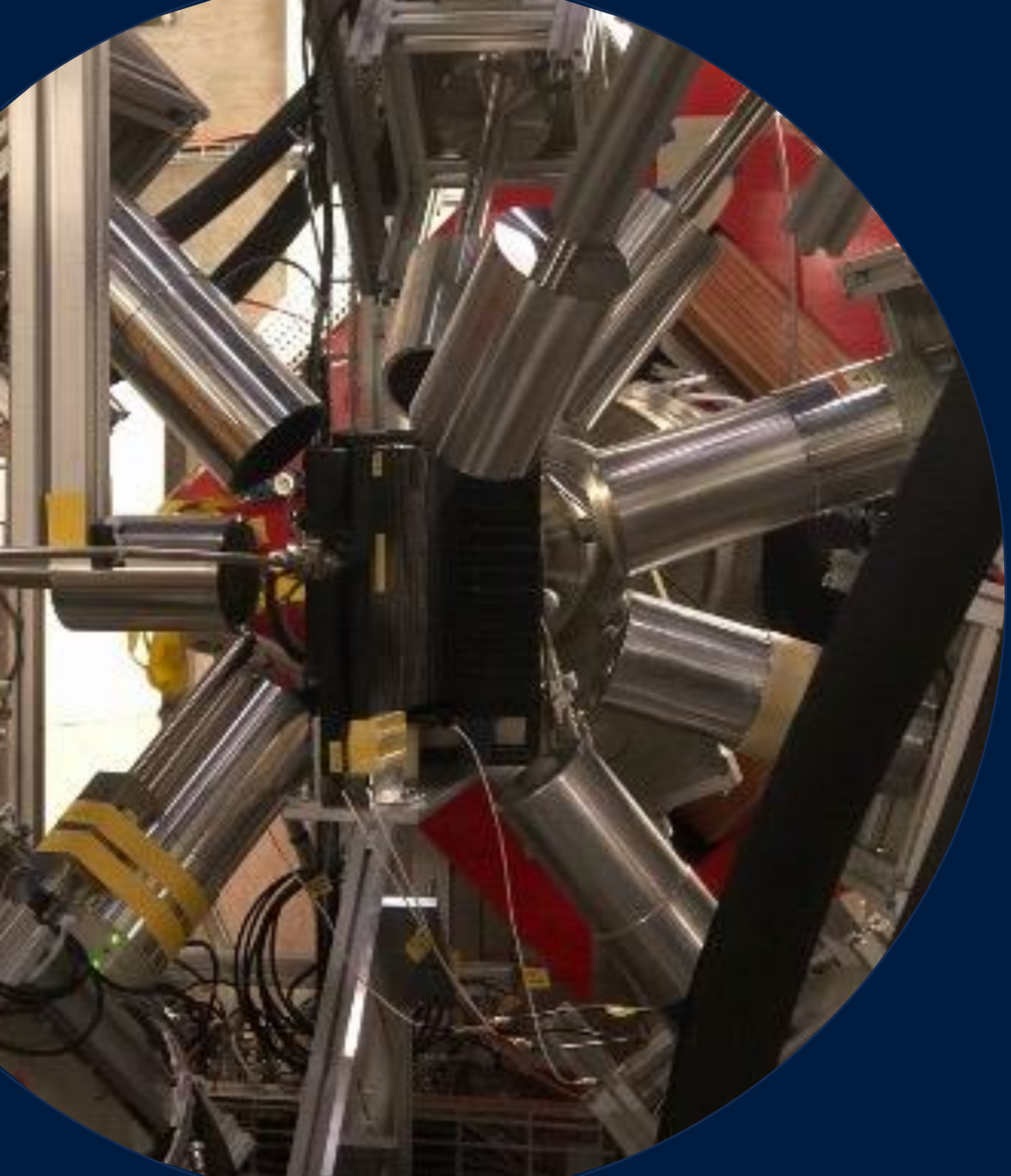


Reference Radii for odd-Z and heavy elements

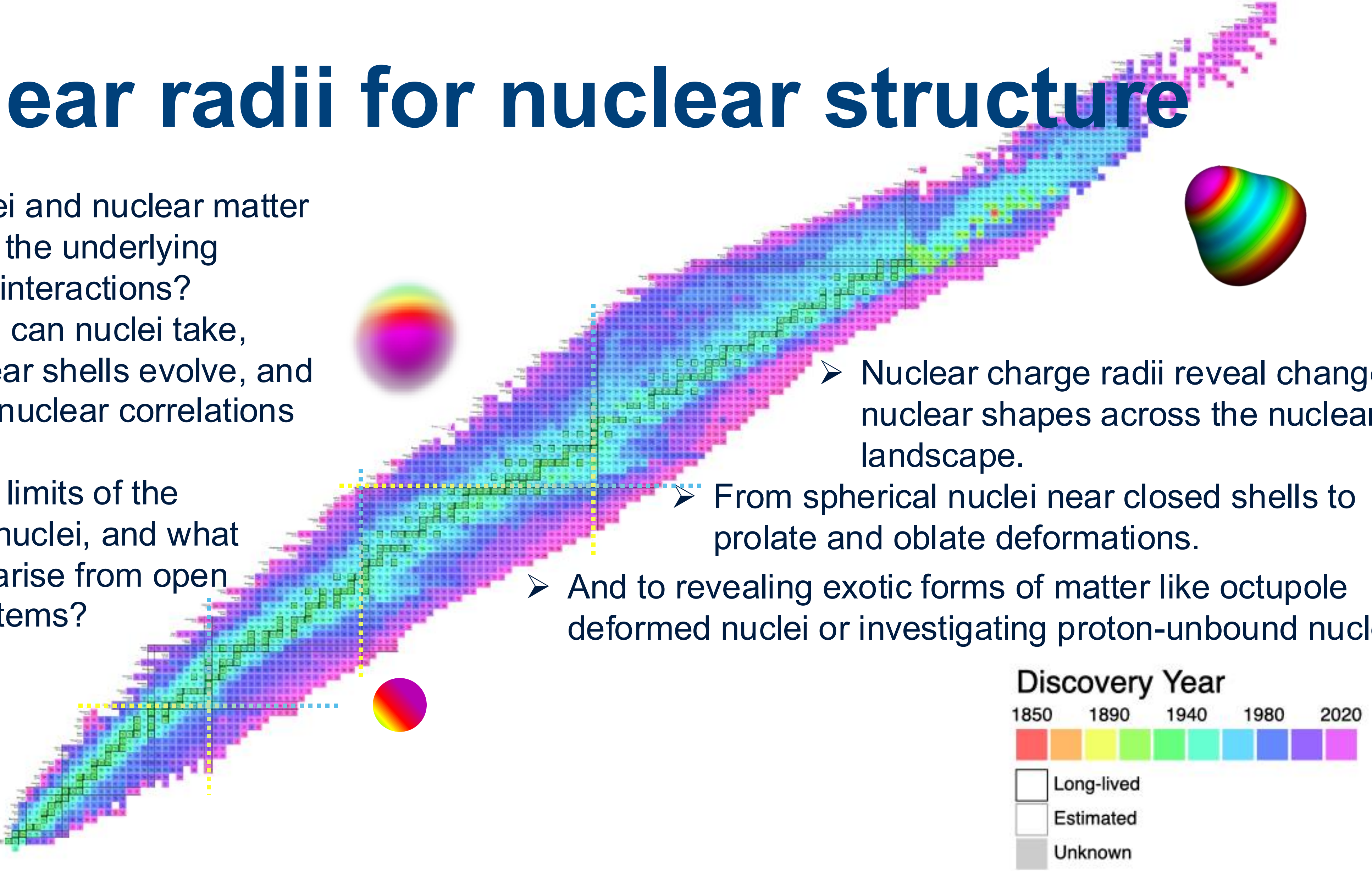
Outline

- Nuclear charge radii as probes of nuclear structure
- Accuracy limit in extracting charge radii
- muX and ReferenceRadii: absolute charge radii with microscopic samples of (radio)isotopes

Nuclear charge radii as probes of nuclear structure

Nuclear radii for nuclear structure

- How do nuclei and nuclear matter emerge from the underlying fundamental interactions?
- What shapes can nuclei take, how do nuclear shells evolve, and what role do nuclear correlations play?
- What are the limits of the existence of nuclei, and what phenomena arise from open quantum systems?



- Nuclear charge radii reveal changes in nuclear shapes across the nuclear landscape.
- From spherical nuclei near closed shells to prolate and oblate deformations.
- And to revealing exotic forms of matter like octupole deformed nuclei or investigating proton-unbound nuclei.

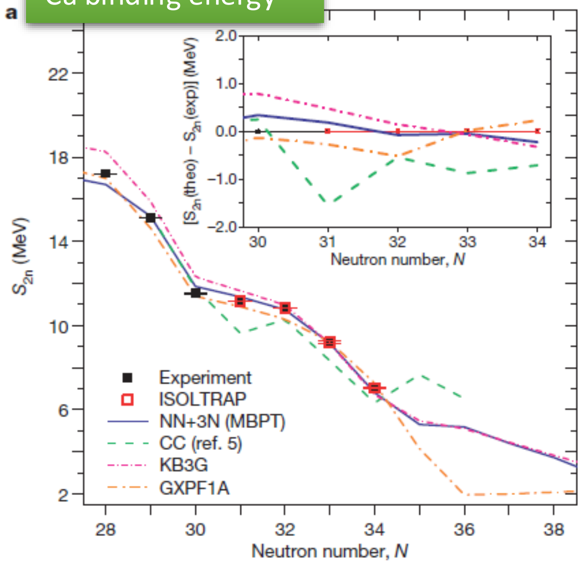
NuPECC Long Range Plan 2024, https://nupecc.org/lrp2024/Documents/nupecc_lrp2024.pdf
The Colourful Nuclear Chart, https://people.physics.anu.edu.au/~ecs103/chart/

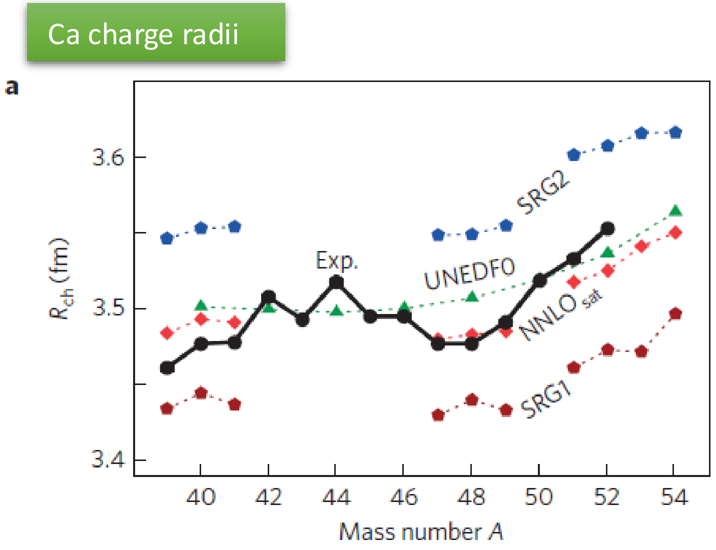
Medium-mass nuclei: $_{19}$K vs $_{20}$Ca

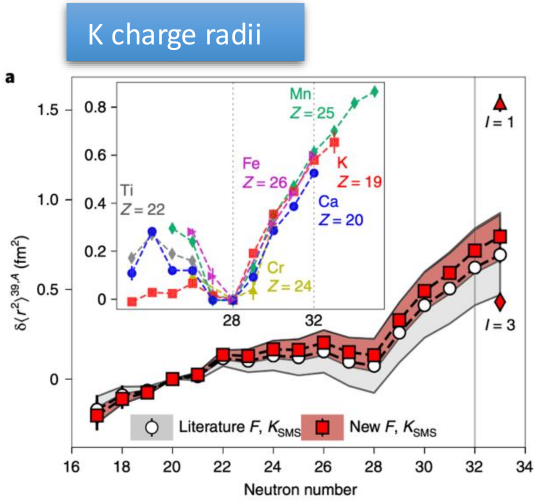
The binding energies suggest there might be a new magic number at N=32 and 34.

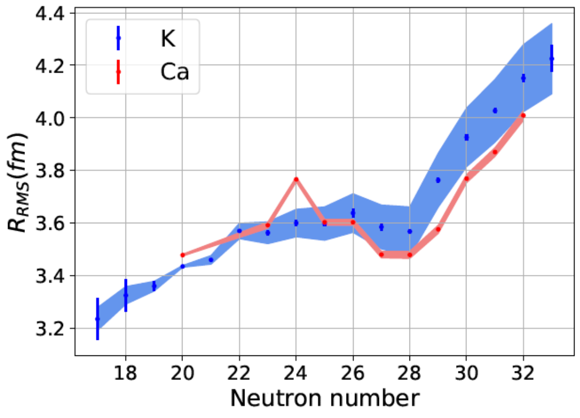
Charge radii show a large kink at N=28 but nothing at N=20 or 32,34.

The radii of $_{19}$K are plagued by the large systematic uncertainties.



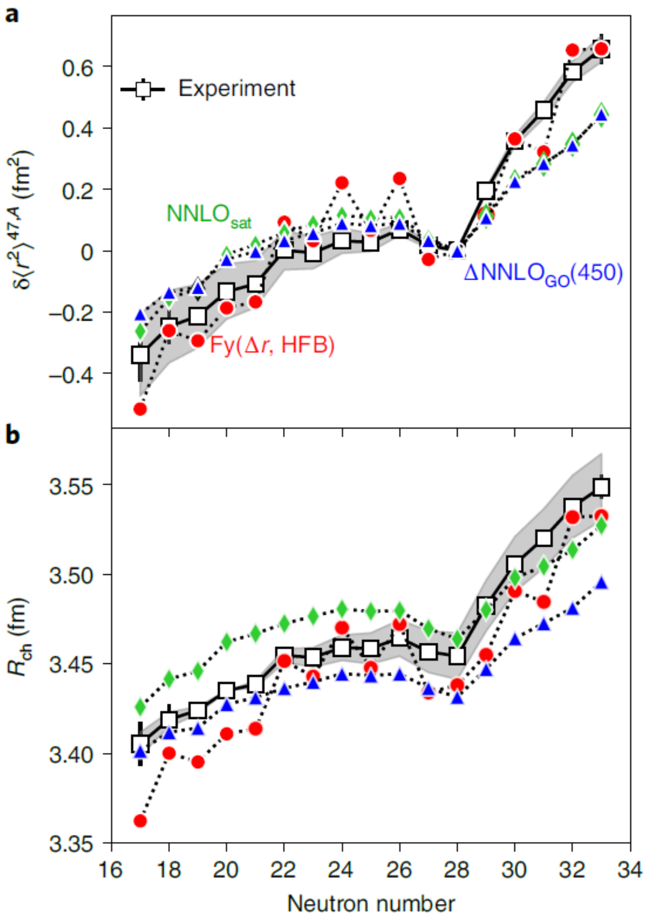






*F. Wienholtz et al., Masses of exotic calcium isotopes pin down nuclear forces, Nature **498** (2013) 346-349.*
*R.F. Garcia Ruiz et al., Unexpectedly large charge radii of neutron-rich calcium isotopes, Nature Physics **12** (2016) 594-598.*
*Á. Koszorús et al, Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of N = 32, Nature Physics **17** (2021) 439-443.*

Medium-mass nuclei: $_{19}$K vs $_{20}$Ca



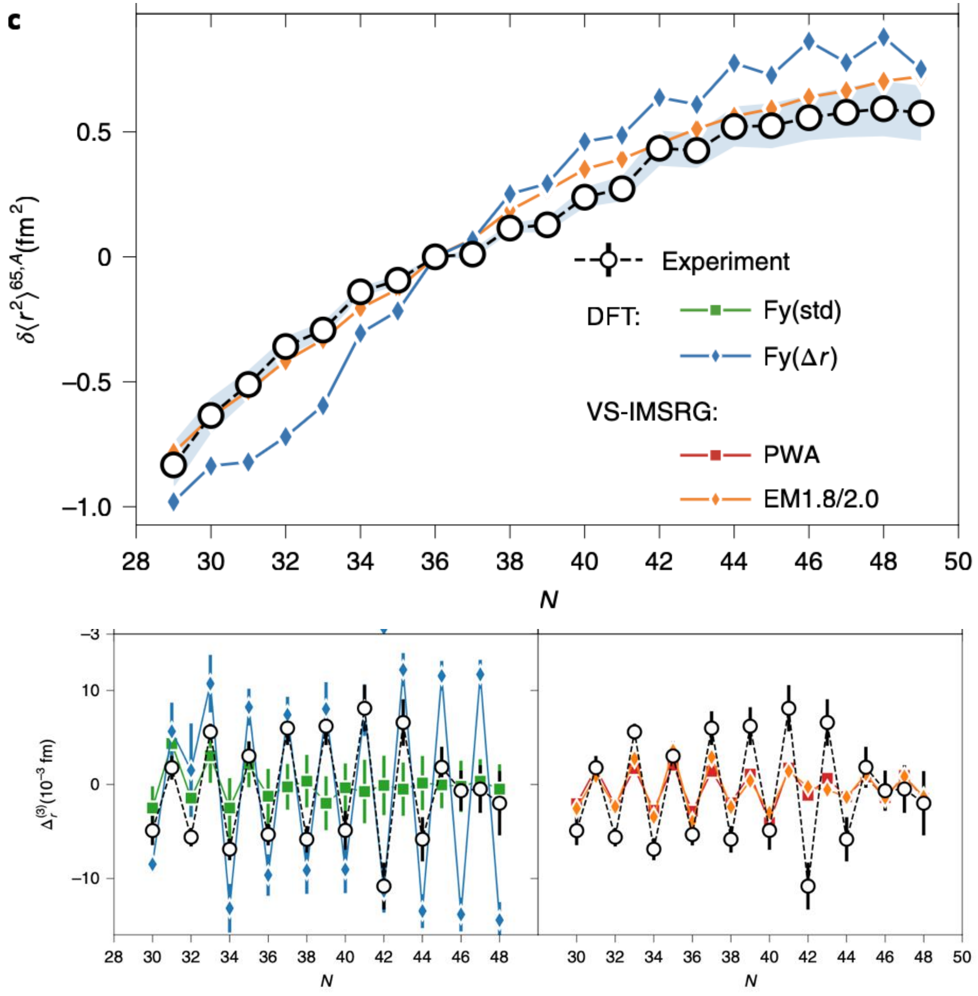
Radii measured up to N=33 probing the N=28 shell closure and N=32 subshell.

Ab initio models reproduce small variations well while DFT captures the global trend much better.

Limited precision on extracted radii induced by systematic uncertainties from the radii extraction from isotope shift, especially when evaluating absolute radii with respect to ^{39,41}K.

Á. Koszorús et al, Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of N = 32, Nature Physics ***17*** *(2021) 439-443*

$_{29}$Cu: jumping up & down



The same observations held at the next magic number: while the Fayans functionals perform well at describing the global scale, they do poorly with the finer details, which are well captured by ab initio models.

A flatening is found approaching N=50.

Odd-even staggering is another observable that is challenging for the models to reproduce.

