The experimental view on odd-mass and odd-odd nuclei

ESNT workshop, 28-31 Oct 2024

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A personal perspective on experiments

- Mapping the experimental approaches

- Pushing boundaries of experimental physics
  - The production boundary
  - The precision boundary

- Beyond interpretation

Mapping the experimental approaches

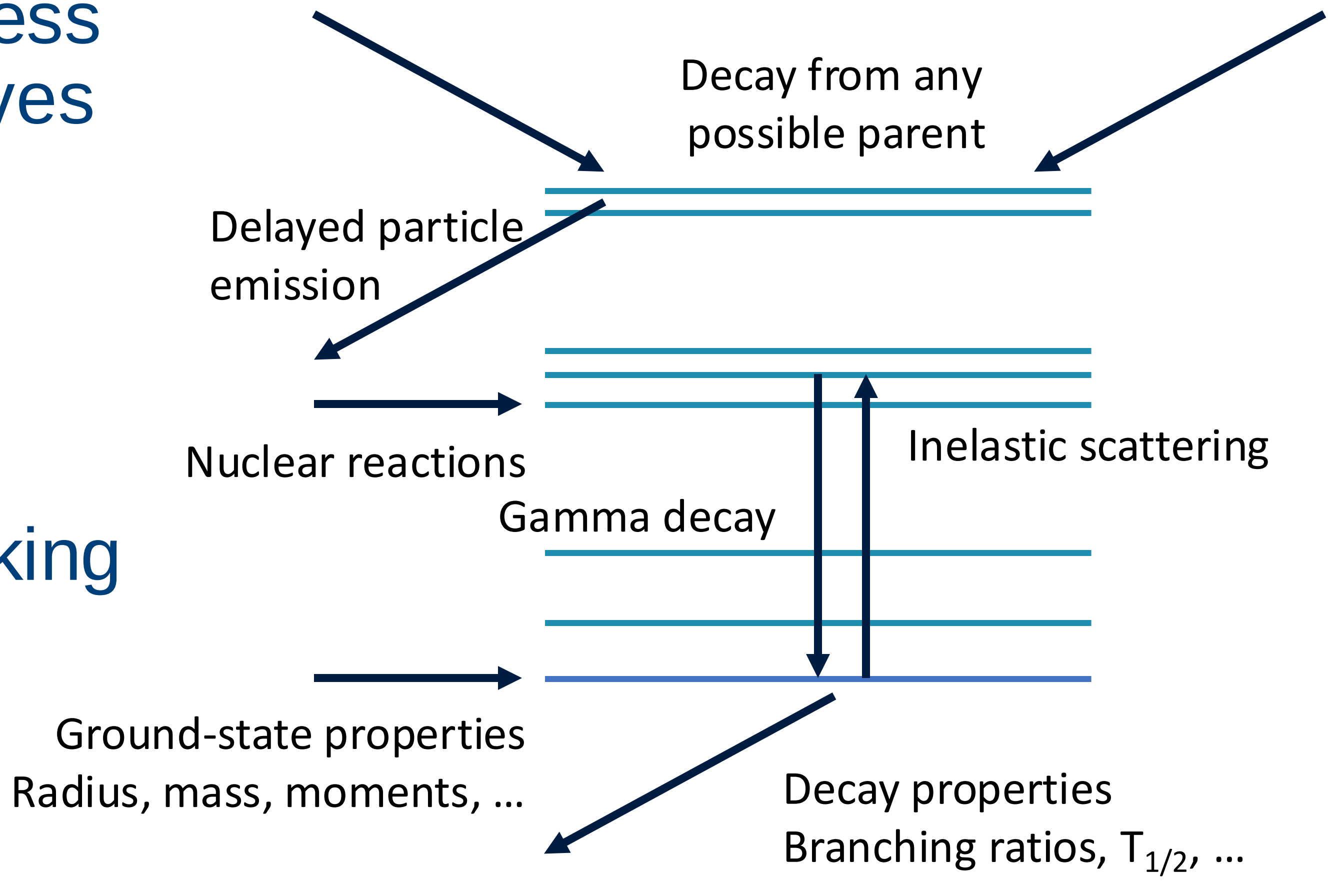
A disclaimer

The multifaceted puzzle of experiments

There are many ways to address the nucleus, none of which gives a full picture, all of which are needed to shed light on the nuclear puzzle.

There are many ways of breaking it down:

- Ground-state vs excited states
- Low-energy vs fast beams



What we get from experiments

Experiments are able to produce lab-frame observables, but experimentalists always hope to get more from their data than it can sometimes deliver… Some observables are easier to deal with than others.

- $T_{1/2}$, branching ratios, mass, energy levels, … can be taken at faith value.
- Nuclear spins and parity have to be handled carefully! Very few experiments can actually MEASURE the spin, most of them infer a spin change and are quick to claim they hold the truth, e.g., the spin of ^{101}Sn…
- Radii, moments, deformation … are CALCULATED based on observables such as isotope shifts, hyperfine structures, scattering cross sections, … Some cases may be clear as water, while others may be as blue as the Seine.

Even-even vs the rest

Even-even nuclei have their advantages that simplify the nuclear picture, with their 0^+ ground state and 0^+-2^+-4^+ structure – *which is why I mostly teach that myself in my nuclear physics course!*

Mostly matters for decay & reaction experiments.

However, the 0^+ ground state does not feature any hyperfine structure → losing information on moments and on the details of the wavefunction that can be accessed in odd or even odd-odd nuclei.

At the heart of laser spectroscopy and NMR experiments.

Radii trend across isotopic chains are revealing of the global structure of nuclei. However, the odd-even staggering within that trend could shed light on more details of the nuclear structure, which cannot be accessed with only even-even nuclei.

Besides involving laser spectroscopy, new approaches are on the horizon with muonic atoms and e^- scattering.

A typical experiment

Intensity, purity, availability, access, …

Acceptance, emittance, cooling, charge state, time structure, …

Detectors, techniques, and analysis

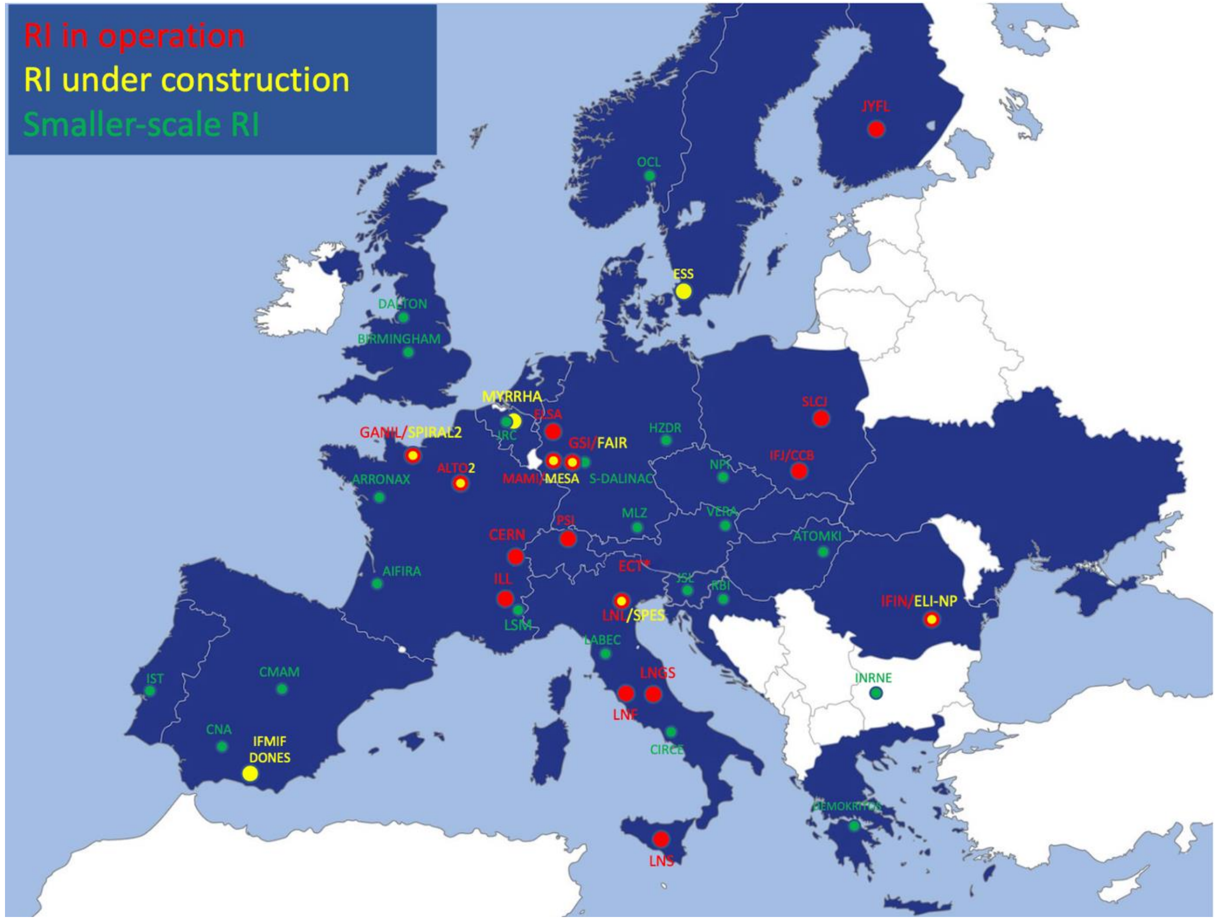
Experiments keep pushing all these aspects to bring new insights

Pushing boundaries of experimental nuclear physics

Radioactive nuclei and where to find them

Most of the cutting-edge nuclear research happens today at Radioactive Ion Beam facilities. RIB facilities are many in types, locations, and approach, each with their specificity and uniqueness.

There are also many facilities currently under construction, hoping to deliver the next beam of your dreams.



Map courtesy from W. Korten, NuPECC LRP 2024.

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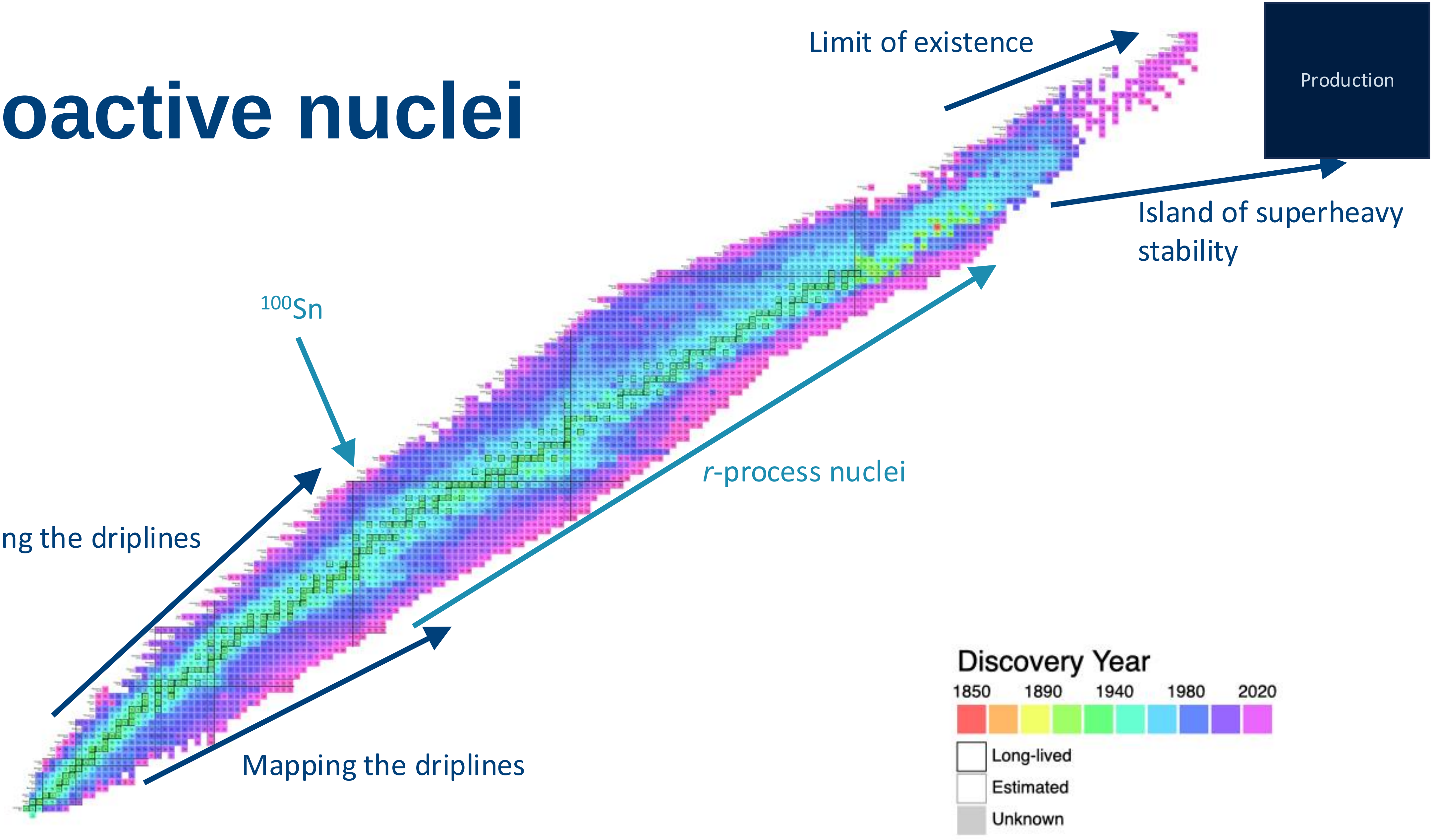
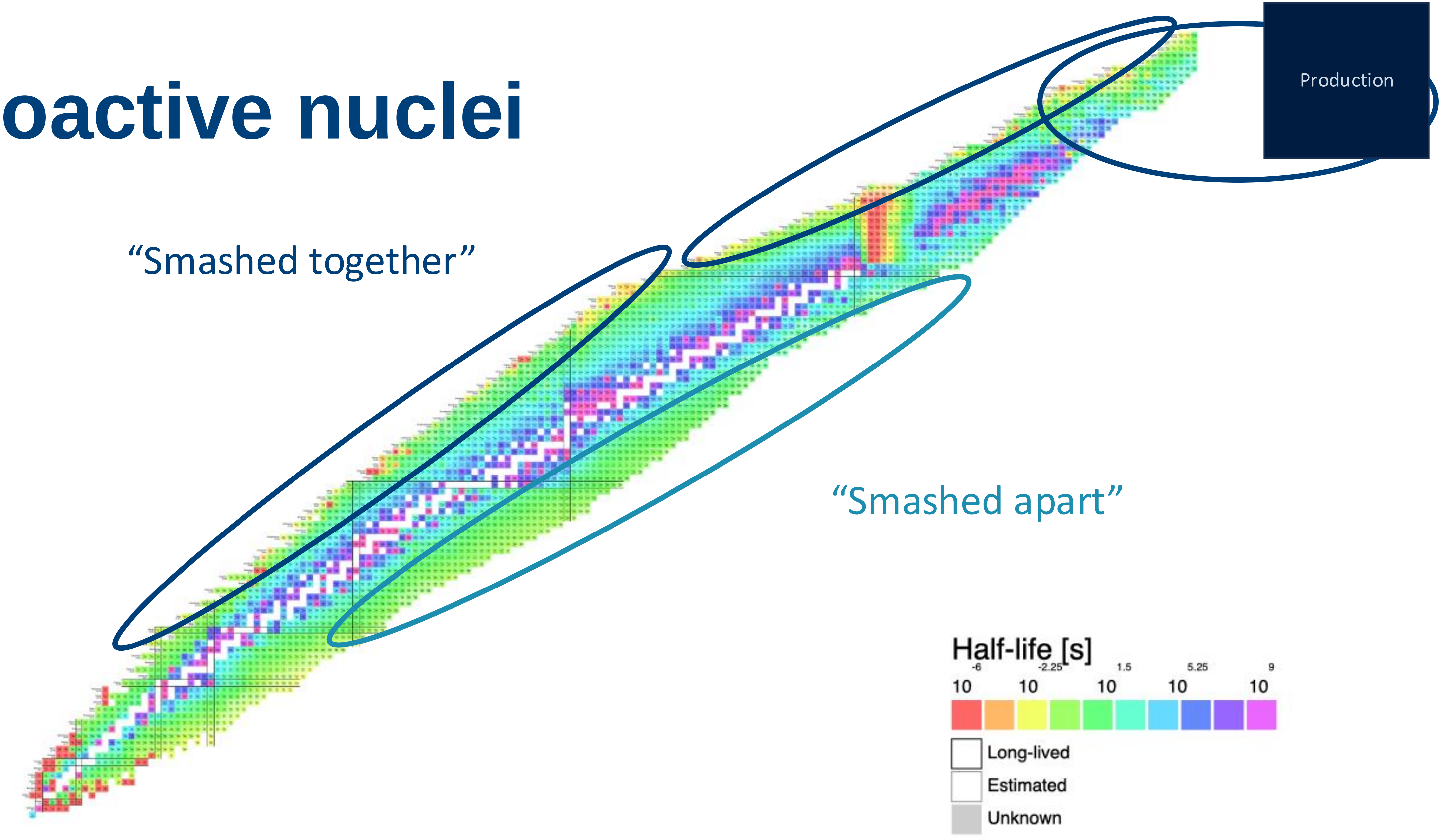
Radioactive nuclei



