La taille des noyaux lourds sous la loupe de la spectroscopie laser

Benjamin Bally

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Publication

Article

Smooth trends in fermium charge radii and the impact of shell effects

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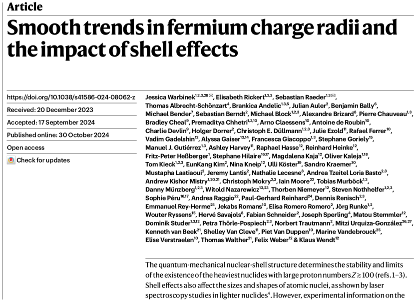
The quantum-mechanical nuclear-shell structure determines the stability and limits of the existence of the heaviest nuclides with large proton numbers $Z \gtrsim 100$ (refs. 1–3). Shell effects also affect the sizes and shapes of atomic nuclei, as shown by laser spectroscopy studies in lighter nuclides[4]. However, experimental information on the

- Article recently published: Warbinek *et al.*, Nature 634, 1075 (2024)



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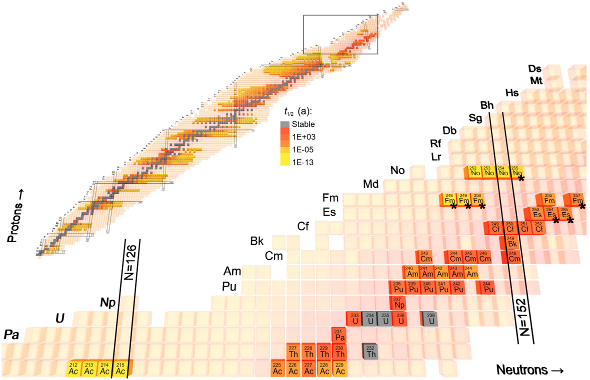
- Contribution from CEA (DRF and DAM)
  - Experimental: M. Vandebrouck, E. Rey-Herme, H. Savajols, N. Lecesne
  - Theoretical: B. Bally, S. Hilaire, S. Péru

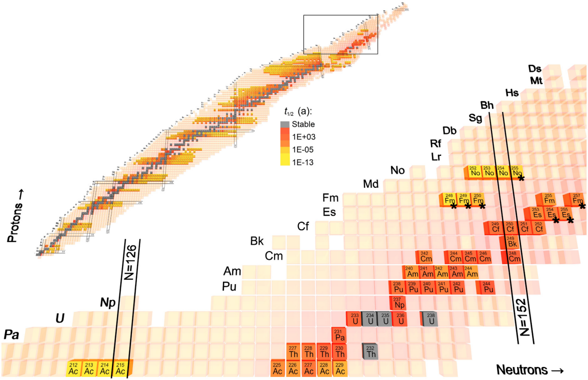
- Major line of research in modern nuclear physics
  - Rich variety of emergent phenomena (deformation, isomerism, fission, etc.)
  - What is the heaviest element in the periodic table?



Block, Prog. Part. Nucl. Phys. 116 (2021)

Context: study of heavy and superheavy atomic nuclei

- Major line of research in modern nuclear physics
  - ◇ Rich variety of emergent phenomena (deformation, isomerism, fission, etc.)
  - ◇ What is the heaviest element in the periodic table?
- Difficulty: production cross sections are small



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- Experimental techniques:
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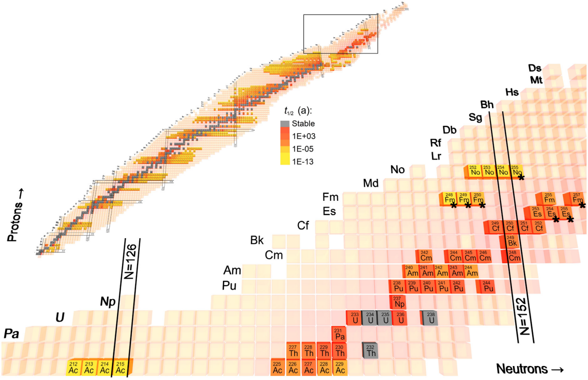
  - Laser spectroscopy
  - . . .



