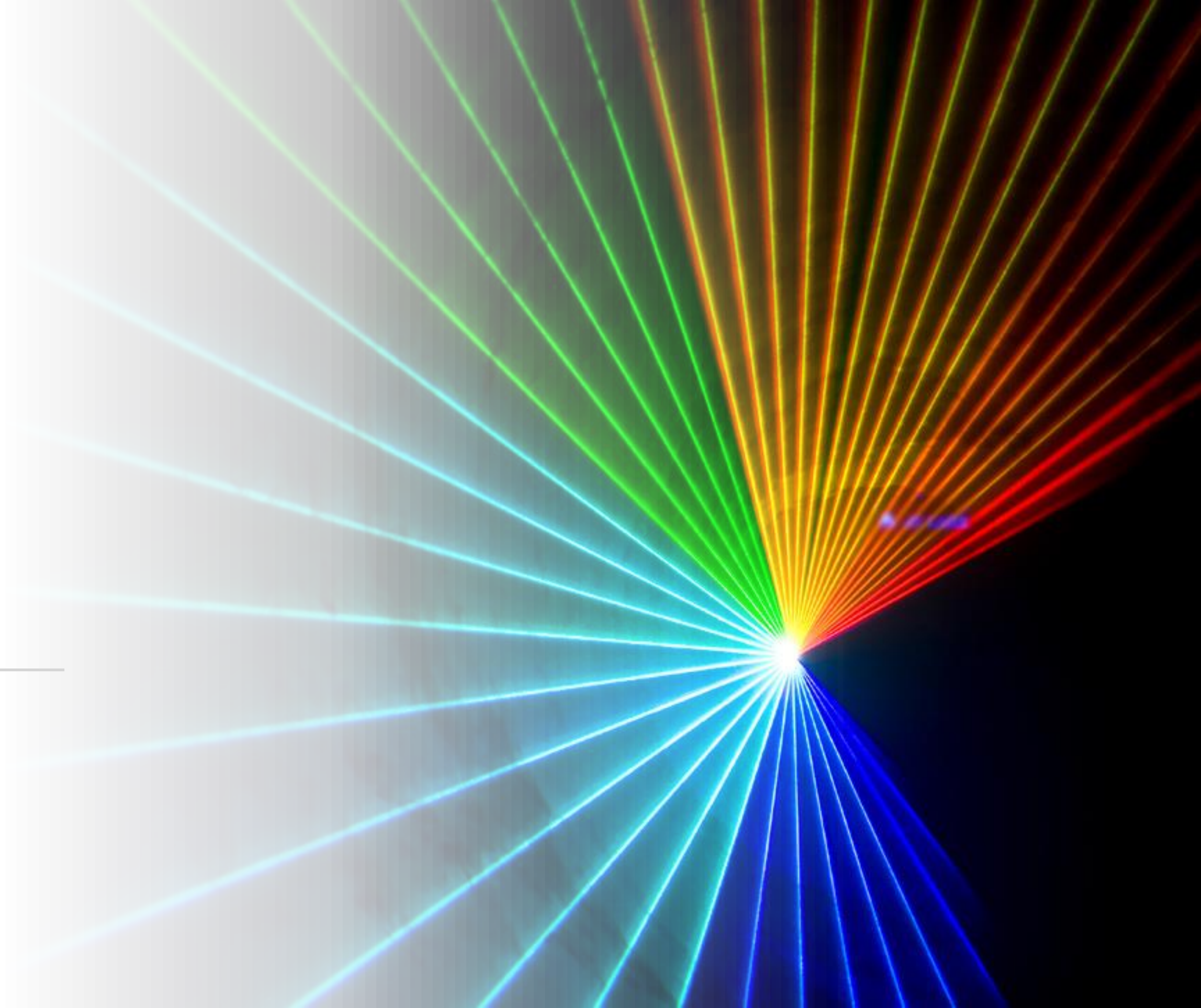
Laser spectroscopy for nuclear structure physics

Ruben de Groote

ruben.degroote@kuleuven.be



Last lectures,

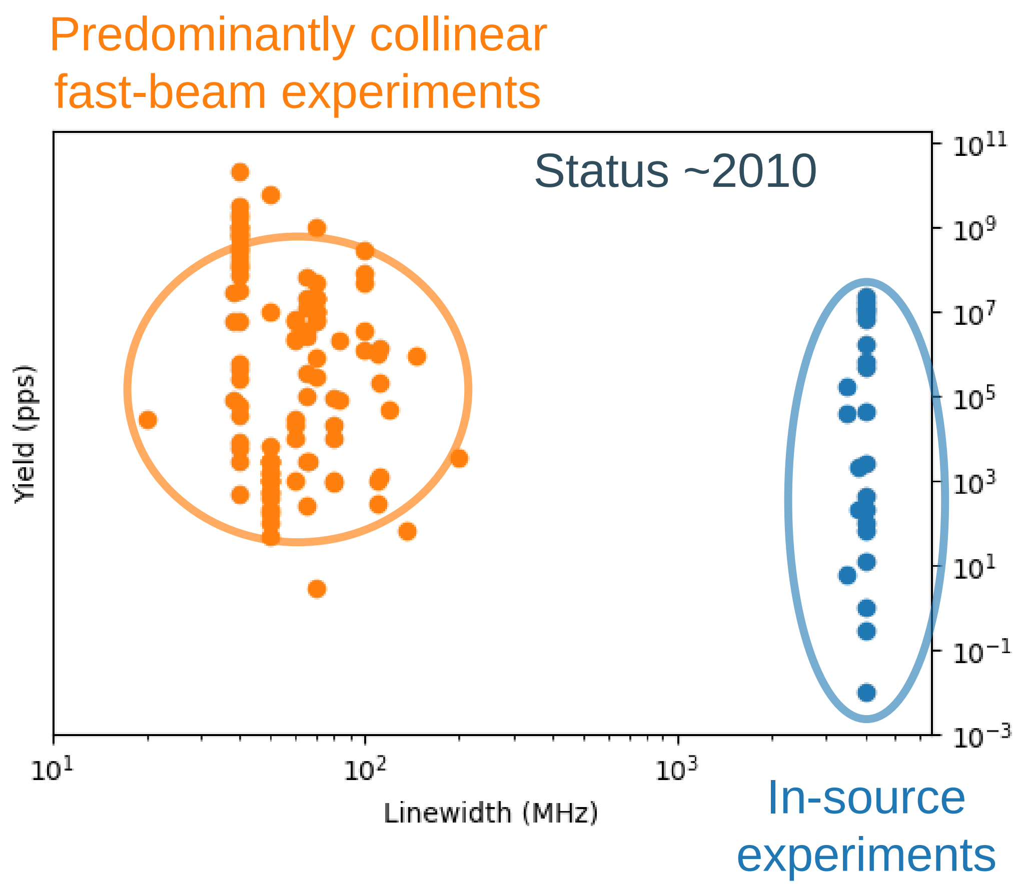
- We’ve discussed a little about the general principles of laser spectroscopy techniques
- You’ve seen examples of the physics we can study with magnetic moments, quadrupole moments and changes in mean-squared charge radii

This lecture,

- examples of the state-of-the-art in experimental techniques
  - In-source laser spectroscopy combined with Penning trap mass spectrometry the at IGISOL laboratory
  - Precision measurements: hyperfine structure beyond the quadrupole

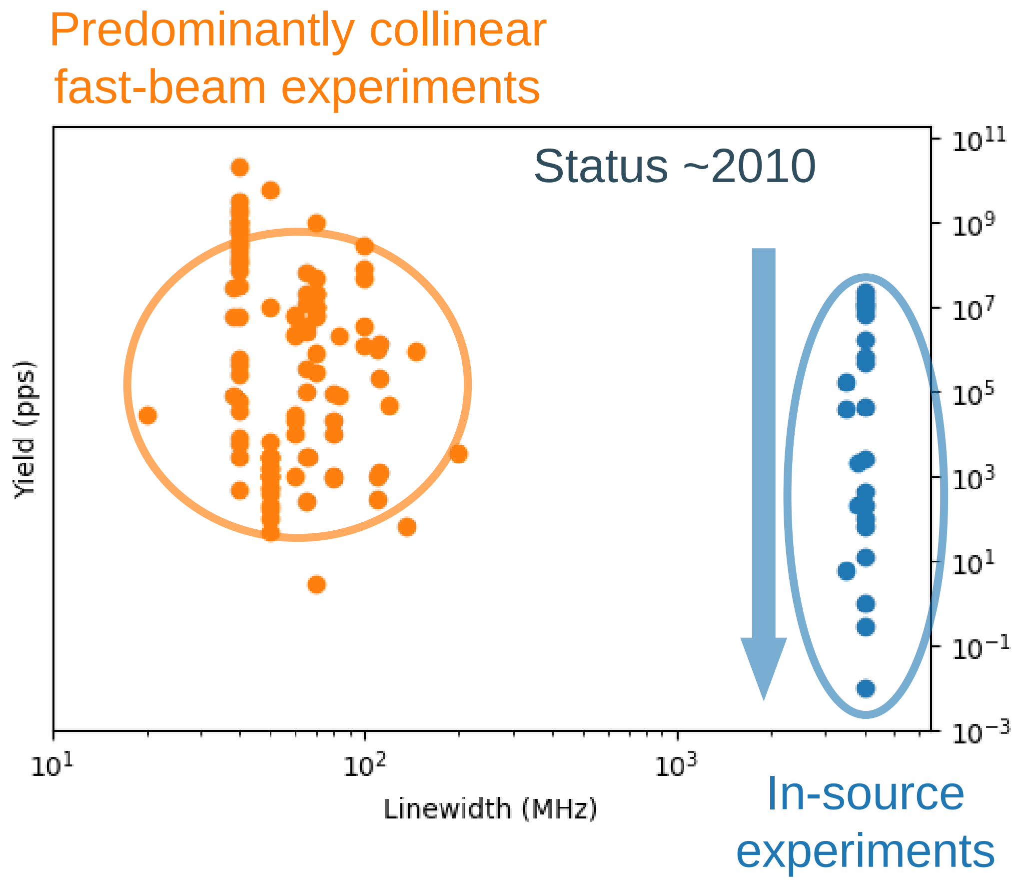
Outline

- Optical spectroscopy for nuclear structure research



Outline

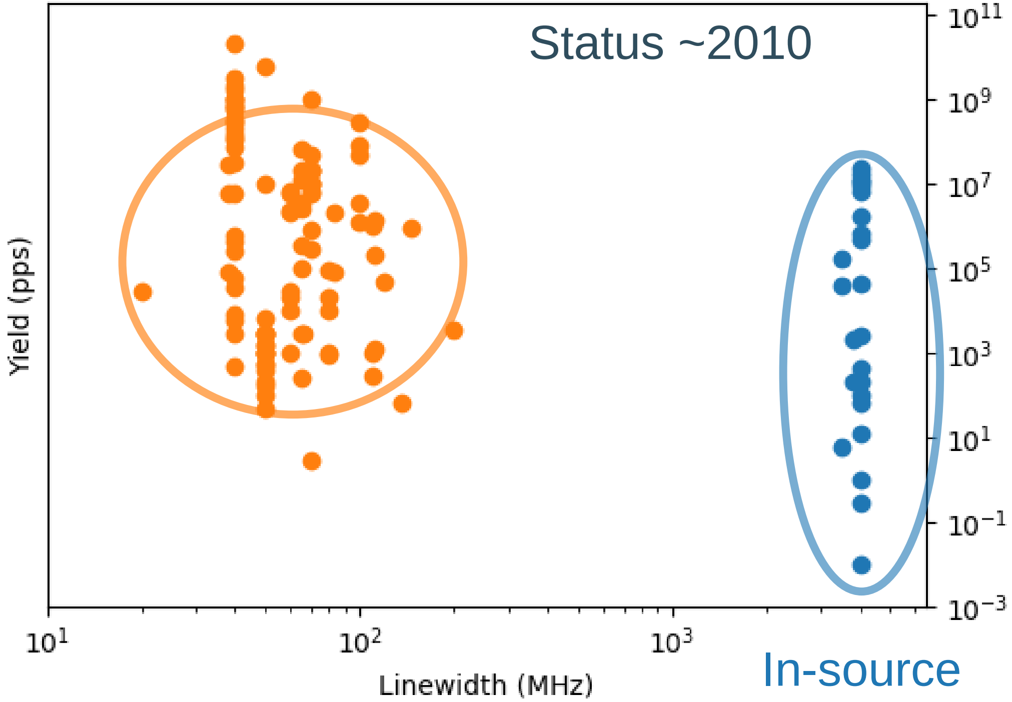
- Optical spectroscopy for nuclear structure research
- Pushing to lower production cross sections
  - in-source laser spectroscopy of silver