The Colourful Nuclear Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Radioactive nuclei



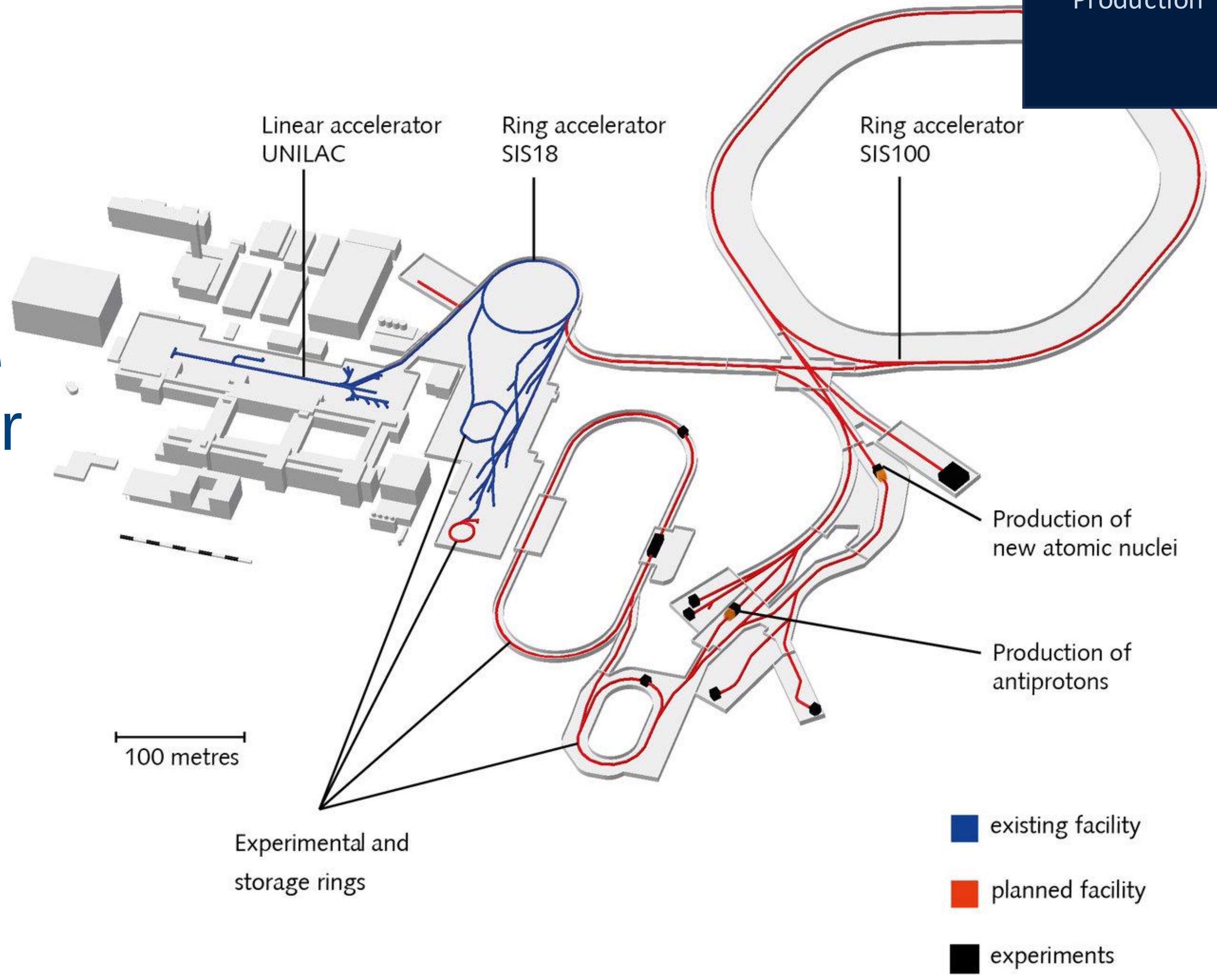
The Colourful Nuclear Chart, https://people.physics.anu.edu.au/~ecs103/chart/

GSI/FAIR

FAIR is the European fragmentation facility, that will aim at producing isotopes at the very edge of existence, going for as exotic as possible.

Beam quality and purity are challenges that then need to be addressed by the experiments.

Beam times will be extremely limited, flagship experiments only.



https://fair-center.eu

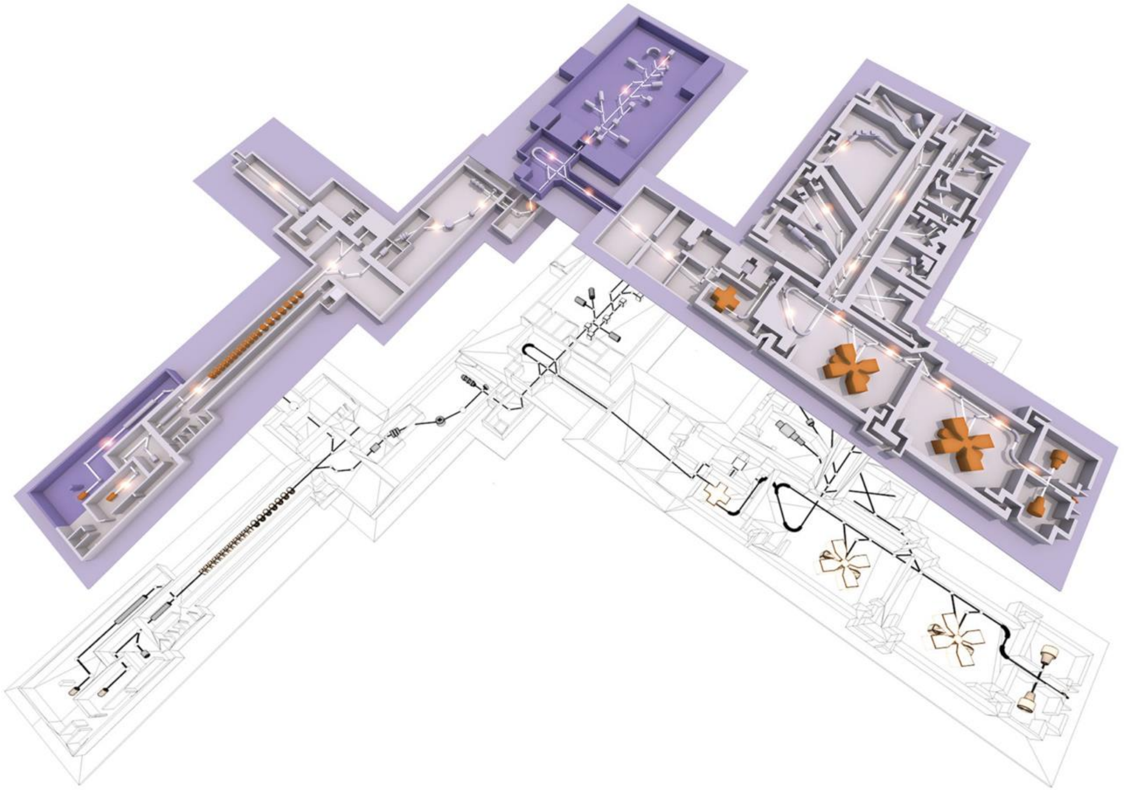
GANIL SPIRAL2

GANIL is a multi-user facility with several different accelerator infrastructures.

On the map is the upcoming S3 separator for fusion-evaporation production.

Either in-flight or stopped beam will be available at different qualities.

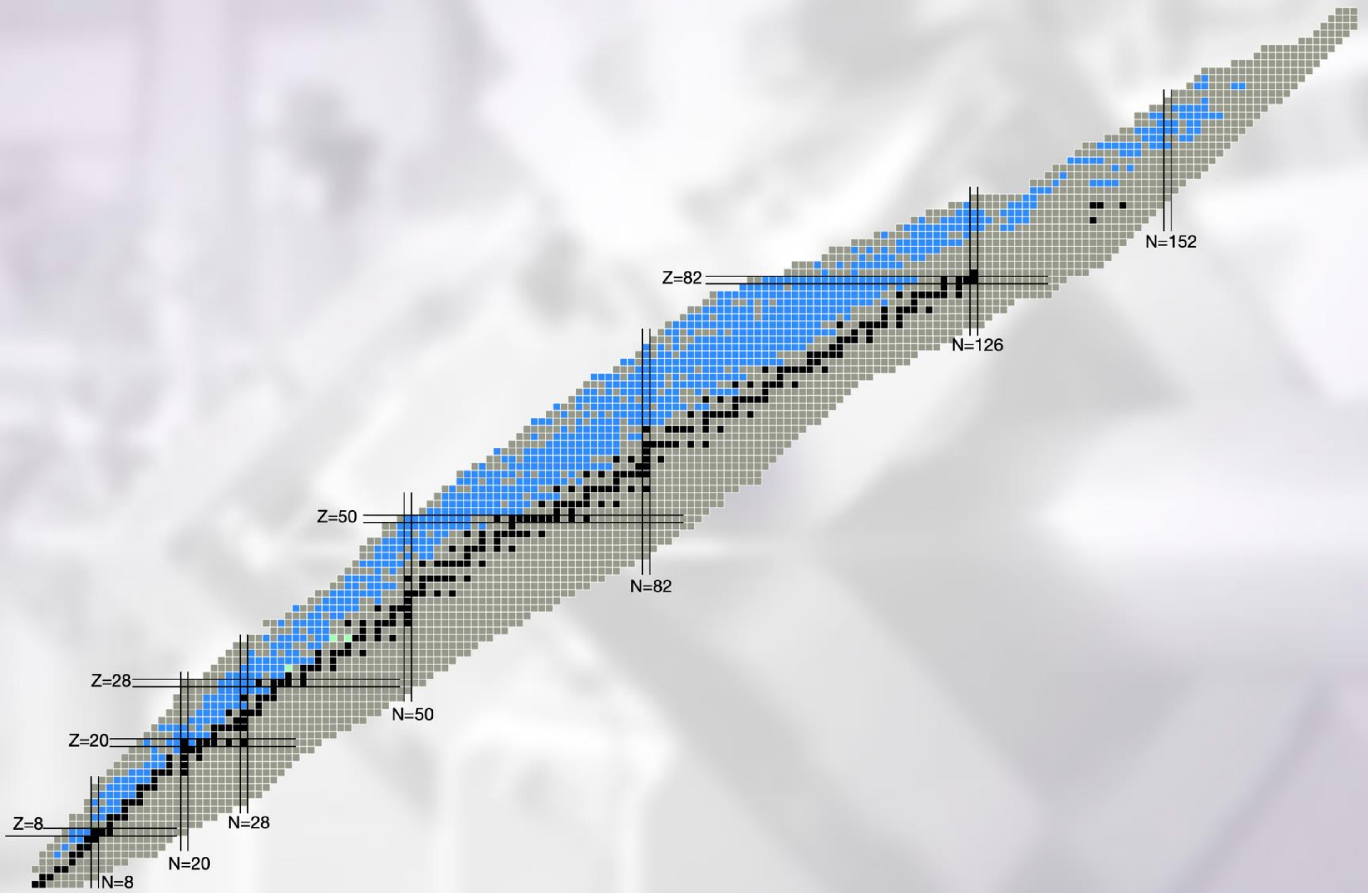
Access remains a question…



https://www.ganil-spiral2.eu

GANIL SPIRAL2 – S3 beams

Clear case for the proton-rich side of the nuclear landscape.



https://u.ganil-spiral2.eu/chartbeams/

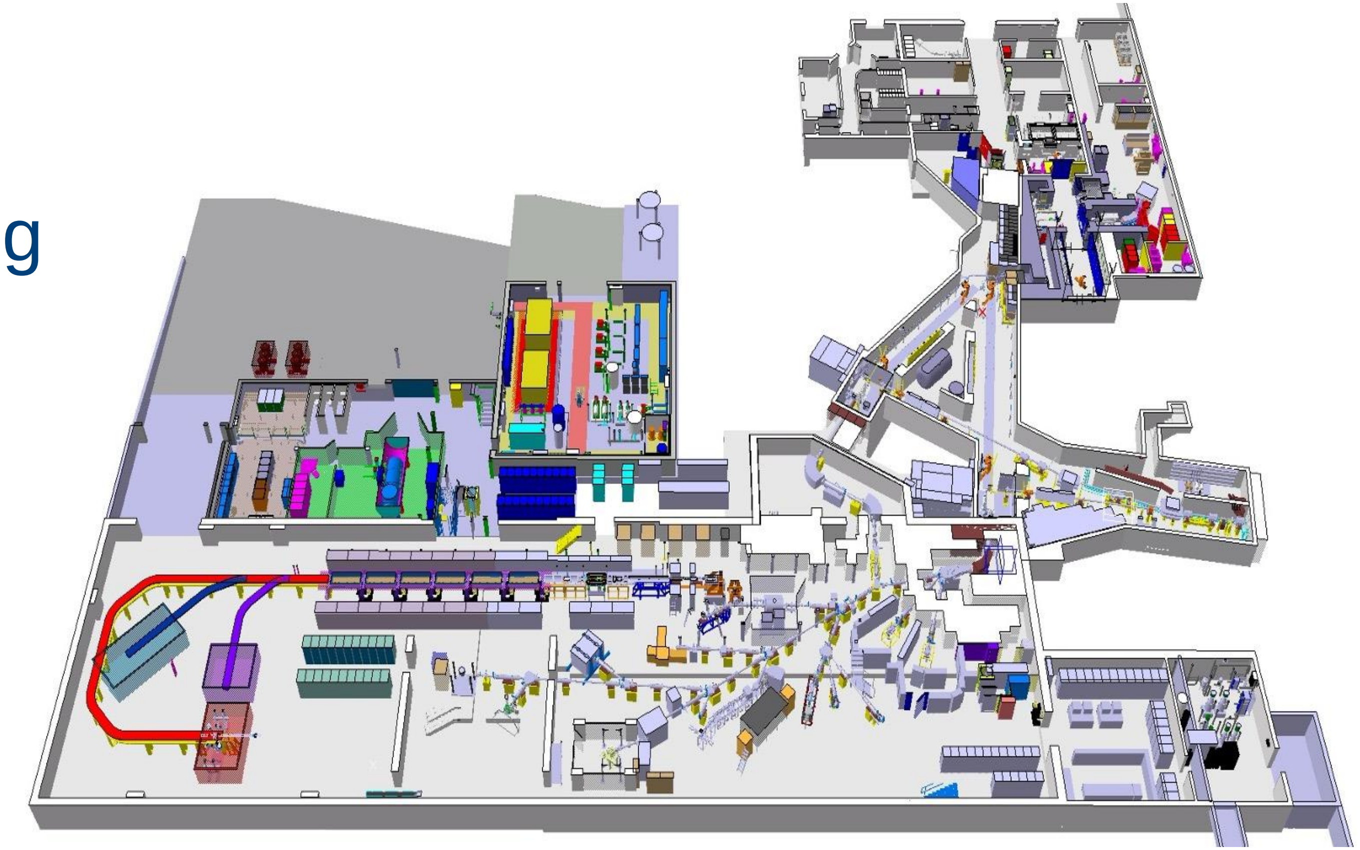
CERN ISOLDE

ISOLDE is the RIB facilities by excellence, with >60 years of operation and people still fighting to get beam.

It provides very high quality beams, though not as exotic as the other facilities.

It suite of experiments gives access to all observables.

Like any other, it has its limits.

