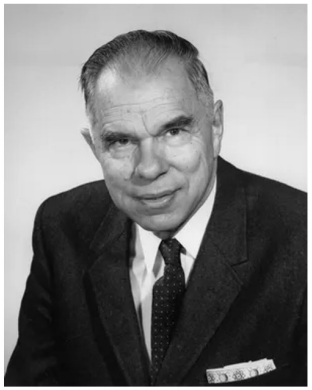
Structure and Production of Superheavy Nuclei and the Island of Stability:

Exploring the Island of Stability

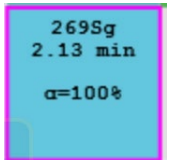
H. Lenske
Institut für Theoretische Physik, JLU Giessen
with
G. Adamian, N. Antonenko, L. Malov, V. Sargsyan
JINR Dubna

Searching for Double Magicity…

The Pioneer



Nobel Price in Chemistry, 1951

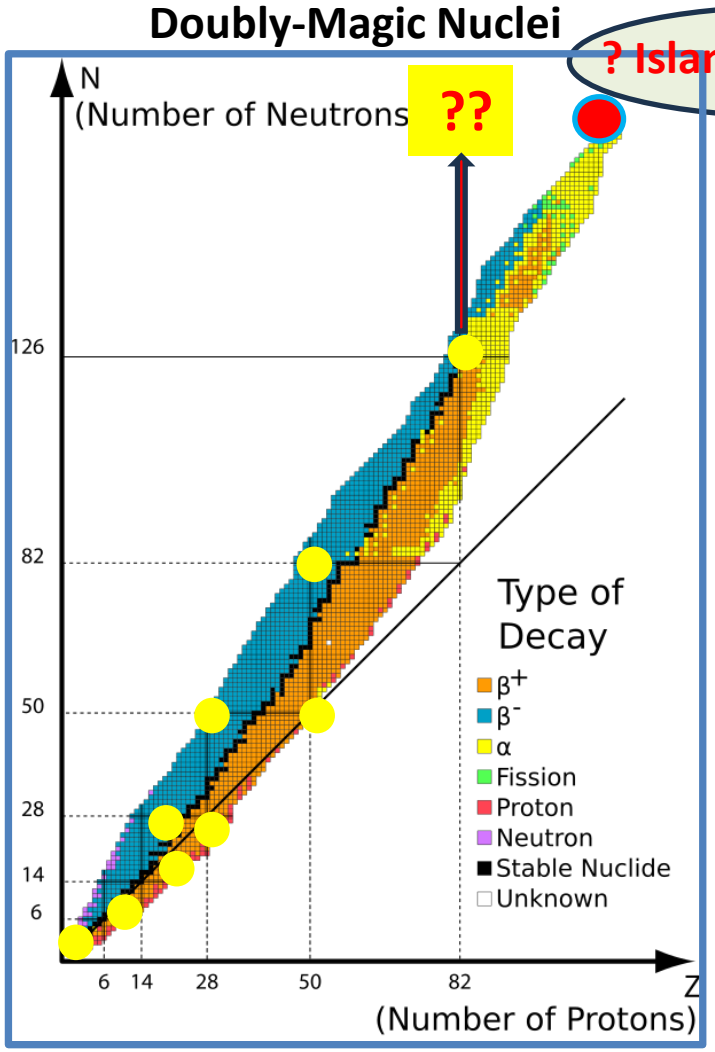


104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

Z ≥ 104: Superheavy Nuclei (SHN) / Superheavy Elements (SHE)

The Prime Numbers of Nuclear Physics: 2, 8, 20, 28, 50, 82, 126…?

Doubly-Magic Nuclei



…the search for SHN motivated to build GSI, UNILAC and SHIP – the discoverers:

