The 7th workshop on nuclear mass table with DRHBc theory,
July 1-4 ,2024,Gangneung,Korea

Progress report for superheavy nuclei with $111 \leq Z \leq 120$

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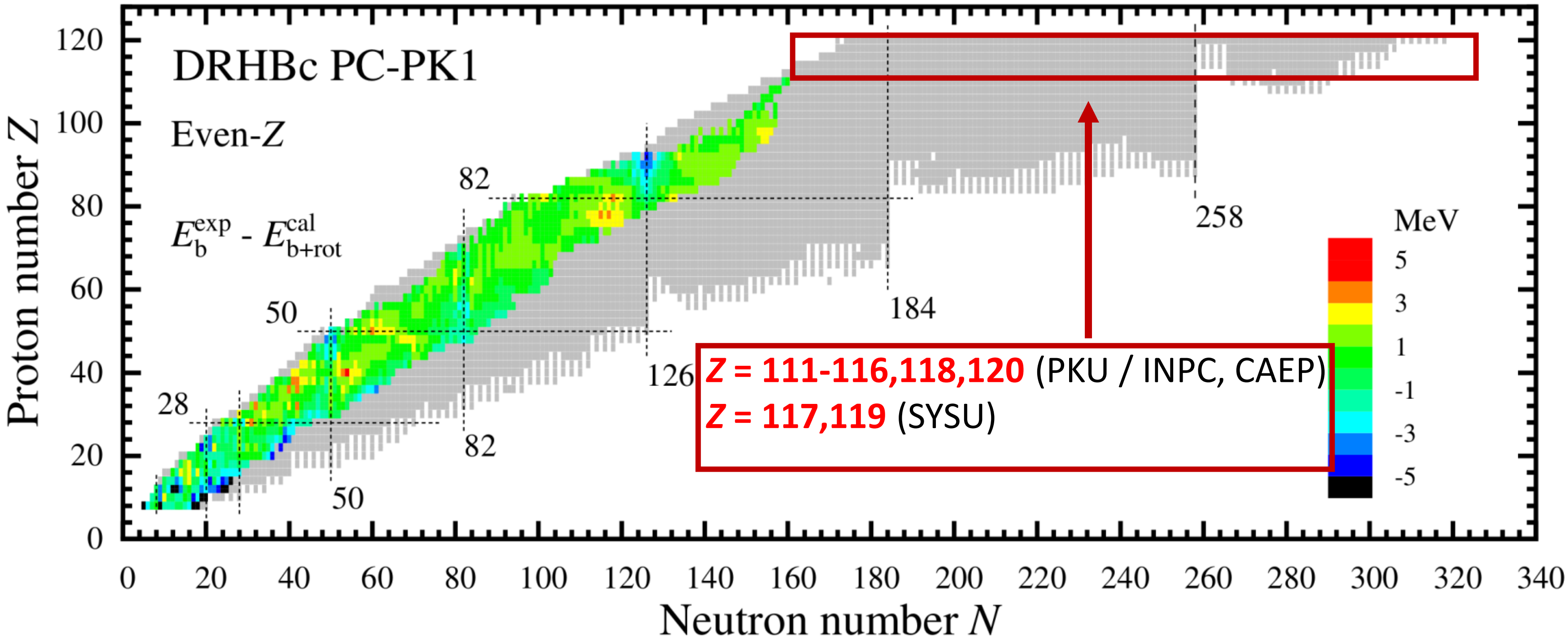
Outline

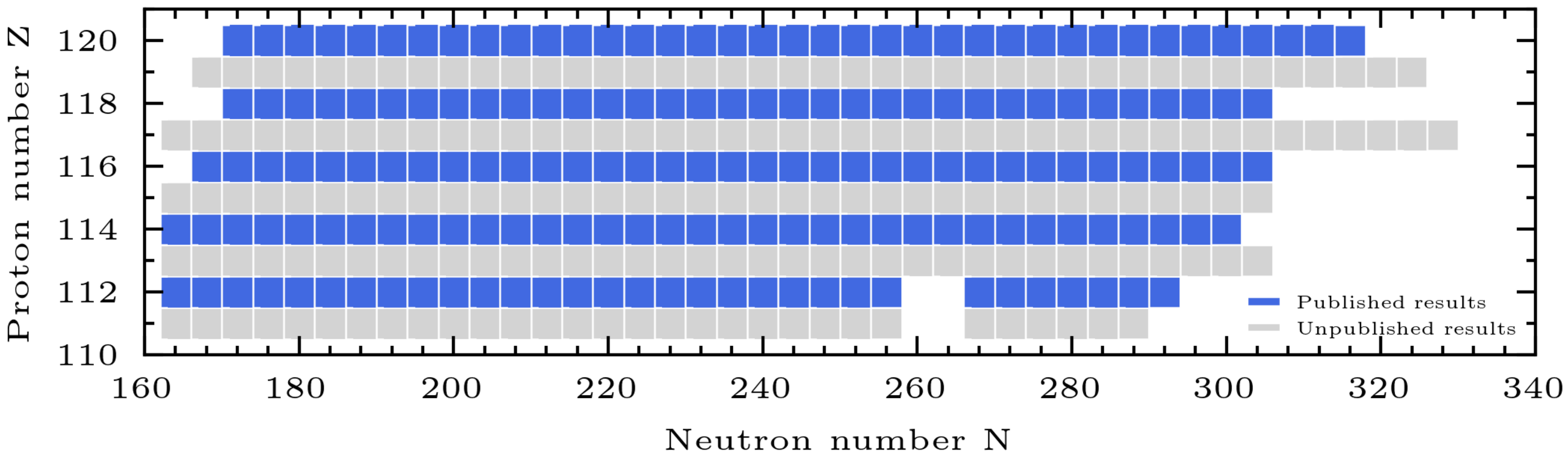
- Introduction
- Numerical details
- Ground-state properties
- Shell structure
- Summary

Project plan



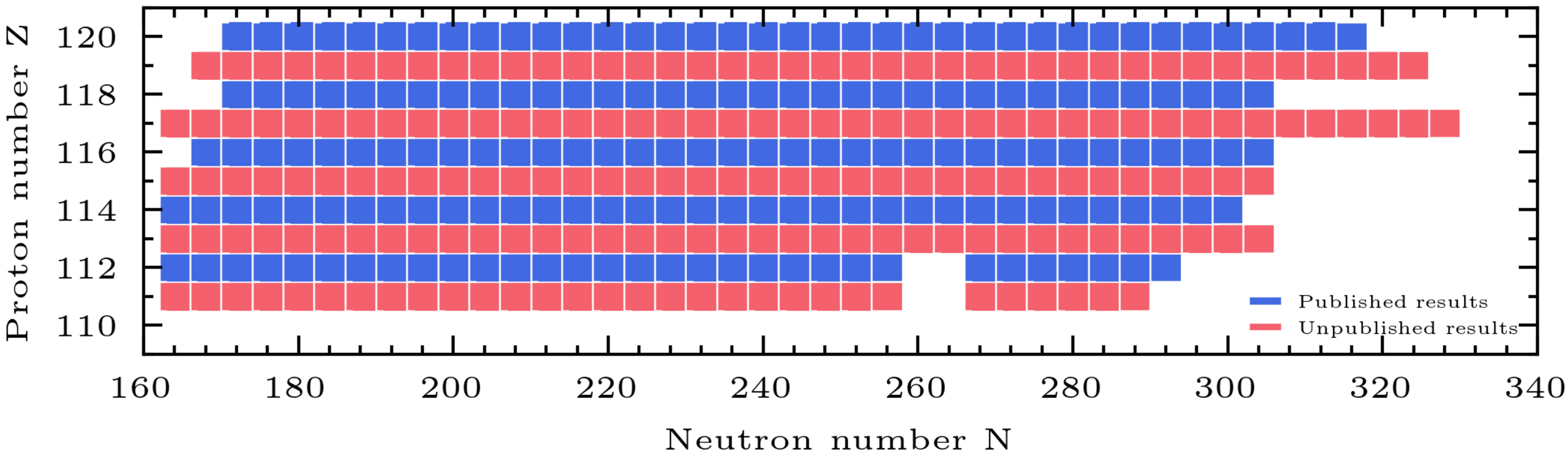
Nuclear region	Team	Principal investigator
Rg (Z = 111) to Z = 120	PKU / INPC, CAEP	Kaiyuan Zhang
	SYSU	Yanxin Zhang, Boran Liu

Progress for superheavy nuclei with $111 \le Z \le 120$



- ✓ The DRHBc mass table for even-even nuclei has been established. DRHBc Mass Table Collaboration, Atom. Data Nucl. Data Tabl. 144, 101488 (2022)
- ✓ The DRHBc mass table for even-Z nuclei has been established. DRHBc Mass Table Collaboration, Atom. Data Nucl. Data Tabl. 158, 101661 (2024)

Progress for odd-Z nuclei with 111 ≤ Z ≤ 119



- ✓ Unconstrained and constrained for PEC calculations for 387 odd-even nuclei and 377 odd-odd nuclei have been finished.

Y. X. Zhang, B. R. Liu, K. Y. Zhang, J. M. Yao, arXiv:2405.07704

- ✓ For each nucleus, 11 initial deformations -0.4, -0.3, …, 0.6 are taken.