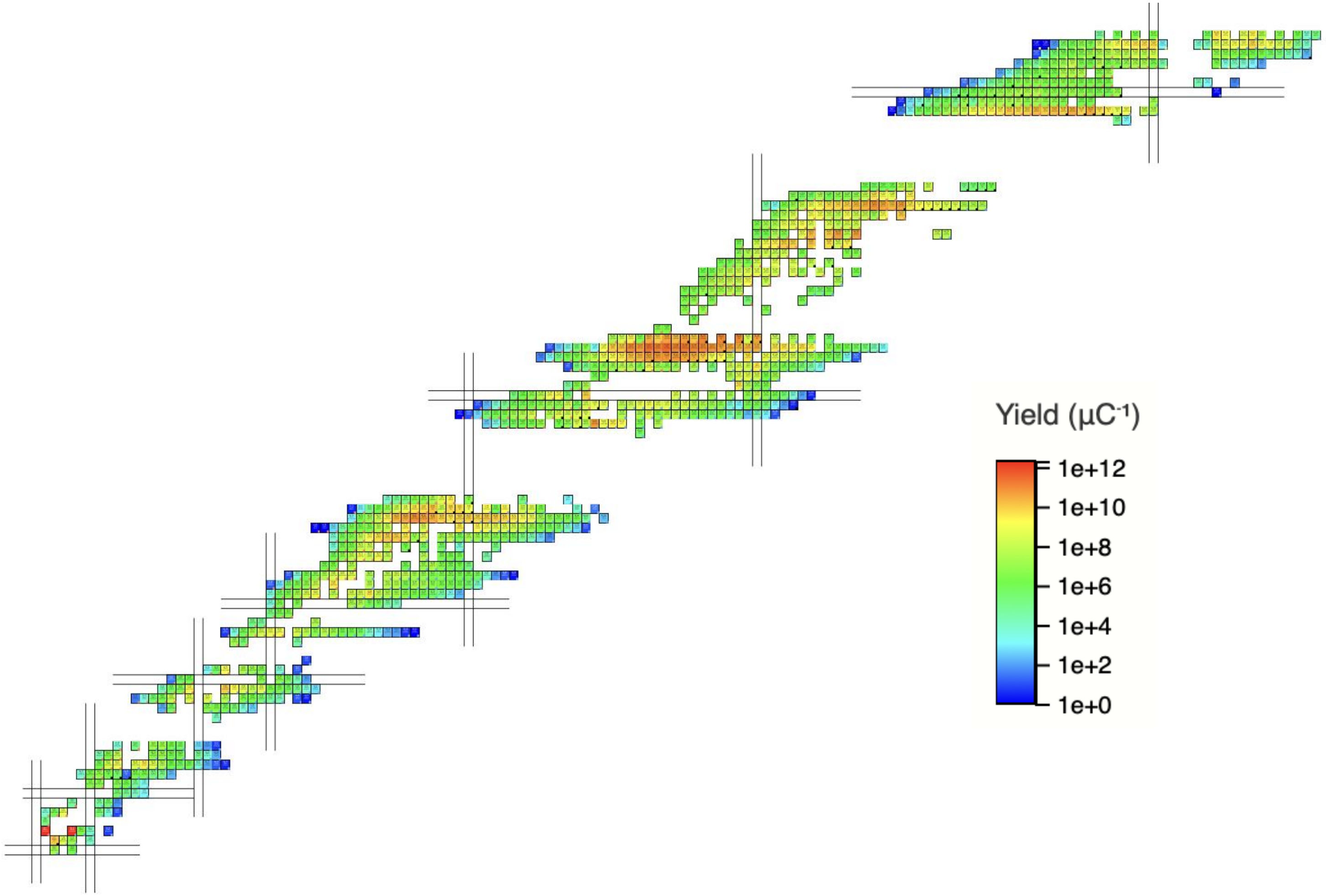


CERN ISOLDE beams

Refractory elements are out of reach of the thick-target ISOL technique.

The production rates drop with cross section and half-life.

The technique is well suited for systematic studies across long isotopic chains.



https://isoyields2.web.cern.ch/IsoldeYieldChart.aspx

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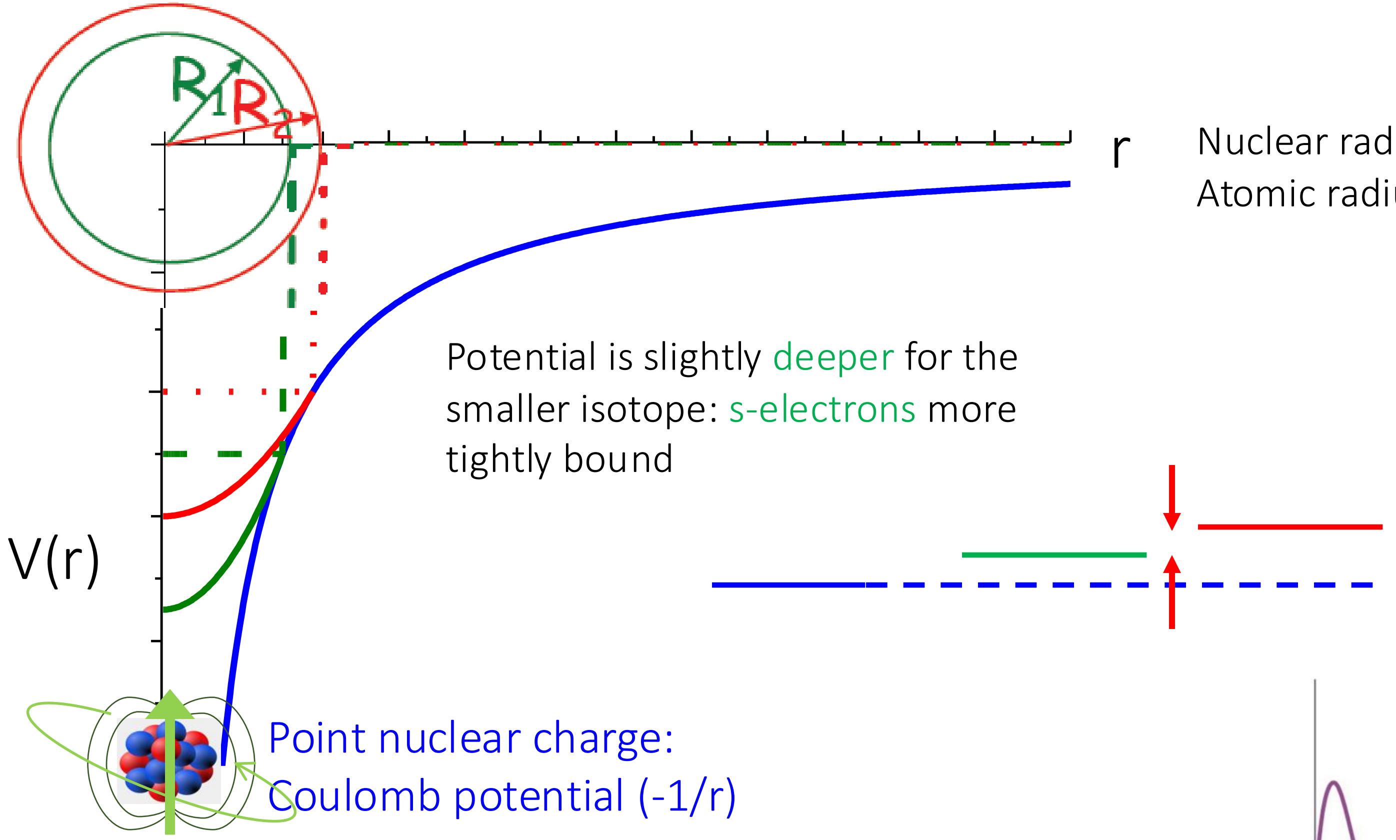
Laser spectroscopy

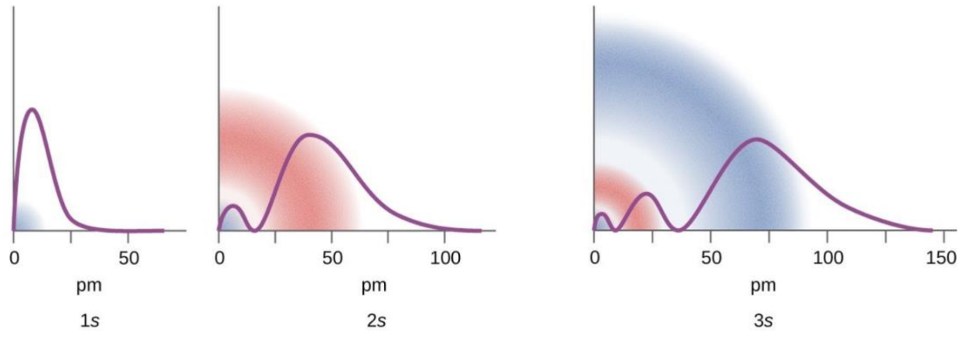


Nuclear radius: few × 10^{-15} m
Atomic radius: few × 10^{-10} m

Potential is slightly deeper for the smaller isotope: s-electrons more tightly bound

Isotope shift of atomic level

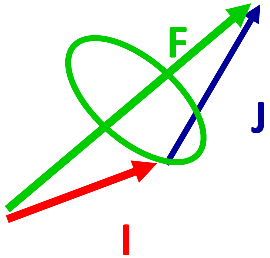
Point nuclear charge:
Coulomb potential (-1/r)



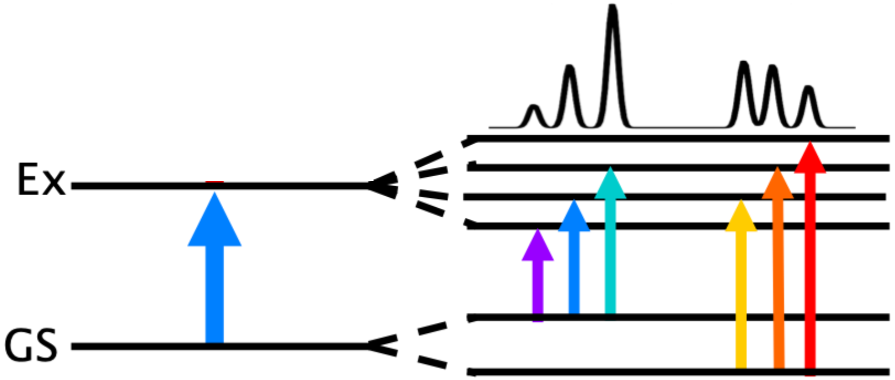
$$\delta\nu^{AA'} = \frac{A'-A}{AA'}\left(m_e\nu + M_{SMS}\right) + F\delta\langle r^2\rangle^{AA'}$$

Slide courtesy from R.P. de Groote

Laser spectroscopy

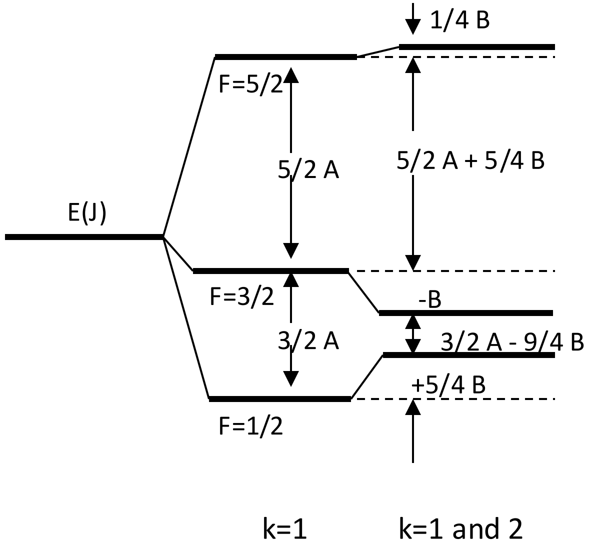


$$H_{hyf} = \sum_k \mathbf{M}_n^{(k)}.\mathbf{T}_e^{(k)}$$



Fields generated by the electrons

Nuclear electromagnetic moment



$$E_F^{(1)} = \sum_k (-1)^{I+J+F} \frac{X_i \begin{Bmatrix} J & I & F \\ I & J & k \end{Bmatrix}}{\begin{pmatrix} I & 1 & I \\ -I & 0 & I \end{pmatrix} \begin{pmatrix} J & 1 & J \\ -J & 0 & J \end{pmatrix}}$$

$$X_1 = IJA \qquad A = \frac{\mu}{IJ} \times H(0)$$

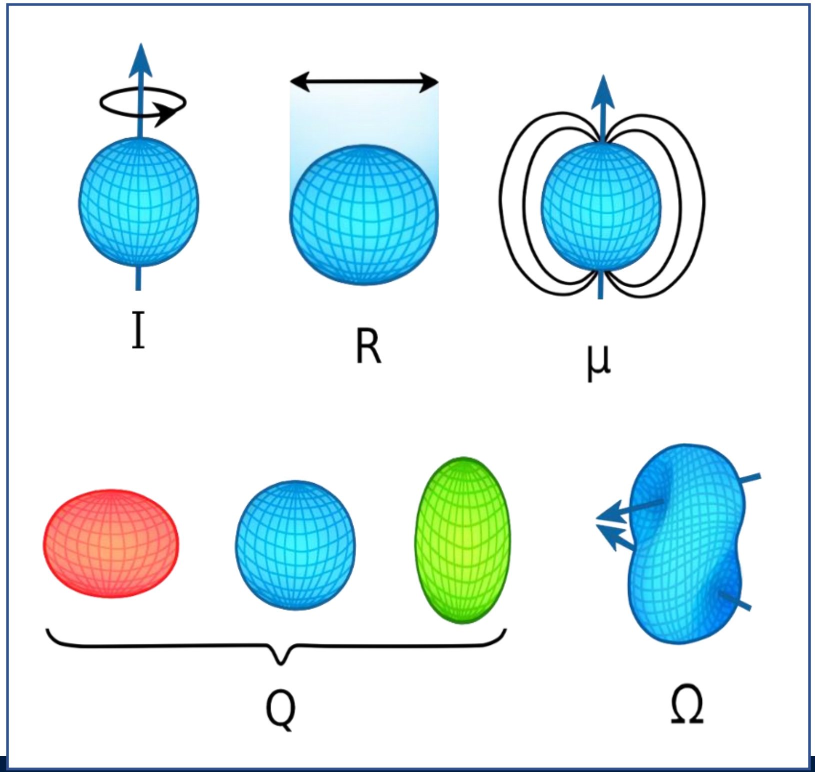
$$X_2 = \frac{1}{4}B \qquad B = 2eQ \times V_{zz}$$