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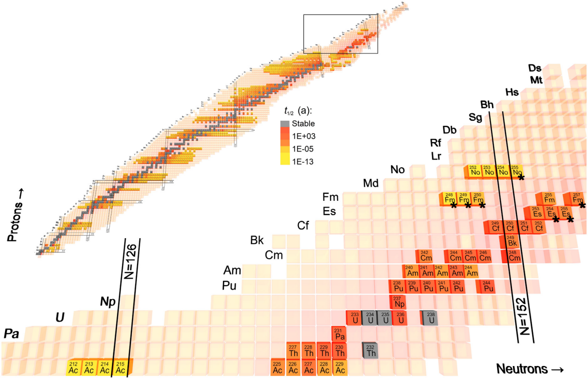
Context: study of heavy and superheavy atomic nuclei

- Experimental techniques:
  - Decay spectroscopy
  - Laser spectroscopy
  - ...
- Laser spectroscopy: expertise of the RADRIS collaboration at GSI



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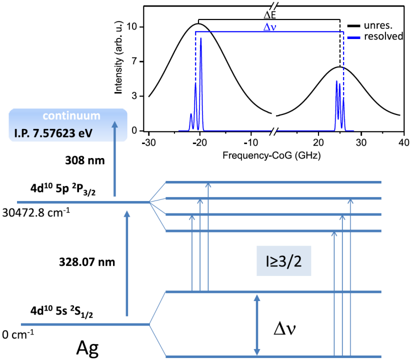
  - Two-steps ionization scheme
  - Scan of transition λ_1
  - Count the number of ions as a function of the frequency λ_1



Ferrer, PLB 728, 191 (2014)

Laser spectroscopy

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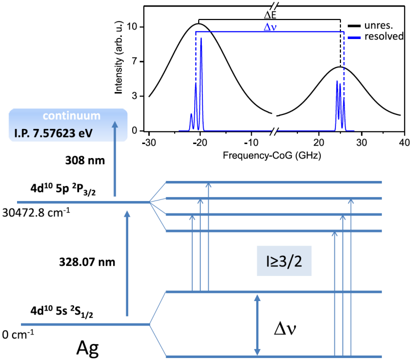

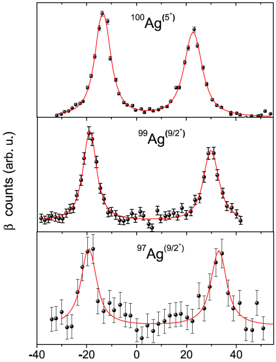

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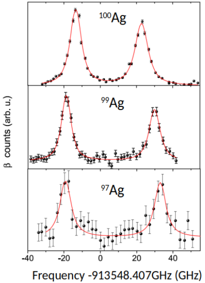
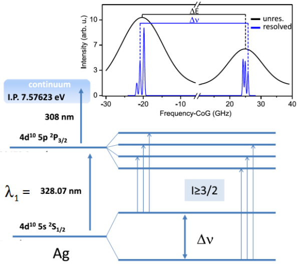


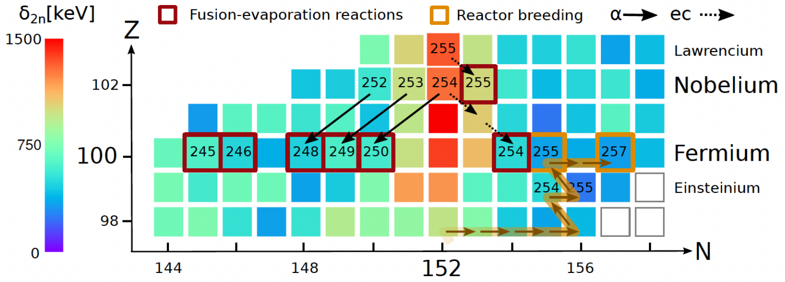


Que mesure-t-on ? — Décalage isotopique/isomérique — Structure hyperfine

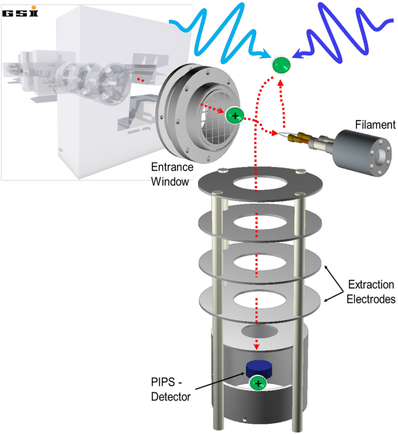
Que déduit-on ?
(indépendamment des modèles nucléaires) — Rayon de charge — Moment E quadrupolaire — Moment M dipolaire — Spins

Que déduit-on ?
(dépendant des modèles nucléaires) — Forme/Paramètre de déformation — Configuration orbitales particules individuelles

