New proposal: Absolute charge radii for laser spectroscopy

Michael Heines, Thomas E. Cocolios

Outline

- Background: laser spectroscopy
- Benchmarking with absolute charge radii
- Potassium as a first physics case
- Beyond potassium

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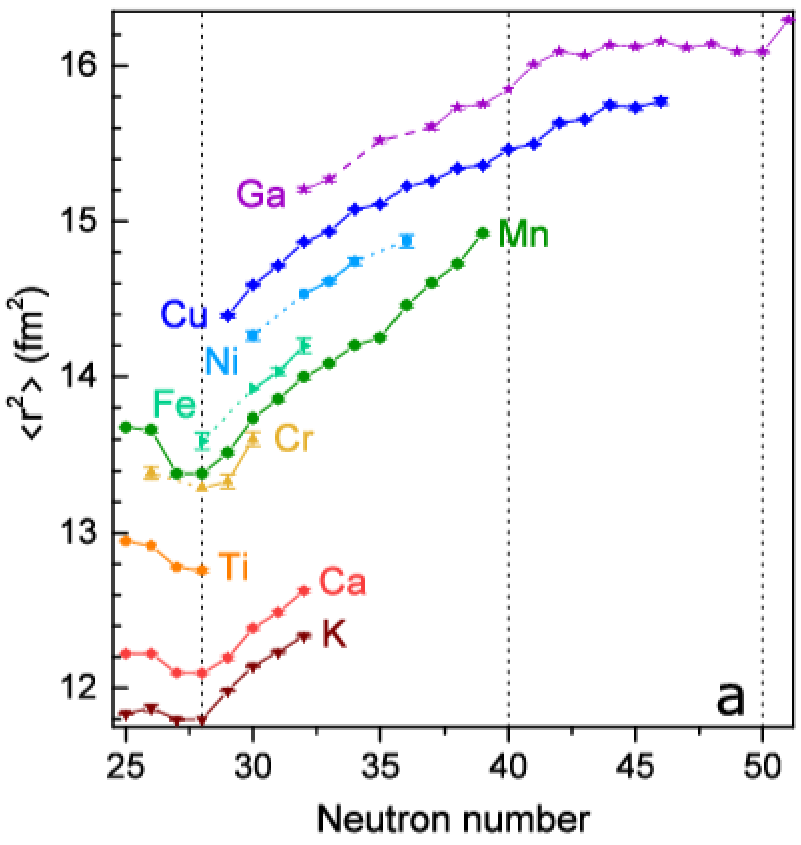
Importance of Charge Radii

- Sensitive probe for nuclear models → Input for theory
- Behavior near magic numbers (also far from stability)
- Other Research interests:
  - Shape staggering
  - Halo nuclei
  - …



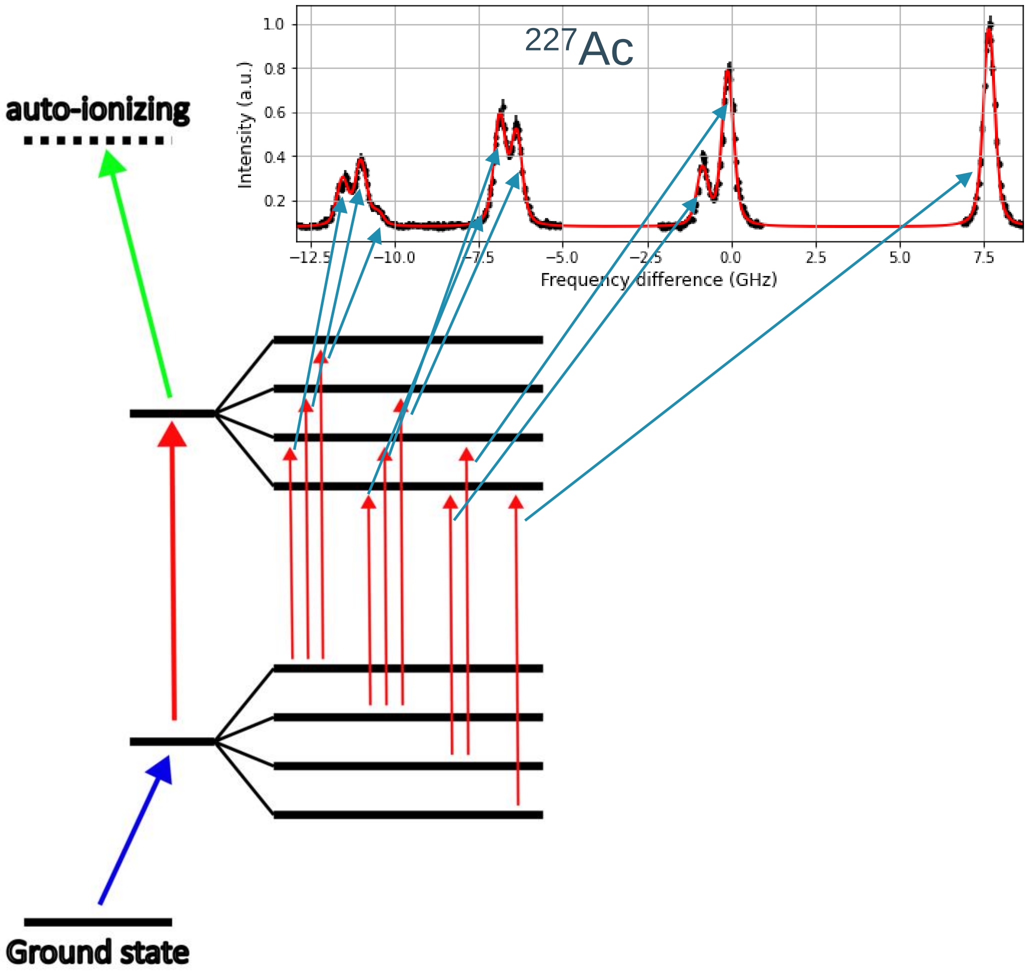
- Neugart, Rainer, et al. "Collinear laser spectroscopy at ISOLDE: new methods and highlights." *Journal of Physics G: Nuclear and Particle Physics* 44.6 (2017): 064002.

Laser Spectroscopy for Nuclear Structure

- Probe electronic hyperfine structure
  → info about the nucleus

- Extract
  - Isotope shift
  - A, B hyperfine parameters

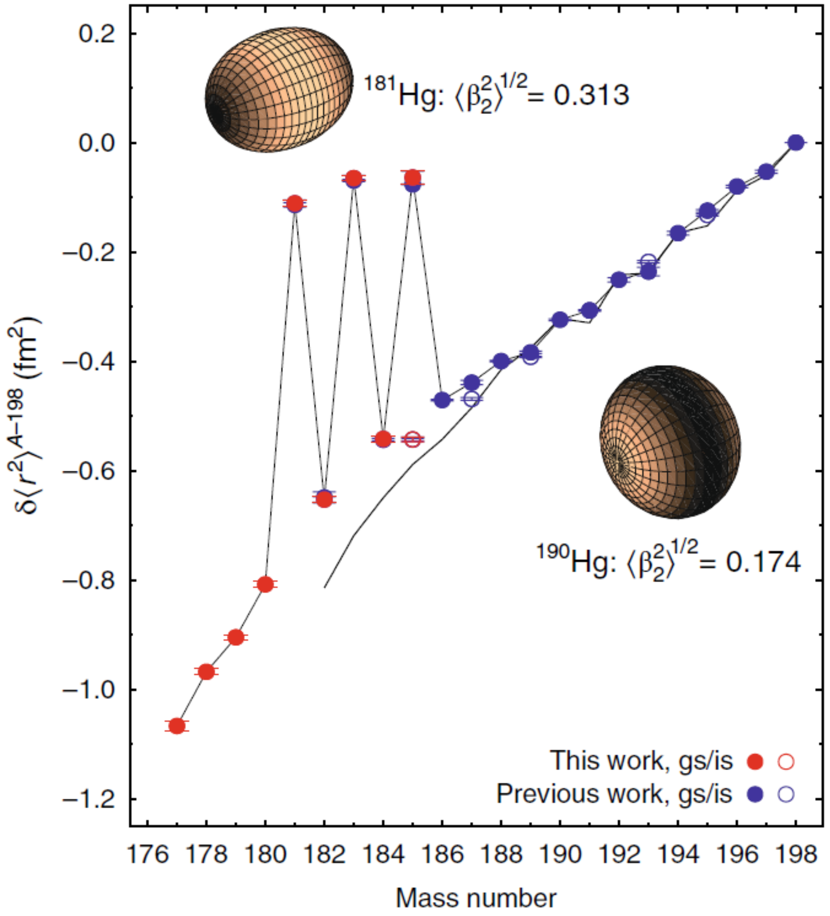
- Determine
  - Charge radius
  - Electric quadrupole moment



Current limits of laser spectroscopy

- Production rate:
    - Collinear: couple per second
    - In source: couple per hour
    - Superheavy: couple per day

- Mainly limited by background rate and systematics in region of interest

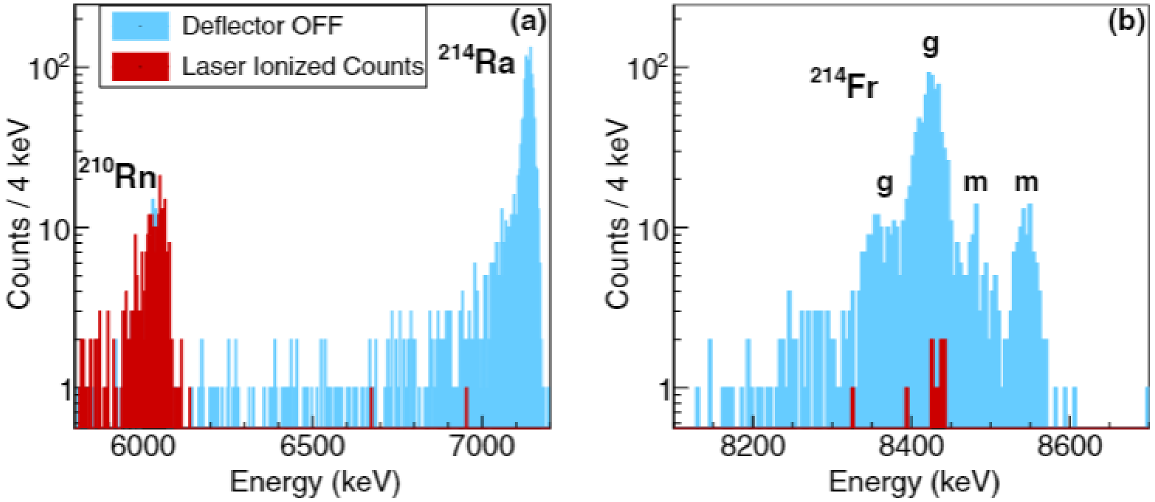


- Marsh, B. A., et al. "Characterization of the shape-staggering effect in mercury nuclei." *Nature Physics* 14.12 (2018): 1163-1167.

Current limits of laser spectroscopy

- Half-life:
  - Collinear: ~ 5ms
  - In source: ~couple 100's μs
  - Superheavy: ~100ms

- Limited by time needed to come out of the ion source



- Farooq-Smith, Gregory James. *Exploring the magical tenacity of doubly closed-core nuclei with gallium and francium isotopes*. Diss. Ph. D. thesis, KU Leuven, 2019.

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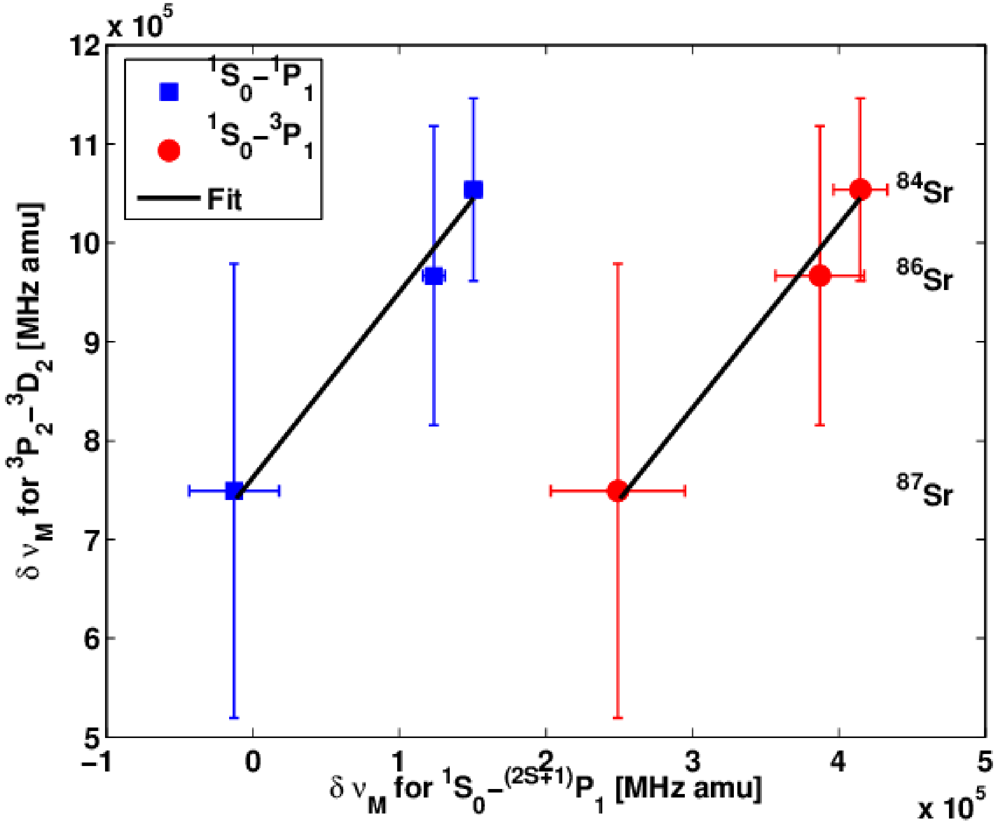
From isotope shift to radii

$$\delta < r^2 >^{A,A'} = \frac{1}{F_i}\left(\delta\nu_i^{A,A'} - \frac{A - A'}{A\,A'} M_i\right)$$

- Mass shift: M_i
  - Normal mass shift (easy)
  - Specific mass shift (very hard)

- Field shift: F_i

- Different for each element & transition!