Outline

- Optical spectroscopy for nuclear structure research
- Pushing to lower production cross sections
  - in-source laser spectroscopy of silver
- When more precision is needed: collinear fast-beam laser spectroscopy
  - Laser spectroscopy of zinc

Predominantly collinear fast-beam experiments



In-source experiments

Outline

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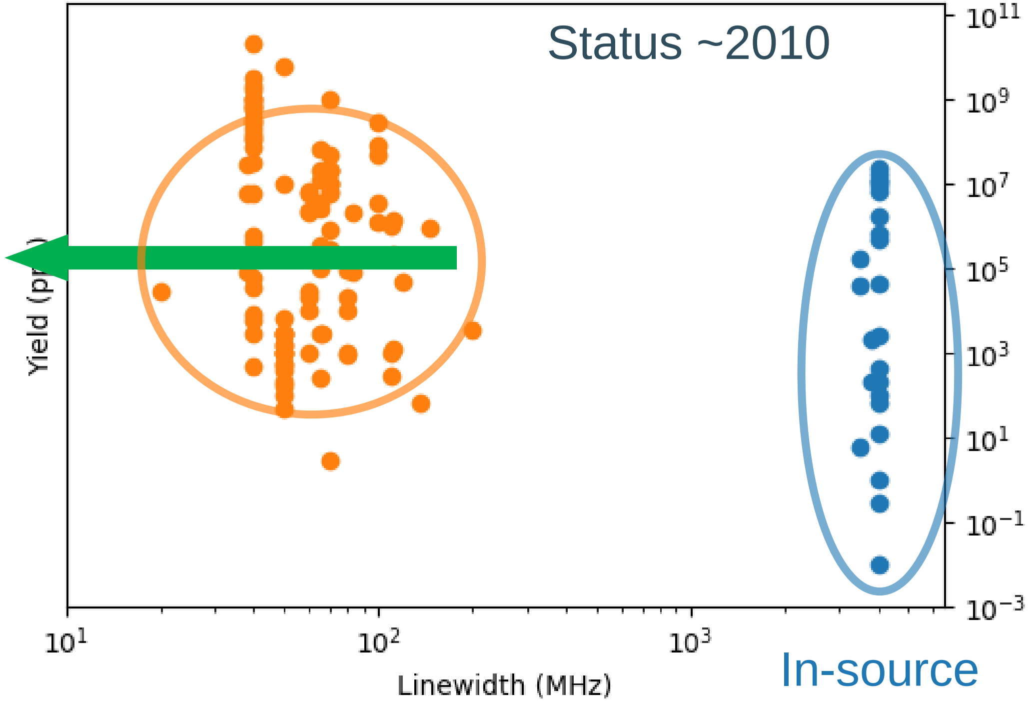
  - in-source laser spectroscopy of silver
- When more precision is needed: collinear fast-beam laser spectroscopy
  - Laser spectroscopy of zinc
- When *even more* precision is needed: beyond conventional optical spectroscopy
  - Future directions?

Predominantly collinear fast-beam experiments

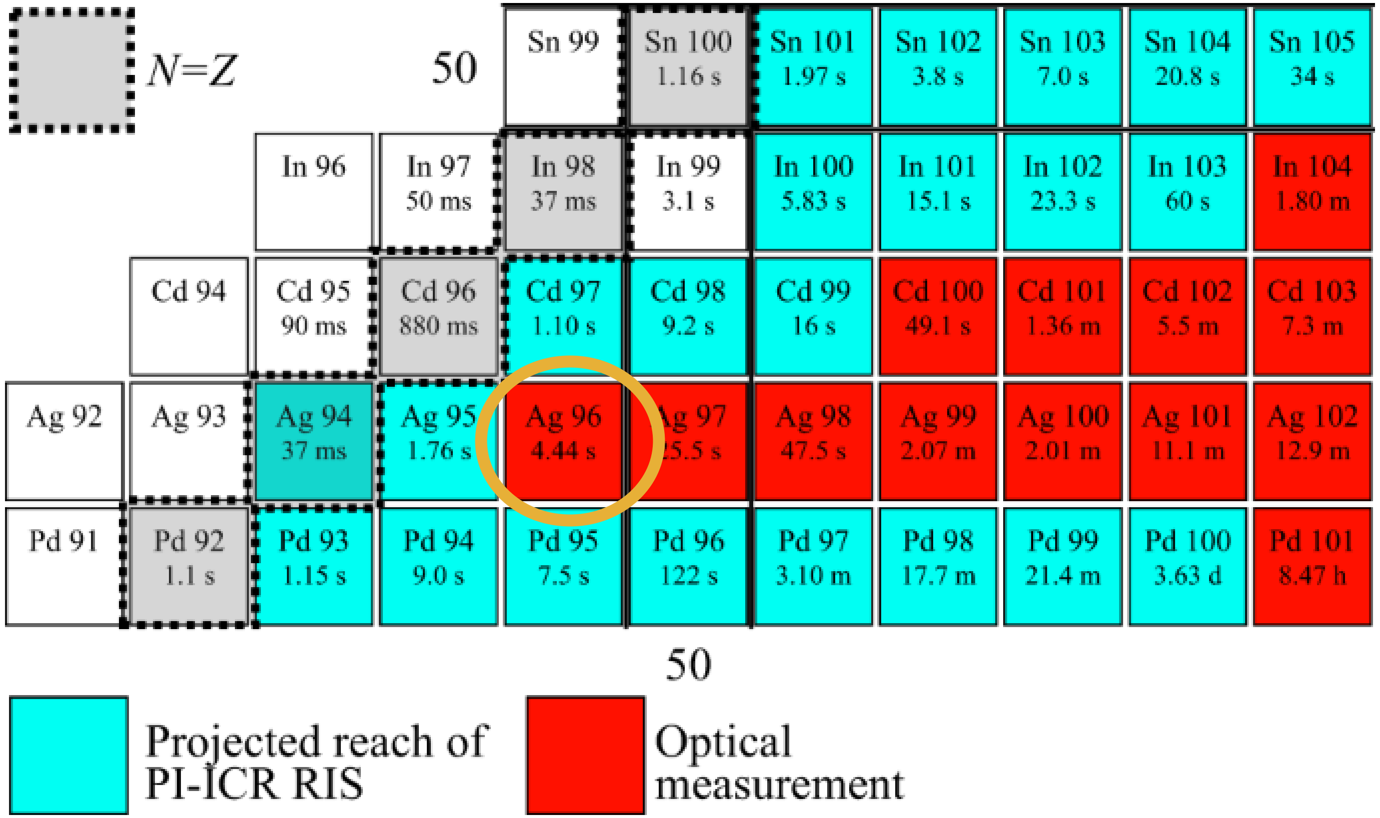


In-source experiments

Pushing towards the edges of production

- ^{100}Sn and the neighbouring isotopes are important isotopes to study in our quest to understand the atomic nucleus

- Producing these very neutron-poor isotopes is **challenging.**
- Reactions offer only small cross section, and other isotopes with the same mass (but closer to stability) are produced in much larger quantities.



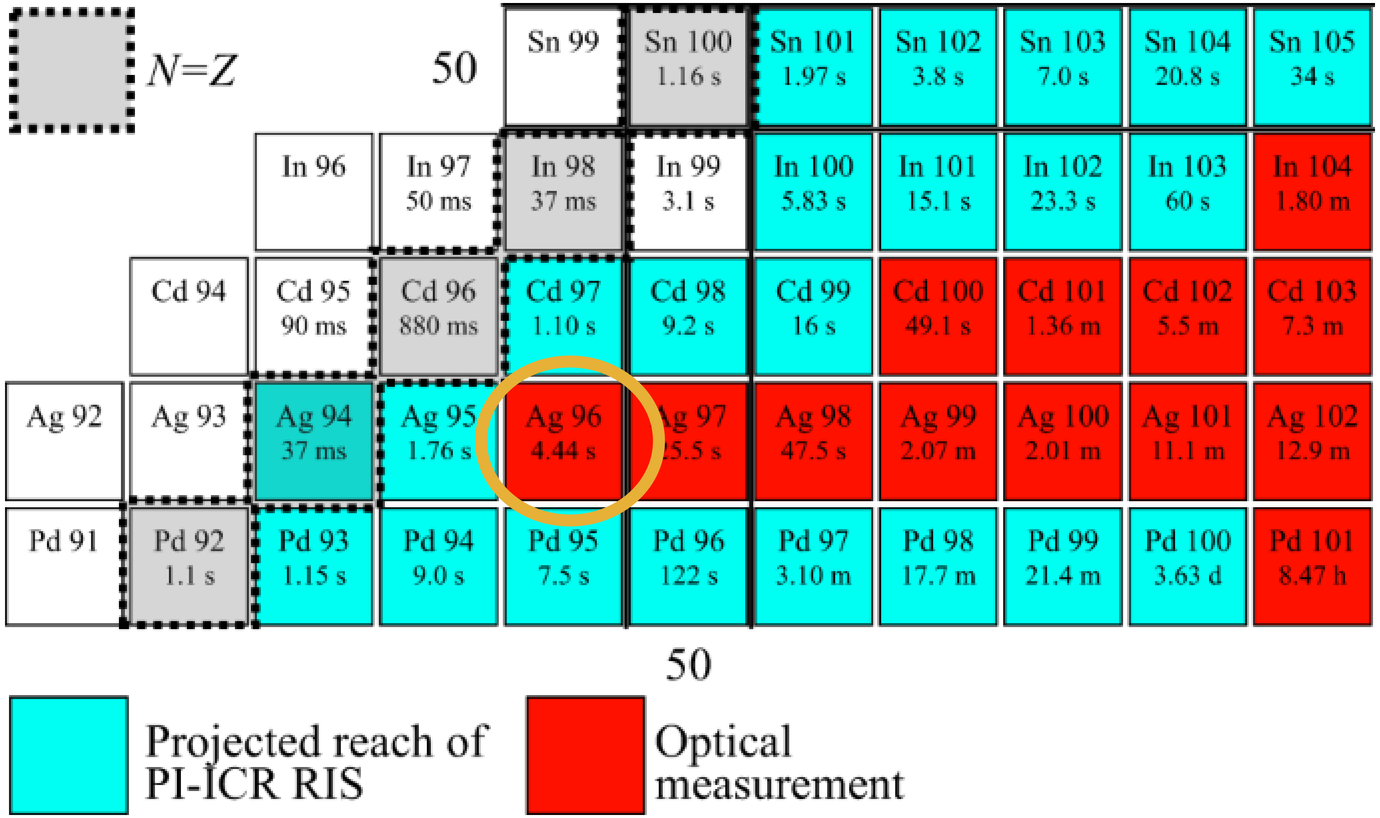
M. Reponen, R. P. de Groote et al, Nature Communications 12 (1), 1-8

