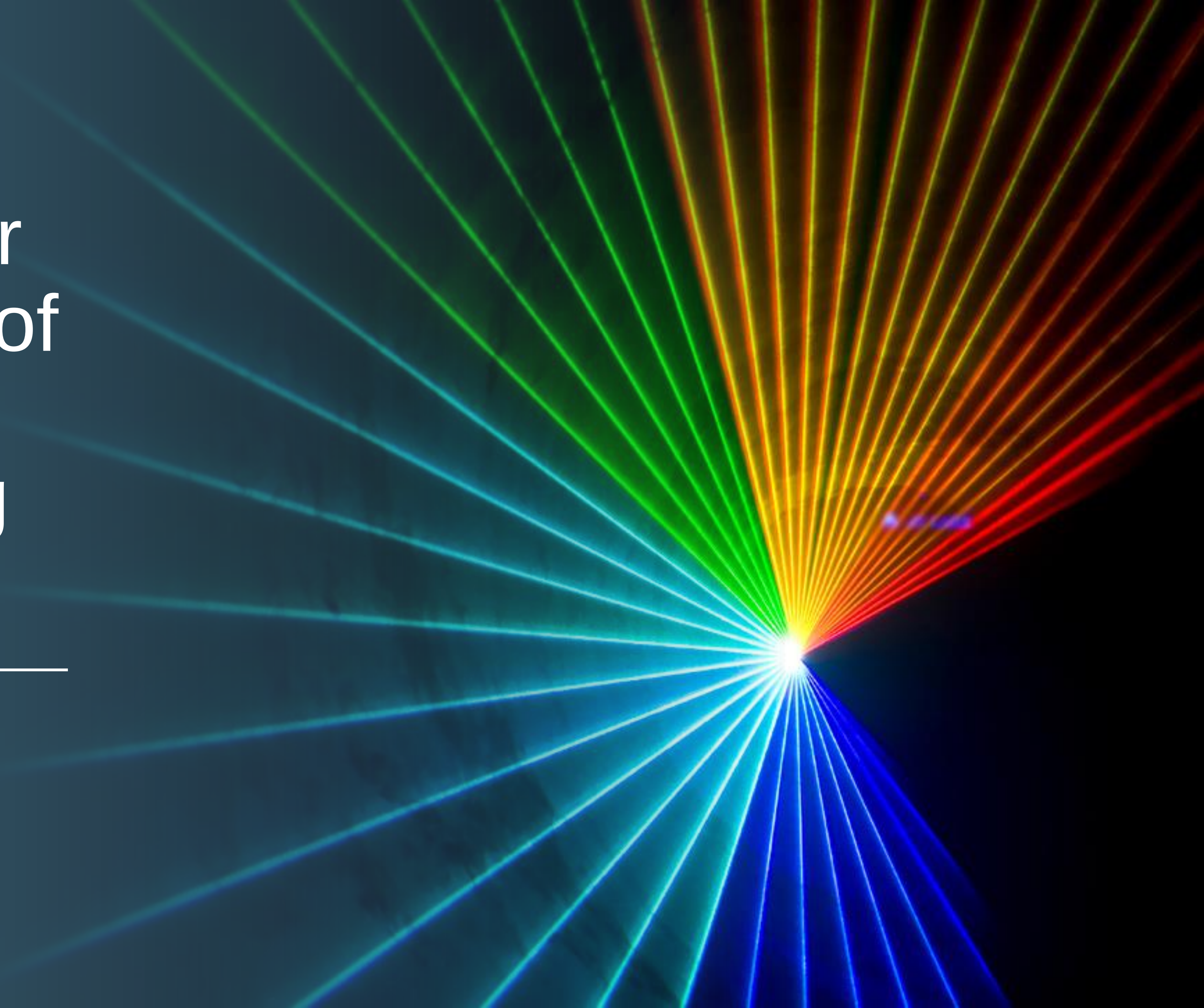
Precision laser spectroscopy of radioactive isotopes using traps



Ruben de Groote

EMIS XIX – 03.10. 22

Daejon, Korea

Outline

- Laser spectroscopy of exotic isotopes
- Study of ultra-rare isotopes with particle-based detection schemes
  - Penning-trap assisted study of $^{95,96}Ag$
  - Collinear resonance ionization spectroscopy of ^{52}K
- Atomic state manipulation with trapped ions
  - Optical pumping of trapped radioactive cobalt isotopes
- Development of precision spectroscopy of trapped ions
  - Future plans towards magnetic octupole moment measurements of ^{87}Sr

Outline

- Laser spectroscopy of exotic isotopes

- Study of ultra-rare isotopes with particle-based detection schemes
  - **Penning-trap** assisted study of $^{95,96}Ag$
  - Collinear resonance ionization spectroscopy of ^{52}K

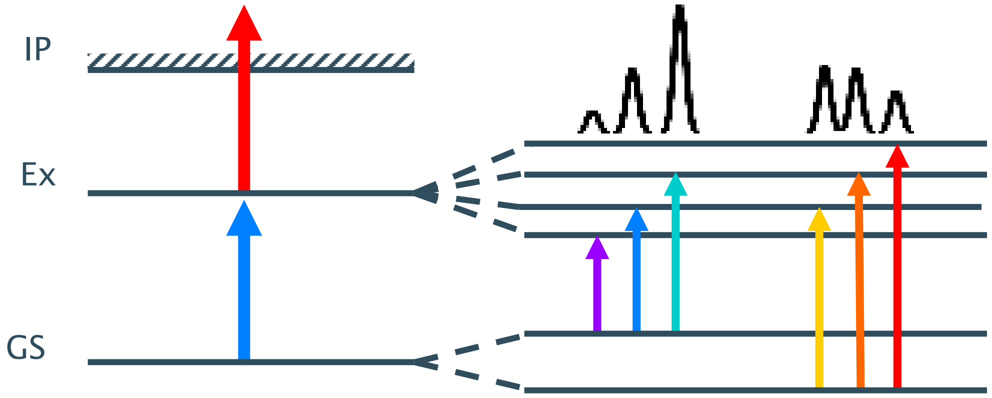
- Atomic state manipulation with **trapped** ions
  - Optical pumping of **trapped** radioactive cobalt isotopes

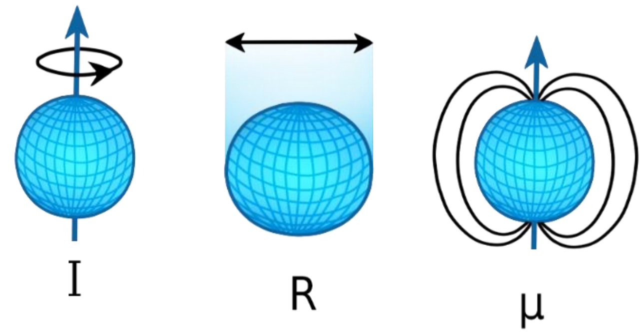
- Development of precision spectroscopy of **trapped** ions
  - Future plans towards magnetic octupole moment measurements of Sr

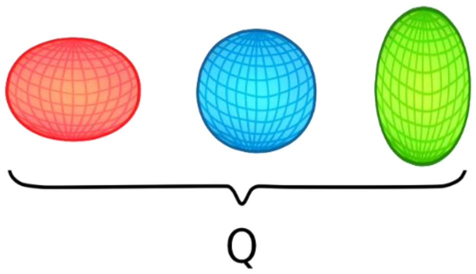
Some fundamentals of laser spectroscopy

Laser spectroscopy: study of atom and nucleus

- Electromagnetic interaction between orbiting electrons and the nucleus
  - Isotopes have a **finite size** leading to isotope shifts
    ➔ nuclear size
  - Orbiting charges and intrinsic nucleon moments lead to **nuclear magnetic moments**
    ➔ valence configuration, wf purity
  - Charge can assume non-spherical charge distribution, and thus **electric moments**
    ➔ deformation, shape, collectivity





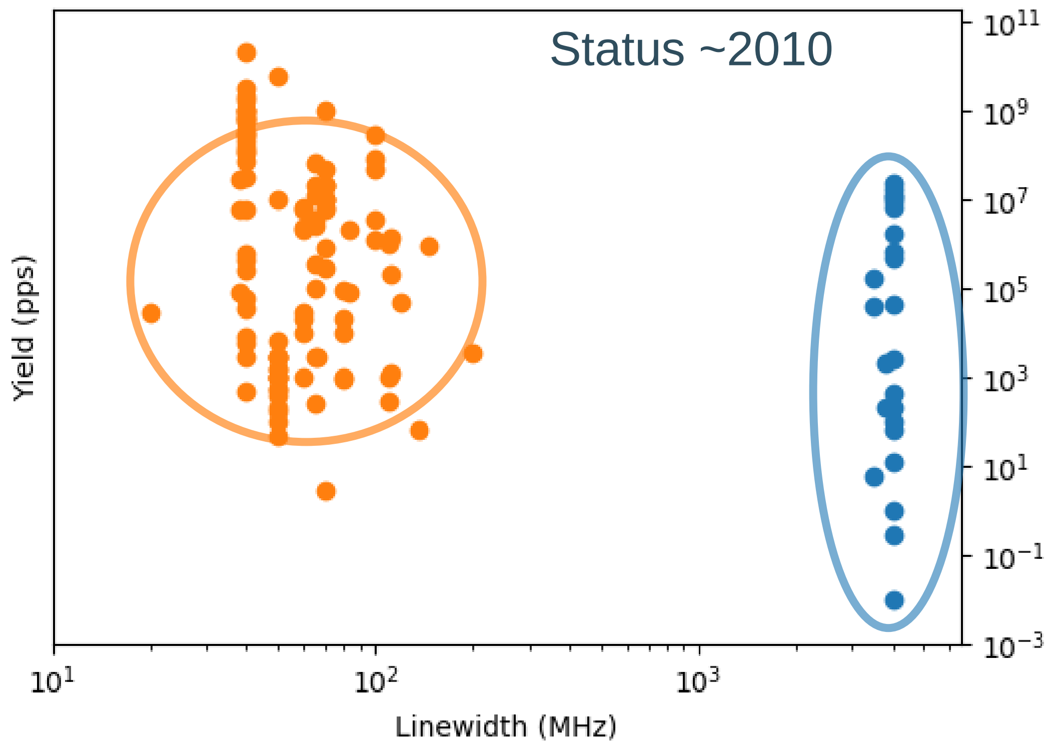


Laser spectroscopy approaches

- In-source laser spectroscopy
  - **Hot cavity**
  - Gas cell

- Collinear laser spectroscopy
  - **Fluorescence detection**
  - **Resonance ionization**
  - Beta-NMR/collisional ionization/state-selective charge exchange/…

- Methods tailed to specific cases
  - **Spectroscopy on trapped ion/atoms** (faaaar to the left on this diagram)



Study of ultra-rare isotopes with particle-based detection schemes

Spectroscopy very far from stability

- Many scientific questions require the study of nuclei far from stability

- This means we are forced to deal with a double-whammy of pain:
  - Production rates of ions of interest will be low;
  - Production rates of isobaric contamination will be high.