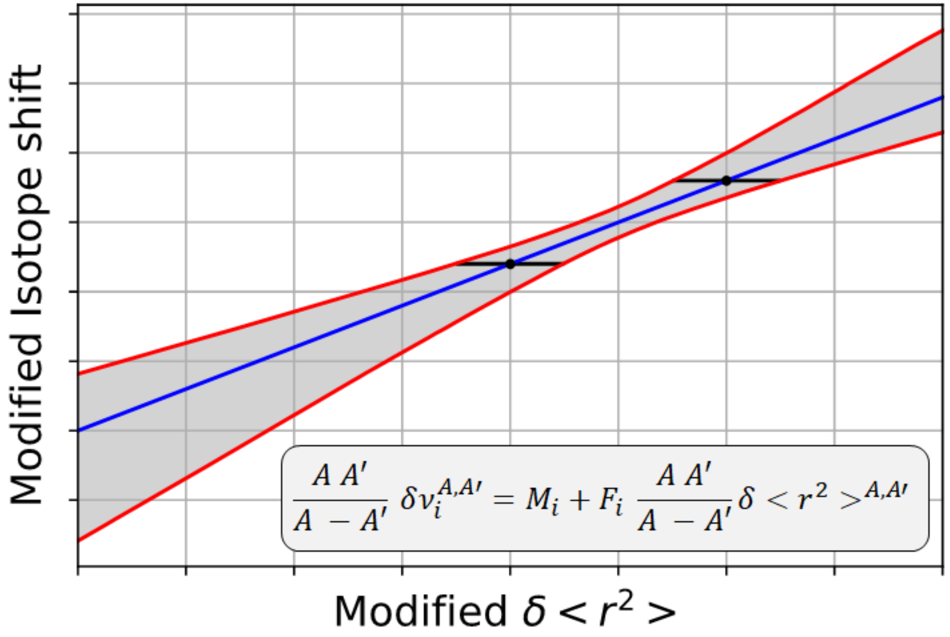
- Mickelson, P. G., et al. "Repumping and spectroscopy of laser-cooled Sr atoms using the (5s5p) 3P2–(5s4d) 3D2 transition." *Journal of Physics B: Atomic, Molecular and Optical Physics* 42.23 (2009): 235001.

Benchmarking with absolute charge radii

$$\frac{A - A'}{A\,A'}\,\delta\nu_i^{A,A'} = M_i + F_i\,\frac{A - A'}{A\,A'}\,\delta < r^2 >^{A,A'}$$

- Mass shift: intercept
- Field shift: slope

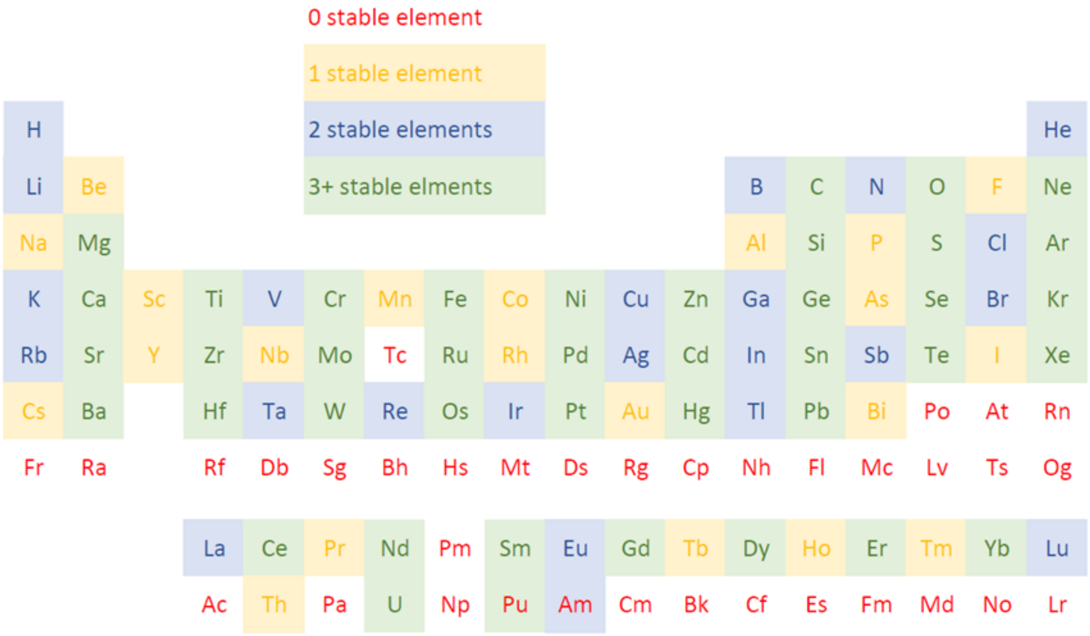
- Absolute charge radii
  - One → Absolute values
  - Two → $\frac{M_i}{F_i}$
  - Three → M_i and F_i



Benchmarking with absolute charge radii

- Charge radius: M_i and F_i
- Quadrupole moments: extracted from ratio of b parameters

- Odd-Z nuclei → No stable benchmark triplets



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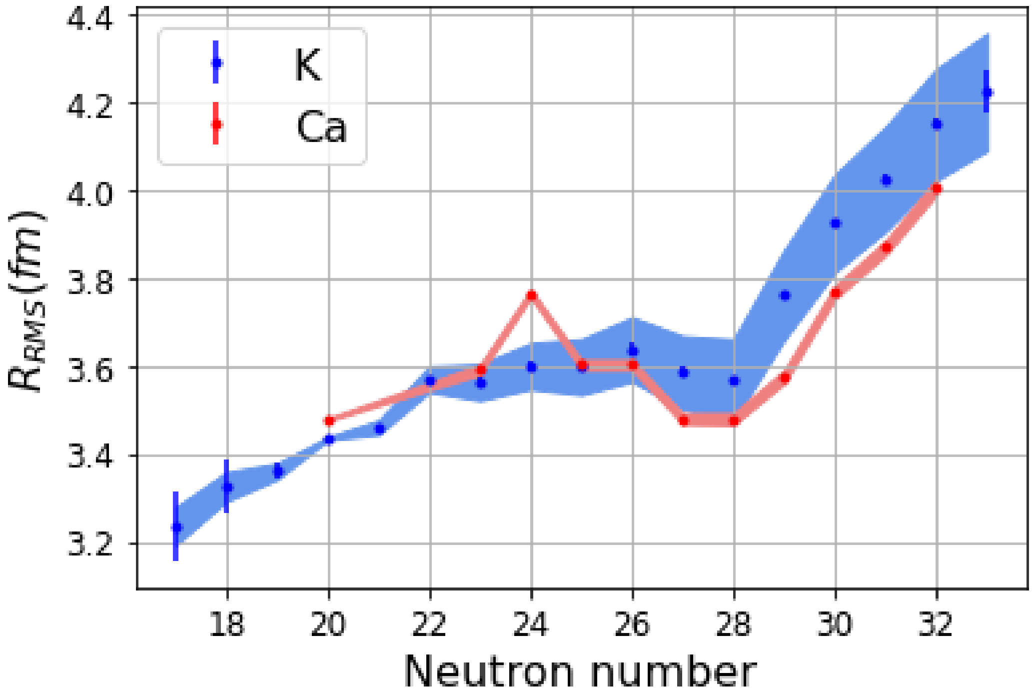
The potassium case

- Z = 19, main interest at N=20, 28, 32
- Charge radii dominated by systematics
- Stable isotopes: K-39 & K-41
- Long lived: K-40
  - Best enrichment ~15%
  - Needed > 95%

→ Implanted K-40 targets produced in LIS (being refurbished)



- Garcia Ruiz, Ronald Fernando, et al. "Unexpectedly large charge radii of neutron-rich calcium isotopes." *Nature Physics* 12.6 (2016): 594-598.
- Koszorús, Á., et al. "Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of N= 32." *Nature Physics* 17.4 (2021): 439-443.

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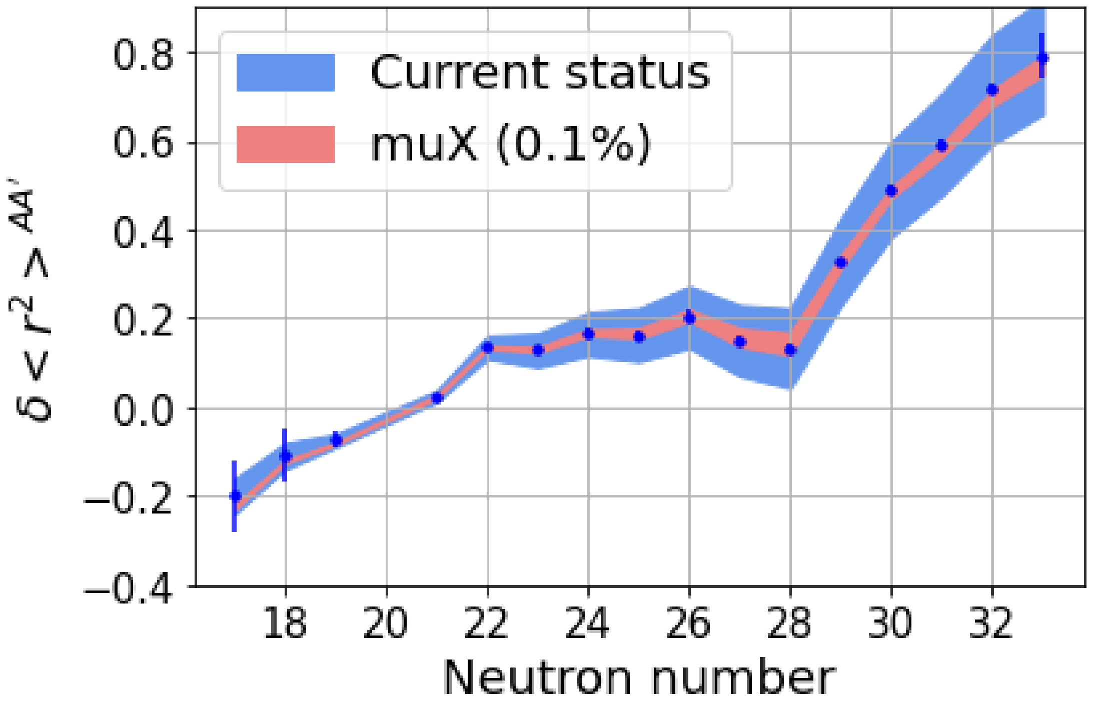