Pushing towards the edges of production

- I'd like to walk you through a recent experiment to show what it takes to perform measurements at the edges of our production capabilities

- Red: published work to date

- Gray: N=Z line, where nuclei have the same number of protons and neutrons



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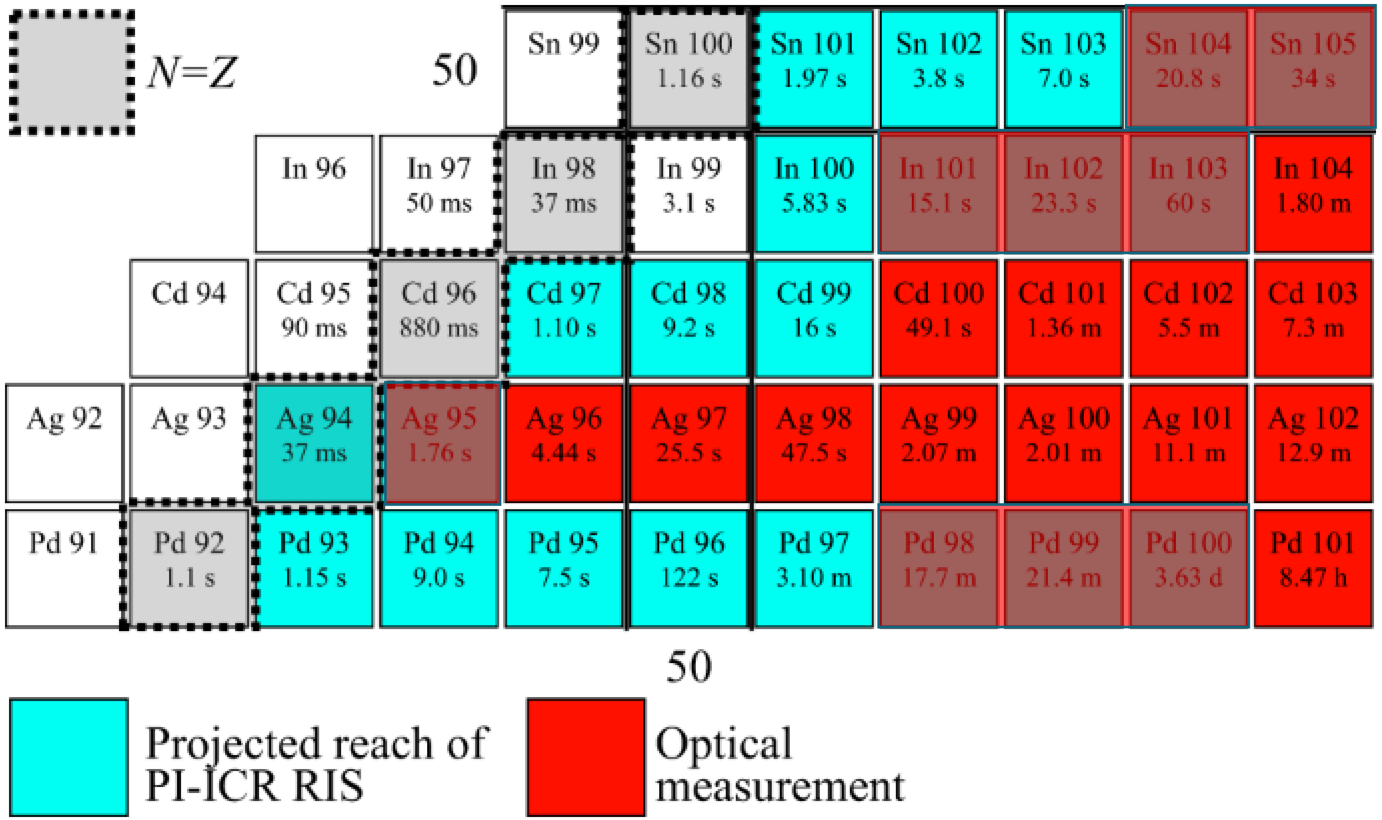
Pushing towards the edges of production

- I'd like to walk you through a recent experiment to show what it takes to perform measurements at the edges of our production capabilities

- Red: measured isotopes, some not yet published (look at how me have achieved over the past years!)
- Gray: N=Z line, where nuclei have the same number of protons and neutrons



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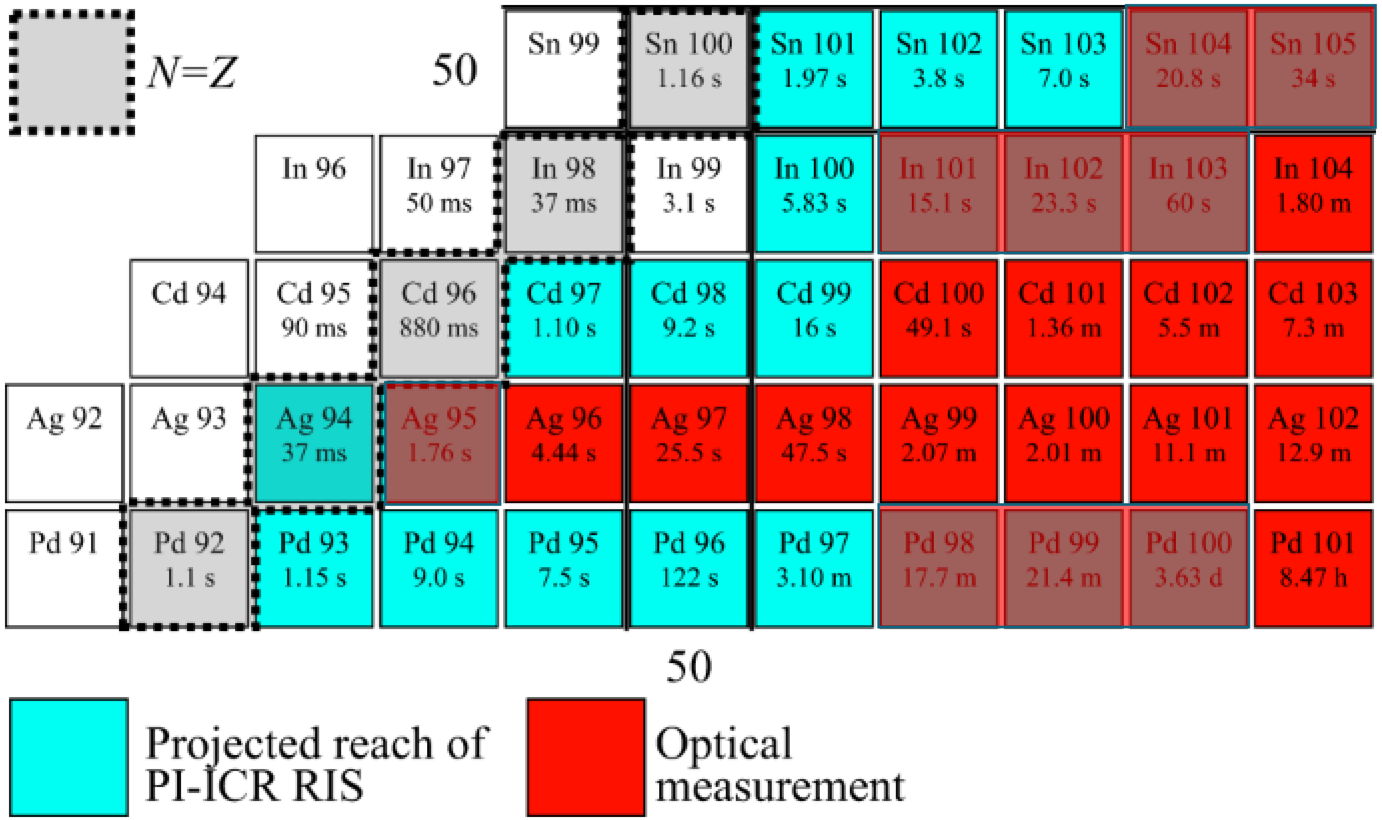
Pushing towards the edges of production

- Why does silver push out so much further than the other isotopes?
- At the heart of the answer: the atomic properties of silver.



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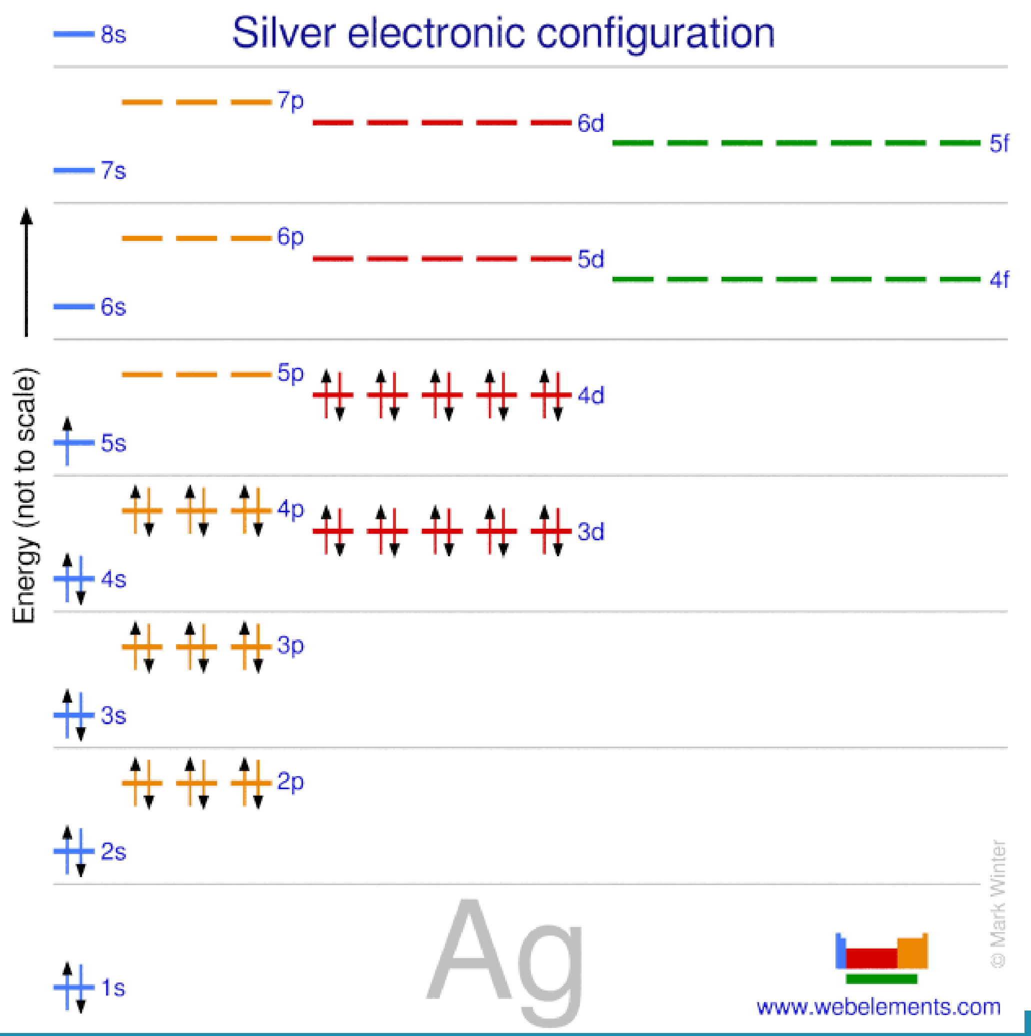

