New frontiers in optical spectroscopy of radioactive nuclei

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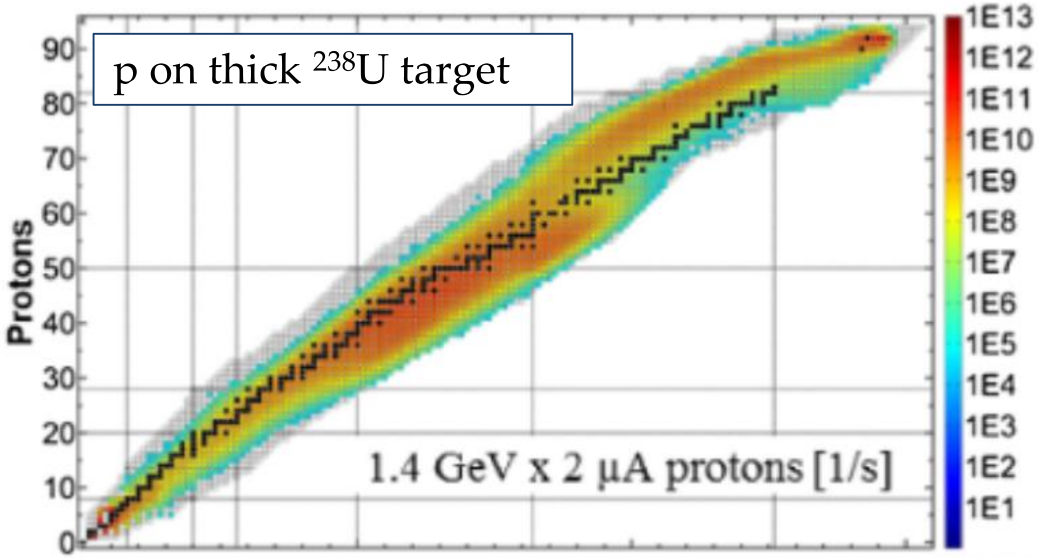
Optical spectroscopy of radioactive ions

- Production of radioactive ions: nuclear reactions
- Some beam and target combinations are not selective
  - e.g. protons on uranium allows production of nearly every element on the periodic table!

- Interesting physics phenomena can often be found at the extremes, which means production rates of the isotope of interest is often very low, and rate for other unwanted species can be very high

- Thus, methods need to be **both efficient and capable of suppressing background** events from unwanted ions, which at the same time have **sufficient resolution** to extract observables of interest

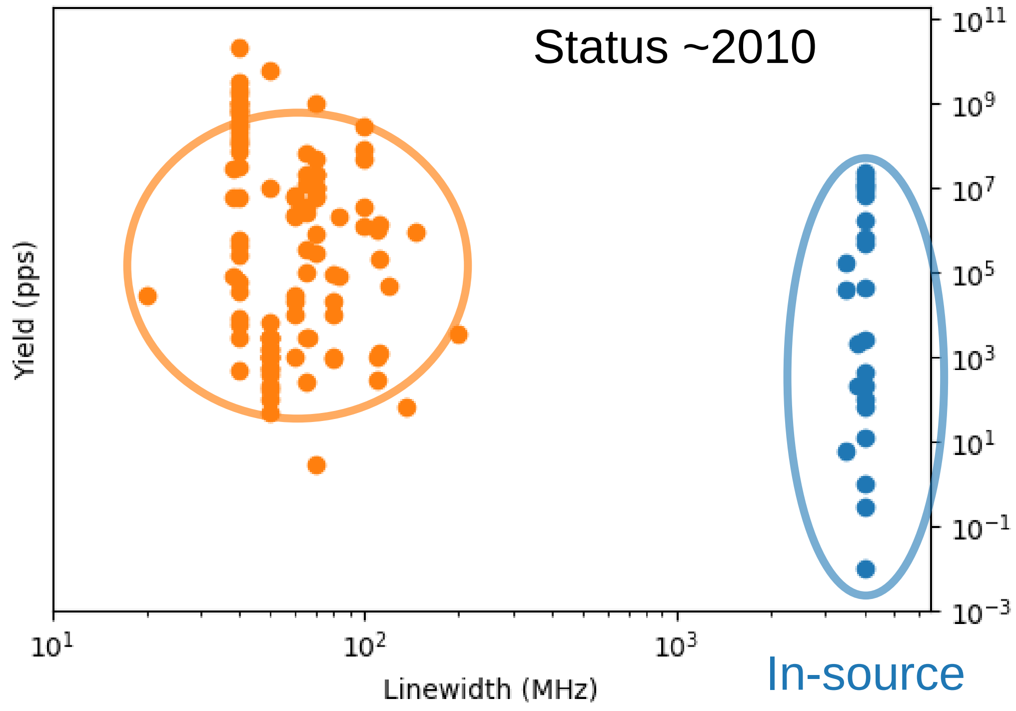


- Example: calculated production yields for 1.4GeV protons directed onto a thick uranium target
- Other reactions may be more selective, i.e. produce fewer isotopes in significant quantities

Outline

- Optical spectroscopy for nuclear structure research

Predominantly collinear fast-beam experiments

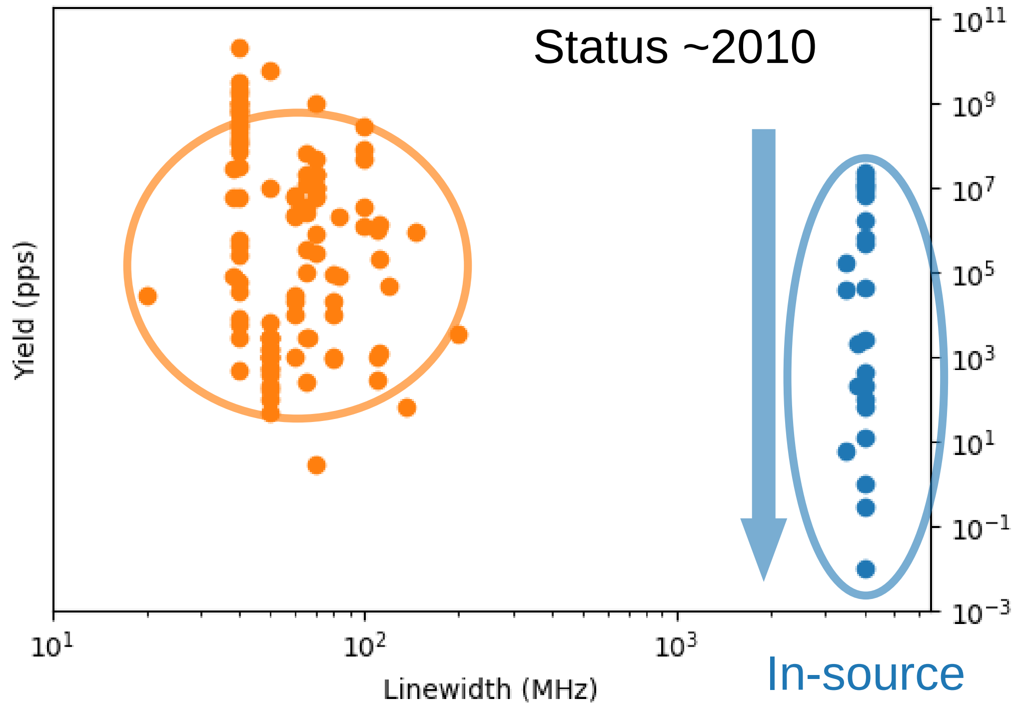


In-source experiments

Outline

- Optical spectroscopy for nuclear structure research
- The sensitivity frontier
  - in-source laser spectroscopy of silver

Predominantly collinear fast-beam experiments



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- Optical spectroscopy for nuclear structure research
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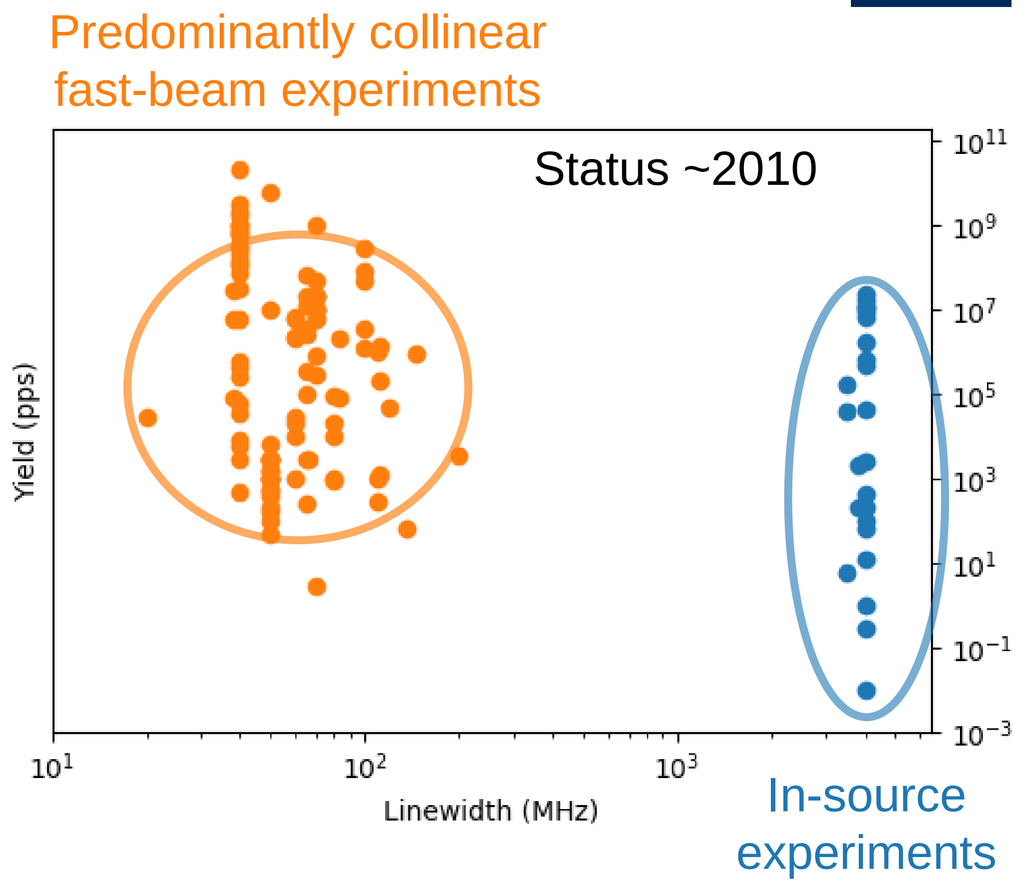
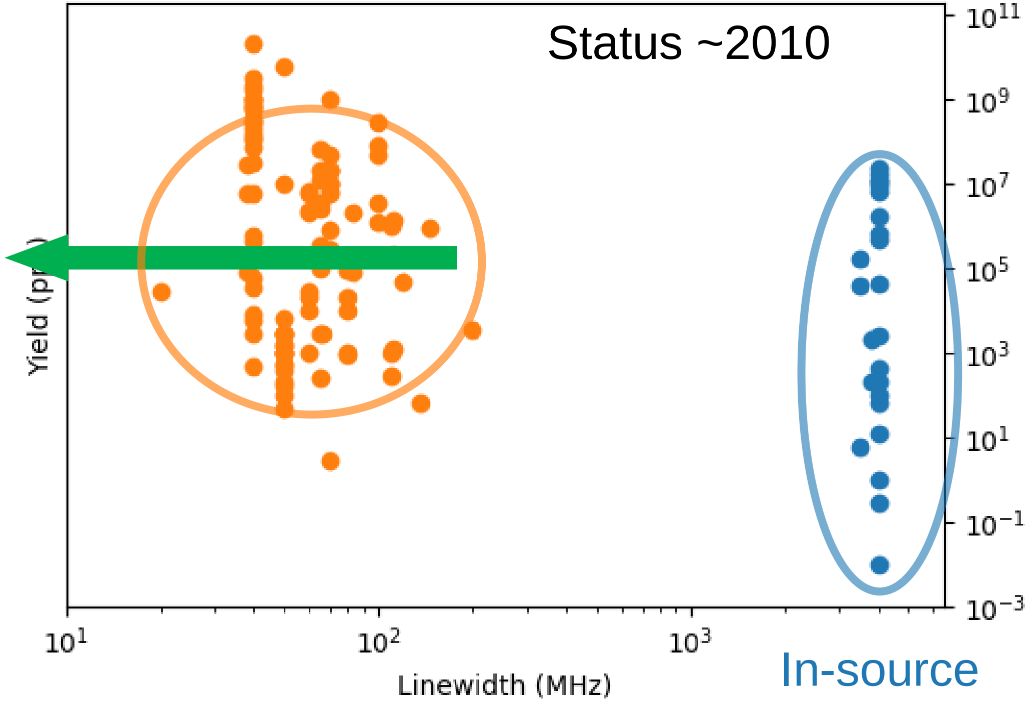
    - in-source laser spectroscopy of silver
- When more precision is needed: collinear fast-beam laser spectroscopy



Outline

- Optical spectroscopy for nuclear structure research
- The sensitivity frontier
  - in-source laser spectroscopy of silver
- When more precision is needed: collinear fast-beam laser spectroscopy
- When *even more* precision is needed: beyond conventional optical spectroscopy
  - Future directions?