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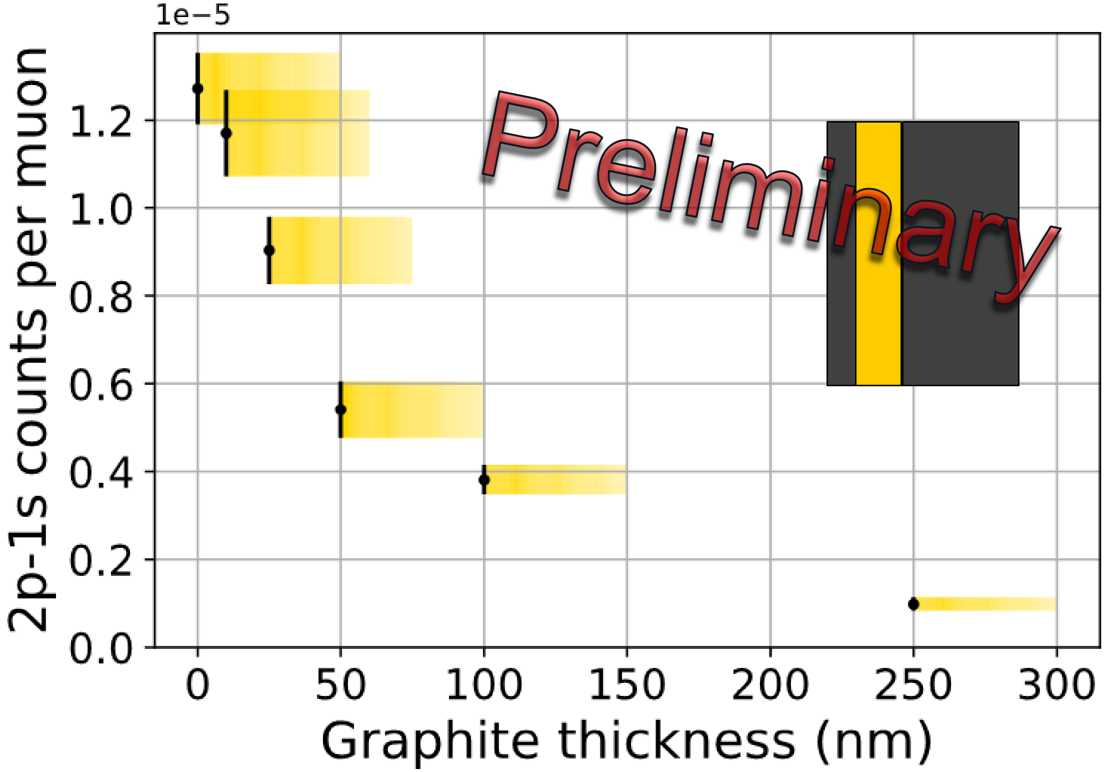
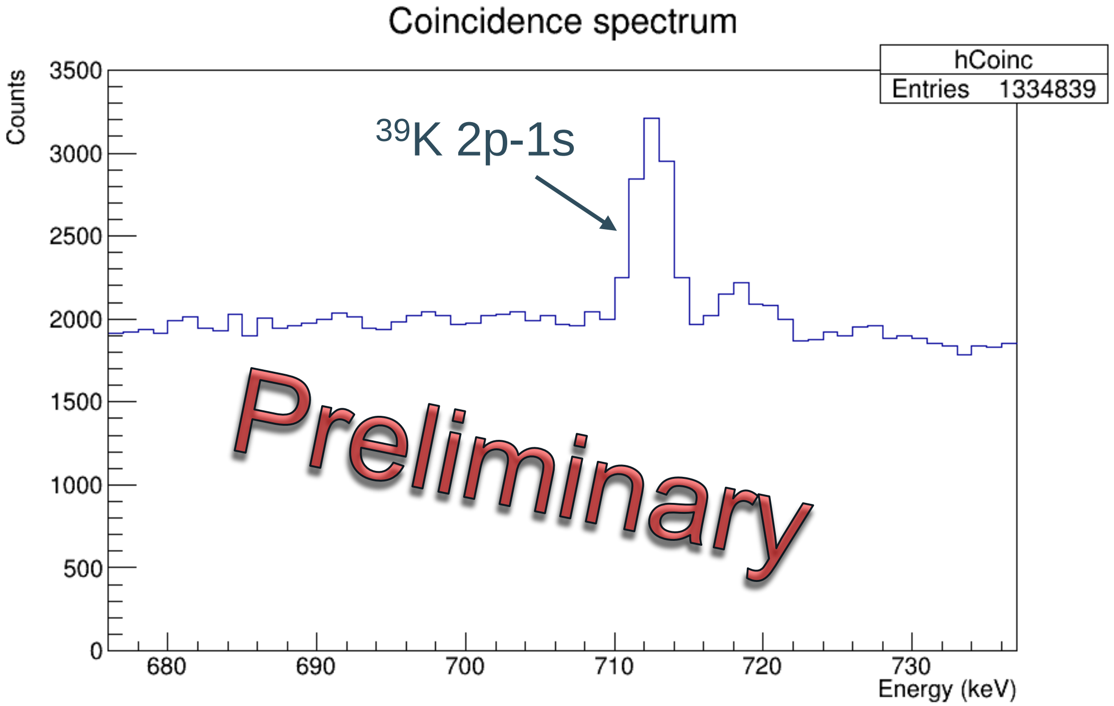
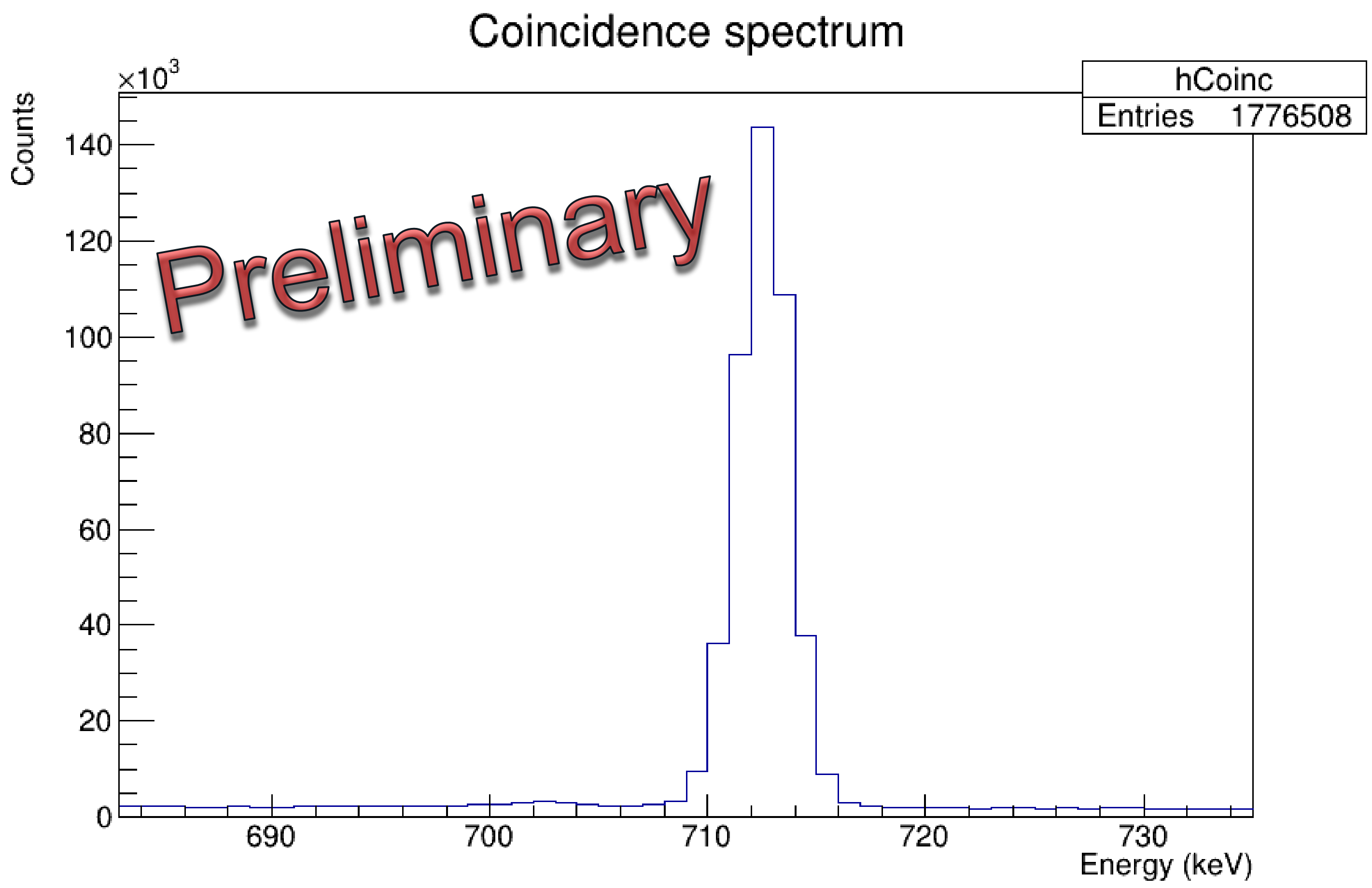
Feasibility



- ^{39}K implanted → Possible with ^{40}K



Natural potassium salt



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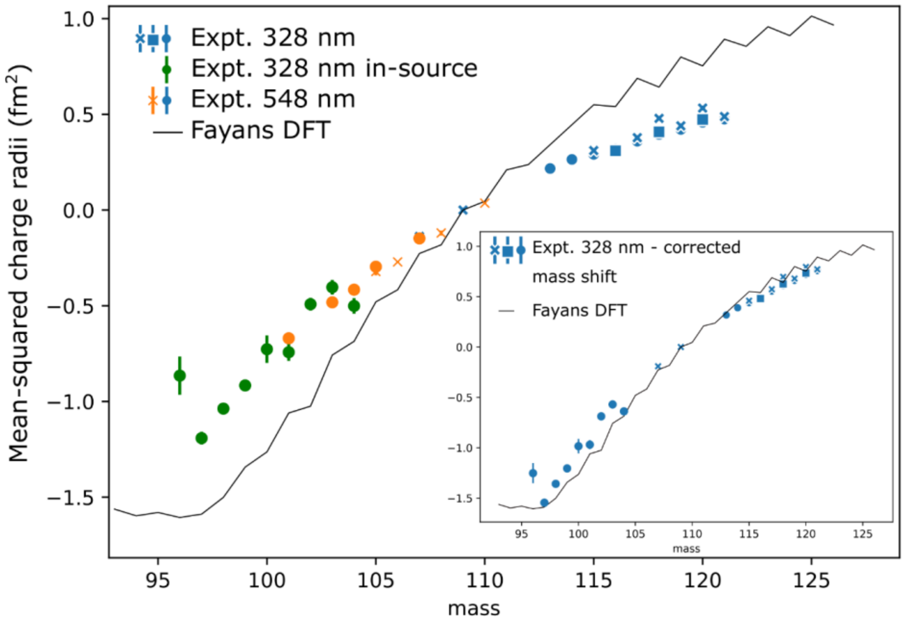
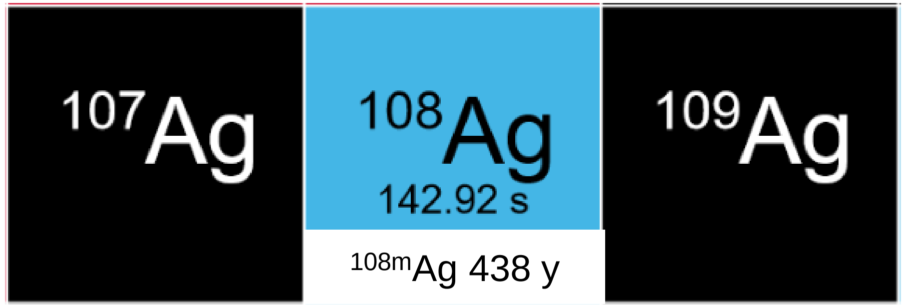
Supporting existing laser programmes: $_{47}$Ag

- Existing data from multiple sources from ^{96}Ag to ^{119}Ag, using different transitions, and not in agreement with each other.
- CRIS running a campaign from ^{98}Ag to ^{129}Ag$_{82}$, with some data already collected from ^{109}Ag to ^{123}Ag
- Jyvaskyla is planning a campaign down to ^{94}Ag, which high-spin isomer is the subject of controversial claims of 2p emission

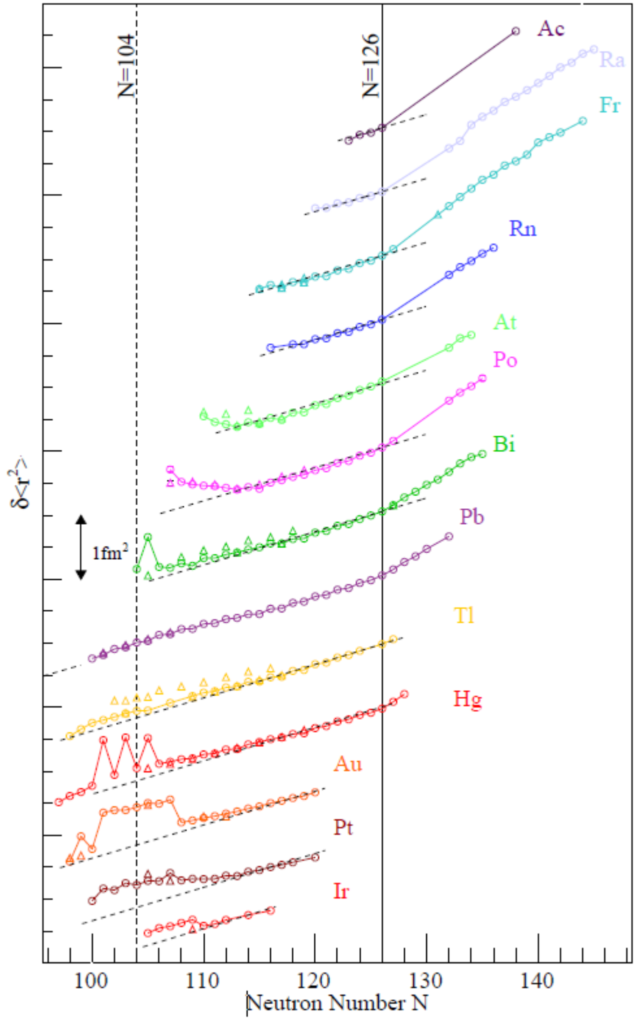
- To complement the stable ^{107}Ag and ^{109}Ag, I propose to measure ^{108m}Ag ($T_{1/2}$=438 years).
- Produced at ILL from ^{107}Ag(n,γ)^{108m}Ag, followed by mass separation at CERN

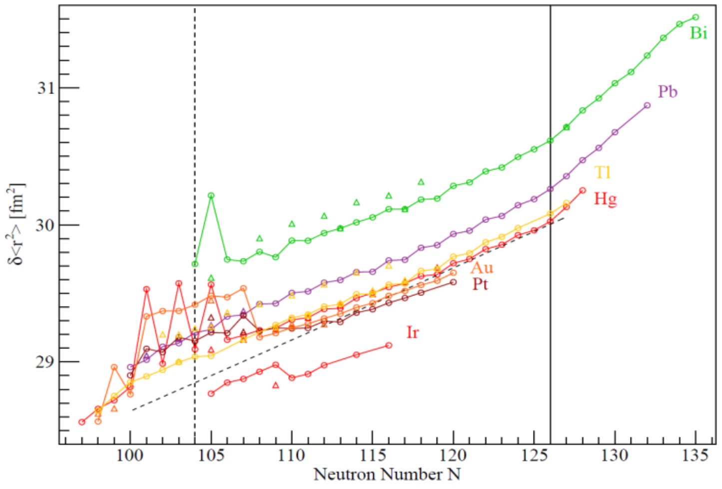




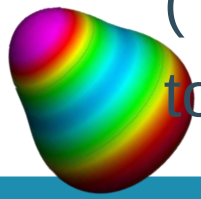
Supporting existing laser programmes: $_{84}$Po and $_{89}$Ac

- There is no anchoring point beyond $_{83}$Bi, besides $_{90}$Th and $_{92}$U, and soon $_{88}$Ra and $_{96}$Cm.
- There is an extensive programme into laser spectroscopy for elements with Z>82 with recent data on $_{84}$Po and $_{89}$Ac.





- muX could investigate ^{209}Po ($T_{1/2}$=127 y) and ^{227}Ac ($T_{1/2}$=22 y) to provide anchoring points.



- Thomas Elias Cocolios, “A new perspective on charge radii around Z=82.” *Hyperfine Interactions* **238** (2017) 16.