- The challenge thus lies in devising a spectroscopic scheme that is **efficient** and **immune to the influence of contaminants**.

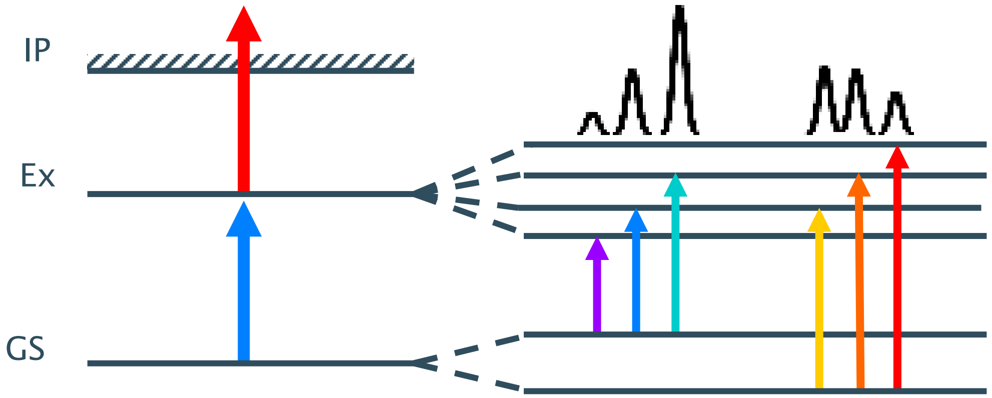
Penning-trap mass spectrometry as an isobar remover

Laser ionization spectroscopy

- Multi-photon, multi-color process to stepwise excite and ionize an atom
- This process is very **efficient**, and **selective**.
- The photon resonance condition is translated into the **creation of an ion**

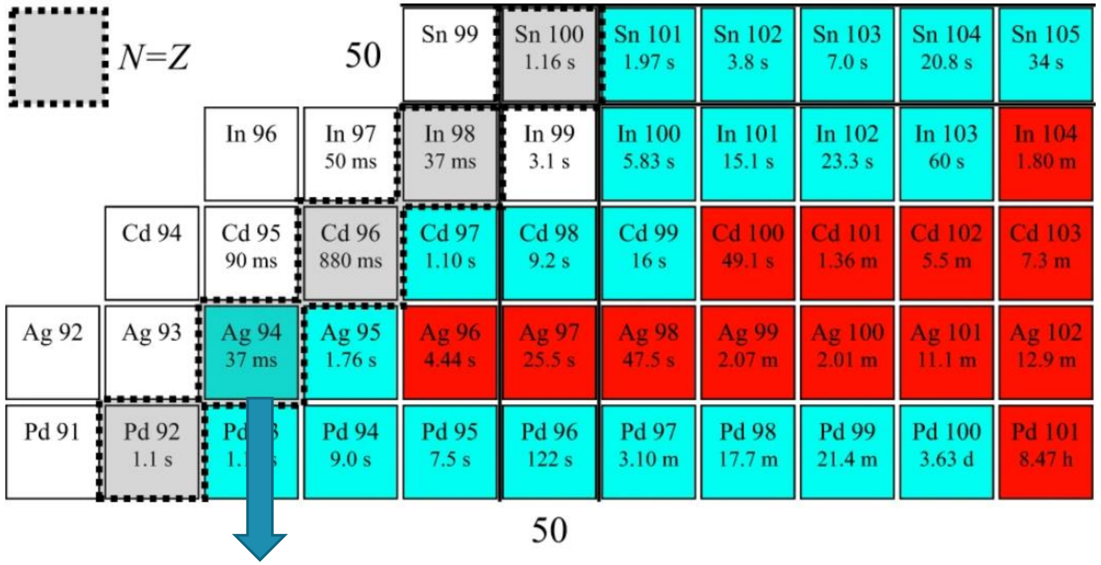
  This ion can then be further manipulated!

- By injecting these laser-induced ions into a Penning trap mass spectrometer, influence of isobars can be **completely removed.**



Project leader: Mikael Reponen, University of Jyväskylä (Finland)

Penning-trap assisted RIS of silver isotopes



One of the most fascinating isotopes on the chart.

- N=Z
- High-spin isomerism
- Double proton decay?

- Production mechanism?

  $^{14}N(^{nat,\,92}Mo,\ 2pxn)\ Ag$

- Silver isotopes: dip well below pps
- Other isotopes: much greater quantities.

- ^{nat}Mo get knocked out of target => more contamination

$\Rightarrow$ Easily thousands of ions per second, of which <<1 pps of interest.

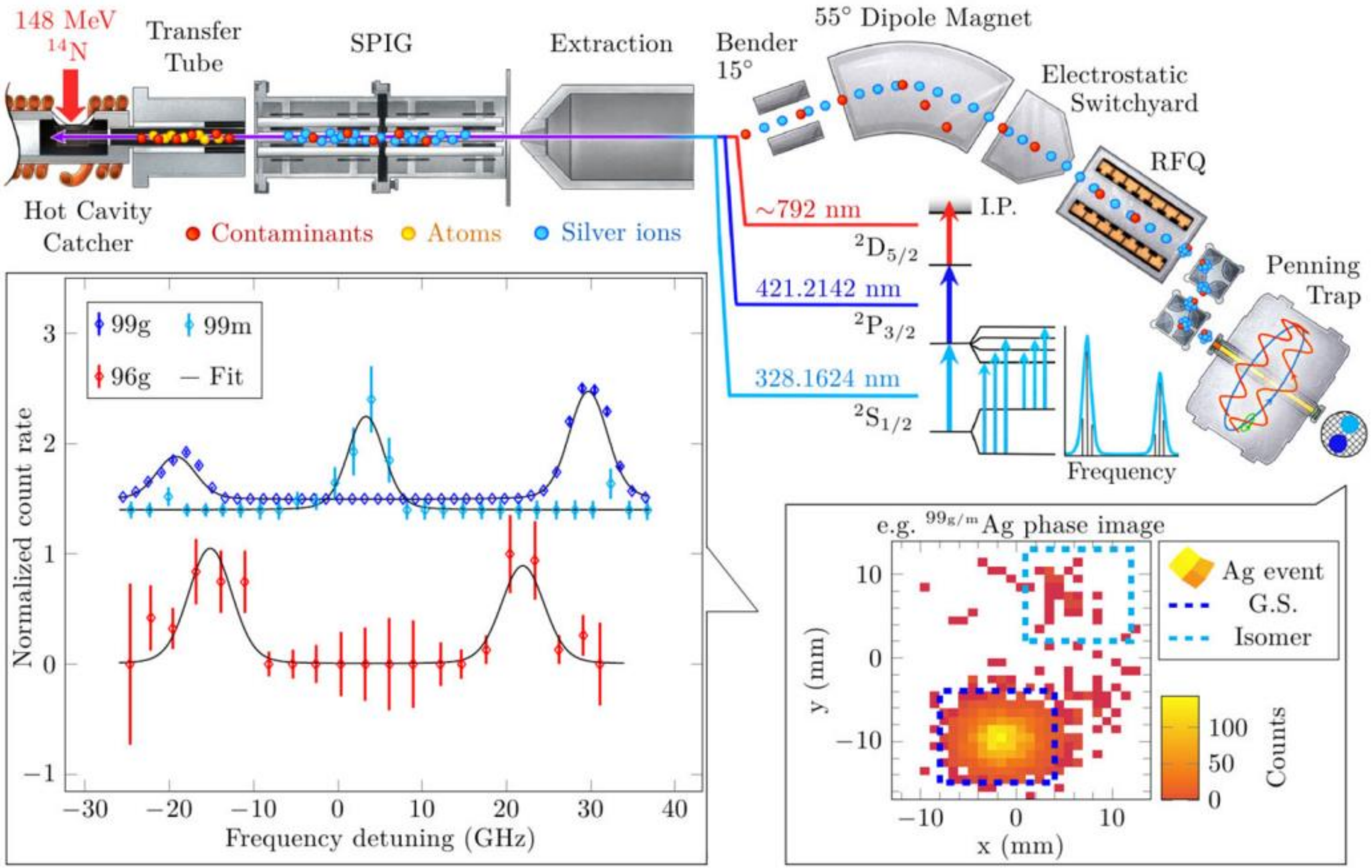
$\Rightarrow$ High-resolution separator required!

Project leader: Mikael Reponen, University of Jyväskylä (Finland)

Reponen, M., de Groote, R.P., et al. Evidence of a sudden increase in the nuclear size of proton-rich silver-96. Nat Commun 12, 4596 (2021)

KU LEUVEN

Penning-trap assisted RIS of silver isotopes



PI-ICR:
Poster Isaac Yandow

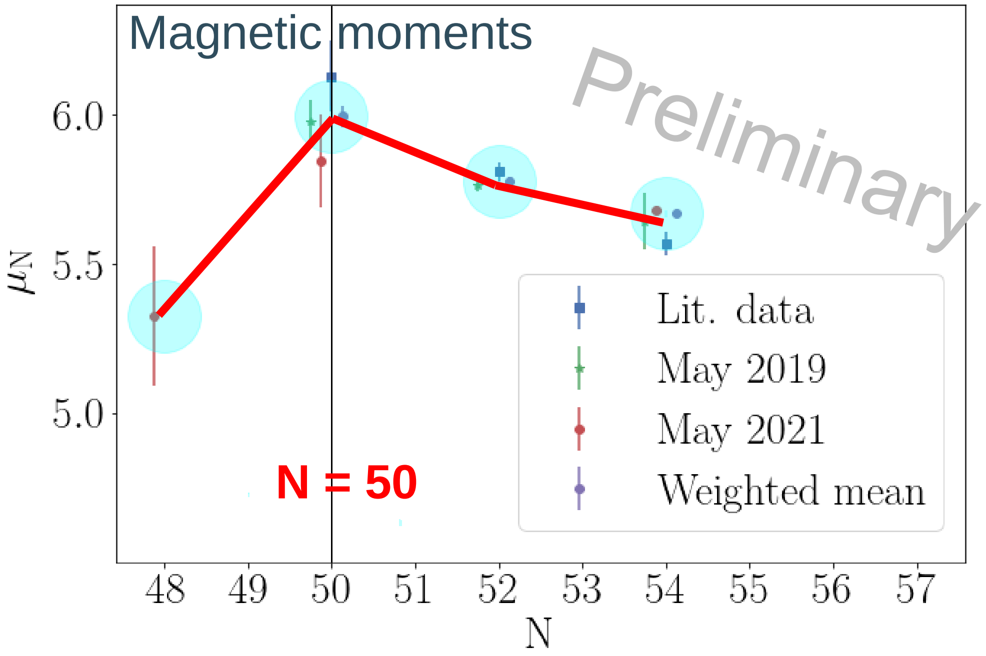
Project leader: Mikael Reponen, University of Jyväskylä (Finland)
Reponen, M., de Groote, R.P., et al. Evidence of a sudden increase in the nuclear size of proton-rich silver-96. Nat Commun 12, 4596 (2021)