Predominantly collinear fast-beam experiments



In-source experiments

The bigger picture…

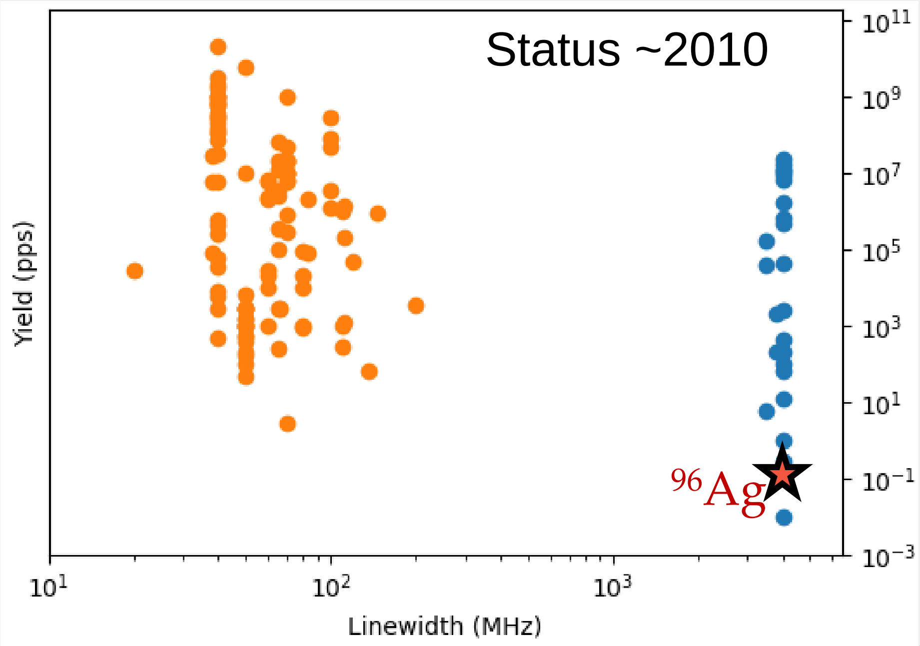
- Optical spectroscopy for nuclear structure research
- The sensitivity frontier
  - in-source laser spectroscopy of silver
- When more precision is needed: collinear fast-beam laser spectroscopy
- When *even more* precision is needed: beyond conventional optical spectroscopy
  - Future directions?

- See talks by Wilfried Nörtershäuser, Iain Moore
- Spectroscopy of *truly* exotic ions
  - See talk by Michael Block
  - See talk by Gerda Neyens
- Collinear resonance ionization and in-gas-jet laser spectroscopy – combine precision and sensitivity
  - See talks by Gerda Neyens and Rafael Ferrer
- Why sub-Hz spectroscopy?
  - See talk by Julian Berengut

And many others...

- Spectroscopy in MRTOF, MOT-traps, …
- Laser polarization (VITO, B-NMR, …)
- …

The sensitivity frontier



The sensitivity frontier: the push to ^{94}Ag

methods need to be both **efficient** and capable of **suppressing background** events from unwanted ions

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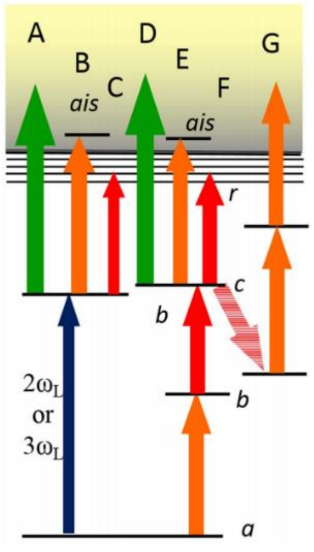

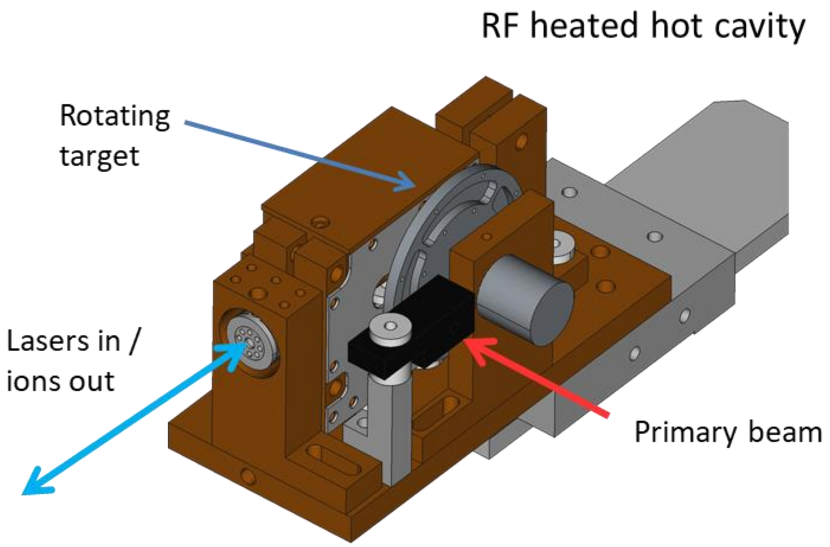

- e.g. ^{14}Ni(^{92}Mo, 2p 10n) ^{96}Ag

  ~ 10/s in-target production as a starting point!

  $t_{1/2}$ = 4.4 s => no time to collect a big sample

- Efficient detection of optical resonance?
  - Detection of fluorescence? Not sufficiently efficient in current methods
  - Instead, multi-step laser ionization and charged particle detection
    - Laser ionization efficiencies >> 1 % routine

The sensitivity frontier: the push to ^{94}Ag

methods need to be both **efficient** and capable of **suppressing background** events from unwanted ions

- Exploit the unique characteristics of a particular element, isotope, …
  - Decay radiation (especially gamma and alpha particles)
  - Atomic spectra
  - **Binding energy**
  - …
- For the silver studies presented next, we detect the laser-ionized atoms in a Penning trap mass spectrometer
  - Only those ions which respond to the laser wavelengths *and* which have the exact mass will be selected

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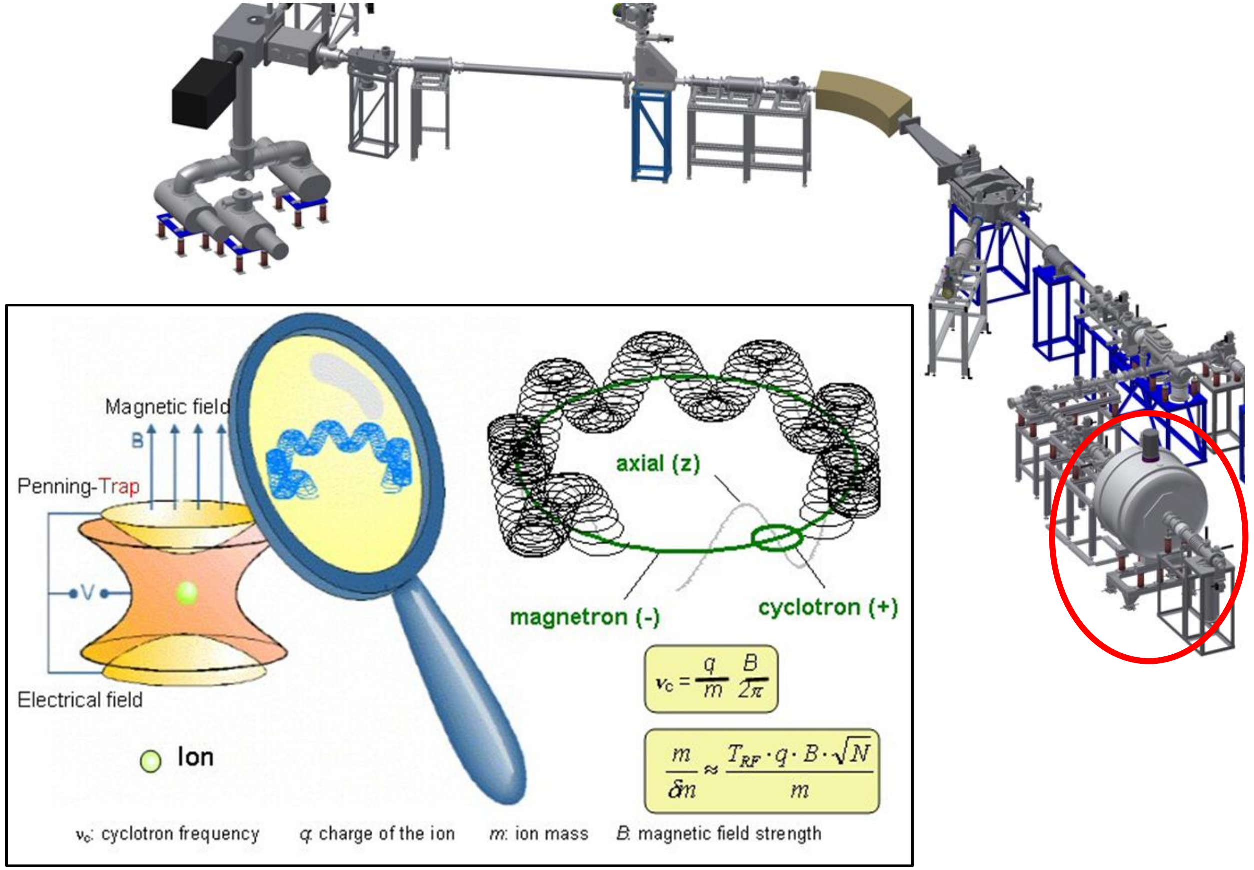
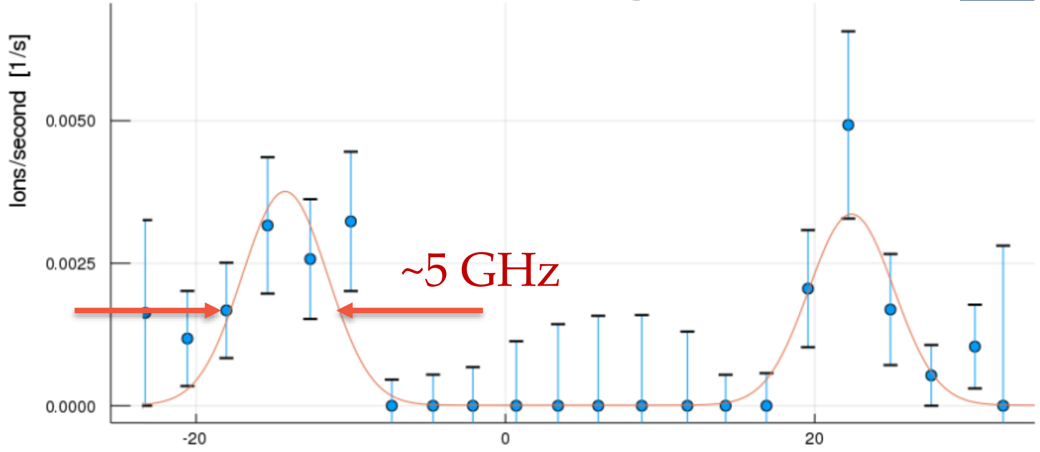
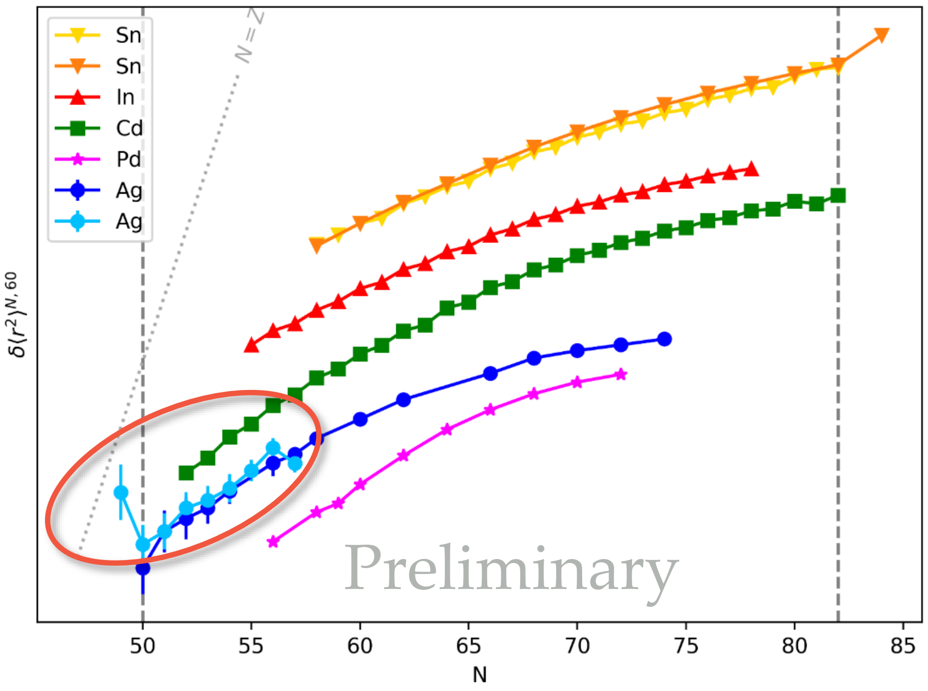