$$X_3 = C \qquad C = -\Omega \times [?]$$

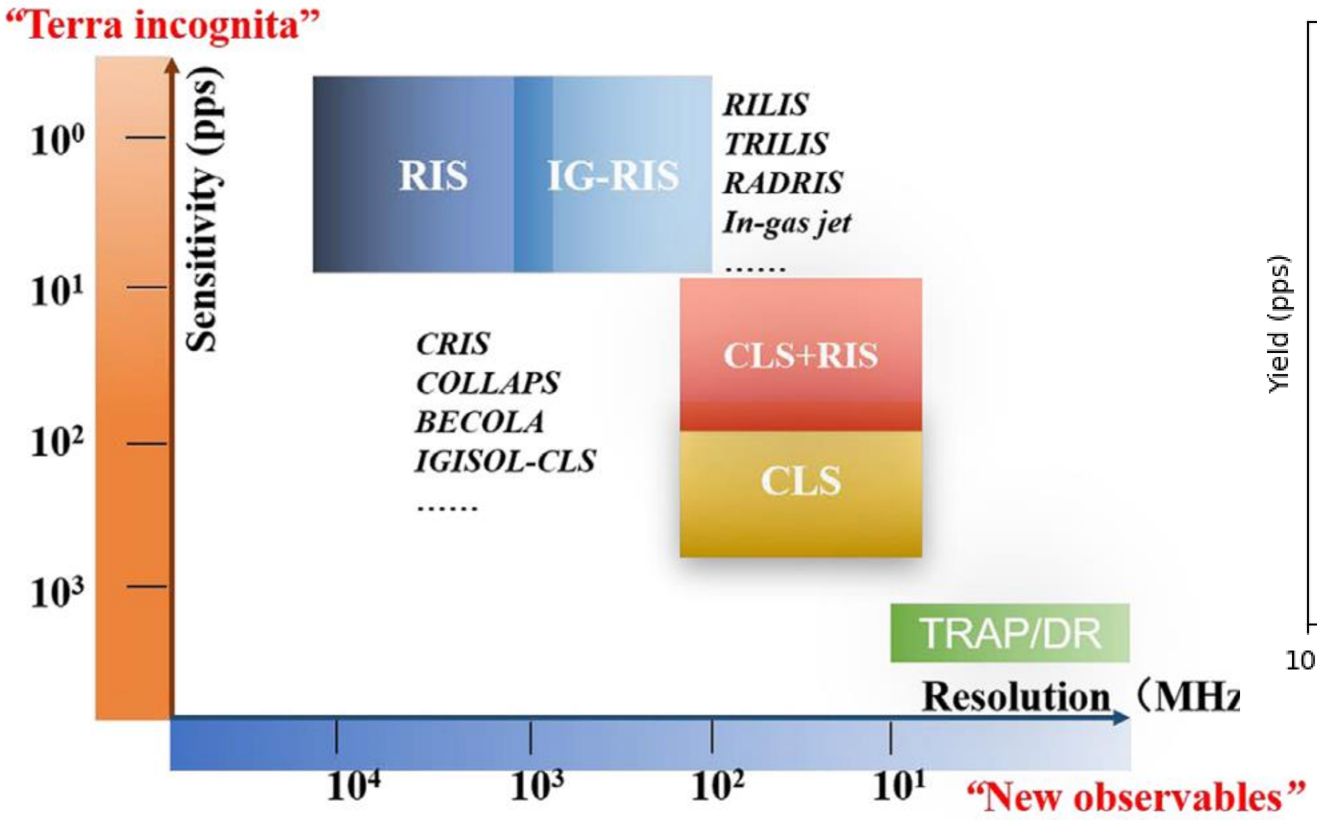
$$X_4 = D \qquad D = \Pi \times [??]$$

$$\ldots$$

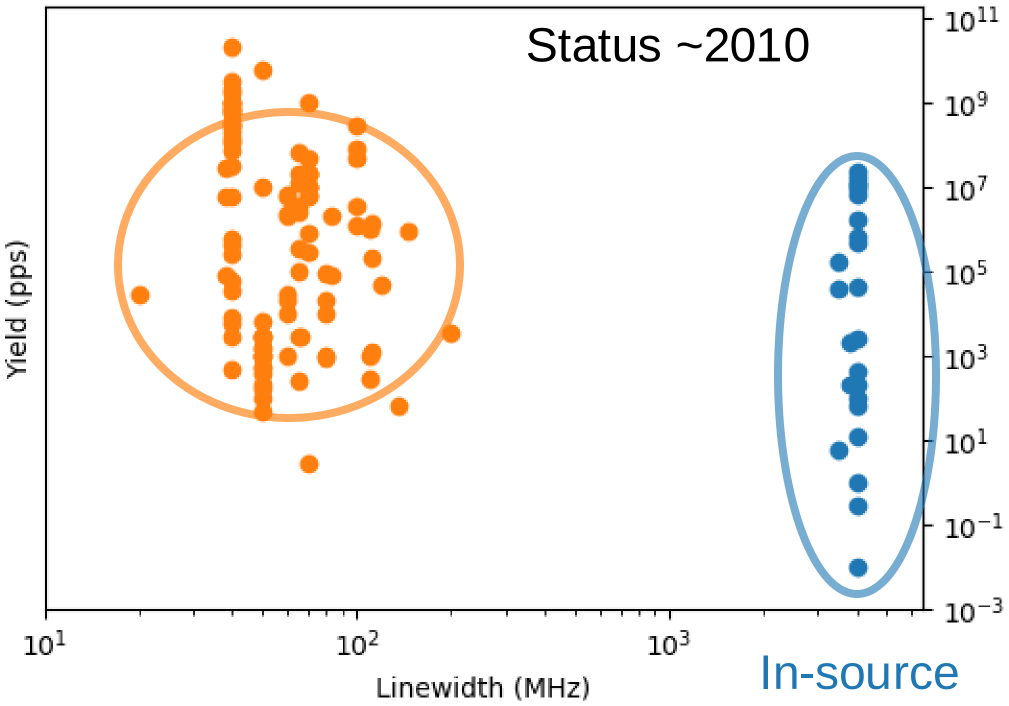
Nuclear x atomic



Laser spectroscopy



Predominantly collinear fast-beam experiments

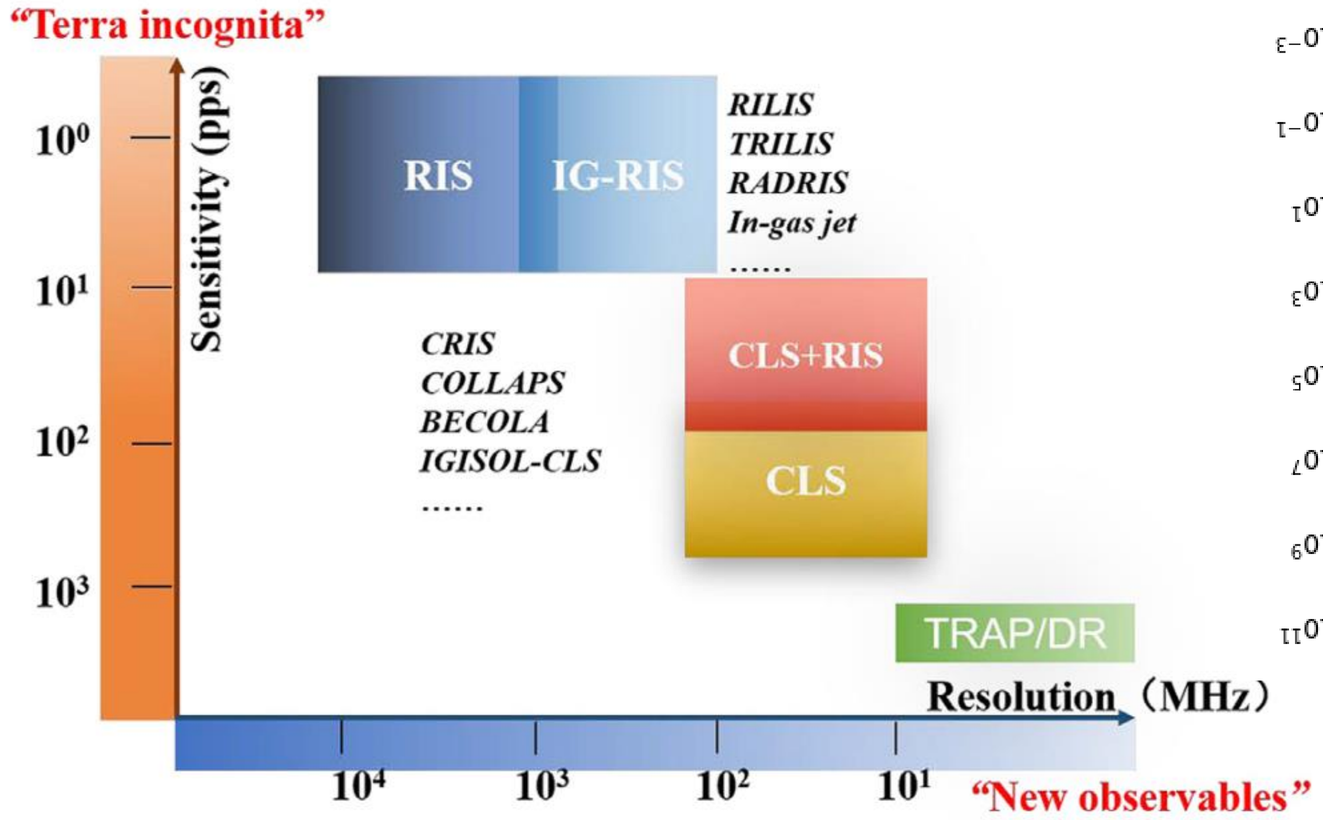


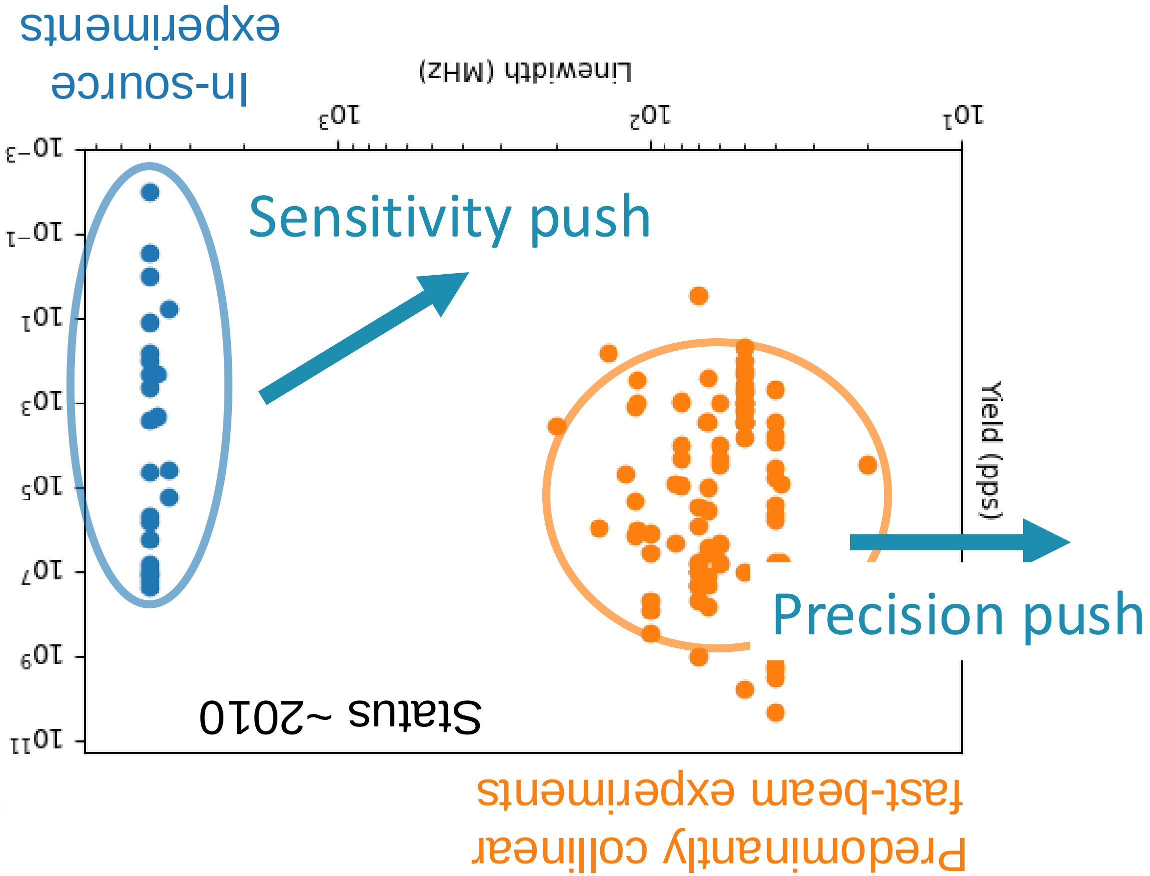
In-source experiments

X.F. Yang et al., PPNP **129** (2023) 104005.

Illustration courtesy from R.P. de Groote

Laser spectroscopy





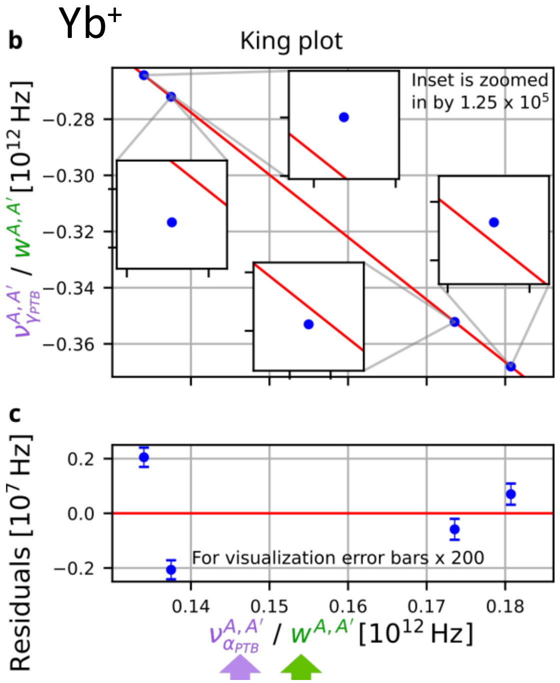
X.F. Yang et al., PPNP **129** (2023) 104005.

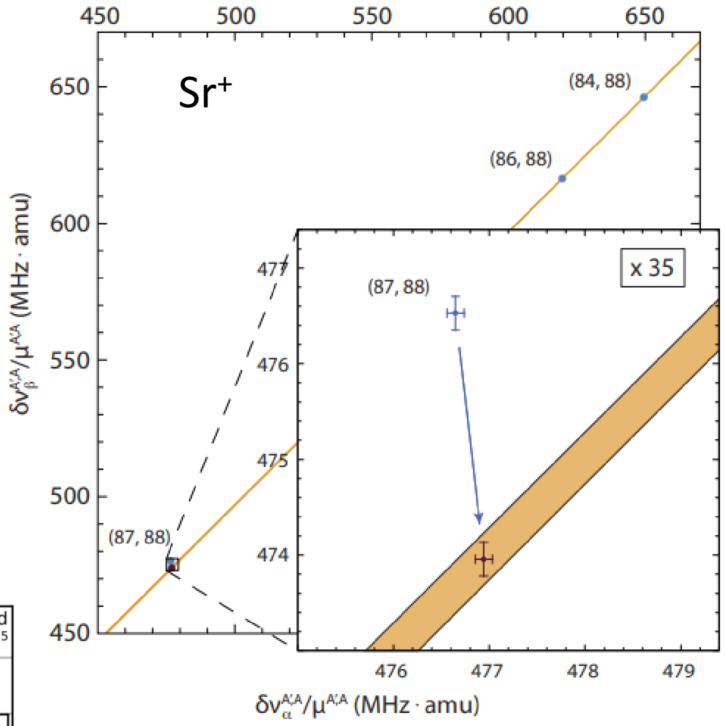
Illustration courtesy from R.P. de Groote

Precision push: next order

With increased precision, we become more sensitive to higher order effects, such as the impact of <r^4> on isotope shifts, and the associated non linearity of the King plot, or the ability to measure magnetic octupole moments of nuclei.

These new developments require careful consideration, lest bold claims of physics beyond the Standard Model be made.





$$\boldsymbol{\nu}_\alpha = F_\alpha \boldsymbol{\delta}\langle r^2\rangle + K_\alpha \boldsymbol{w} + G^{(2)}_\alpha \boldsymbol{\delta}\langle r^2\rangle^2 + G^{(4)}_\alpha \boldsymbol{\delta}\langle r^4\rangle + \frac{\alpha_{\rm NP}}{\alpha_{\rm EM}} D_\alpha \boldsymbol{h} + \ldots\,.$$

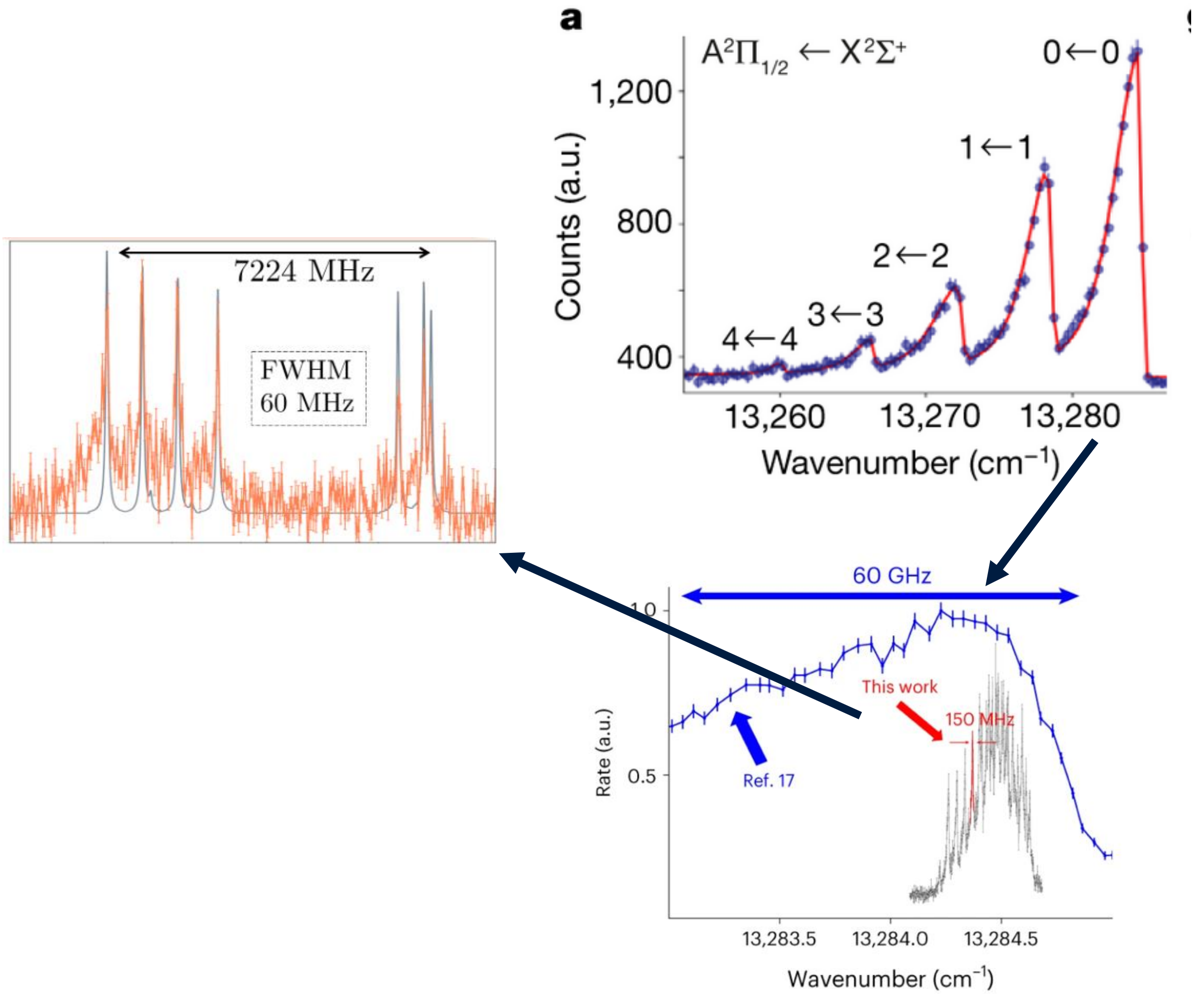
arXiv:2403.07792

*P.G. Reinhard, W. Nazarewicz, R.F. Garcia Ruiz, Beyond the charge radius: the information content of the 4th radial moment, PRC **101** (2020) 021301R.*

Sensitivity push: radioactive molecules

Molecular spectroscopy is particularly challenging because of the spread of the population across the many rovribrational levels.