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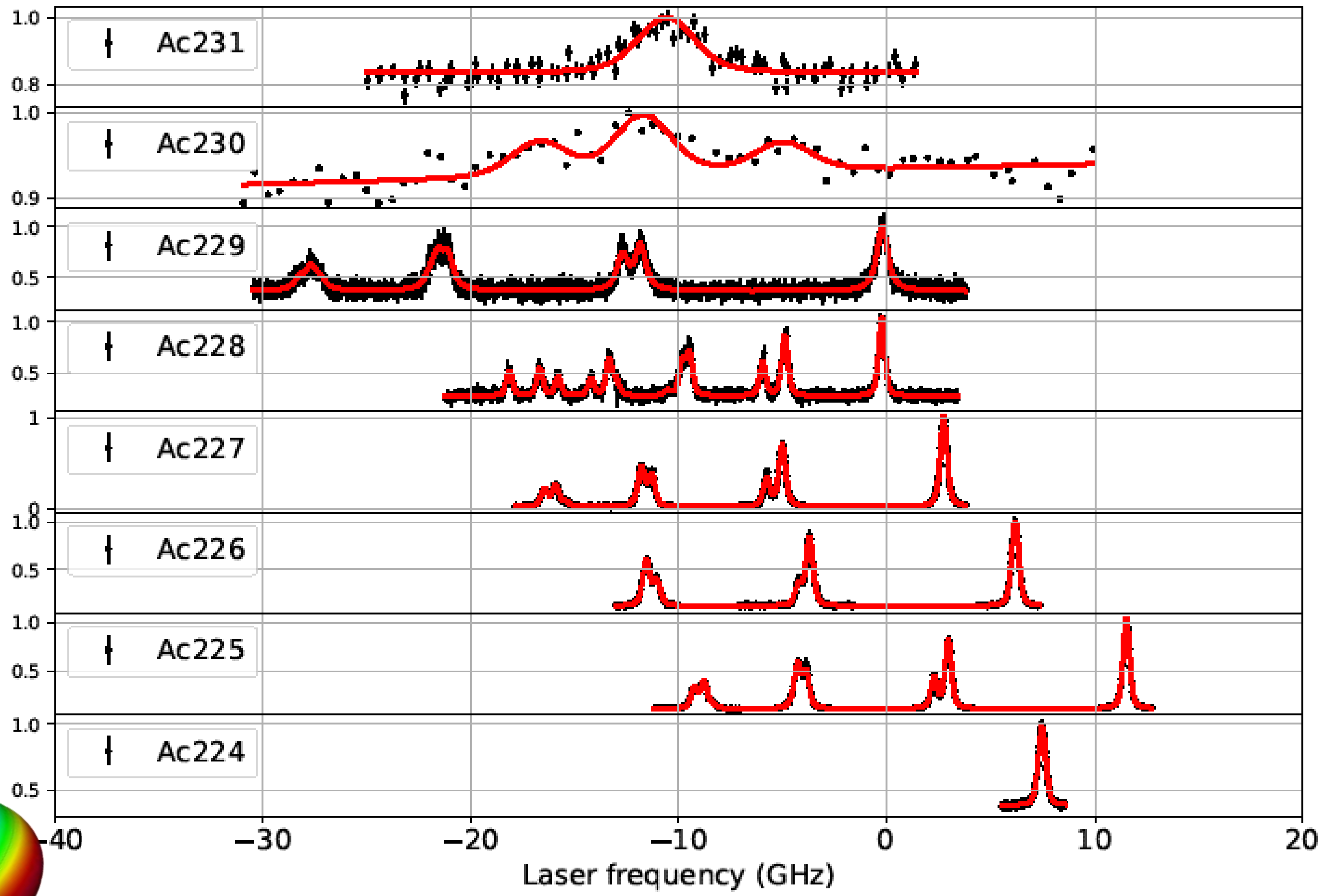
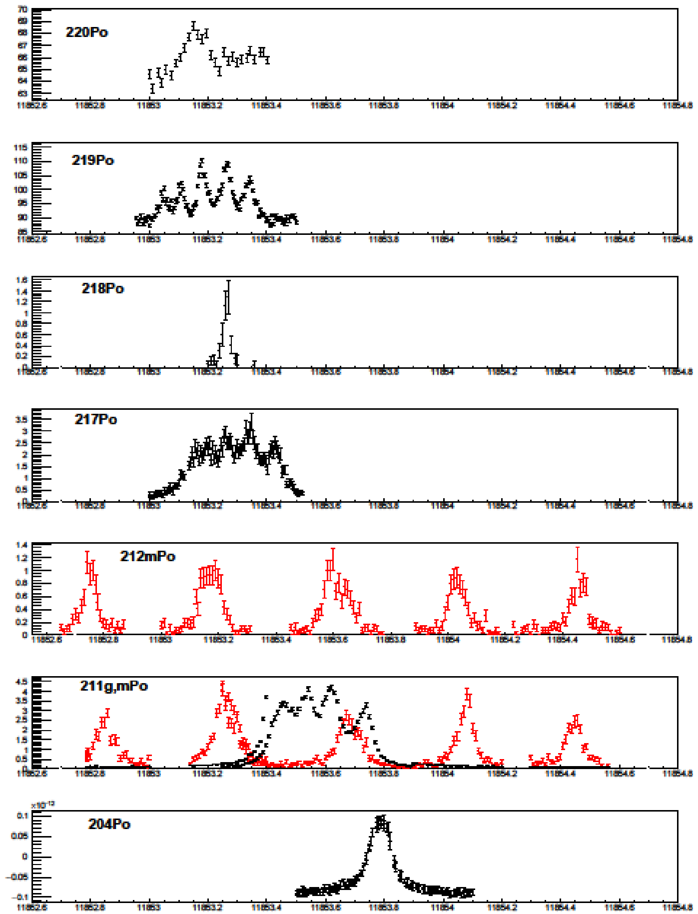
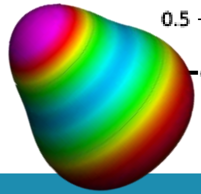
Supporting existing laser programmes: $_{84}$Po and $_{89}$Ac

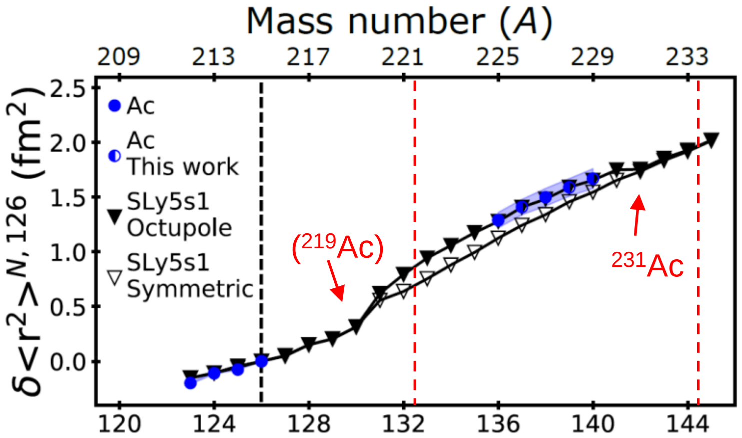


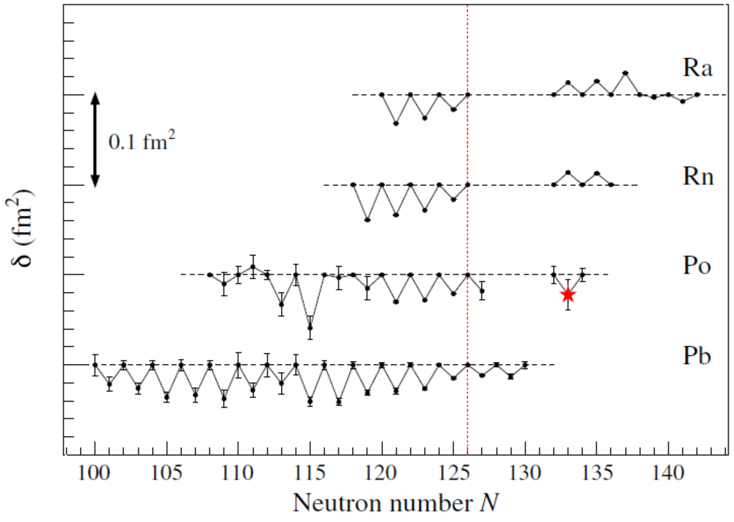




Supporting existing laser programmes: $_{84}$Po and $_{89}$Ac

- The interest in this region is to explore the octupole deformation in that region through the charge radii.
- This helps identifying which isotope is suited for search for physics beyond the standard model, where symmetry-breaking effects would be enhanced.

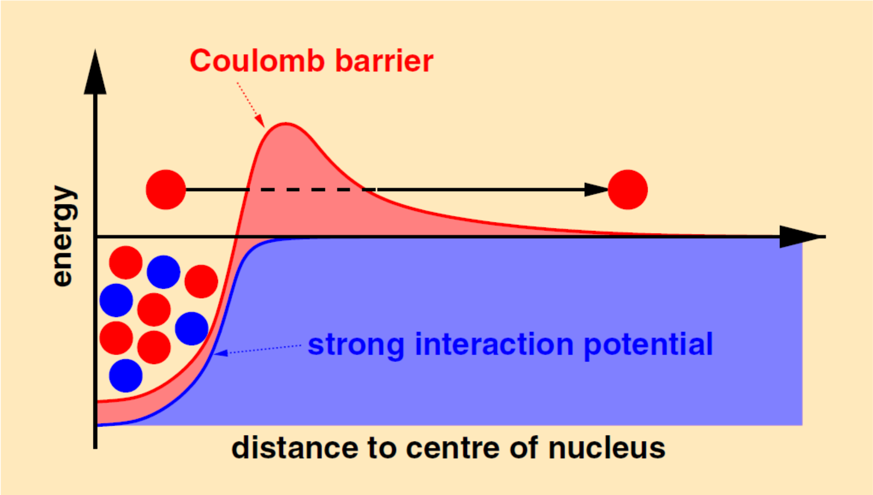




- Elise Verstraelen et al., “Search for octupole-deformed actinium isotopes using resonance ionization spectroscopy.” *Physical Review C* **100** (2019) 044321.
- Daniel Fink et al., “In-Source Laser Spectroscopy with the Laser Ion Source and Trap: First direct study of the ground-state properties of $^{217;219}$Po”, *Physical Review X* **5** (2015) 011018.

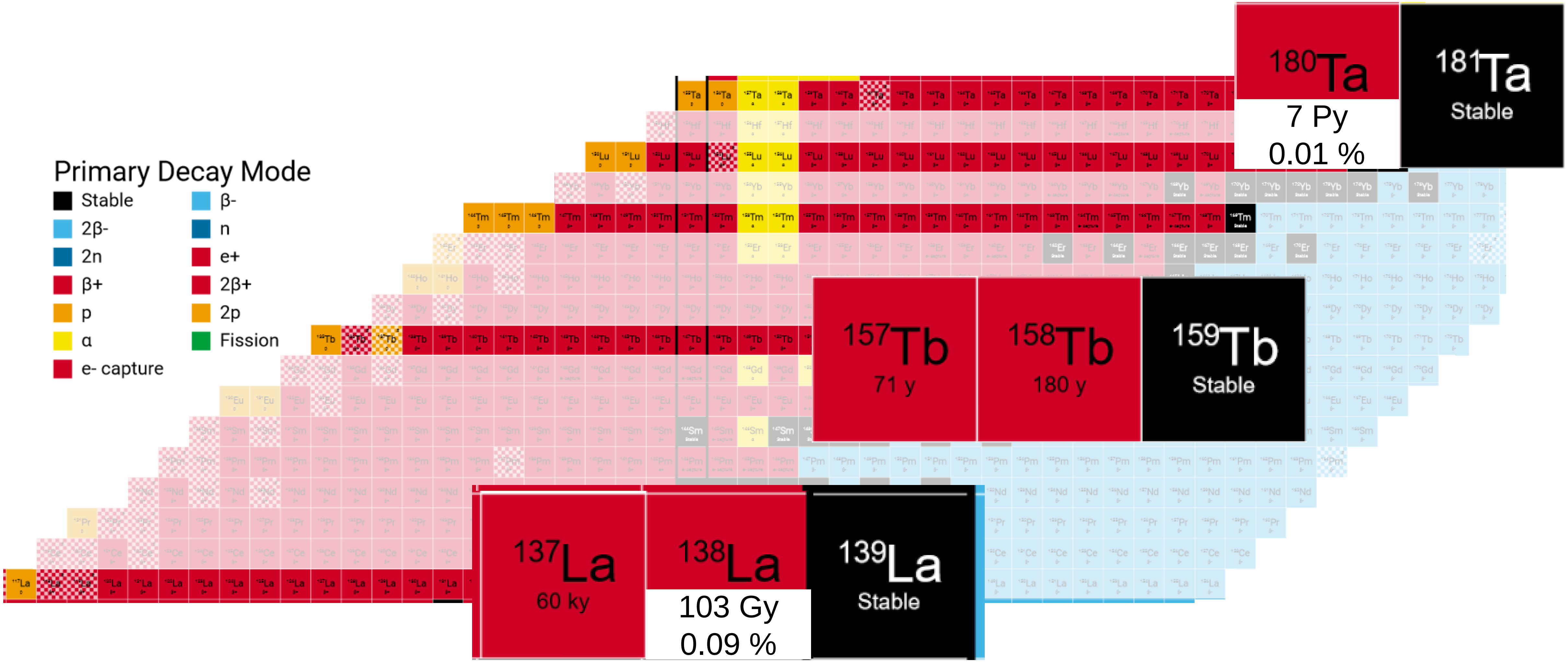
Proton-unbound nuclei

- At the edge of the nuclear landscape
- Last proton no longer bound by the strong force, but by the Coulomb barrier generated by the other protons
- Proton is 'elementary' for nuclear physics and thus provides direct structure information
- Knowledge limited to decay energies, branchings and half-lives.