- Combination of several production methods:
  - Direct fusion-evaporation: ^{208}Pb(^{40}Ar,2-3n)^{245,246}Fm
  - Indirect fusion-evaporation: ^{206,207,208}Pb(^{48}Ca,2n)^{252,253,254}No
  - Re-irradiation of samples collected in nuclear reactor: ^{255,257}Fm



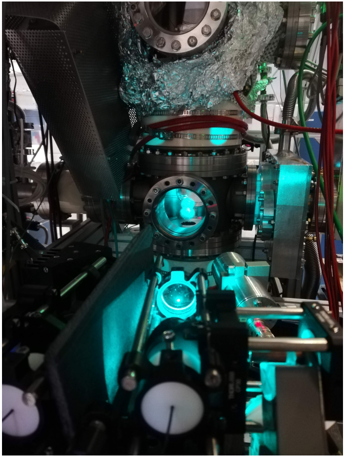
Laser spectroscopy: the RADRIS method

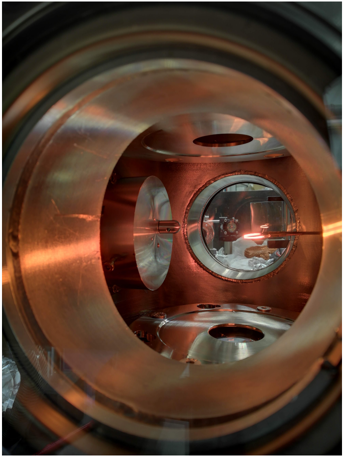


Courtesy of S. Raeder

- Laser spectroscopy of 8 isotopes thanks to the RADRIS technique

Experimental setup





Courtesy of A. Raggio and J. Warbinek

Shell closures and magic numbers

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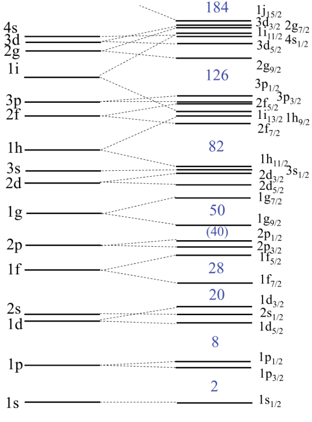

Hagino, Found. Chem. 22, 267 (2020)

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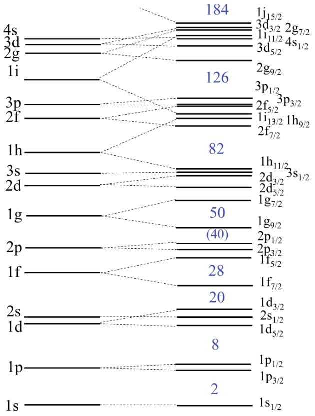

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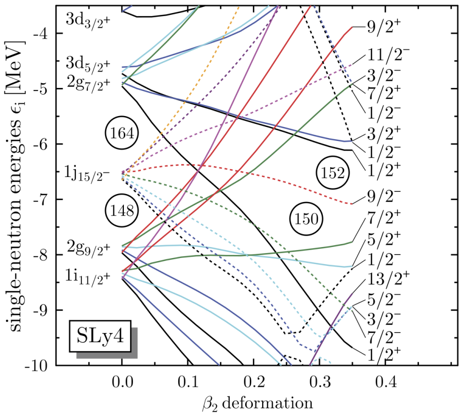
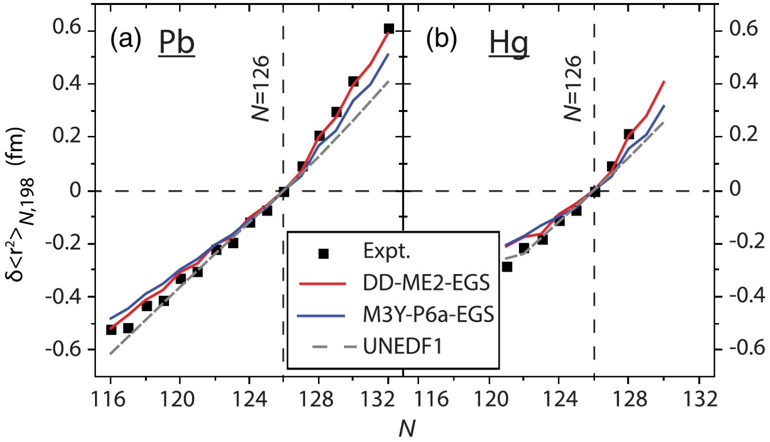