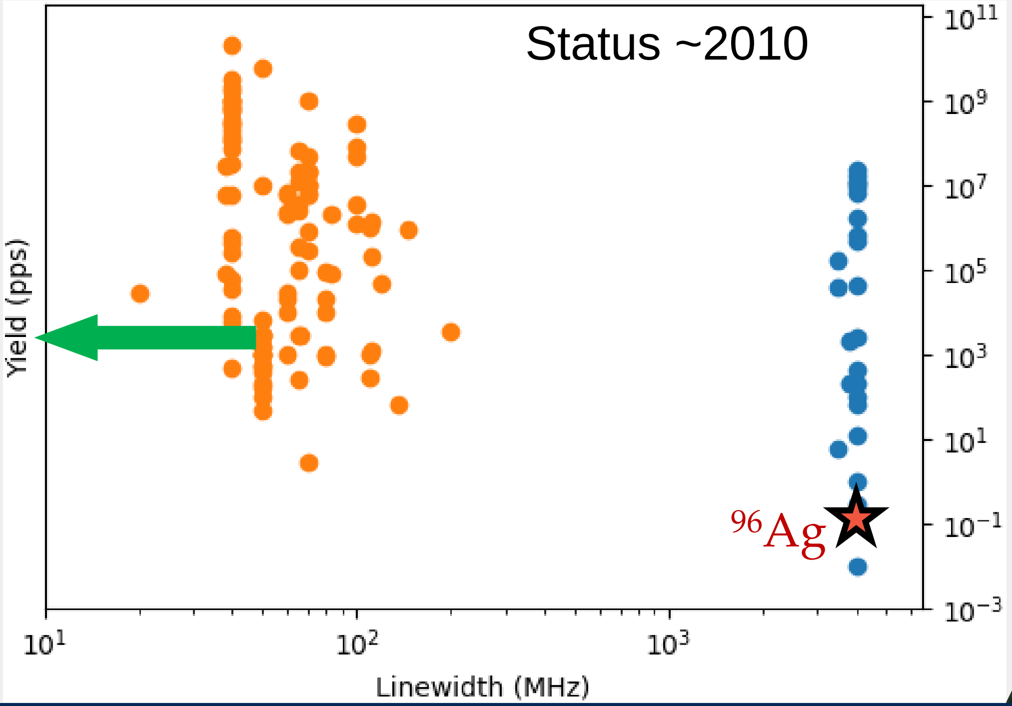
The sensitivity frontier: the push to ^{94}Ag

- Successful measurement on ^{96}Ag
- Low statistics, but with background rates << 1/min that is not an issue
- Magnetic dipole moment and mean-squared charge radius could be extracted
  - Magnetic moment: under analysis
  - Charge radius: clear change in the trend when crossing N=50
  - Clear shell effect (see talk W. Nörtershäuser)
- Future goals:
  - Using different reaction, ^{94,95}Ag should be possible
  - Magnetic moment of ^{95}Ag: investigate purity of configuration and thus probe strength of shell closure Z, N=50
- **We have developed a rich toolbox of experimental methods; many compelling physics cases require us to combine them**

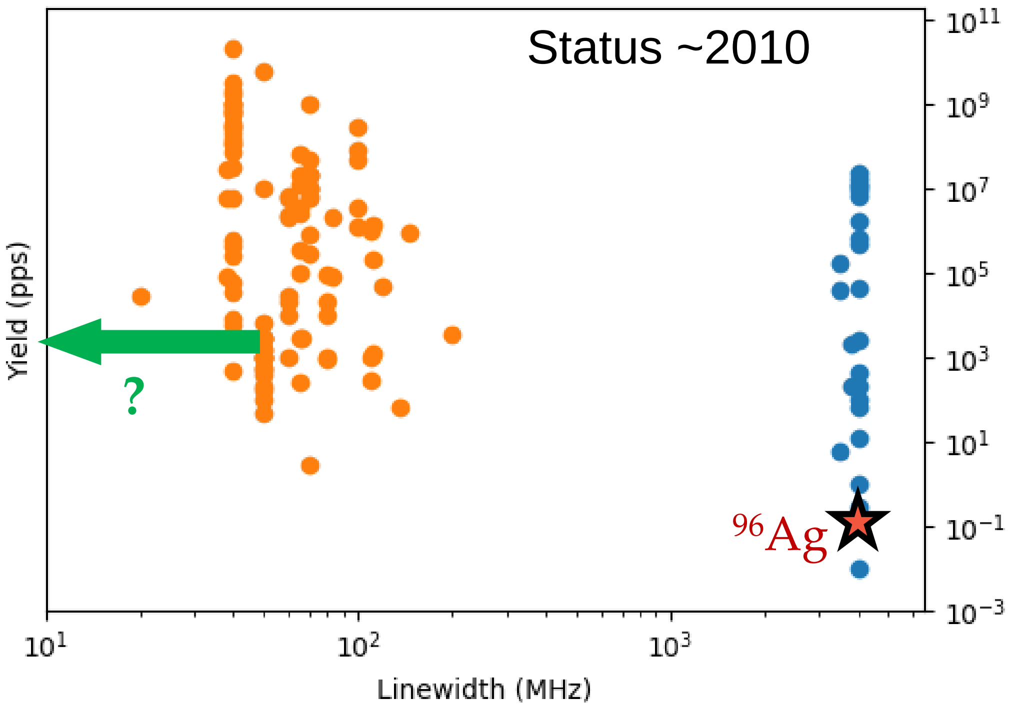




The precision frontier



Do we need to go beyond ~50 MHz?



GHz

sub-Hz

- Magnetic dipole moments
- Electrical quadrupole moments and charge radii
- Hyperfine anomaly
  - Relates to the distribution of magnetization inside nuclear volume
- Higher-order moments
  - Magnetic octupole, electric hexadecupole, …
- Higher-order moments of the charge radii
  - E.g. $\langle r^4 \rangle$ relates to surface thickness of nuclear density [1]
- Beyond-standard model physics from Hz-level isotope shift spectroscopy

[1] PG Reinhard, W Nazarewicz, RF Ruiz - arXiv preprint arXiv:1911.00699, 2019

Do we need to go beyond ~50 MHz?

Discussed so far

In-source optical spectroscopy

Collinear, in-gas-jet, …

Current state-of-the-art

What could we investigate with these methods?

Laser-rf methods on fast ion beams and thermal beams in traps

Feasible on RIB

Atom/ion traps + laser cooling + ultra-narrow lines

Currently only on stable

GHz

sub-Hz

- Magnetic dipole moments
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  - **Magnetic octupole**, electric hexadecupole, …
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Puzzling octupole moments

- Magnetic octupole constant *C* relates hyperfine structure intervals to the underlying magnetic octupole moment Ω
  - C typically 1 kHz or less…
  - Accurate C/Ω values required to extract absolute octupole moment!
  - Challenging for atomic structure calculations

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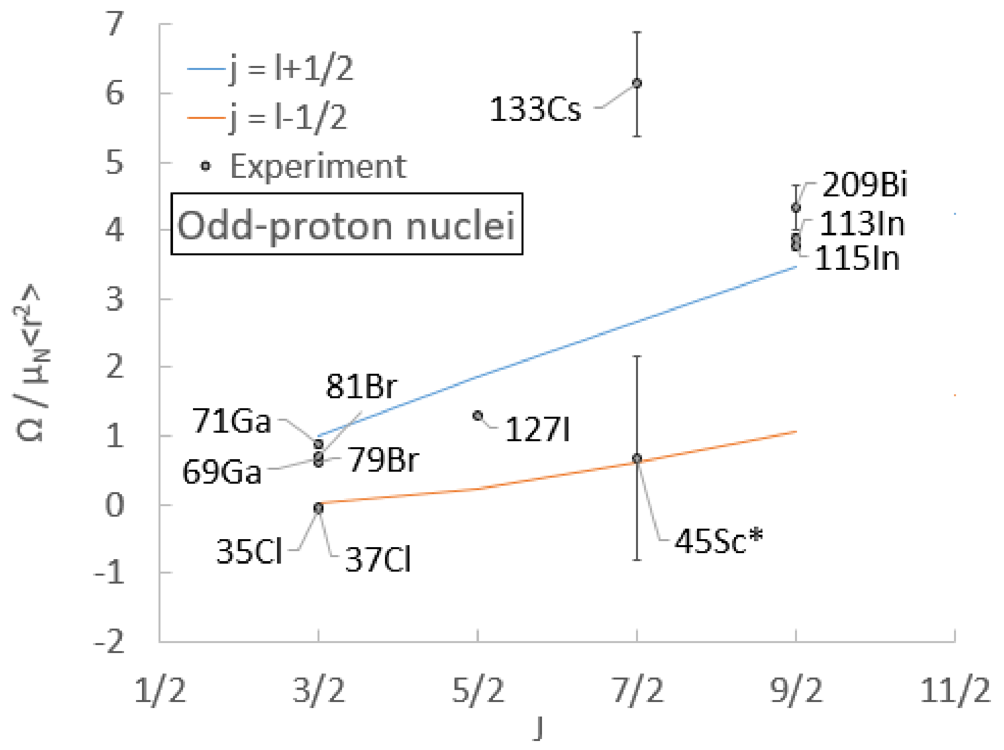
  - Accurate C/Ω values required to extract absolute octupole moment!
  - Challenging for atomic structure calculations
- Simplest possible model (single particle shell model) yields simple predictions
  - Figure made using quenched g-factors (same as dipole)

$$\Omega=-M_3=+\mu_N\frac{3}{2}\frac{(2I-1)}{(2I+4)(2I+2)}\langle r^2\rangle$$

Valence nucleon radius

$$\times\begin{cases}(I+2)[(I-\frac{3}{2})g_l+g_s], & I=l+\frac{1}{2};\\(I-1)[(I+5/2)g_l-g_s], & I=l-\frac{1}{2}.\end{cases}$$