- Laser spectroscopy to probe shape and spread of wavefunction of unbound proton

Laser spectroscopy of rare-earth elements



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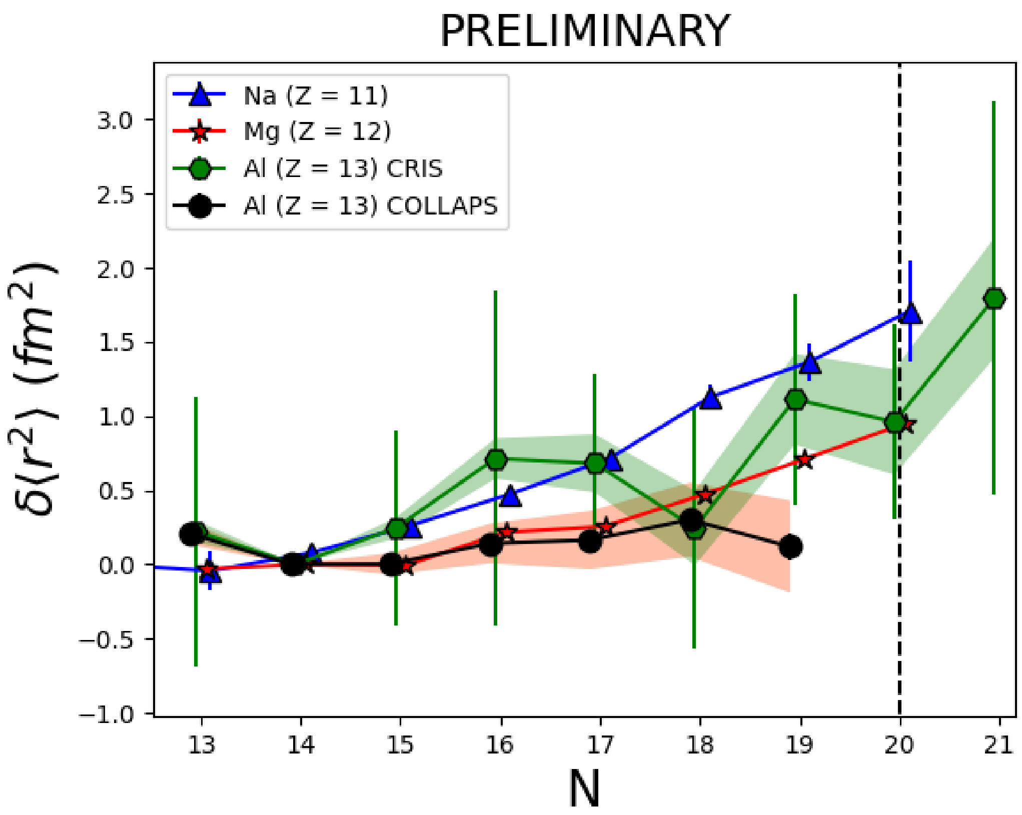
^{26}Al

- Recent campaign on neutron-rich Al at CRIS, showing discrepancy against COLLAPS data
  - Having 2 radii would give $\frac{M_i}{F_i}$
- ^{26m}Al ($T_{1/2}$=6.35s) contributes to V_{ud} estimates to check the unitarity of the Cabibbo-Kobayashi-Maskawa matrix.
  - The uncertainty on the charge radius is one of the main contributions to the uncertainty
  - Having $<r^2>^{26g}$ removes the source of uncertainty on the mass shift



muX for lasers: timeline

- Phase 0: feasibility test
  - ✓2022: implanted targets work, K is possible
- Phase 1: FWO NSHAPE
  - ➢2023: $^{39,40,41}K$, (^{107}Ag, ^{nat}Ag)
  - ➢2024: $^{107,108m,109}Ag$
  - o FWO proposal ^{26}Al (to be submitted in 2023)

Research Foundation Flanders
Opening new horizons

- o Phase 2: Rare-earth elements
- o Phase 3: Alpha emitters

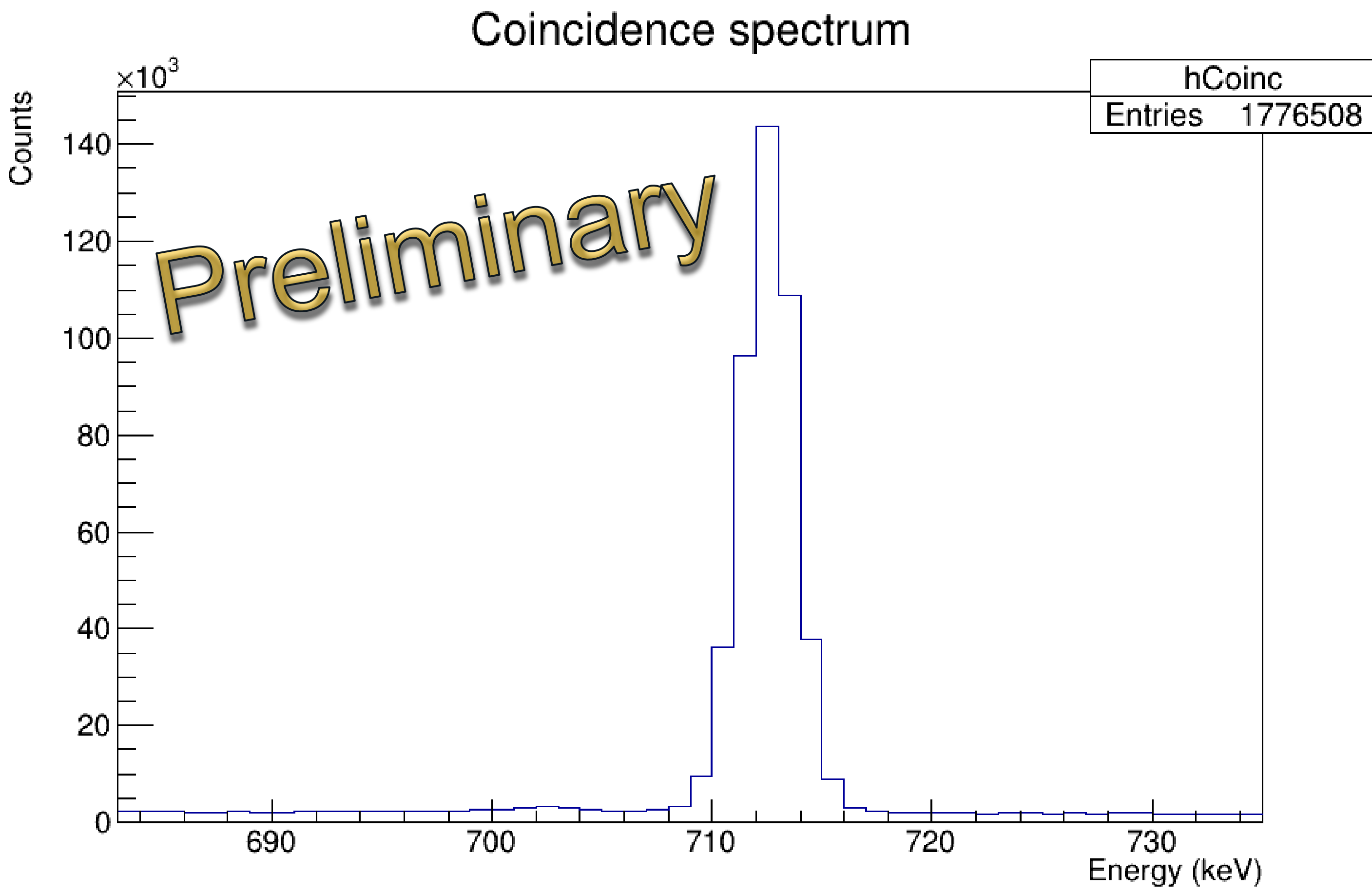
Pending funding

Backup slides slides

Feasibility

Natural potassium salt

- Mudirac
  - K-39: (R = 3.435 fm)
    - $2p_{3/2}$ – 1s: 713.099 keV
    - $2p_{1/2}$ – 1s: 711.890 keV
  - K-41: (R = 3.4546 fm)
    - $2p_{3/2}$ – 1s: 712.752 keV
    - $2p_{1/2}$ – 1s: 711.542 keV
  - Resolution: $\sigma \approx 1\ keV$



Which parameters can we fix?

- 4 gaussians + bg → 22-23 parameters
  - Fix $p_{3/2}$-$p_{1/2}$ amplitude ratio
  - Constrain ^{39}K-^{41}K amplitude ratio
  - Fix $p_{3/2}$-$p_{1/2}$ energy difference
  - Fix peak shape (from calibration sources)

- 4 parameters (one of which is constrained) + bg

$$f(E) = N_{\text{signal}}[f_{\text{gauss}} \cdot g(E) + f_{\text{tail}} \cdot t(E) + s(E)] + B, \quad (17)$$

where

$$g(E) = \frac{1}{\sqrt{2\pi}\sigma} \cdot \exp\left(-\frac{(E-x_0)^2}{2\sigma^2}\right),$$

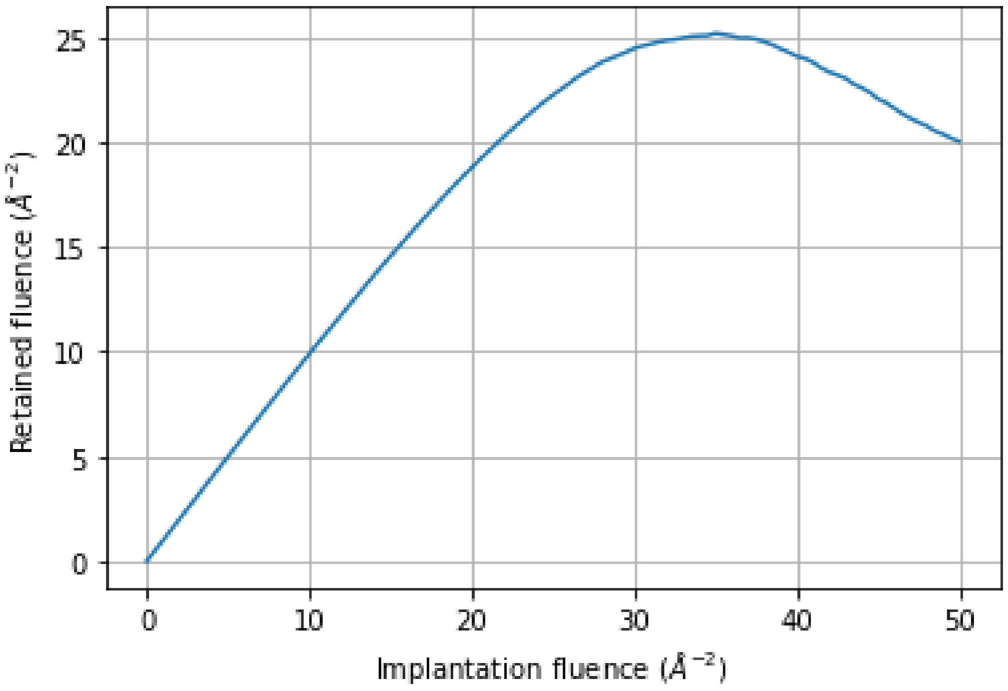
$$t(E) = \frac{1}{2\beta} \cdot \exp\left(\frac{E-x_0}{\beta} + \frac{\sigma^2}{2\beta^2}\right) \cdot \mathtt{erfc}\left(\frac{E-x_0}{\sqrt{2}\sigma} + \frac{\sigma}{\sqrt{2}\beta}\right),$$

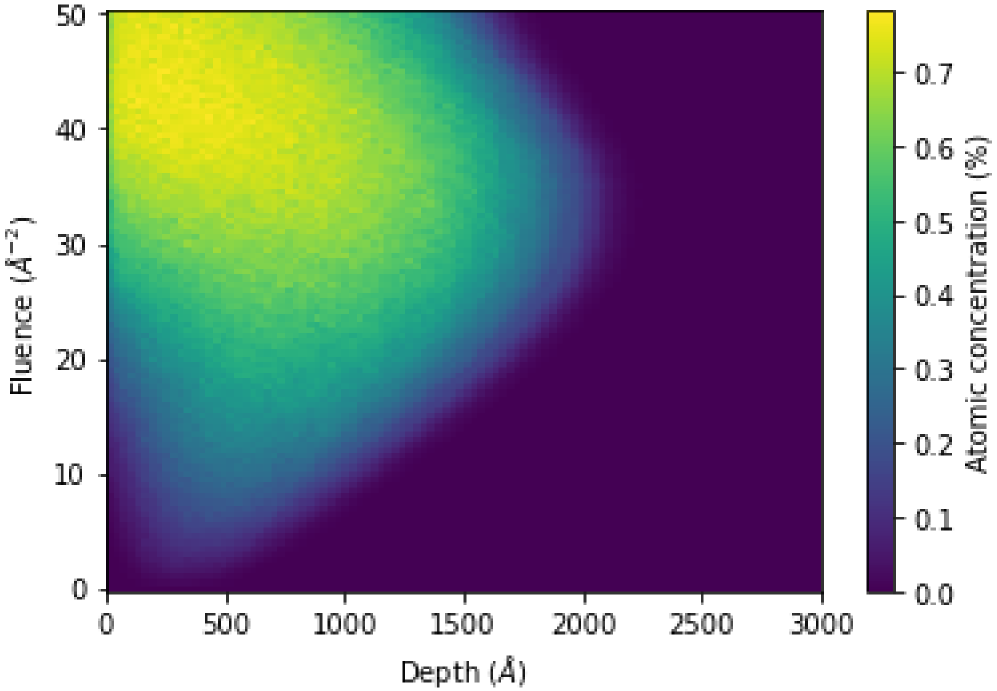
$$s(E) = \frac{A}{2} \cdot \mathtt{erfc}\left(\frac{E-x_0}{\sqrt{2}\sigma}\right).$$