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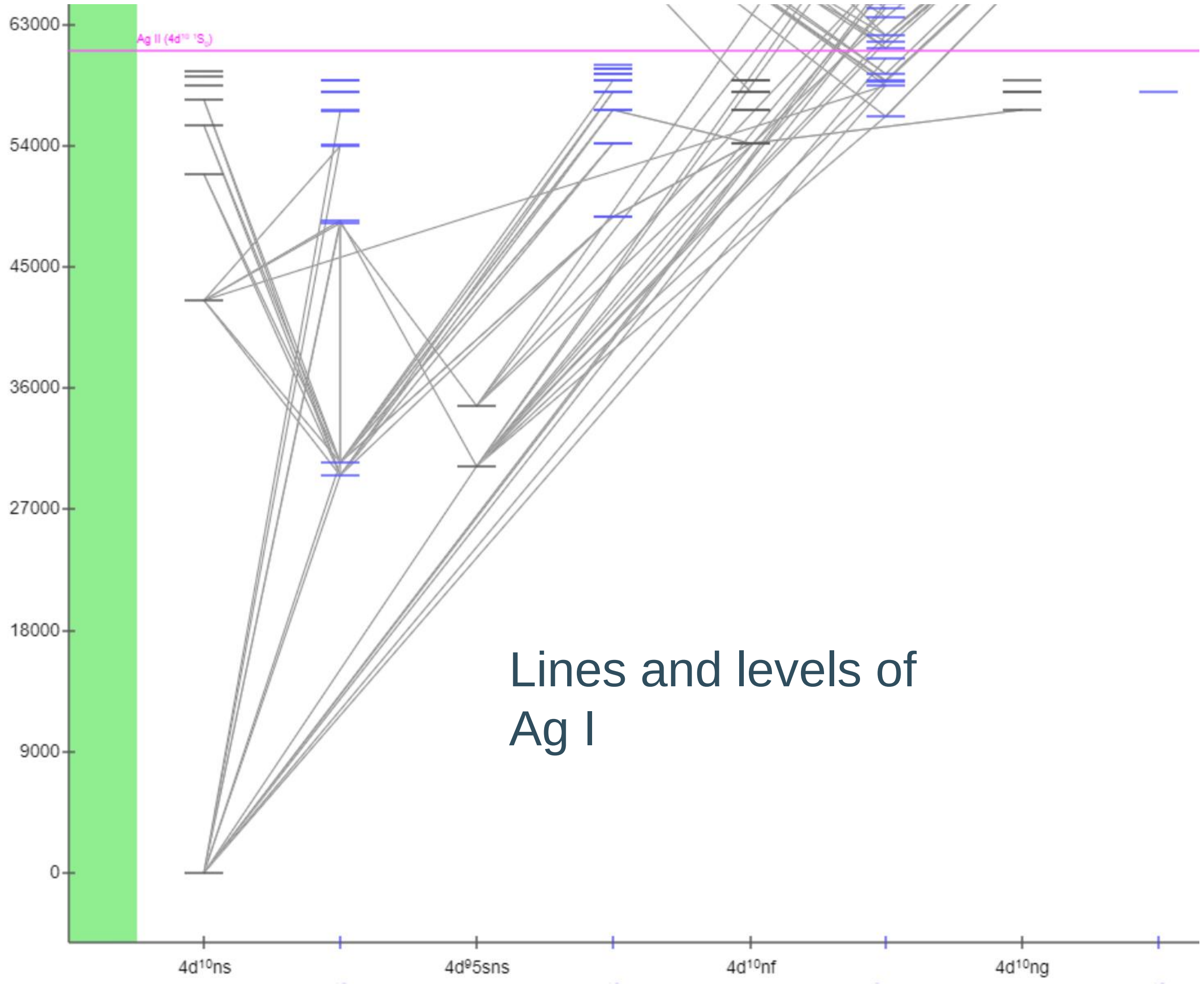
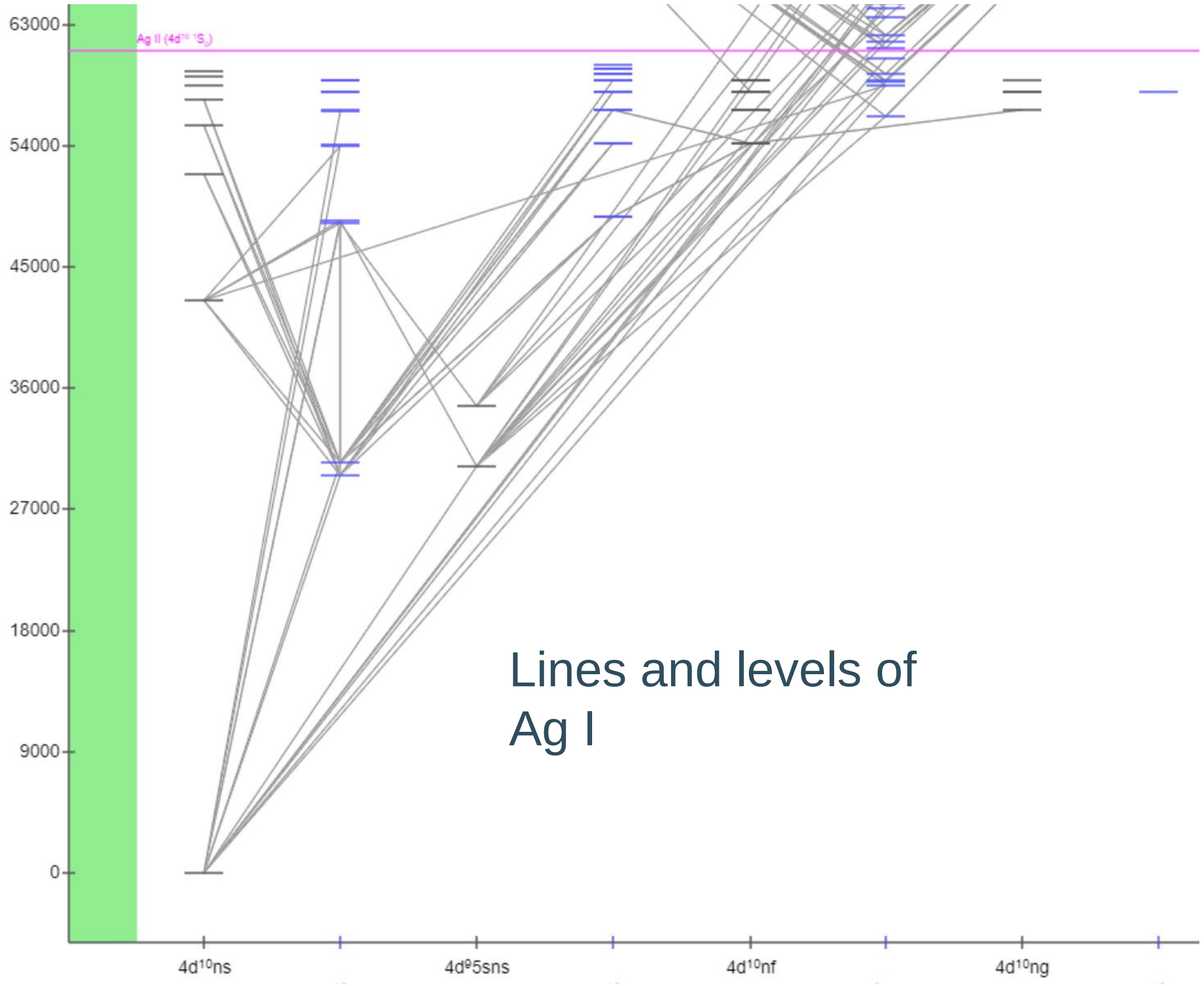
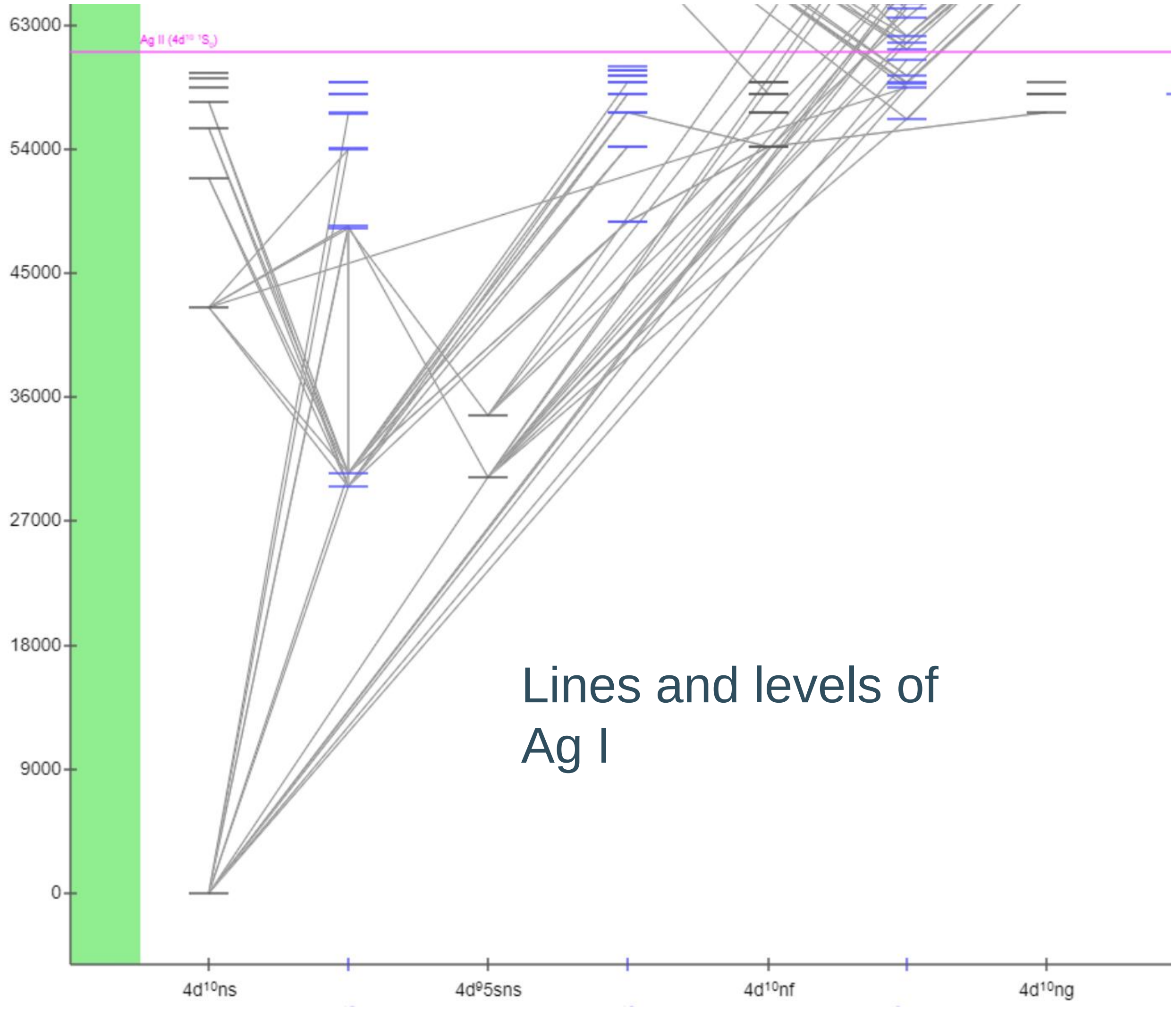


Lines and levels of Ag I



Lines and levels of Ag I

Structure is alkali-like:
easy to understand, easy to perform spectroscopy on!