*Preliminary value, R. P. de Groote, B. Sahoo et al, in preparation

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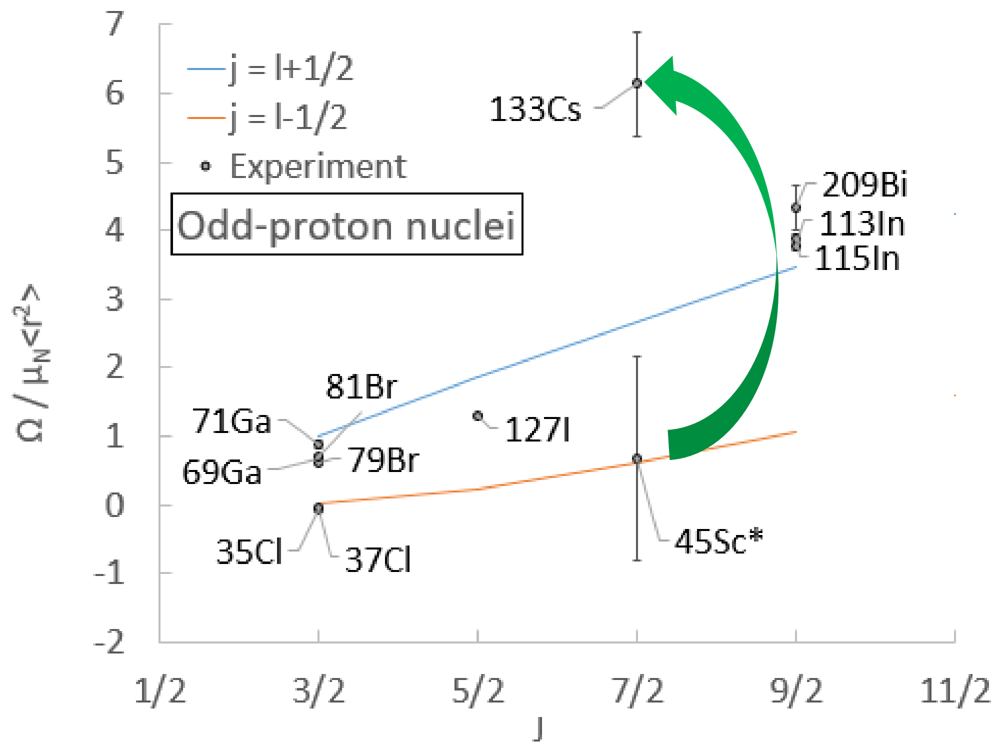
  - Accurate C/Ω values required to extract absolute octupole moment!
  - Challenging for atomic structure calculations
- Simplest possible model (single particle shell model) yields simple predictions
  - General trend more or less understood… but clear discrepancies visible
  - Deficiency in nuclear model or *C*/Ω?
- Several other strange examples in literature
  - ^{177,179}Hf: ratio of Ω hard to explain
  - ^{155}Gd: unusually large Ω



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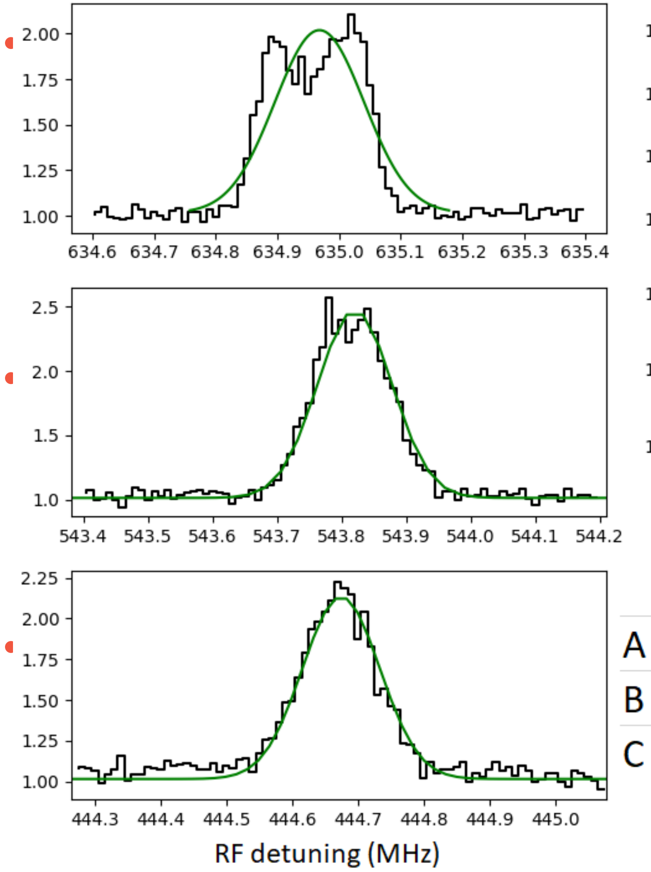
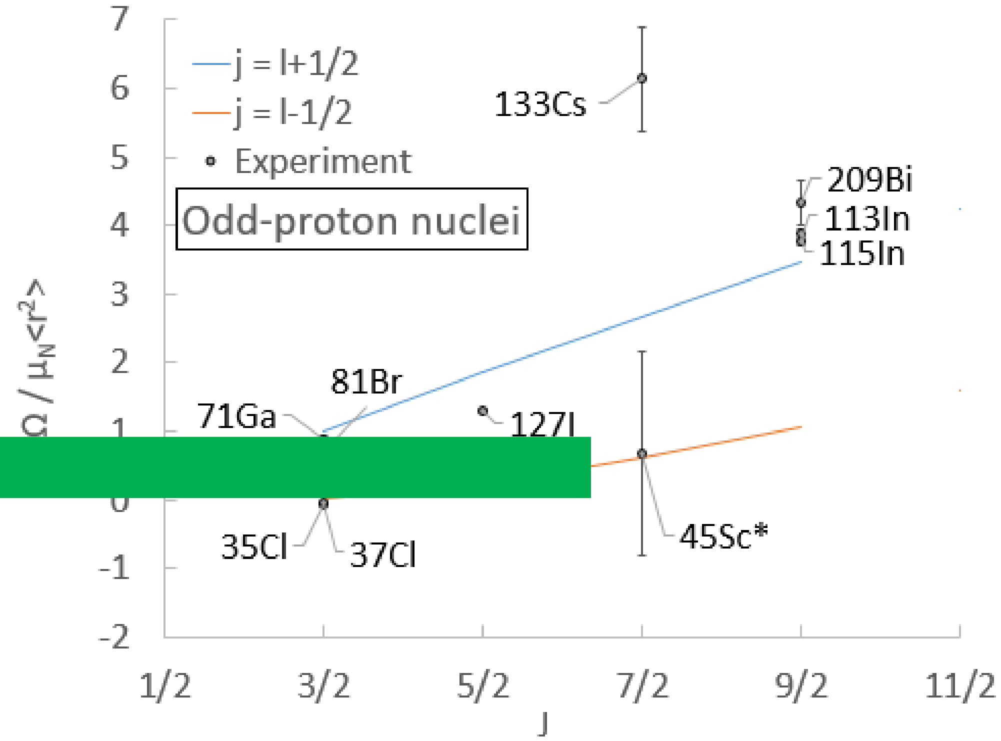


	This work		Childs et al	
A (MHz)	109.03213	0.0002	109.032	0.001
B (MHz)	-37.3889	0.003	-37.387	0.012
C (kHz)	0.96	under analysis	1.7	1



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Looking towards the future

- First steps: revive radiofrequency spectroscopy on radioactive beams
- Exploit several decades' worth of technology
  - Cooler-bunchers and other emittance improving devices
  - Turnkey laser systems
  - RF generators and amplifier technology
  - Ion- and atom trapping technology
- In my opinion, measurements on >10 elements for at least 5-10 isotopes each are currently achievable!
  - Atoms: Bi, In, Hg, Sc
  - Ions: Ca, Sr, Ba, Ra, Hf, Eu, … especially in ion traps!
- At the same time, these developments will provide a major boost to
  - Hyperfine anomaly studies (also largely unexplored on RIB [1])
  - Charge radii measurements beyond $\langle r^2 \rangle$ (importance? See [2])
  - …

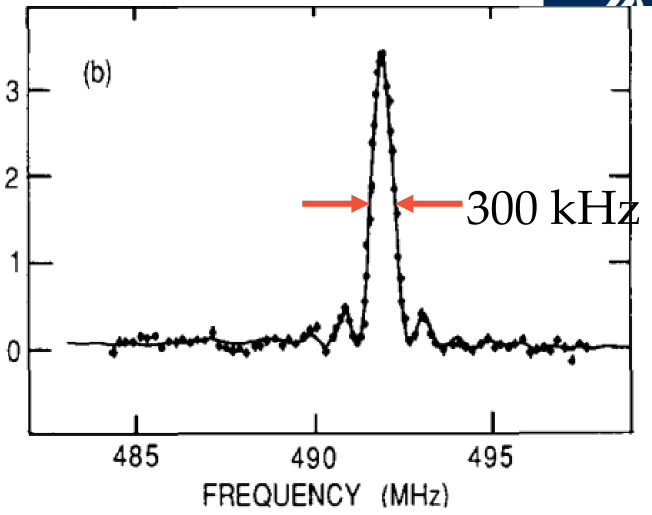


Fig.1: collinear laser-rf (using RIS) on ^{4}He Rydberg atoms at 13 keV beam energy

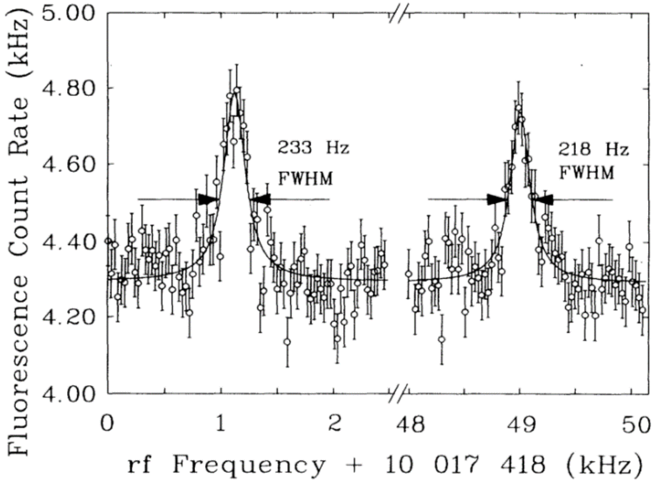


Fig.2: Laser-rf spectroscopy of $^{151}Eu^+$ ions in a Paul trap. Note: no laser cooling required!