R.P. de Groote et al., Measurement and microscopic description of odd-even staggering of charge radii of exotic copper isotopes, Nature Physics ***16 (2020) 620-624.***

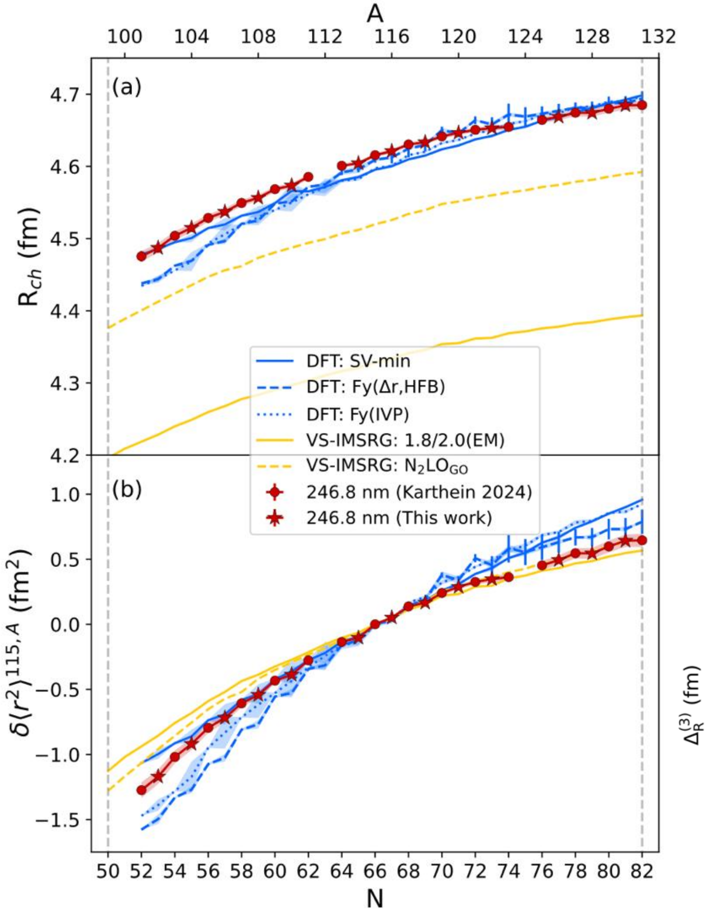
$_{49}$In & $_{50}$Sn

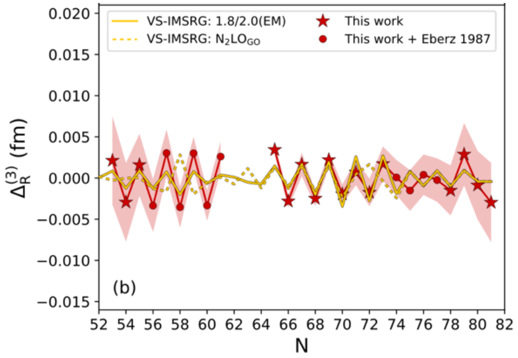
Extensive work has been performed from N=50 to N=82 and beyond.

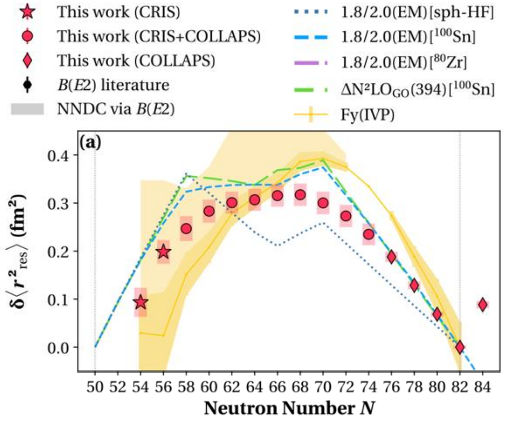
Known parabolic behaviour but hard to capture for the models.

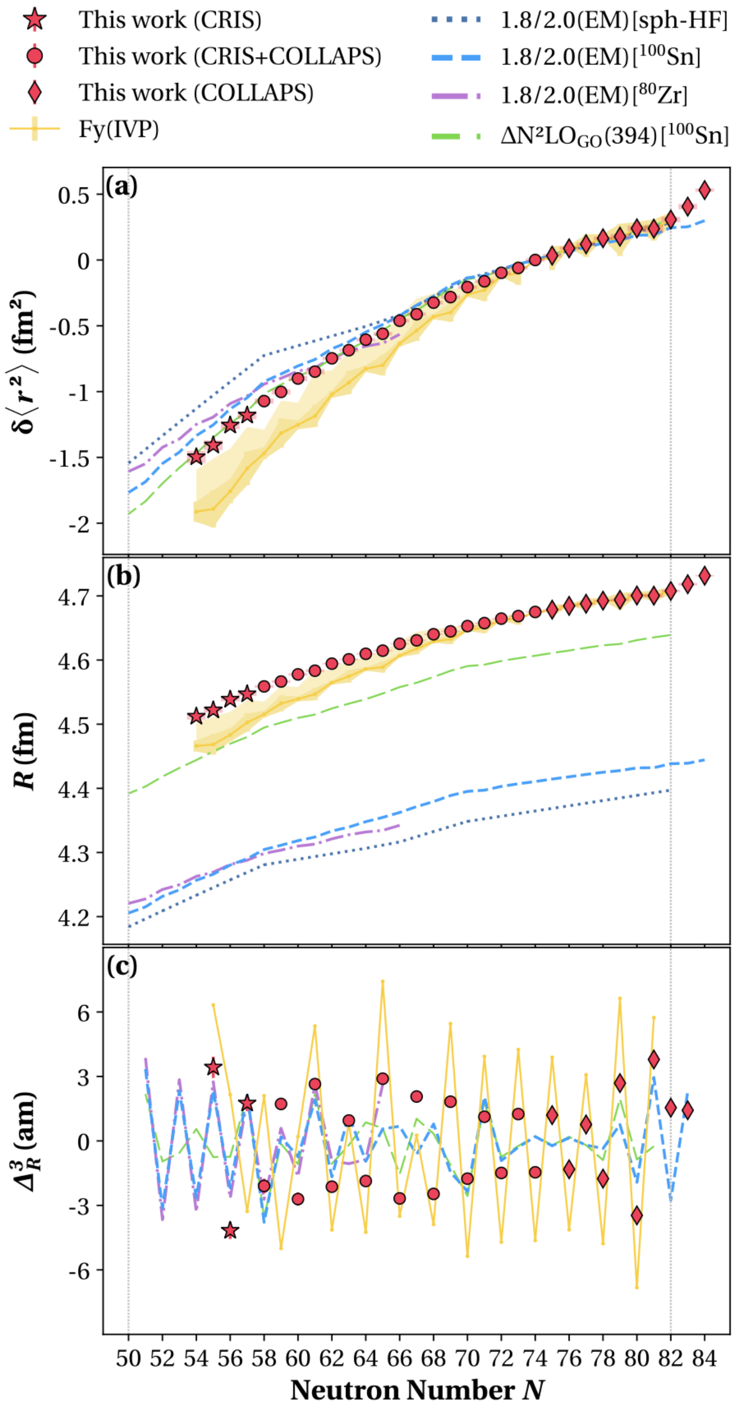
N=50, 82 magic numbers are far from stability but seem to be strong in their magicity.

Other nearby chains are under strong scrutiny: $_{46}$Pd, $_{47}$Ag, $_{51}$Sb



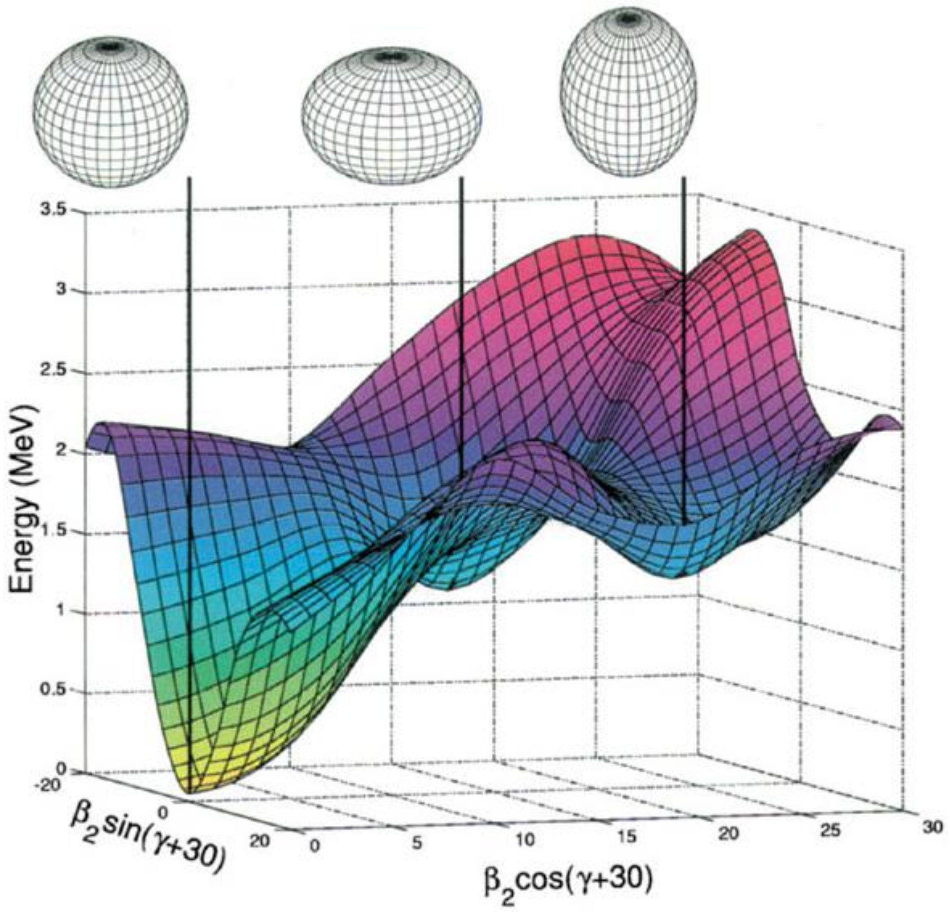


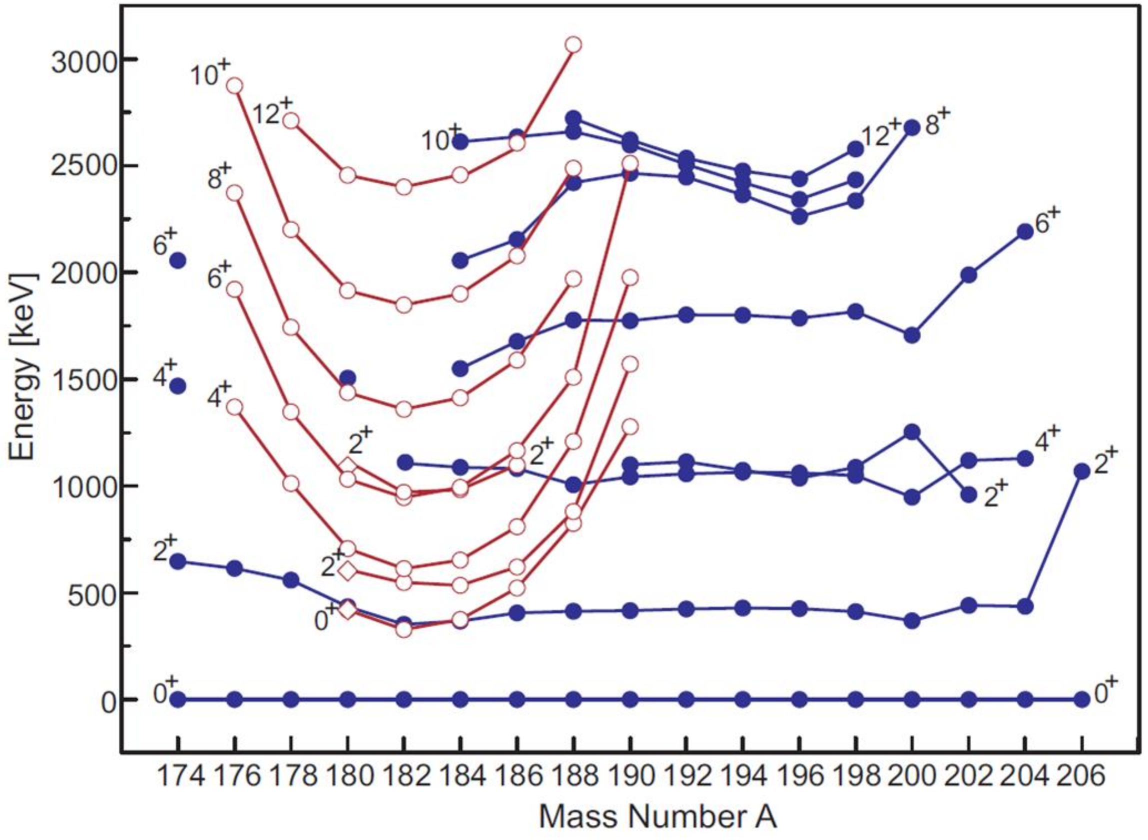




A.R. Vernon et al., Variations in the charge radii of indium isotopes between N=52 and 82, Physical Review C ***111*** *(2025) 054325.* *F.P. Gustafsson et al., Charge radii measurements of exotic tin isotopes in the proximity of N=50 and N=82, Submitted to Physical Review Letters.*

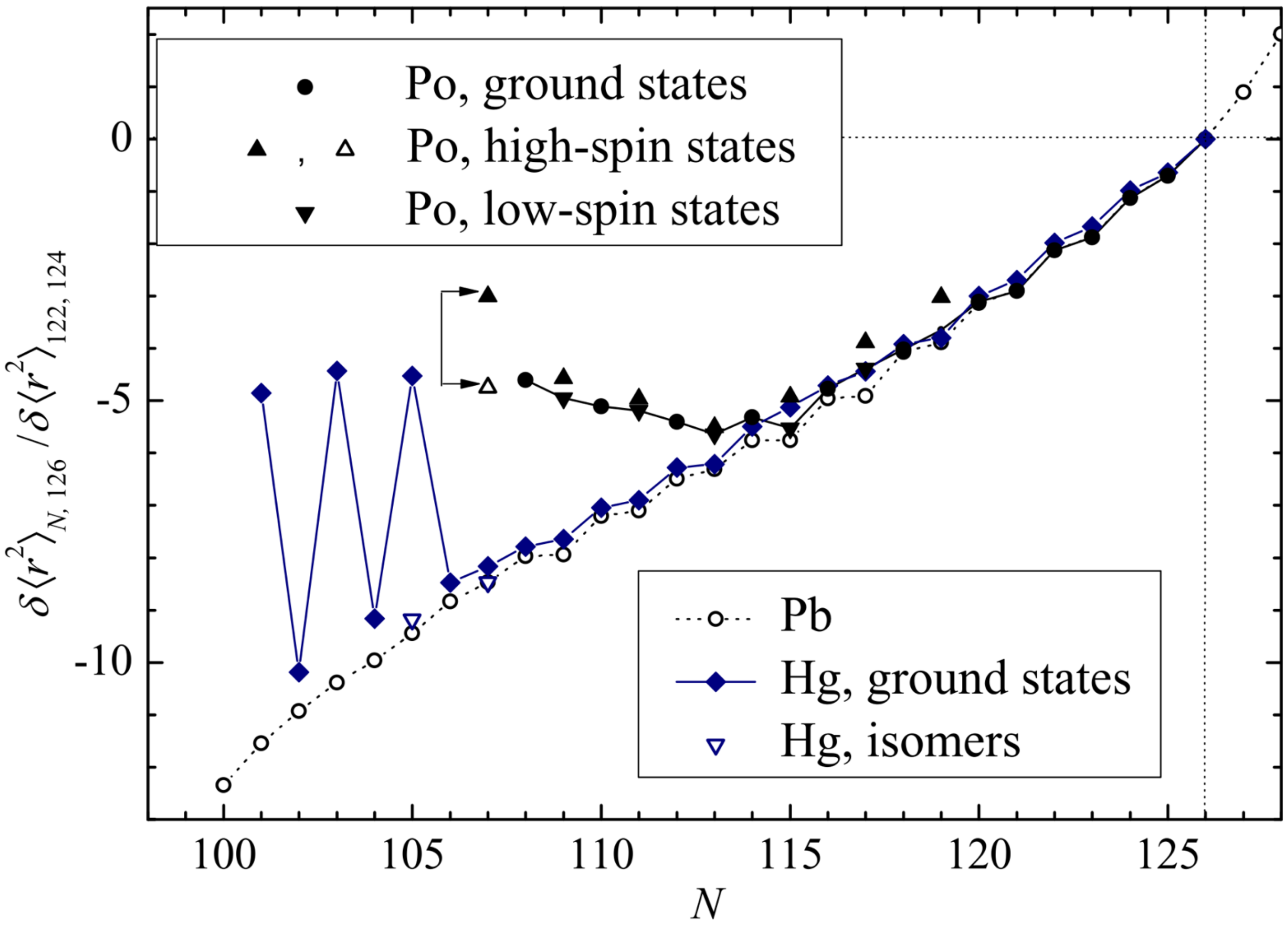
Shape coexistence around $_{82}$Pb





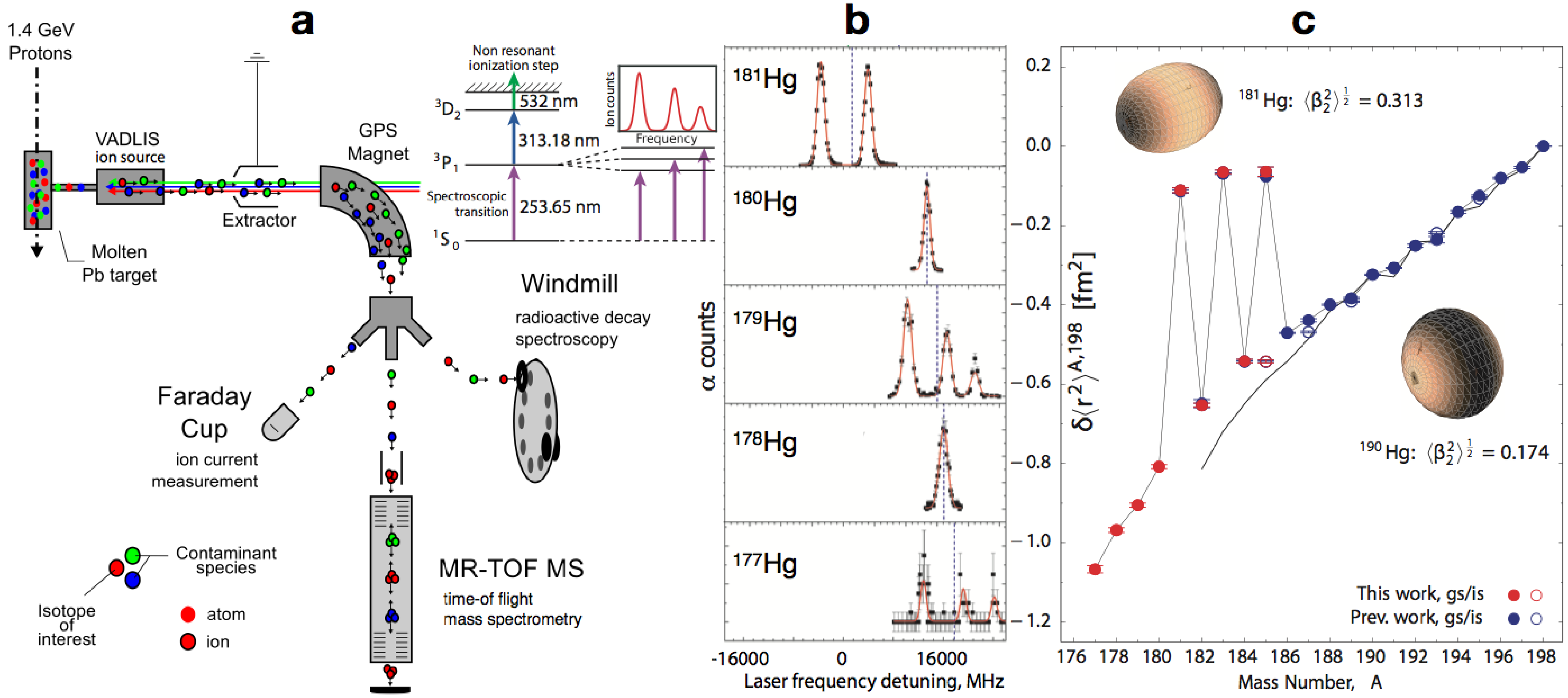
A.N. Andreyev et al. Nature ***405*** *(2000) 430-433.*
J. Elseviers et al. PRC ***84*** *(2011) 034307.*

$_{80}$Hg-$_{82}$Pb-$_{84}$Po: this is not all the same!