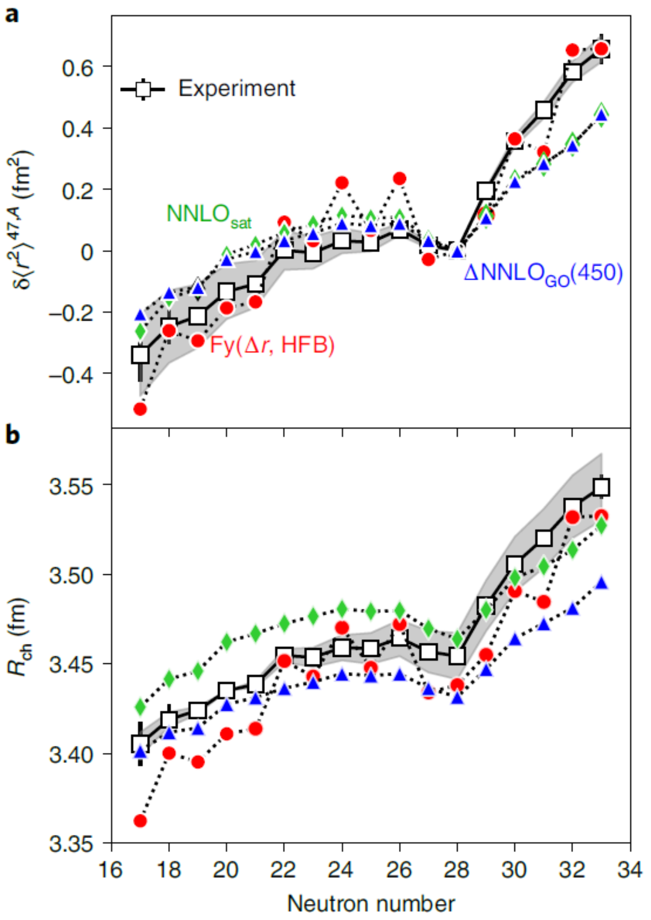
Molecules containing octupole deformed nuclei (Ra, Ac, Th) are however of great interest as parity-violating effects are strongly enhanced, which could give access to measurable EDM or Schiff moments.



Garcia Ruiz et al., Nature ***581*** *(2020) 396-400.*
Udrescu et al., Nature Physics ***20*** *(2024) 202-207.*
S.G. Wilkins et al., arXiv 2311.04121 (2023).

Some recent highlights

Recent highlights from CRIS: $_{19}$K



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.

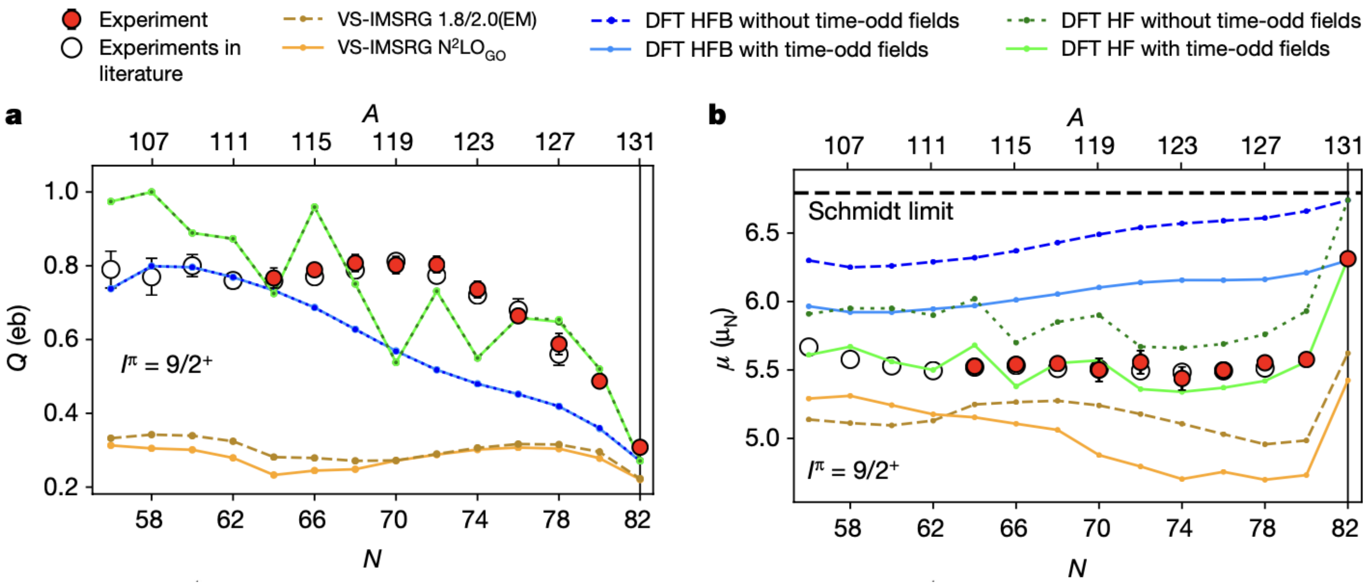
Limited precision on extracted radii induced by systematic uncertainties from the radii extraction from isotope shift, especially when evaluating absolute radii with respect to ^{39,41}K.

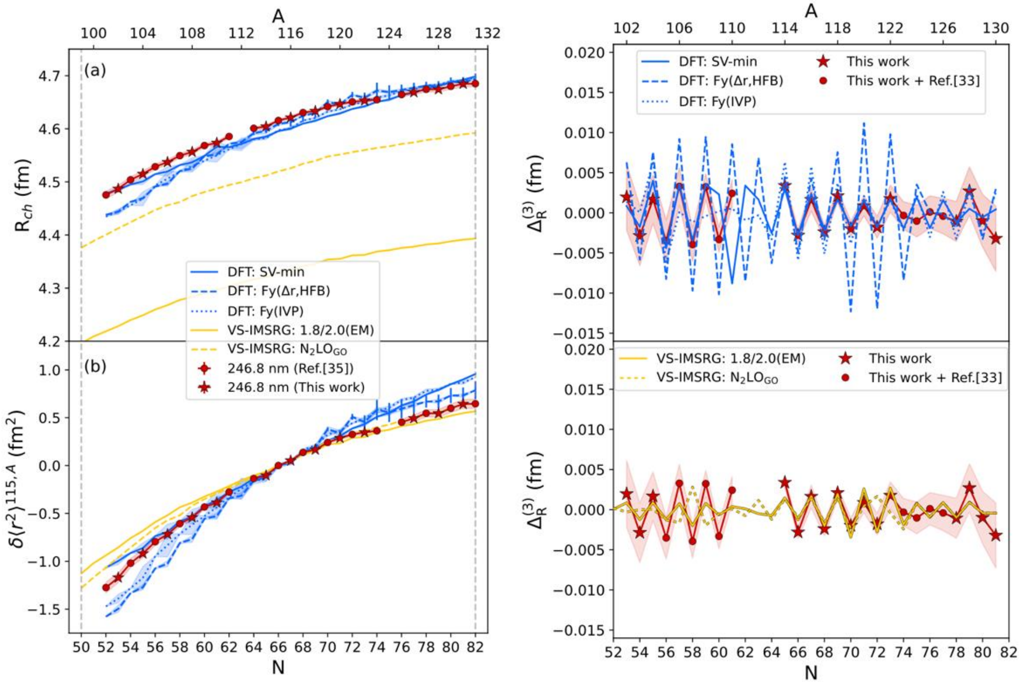
Á. Koszorús et al, Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of N = 32, Nature Physics ***17*** *(2021) 439-443.*

Recent highlights from CRIS: $_{49}$In

Probed across the isotopic chain up to N=82 with plans to go beyond.

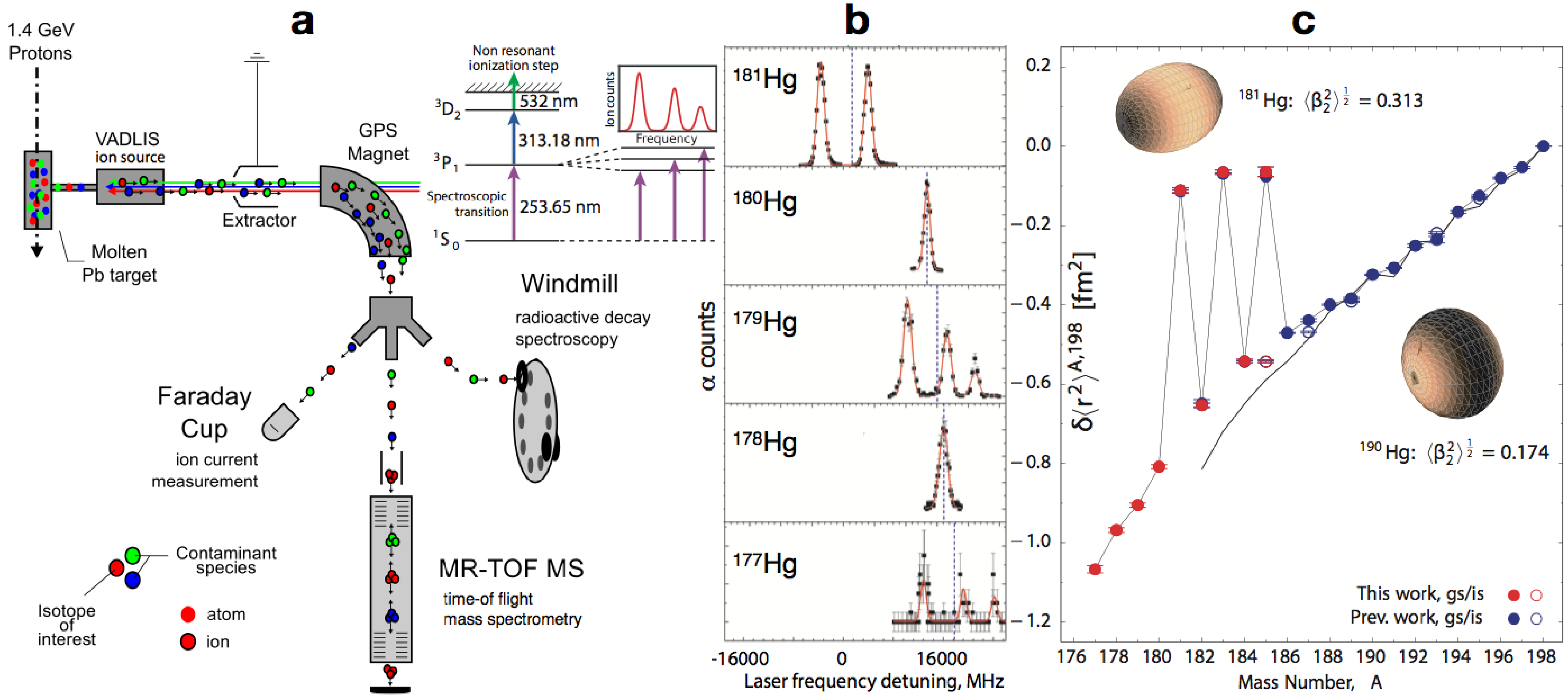
Study towards N=50 thwarted by production, but plans remain.





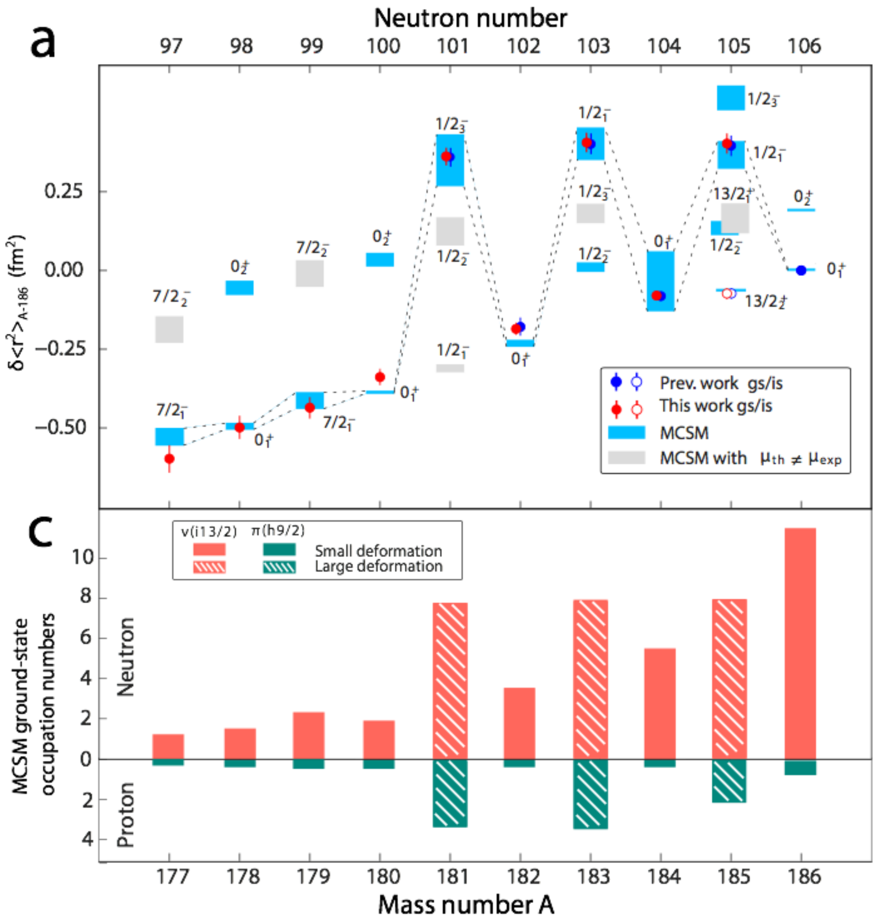
*A. Vernon et al, Nuclear moments of indium isotopes reveal abrupt change at magic number 82, Nature **607** (2022) 260-265.*
K.M. Lynch et al, Variation in the charge radii of indium isotopes between N=52 and 82, in preparation.