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Numerical Details

- ✓ Nuclei : Odd-even and odd-odd nuclei with $Z = 111 - 119$
- ✓ Box size : $R_{\mathrm{box}} = 20$ fm
- ✓ Mesh size : $\Delta r = 0.1$ fm
- ✓ Energy cutoff : $E_{\mathrm{cut}} = 300$ MeV
- ✓ Angular momentum cutoff : $J_{\mathrm{max}} = 23/2\ \hbar$
- ✓ Legendre expansion order : $\lambda_{\mathrm{max}} = 10$
- ✓ Density functional : PC-PK1
- ✓ Pairing strength : -325.0 MeV fm^3

DRHBc Mass Table Collaboration, Phys. Rev. C 102, 024314 (2020)
DRHBc Mass Table Collaboration, Phys. Rev. C 106, 014316 (2022)

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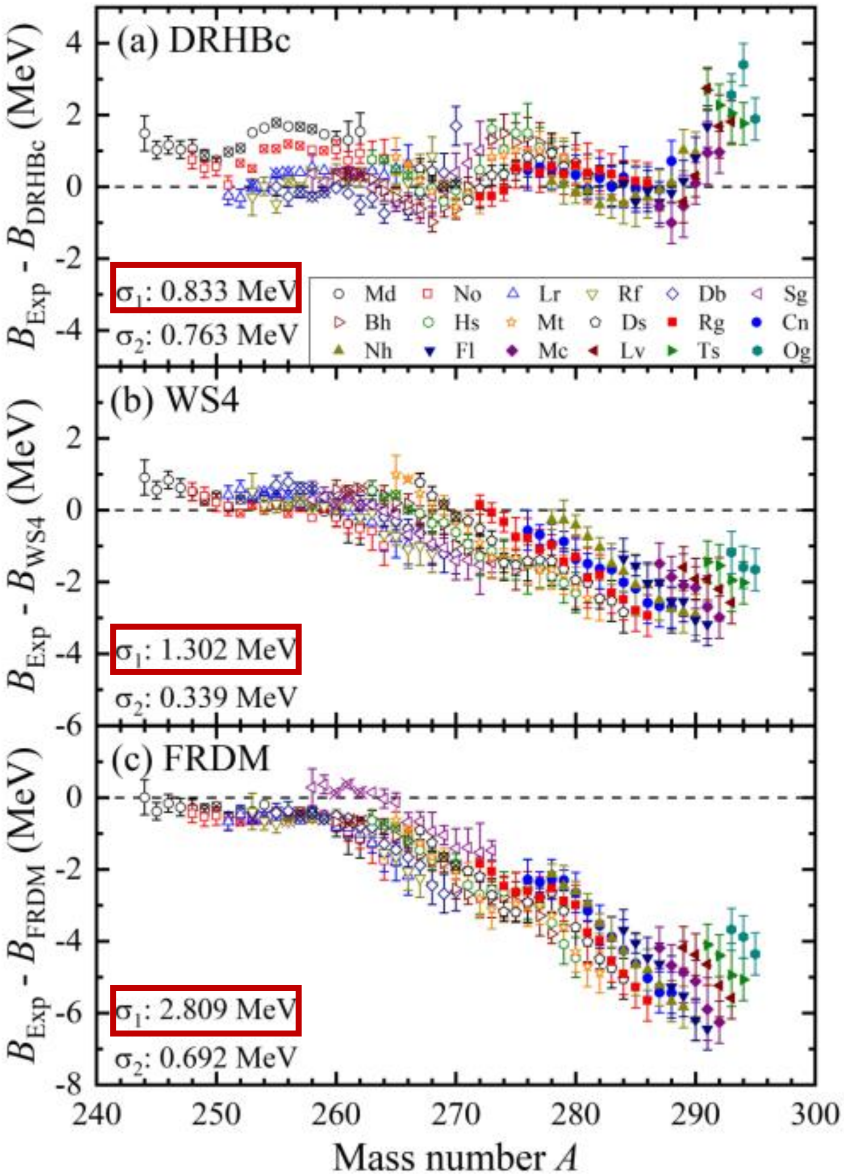
Comparison with AME2020 empirical mass data



- ✓ The empirical data from AME2020 are estimated from the trends in mass surface, together with all available experimental information.

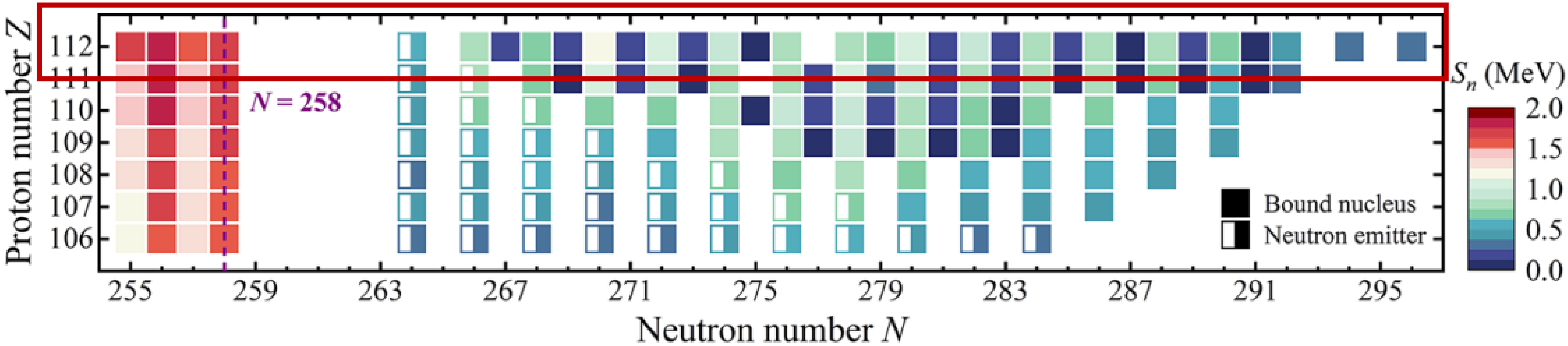
  M. Wang, et. al., Chin. Phys. C 45, 030003 (2021).

- ✓ Considering 204 evaluated data, DRHBc provides an accurate prediction with most of the deviations within 1 MeV.

He, et. al., Phys. Rev. C 110, 014301 (2024)

See X.T. He's talk

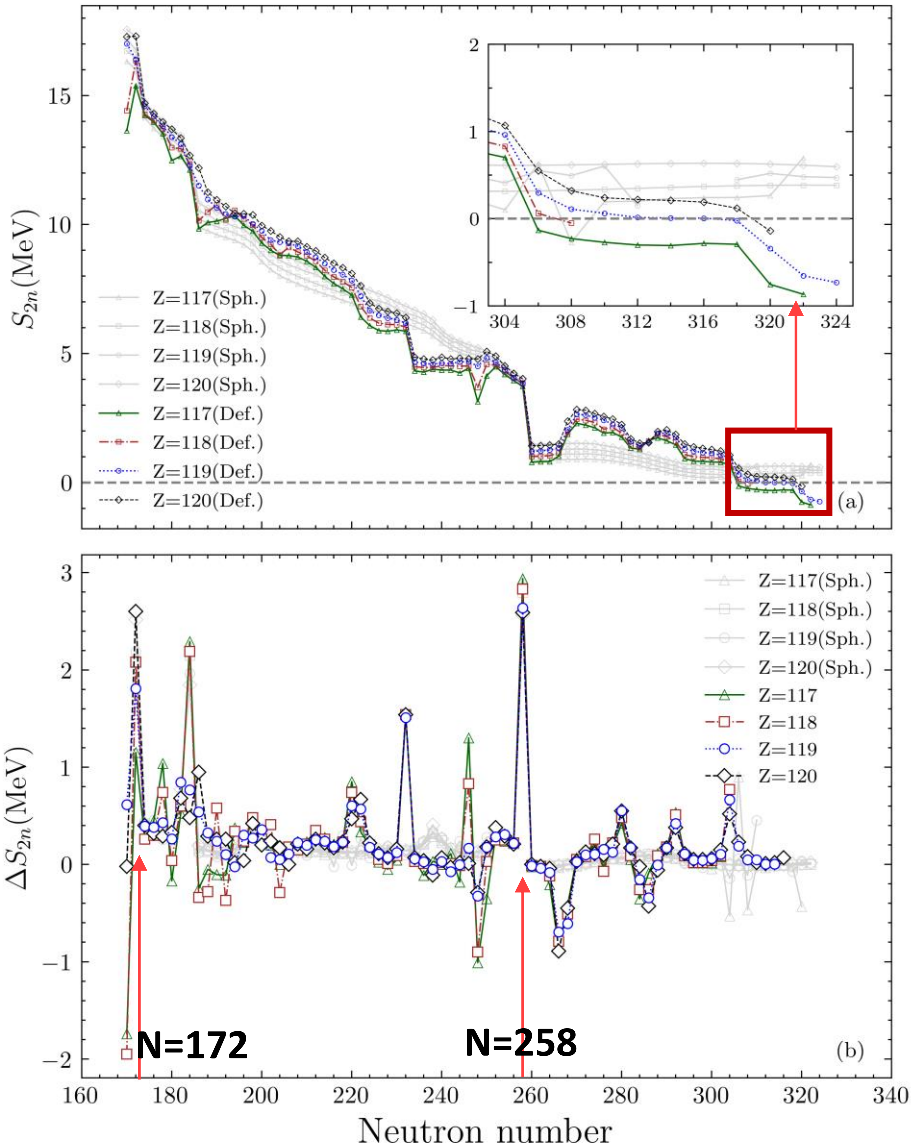
The stability peninsula



- ✓ The sudden decrease of S_n from positive to negative after N = 258 suggests it as a possible magic number.
- ✓ The stability peninsula formed beyond N = 258 in the Z = 106-112 region.
- ✓ A odd-N nucleus is less stable than its neighboring even-N nuclei with a smaller one-neutron separation energy in the peninsula.