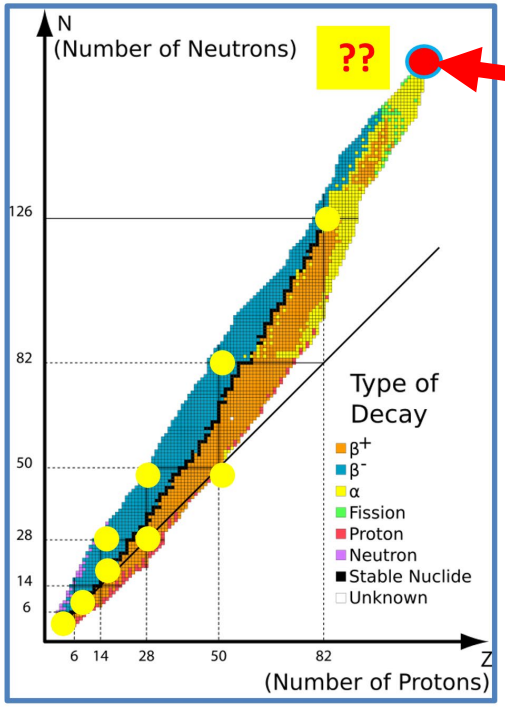
1940-2024 **1931-2024**

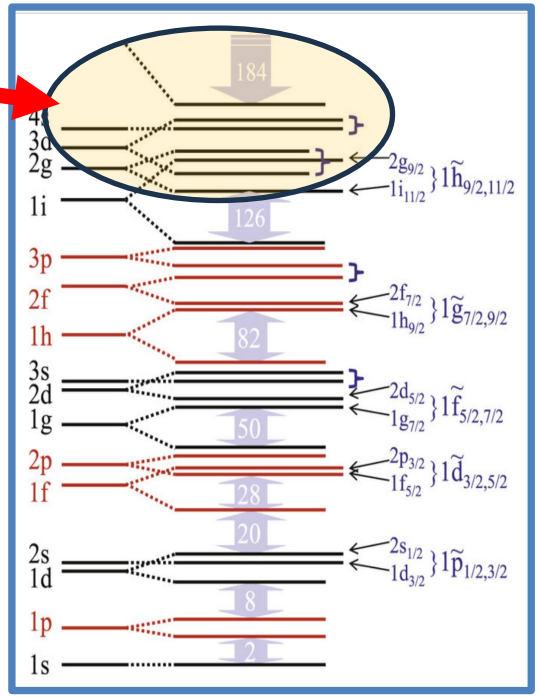
1944-2022

107	108	109	110	111	112
Bh	Hs	Mt	Ds	Rg	Cn

J. Khuyagbaatar *et al.*, "Stepping into the sea of instability: The new sub-μs superheavy nucleus ^{252}Rf," Phys. Rev. Lett. 134, 022501 (2025).

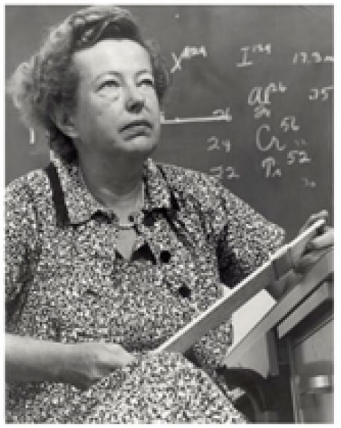
Magic Numbers: A Consequence of the Single Particle Nuclear Shell Model





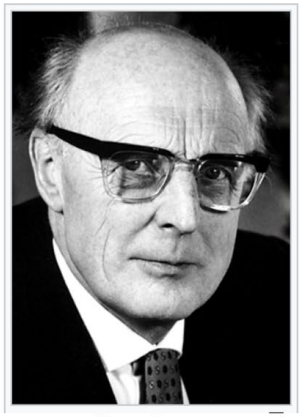
$$\left(-\frac{\hbar^2}{2m_q}\nabla^2 + U_q(r) + U_q^{(ls)}(r)\,\mathbf{L}\cdot\mathbf{s} - \varepsilon_q\right)\psi_q(r) = 0$$

Nobel Prize 1963



Marie Goeppert-Mayer

- 28. Juni 1906,
- † 20. Februar 1972



Hans Jensen

- 25. Juni 1907
- † 11. Februar 1973

Droplet Model and Shell Corrections

The Standard Approach to SHN Modeling:
Liquid Drop, and Droplet Model

$$E(Z,N)/A = -16MeV + E_{surf}/A^{1/3} + E_{pair} + E_{shell} + E_{coul} + [(N-Z)/A]^2(a_4 + C_{sym}/A^{1/3})$$