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



*B.A. Marsh et al, Characterization of the shape-staggering effect in mercury nuclei, Nature Physics **14** (2018) 1163.*

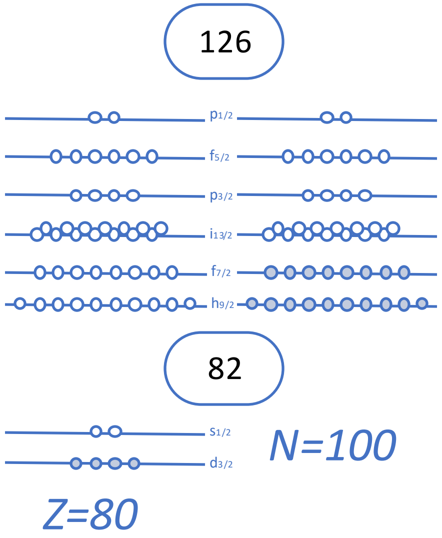
In-source laser spectroscopy: $_{80}$Hg



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, Characterization of the shape-staggering effect in mercury nuclei, Nature Physics ***14*** *(2018) 1163.*

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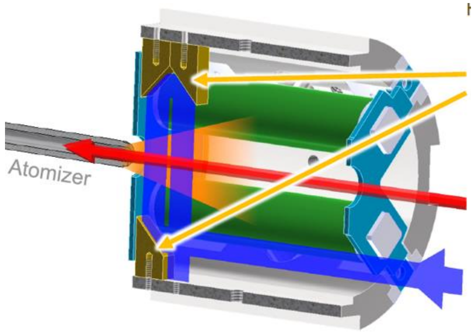
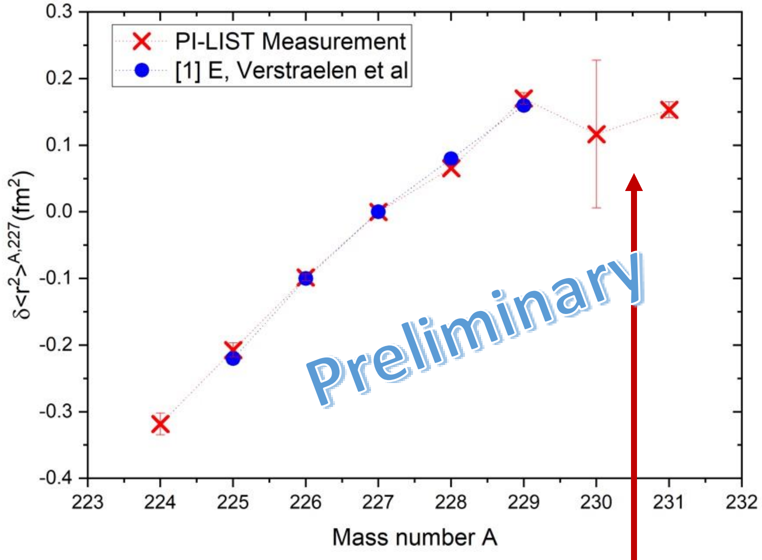
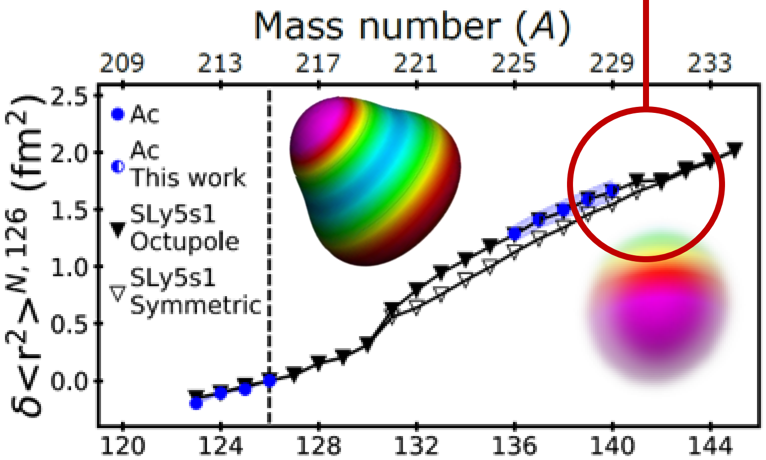
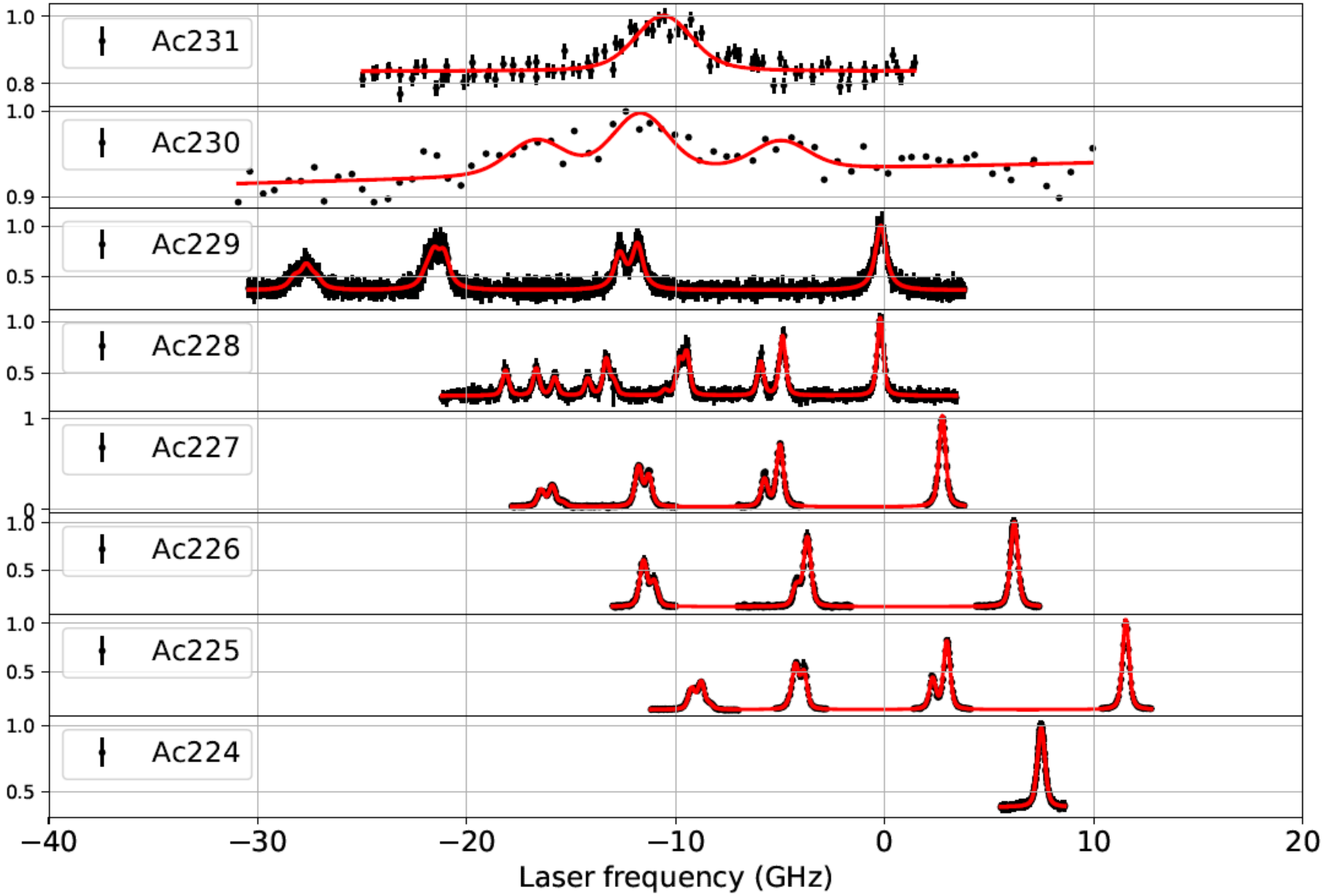
$_{89}$Ac: where theory led









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

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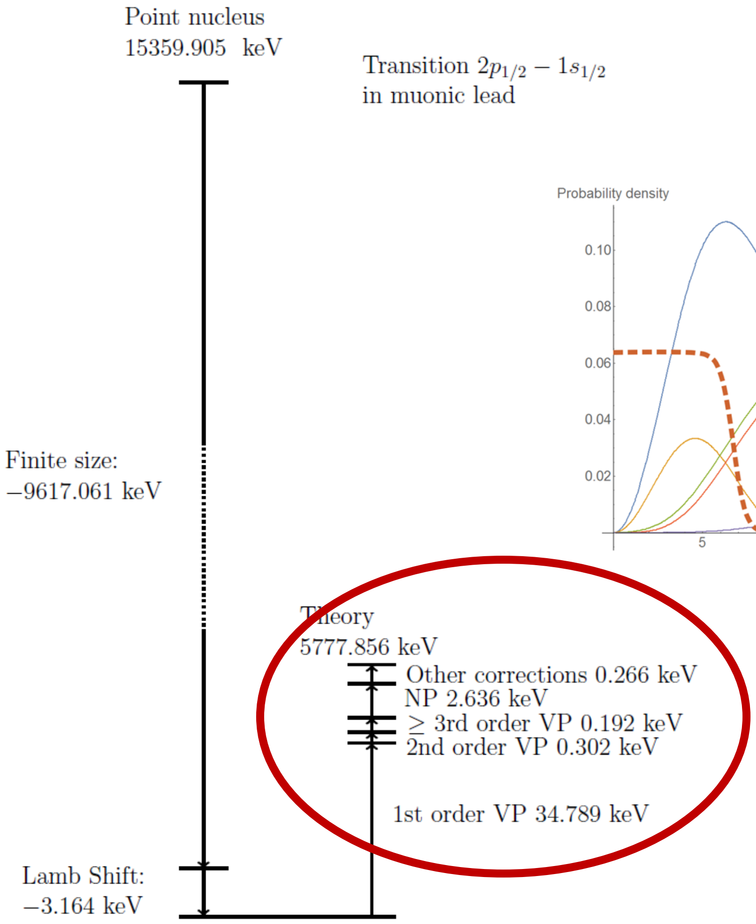
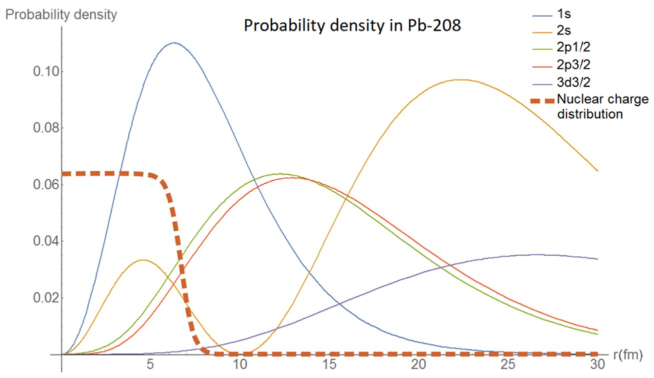
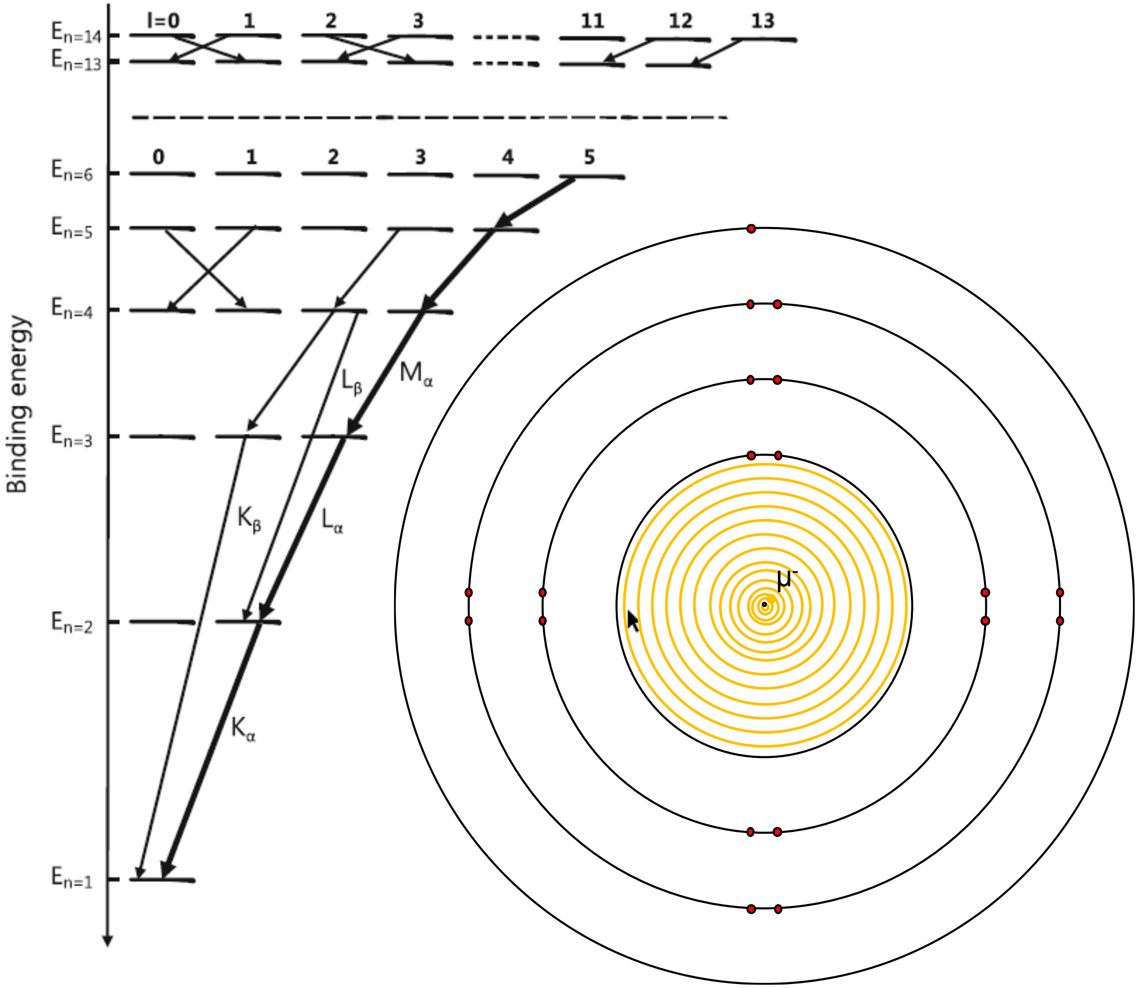
Beyond interpretation

Muonic x-rays as “new” probes







Field-theoretical approach

$$\hat{J}^{\mu}_{\mathrm{N,\,total}}(x) = J^{\mu}_{\mathrm{N,\,stat}}(\mathbf{x}) + \hat{J}^{\mu}_{\mathrm{N,\,fluc}}(x)$$

$$\hat{A}^{\mu}_{\mathrm{total}}(x) = \mathcal{A}^{\mu}_{\mathrm{stat}}(\mathbf{x}) + \hat{A}^{\mu}_{\mathrm{fluc}}(x) + \hat{A}^{\mu}_{\mathrm{free}}(x)$$

dressed muon propagator

$$:= \hat{A}^{\mu}_{\mathrm{rad}}(x)$$

$$iD_{\mu\nu}(x - x')$$

$$= \langle 0 | T[\hat{A}^{\mathrm{free}}_{\mu}(x)\hat{A}^{\mathrm{free}}_{\nu}(x')] | 0 \rangle$$

modified photon propagator:

$$i\mathcal{D}_{\mu\nu}(x, x') = \langle 0 | T[\hat{A}^{\mathrm{rad}}_{\mu}(x)\hat{A}^{\mathrm{rad}}_{\nu}(x')] | 0 \rangle$$

$$= iD_{\mu\nu}(x - x') + \langle 0 | T[\hat{A}^{\mathrm{fluc}}_{\mu}(x)\hat{A}^{\mathrm{fluc}}_{\nu}(x')] | 0 \rangle$$

Modified photon propagator

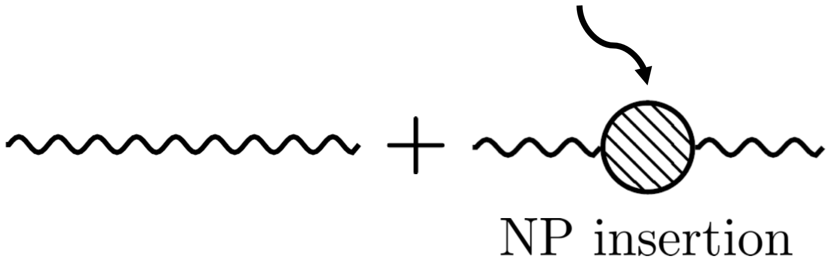
$$\mathcal{D}_{\mu\nu}(x, x') = D_{\mu\nu}(x - x') + D^{\mathrm{NP}}_{\mu\nu}(x, x')$$