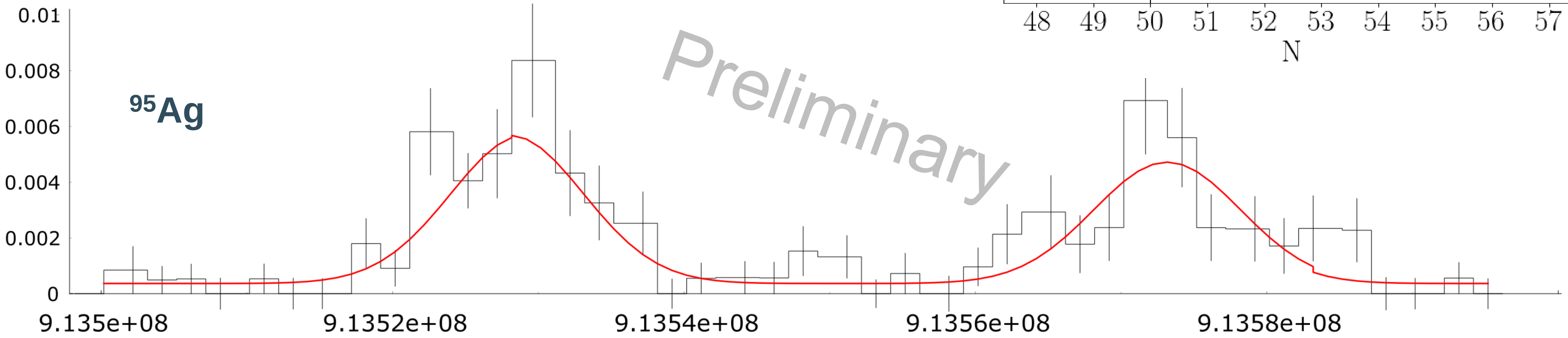
KU LEUVEN

Penning-trap assisted RIS of silver isotopes

- $^{104-96}$Ag using ^{14}N(^{92}Mo, 2pxn) Ag and **^{96,95}Ag** using ^{40}Ca($^{58/60}$Ni, pxn) Ag
- *Totally* background-free measurements
  Production rate: **< 1 per minute**
  Detection rate: 1 per 20 minutes…

See poster M. Reponen!





Project leader: Mikael Reponen, University of Jyväskylä (Finland)

Reponen, M., de Groote, R.P., et al. Evidence of a sudden increase in the nuclear size of proton-rich silver-96. Nat Commun 12, 4596 (2021)

Collinear resonance ionization spectroscopy of potassium

- Study of potassium isotopes beyond the proposed shell closure of N=32
  - Issue: production rates below 1000/s
  - Issue: large isobaric chromium content
  - Issue: small hyperfine structure, small isotope shift
  - **Solution: collinear geometry, efficient RIS, use of decay detection**

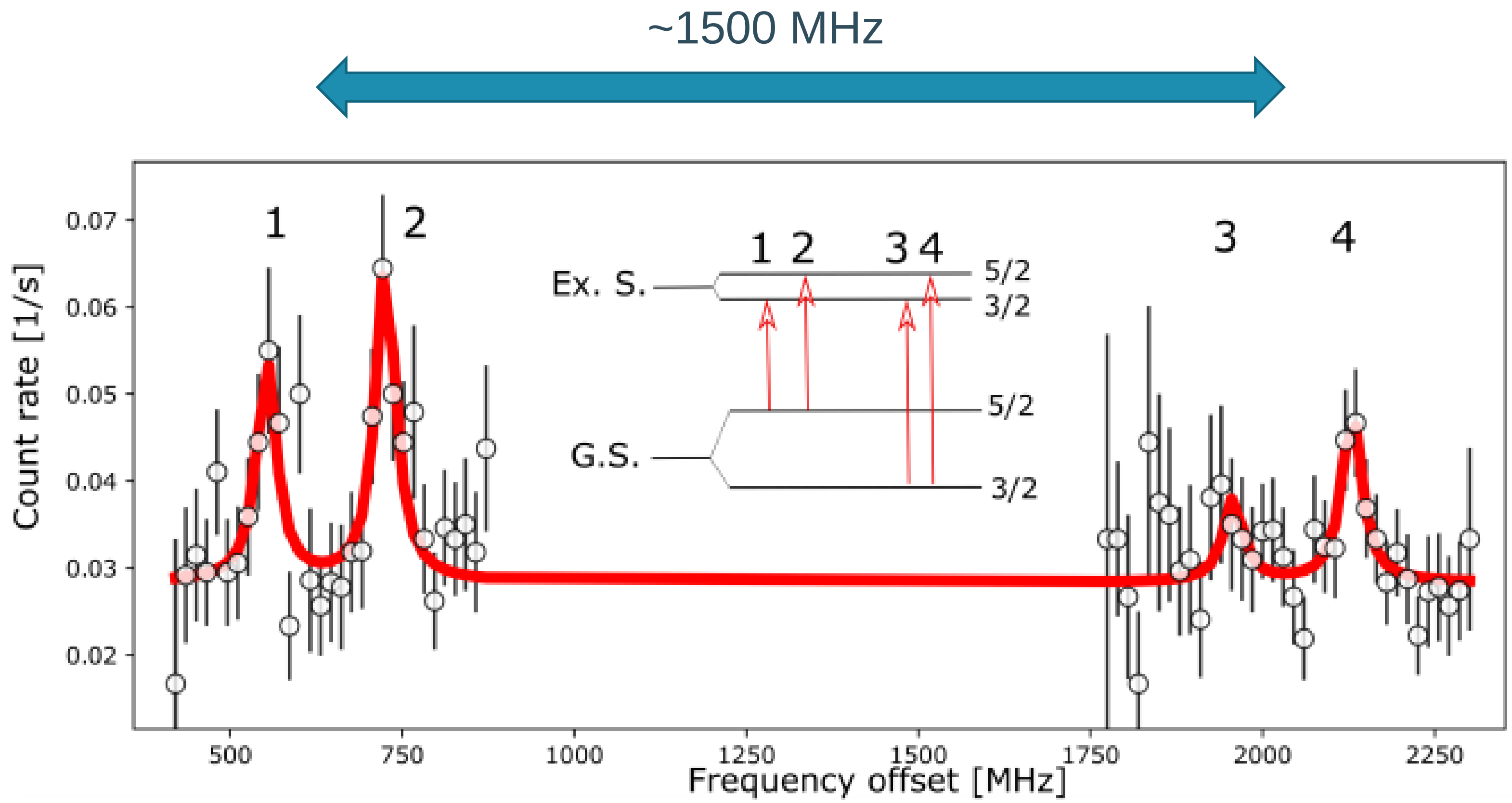
- Laser ionization spectroscopy can be implemented on fast ion beams as well in a collinear geometry: **Collinear Resonance Ionization Spectroscopy**

  See talks by
  - *M. Athanasakis-Kaklamanakis – CRIS at ISOLDE (this session)*
  - *S. Kujanpää – CRIS at IGISOL, Finland (next session)*

- Advantage: **removal of broadening effects** enhances the resolution of the measurement
  - In-source spectroscopy (without modern adaptation): cannot study all elements and extract all information… ☹

Project leader: Ágota Koszorús, CERN
Á. Koszorús, X. F. Yang et al., Charge radii of exotic K isotopes challenge nuclear theory and the magic character of N = 32, Nature Physics **17**, 439–443 (2021)

Results



- 300 pps ^{52}K
- **>10^{6} pps stable contamination**

- Beta-detection: remove stable contaminants

- < 1 day of data!!
- (background in part due to faulty electronics - 'user error'….!)

Project leader: Ágota Koszorús, CERN

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

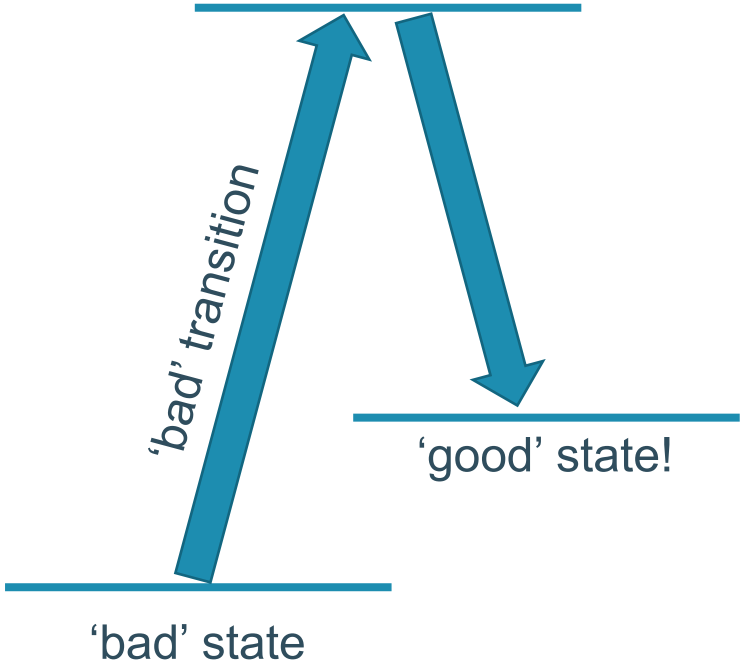
KU LEUVEN

Atomic state manipulation with trapped ions

Atomic state manipulation

- Sometimes the state the atom is produced in is not suitable for spectroscopy
  - Atomic spin may be too low to access moments;
  - There may not be transitions accessible with current laser technology;
  - Transitions may not be sufficiently strong, may not have sensitivity to the nuclear size.

