- ✓ The shell gap at Z = 120 is influenced by the spin-orbit splitting of the 3d states.



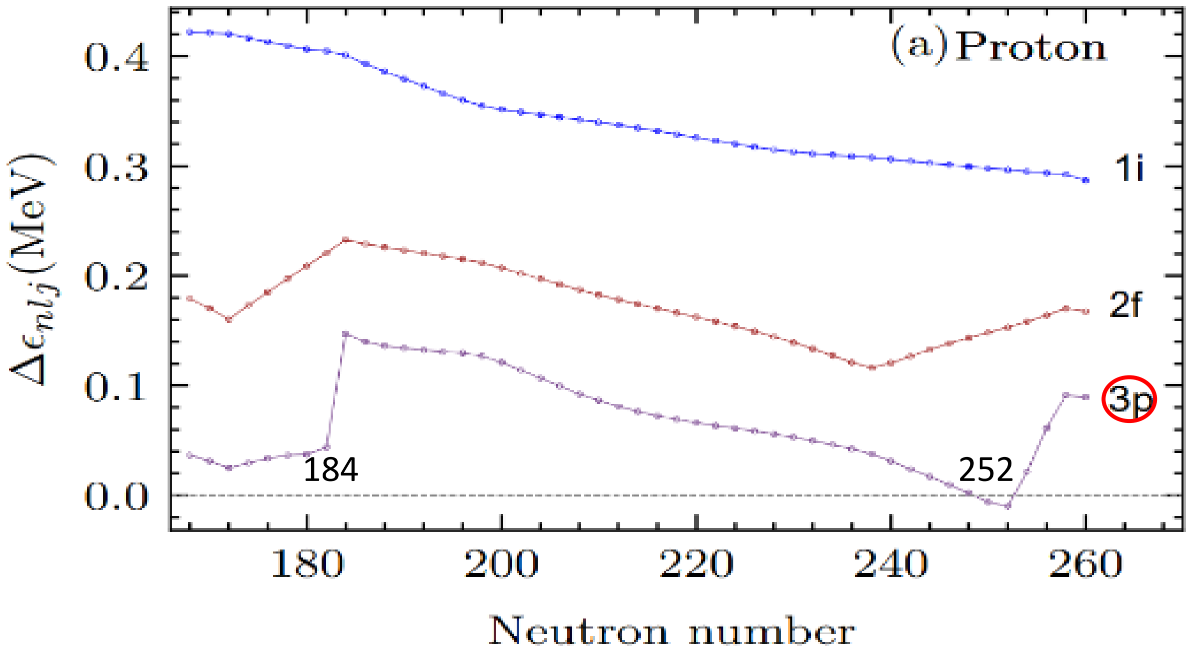
Spherical single-proton levels in the vicinity of the Fermi energy for the isotopes of Z=120 versus the neutron number.

The spin-orbit splitting

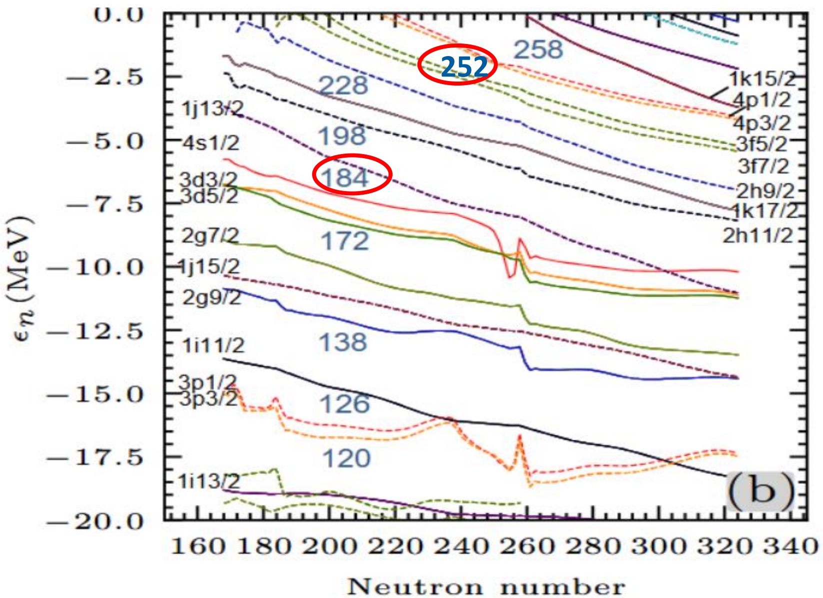
- ✓ The energy splitting of spin-orbit doublet states is defined as:

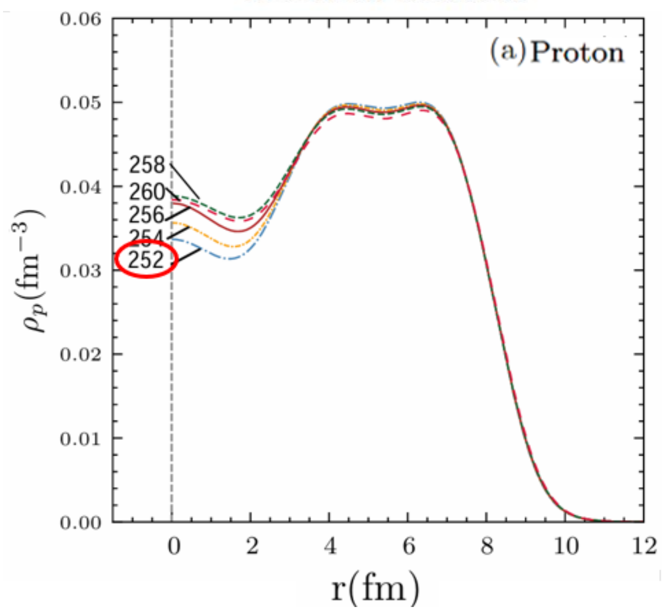
$$\Delta\epsilon_{nlj} = \frac{\epsilon_{nlj_<} - \epsilon_{nlj_>}}{2l+1}, \quad j_{\gtrless} = l \pm 1/2.$$

- ✓ The energy splittings of the 3p doublet proton states are general small, changing sign around N=252.
- ✓ It is attributed to the central depression (bubble structure) in nucleonic densities.



The spin-orbit splitting and nucleonic density





The L = 0 component of the nucleon density in Z = 120 isotopes

- ✓ The densities are expanded in terms of the Legendre polynomials :

$$f(\boldsymbol{r}) = \sum_{L\geq 0} f_L(r) P_L(\cos\theta),$$

- ✓ The formation of bubble structure induces a spin-orbit potential around the nuclear center, which cancels the contribution around the nuclear surface.

- ✓ It mainly affects the spin-orbit splitting of low orbital angular momentum states.

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Summary

- ✓ We extensively explore the evolution of shell structure and shape transition in the Z = 111 − 120 isotopes at the mean-field level.
  1. Shape coexistence is responsible for the sudden shape evolution .
  2. Shape evolution is associate with intruder orbital and spin-orbit splitting, which is associate with the nucleonic density.
- ✓ Next:
  - ➢ Considering the higher order deformation.
  - ➢ Considering the effect of shape mixing.
  - ➢ Developing projection method and generator coordinate method, calculating the low excitation energy.

Thank you for your attention!