[1] Persson, J. R. Atomic Data and Nuclear Data Tables, 99(1), 62-68 (2013) .
[2] PG Reinhard, W Nazarewicz, RF Ruiz - arXiv preprint arXiv:1911.00699, 2019

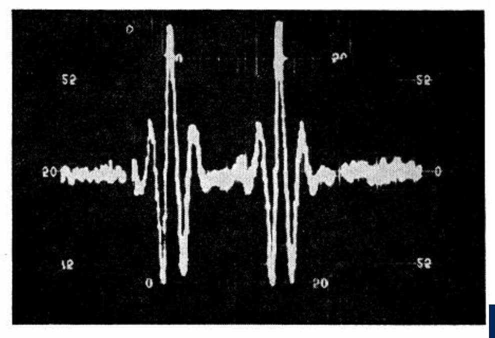
Looking towards the future

Atomic structure calculations

- Calculations of C/Ω
  - Get Ω as accurately as possible
  - Conversely, several elements where C can be measured for several states
=> benchmark calculations
  - Aid in planning new experiments by identifying optical spectroscopic schemes
- Calculations of second-order hyperfine effects
- Re-evaluate existing data?

Nuclear structure calculations

- Evaluation of $\langle r^2 \rangle$ of valence nucleon to compare to simple models
- Theory work close to spherical systems as well as for well-derformed systems
- Systematic surveys to identify interesting regions?
  - i.e. is there a link with quadrupole, octupole deformation?
  - Can we learn something about quenching? Different aspects of configuration mixing? Neutron magnetization distribution? Neutron skins? …



A challenging road ahead…!

Ω Measurement on Ga - R. T. Daly Jr et al, Phys. Rev. **96**, 539 (1954)

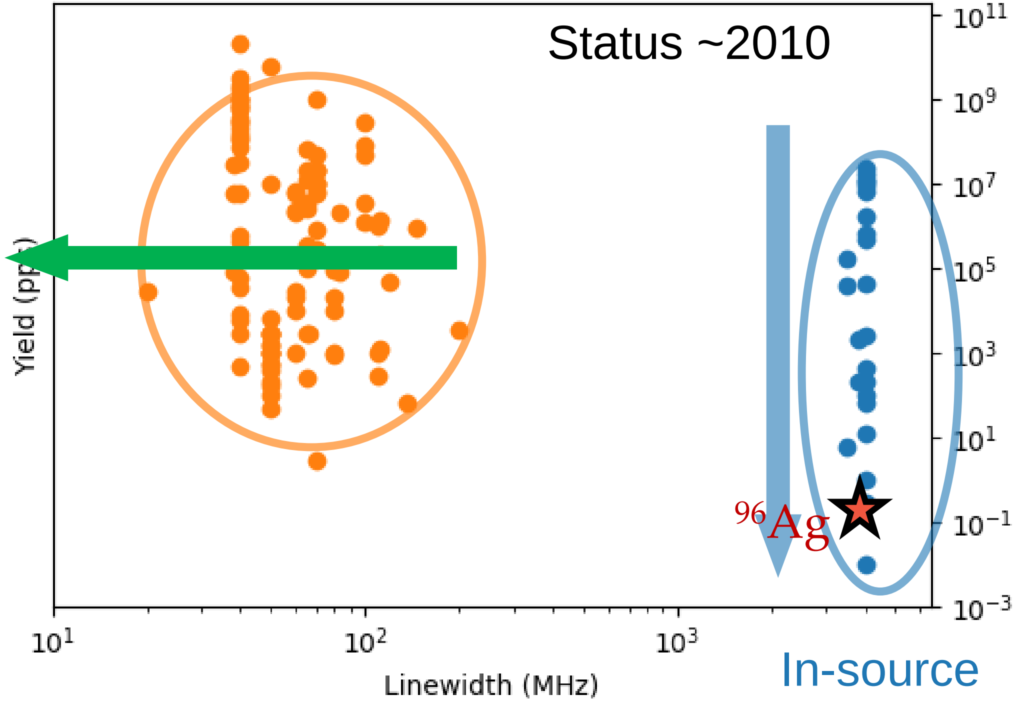
In summary…

Frontiers of optical spectroscopy on radioactive isotopes…

- Dealing with RIB requires **sensitivity**
- Extraction of charge radii, magnetic moments, quadrupole moments requires **resolution**
- We are currently developing the tools to meet these requirements, (if possible even at the same time)

- The interaction between experiment and theory, atomic and nuclear, is **crucial**
- I expect these synergies to only get more important as we push our fields further

Predominantly collinear fast-beam experiments

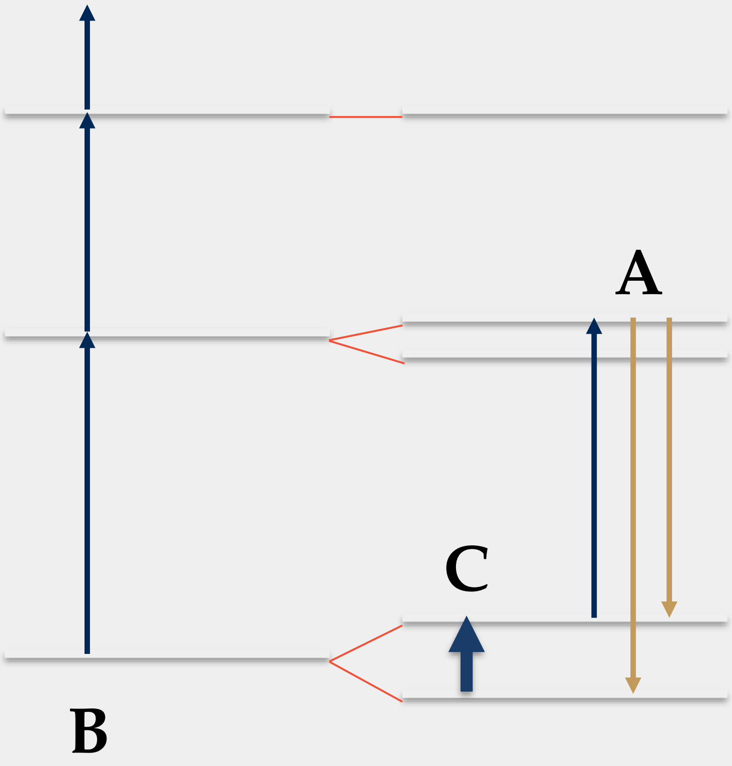


In-source experiments

Thank you!

MARIE CURIE ACTIONS

laser-rf spectroscopy



Pump – Invert – Probe

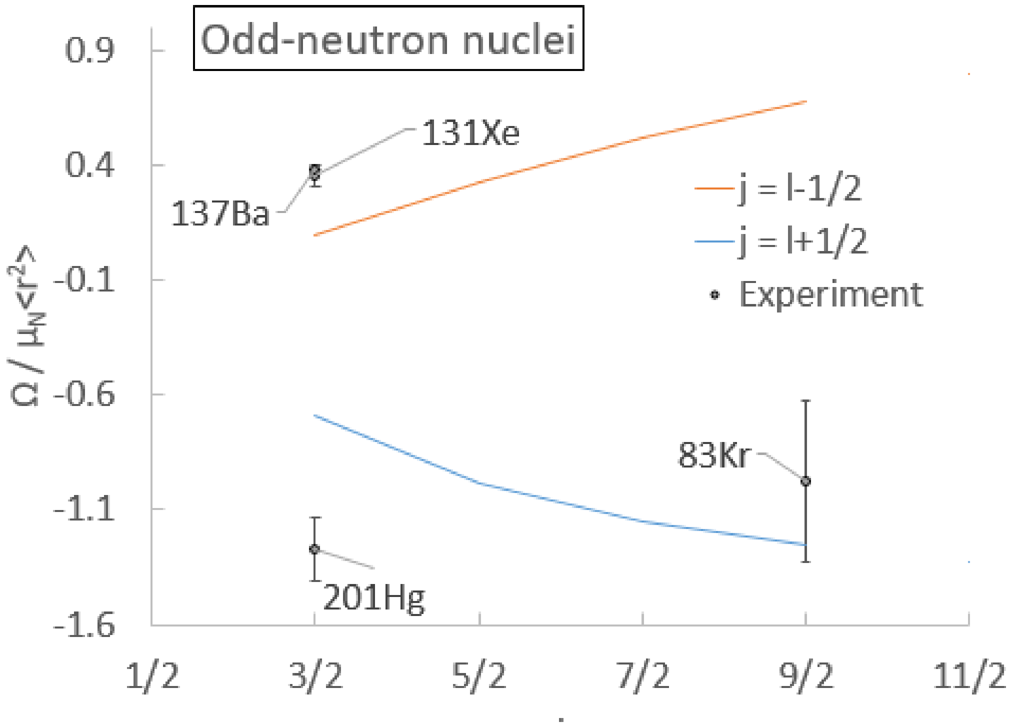
A. Optically **pump** hyperfine level to deplete it

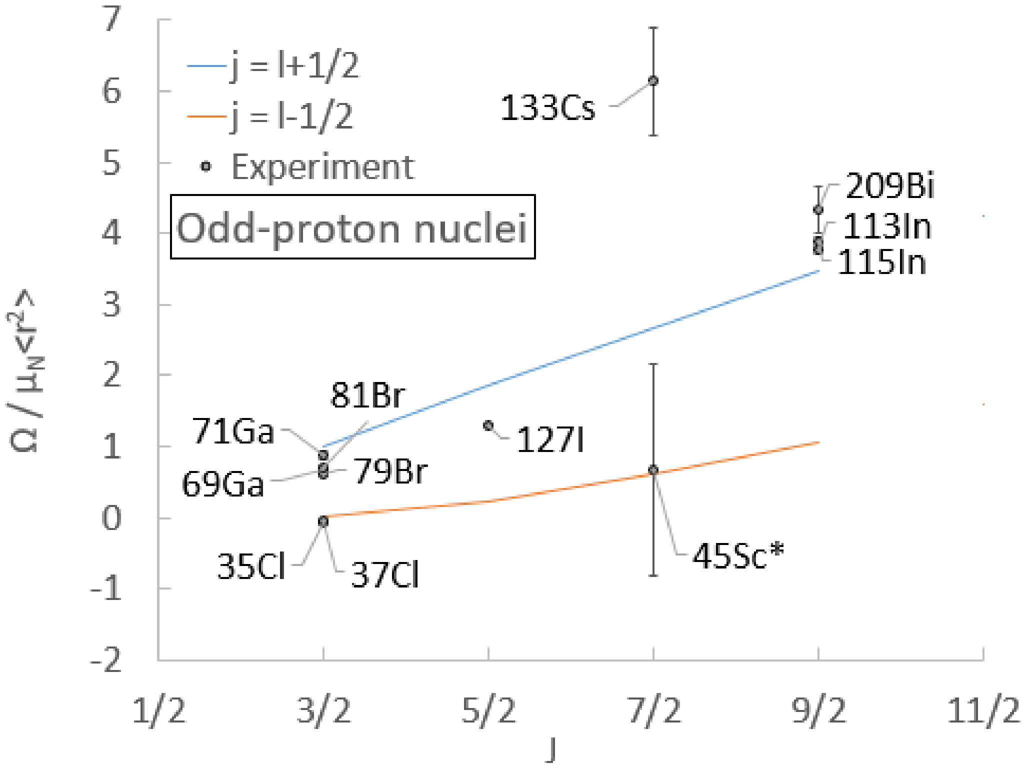
C. Apply **RF** at the hyperfine resonance to undo the depletion

B. Optically **probe** population of the hyperfine level with photon detection, RIS, …

Can be done in many different geometries, including those that work well for RIB!