T.E. Cocolios et al. PRL ***106*** *(2011) 052503.*
M.D. Seliverstov et al. PLB ***719*** *(2013) 362-366.*
D.A. Fink et al., PRX ***5*** *(2015) 011018.*

In-source laser spectroscopy: $_{80}$Hg



B.A. Marsh et al. *Nature Physics* ***14*** *(2018) 1163.*

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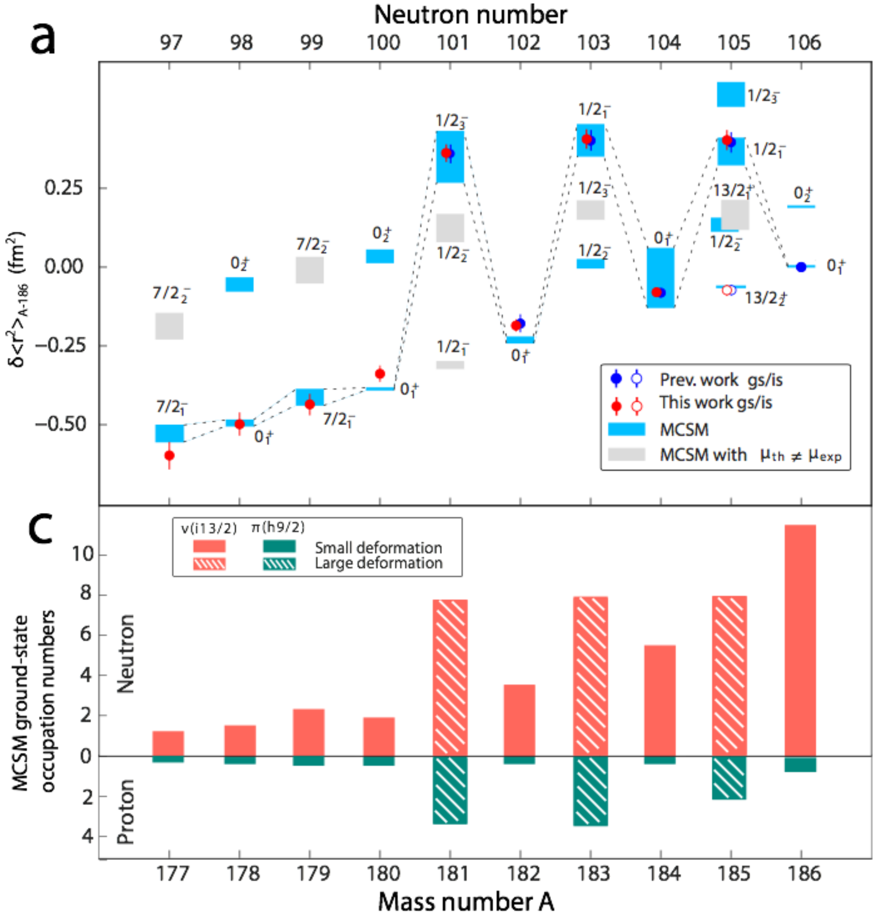
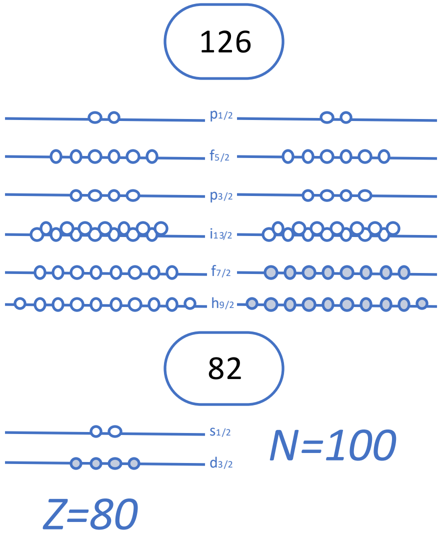


Monte Carlo Shell Model calculations on the Super K computer in Japan revealed new insight on the shape staggering in Hg.

Magnetic moments were used to guide the selection of the correct shell model states amidst the high degeneracy.

It takes many particle-hole pairs to create those shapes!



 B.A. Marsh et al. Nature Physics **14** (2018) 1163.

Octupole deformation

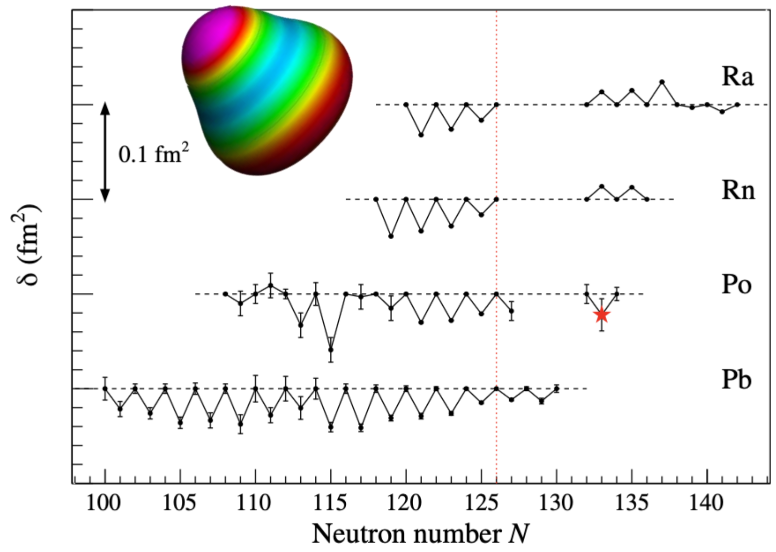
Nuclei are deformed by default, spherical being the 3rd most found in nuclear ground states. Prolate is #1, oblate is #2.

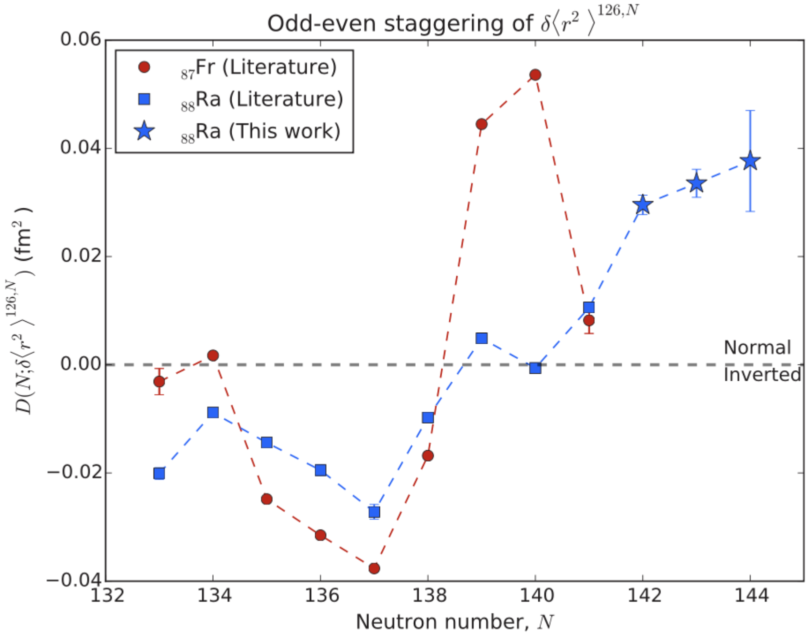
Other identified shapes are triaxial nuclei and **octupole deformed** nuclei.

Their assymetric profile provides orientation to the nucleus, and thus is ideal when exploring parity violating effects in atoms.

This effect is most prominent near N=136 – where nothing is stable! And knowing the radius is crucial.

Octupole-deformed nuclei show a peculiar reversal of the odd-even staggering, that can be used to reveal whether or not their belong to that family.

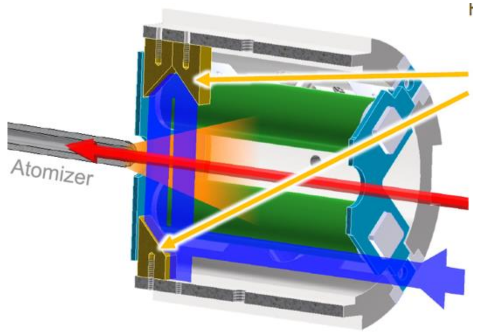




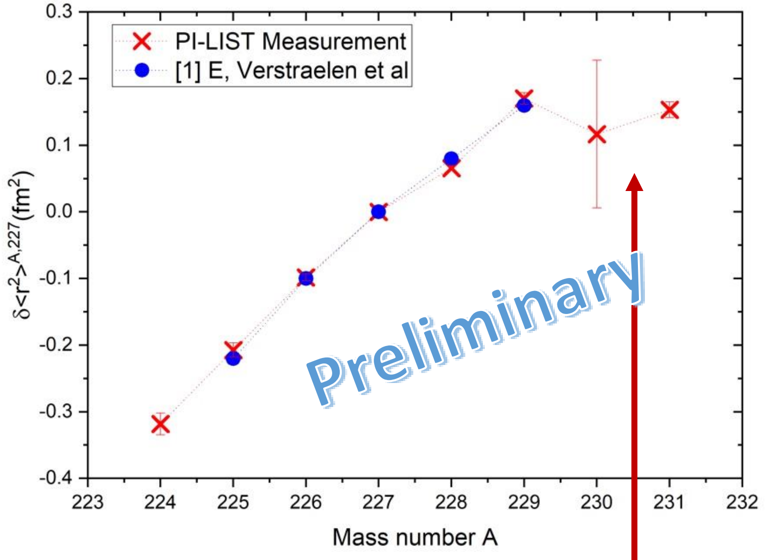
D.A. Fink et al., In-source laser spectroscopy with the LIST: first direct study of the ground-state properties of ^{217,219}Po, Physical Review X **5** *(2015) 011018.*
K.M. Lynch et al., Laser-spectroscopy studies of the nuclear structure of neutron-rich radium, Physical Review C **97** *(2018) 024309.*

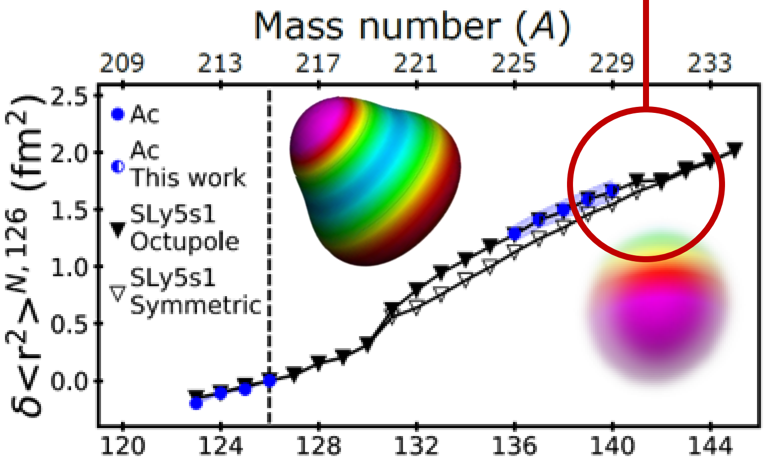
KU LEUVEN

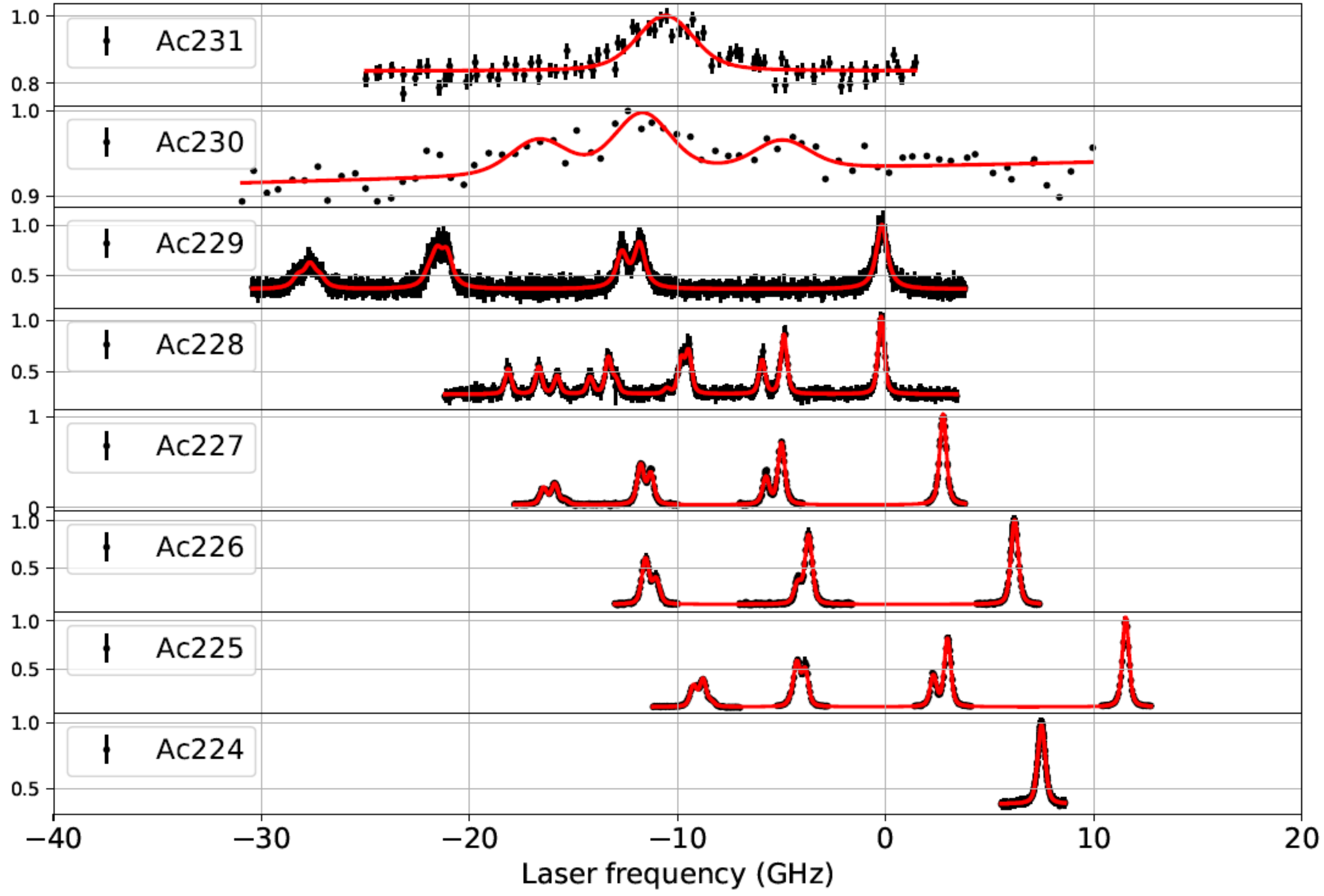
$_{89}$Ac: where theory led



LASER IONISATION AND SPECTROSCOPY OF ACTINIDES



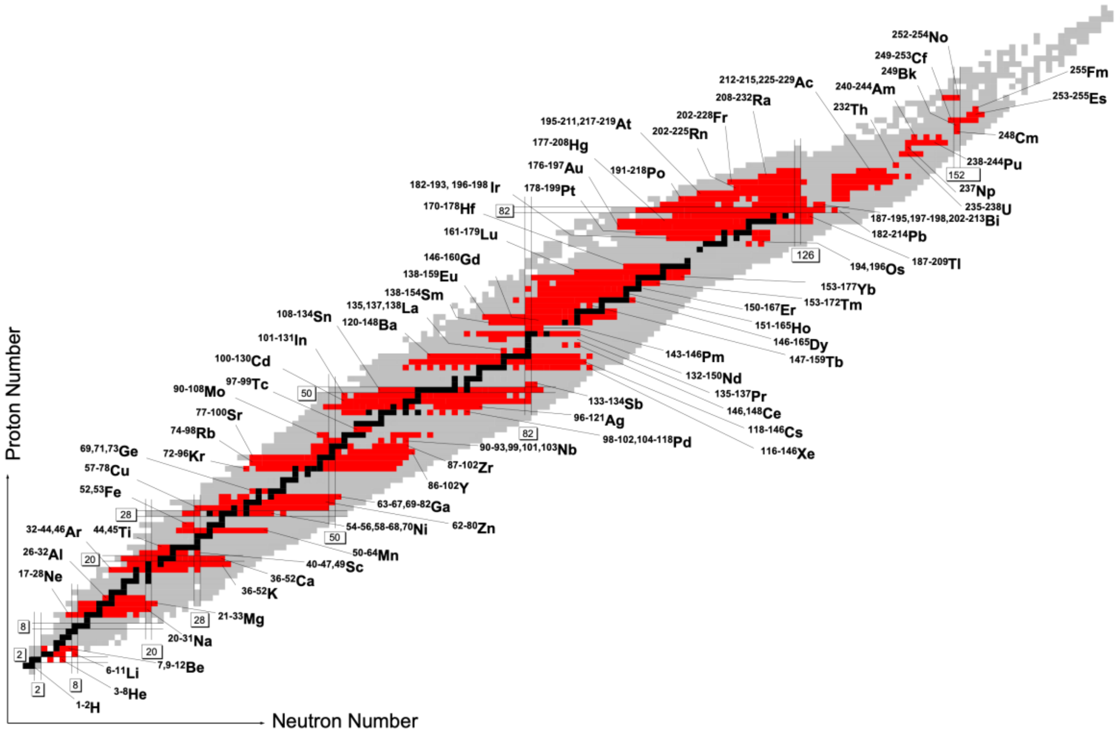




 E. Verstraelen et al., Search for octupole-deformed actinium isotopes using resonance ionization spectroscopy, Physical Review C ***100*** *(2019) 044321.*

Overview of laser spectroscopy

- Many chains of isotopes have been investigated across the nuclear landscape.
- Current efforts are made to expand the reach: to the driplines, to the superheavies, across refractory elements, and for higher precision.
- Full survey: TU Darmstadt



X.F. Yang, S.J. Wnag, S.G. Wilkins, R.F. Garcia Ruiz, *Laser spectroscopy for the study of exotic nuclei*, Progress in Particle and Nuclear Physics **129** (2023) 104005.
P. Campbell, I.D. Moore, M.R. Pearson, *Laser spectroscopy for nuclear structure physics*, Progress in Particle and nuclear Physics **86** (2016) 127-180.
K. Blaum, J. Dilling, W. Nörterhäuser, *Precision atomic physics techniques for nuclear physics with radioactive beams*, Physica Scripta **T152** (2013) 014017.