NP tensor

“seagull” term

$$D^{\mathrm{NP}}_{\mu\nu}(x, x') = \int d^4x_1\, d^4x_2\, D_{\mu\xi}(x - x_1) \underbrace{\left[\Pi^{\xi\zeta}_{\mathrm{N}}(x_1, x_2) + S^{\xi\zeta}_{\mathrm{N}}(x_1, x_2)\right]} D_{\zeta\nu}(x_2 - x')$$

$$\mathcal{D}_{\mu\nu}(x, x') =$$



$$i\Pi^{\xi\zeta}_{\mathrm{N}}(x_1, x_2) = \langle 0 | T[\hat{J}^{\xi}_{\mathrm{N,\,fluc}}(x_1)\hat{J}^{\zeta}_{\mathrm{N,\,fluc}}(x_2)] | 0 \rangle$$

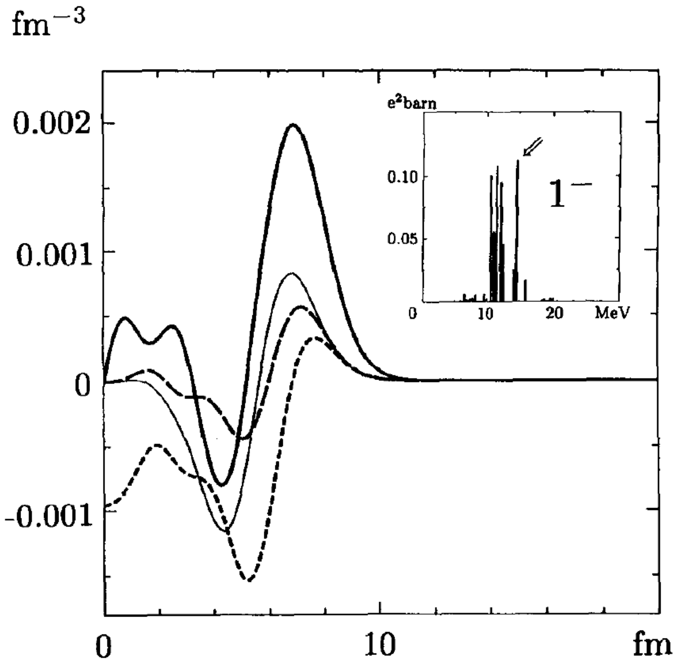
Slide courtesy Igor Valuev

What is needed from the nuclear side

$$\mathrm{NP} \to \sum_{|\lambda\rangle} [\text{the entire nuclear spectrum}]$$

- excitation energies $\omega_\lambda = E_\lambda - E_0$
- reduced matrix elements:
  - transition (charge) densities
    $\varrho_J^\lambda(\mathrm{x}) = \langle\lambda|| \int d\Omega_{\mathbf{x}}\, Y_J(\Omega_{\mathbf{x}})\hat{\rho}_{\mathrm{N}}(\mathbf{x})||0\rangle$
  - transition current densities
    $\mathcal{J}_{JL}^\lambda(\mathrm{x}) = \langle\lambda|| \int d\Omega_{\mathbf{x}}\, \mathbf{Y}_{JL}(\Omega_{\mathbf{x}}) \cdot \hat{\mathbf{J}}_{\mathrm{N}}(\mathbf{x})||0\rangle$

  for different excitation modes:
  $0^+,\ 1^-,\ 2^+,\ 3^-,\ (4^+,\ 5^-,\ 1^+)$
  in the laboratory frame



Y. Tanaka and Y. Horikawa, Nucl. Phys. A580, 291 (1994).

*simplifications are possible in terms of transition probabilities $B(EL)$

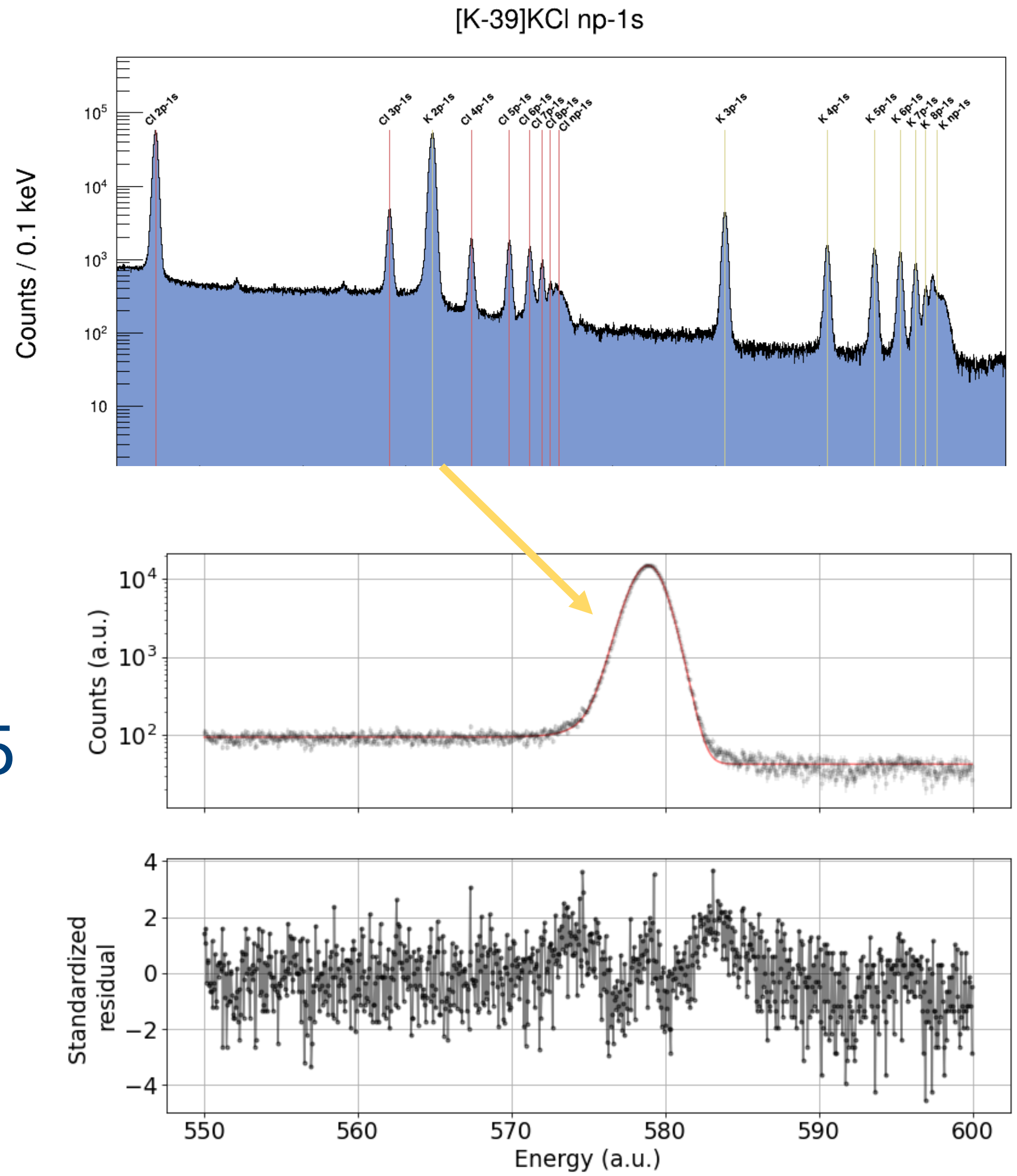
Slide courtesy Igor Valuev

$_{17}$Cl: Mirror nuclei

Measured muonic x rays from ^{35,37}Cl during the 2023 campaign at PSI → first measurement with enriched Cl to bring first precise insight into this element.

Analysis nearly completed, with precision on x-ray energies down to 15 eV on 2p1s, 3p1s, and 4p1s.

Pending nuclear polarization calculation to extract absolute charge radii.



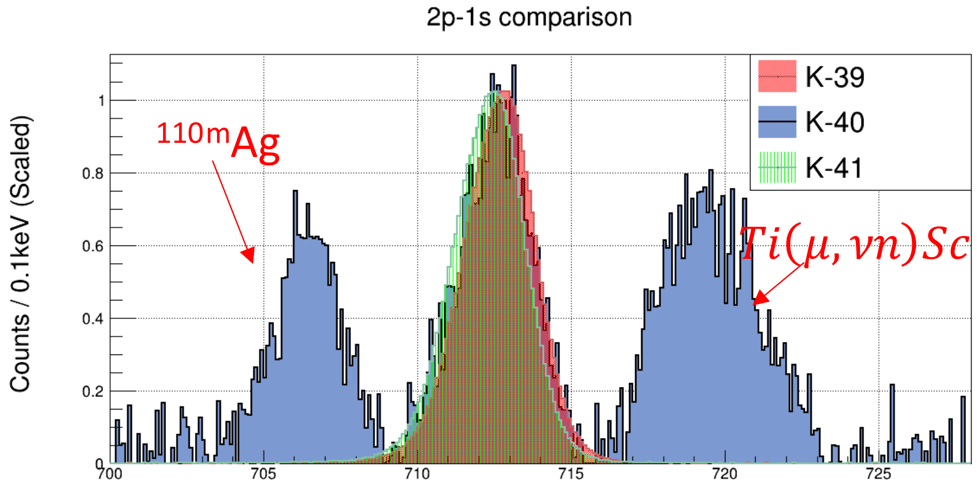
PhD work Michael Heines, KU Leuven.

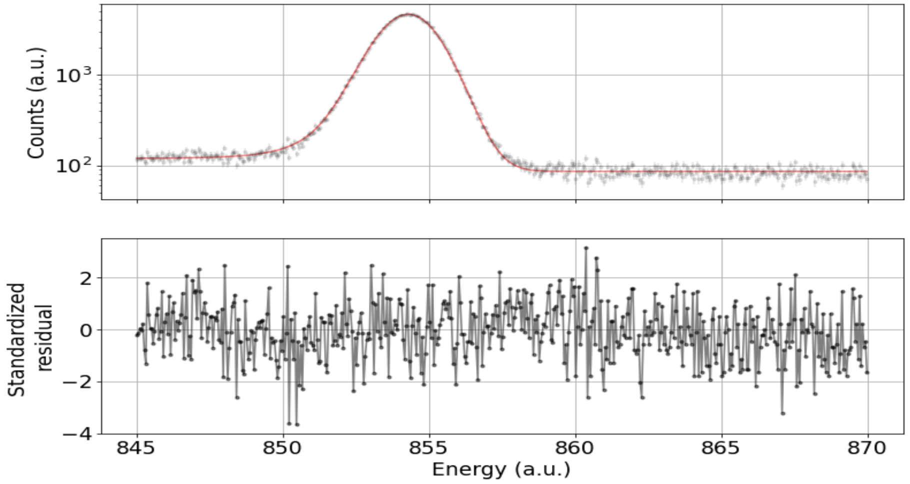
$_{19}$K: benchmarking the laser work

The K work mentioned earlier suffers greatly from the lack of reference with which to benchmark the isotope shifts.

Atomic calculations are great but have their limits and experimental benchmarks require 3 isotopes → ^{39,40,41}K.

During the 2023 campaign at PSI, we obtained excellent data and the analysis is nearly complete – pending input from nuclear polarization and V2.





PhD work Michael Heines, KU Leuven.

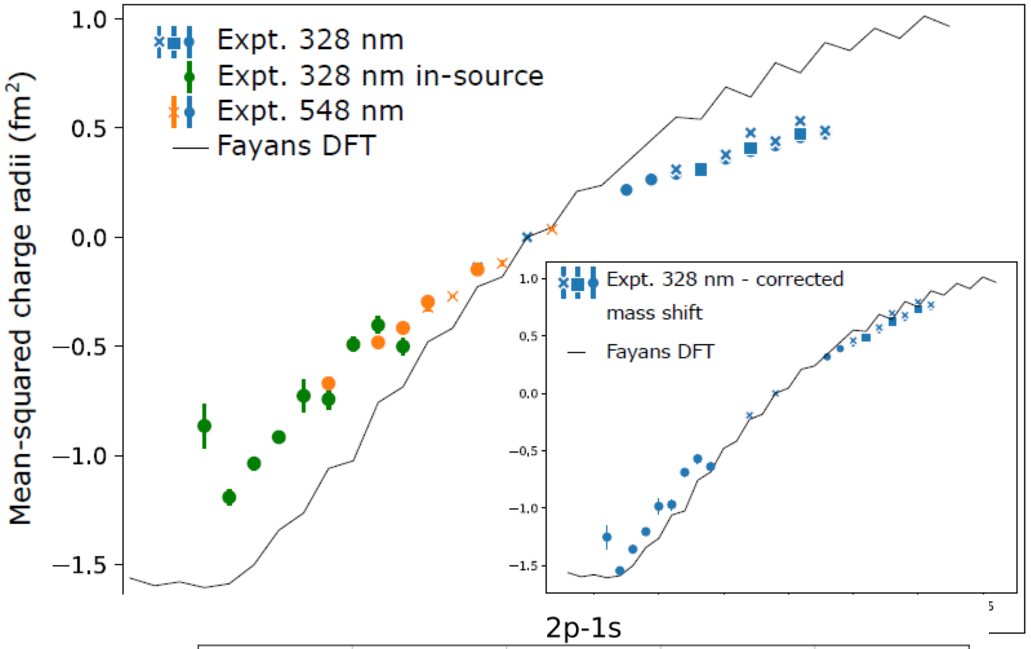
$_{47}$Ag

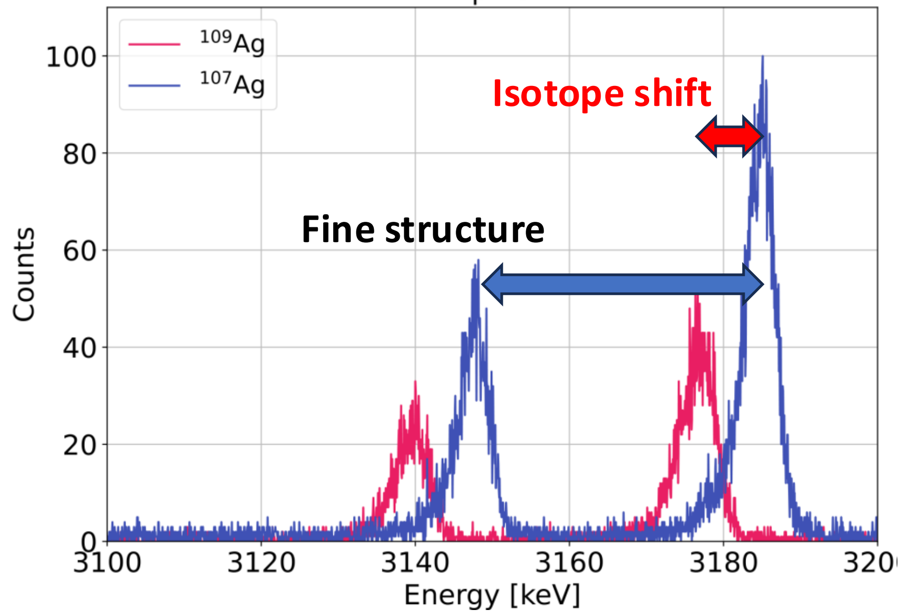
Extensive new data have recently been collected on Ag, from ^{95}Ag to ^{129}Ag, at Jyväskylä and ISOLDE.

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.

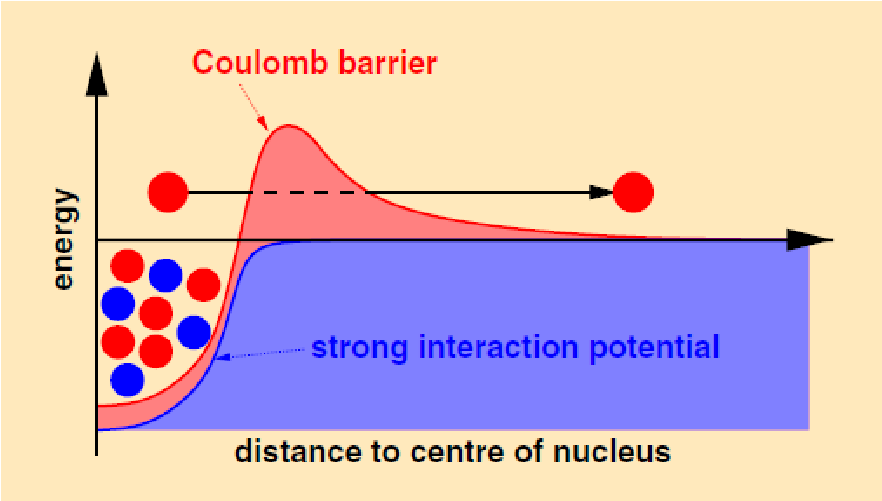
$_{71}$Lu

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).