Implantation

TRIDYN – ^{39}K

30 keV





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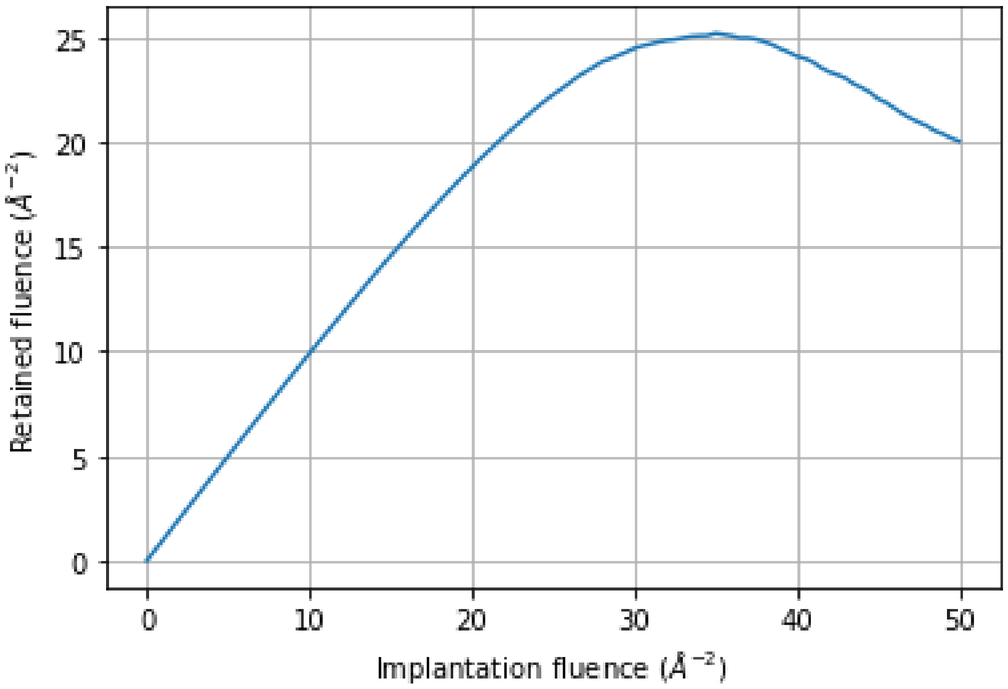
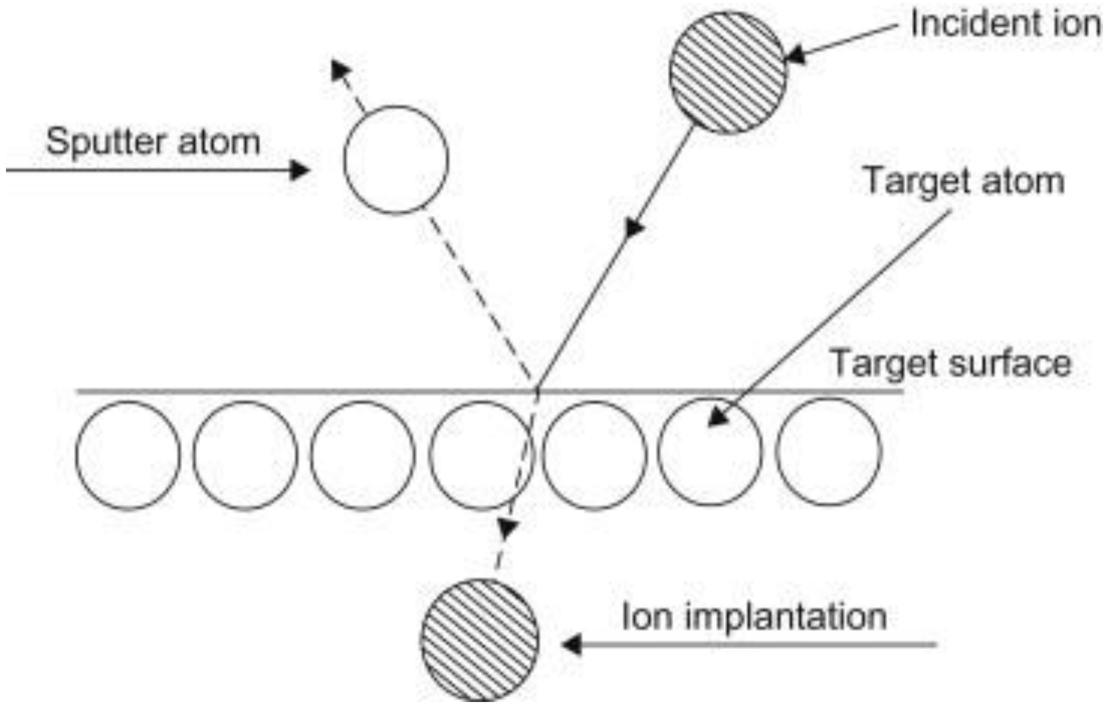
Implantation of K in carbon

- Glassy carbon: ~5 µg
- Pyrolytic graphite: potentially 25 µg
- Systematic study ongoing via RADIATE
- Assuming beam spot ~sample size: ~100 mC = ~20 µA h
- Typical beam currents K: 0.1-1µA (enriched 5% ^{40}K)



Implanted targets

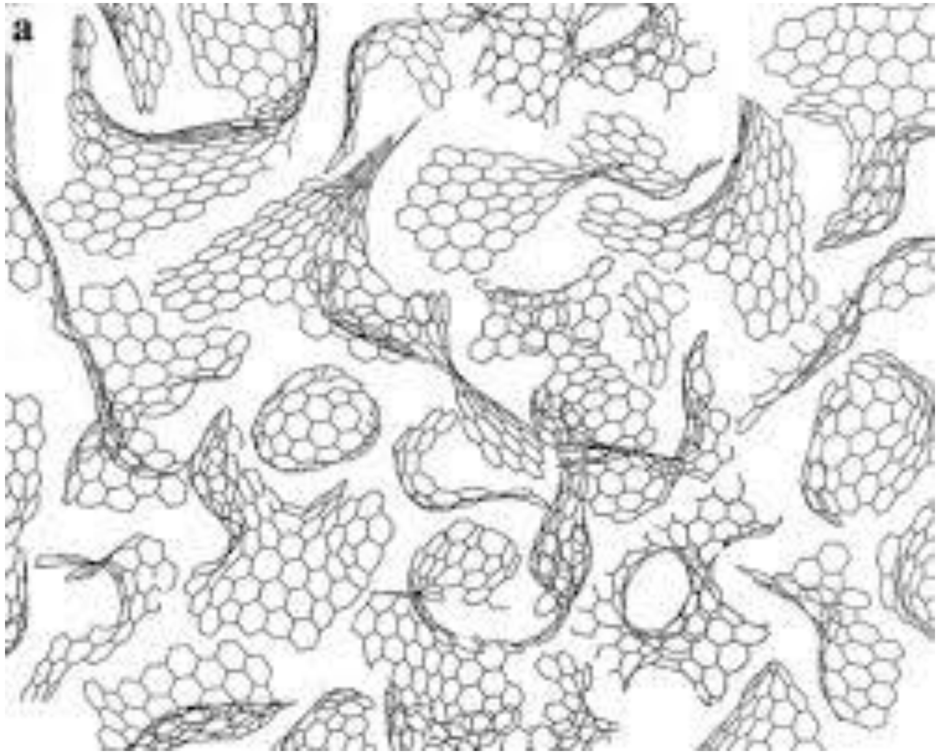
- Au-197: $5\mu g = \ 1.5 \times 10^{16}$ particles
- K-39: : $5\mu g = 7.7 \times 10^{16}$ particles
- Target area ~ $1\ cm^2$ → massive fluence
- How much material can we implant?
  → self-sputtering simulations



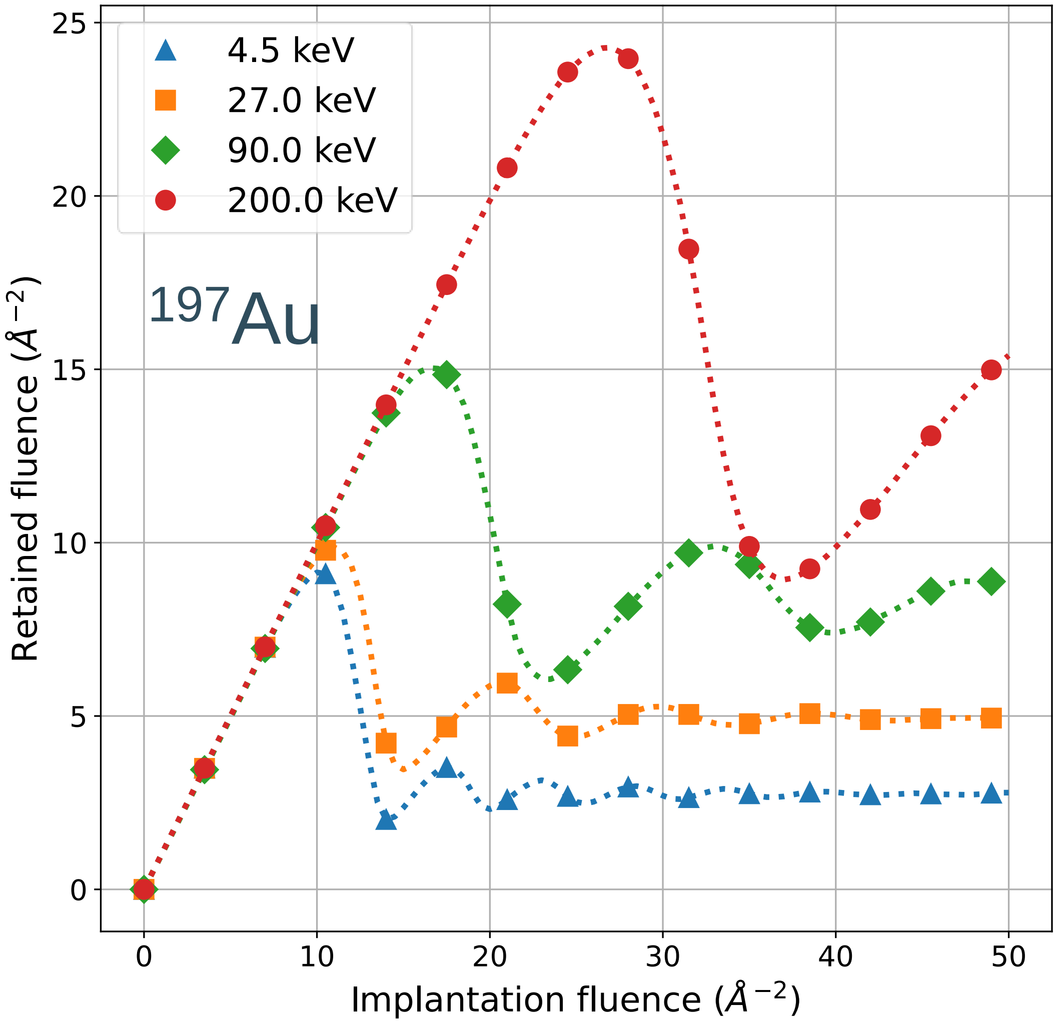
- Wasa, Kiyotaka, Isaku Kanno, and Hidetoshi Kotera, eds. *Handbook of sputter deposition technology: fundamentals and applications for functional thin films, nano-materials and MEMS*. William Andrew, 2012

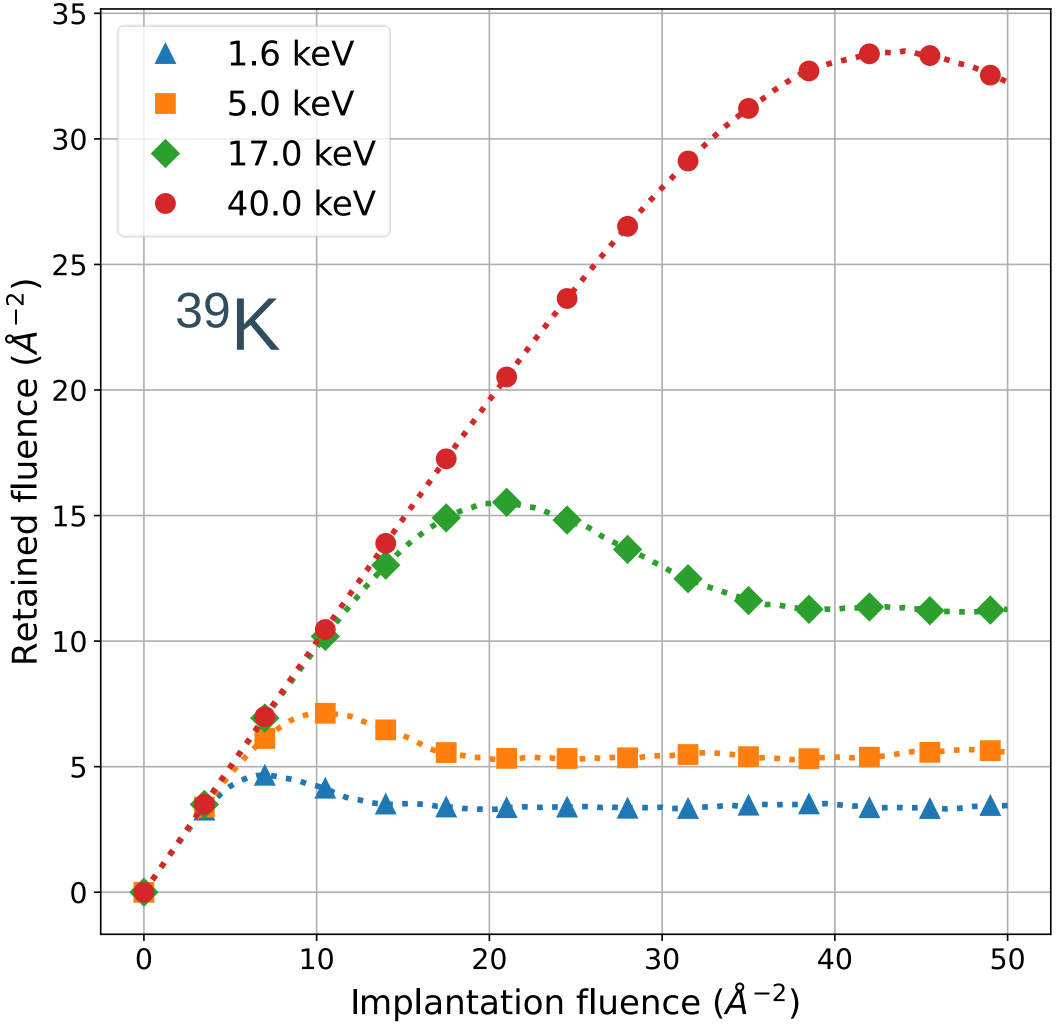
Carbon samples

- Minimize sputtering → Low-Z substrates
- Lithium: explosive
- Beryllium: Extremely toxic
- Carbon:
  - Graphite → Weak interlayer bonding
  - Glassy carbon?