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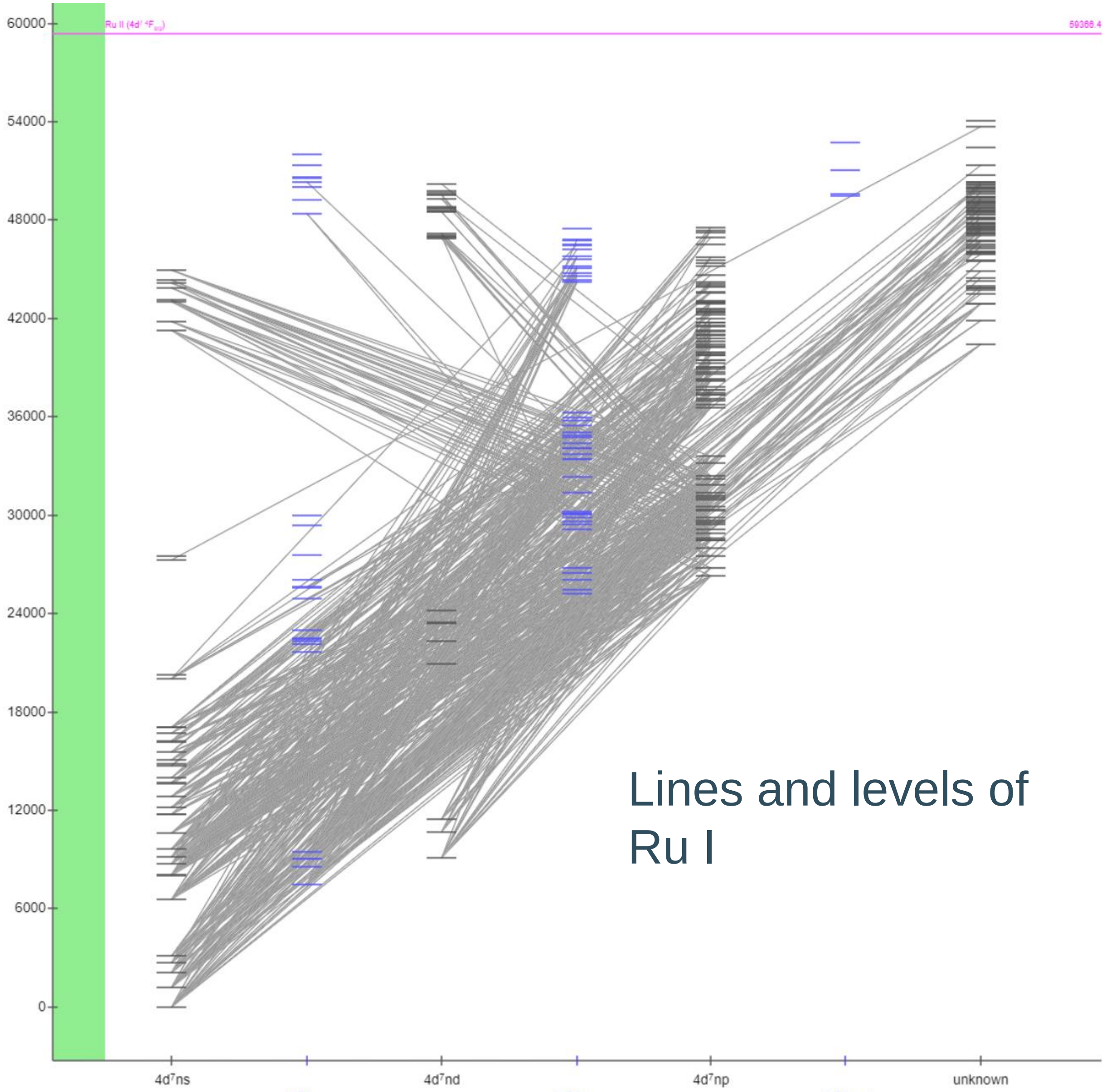

Lines and levels of Ru I

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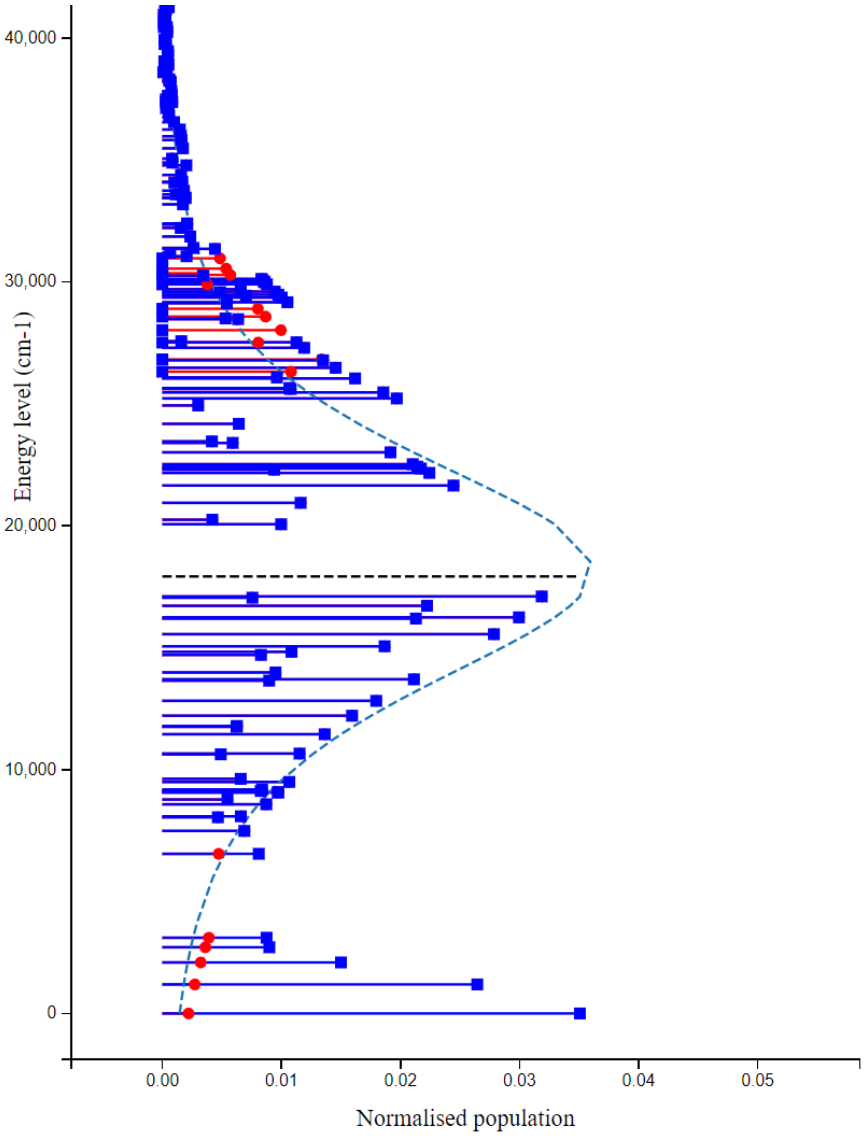
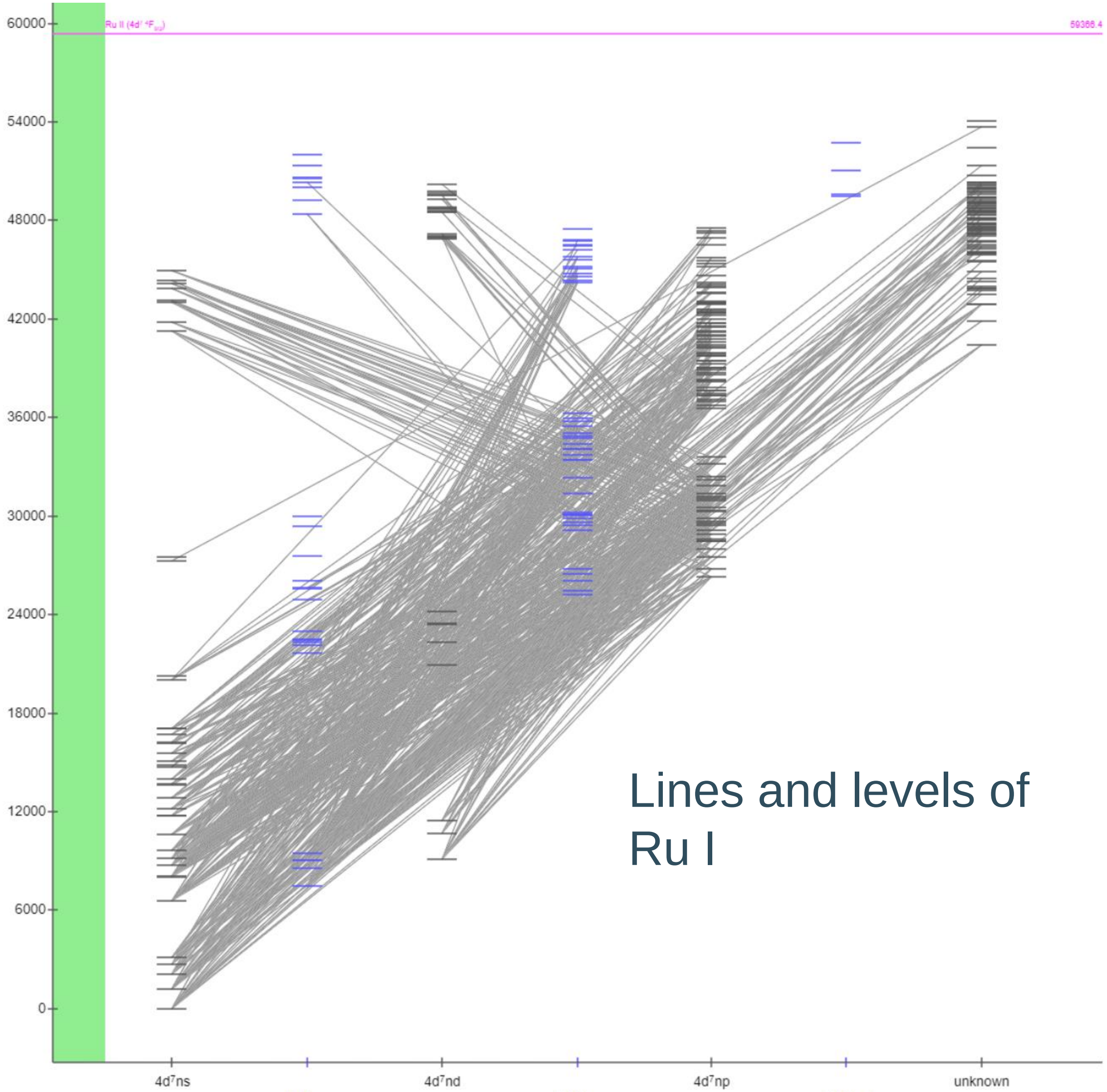
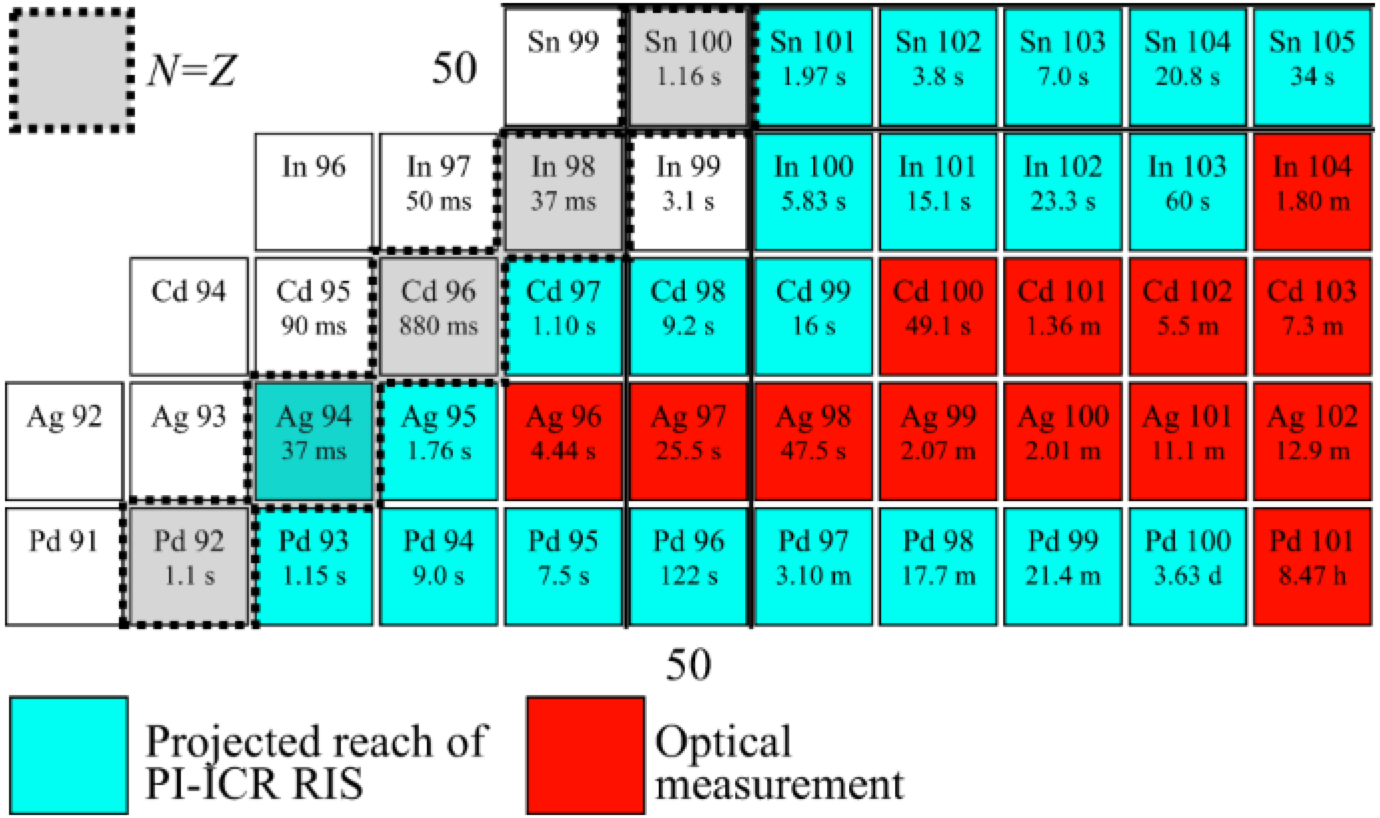