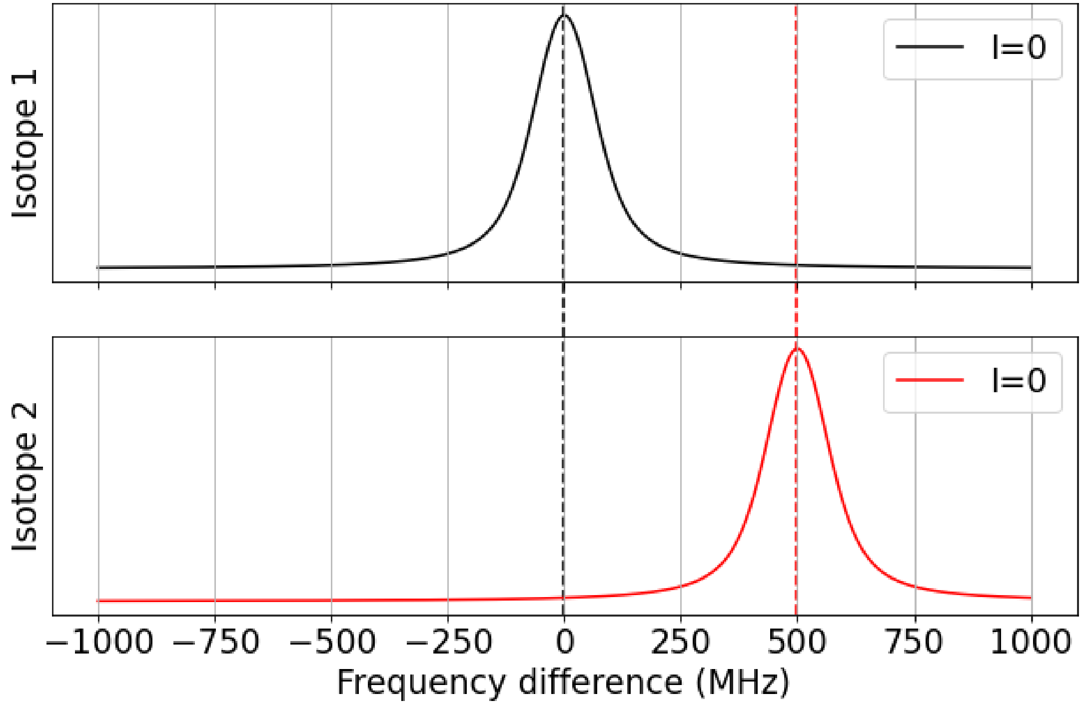
Accuracy limit in extracting charge radii

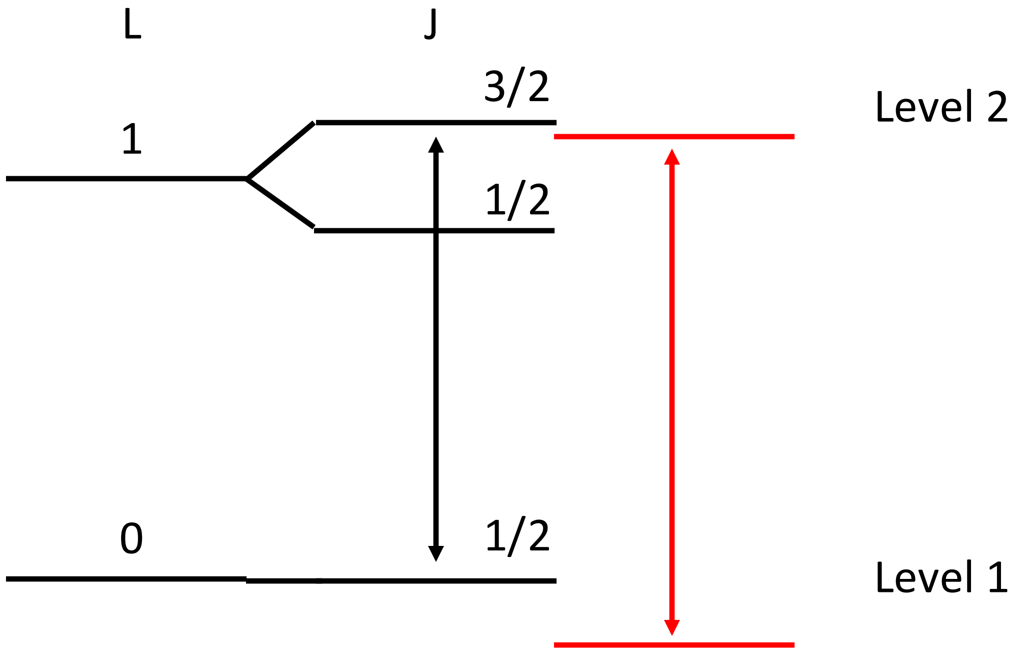
Probing the nucleus through its electrons

Extract isotope shifts $\delta\nu^{A,A'}$ → Infer $\delta < r^2 >^{A,A'}$

$$\delta < r^2 >^{A,A'} = \frac{1}{F}\left(\delta\nu^{A,A'} - M\,\frac{m_{A'} - m_A}{m_A\, m_{A'}}\right)$$

Use lasers to scan for transition energies





I = 0 → No hyperfine splitting

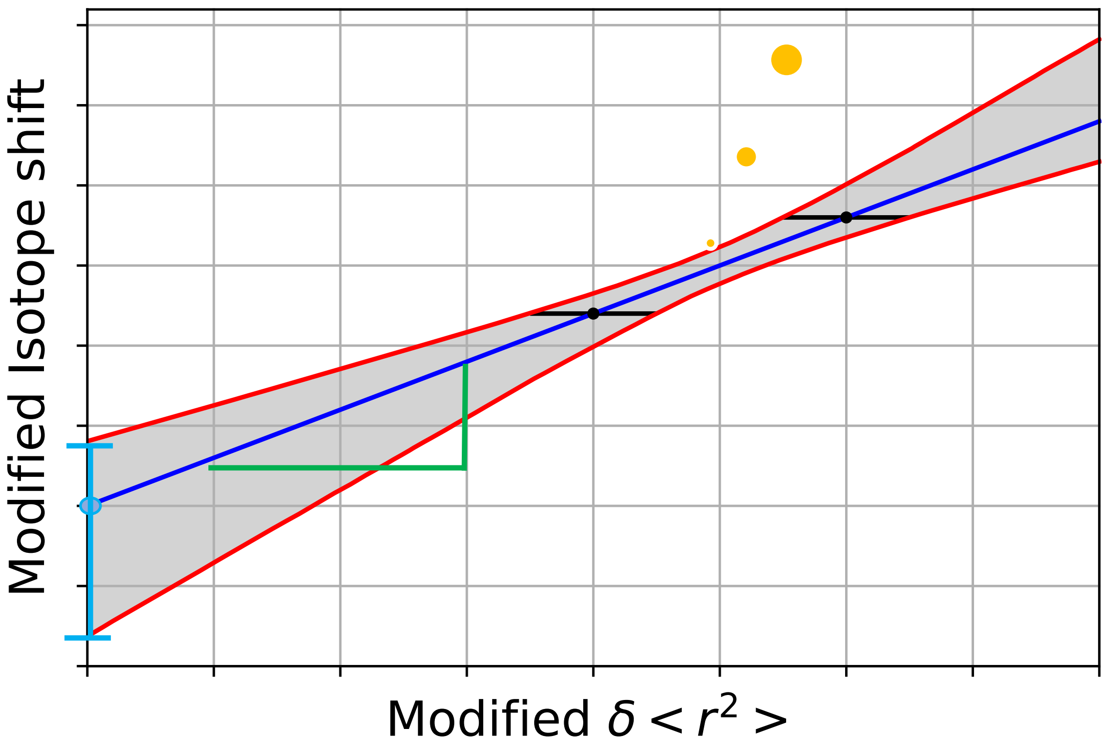
King plot against absolute radii

It takes 3 absolute radii
to produce 2 ∂<r²>

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

- M_i : Mass shift factor
- F_i : Field shift factor

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



From isotope shift to charge radii

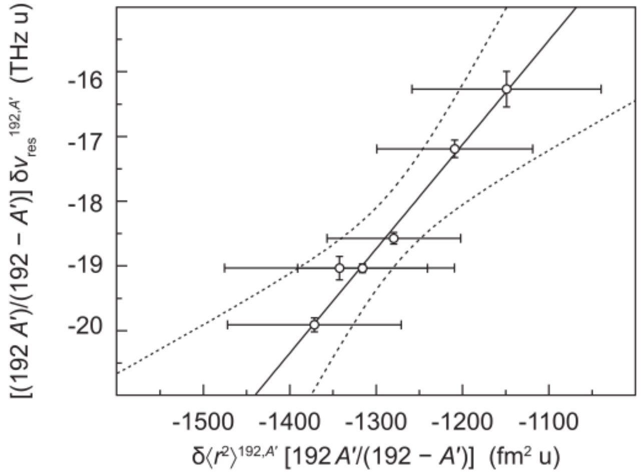
$$\delta\nu^{AA'} = \frac{A'-A}{AA'}\left(m_e\nu + M_{SMS}\right) + F\delta\langle r^2\rangle^{AA'}$$

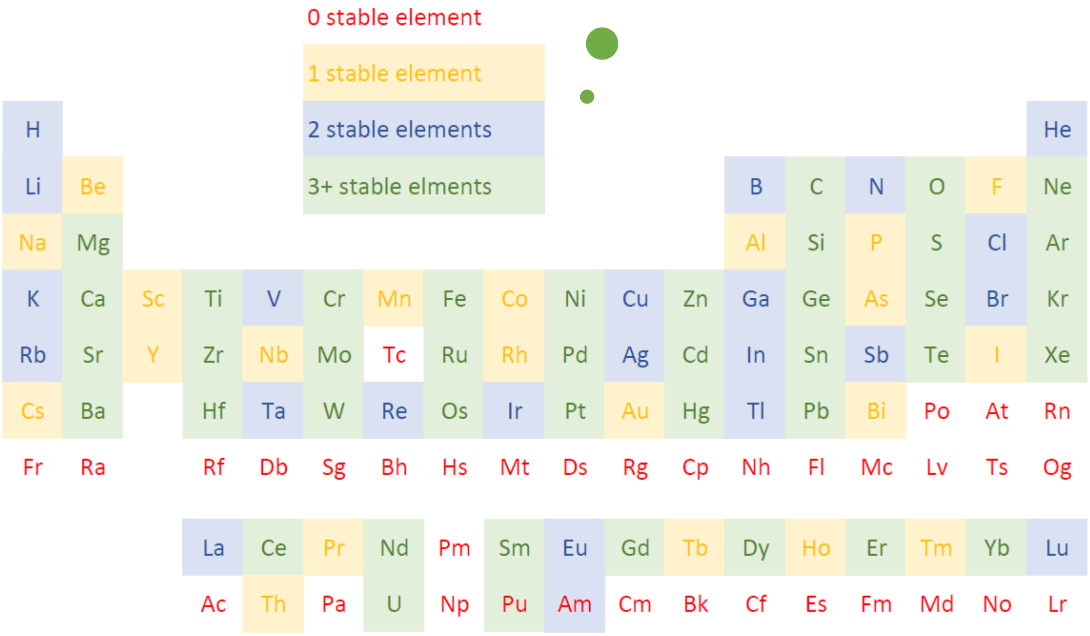
Many elements – all odd-Z & heavy elements – do not possess 3 stable isotopes to work with!

The atomic parameters are essential to extract ∂<r²>
There are atomic theorists who can calculate them.
Experimental extraction or validation is still needed

$$\mu_{AA'}\delta\nu^{AA'} = M + F\mu_{AA'}\delta\langle r^2\rangle^{AA'}$$

$$\mu_{AA'} = \frac{AA'}{A'-A}$$

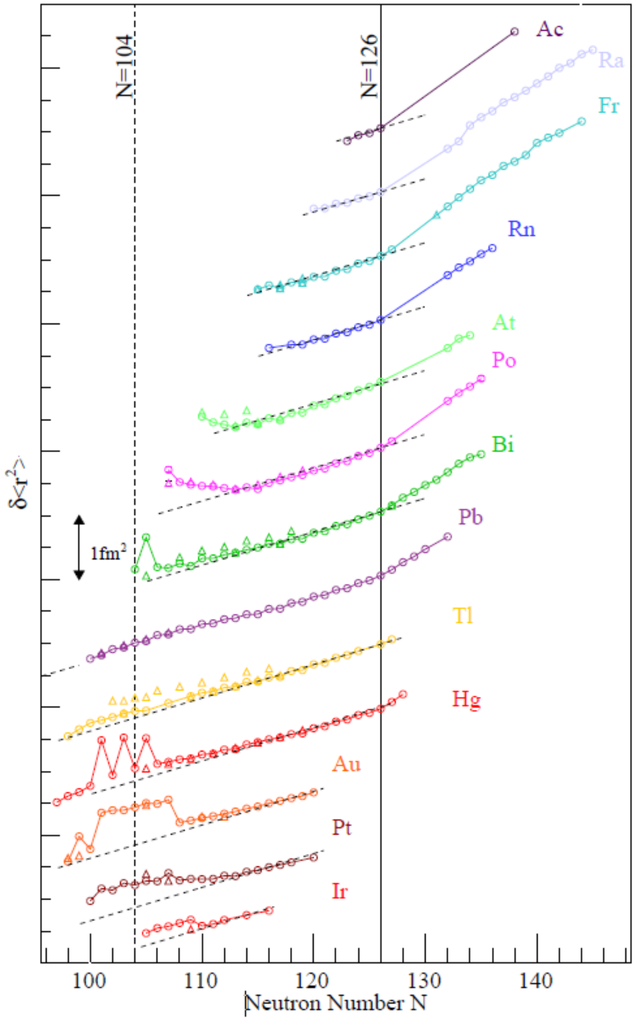




A. Kellerbauer et al., Isotope shift of the electric-dipole transition in Os⁻, Physical Review A ***84*** *(2011) 062510.*
T.E. Cocolios, A new perspective on charge radii around Z = 82, Hyperfine Interactions ***238*** *(2017) 16.*

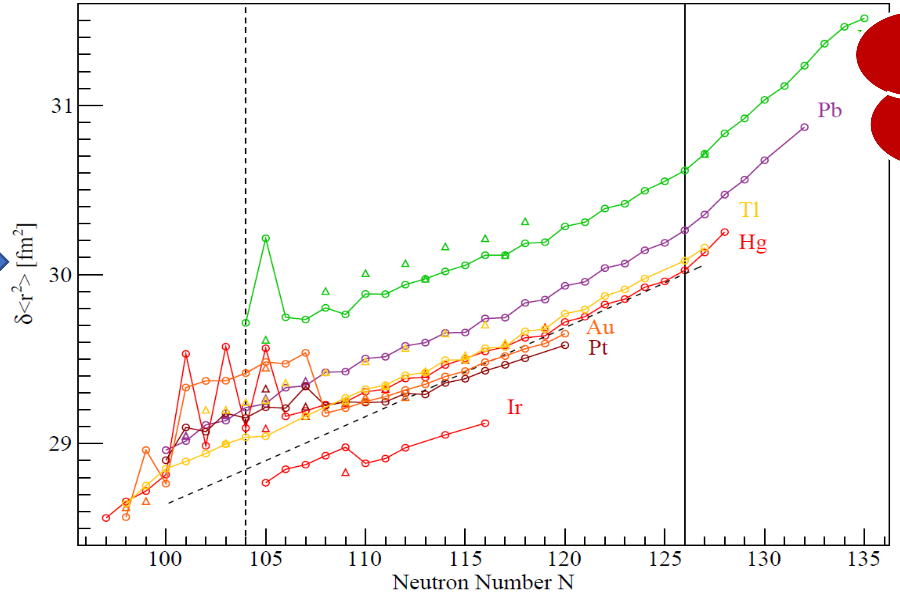
Absolute size of the heavy elem

Key measurements of absolute charge radii could easily complete this picture

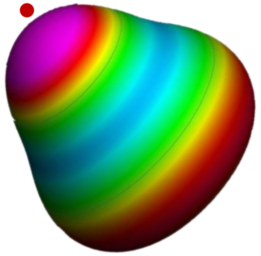


Exploring isotonic chains across Z=82

- Last known magic proton number
- No anchor point between $_{83}$Bi and $_{90}$Th prevents to investigate these isotopes extensively



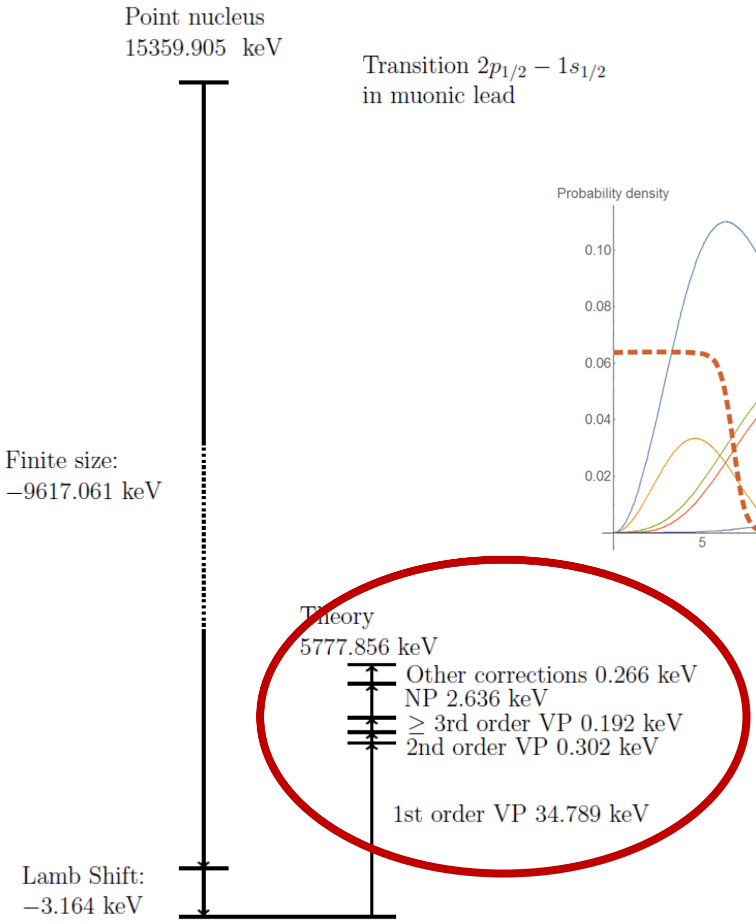
Absolute charge radii are needed for the searches of physics beyond the standard model