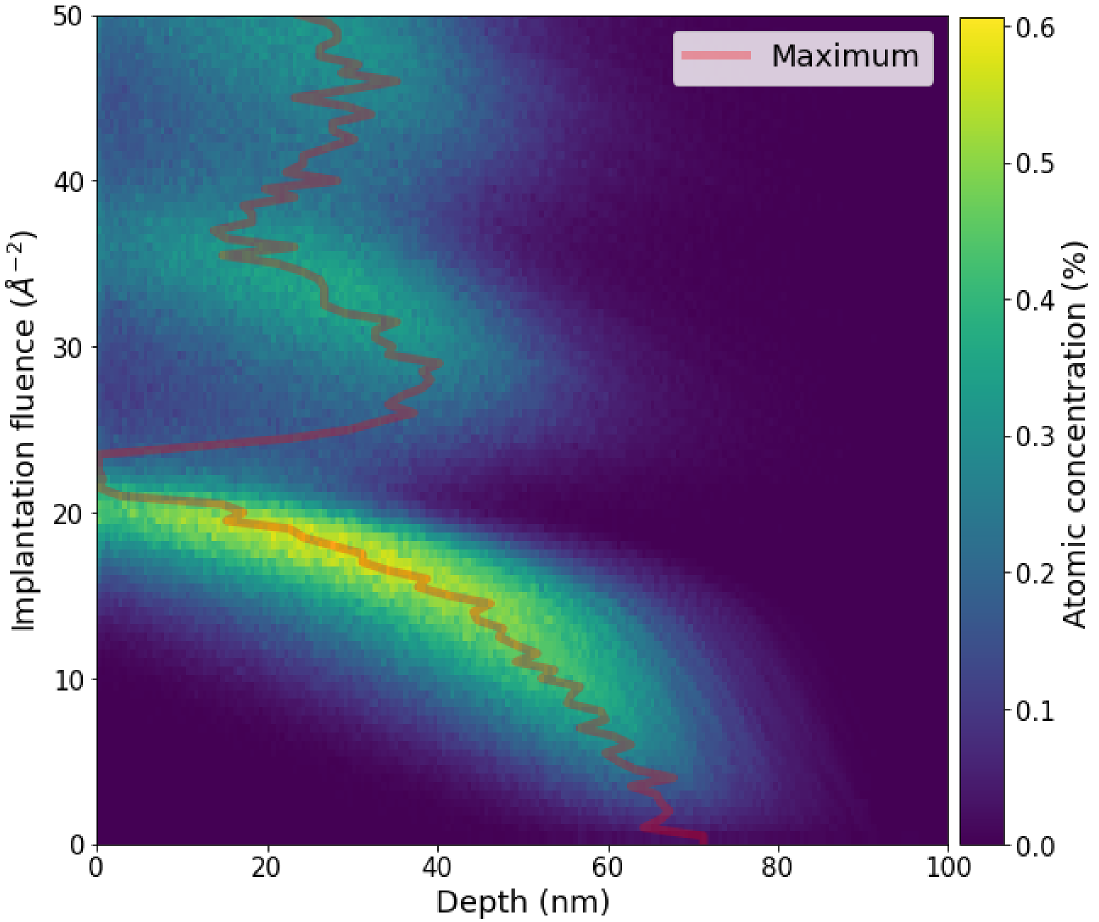
TRIDYN simulations





TRIDYN simulations

- Gold at 90 keV in glassy carbon
- Reduced implantation depth
    - Sputtering
    - Reduced range
- Reach the surface → Very large sputter yield
- Almost “resetting” the sample



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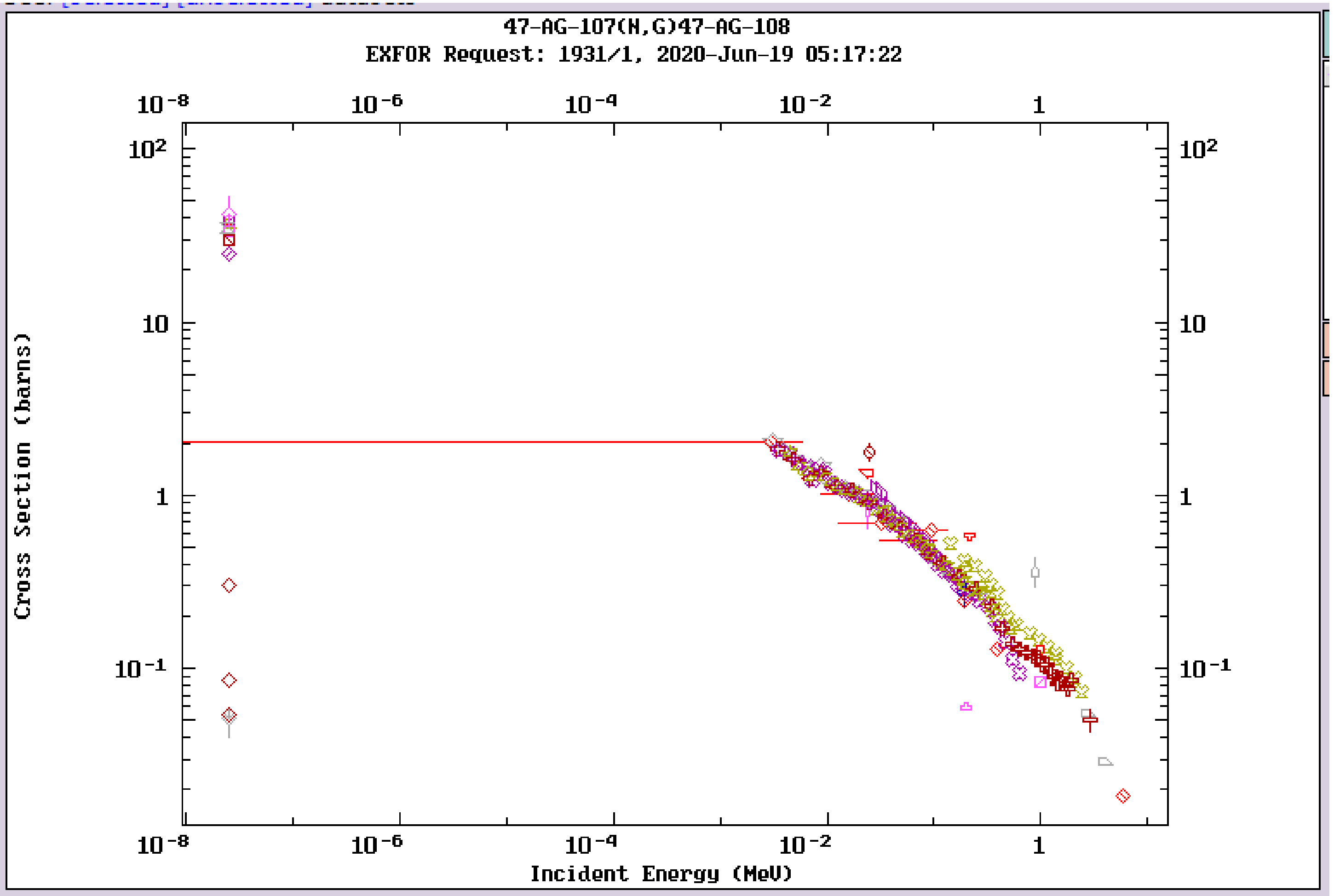
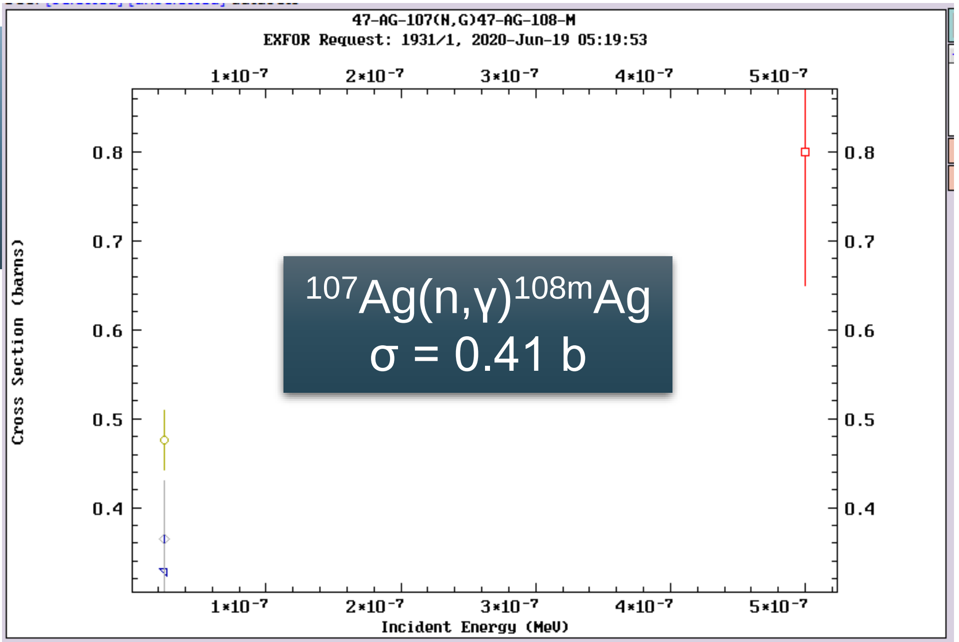
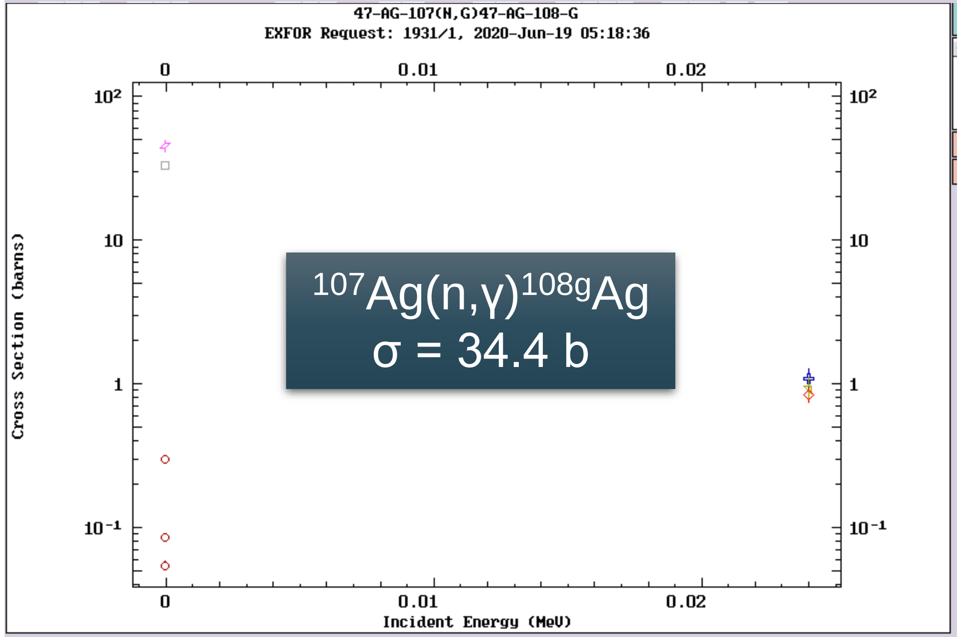
Beyond potassium

$_{47}$Ag

- TAC: Is the isomer produced?
  - ✓ Yes







EXFOR database from NNDC: https://www.nndc.bnl.gov/

$_{47}$Ag

- TAC: Ratio of ^{107}Ag to ^{108m}Ag?
- TAC: Can the ion source handle the throughput?

- Situation similar to the ^{168}Er(n,γ)^{169}Er case at MEDICIS
  - Same order of magnitude cross section
  - Enriched material as starting point
  - 2% radioisotope content at the end of irradiation
  - Demonstrated a collection of 17 MBq = 2×10^{13} atoms without RILIS (ε_{ion}~0.2%)

✓1mg of ^{107}Ag can yield 12MBq of ^{108m}Ag, i.e. 2.3×10^{17} atoms, after 50 days irradiation + 10 days cooling

✓This represents ~4% fraction of the total sample size

✓RILIS reports a 14% ionization efficiency, resulting in 3×10^{16} collected atoms.

R. Formento-Cavaier et al, … ^{169}Er production…, NIMB **463** (2020) 468-471.

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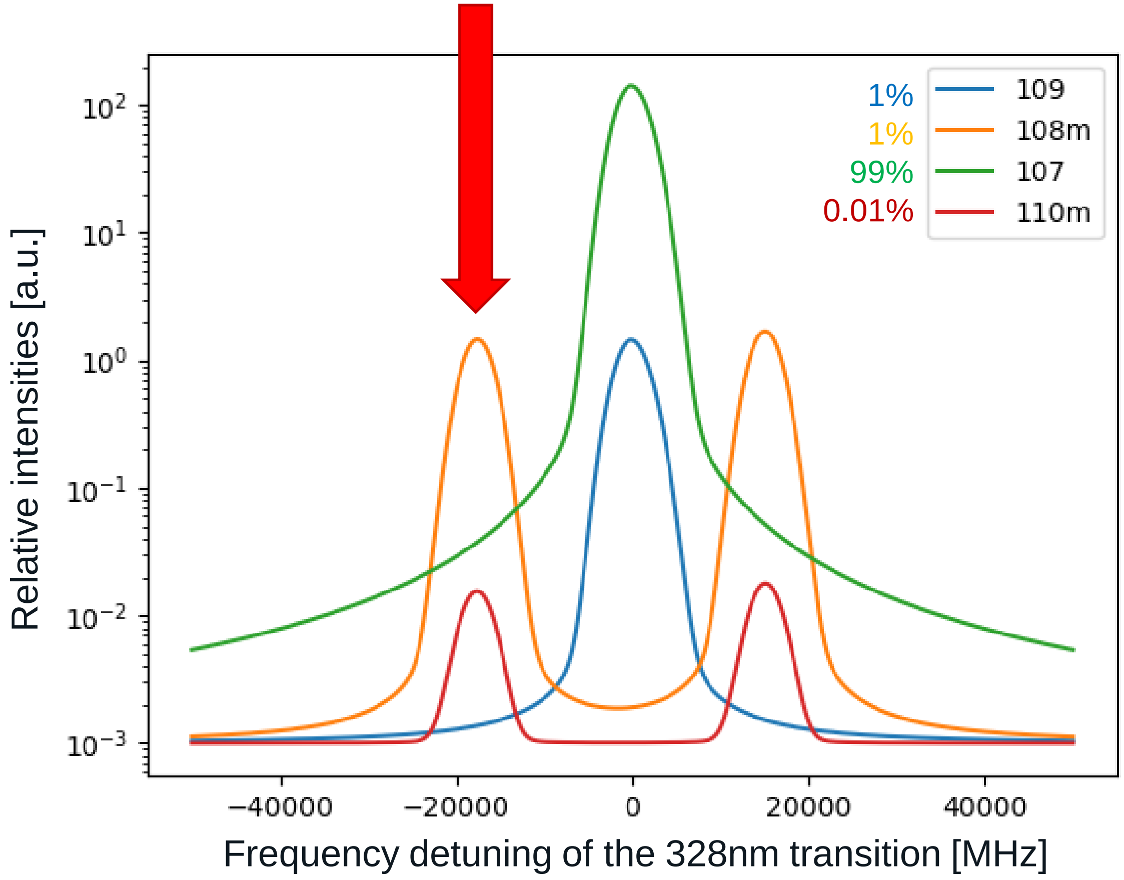
$_{47}Ag$

✓ TAC: Ratio of ^{107}Ag to ^{108m}Ag?