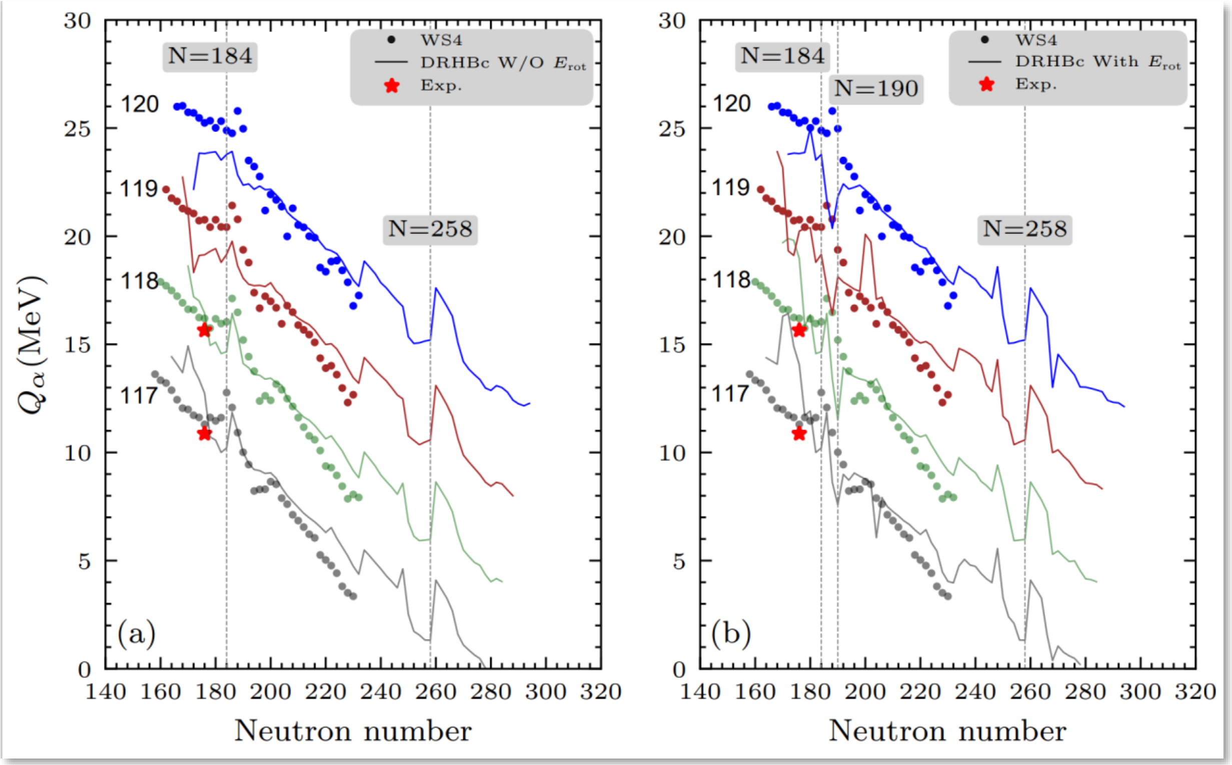
He, et. al., Phys. Rev. C 110, 014301 (2024)

Two-neutron separation energies and shell gap



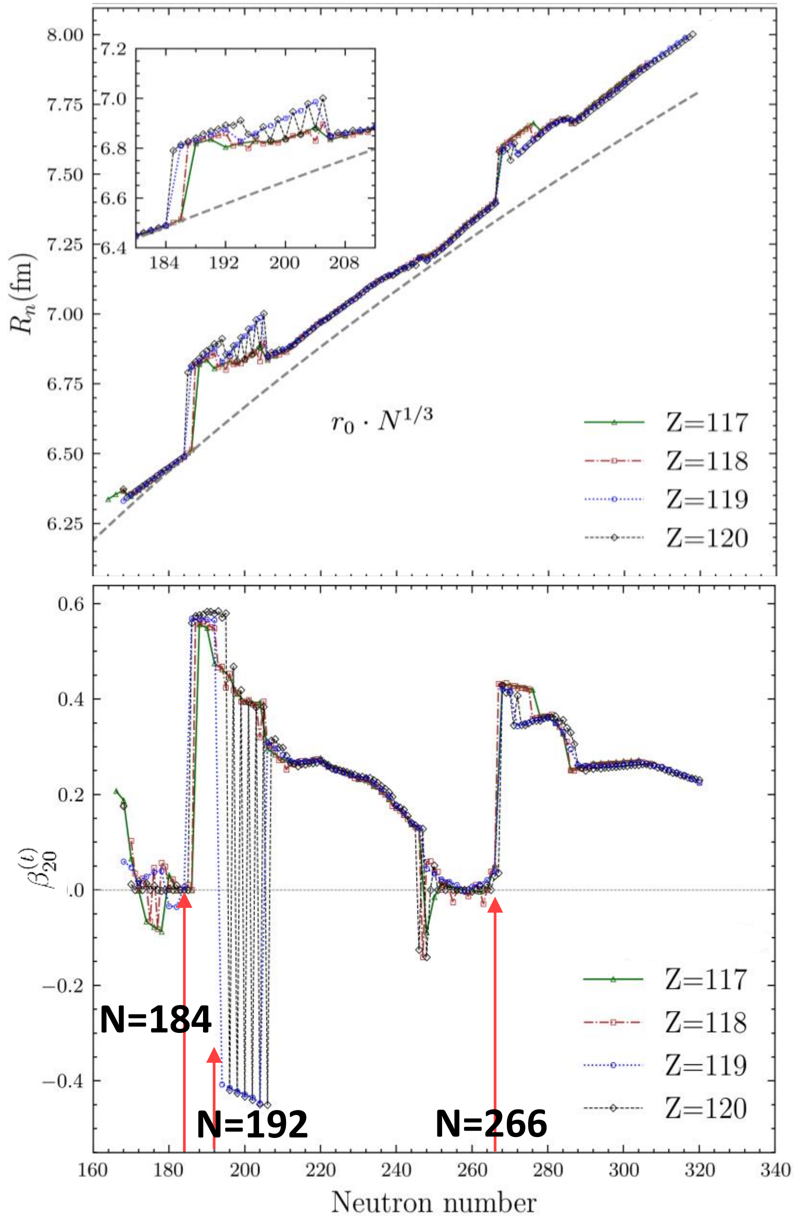
- ✓ Apparent peaks of Z=117-120 isotopes at N = 172, 258.
- ✓ Apparent peak of Z=117, 118 isotopes at N = 184.
- ✓ The neutron dripline is contracted by deformation.

α-decay energies



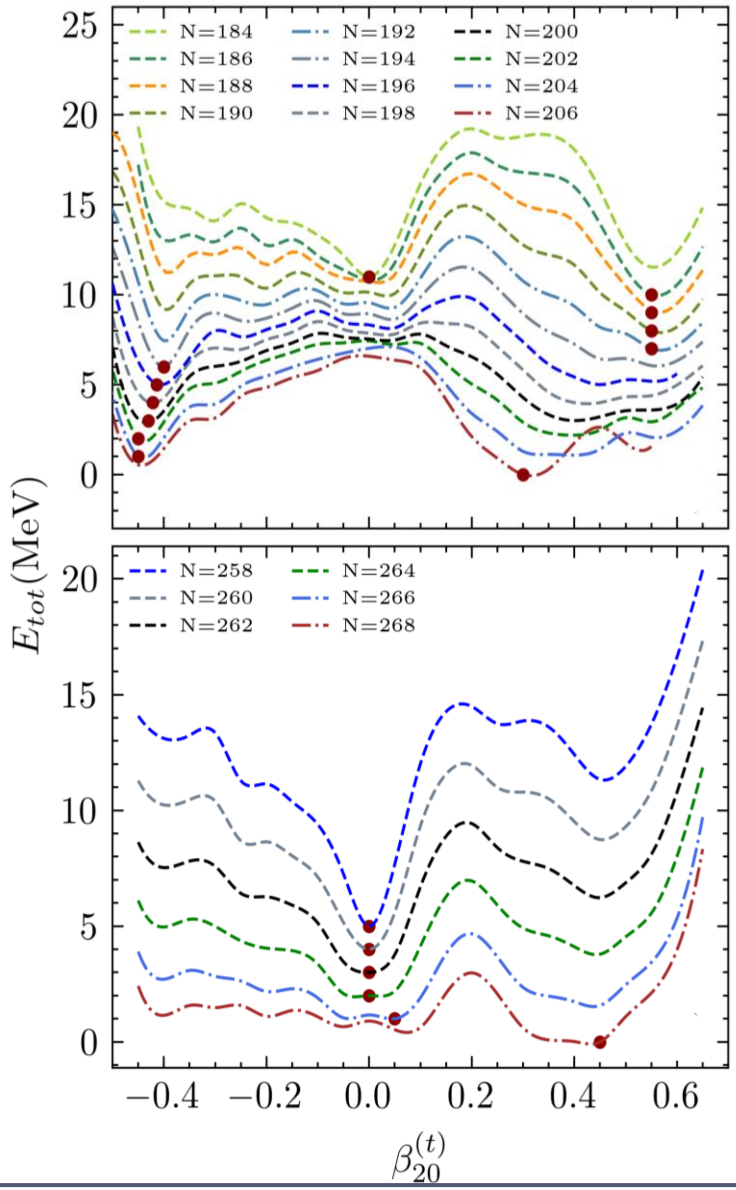
- There are apparent peak after N = 258 in the four isotopic chains. An additional peak after N = 184 in the Z = 117, 118 isotopes.
- With the rotational correction energies, we can observe more oscillations in the Q_α values around N = 180.
- The observed irregular behavior of the Q_α values in each isotopic chain is attributed to shell effects and shape transition.

Rms radius and quadrupole deformation



- ✓ The sudden shape transformations 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.