- Through a careful choice of optical process, we can change the state of the atom
  - Optical pumping: through many cycles of excitation and spontaneous decay, the electron eventually ends up in a more favourable atomic state.
  - This process takes *time.* Thus, it is applied to ions inside an ion trap.
  - First developed and used in IGISOL laboratory
    B. Cheal et al, PRL ***102****, 222501, 2009*

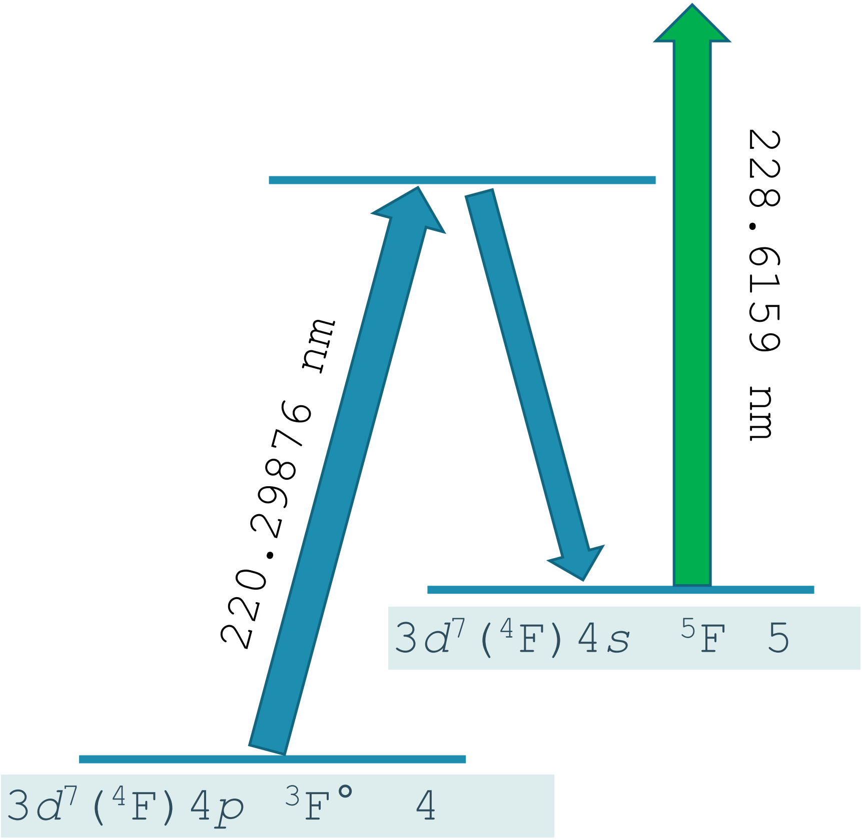


KU LEUVEN

Laser spectroscopy of optically pumped cobalt

- With 27 protons, cobalt is an ideal probe of the magic nickel isotopes
  - Radii, moments, … would provide lots of insight!

- But, Co chain never studied with laser spectroscopy
  - Refractory: not available in ISOLDE
  - Complex atomic/ionic system:
    - Lots of metastable states
    - deep-UV lasers required
    - Ionic ground-state not very useful…
- Optical pumping at 221 nm with 10 kHz pulsed-TiSa laser
- Spectroscopy at 229 nm

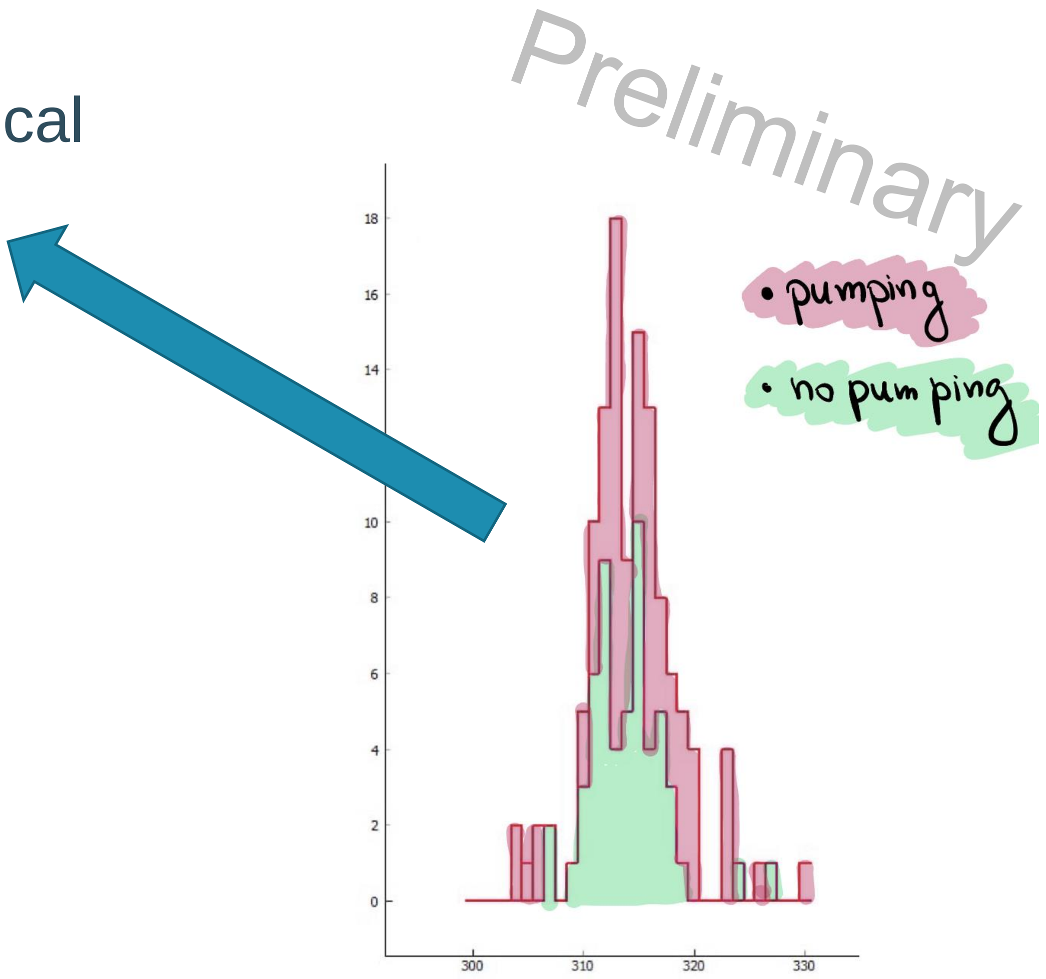


 Project leader: B. Cheal, Liverpool; Ágota Koszorús, CERN

KU LEUVEN

Laser spectroscopy of optically pumped cobalt

- Factor 3 enhancement of signal due to optical pumping
- Enabled study of $^{54,55,57\text{-}59}$Co!

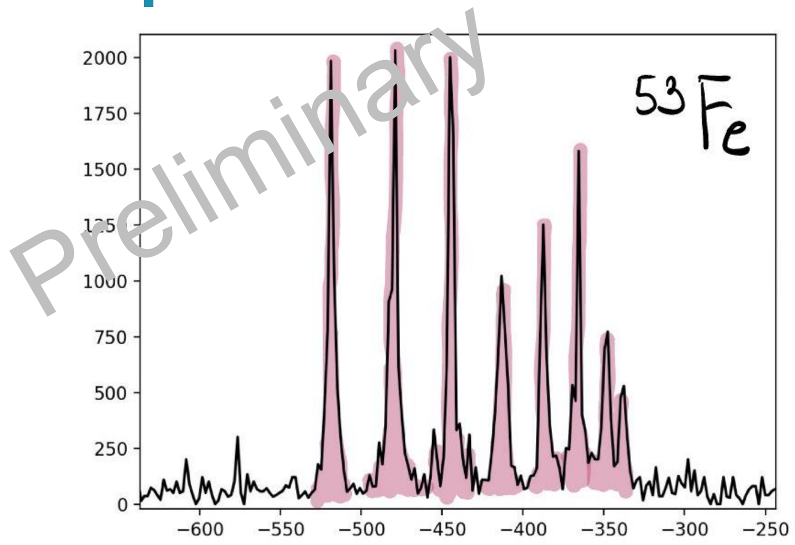


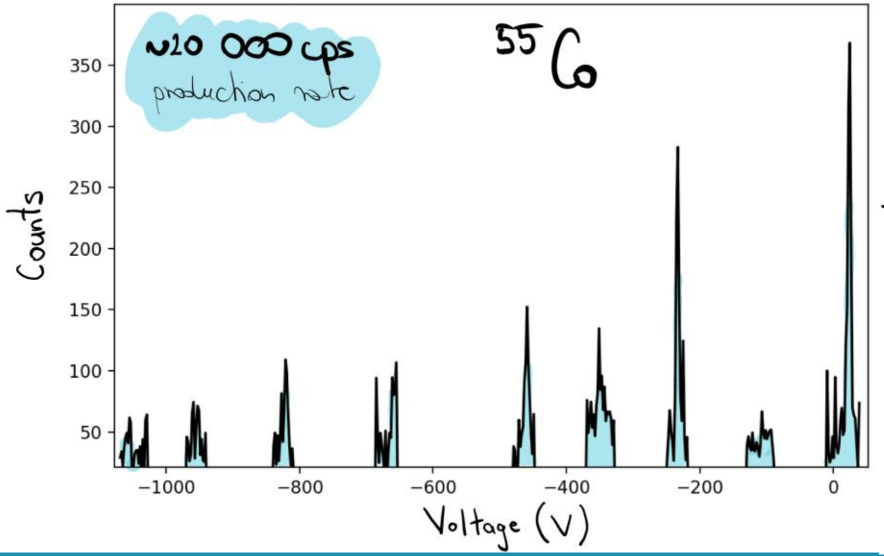
Project leader: B. Cheal, Liverpool; Ágota Koszorús, CERN