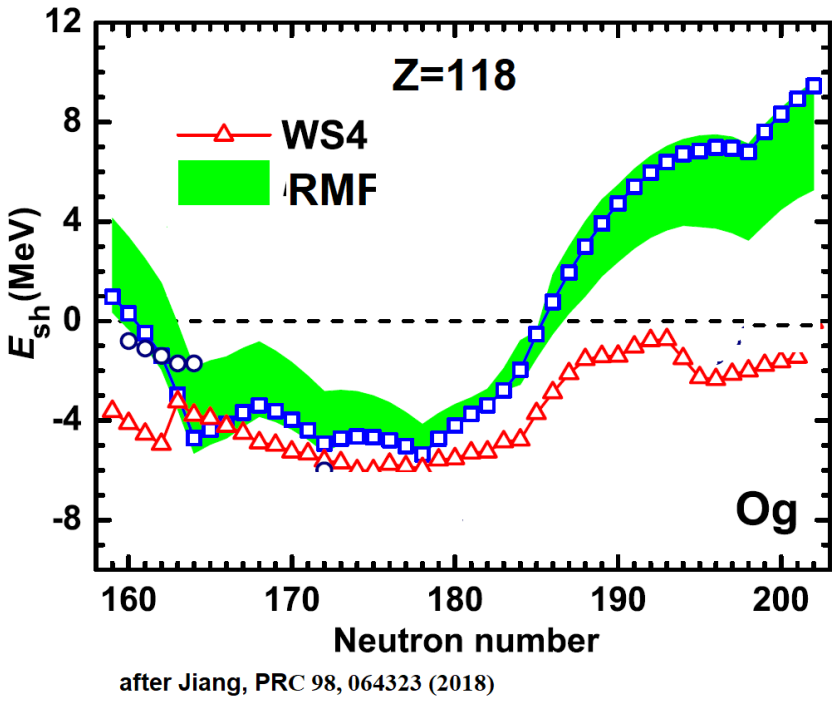
Bethe-Weizsäcker Mass Formula (1935) → Liquid Drop Model (Gamow, Bohr…)

First Theoretical Prediction of Superheavy Nuclei
A. Sobiczewski, F. A. Gareev, and B. N. Kalinkin, Phys. Lett. B22, 500 (1966).

Droplet Model and Macroscopic-Microscopic Model
W. D. Myers and W. J. Swiatecki, Ark. Fys. 36, 343 (1967).
P. Moeller, J.R. Nix, *Atom.Data Nucl.Data Tabl.* 26 (1981) 165
Today: various generalized Droplet Models

Caveat:

Nuclei at Z >104 exist only by shell effects!



after Jiang, PRC 98, 064323 (2018)

Strutinski Shell Corrections

Rev.Mod.Phys. 44 (1972) 320

$$E_{\mathrm{sh}} = \sum_{i=1}^{Z(N)} \varepsilon_i - \int_{-\infty}^{\tilde{\lambda}} \varepsilon \tilde{g}(\varepsilon)\, d(\varepsilon).$$

$\sim \lambda_q A_q$ (q=Z,N)

$$\tilde{g}(\varepsilon) = \frac{1}{\gamma} \int_{-\infty}^{\infty} \left[\sum_{i=1}^{\infty} \delta(\varepsilon' - \varepsilon_i) \right] f\left(\frac{\varepsilon' - \varepsilon}{\gamma} \right) d\varepsilon'$$

Smoothed Level Density

Paradigm of SHN Theory:
Shell Corrections = Stability Criterion

Microscopic EDF Approach to SHN Structure

The Giessen EDF Approach:

EDF by BHF/DBHF Theory, HFB and Multi-Phonon QRPA Theory

$$E(\rho,\kappa) \approx E(\rho_0,\kappa_0) + \sum_{q=p,n}\left(\left(T_q + U_q(\rho_0)\right)\delta\rho_q + \Delta_q\delta\kappa_q\right) + \sum_{q,q'=p,n} f_{qq'}(\rho_0)\delta\rho_q\delta\rho_{q'} + \ldots$$

$$\delta\rho_q \sim \left\langle \varphi_k^\dagger \varphi_n \right\rangle - \varphi_k^\dagger \varphi_n \quad ; \quad \delta\kappa_q \sim \left\langle \varphi_k \varphi_n \right\rangle - \varphi_k \varphi_n \ \ \& \text{ h.c.}$$