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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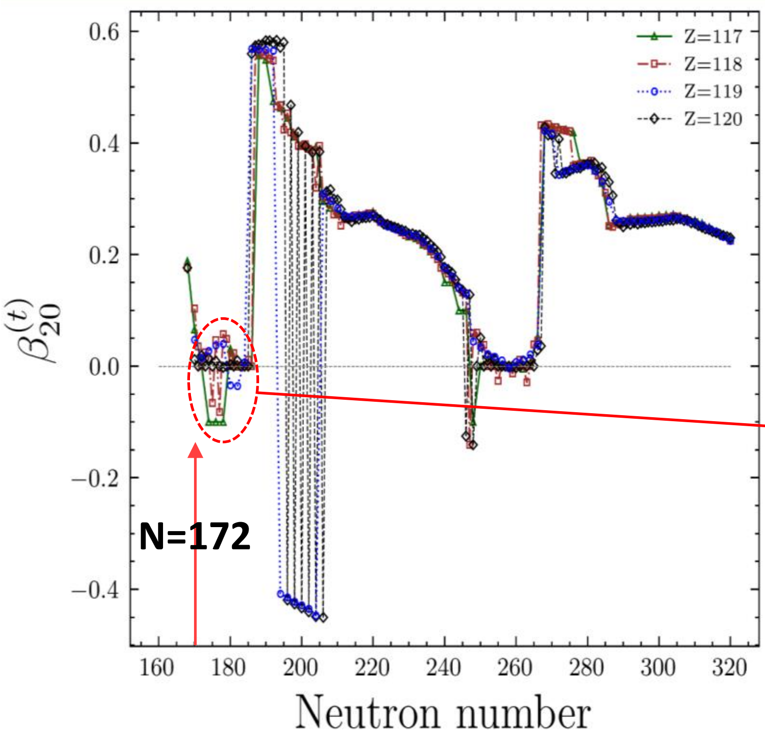
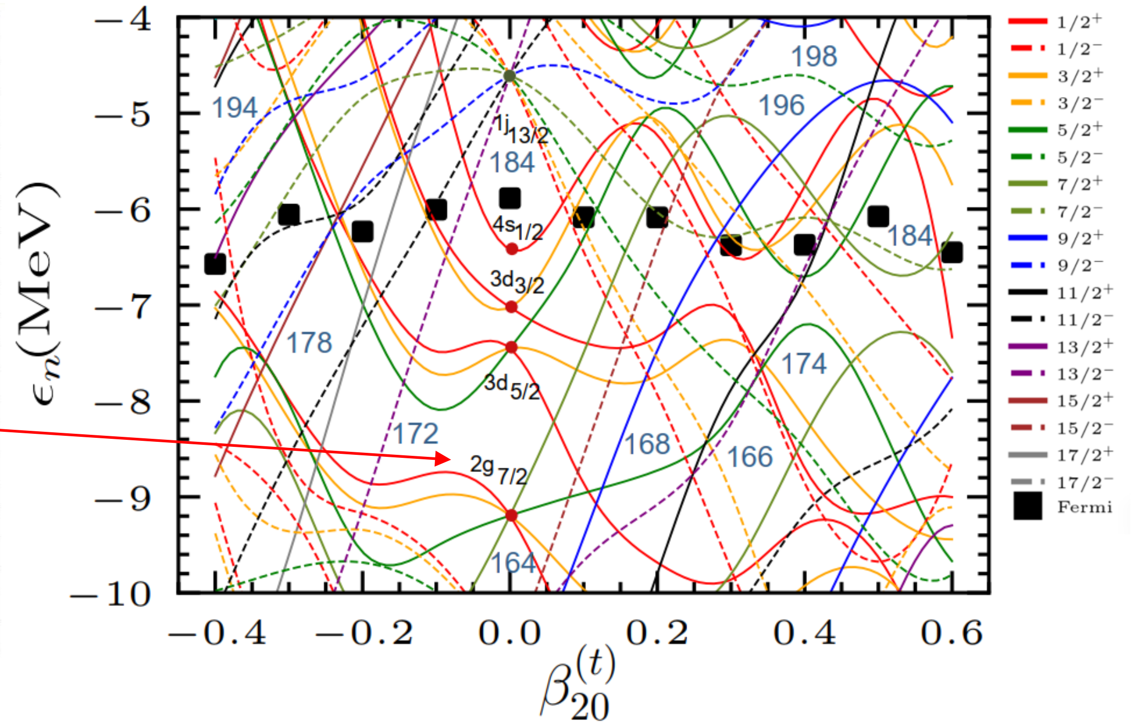
Single-particle orbitals and shell gap

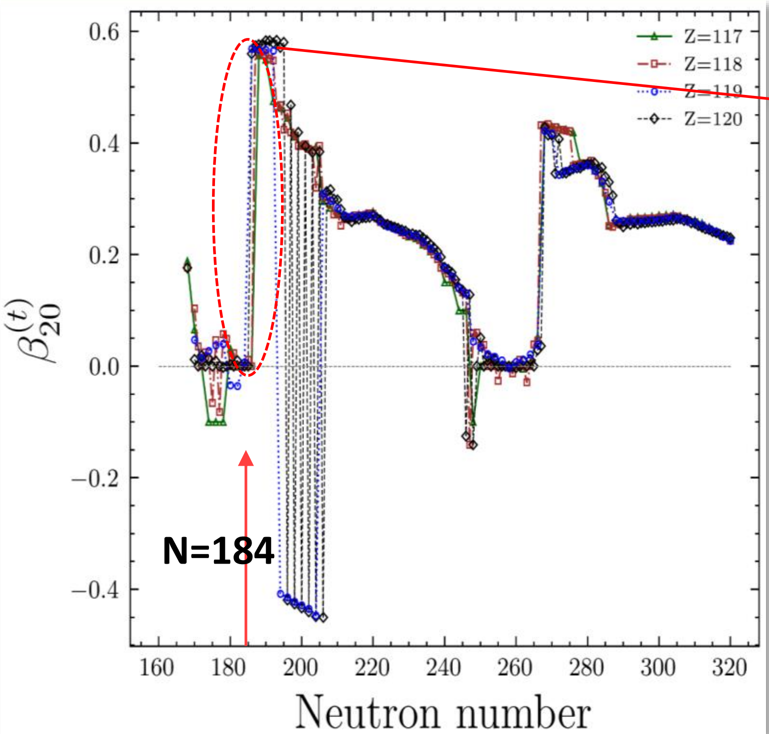


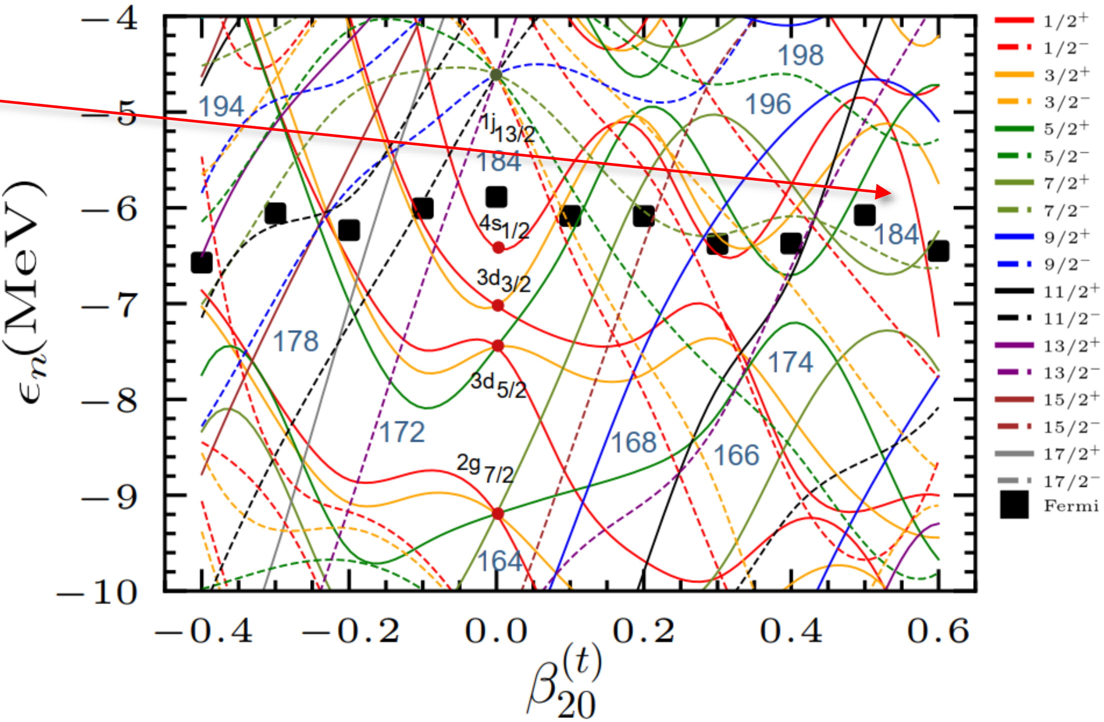


Nilsson diagrams obtained for N=184,Z=120.

- ✓ There are two large spherical neutron shell gaps at N = 172 and N = 184.
- ✓ The N = 172 shell gap extends from sphericity to an oblate shape β ≃ -0.15, explaining the isotopes around N=172 are spherical or weakly deformed.