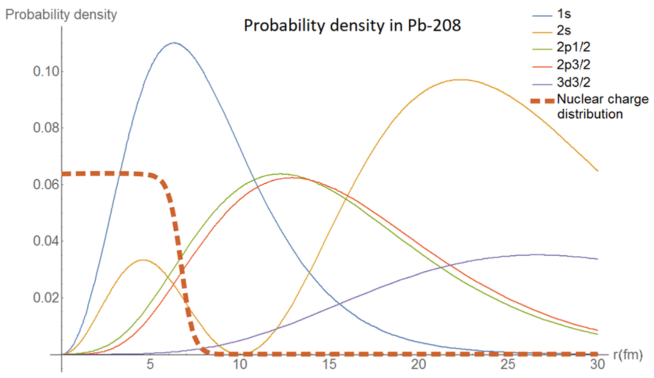


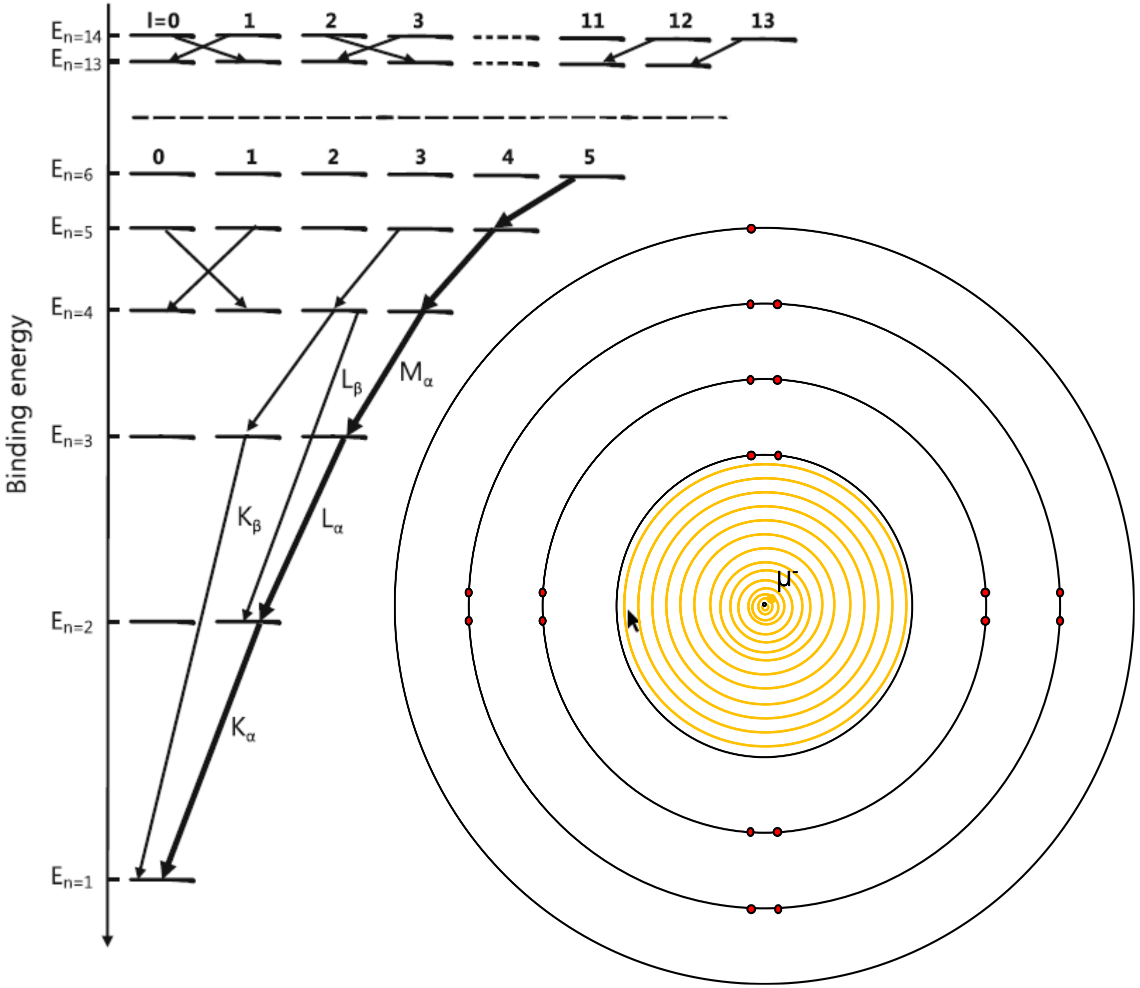
*Pictures adapted from T.E. Cocolios, A new perspective on charge radii around Z = 82, Hyperfine Interactions **238** (2017) 16.*

muX and ReferenceRadii

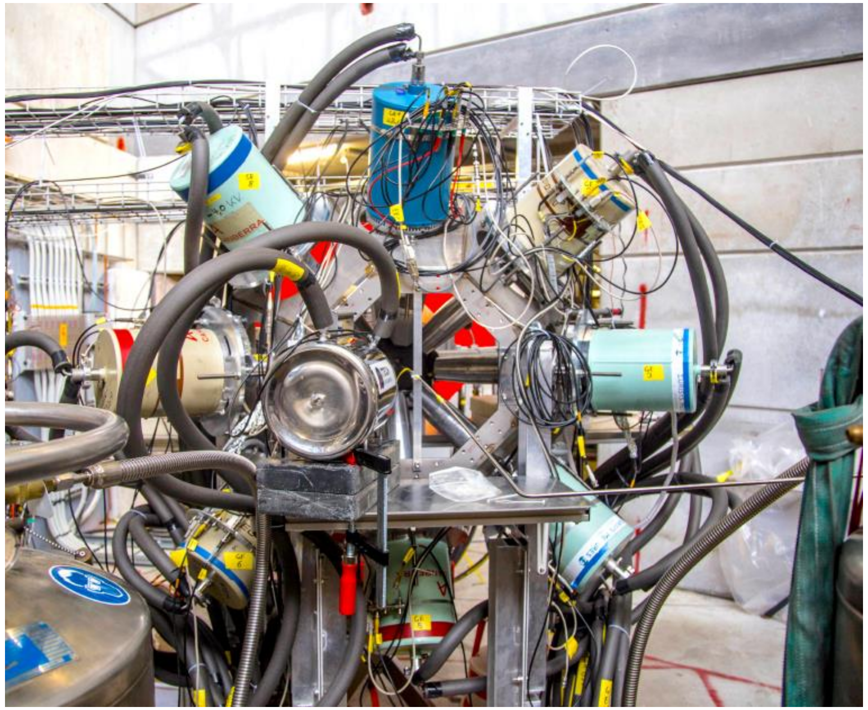
Muonic x-rays as probe

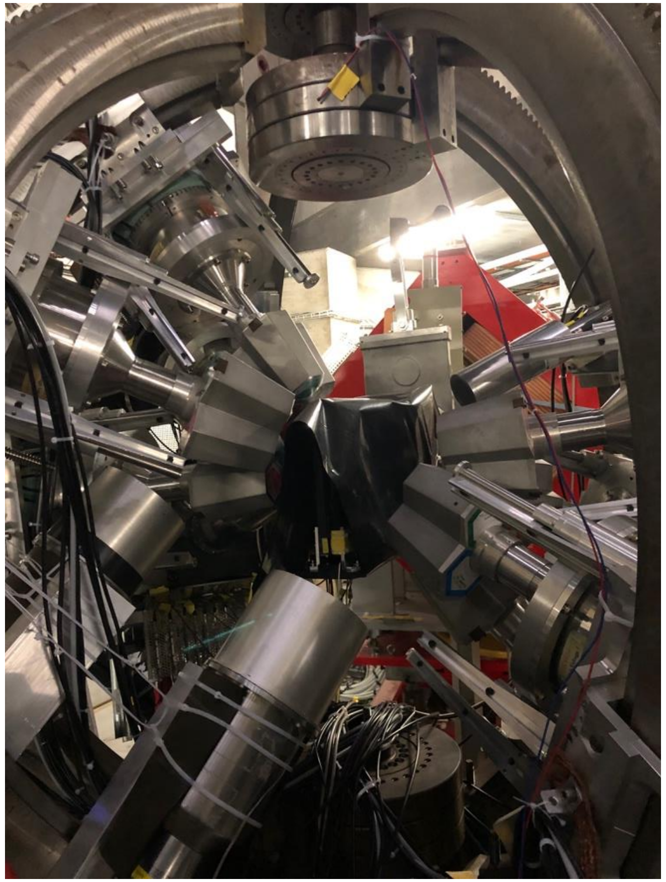






μ-atomic spectroscopy with muX at PSI





- 2016: 2 HPGe from Leuven
- 2017/18: the Death Star Array

  MiniBall Cluster + detectors from PSI & IPNO
- 2019: MiniBall @ PSI campaign
- 2020+: GIANT Array with MIXE, muX and muon capture

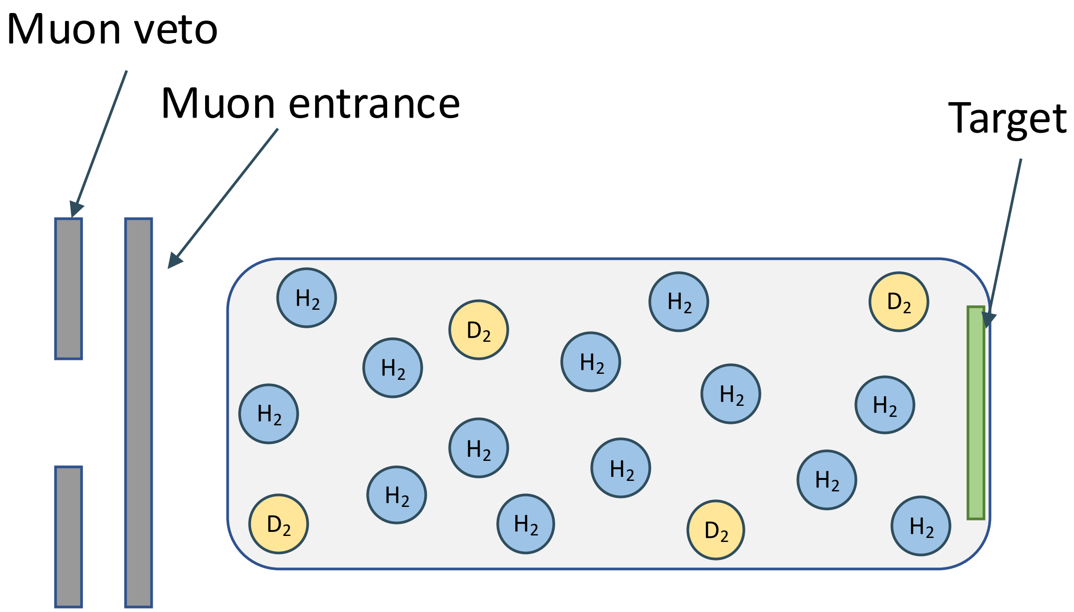
A. Adamczak et al, Nuclear structure with radioactive muonic atoms, EPJ WC ***193*** *(2018) 04014.*
A. Skawran et al, Towards nuclear structure with radioactive muonic atoms, Il Nuovo Cimento ***42 C*** *(2019) 125.*

Measuring microgram materials

Traditionally: Limited to target mass O(10-100 mg)

Hydrogen gas cell (100 bars; 0.25% deuterium)

- Limited to O(5 µg)
- Down to 20 year half-life (radioprotection)



Bubak, M., & Fajman, M. P. (1987). *Cross sections for hydrogen muonic atomic processes in two-level approximation of the adiabatic framework* (No. JINR-E--4-87-464). Joint Inst. for Nuclear Research.
Adamczak, Andrzej, et al. "Muonic atom spectroscopy with microgram target material." *The European Physical Journal A* **59** (2023): 15.

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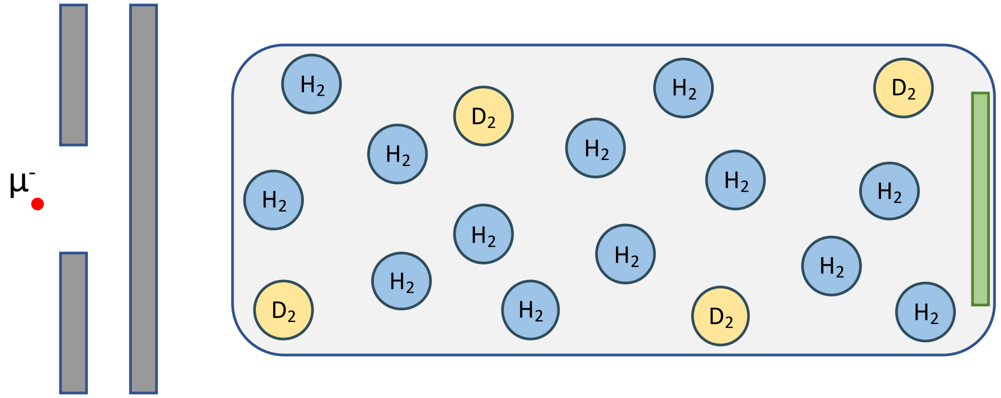

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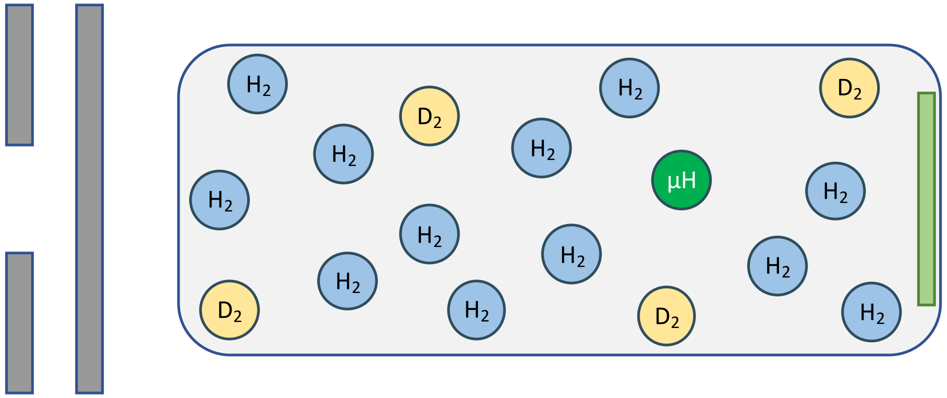

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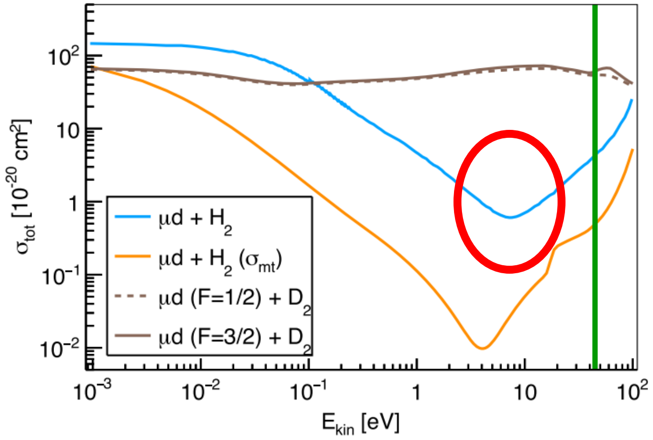
Measuring microgram materi



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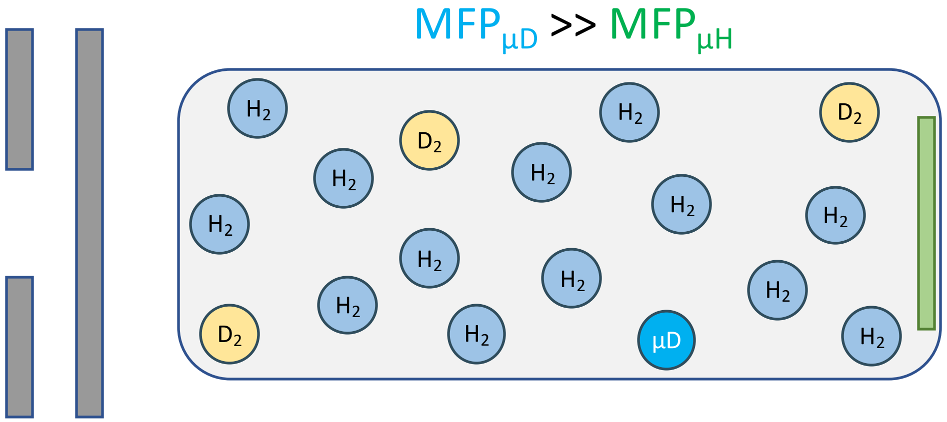

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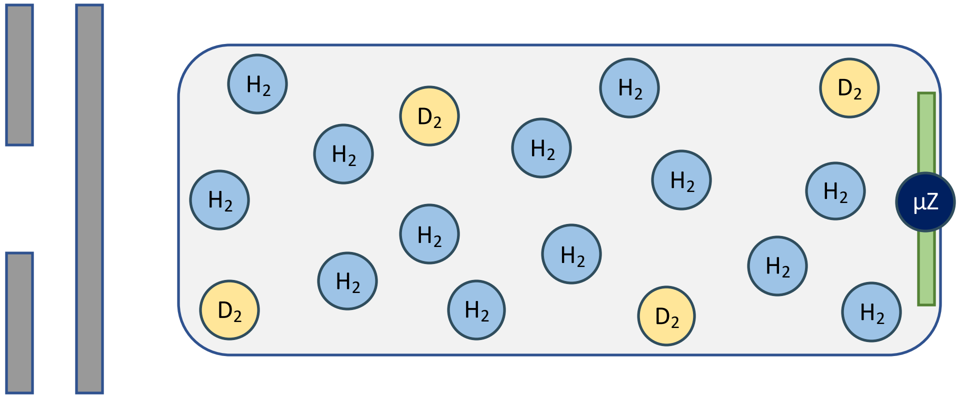