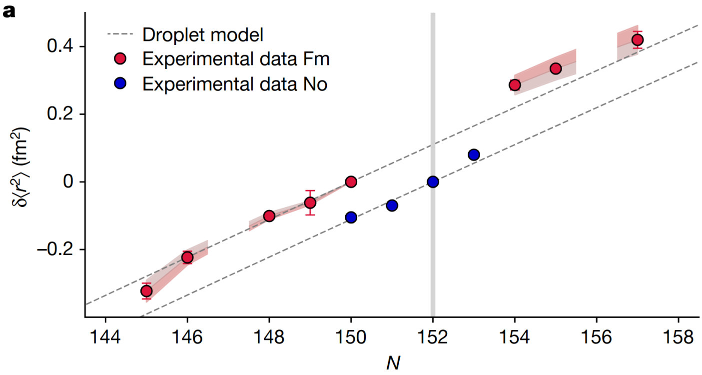
Dobaczewski, Nucl. Phys. A, 388 (2015)

"Kink" in change in $\langle r^2 \rangle$



Day Goodacre, PRL 126, 032502 (2021)

Experimental results for Fm and No isotopes



- Slight increase but no clear “kink” contrary to lighter nuclei
- Good agreement with simple liquid drop model: $r \propto A^{1/3}$

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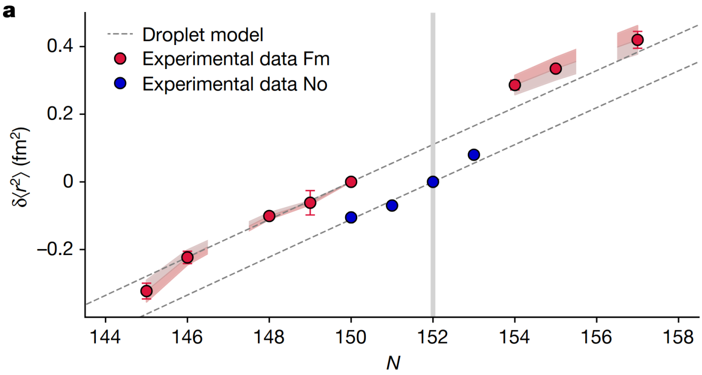

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→ Towards a more **macroscopic** behavior of nuclear matter?

Theoretical analysis: microscopic models

- Phenomenological interactions (Skyrme, Gogny, Fayans)

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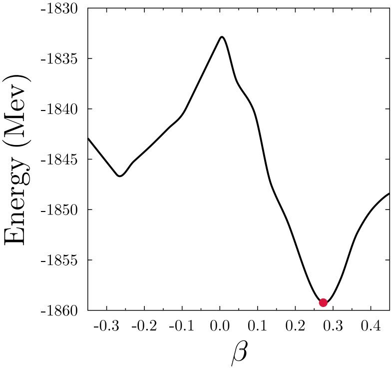
  ≡ "Mean field", "Hartree-Fock-Bogoliubov"

$$\delta\langle\Phi|H_{\text{eff}}|\Phi\rangle = 0$$

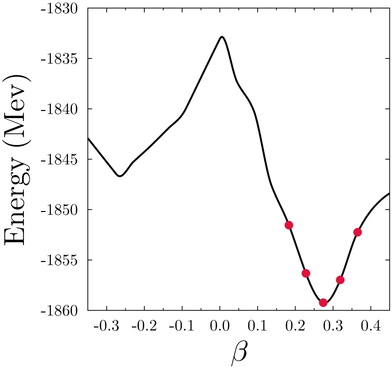


Theoretical analysis: microscopic models

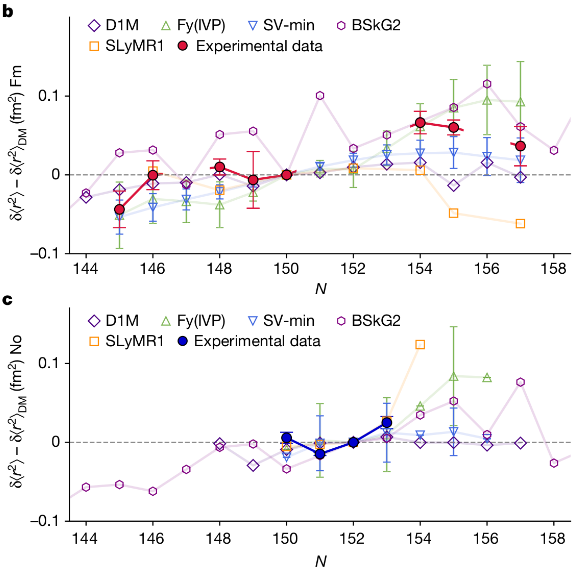
- Phenomenological interactions (Skyrme)
- **Multi-Reference** Energy Density Functional (MR-EDF)
  ≡ "Beyond the mean field", "Generator Coordinate Method"