Single Particle Self-Energy (Potential):

$$U_q = \frac{\delta}{\delta\rho_q}\frac{1}{2}\langle V\rangle = \sum_{q'} V_{qq'}(\rho)\rho_{q'} + \frac{1}{2}\sum_{q'q''}\rho_{q'}\rho_{q''}\frac{\delta}{\delta\rho_q}V_{q'q''}(\rho)$$

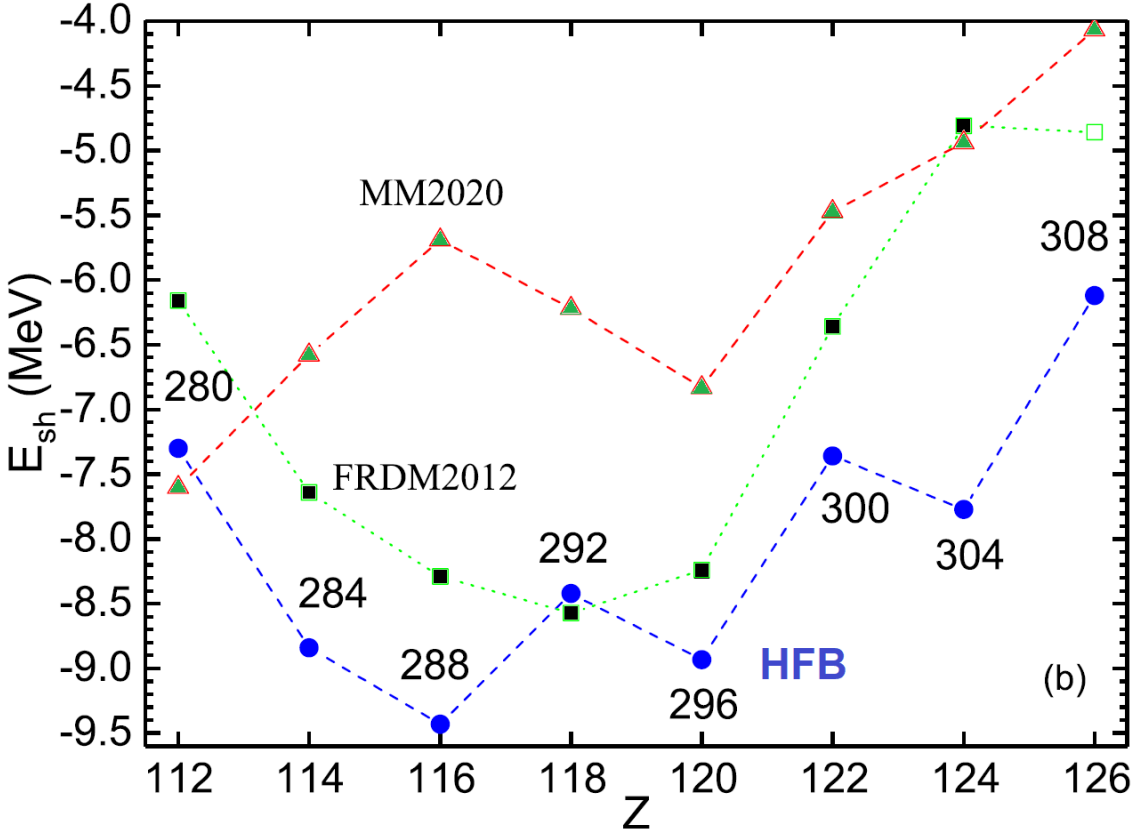
Self-consistent Mean-Field Dynamics:

$$\left(-\nabla\cdot\frac{\hbar^2}{2m_q^*(\mathbf{r})}\nabla + V_q(\mathbf{r},\mathbf{k}) + V_q^{(ls)}(\mathbf{r})\,\mathbf{L}\cdot\mathbf{s} - \varepsilon_q\right)\psi_q(\mathbf{r}) = 0$$

plus Pairing: Quasiparticle Spectrum and Wave Functions

N. Tsoneva, H.L., *Phys.Rev.C* 77 (2008) 024321,*Nature Commun.* 11 (2020), *Phys.Atom.Nucl.* 79 (2016) 6, 885, *Phys.Rev.Lett.* 110 (2013) 022503, *Eur.Phys.J.A* 55 (2019) 238, *Phys.Rev.C* 108 (2023) 5, L051301…and many more

EDF-HFB Theory, Deformation, and Shell Corrections along α-Decay Chains



PRC 104, 064303 (2021)