Lines and levels of Ru I

Pushing towards the edges of production

- Why does silver push out so much further than the other isotopes?
- At the heart of the answer: the atomic properties of silver
- Silver also doesn't stick very much inside of a thick target, which means the decay losses during extraction are minimal



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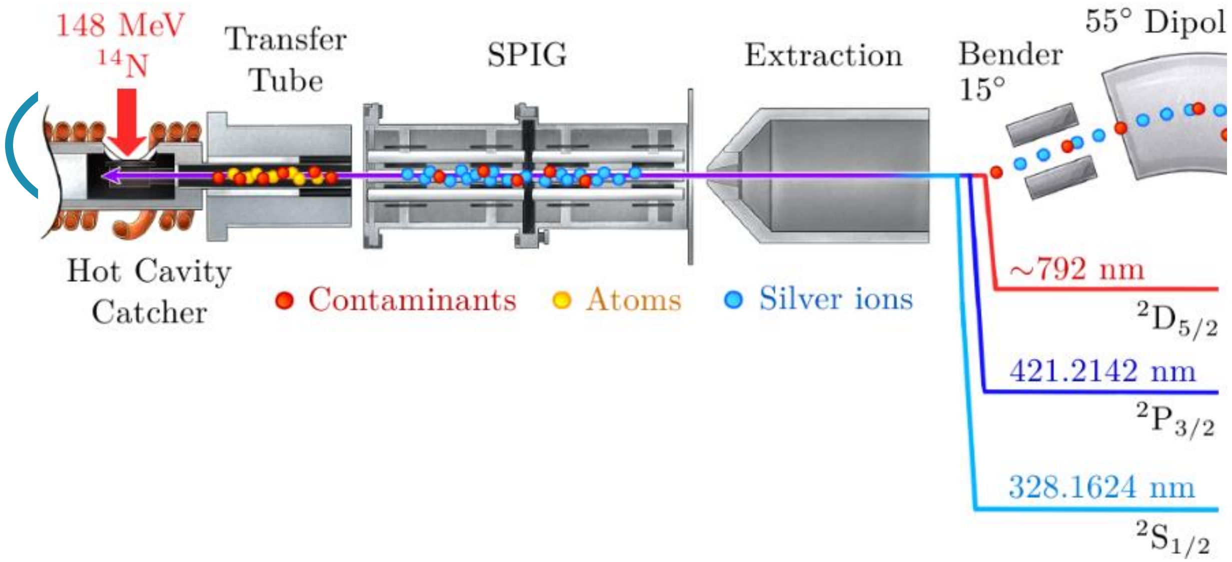
In-source laser spectroscopy of ^{96}Ag



1. Production
- ^{14}N(^{92}Mo, 2p *x*n) Ag
- Ag ions stopped in graphite catcher foil
- Diffuse into hot cavity (few ms)

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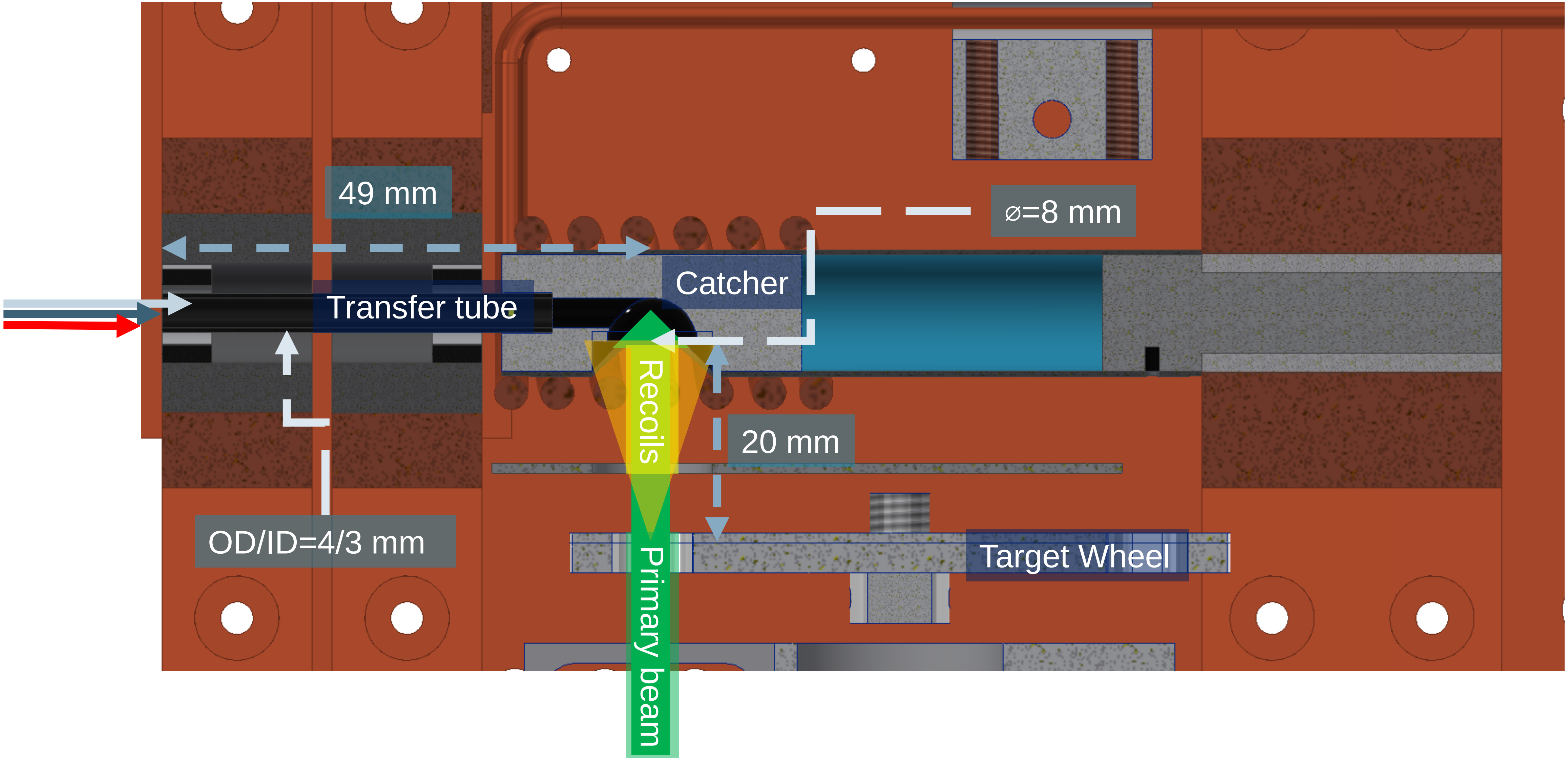

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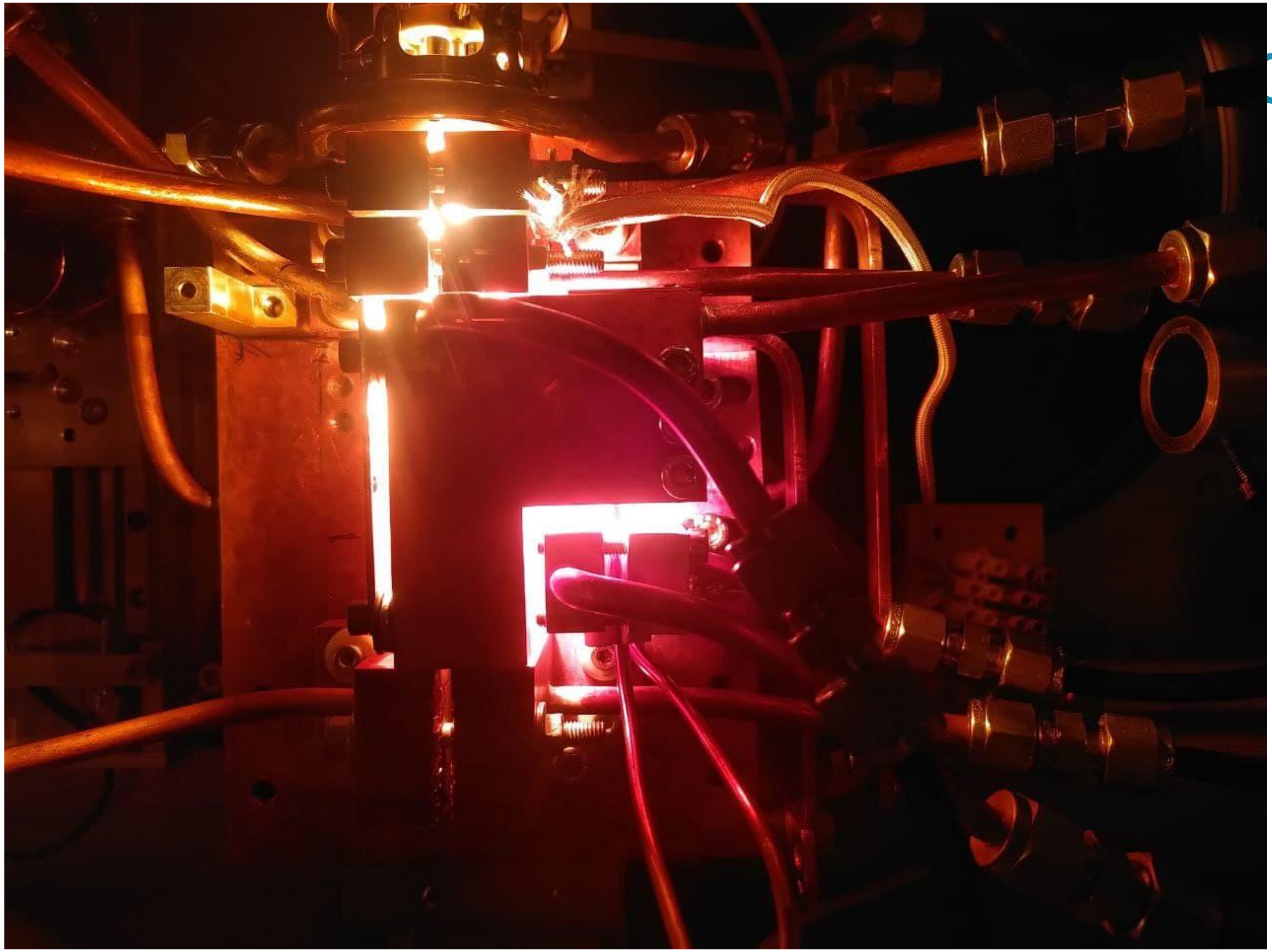