Single-particle orbitals and shell gap

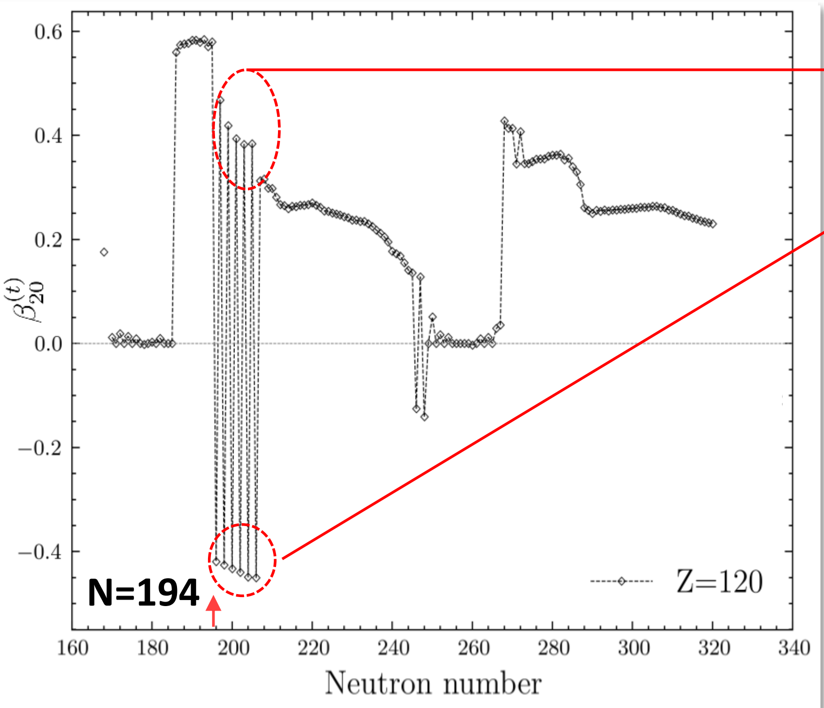


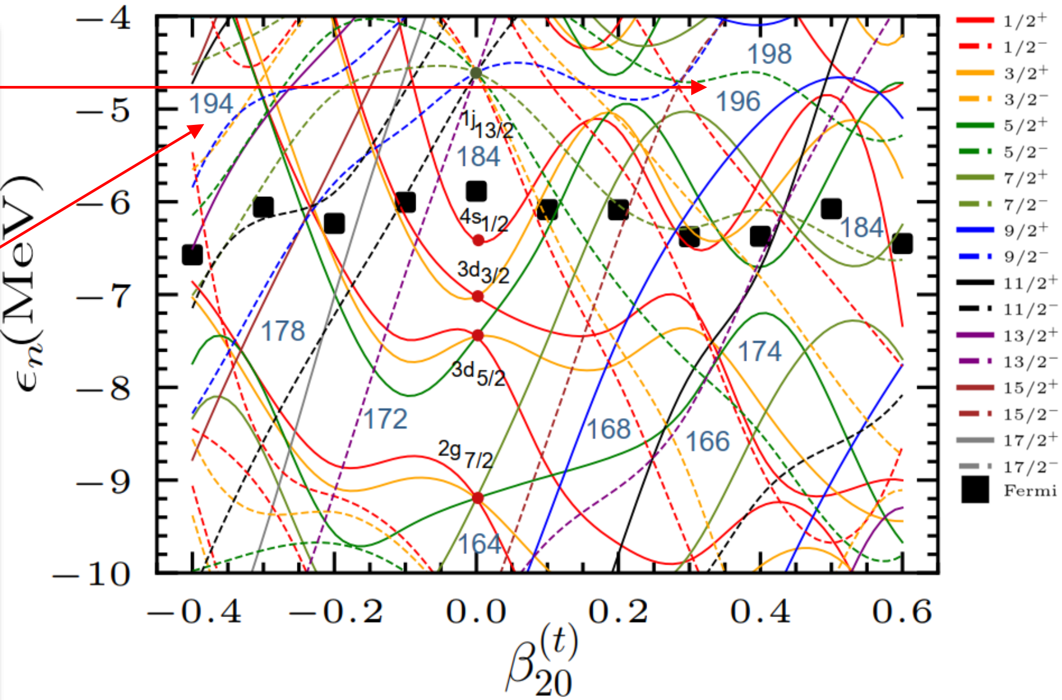


Nilsson diagrams obtained for N=184,Z=120.

- ✓ 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

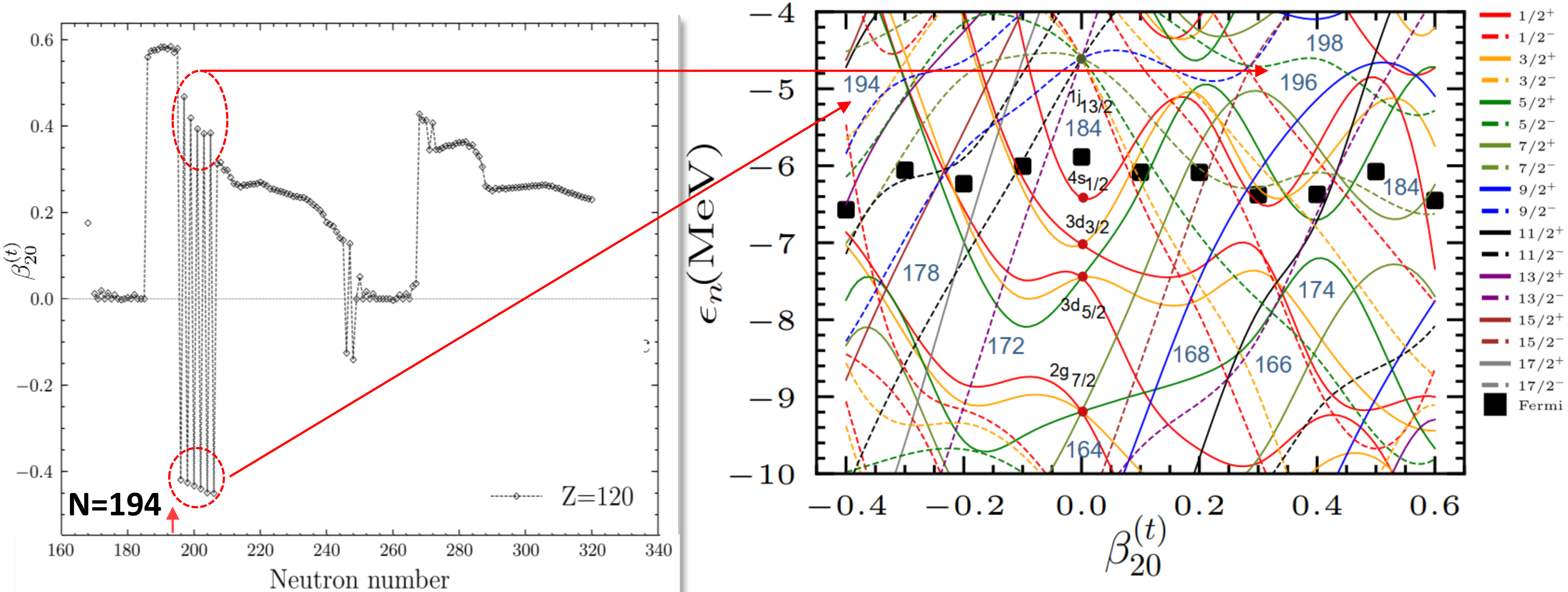




Nilsson diagrams obtained for N=184,Z=120.

- ✓ 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.

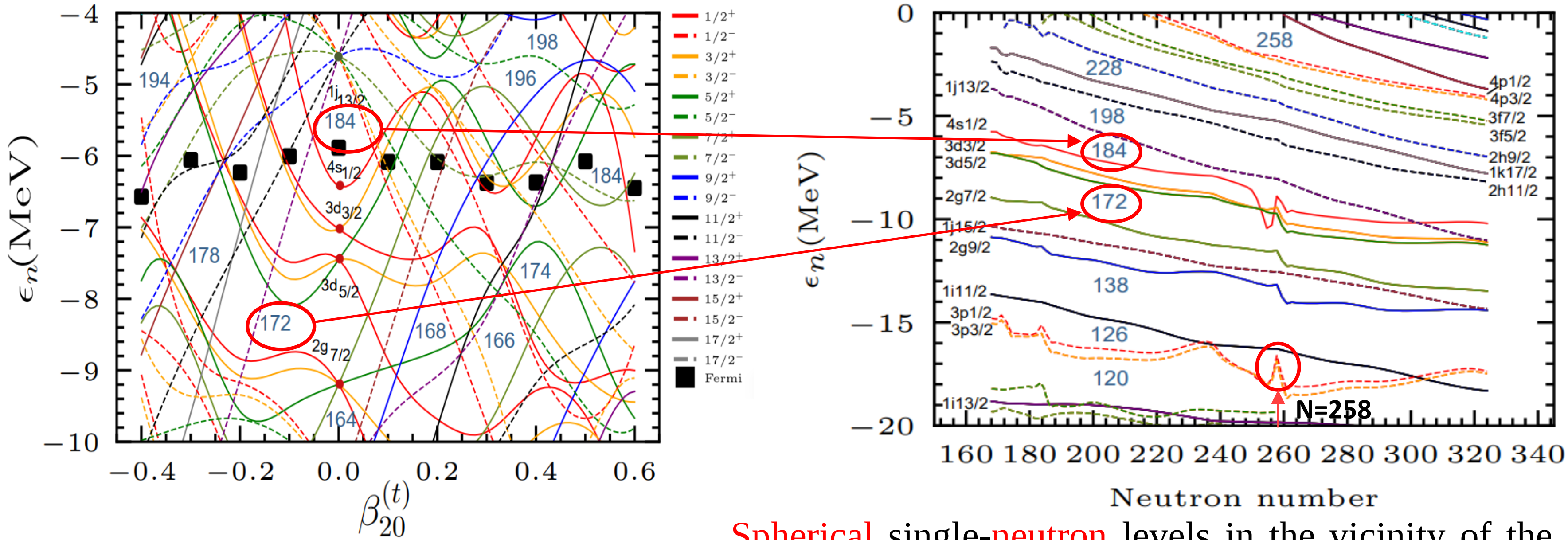
Shape coexistence



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

✓ The coexistence of competing prolate, oblate, and spherical shapes leads to sudden changes in both quadrupole deformations and rms radii as functions of neutron numbers.