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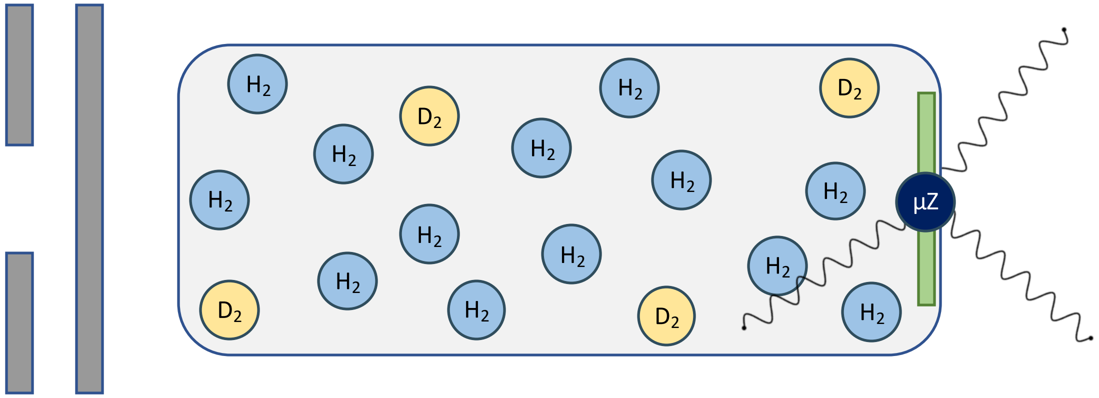
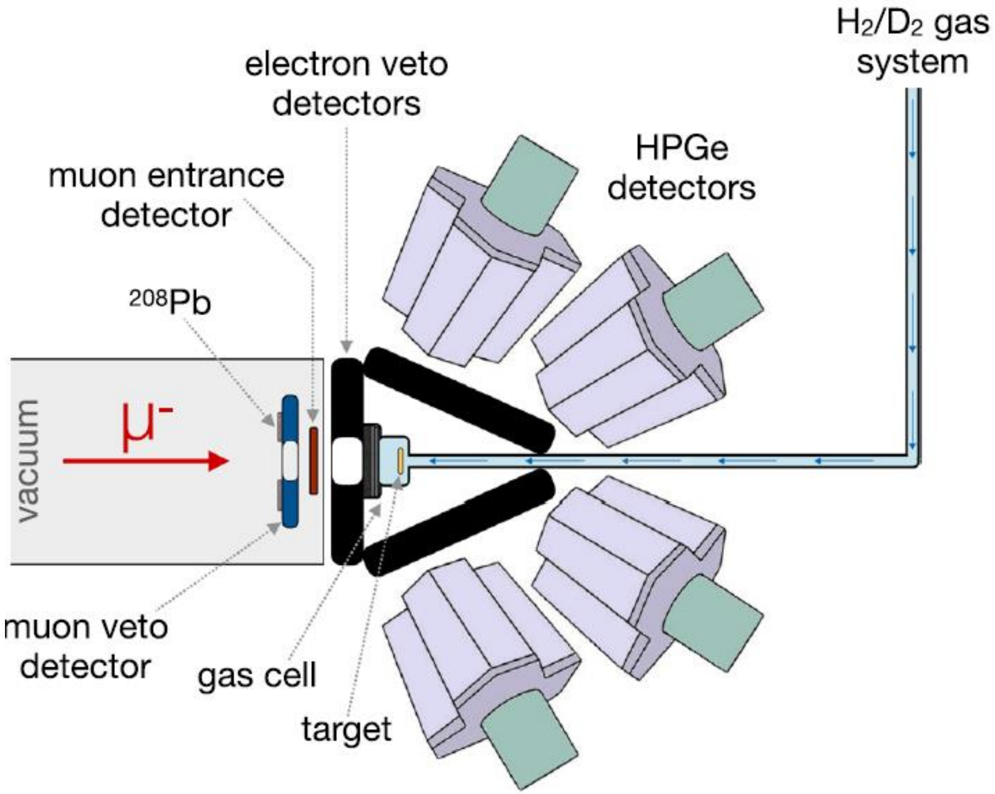
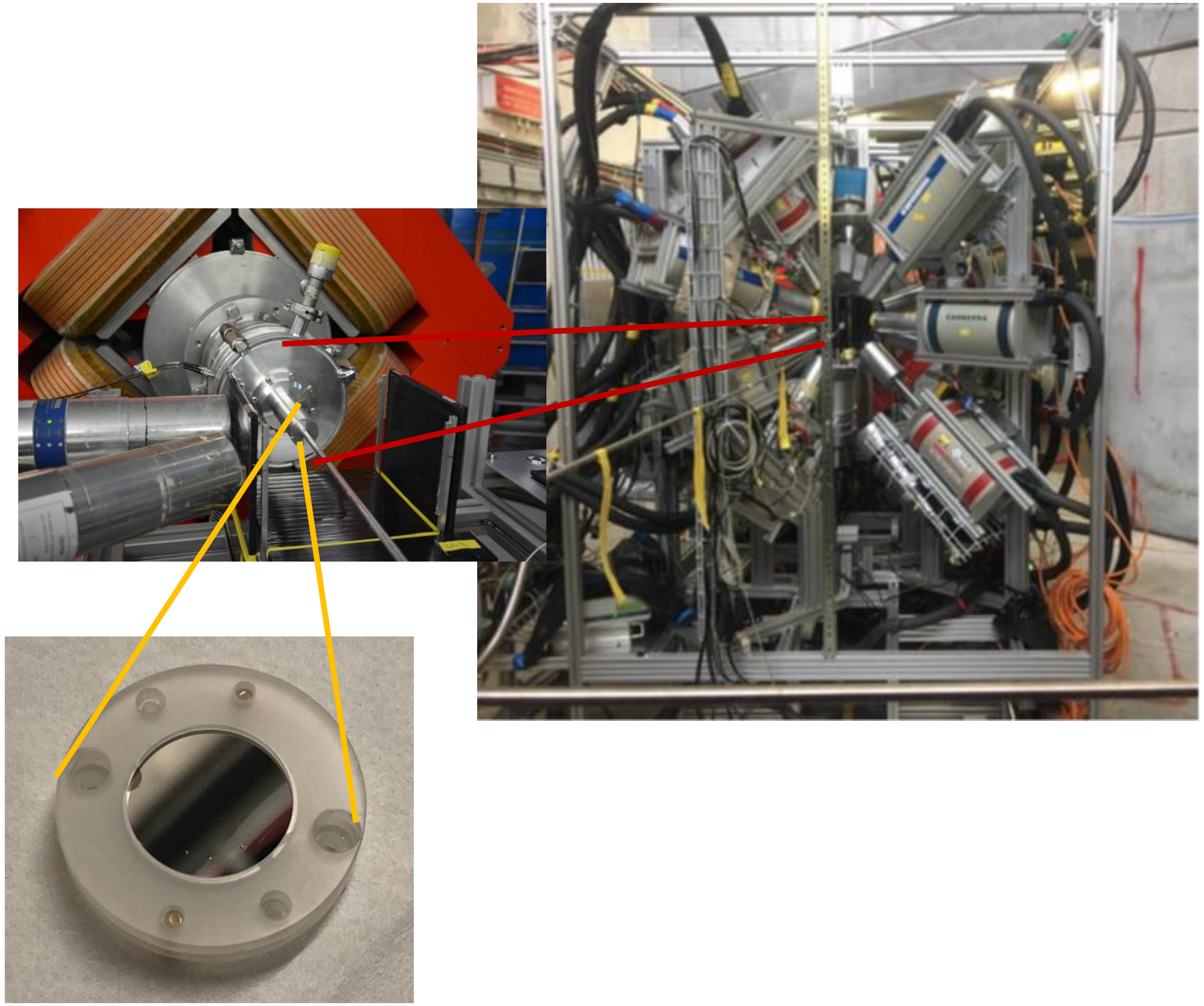


Bubak, M., & Fajman, M. P. (1987). *Cross sections for hydrogen muonic atomic processes in two-level approximation of the adiabatic framework* (No. JINR-E--4-87-464). Joint Inst. for Nuclear Research.
Adamczak, Andrzej, et al. "Muonic atom spectroscopy with microgram target material." The European Physical Journal A ***59*** *(2023): 15.*

μ-atomic spectroscopy with muX at PSI





A. Adamczak et al., Muonic atom spectroscopy with microgram target material, Eur. Phys. A ***59*** *(2023) 15.*

$_{17}$Cl and $_{19}$K: probing near Z=20

2023

- Used enriched targets of ^{35}Cl, ^{37}Cl, ^{39}K, ^{40}K, ^{41}K.
- ^{40}K required mass separation to obtain a pure sample.

NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

- First measurement with pure Cl isotopes and first measurement of ^{40}K for a full triplet.

L. Antwiss et al., A comparative study of target fabrication strategies for microgram muonic atom spectroscopy, Scientific Reports ***15*** *(2025) 6939.*

KU LEUVEN 600

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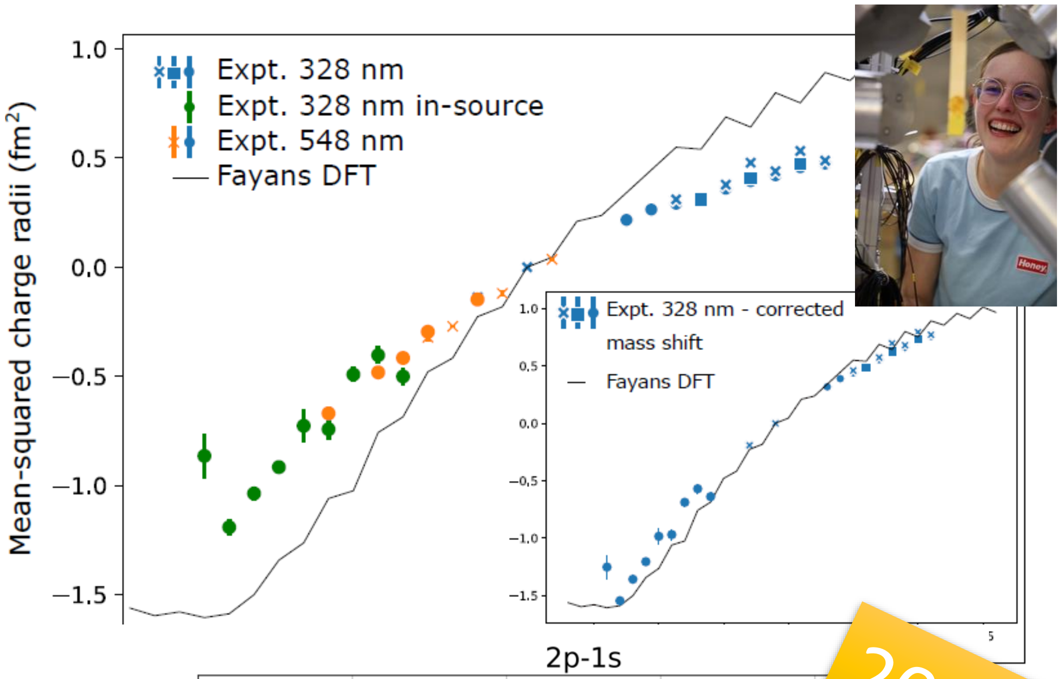
$_{47}$Ag

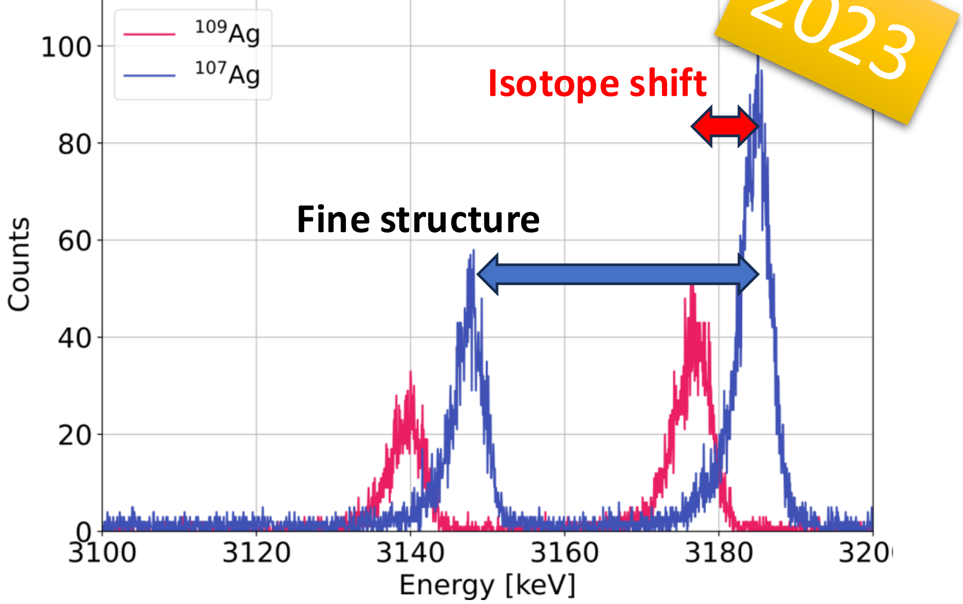
Extensive new data have recently been collected on Ag, from ^{95}Ag to ^{129}Ag, at Jyväskylä and ISOLDE.

The N=Z isotope ^{94}Ag remains a major interest to elucidate the infamous 2-proton emission and measure the shape of that emitting state.

However, all the current data are is mutual disagreements and also with nuclear theory. Atomic theory is the one to blame!

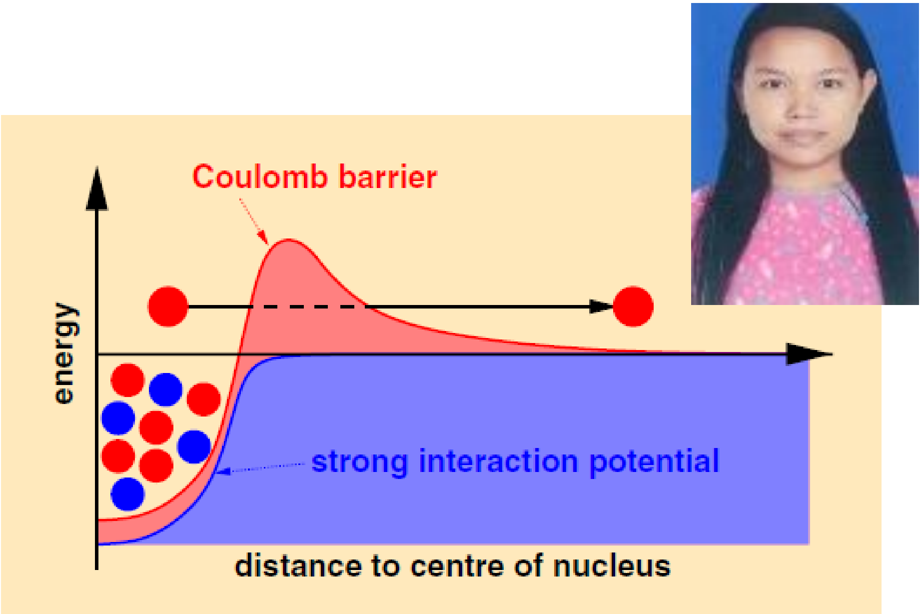
Experimental benchmark require ^{107,108m,109}Ag – and input for radii extraction when we get the data (expected in 2026).





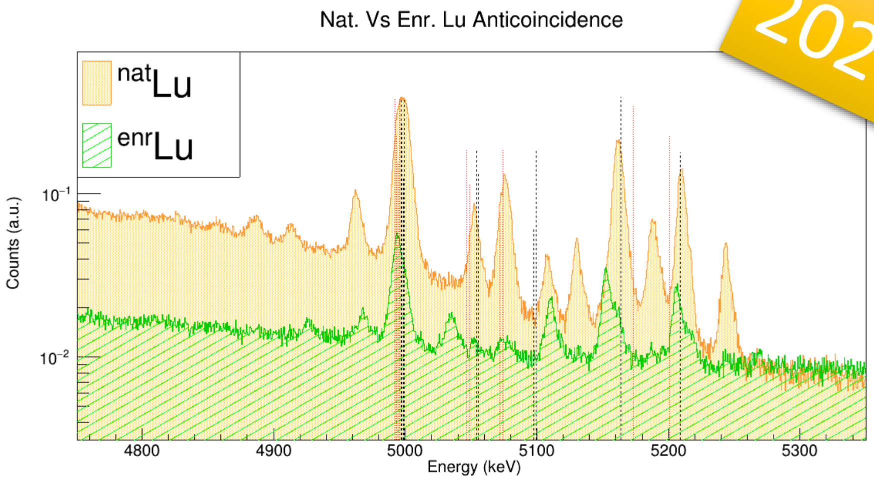
PhD work Marie Deseyn (KU Leuven).
Ag laser spectroscopy data courtesy B. van den Borne & R.P. de Groote.

$_{71}$Lu



Across the rare earth elements, there is a big effort to reach out to proton emitters with laser spectroscopy: $_{57}$La, $_{65}$Tb, $_{67}$Ho, $_{69}$Tm, $_{71}$Lu all seem within reach of the upcoming facilities (FRIB, MARA, S3).

2024

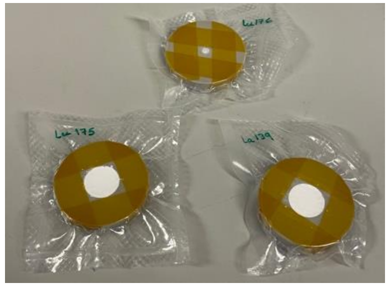


The question being: 'where' is the proton? Is it still confined? Already spread beyond the nucleus?

All those are, by default, odd-Z elements…

Amazing data from 2024!