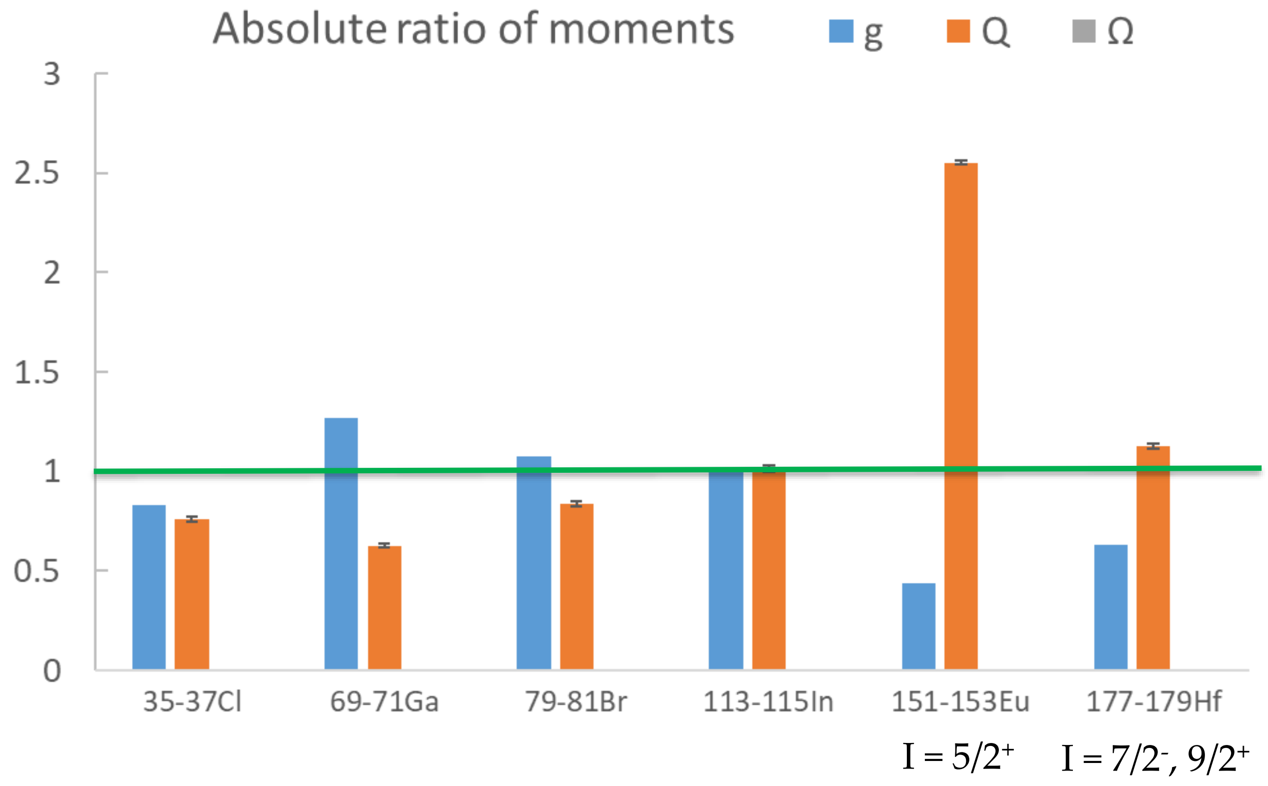
- Collinear – proven!
- Ion- and atom traps – proven!
- Gas-jet? PI-LIST? – no obvious showstoppers


Odd-neutron nuclei
0.9
0.4
-0.1
-0.6
-1.1
-1.6
Ω / μ_N<r²>
131Xe
137Ba
j = l-1/2
j = l+1/2
Experiment
83Kr
201Hg
1/2
3/2
5/2
7/2
9/2
11/2


7
6
5
4
3
2
1
0
-1
-2
Ω / μ_N<r²>
j = l+1/2
j = l-1/2
Experiment
133Cs
Odd-proton nuclei
209Bi
113In
115In
81Br
71Ga
69Ga
79Br
127I
35Cl
37Cl
45Sc*
1/2
3/2
5/2
7/2
9/2
11/2
J

Puzzling octupole moments

- Ratio of moments of nuclei of mass A and A+2
  - Ratio ~ 1: similar electromagnetic structure
  - e.g. ^{113,115}In: very similar nuclear structure
  - ^{153}Eu is significantly more deformed than ^{151}Eu



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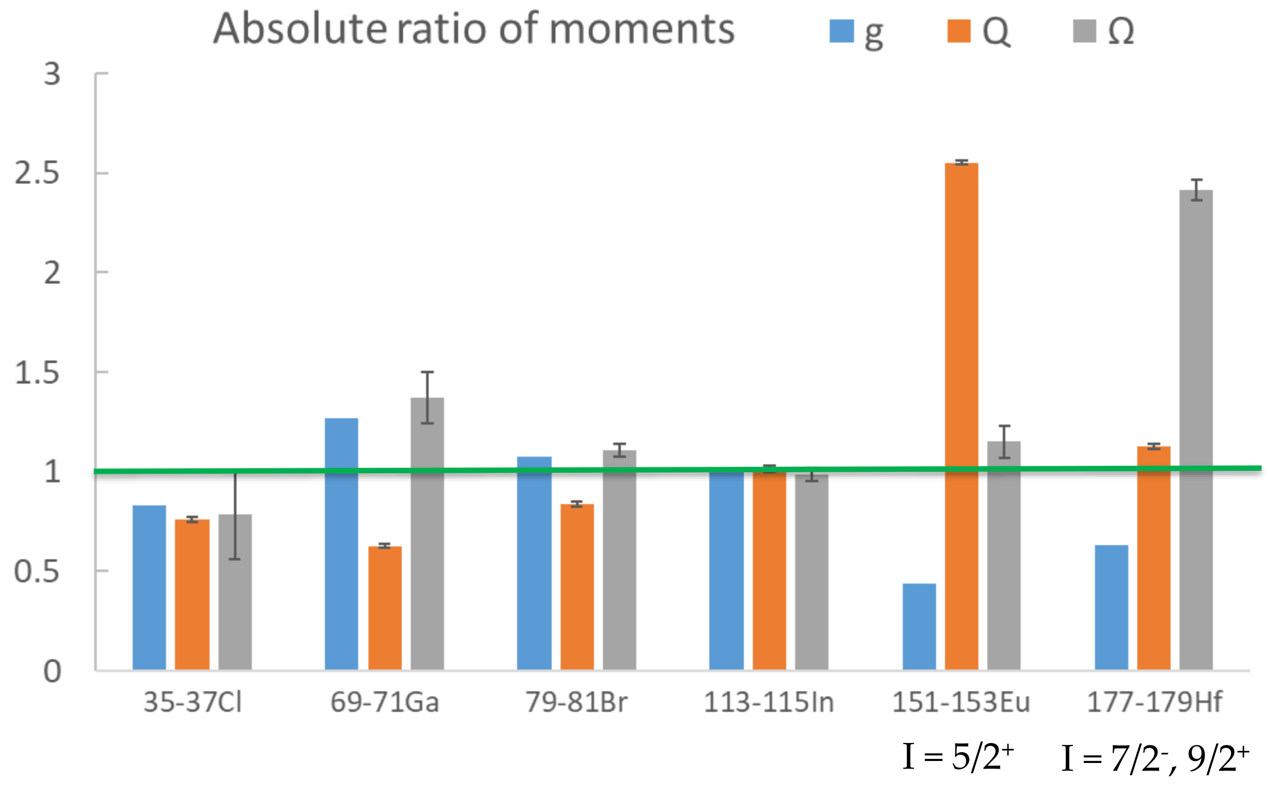
- Same exercise for Ω
  - / Ratio of C-parameters avoids theoretical uncertainties in first order
  - / Ω probes magnetization of the nucleus in a different way than magnetic moment
  - / Role of deformation?
  - / Hard to tease out information…
  - / **More data absolutely needed…**



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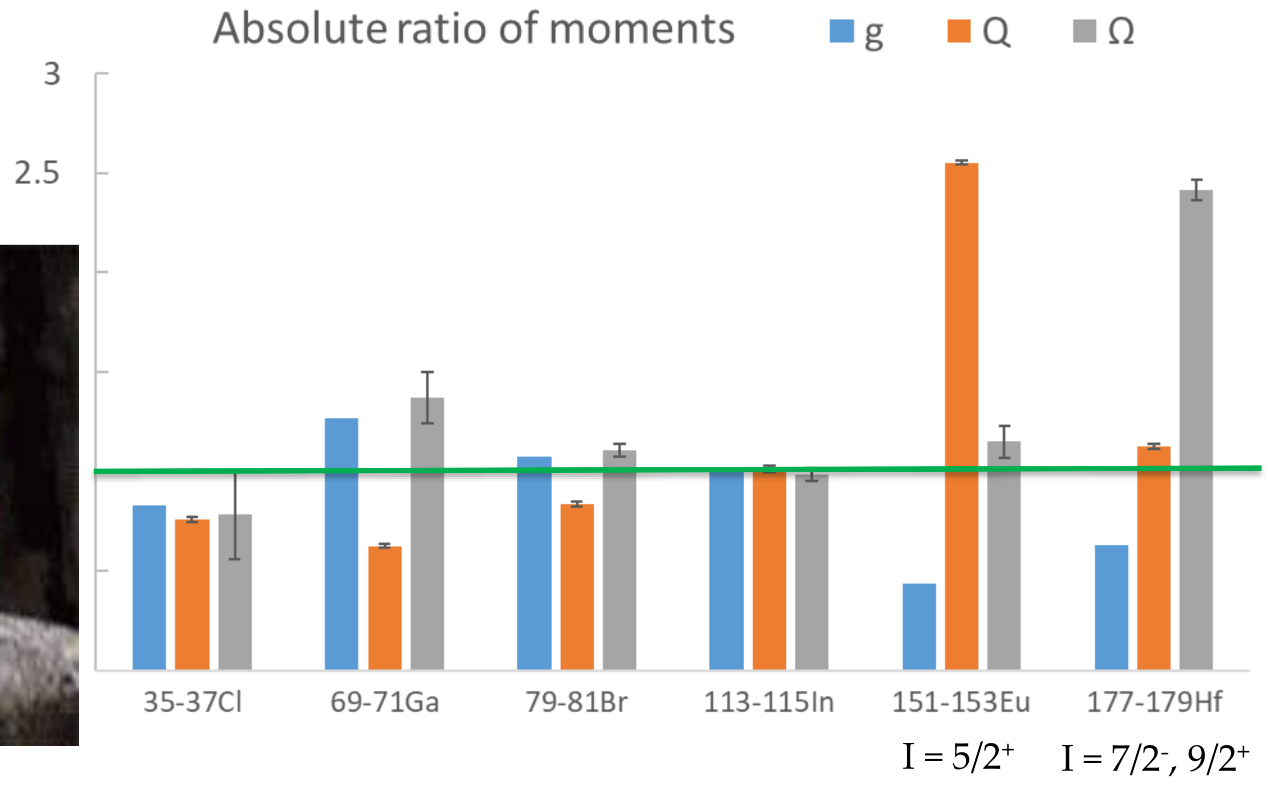