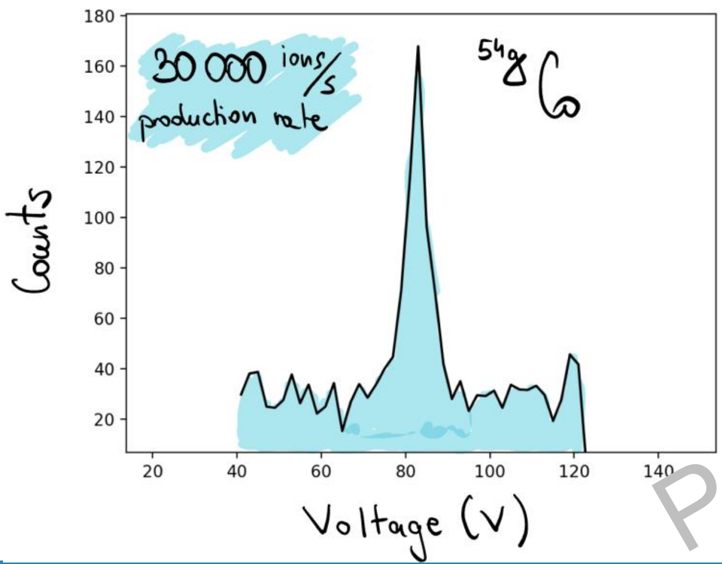
KU LEUVEN

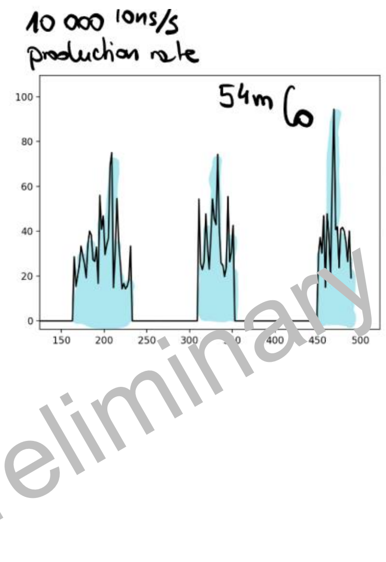
Laser spectroscopy of optically pumped cobalt

- Factor 3 enhancement of signal due to optical pumping
- Enabled study of $^{54,55,57-59}Co$!
- Same experiment: $^{53-58}Fe$!









 Project leader: B. Cheal, Liverpool; Ágota Koszorús, CERN

KU LEUVEN

Development of precision spectroscopy of trapped ions

New observables through higher precision spectroscopy

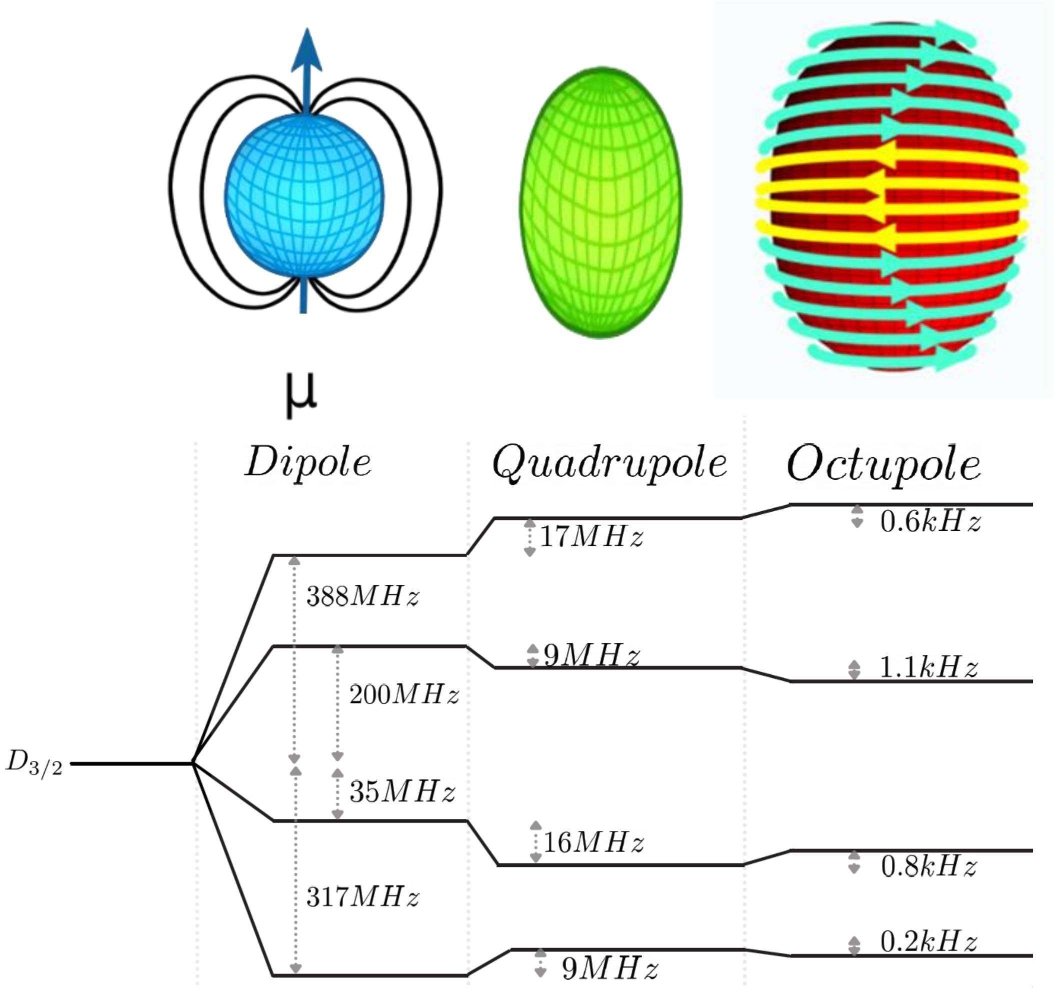
- Nuclear moments lead to shift and splitting of fine structure levels (*hyper*fine structure)

- Multipole expansion *does not stop at the quadrupole!*
    - Magnetic octupole moment: 20 known values [1]

- Contribution of higher-order magnetic octupole moment is three or more orders of magnitude smaller

$\Rightarrow$ Three or more orders of magnitude precision boost has to be found.

- **There are other observables we could hope to access!**

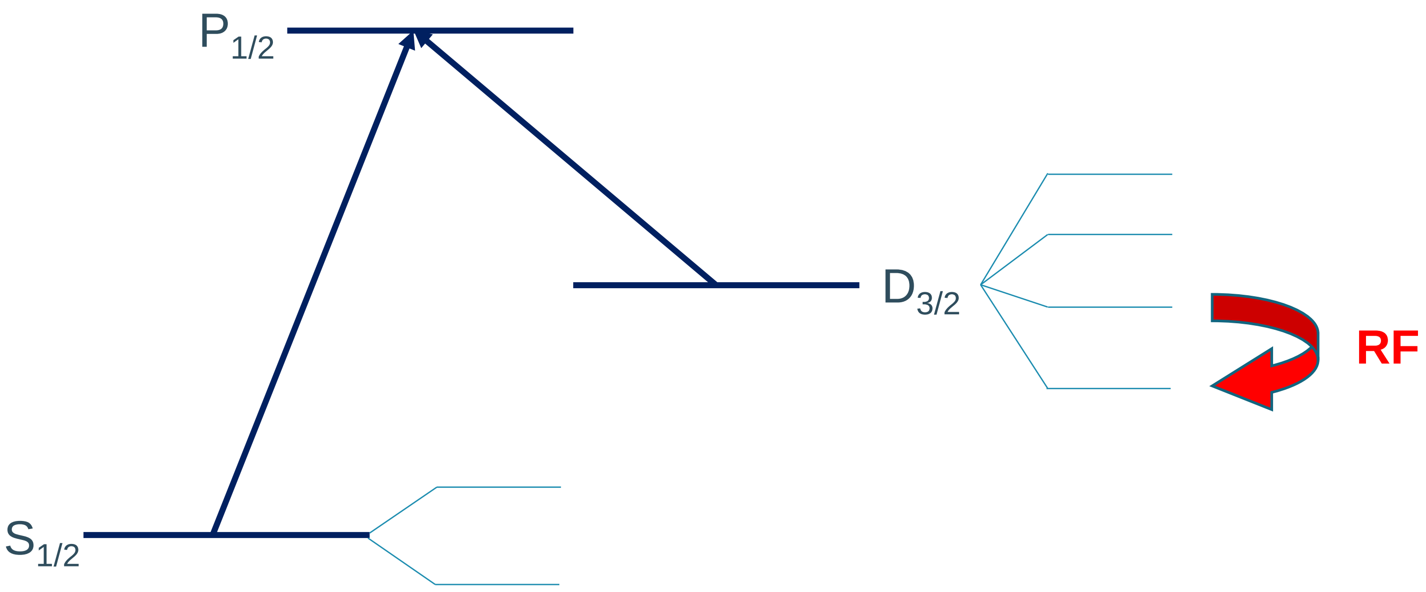


Example: D3/2 state in Sr+. Octupole contribution has not been measured yet.

[1] RP de Groote, S Kujanpää, et al, Physical Review A 103 (3), 032826

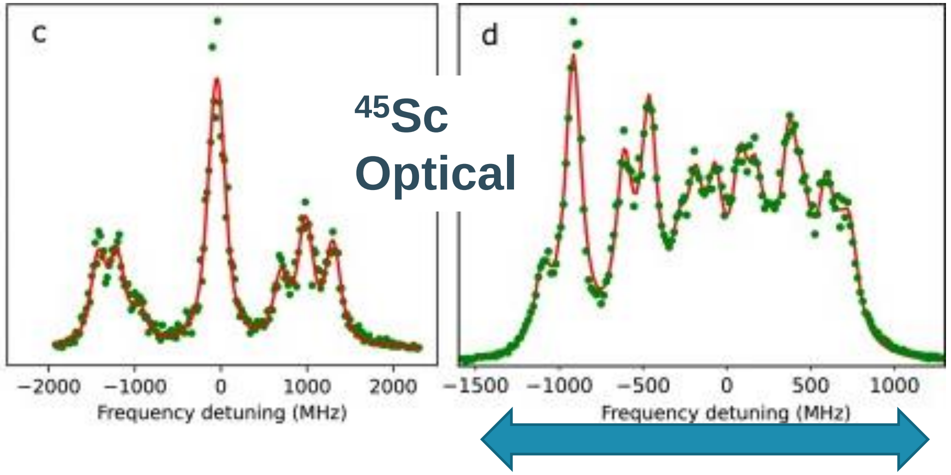
New observables through higher precision spectroscopy

- Laser-radiofrequency double-resonance spectroscopy
    - Lasers are used for state preparation and readout;
    - Spectroscopy is performed using a radiofrequency excitation;
    - Linewidth: $\Delta\upsilon \propto \frac{1}{\tau}$



New observables through higher precision spectroscopy

- Laser-radiofrequency double-resonance spectroscopy
  - Lasers are used for state preparation and readout;
  - Spectroscopy is performed using a radiofrequency excitation;
  - Linewidth: $\Delta\upsilon \propto \frac{1}{\tau}$
- On a thermal beam?