✓ TAC: Can the ion source handle the throughput?



✓RILIS reports a 14% ionization efficiency, resulting in 3 x 10^{16} collected atoms.

- RILIS in normal mode can already separate Ag isotopes with widely different spin/nuclear structure:
  - If tuned on ^{108m}Ag, both $^{107,109}Ag$ are naturally suppressed from the source

  ✓No throughput difficulty

 - *HFS simulation courtesy of R.P. de Groote.*

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$_{57}$La

- TAC: La scheme?
- TAC: What can Mainz do?

^{136}Ce Stable	^{137}Ce β+	^{138}Ce Stable	^{139}Ce e- capture	^{140}Ce Stable
^{135}La β+	^{136}La β+	^{137}La e- capture	^{138}La Stable	^{139}La Stable
^{134}Ba Stable	^{135}Ba Stable	^{136}Ba Stable	^{137}Ba Stable	^{138}Ba Stable

- $_{57}$La contains 2 stable isotopes: ^{138}La and ^{139}La
  - ❖Natural abundance of ^{138}La: 0.00088
  - ➢Has not been studied with μx rays or e^{-} scattering
  - ❑Commercially available with enrichment to 5%
  - ➢Requires further enrichment to be suitable at muX
- An additional long-lived isotopes is available: ^{137}La with $T_{1/2}$=60,000 years
  - Can be produced in ^{136}Ce(n,γ)^{137}Ce(β^{+}/EC)^{137}La with the intermediate isotope having $T_{1/2}$=9h, followed with radiochemistry to isolate La from Ce
  - ❑Risks to produce isotopic contamination from ^{138}Ce(n,γ)^{139}Ce(EC)^{139}La where the intermediate isotope has $T_{1/2}$=137.6d
  - ➢Sample purity requires mass measurement for quality control (no γ/stable)

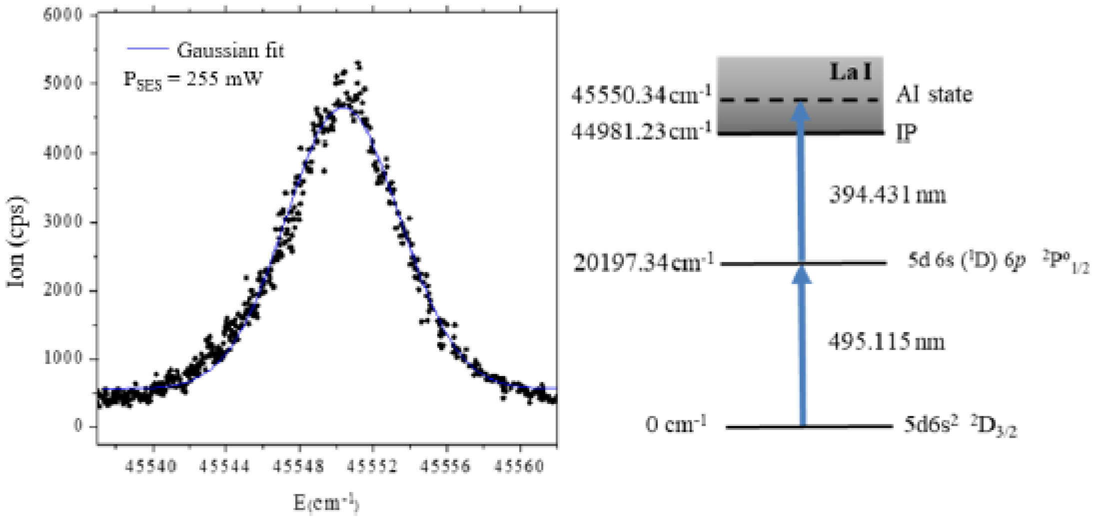
*H. Iimura et al, … isotope shifts of ^{135}La, ^{137}La, and ^{138}La…, PRC **68** (2003) 054328.*
T.E. Cocolios, Master Thesis, McGill University 2005.
H.A. Schuessler et al, Nuclear moments of … ^{131}La…, Proceedings to LAP2006, p95-96 (2006).

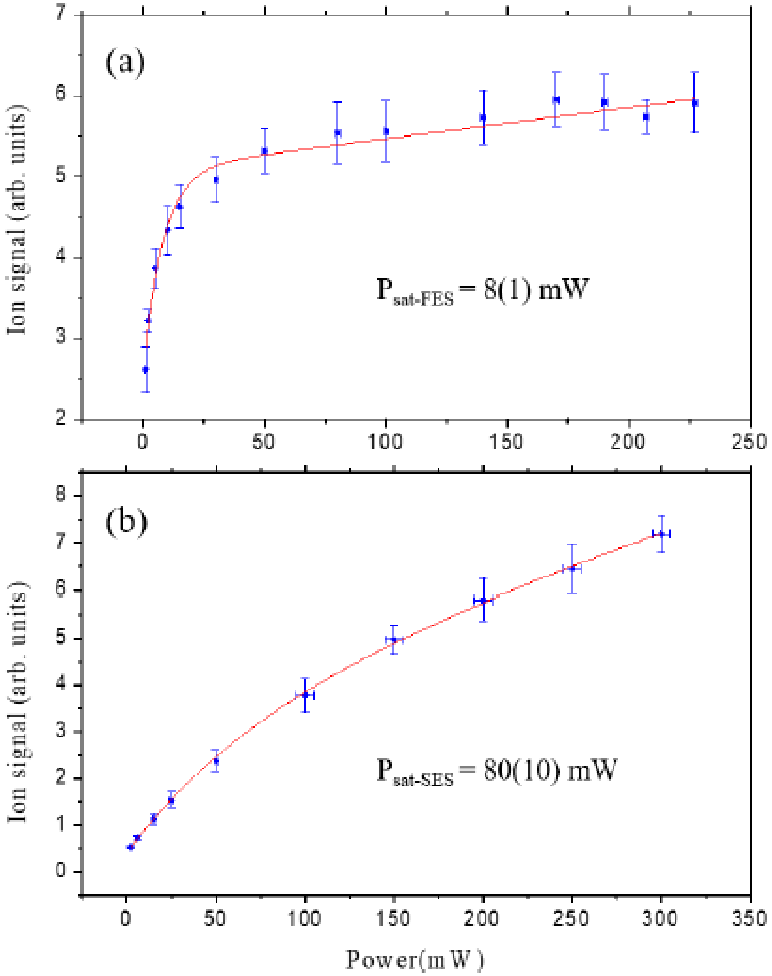
$_{57}$La

- ✓ TAC: La scheme?
- ✓ TAC: What can Mainz do?

✓ $_{57}$La has been successfully laser ionized at TRIUMF and the scheme is available.

✓ Mainz can perform the characterization of the isotope ratio in the case of ^{137}La.





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$_{65}$Tb

- TAC: What can Mainz do?

- $_{65}$Tb has only 1 stable isotope: ^{159}Tb
- It however also has 2 long-lived isotopes:
  - ➢ ^{158}Tb, $T_{1/2}$=180 years
    - ✓ Production via ^{158}Gd(d,2n)^{158}Tb
      - ❖ Risks of isotopic contamination with ^{nat}Gd(d,xn)^{157,159}Tb
  - ➢ ^{157}Tb, $T_{1/2}$=99 years
    - ✓ Production via ^{156}Dy(n,γ)^{157}Dy(EC)^{157}Tb
      - ❖ Risks of isotopic contamination with ^{158}Dy(n,γ)^{159}Dy(EC)^{159}Tb
- Requires characterization

^{156}Dy Stable	^{157}Dy β+	^{158}Dy Stable	^{159}Dy e- capture	^{160}Dy Stable
^{155}Tb e- capture	^{156}Tb β+	^{157}Tb e- capture	^{158}Tb β+	^{159}Tb Stable
^{154}Gd Stable	^{155}Gd Stable	^{156}Gd Stable	^{157}Gd Stable	^{158}Gd Stable
^{153}Eu Stable	^{154}Eu β-	^{155}Eu β-	^{156}Eu β-	^{157}Eu β-

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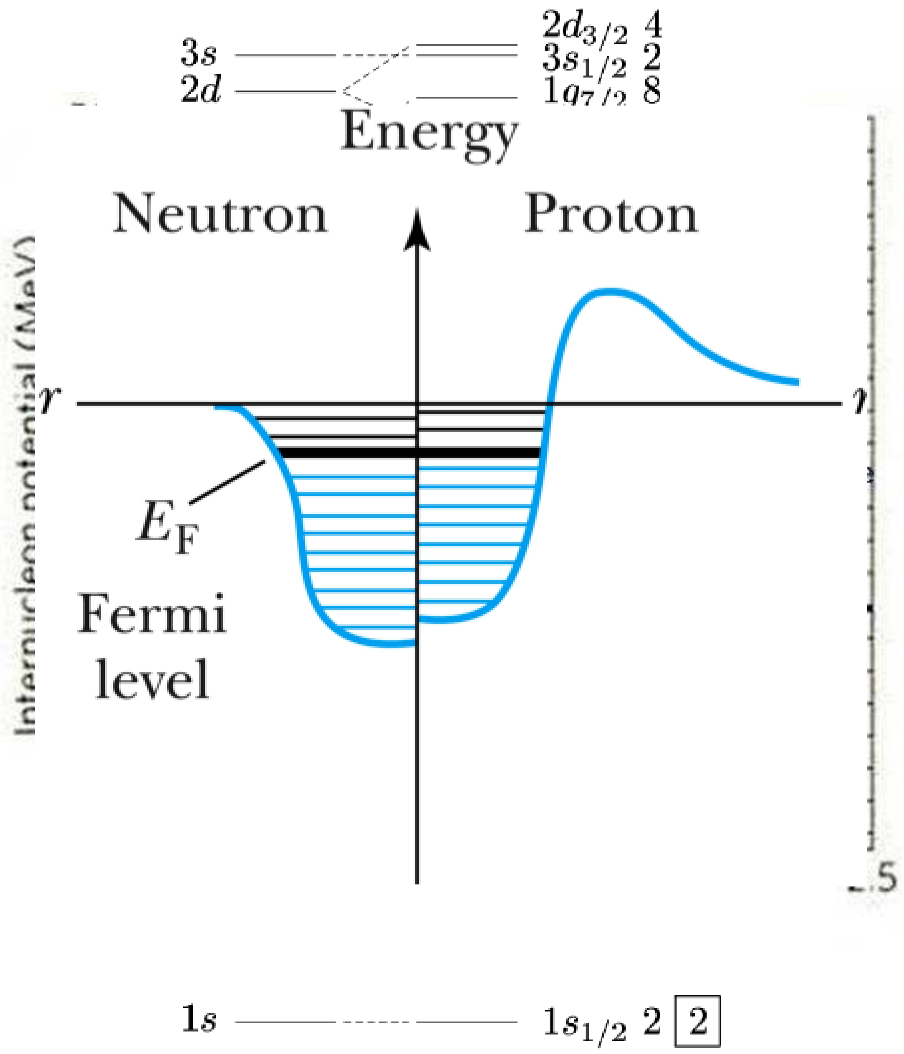
Importance of Charge Radii

- Sensitive probe for nuclear models → Input for theory
- Behavior near magic numbers (also far from stability)
- Other Research interests:
  - Shape staggering
  - Halo nuclei
  - …



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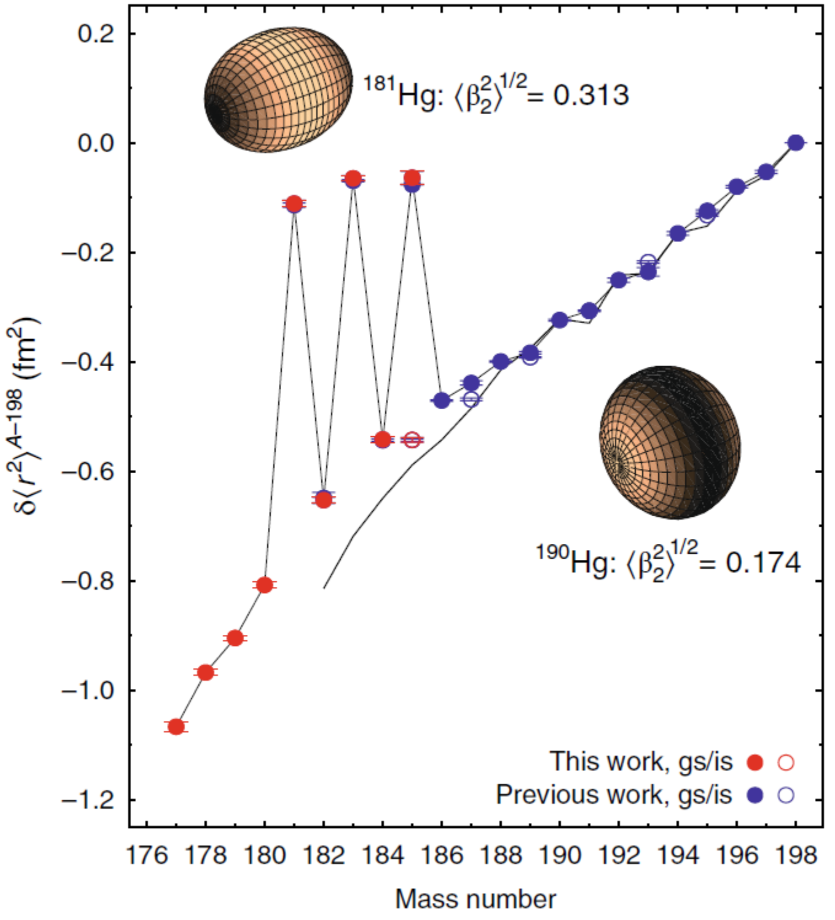

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