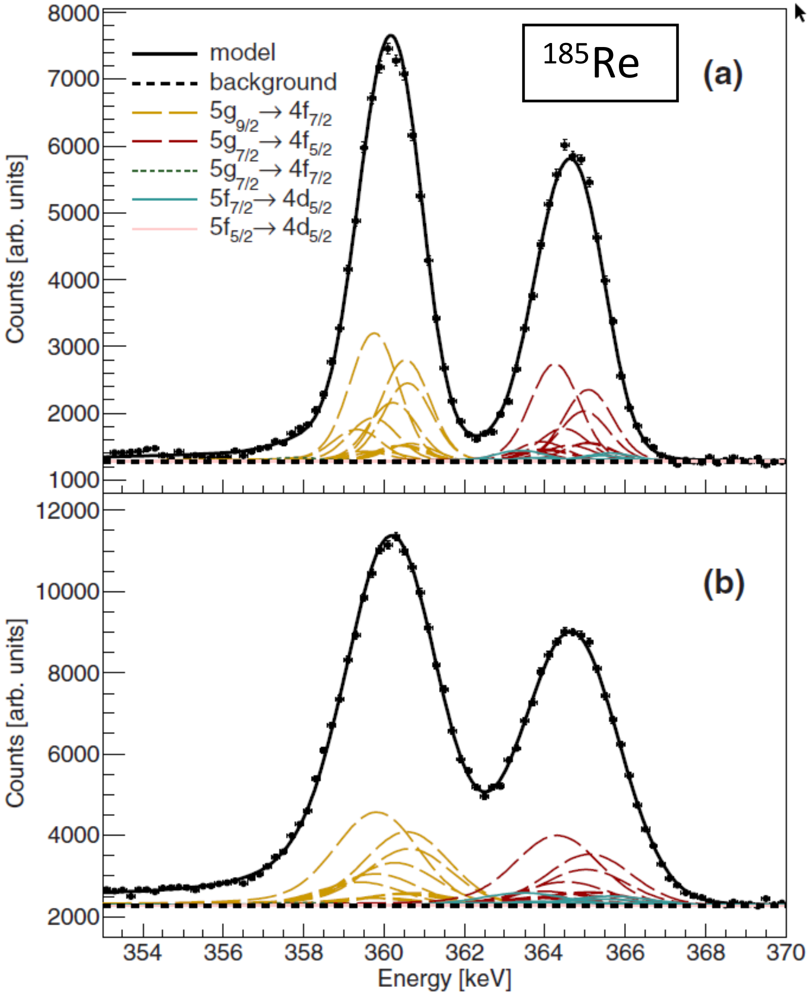
- ^{nat}Lu (97.4% ^{175}Lu vs 2.6% ^{176}Lu)
- ^{enr}Lu (25% ^{175}Lu vs 75% ^{176}Lu)

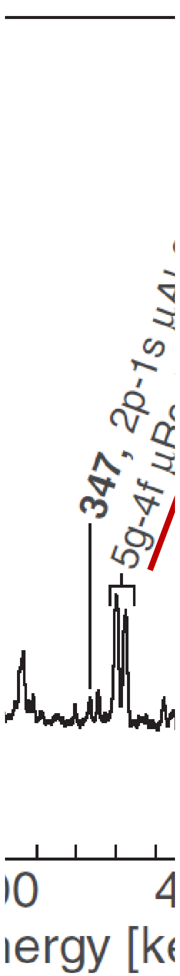


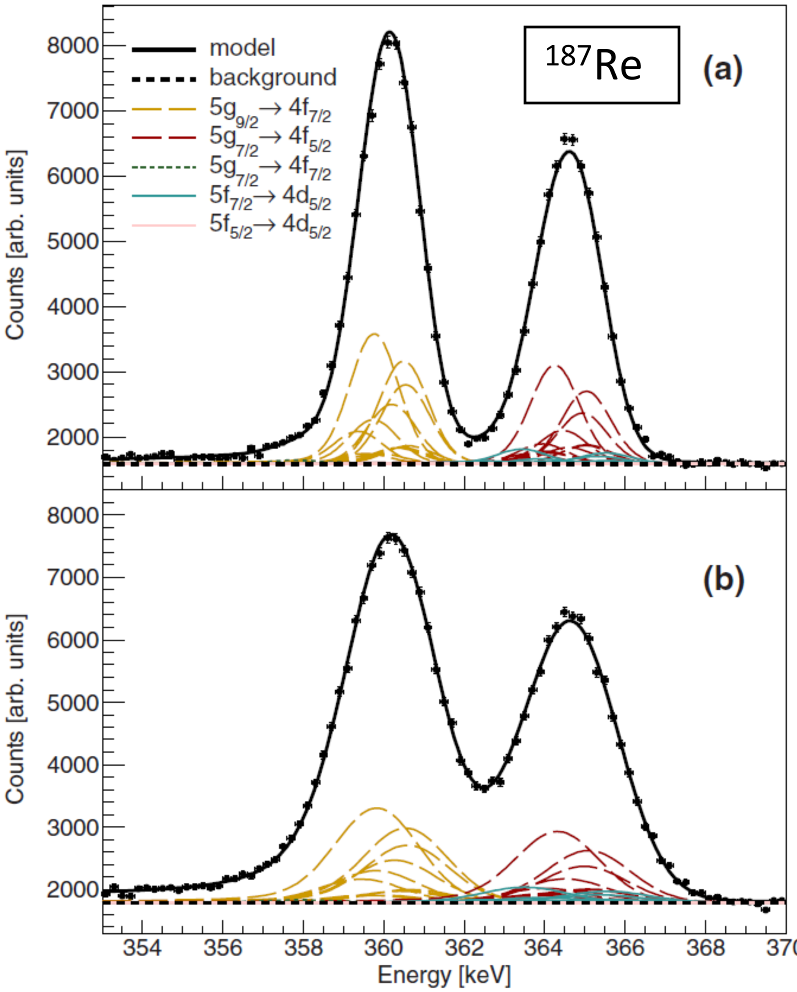
PhD work War War Myint Myat Phyo (KU Leuven).

*B. Blank & M Płoszajczak, Two-proton radioactivity, Report on Progress in Physics **71** (2008) 046301.*

Quadrupole moment of ^{185,187}Re







:

test on macroscopic

les of ^{185,187}Re

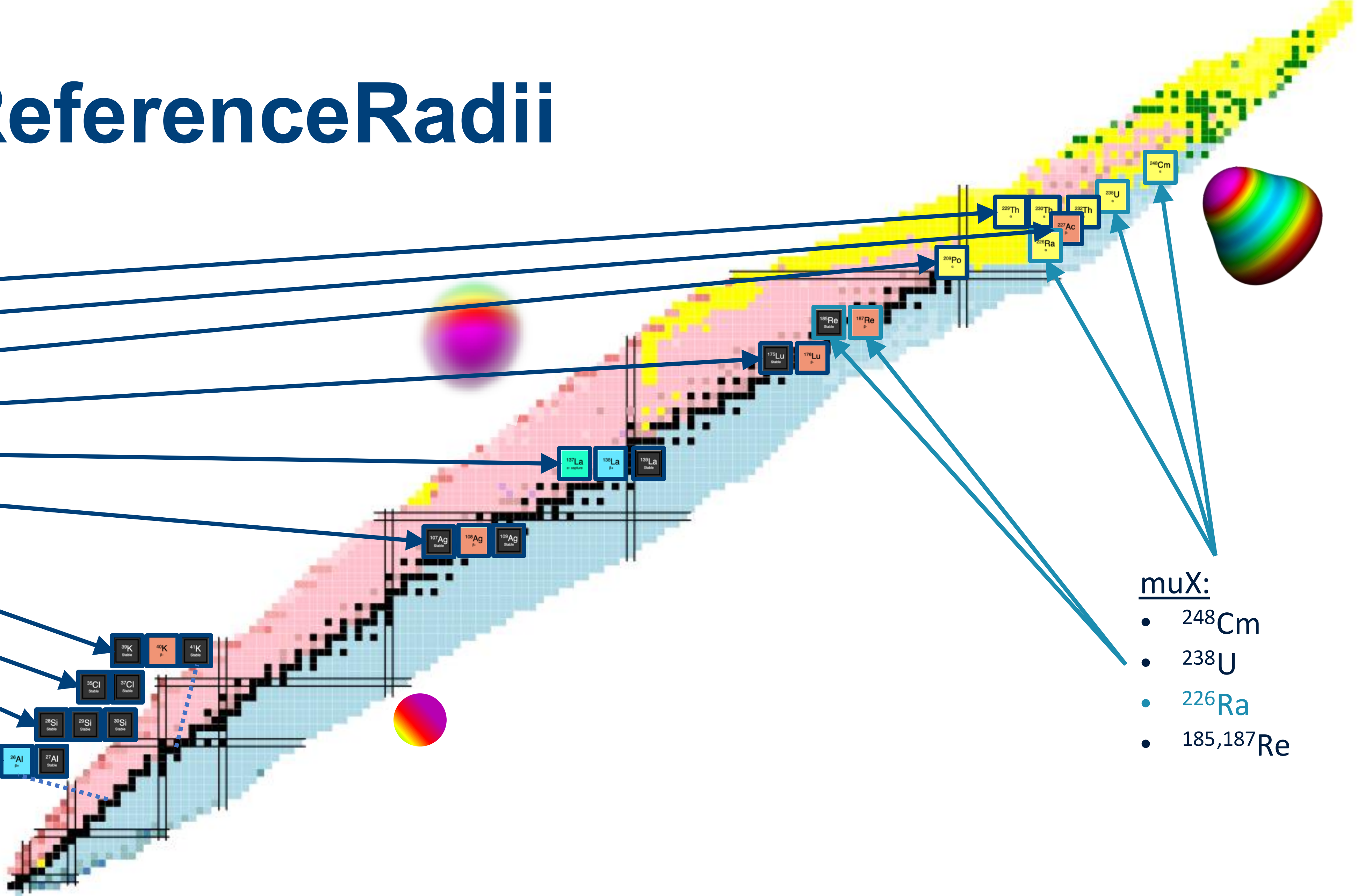
Those two peaks contain 76 different components fitted simultaneously!

A. Antognini et al, Measurement of the quadrupole moment of ^{185}Re and ^{187}Re from the hyperfine structure of muonic X rays, Physical Review C ***101*** *(2020) 054313.*

muX & ReferenceRadii

ReferenceRadii:

- ^{229,230,232}Th
- ^{227}Ac
- ^{209}Po
- ^{175,176}Lu
- ^{137,138,139}La
- ^{107,108m,109}Ag
- ^{39,40,41}K
- ^{35,37}Cl
- ^{28,29,30}Si
- ^{26,27}Al



muX:

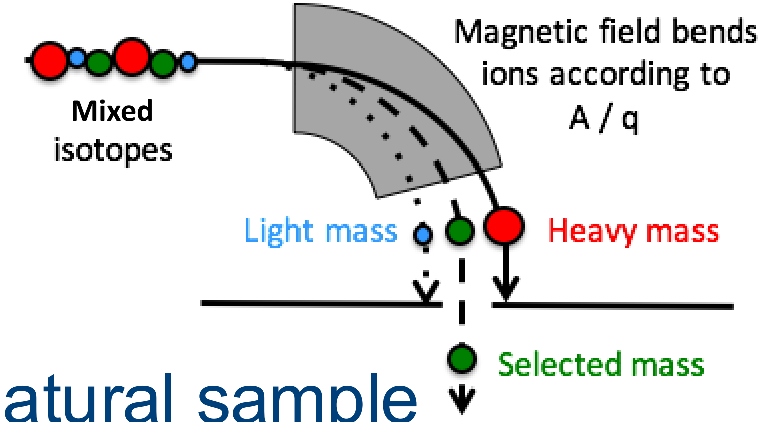
- ^{248}Cm
- ^{238}U
- ^{226}Ra
- ^{185,187}Re

- Charge radii are used extensively to probe nuclear structure and challenge nuclear models.
- Long isotopic chains have been investigated thanks to laser spectroscopy, but accuracy is highly impacted by the shortage of absolute radii, especially for odd-Z and heavy elements.
- muX and ReferenceRadii have an intense program addressing this, from $_{13}Al$ to $_{96}Cm$.
- Challenges include target production, background suppression, data analysis, atomic & nuclear corrections, …
- Our first results are out (quadrupole moments of $^{185,187}Re$, absolute radii of $^{35,37}Cl$) and more is coming!
- We are bringing the IDS detector array to PSI in 2026 for an exciting campaign!

This project has received support from the FWO, grant G0G3121N and fellowship 11P6V24N, and for the European Commission, ERC Consolidator Grant 101088504 (NSHAPE).

Back up:
Production of ^{40}K

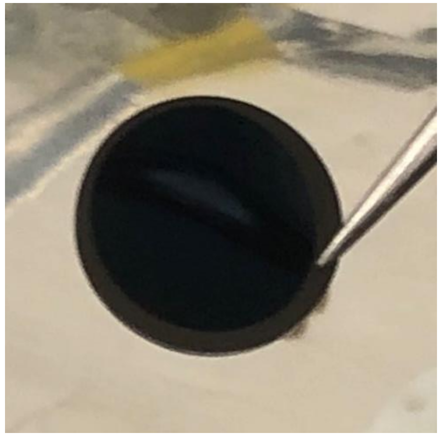
^{40}K target

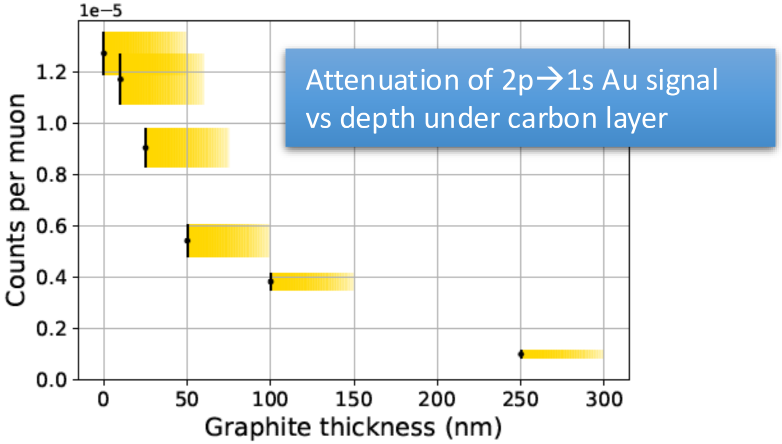


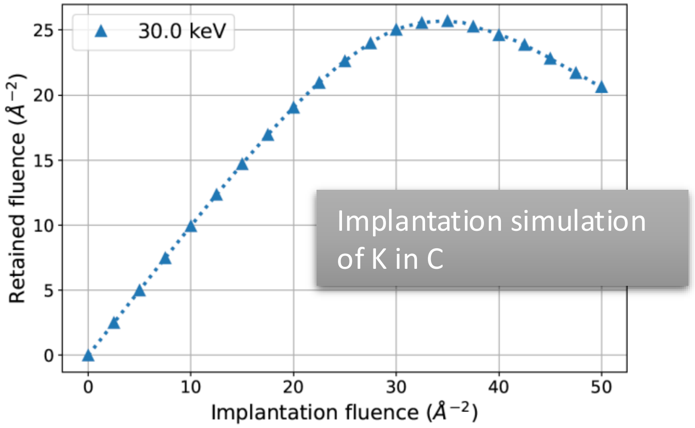
With its natural abundance of only 0,01%, ^{40}K from a natural sample is not sufficient to allow for a measurement at muX.

Commercially available enrichment is limited to 17%, which is still insufficient.

➢Use of the mass separator at iThemba LABS (South Africa) to implant ^{40}K in a carbon sample.





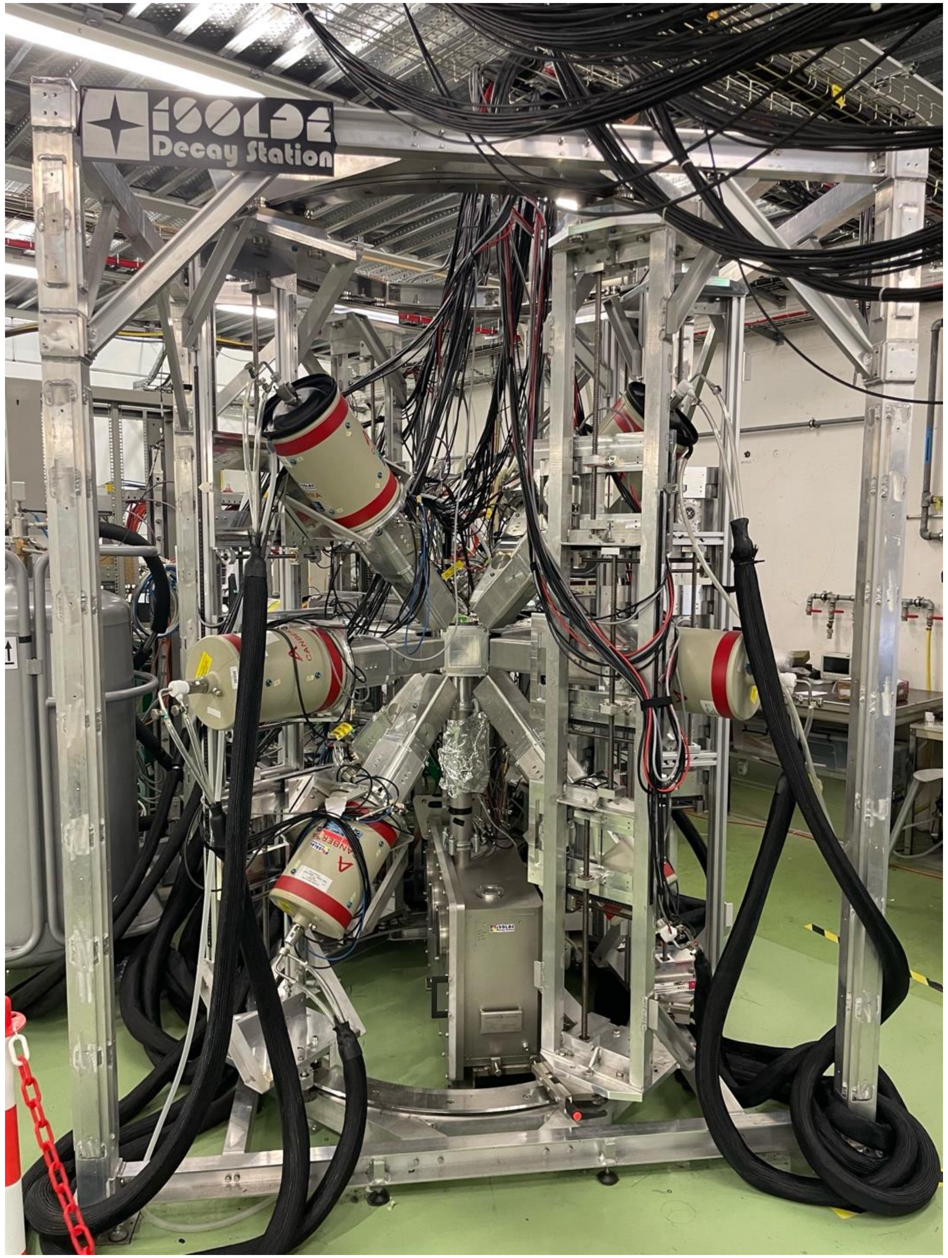


L. Antwiss et al., *A comparative study of target fabrication strategies for microgram muonic atom spectroscopy*, *Scientific Reports* **15** (2025) 6939.

ISOLDE Decay Station:
A large HPGe array with up to 15 clovers

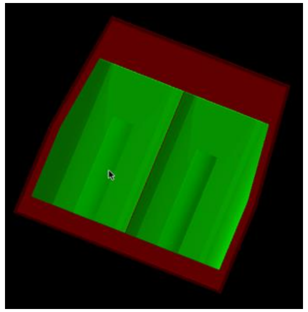
IDS

- IDS is a permanent setup at CERN ISOLDE, used for the decay spectroscopy of exotic radionuclides.
- It consists of 12 HPGe clovers that can be placed in various configurations around a decay point equipped with a tape for activity build-up removal and charged particle detectors.
- Its support system is made of 5 gantries that can each host up to 3 clovers at once with various degrees of freedom for positioning.