2500 MHz

R.P. de Groote, J. Moreno et al, Precision measurement of the magnetic octupole moment in ^{45}Sc as a test for state-of-the-art atomic- and nuclear-structure theory, Phys. Lett. B **827**, 136930, 2022

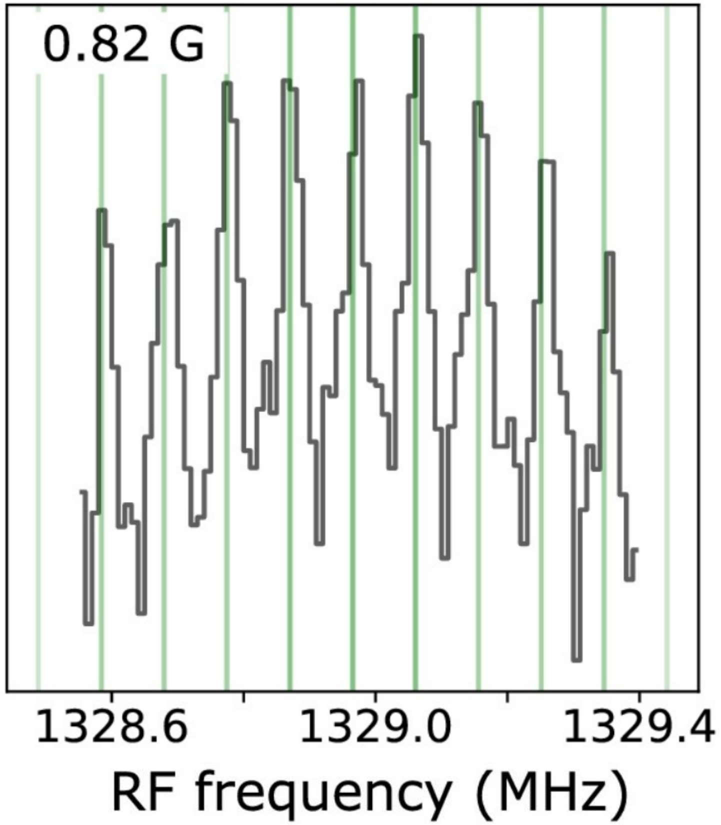
KU LEUVEN

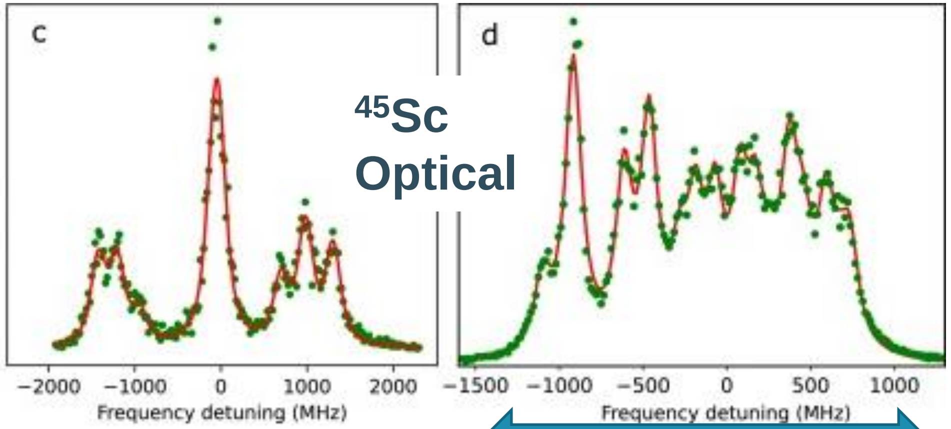
New observables through higher precision spectroscopy

- Laser-radiofrequency double-resonance spectroscopy
  - Lasers are used for state preparation and readout;
  - Spectroscopy is performed using a radiofrequency excitation;
  - Linewidth: $\Delta\upsilon \propto \frac{1}{\tau}$
- On a thermal beam?
  - Rf interaction zone of a few cm => $\Delta\upsilon$ = 10 kHz

^{45}Sc
RF

1 MHz

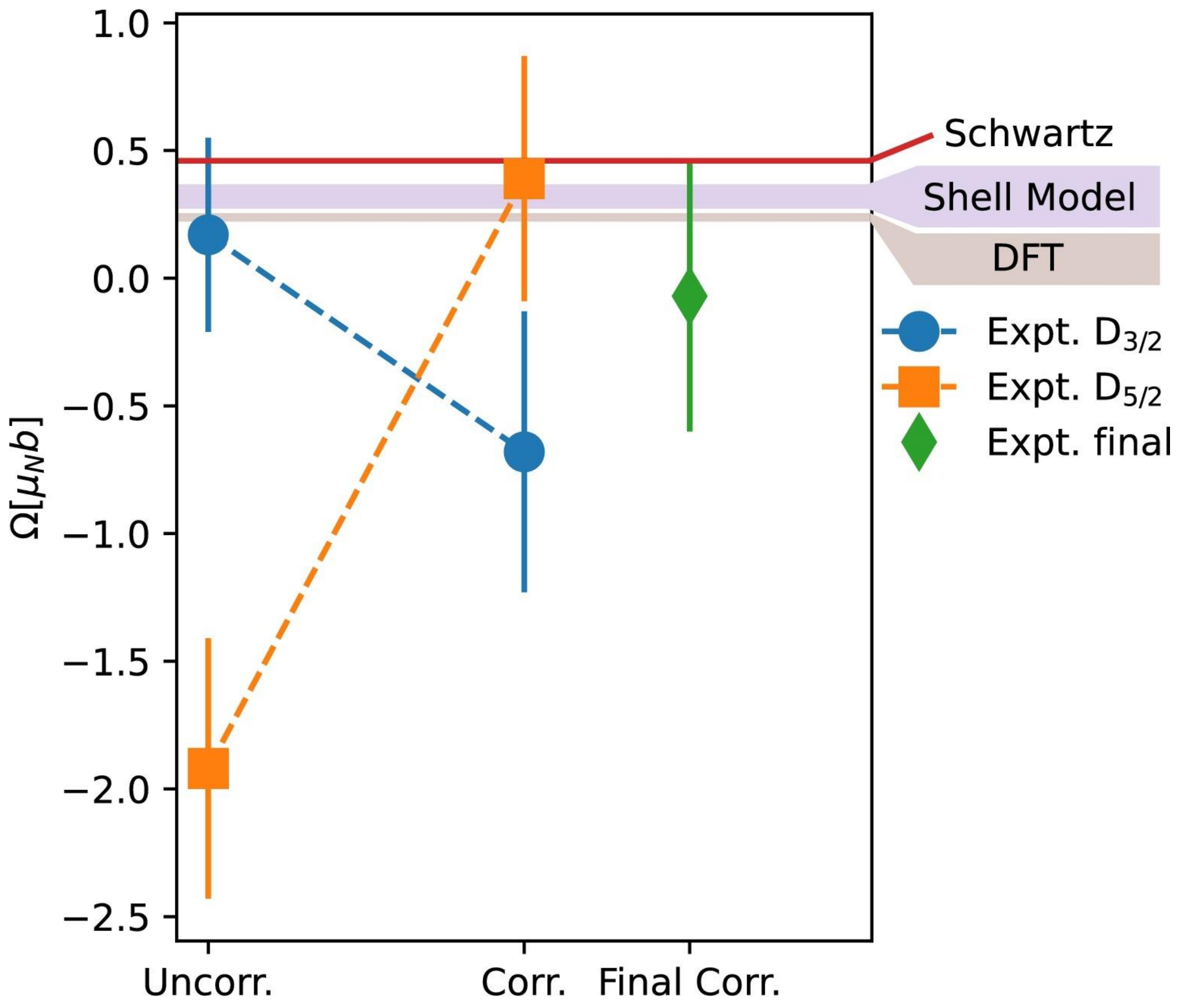




2500 MHz

R.P. de Groote, J. Moreno et al, Precision measurement of the magnetic octupole moment in ^{45}Sc as a test for state-of-the-art atomic- and nuclear-structure theory, Phys. Lett. B **827**, 136930, 2022

		Theory this work	Expt. Ref. [17]		Expt. this work	
			Uncorrected	Corrected	Uncorrected	Corrected
$D_{3/2}$	A [MHz]	271(3)	269.556(1)	269.558(1)	269.55817(5)	269.55844(7)[3]
	B [MHz]	-27.5(5)	-26.346(4)	-26.360(8)	-26.3531(9)	-26.3596(5)[5]
	C [kHz]		–	–	-0.010(22)	0.039(28)[2]
	Ω [μ_Nb]		–	–	0.17(38)	-0.68(49)[6]
$D_{5/2}$	A [MHz]	108(2)	109.032(1)	109.033(1)	109.03275(7)	109.03297(5)[3]
	B [MHz]	-38.5(5)	-37.387(12)	-37.373(15)	-37.3954(12)	-37.3745(8)[15]
	C [kHz]		1.7(10)	1.5(12)	0.31(8)	-0.062(59)[17]
	Ω [μ_Nb]		-10.7(63)	-9.4(75)	-1.92(51)	0.39(37)[11]



New observables through higher precision spectroscopy

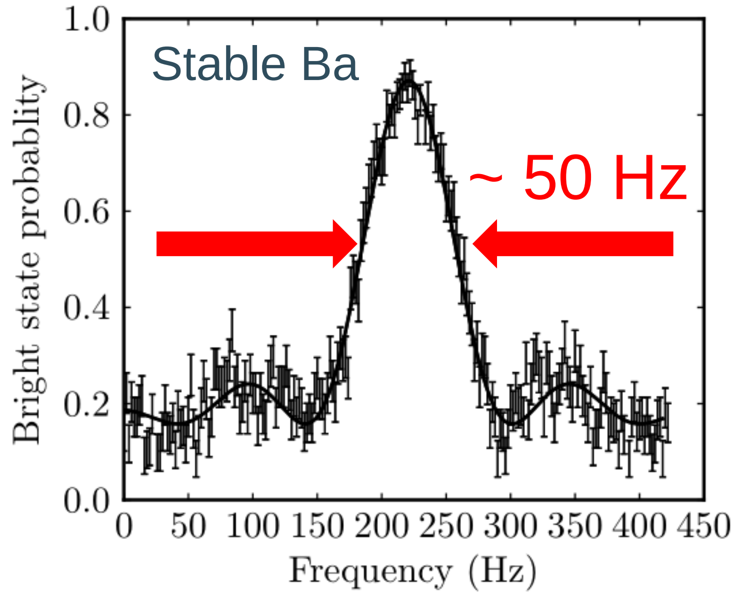
- On a thermal beam?
  - Rf interaction zone of a few cm => $\boldsymbol{\Delta\upsilon}$ **= 10 kHz**