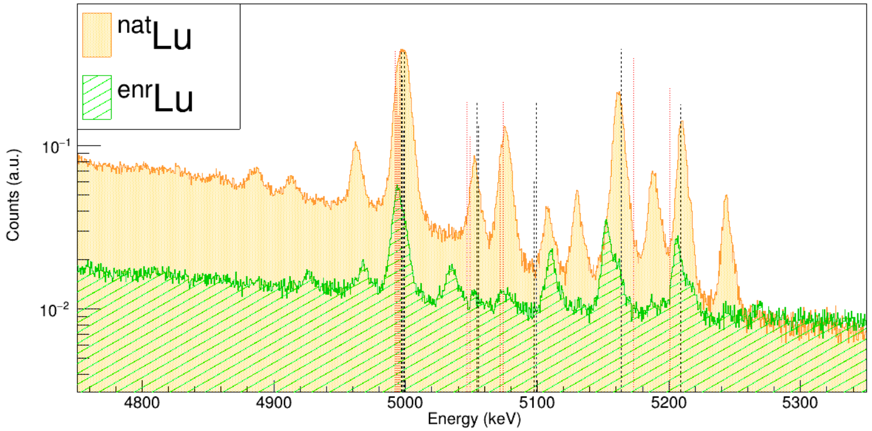
The question being: ’where’ is the proton? Is it still confined? Already spread beyond the nucleus?

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

Amazing data from 2024!

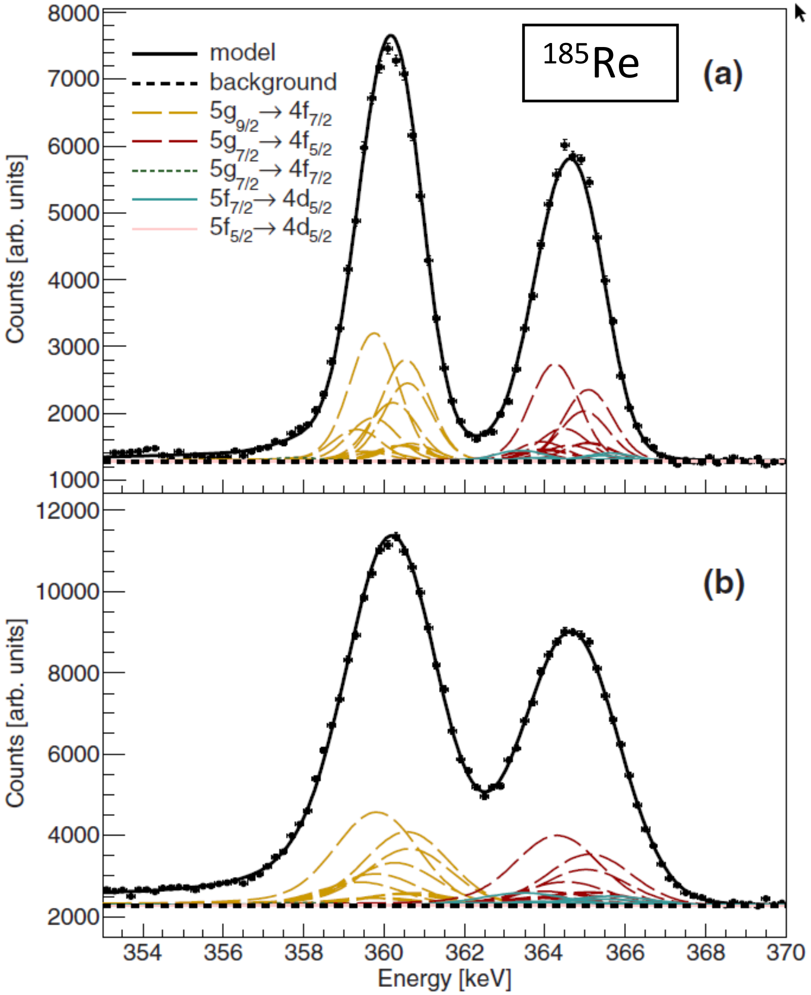


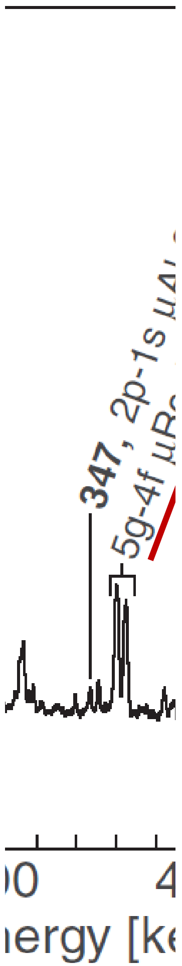
Nat. Vs Enr. Lu Anticoincidence

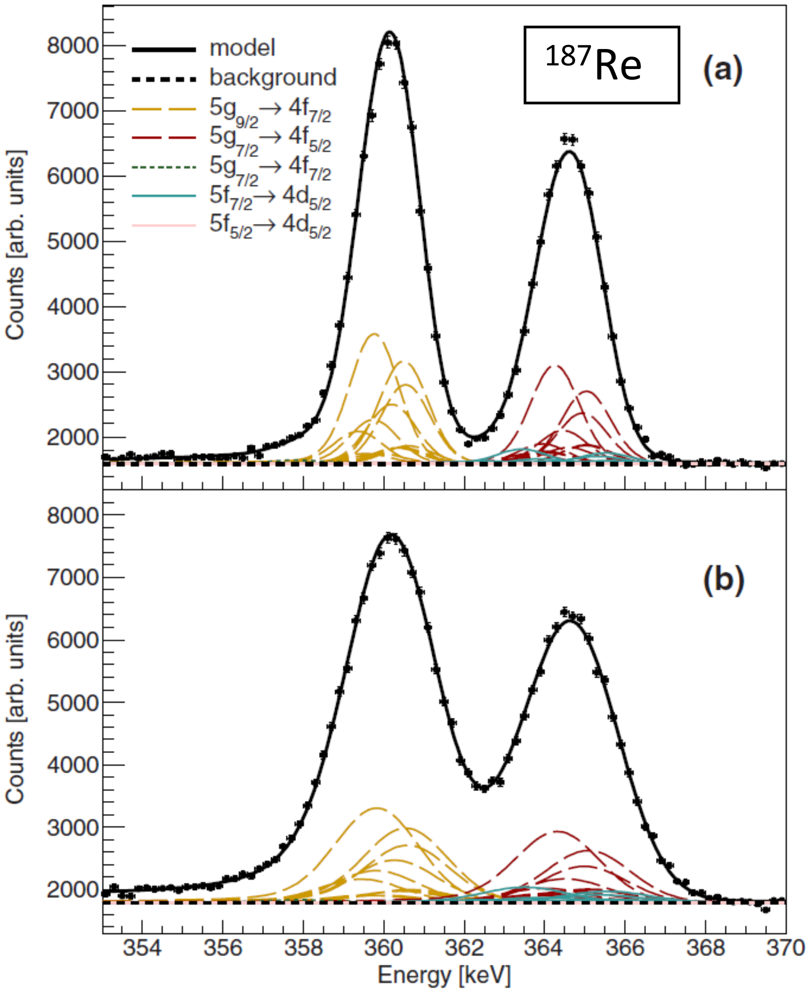


PhD work War War Myint Myat Phyo, KU Leuven.
*B. Blank & M Płoszajczak, Two-proton radioactivity, Report on Progress in Physics **71** (2008) 046301.*

Quadrupole moment of ^{185,187}Re





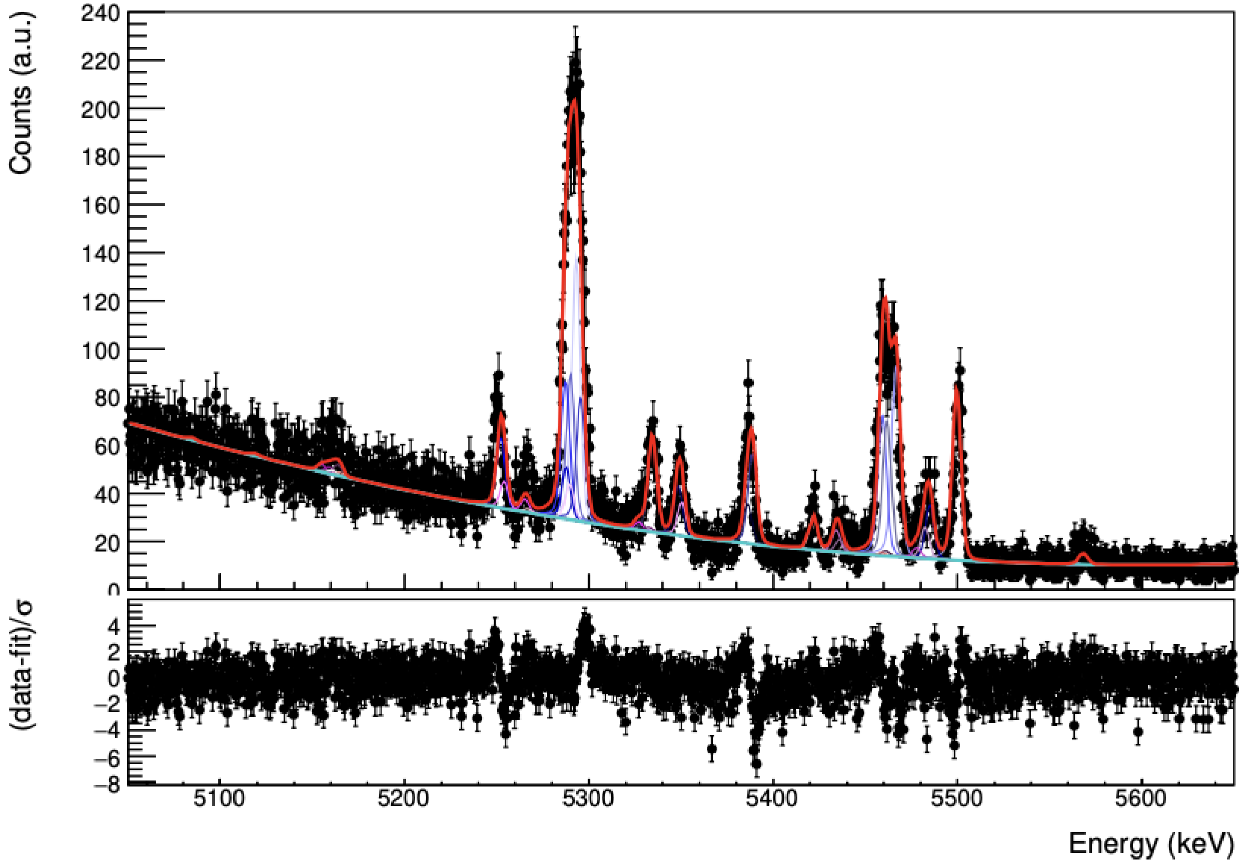


:
test on macroscopic
les of ^{185,187}Re

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.*

Absolute charge radius of ^{185,187}Re



(b) ^{187}Re

2016:

First test on macroscopic samples of ^{185,187}Re

Today:

Still cannot extract charge radius from 2p1s transition because of missing nuclear polarization correction.

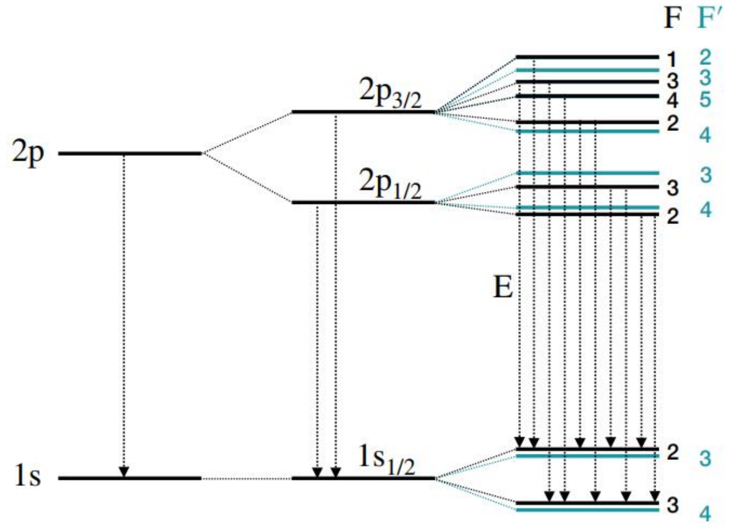
PhD thesis Stella Vogiatzi, ETH Zurich (2023).

Dynamic hyperfine splitting

Slide courtesy: Stella Vogiatzi

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

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



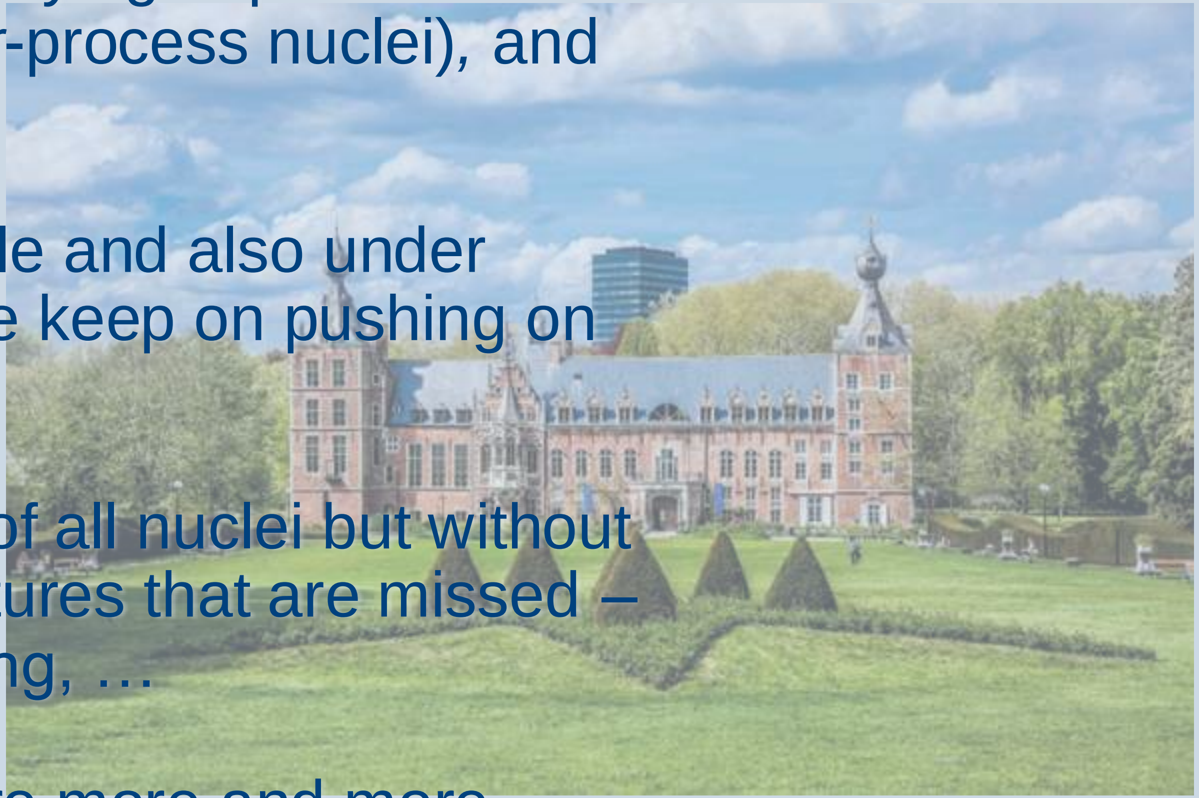
$I_{\text{ground}} = \frac{5}{2}^{+}$ $I_{\text{excited}} = \frac{7}{2}^{+}$

- 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

Experimental nuclear physics keeps on trying to push its boundaries left (proton emitters), right (*r*-process nuclei), and above (superheavies).



The experimental techniques are multiple and also under constant improvements. In particular, we keep on pushing on both sensitivity and precision.

Non even-even nuclei represent ~75% of all nuclei but without them, it is even more the measured features that are missed – like moments, spins, odd-even staggering, …

Besides nuclear structure, those radii are more and more implicated in searches for physics beyond the Standard Model.

Kennis kent geen einde

KU LEUVEN

Knowledge knows no end

This work is supported by the Flemish Science Foundation (FWO), by the Europe Commission through Horizon 2020, MSCA Innovative Training Network (no. 861198, LISA), and the European Research Council (no. 101088504, NSHAPE).