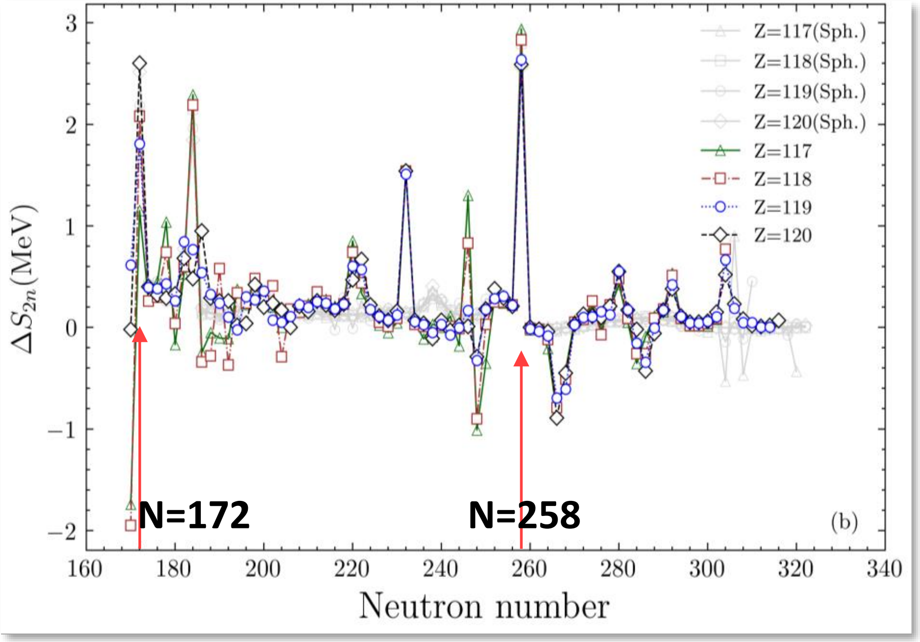
The evolution of shell gaps

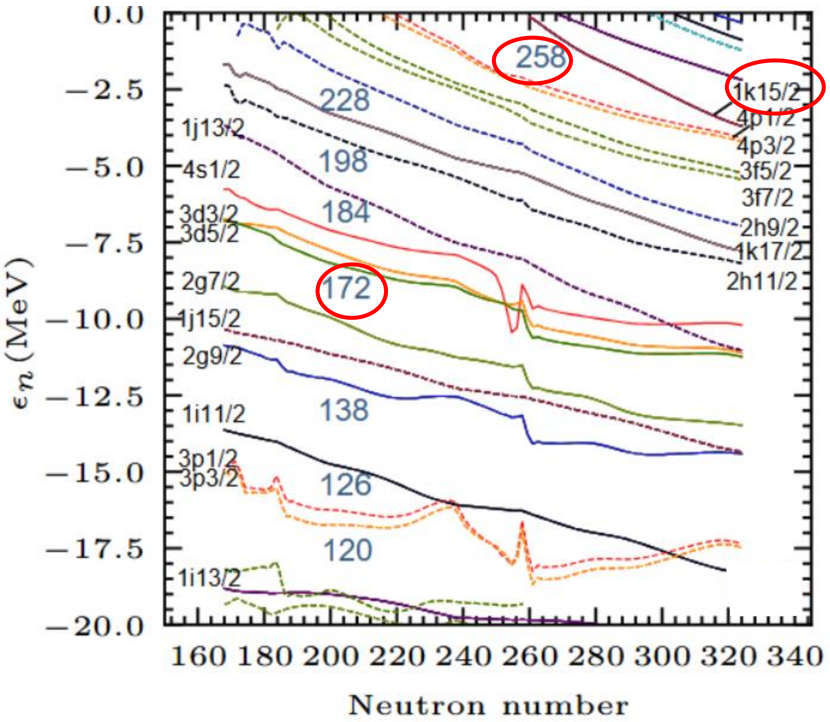


Spherical single-neutron levels in the vicinity of the Fermi energy for the isotopes of Z=120 versus the neutron number.

- ✓ With the increase of neutron number, the N = 184 shell gap decreases significantly, while N = 172 shell gap is rather robust.
- ✓ An evident discontinuity occurs at N = 258, where pairing correlation between neutrons collapses.

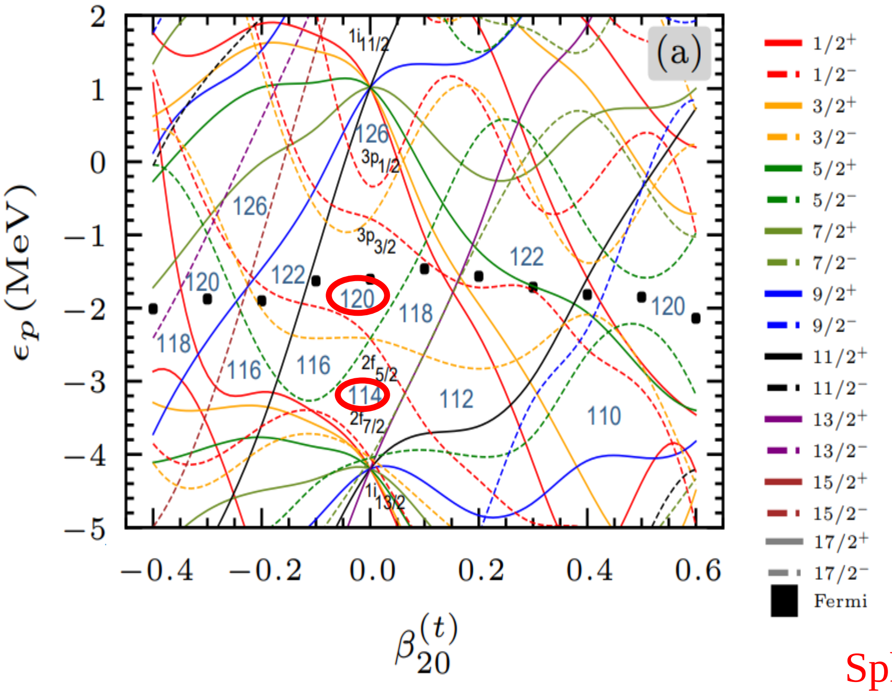
The evolution of shell gaps

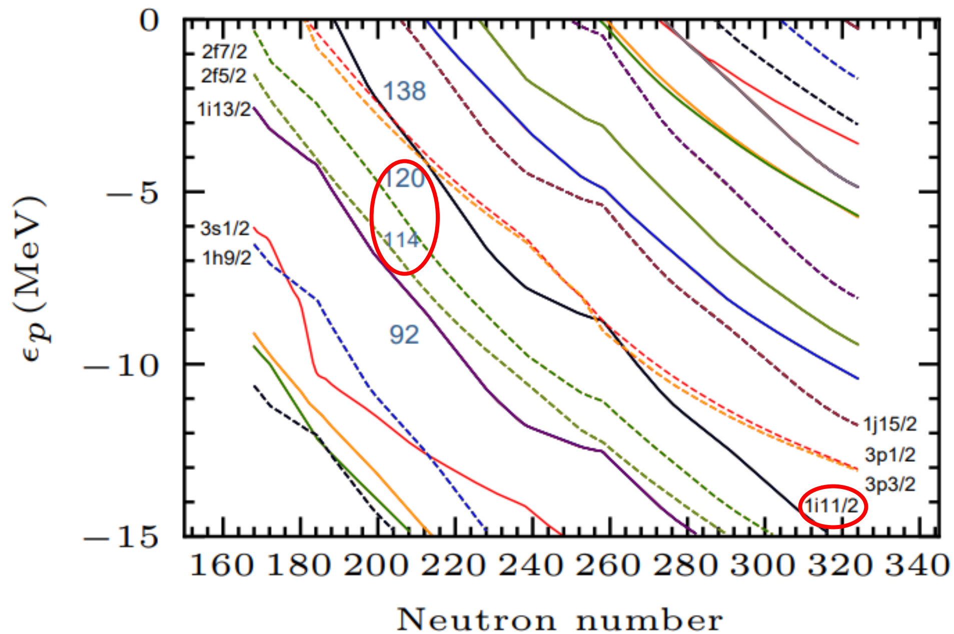




- ✓ Our results indicate that N = 172, 258 are the next two magic numbers for neutrons in superheavy nuclei beyond N = 126.
- ✓ The spherical neutron shell gap N = 258 decreases monotonically as the neutron number increases due to intruder state $1k_{15/2}$

The evolution of shell gaps

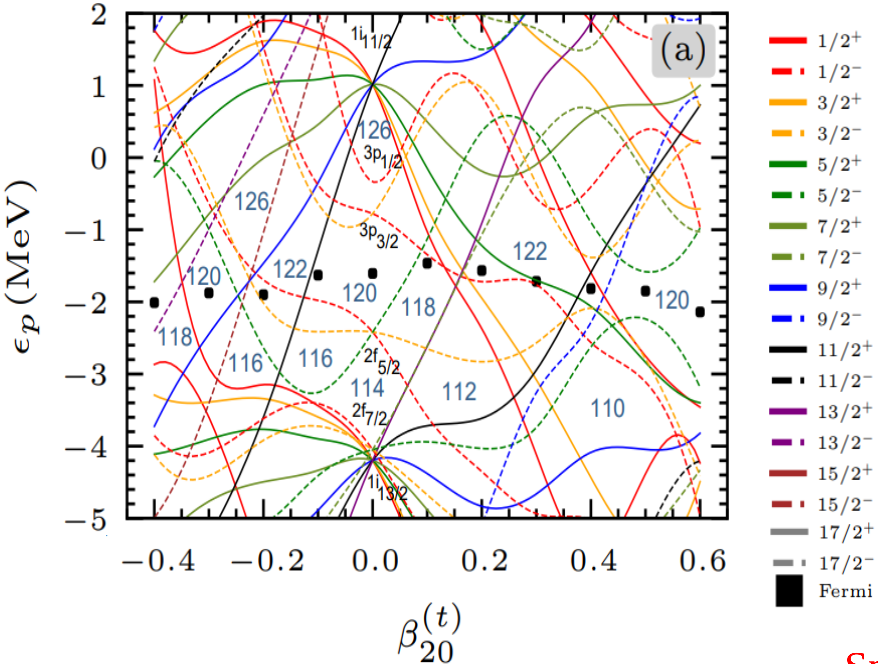


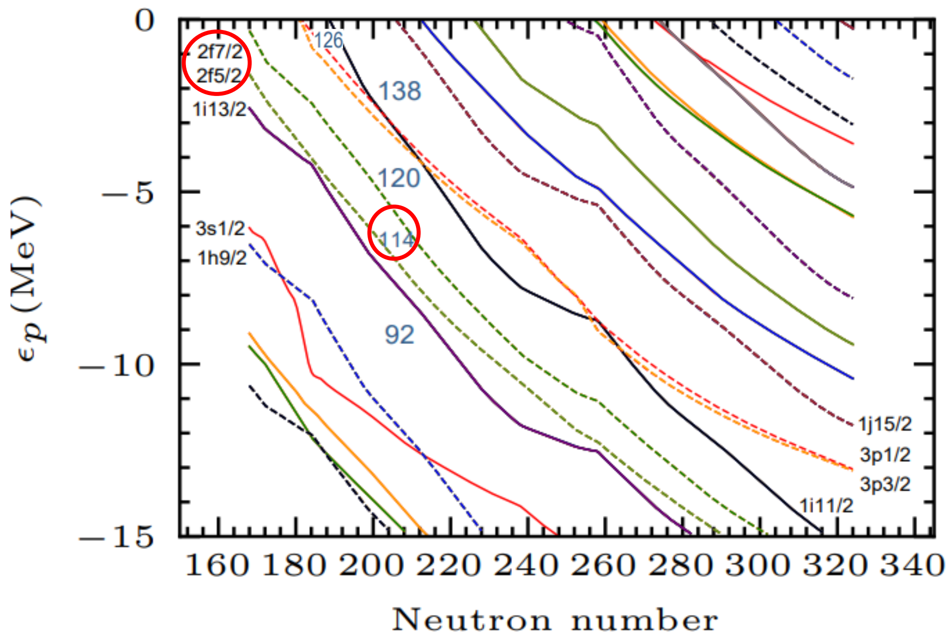


Spherical single-proton levels in the vicinity of the Fermi energy for the isotopes of Z=120 versus the neutron number.