- In a collinear geometry?
  - Interaction time can be a few microseconds $\boldsymbol{\Delta\upsilon} \geq$ **100 kHz**
  - Implementation in RAPTOR experiment at IGISOL planned

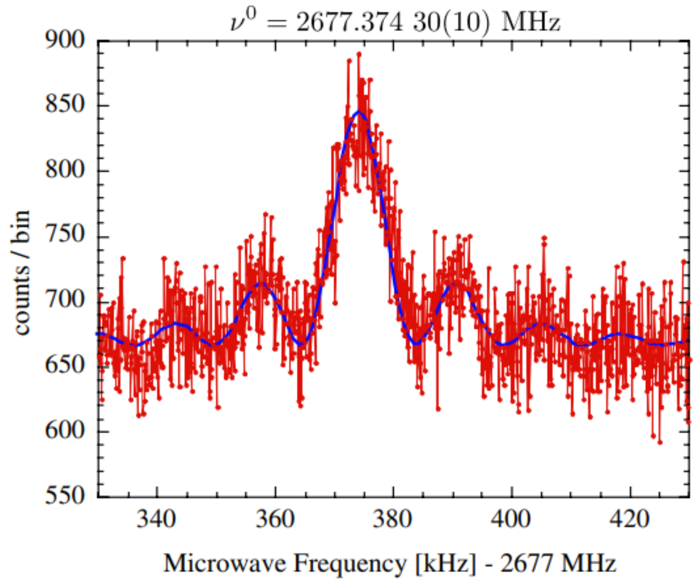
KU LEUVEN

New observables through higher precision spectroscopy

- On a thermal beam?
  - Rf interaction zone of a few cm => ***Δυ* = 10 kHz**
- In a collinear geometry?
  - Interaction time can be a few microseconds ***Δυ* ≥ 100 kHz**
  - Implementation in RAPTOR experiment at IGISOL planned.
- In an atom or ion trap…?
  - Offline: **Hz-level!**
  - Only on-line so far: ^{7,11}Be in RIKEN



PhD thesis N. C. Lewty, U of Singapore

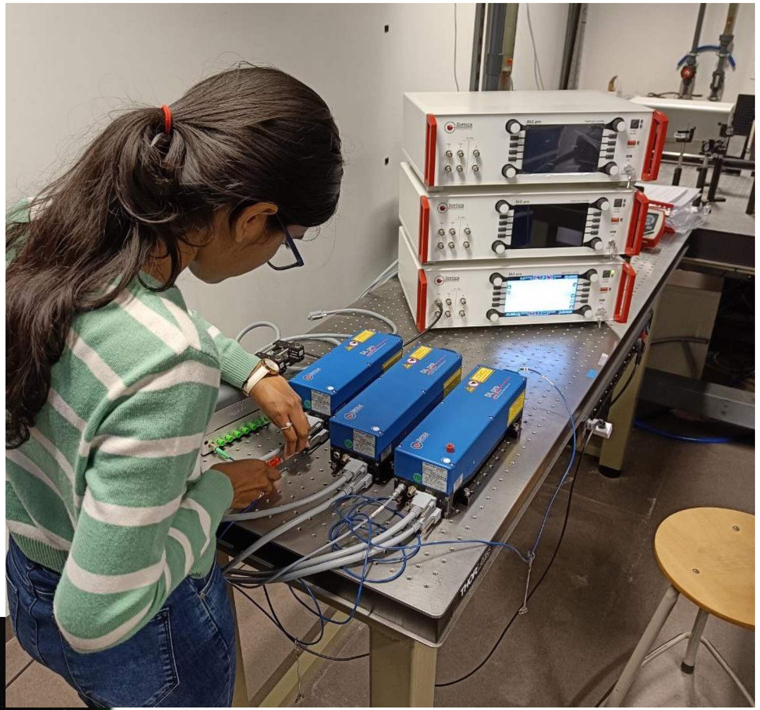


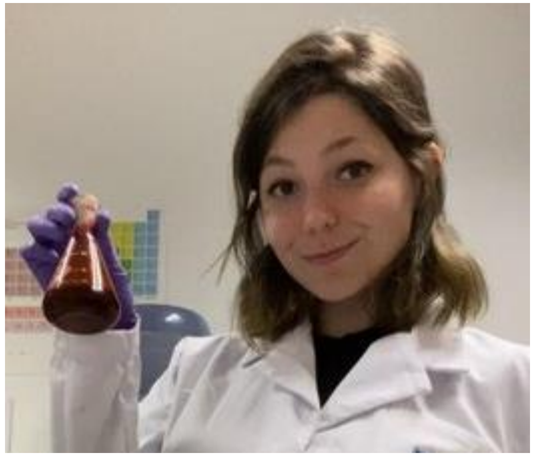
A. Takamine et al., PRL **112**, 162502 (2014)

Isotope	A [MHz]
^{7}Be	−742.772 28(43)[c]
^{9}Be	−625.008 837 048(10)[d]
^{11}Be	−2677.302 988(72)[b]

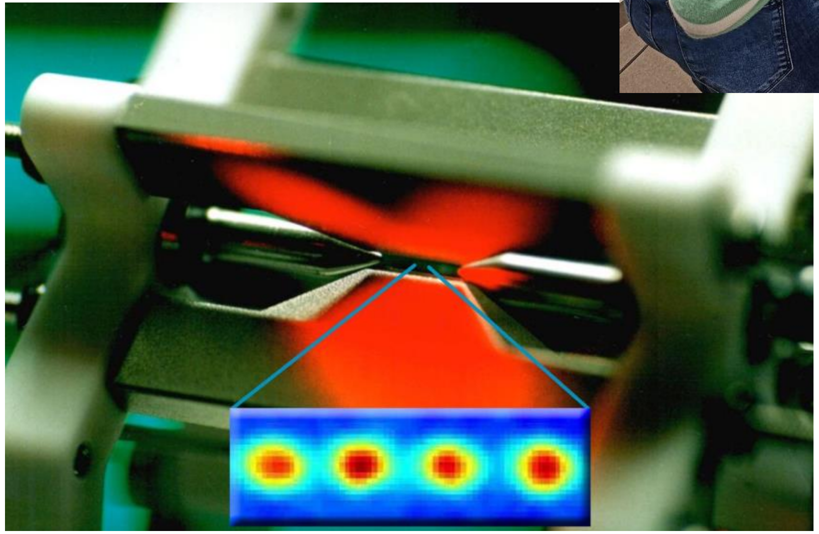
KU LEUVEN

Our aim: magnetic octupole moment of strontium





PhD project Anaïs Dorne



5µm

Picture: Univ of Innsbruck. Group R. Blatt

Thank you all for your attention!

Thanks to many people for their hard work and enthusiasm (and slides)

Wider context: higher-precision spectroscopy of radioactive ions

- 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. <r^4> relates to surface thickness of nuclear density