Our most Recent Publications on the Topics of this Contribution:

1. **Application of a universal reaction function to the description of heavy-ion reaction cross sections**, G.G. Adamian, N.V. Antonenko, H. Lenske, V.V. Sargsyan, DOI: 10.1103/PhysRevC.109.014602, Published in: Phys.Rev.C 109 (2024) 1, 014602

2. **Double-folding nucleus-nucleus interaction potential based on the self-consistent calculations**, N.V. Antonenko, G.G. Adamian, V.V. Sargsyan, H. Lenske, DOI:, Published in: Eur.Phys.J.A 58 (2022) 11, 211

3. **On the possibility of formation of binary cosmic systems from the single cosmic objects** G.G. Adamian, N.V. Antonenko, H. Lenske, V.V. Sargsyan, DOI: 10.1142/S0218301322500719 Published in: Int.J.Mod.Phys.E 31 (2022) 07, 2250071

4. **Constraints on the appearance of a maximum in astrophysical S-factor**, V.V. Sargsyan, G.G. Adamian, N.V. Antonenko, H. Lenske, DOI: 10.1016/j.physletb.2021.136792, Published in: Phys.Lett.B 824 (2022), 136792

5. **Landscape of the island of stability with self-consistent mean-field potentials**, L.A. Malov, G.G. Adamian, N.V. Antonenko, H. Lenske, DOI: 10.1103/PhysRevC.104.064303, Published in: Phys.Rev.C 104 (2021) 6, 064303

6. **Shaping the archipelago of stability by the competition of proton and neutron shell closures** L.A. Malov, G.G. Adamian, N.V. Antonenko, H. Lenske, DOI: 10.1103/PhysRevC.104.L011304, Published in: Phys.Rev.C 104 (2021) 1, L011304

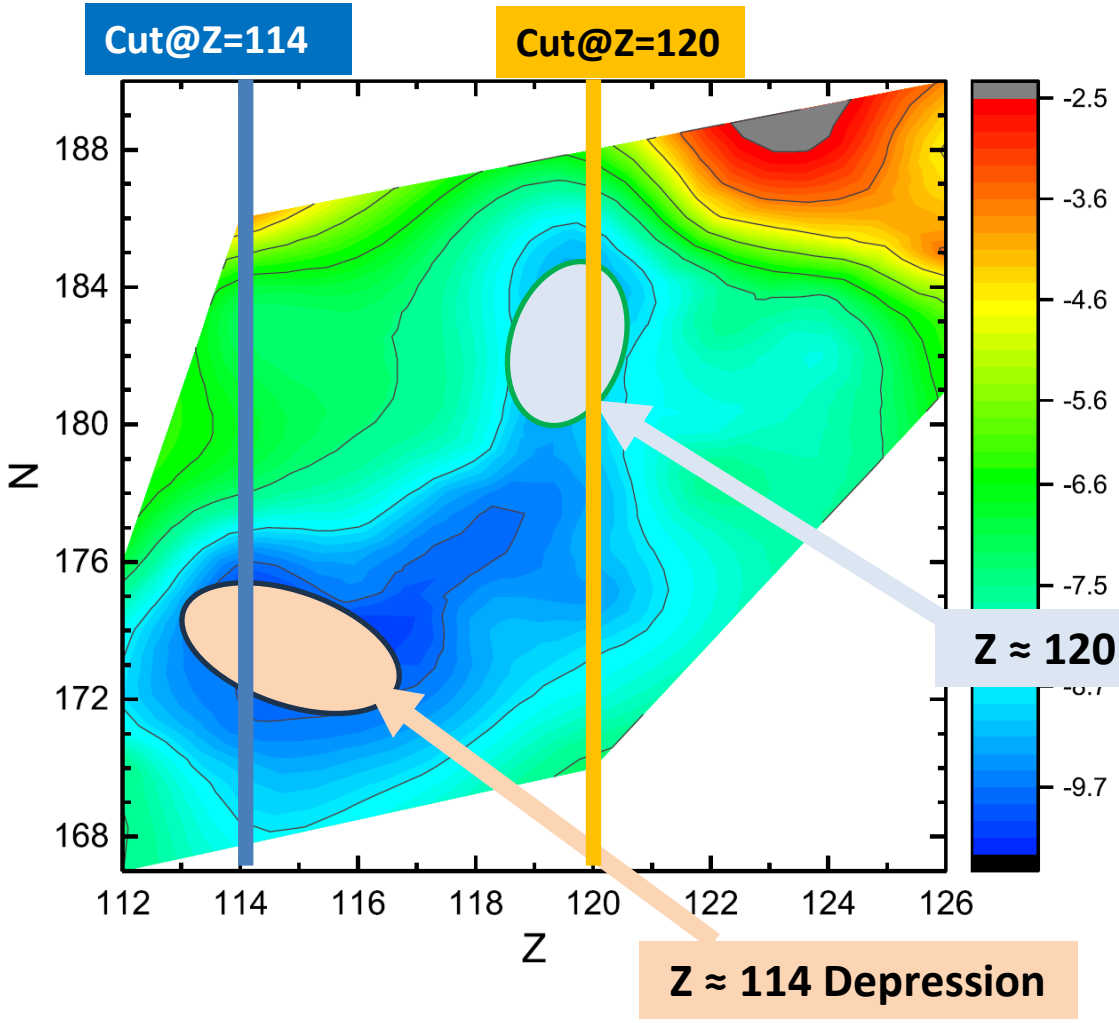
7. **Self-consistent methods for structure and production of heavy and superheavy nuclei**, G.G. Adamian (Dubna, JINR), N.V. Antonenko (Dubna, JINR and Tomsk Polytechnic U.), H. Lenske (Giessen U.), L.A. Malov (Dubna, JINR), Shan-Gui Zhou (Beijing, KITPC and Beijing, GUCAS and Natl. Lab. Heavy Ion Accel., Lanzhou and Hunan Normal U.), DOI: 10.1140/epja/s10050-021-00375-1, Published in: Eur.Phys.J.A 57 (2021) 3, 89