- ✓ The large spherical shell gaps at Z = 114,120.
- ✓ The shell gap at Z = 120 decreases globally with the increase of neutron number due to the intruder orbital $1i_{11/2}$.

The evolution of shell gaps



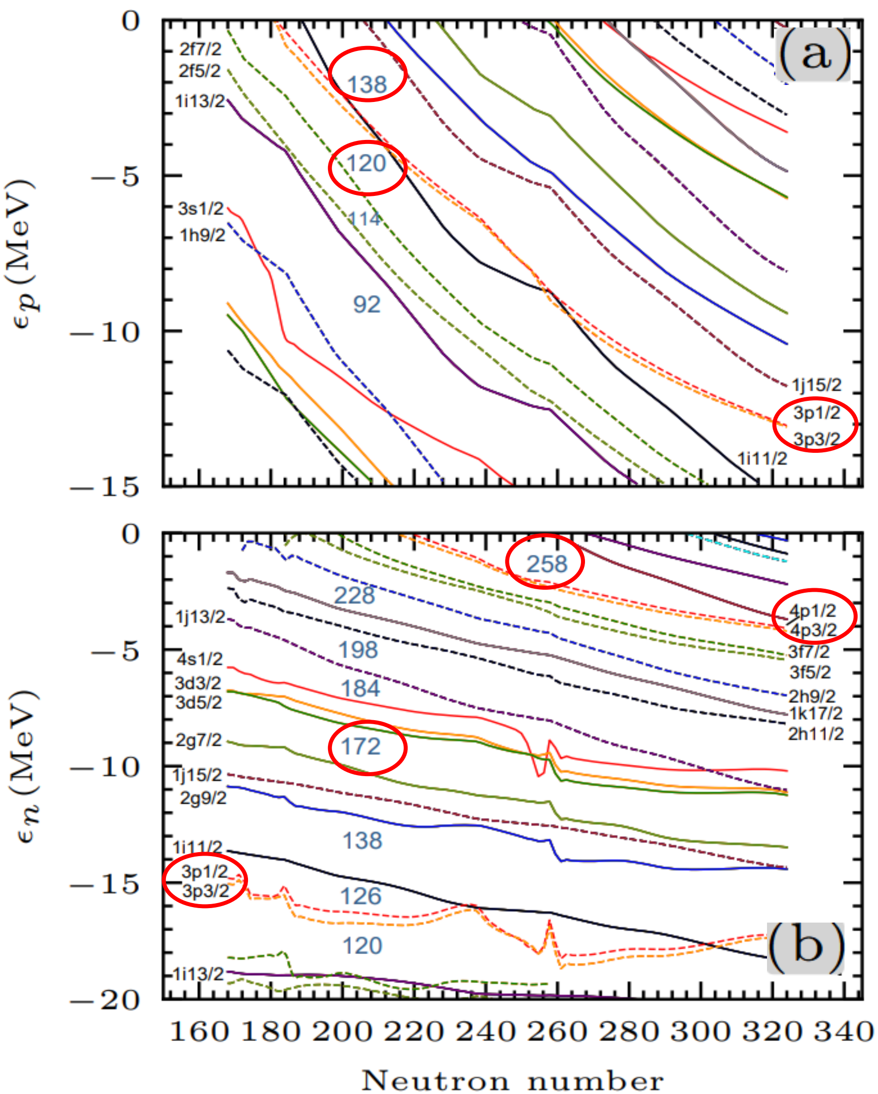


Spherical single-proton levels in the vicinity of the Fermi energy for the isotopes of Z=120 versus the neutron number.

✓ The shell gap at Z = 114 is formed by the spin-orbit splitting of the 2f states.

✓ The intruder orbital and spin-orbit potential has an obvious effect on the shell gap.

Shell gap and spin-orbit splitting

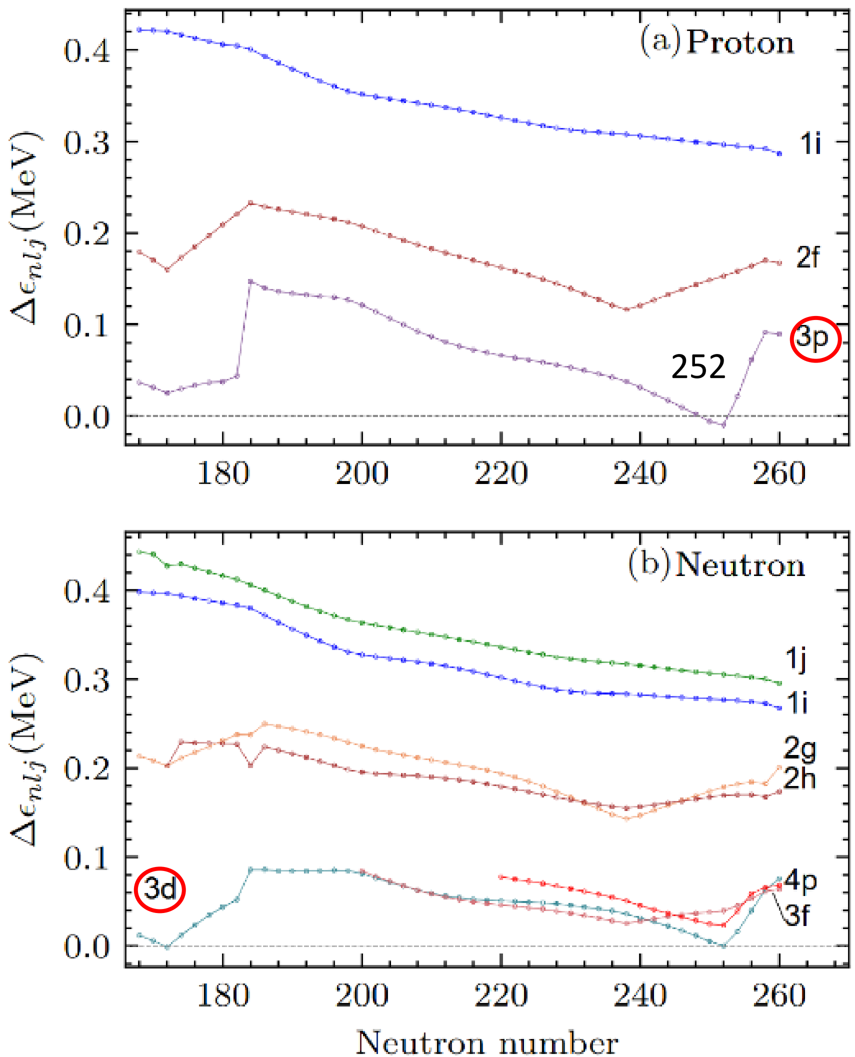


Single-particle levels in the vicinity of the Fermi energy for the isotopes of Z=120 versus the neutron number.

- ✓ The size of the Z = 120 and Z = 138 shell gaps are influenced by the splitting of the proton 3p states, smaller splittings correspond to larger shell gaps .

- ✓ N=172, 258 proton shell closure is related to the spin-orbit splitting of neutron 3d and 4p states, respectively.

The spin-orbit splitting



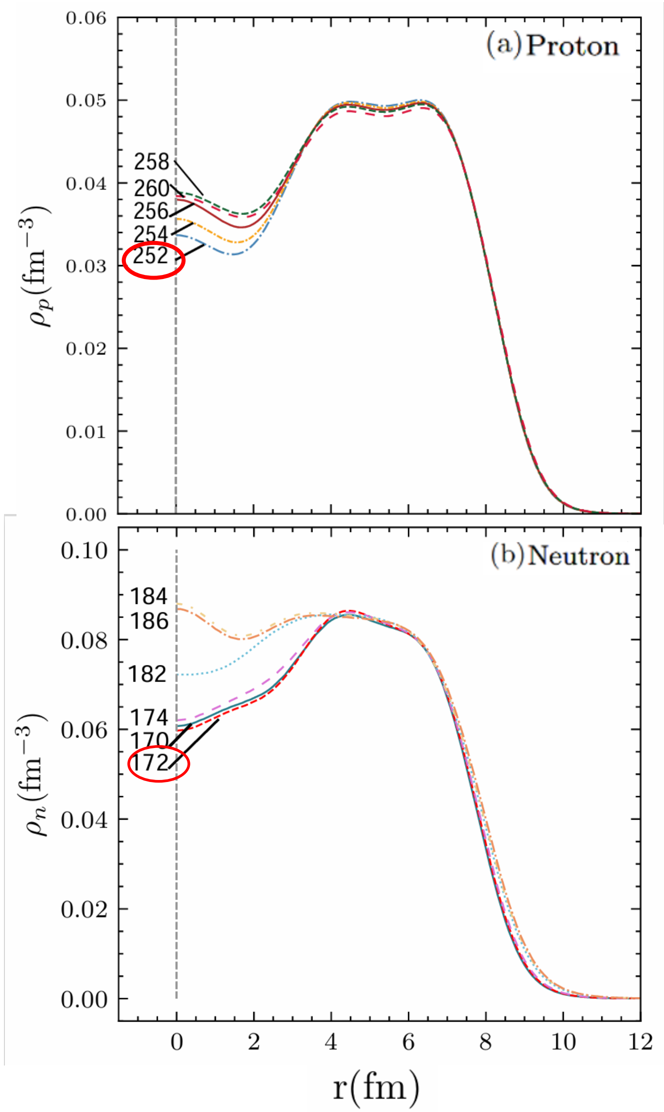
Spin-orbit splitting in the spherical states of Z = 120 isotopes as a function of neutron number

- ✓ 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 and 3d neutron states are generally small, changing sign around N =252 and N=172, respectively.
- ✓ 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

✓ The DRHBc mass table calculations for odd-even and odd-odd nuclei with Z = 111-119 have been finished.