- Beyond-standard model physics from Hz-level isotope shift spectroscopy

GHz

In-source optical spectroscopy

Collinear, in-gas-jet, …

Current state-of-the-art

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

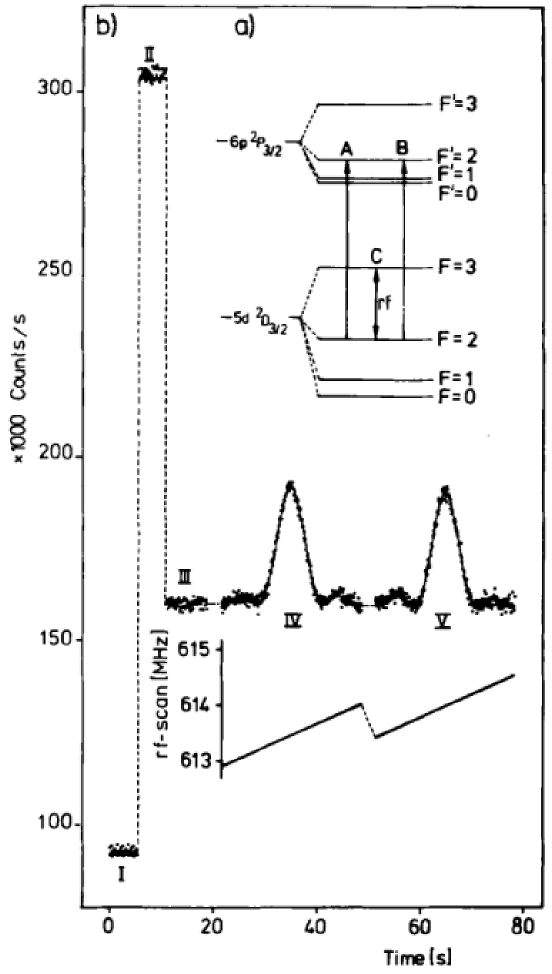
Feasible on RIB

More on this today

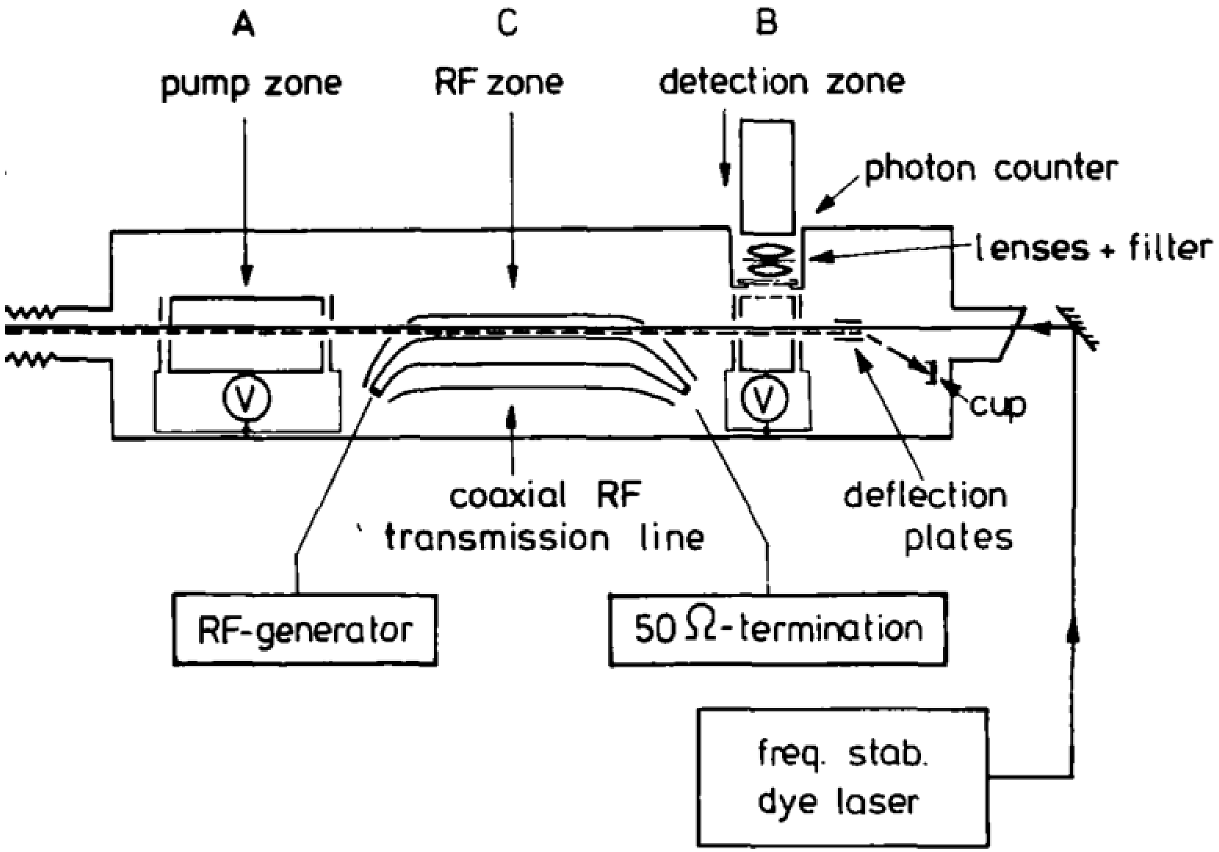
Atom/ion traps + laser cooling + ultra-narrow lines

Currently only on stable species

sub-Hz



b)
a)
300
250
200
150
100
×1000 Counts/s
I
II
III
IV
V
F'=3
F'=2
F'=1
F'=0
F=3
F=2
F=1
F=0
A
B
C
rf
615
614
613
rf-scan [MHz]
0
20
40
60
80
Time [s]



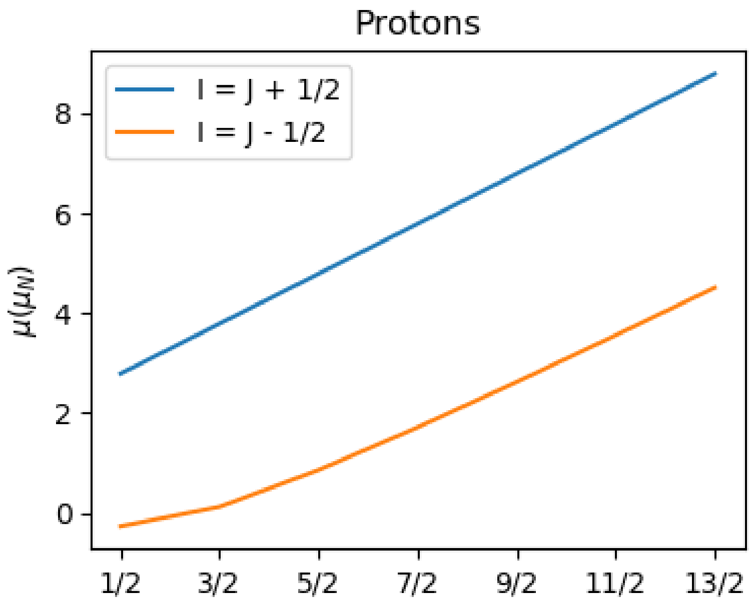
A
pump zone
C
RF zone
B
detection zone
photon counter
lenses + filter
cup
coaxial RF
transmission line
deflection
plates
RF-generator
50 Ω-termination
freq. stab.
dye laser

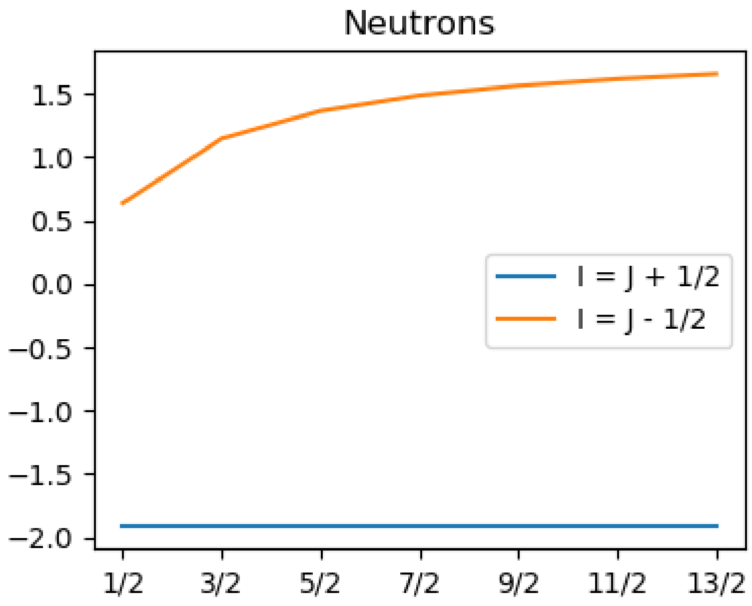
Magnetic dipole moments

- Most basic model: assume only the valence nucleon contributes; all other particles paired to *l*=0

  => Schmidt lines

- Provides a very powerful tool to establish valence nucleon configurations!





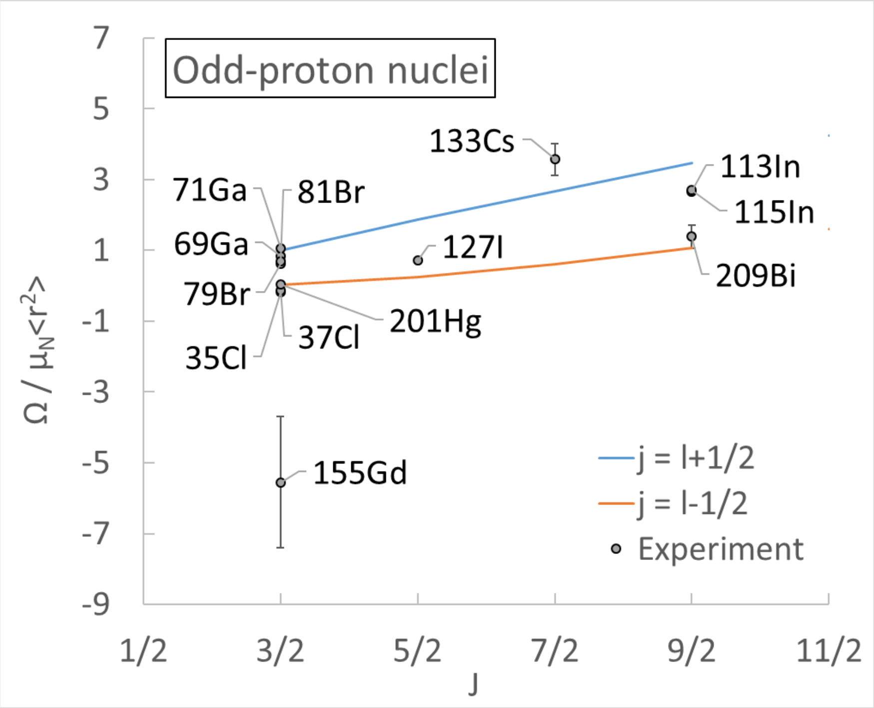
$$\mu = j - \frac{1}{2} + \frac{g_s^{\pi}}{2} \qquad \text{for } j = l + \frac{1}{2}$$

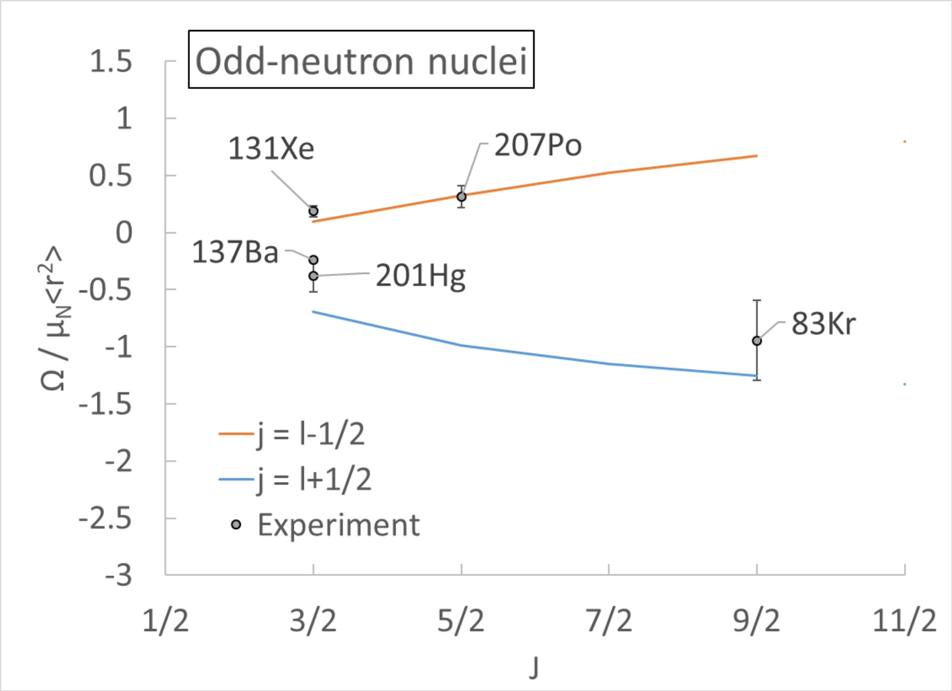
$$\mu = \frac{j}{j+1}\left(j + \frac{3}{2} - \frac{g_s^{\pi}}{2} \right) \qquad \text{for } j = l - \frac{1}{2}$$

$$\mu = \frac{g_s^{\nu}}{2} = -1.913 \qquad \text{for } j = l + \frac{1}{2}$$

$$\mu = -\frac{j}{j+1}\frac{g_s^{\nu}}{2} \qquad \text{for } j = l - \frac{1}{2}$$

Nuclear magnetic octupole moments





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

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