$$|\Psi^{\Lambda}\rangle = \sum_k f_k P^{\Lambda} |\Phi_k\rangle$$

$$\delta \langle \Psi^{\Lambda} | H_{\text{eff}} | \Psi^{\Lambda} \rangle = 0$$

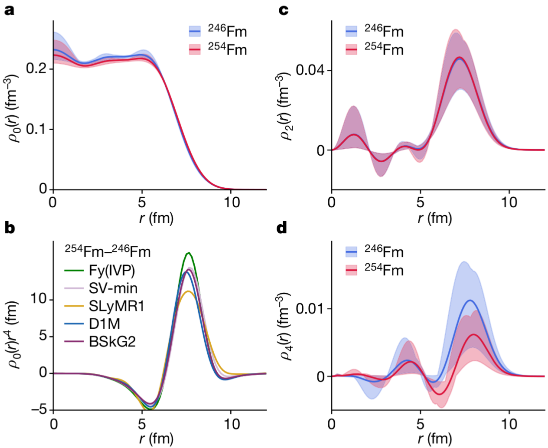


Theoretical analysis: comparison with experiment



$$\frac{\Delta r^2 = 0.1}{r^2 = 36} \approx 0.3\%$$

Theoretical analysis: proton densities



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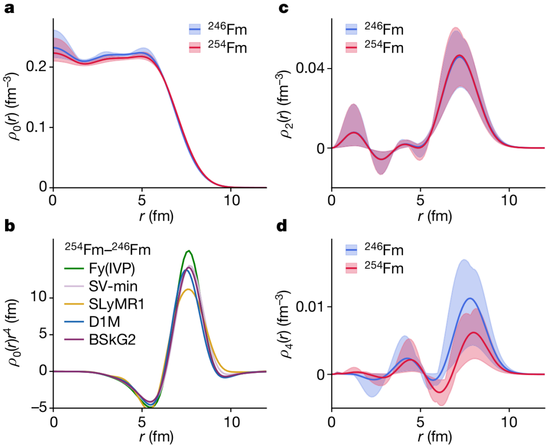

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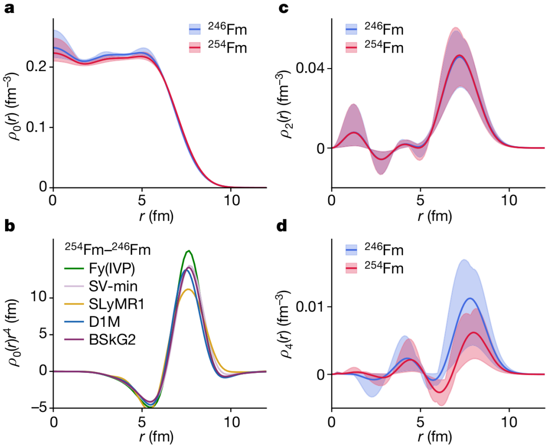

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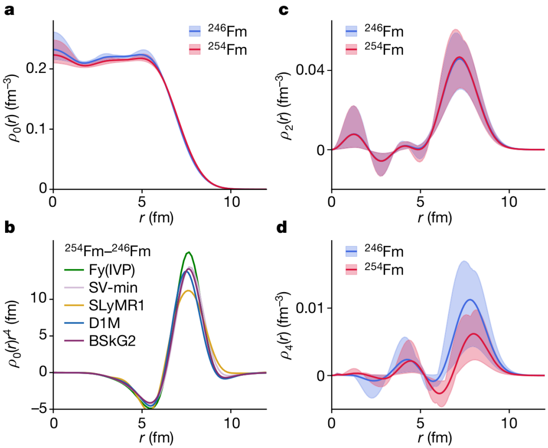

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- Different hexadecapolar deformations [$\rho_4(r) = \int \rho_p(\mathbf{r})\, Y_{40}(\Omega)\, d\Omega$]

Conclusion and outlook

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  - ◇ Moments: dipole magnetic (μ) and quadrupole electric (Q_S) of odd-mass nuclei
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