8. **Application of Regge Theory to Astronomical Objects**, Gurgen G. Adamian (Dubna, JINR), Nikolai V. Antonenko (Dubna, JINR), Horst Lenske (Giessen U.), Vazgen V. Sargsyan (Dubna, JINR), e-Print: 2012.14276 [physics.class-ph], DOI: 10.3390/physics3030040, Published in: MDPI Physics 3 (2021) 3, 669-677

The ***Archipelago*** of Stability

Towards Magicity in the Superheavy Region

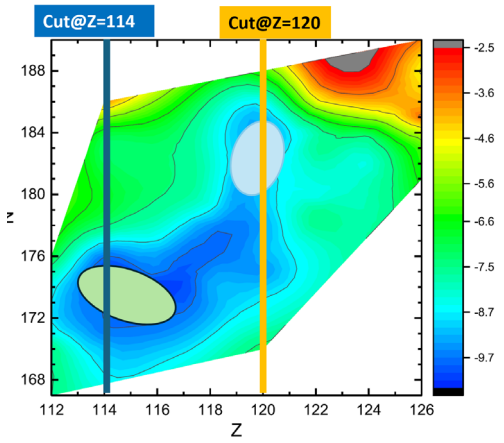
Shell Corrections in the (Z,N)-Plane

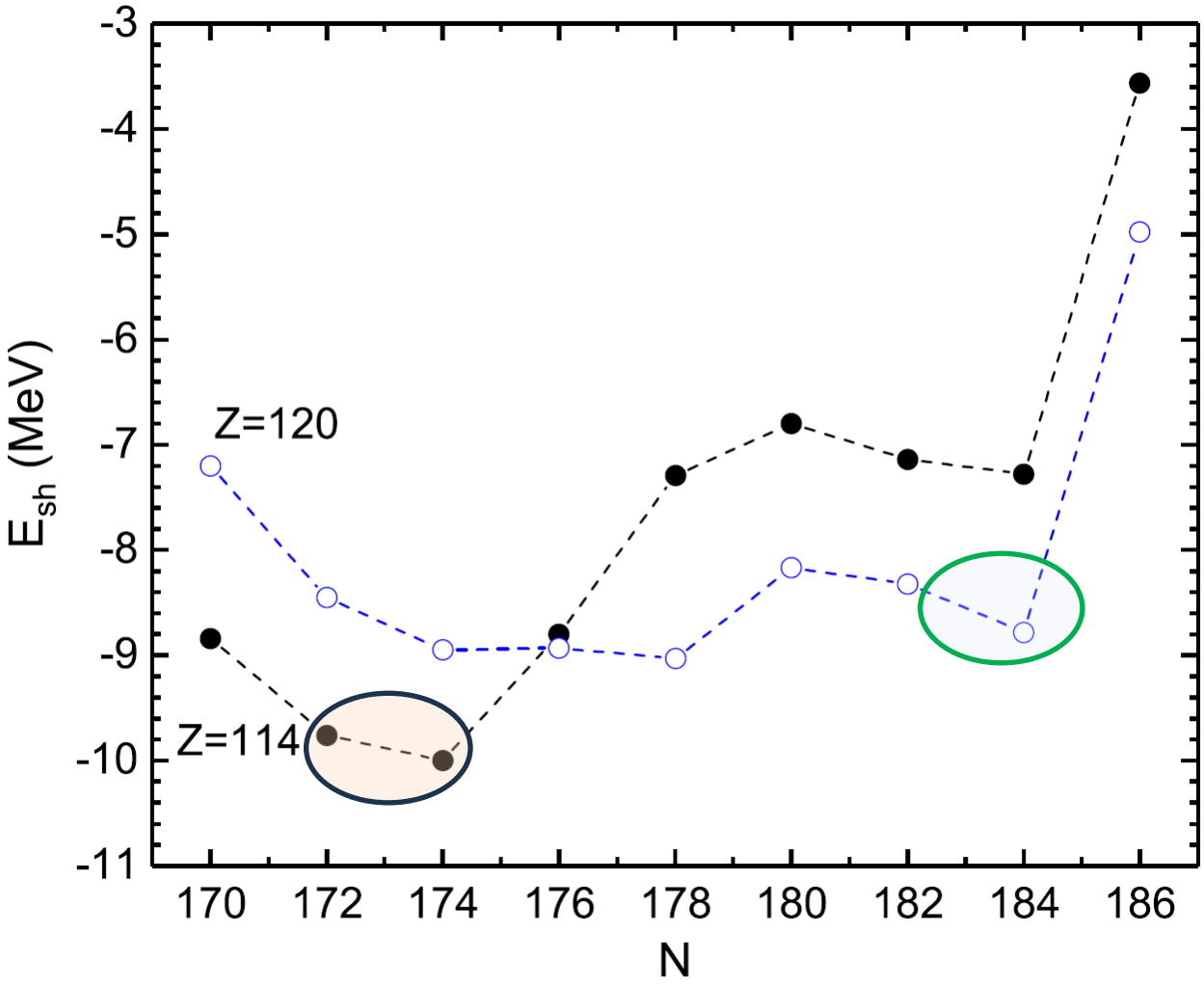


…(blue-ish) ditch extending along $N \approx 1.5Z$, then bending towards the N axis, surrounded by a rather flat and structureless ridge.

PHYS. REV. C **104**, L011304 (2021)
PHYS. REV. C **104**, 064303 (2021)

Nucleodatics of the Archipelago





Conclusion:

Hence, within our approach we conclude that the Fl nuclei at $N \approx 174$ and $Z = 120$ nuclei at $N \approx 184$ will be of double magic structure, implying strong binding and increased stability.

PHYSICAL REVIEW C **104**, L011304 (2021)

Take-Home Message:

- **$^{288}Fl_{174}$ (Z=114) is the next-to-Pb doubly-magic nucleus**
  shell closures: n{1/2⁺[611] and p{3/2⁻[512]}
  chemical homologs of Pb and Sn (group IV of the Periodic Table)

- **$^{304}X_{184}$ (Z=120) is the next-to-next-to-Pb doubly-magic nucleus**
  shell closures: n{3/2⁺[602]} and p{5/2⁻[503]}
  chemical homologs of Ra and Ba (group II of the Periodic Table)

Supported by DFG, grant Le439/16 and
BMBF „Heisenberg-Landau-Program“

Superheavies and Astrophysics:

Eur. Phys. J. A (2023) 59:28

Nucleosynthesis and observation of the heaviest elements

E. M. Holmbeck[1,a], T. M. Sprouse[2,3,b], M. R. Mumpower[2,3,c]

"…In the course of creating the actinides and potentially superheavies, the *r* process must necessarily synthesize superheavy nuclei (those with extreme proton numbers, neutron numbers or both) far from isotopes accessible in the laboratory. Many questions about this process remain unanswered, such as where in nature may this process occur?..."