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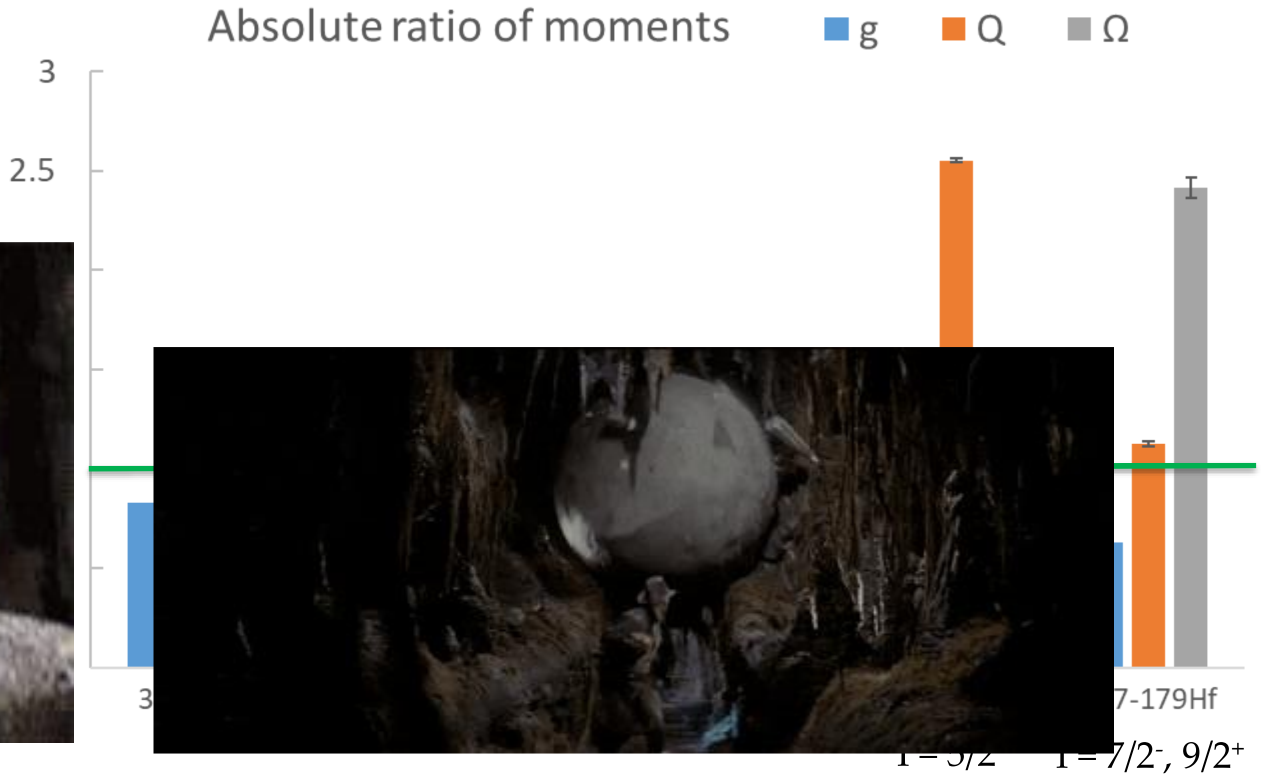
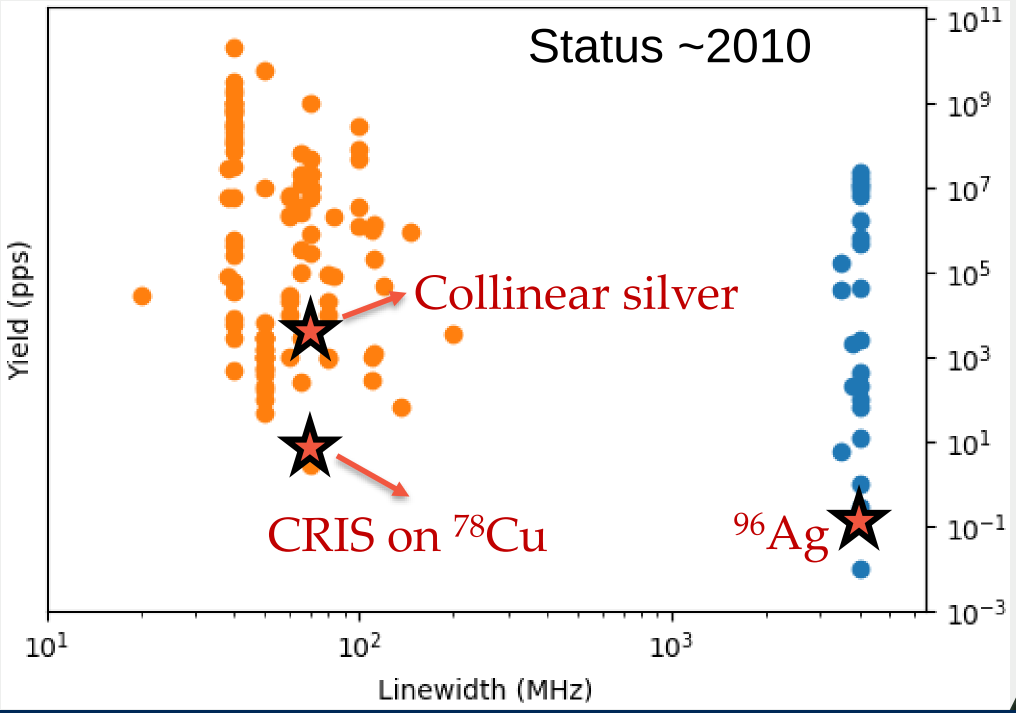
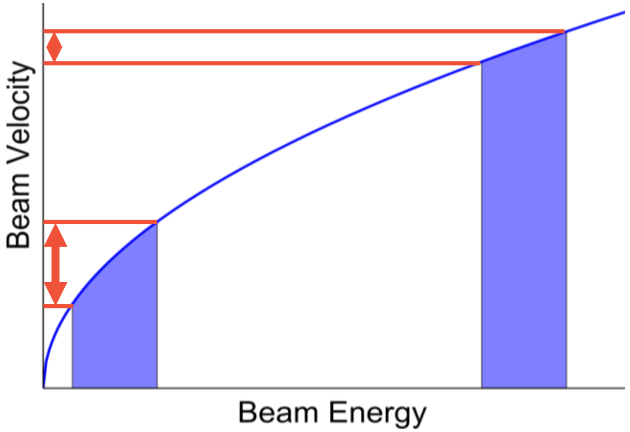


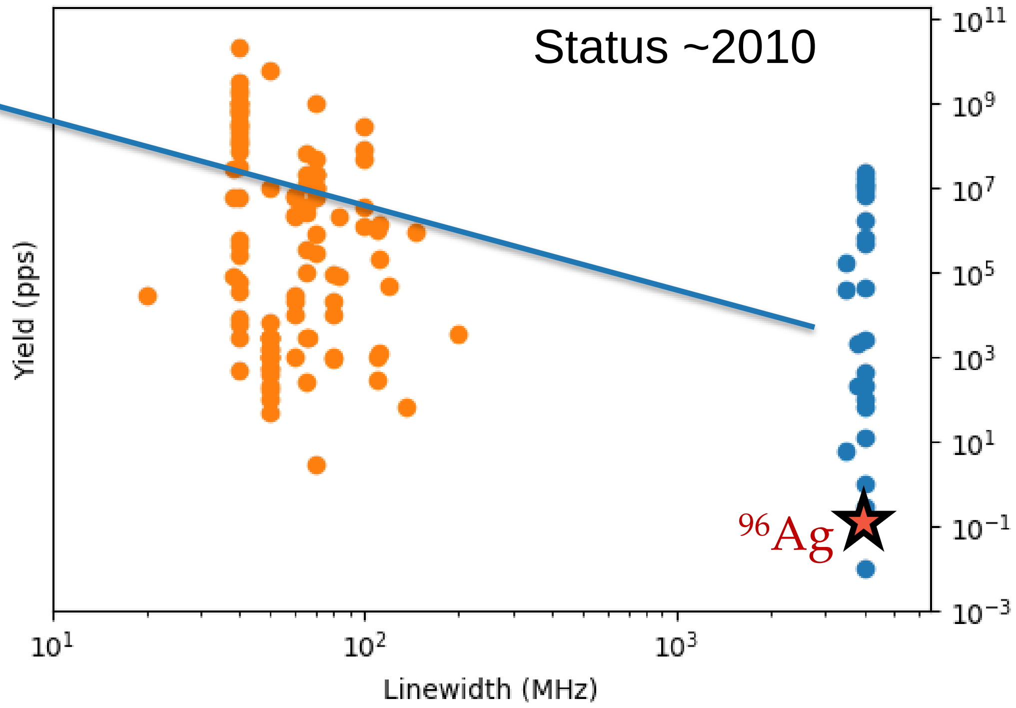
Precision and resolution



The role of resolution

- In many cases, details are obscured by these wide lineshapes
- Workhorse of ~100 MHz linewidth resolution: collinear laser spectroscopy

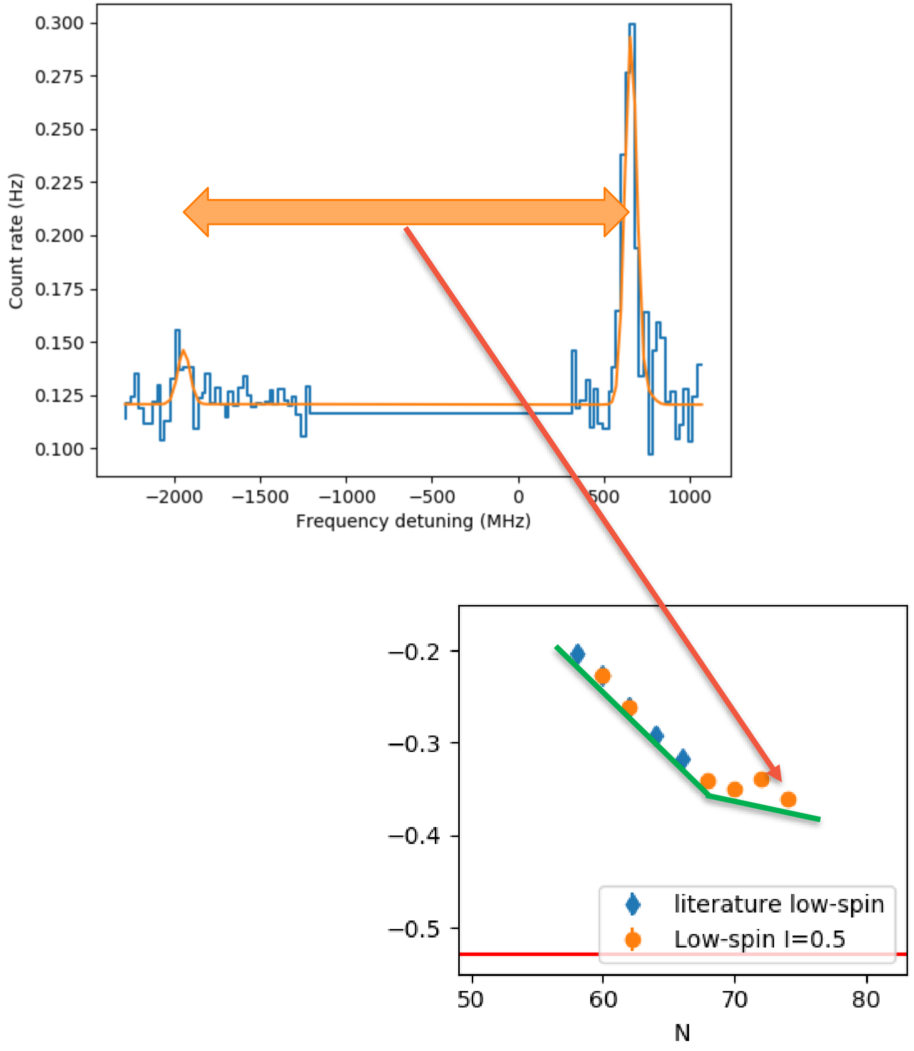




- Acceleration compresses velocity spread of the ensemble, which leads to reduced Doppler widths, which reduces linewidhts

Collinear laser spectroscopy of silver

- Higher resolution allows to study nuclear states with small *g*-factors
  - Trend of the spin *I*=½ states quite out of the ordinary!