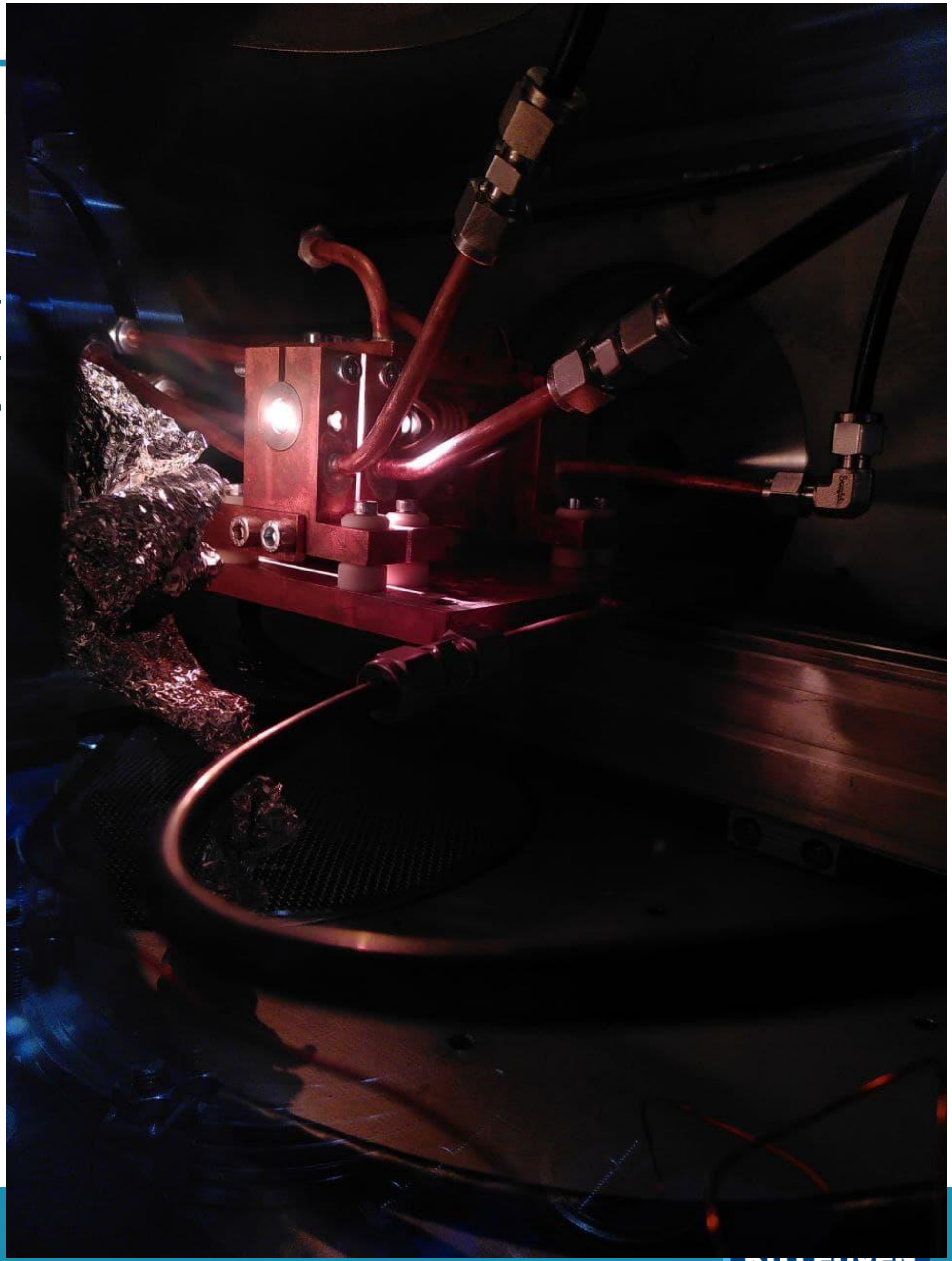

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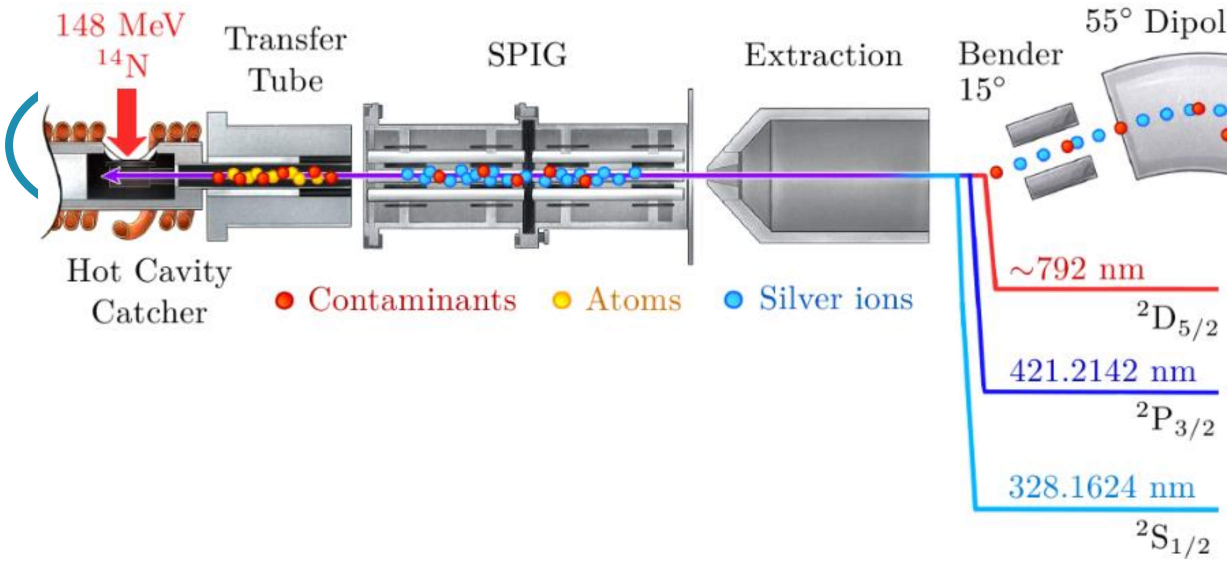

1. Production

2. Spectroscopy
- Laser ionization spectroscopy
- Possible to measure dipole moments and radii because the $S_{1/2}$ ground-state of silver possesses a very large A/μ-ratio

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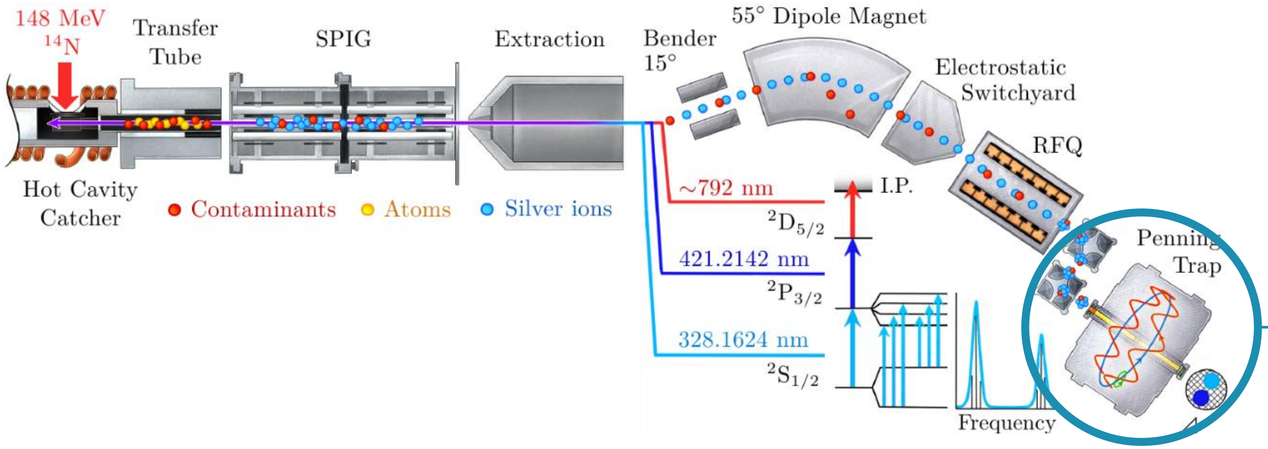
In-source laser spectroscopy of ^{96}Ag



1. Production
2. Laser ionization spectroscopy

3. Detection and removal of contaminants

- Ions are injected into Penning trap
- Excitations of the ion motion in the trap
  - Kick out isobars
  - States in silver land on different areas of 2D-MCP detector