IDS Clover

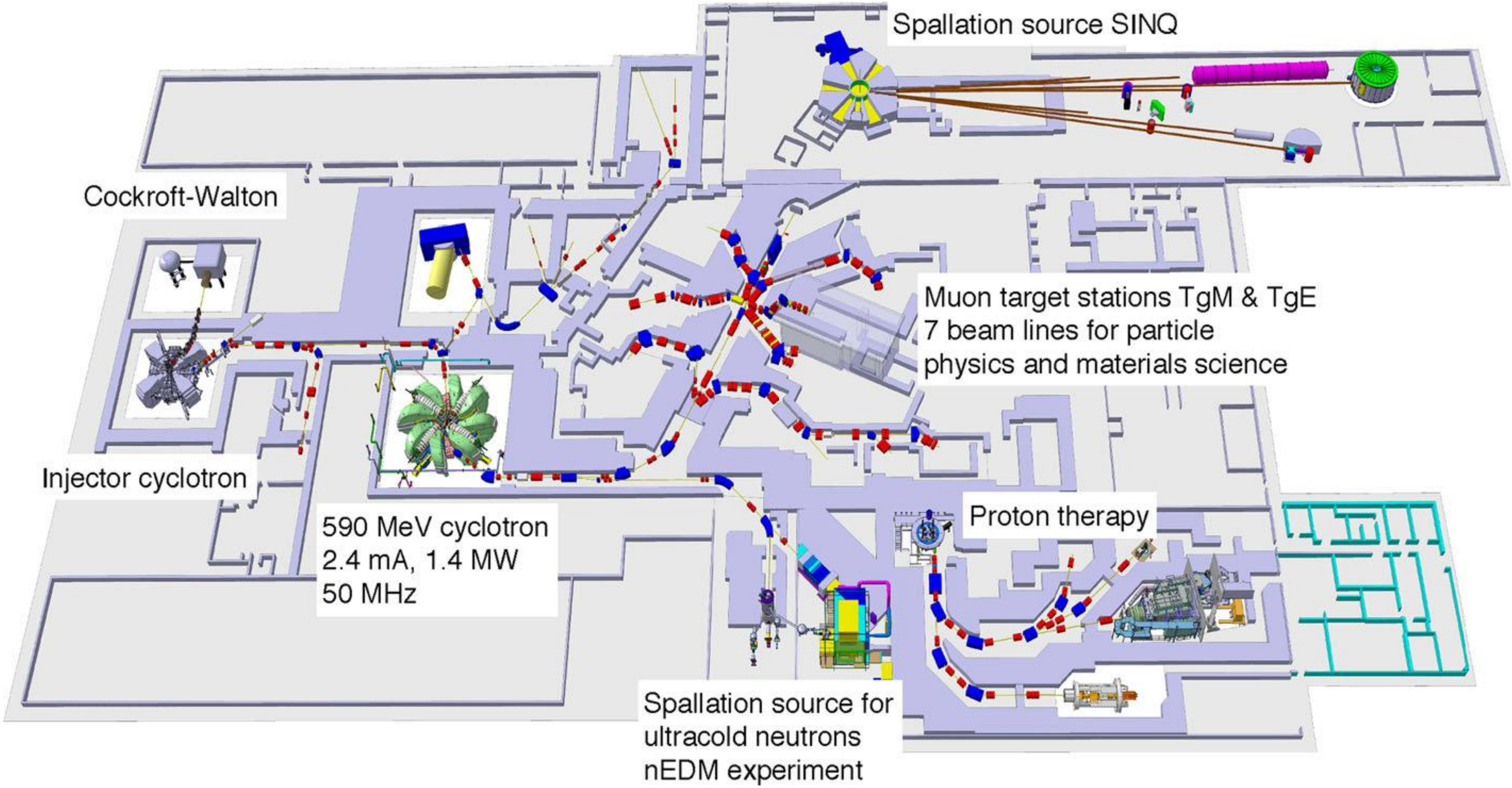
2 new clovers received today at KU Leuven!!



- Based on the Euroball design from Mirion with reduced distance from front to crystal.
- Each clover consists of 4 crystals with 23% relative size.
- With very thin layers between each crystal, it is possible to perform add-back to compensate for Compton scattering, resulting in an equivalent total size of 140% per clover.
- 2 of the clovers are equiped with a thin carbon windown to increase the dynamic range towards the lowest photon energies.
- A total of 15 clovers are available within the collaboration.

Back up:
Measurements at PSI

muX @ PSI



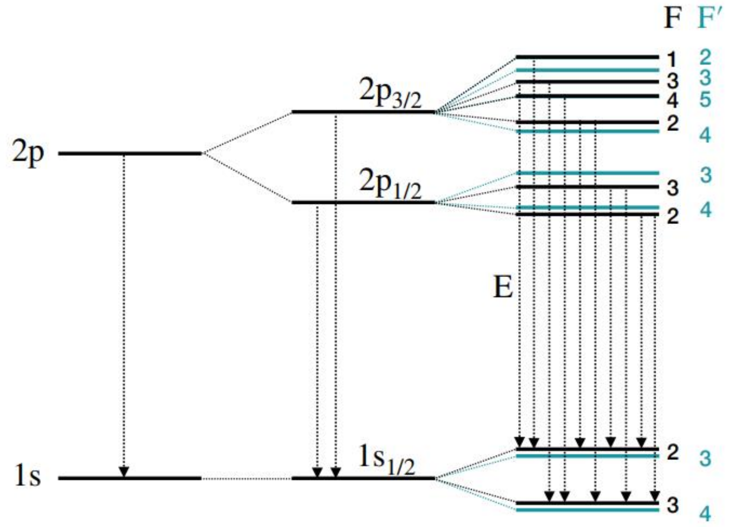
A. Knecht, A. Skawran, S.M. Vogiatzi, Study of nuclear properties with muonic atoms, Eur. Phys. J. Plus **135** (2020) 135.

Dynamic hyperfine splitting

Slide courtesy: Stell[a]
Vogiatzi

Fine splitting (FS): $\vec{J} = \vec{l} + \vec{s}$

Static hyperfine splitting (HFS): $\vec{F} = \vec{I} + \vec{J}$



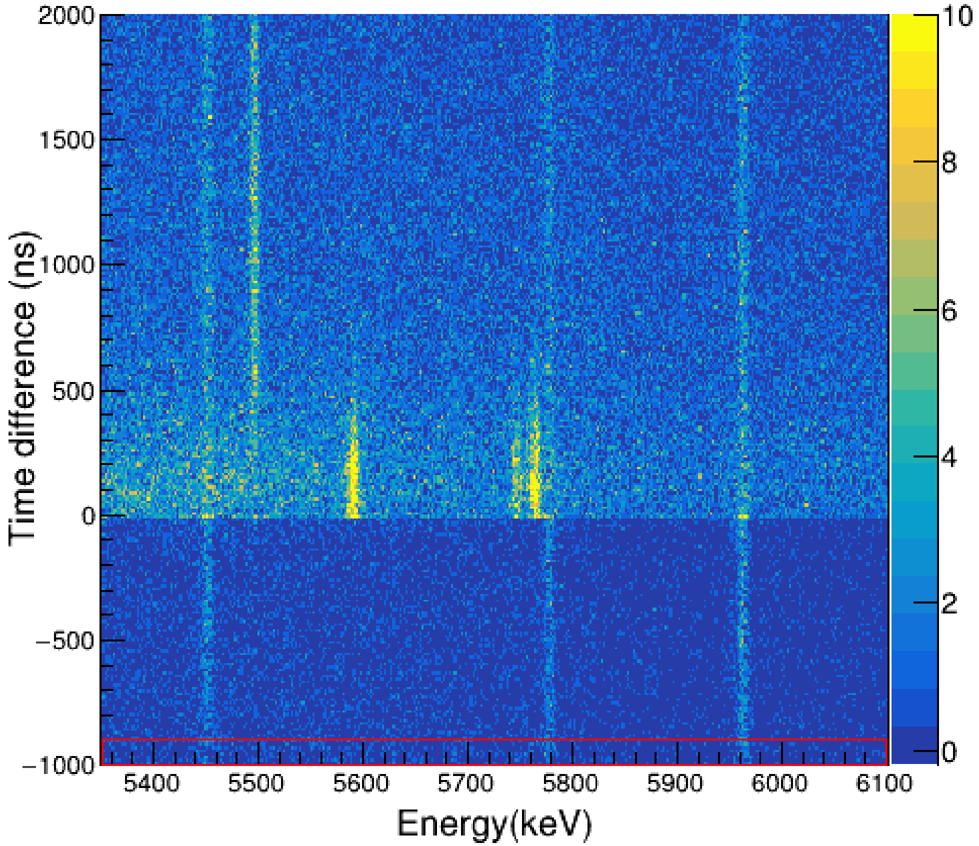
$I_{ground} = \frac{5}{2}^{+}$ $I_{excited} = \frac{7}{2}^{+}$

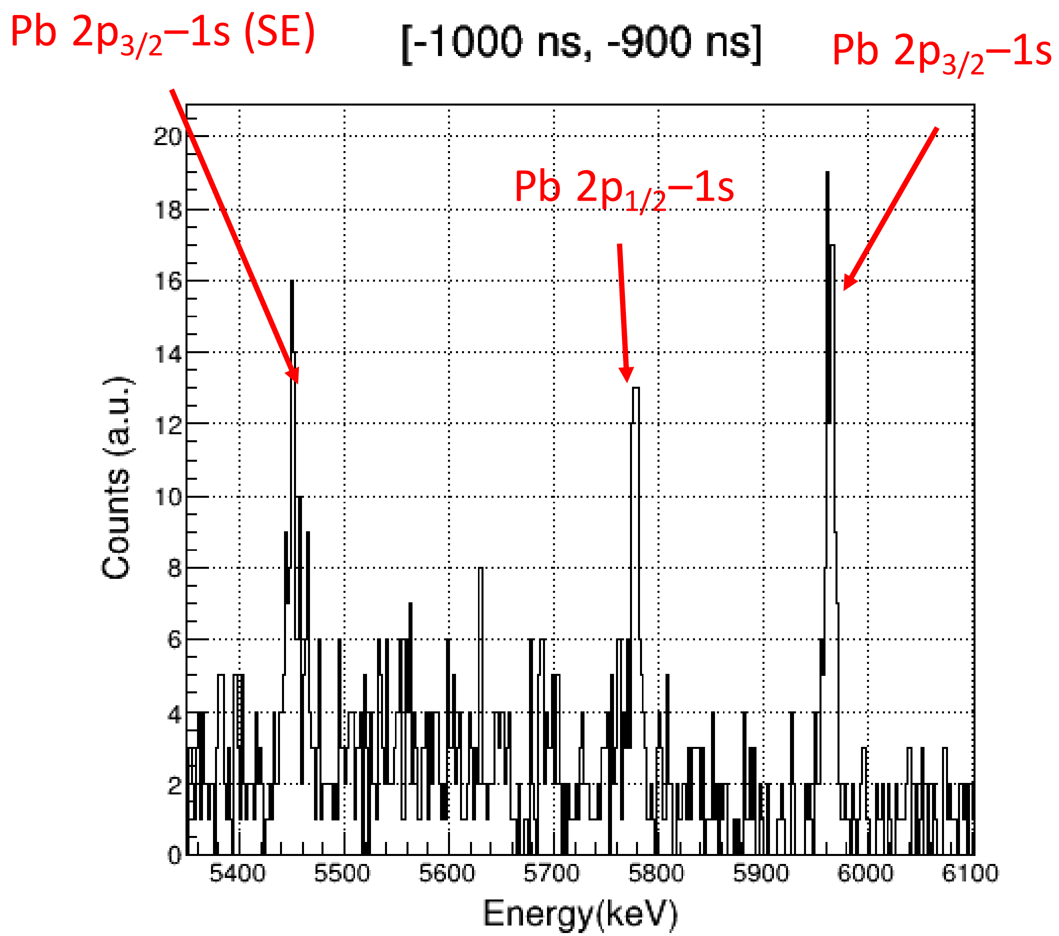
- Energy shift of hyperfine states due to the electric quadrupole (E2) and magnetic dipole (M1) interaction

Dynamic hyperfine splitting

- The hyperfine levels from ground and excited nuclear states are mixed due to the high energy of muonic transitions
- HFS also observed in even-even nuclei with zero spin in the ground state

Interpreting energy Vs time plots





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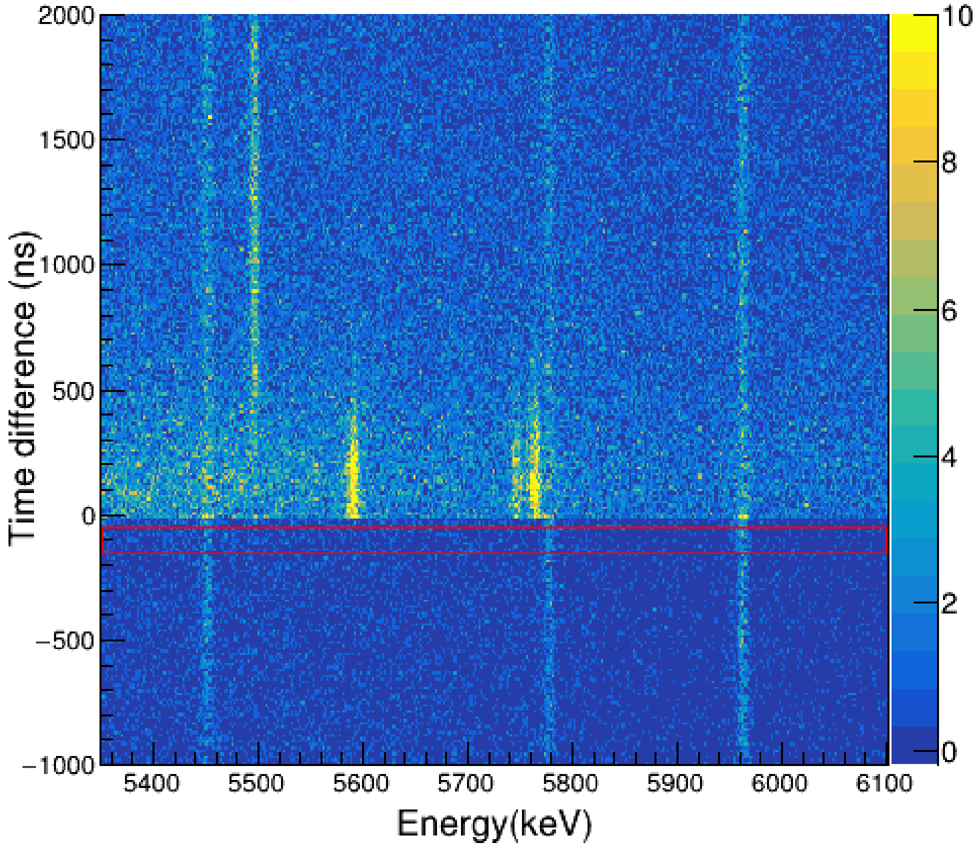

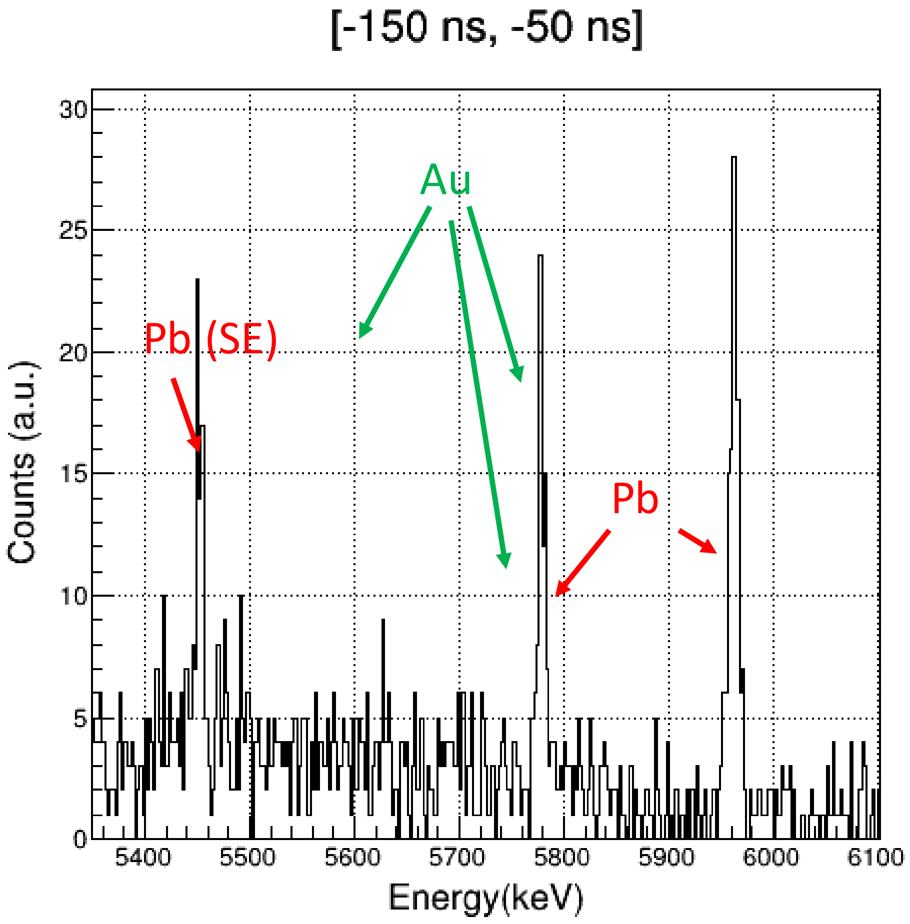

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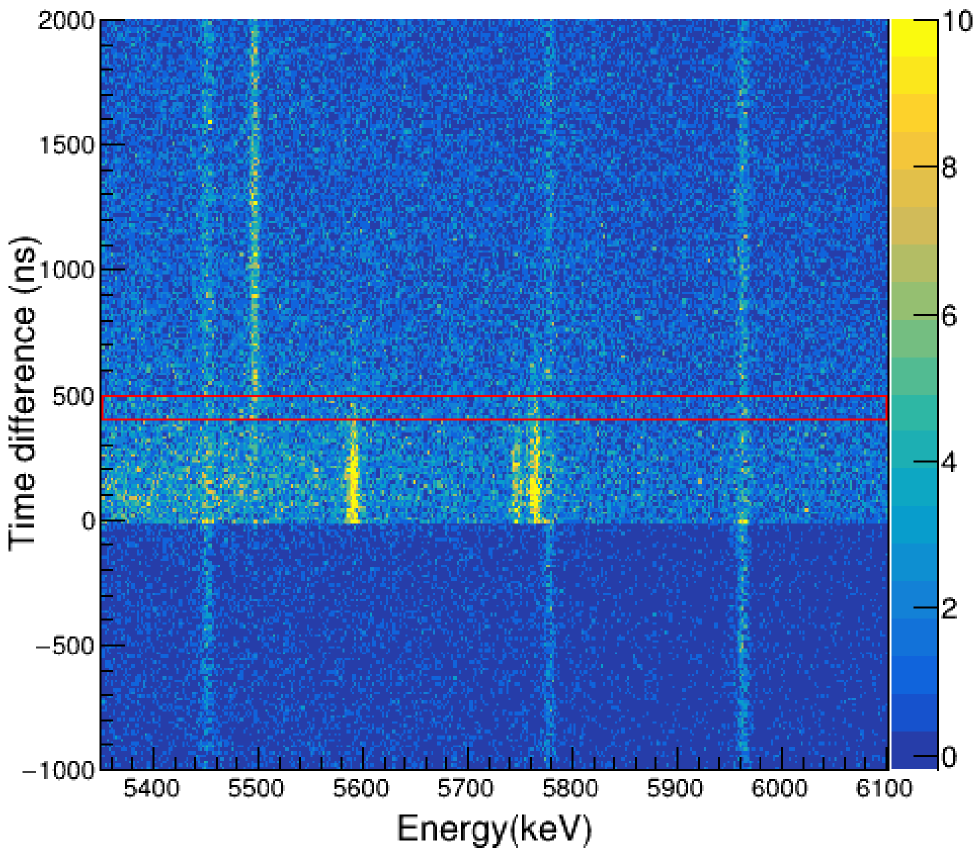

[400 ns, 500 ns]