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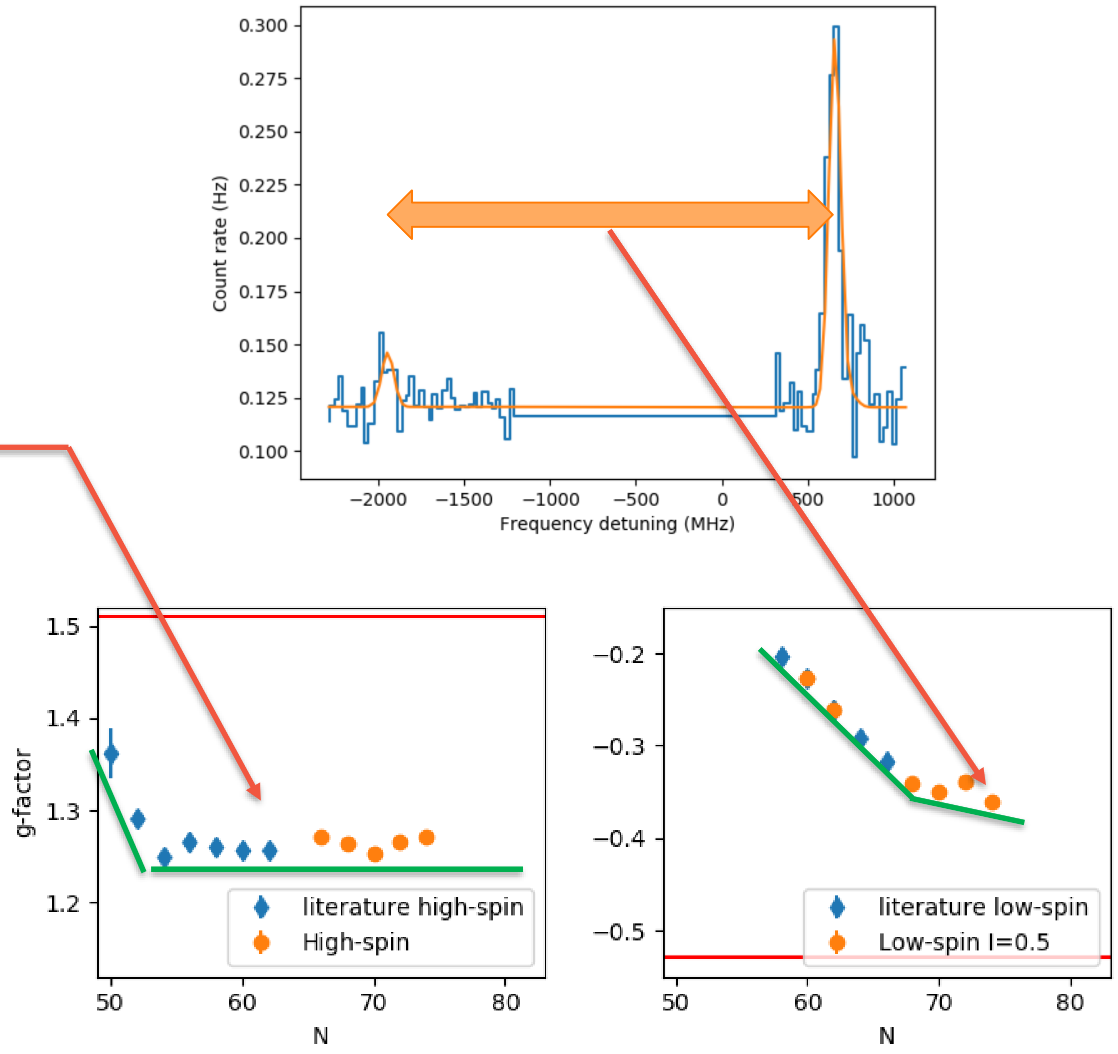
  - So, why is there this clear trend here, and why does it appear to change slope?



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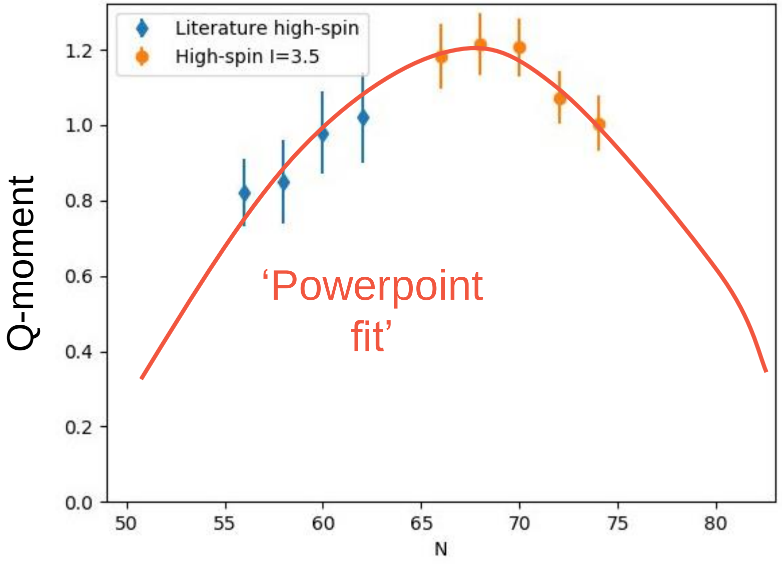
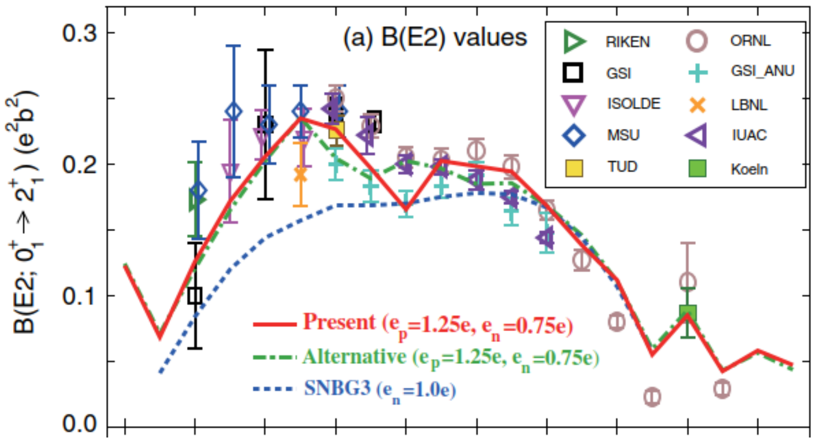
  - So, why is there this clear trend here, and why does it appear to change slope?
- Higher resolution allows to access e.g. quadrupole moments for silver
  - Similar trends observed in transition probabilities B(E2) in the region as deformation parameter

$$\beta_2 \approx \left(\frac{4\pi}{3ZeR_0^2}\right)\sqrt{B(E2)}$$



Example from Sn isotopes

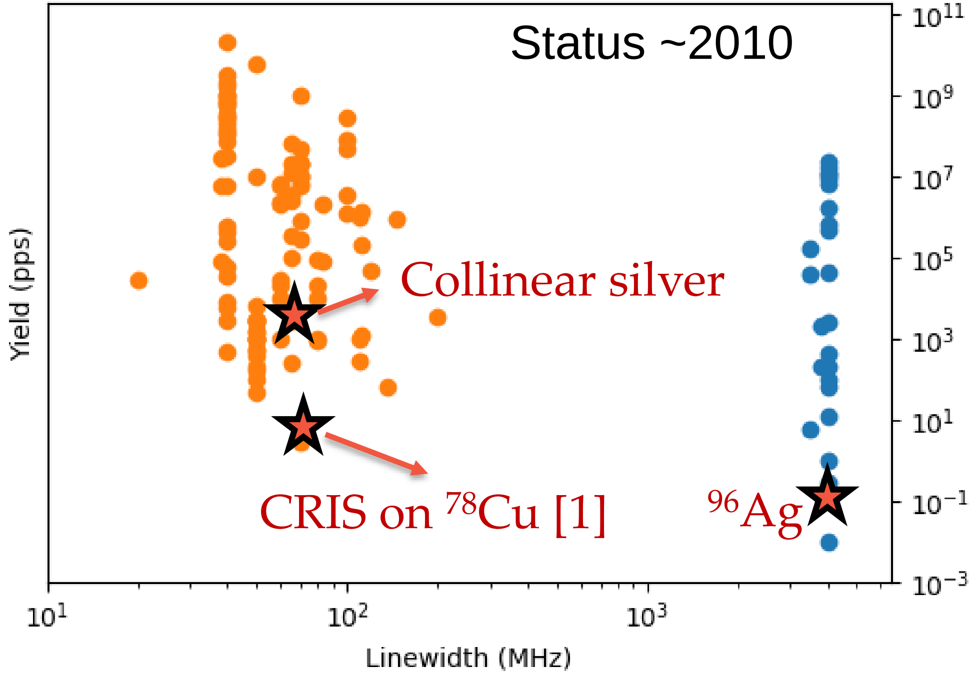


T. Togashi et al., Phys. Rev. Lett. 121, 062501 (2018)

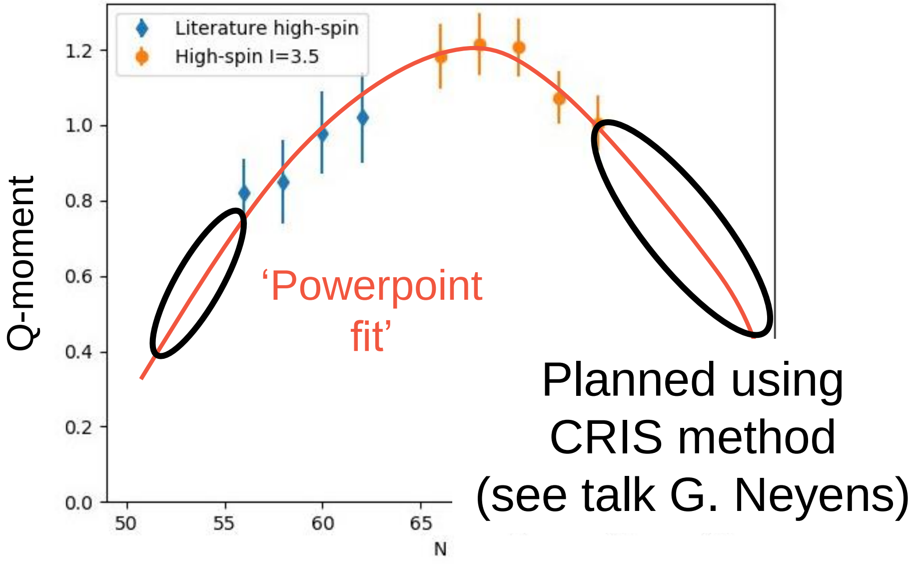
[1] A. Arima and H. Horie, Prog. in Theor. Phys. 12 (1954) 623

Collinear laser spectroscopy of silver

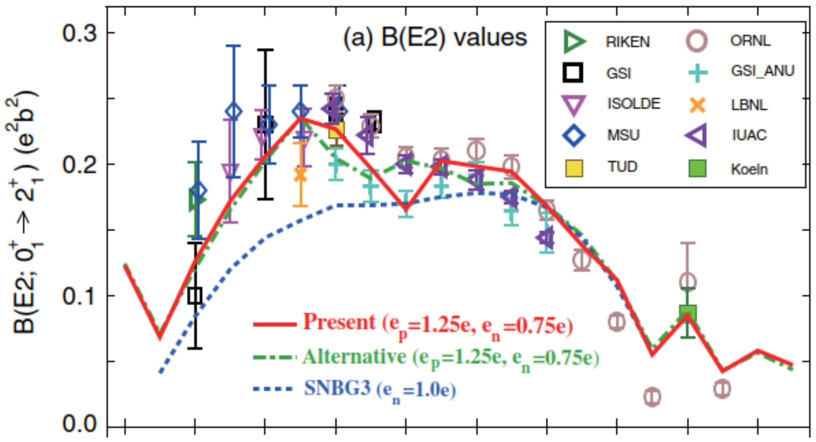
- To put these measurements in to context:



- Production yields being equal, future measurements will require a higher sensitivity method, e.g. collinear resonance ionization spectroscopy (see talk G. Neyens)



Example from Sn isotopes



T. Togashi et al., Phys. Rev. Lett. 121, 062501 (2018)