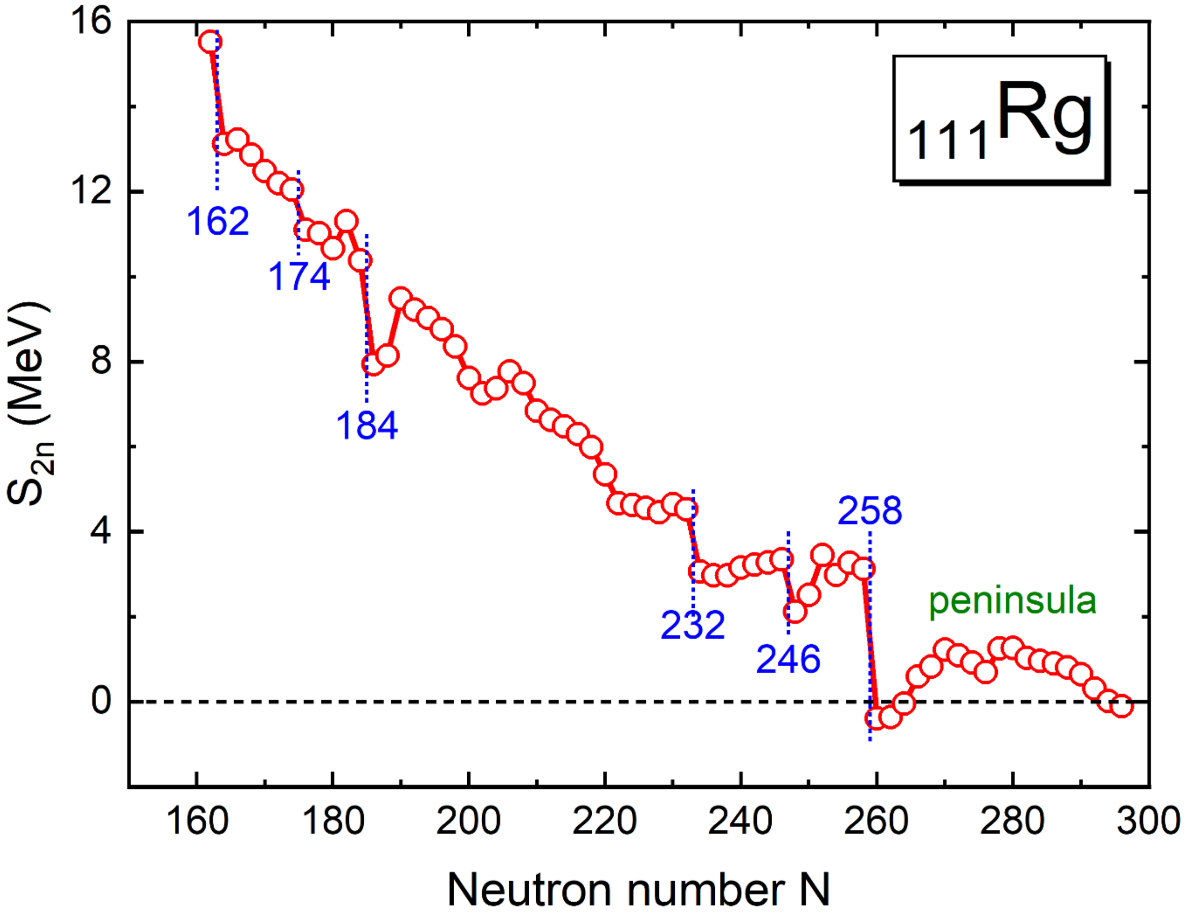
1. The properties of ground states of Z = 111 − 120 isotopes are discussed.
2. Shape coexistence is responsible for the sudden shape transitions.
3. Shell structure is associate with intruder orbital and spin-orbit splitting, which is associate with the nucleonic density.

✓ Next: Developing projection method and generator coordinate method .

- Verifying the calculation of rotational correction energy.
- Considering the effect of shape mixing.
- Calculating the low excitation energy.

Thank you for your attention!

Two-neutron separation energy and drip line

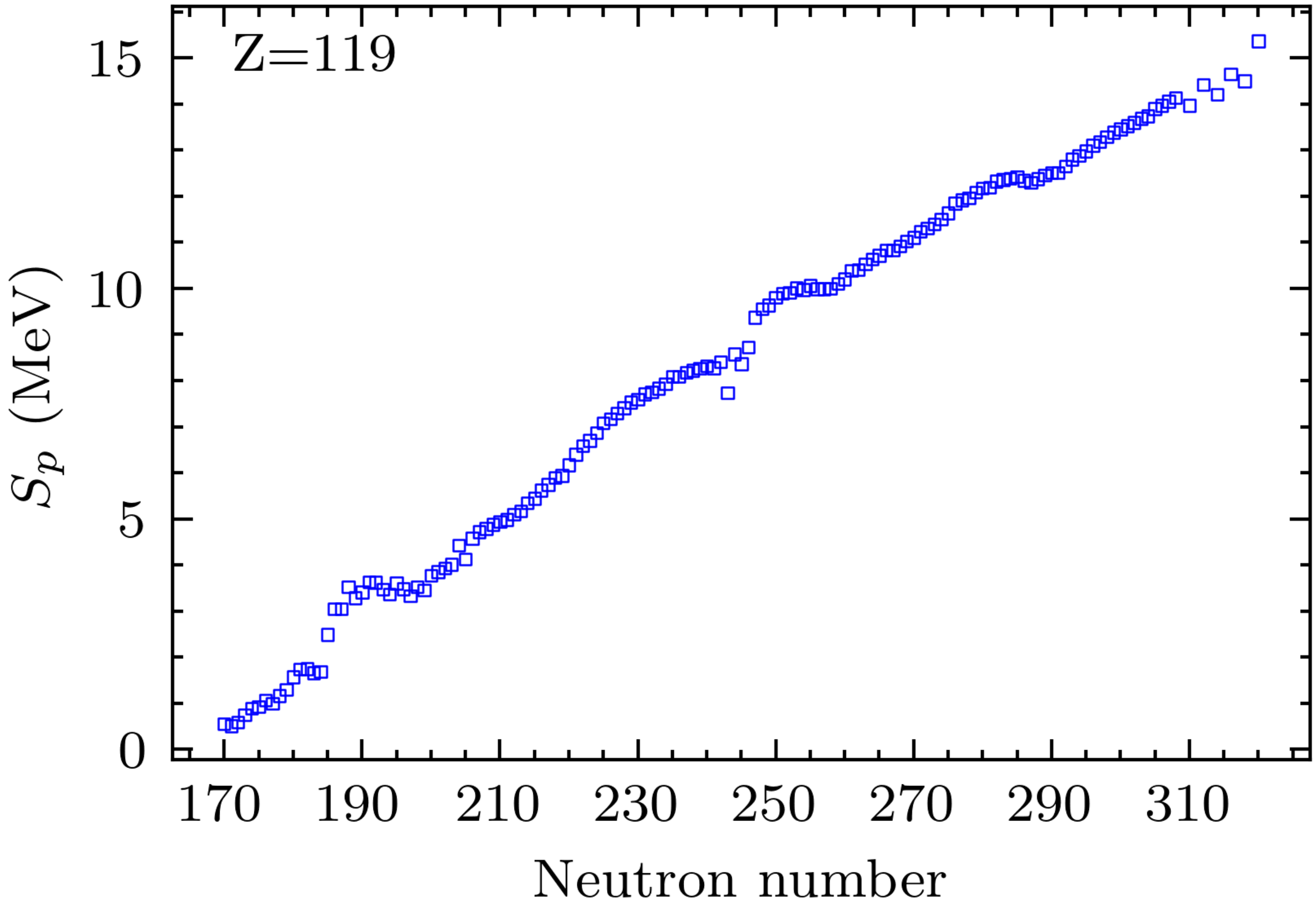


Two-neutron drip line

Z	DRHBc	RCHB
111	^{403}Rg	^{369}Rg
113	^{415}Nh	^{371}Nh
115	^{417}Mc	^{373}Mc
117	^{421}Ts	^{405}Ts
119	^{435}119	^{407}119

- ✓ Sudden decreases indicate shell closures and subshells.
- ✓ Several odd-even nuclei are also found in the predicted peninsula.

One-proton separation energy



- ✓ S_p gradually increases with the neutron number.
- ✓ The proton drip line could be $^{288}119$ or $^{289}119$.

Shell structure of superheavy nuclei

- ✓ Shell structure is crucial for the stability of superheavy nuclei.

- ✓ The structural properties of superheavy nuclei have been studied with different types of nuclear model:

  Mic-mac model: Wang, et.al., Phys. Lett. B 734, 215(2014)
  Mean-field model : Cwiok, et.al., Nucl. Phys. A 611, 211 (1996)

- ✓ Previous studies based on self-consistent mean-field approaches indicate that the proton and neutron numbers with ($Z = 114$, $N = 184$), ($Z = 120$, $N = 172$), and ($Z = 126$, $N = 184$) are possible magic numbers in superheavy nuclei .

  Bender, et.al., Phys. Rev. C 56, 238 (1997)
  Cwiok, et.al., Phys. Rev. Lett. 83, 1108(1999)

- ✓ The specific values vary with the employed parametrizations of EDFs

  Bender, et.al., Phys. Rev. C 60, 034304 (1999)