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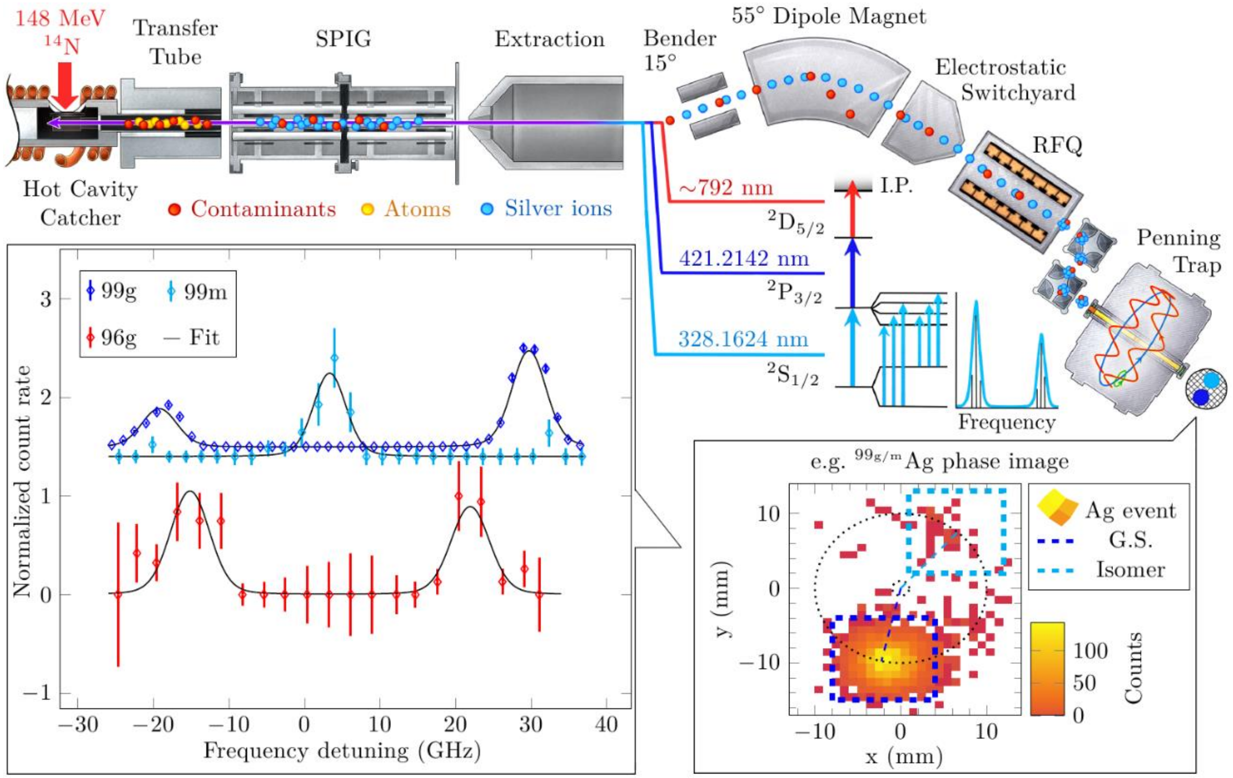
In-source laser spectroscopy of ^{96}Ag



1. Production
2. Laser ionization spectroscopy
3. Detection
   - Count ions as function of laser frequency
   - Different gates on detector area select different nuclear state

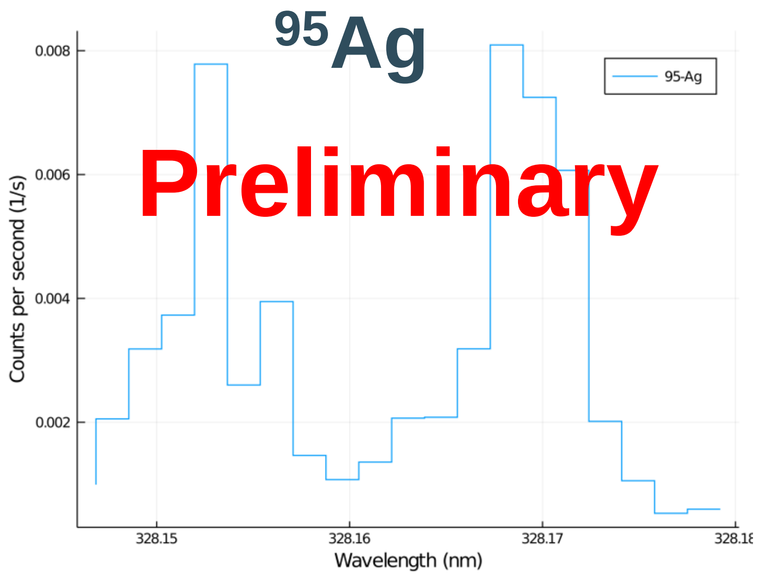
Result:
Ultra clean background conditions

^{96}Ag studied with an ”on resonance” detection rate of **1 ion per 5 mins**

Demonstrated for ^{95}Ag, too!

M. Reponen, R. P. de Groote et al, Nature Communications 12 (1), 1-8

In-source laser spectroscopy of ^{96}Ag



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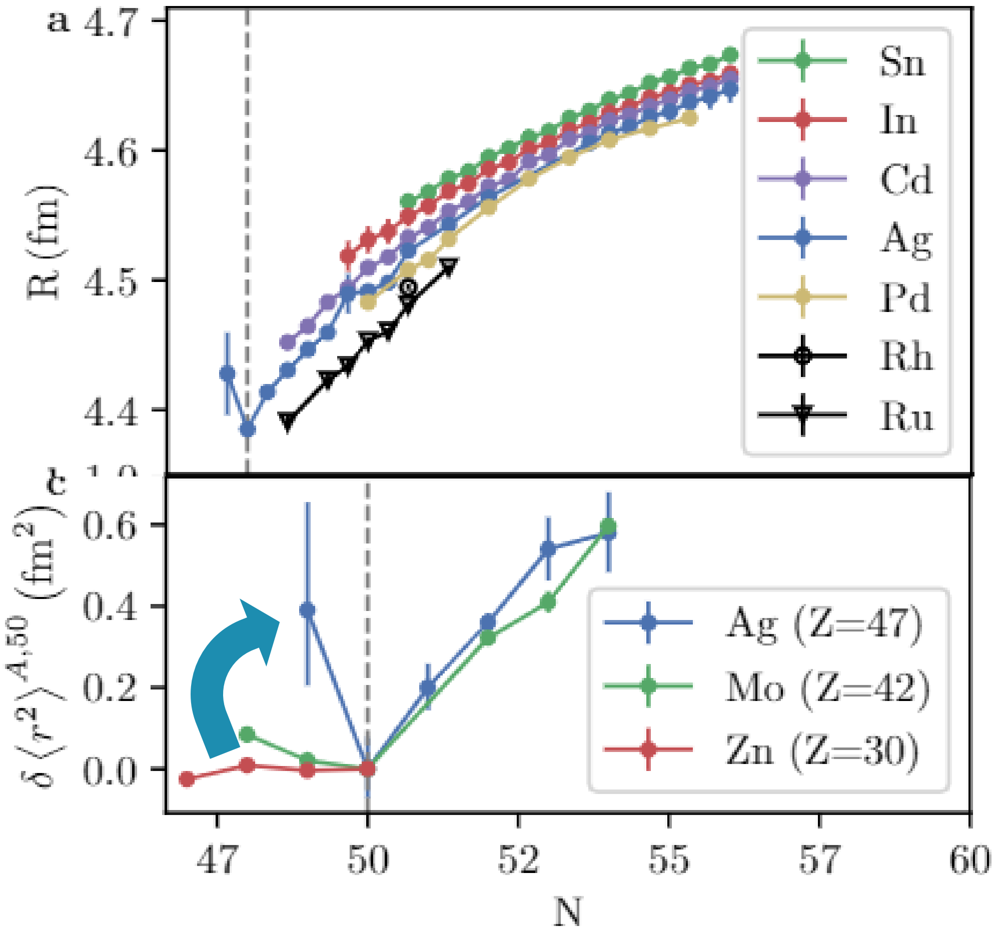
In-source laser spectroscopy of ^{96}Ag

- Closest crossing of N=50 in this region to date
  - 2nd closest: Mo (*Z*=42)
- Event rate at the end of Penning trap: 0.005 events/s
- Background rate: … 0?

- Remarkably sharp increase in radius observed
  - Comparison to state-of-the-art nuclear Fayans DFT is ongoing – but seems hard to explain with current theoretical tools



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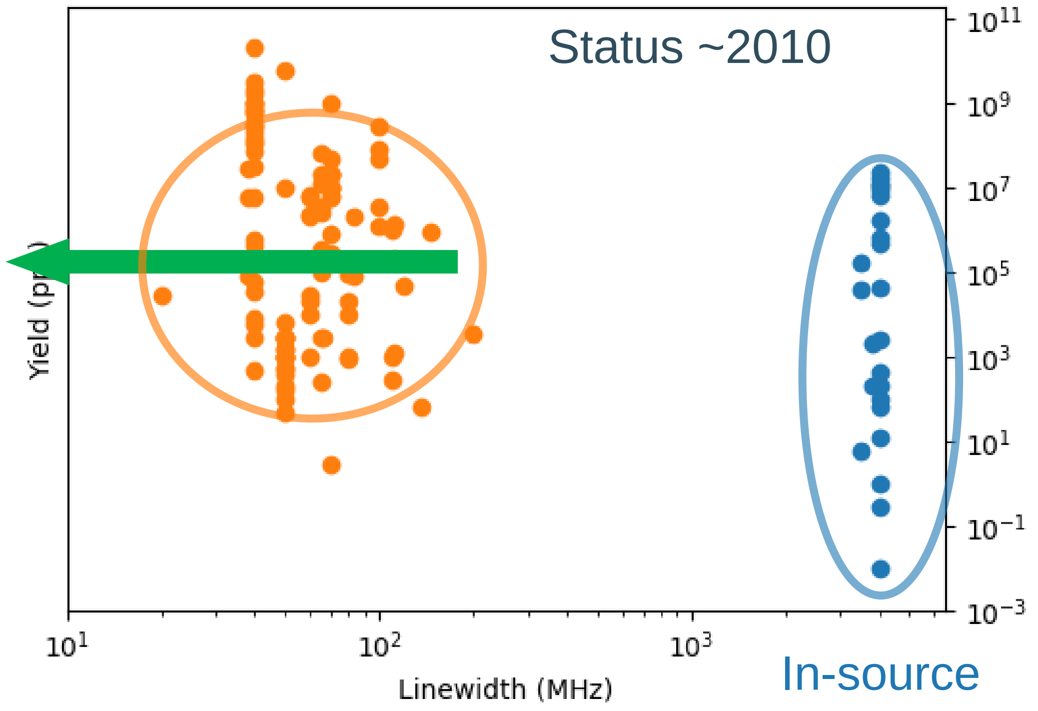


In-source experiments

Eye-watering higher orders……

UNIVERSITY OF JYVÄSKYLÄ

PHYSICAL REVIEW A **103**, 032826 (2021)

Magnetic octupole moment of ^{173}Yb using collinear laser spectroscopy

R. P. de Groote,[1,*] S. Kujanpää,[1] Á. Koszorús,[2] J. G. Li,[3] and I. D. Moore[1]
[1]*Department of Physics, University of Jyväskylä, PB 35(YFL) FIN-40351 Jyväskylä, Finland*
[2]*Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[3]*Institute of Applied Physics and Computational Mathematics, Beijing 100088, China*

Defining $K = F(F+1) - I(I+1) - J(J+1)$, this can be written as (truncated at the octupole ($k = 3$) term):

$$E_F^{(1)} = \frac{AK}{2} + \frac{3B}{4}\frac{K(K+1) - I(I+1)J(J+1)}{(2I(2I-1)J(2J-1))} + \frac{5C}{4}\frac{K^3 + 4K^2 + \frac{4}{5}K(-3I(I+1)J(J+1) + I(I+1) + J(J+1) + 3) - 4I(I+1)J(J+1)}{I(I-1)(2I-1)J(J-1)(2J-1))},$$

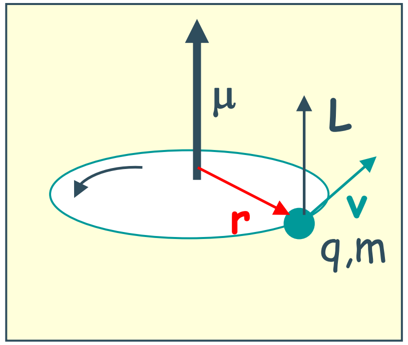
with hyperfine constants

$$A = \frac{1}{IJ}\langle II|T_2^{(n)}|II\rangle\langle JJ|T_1^{(e)}|JJ\rangle = \frac{\mu_I}{IJ}\langle JJ|T_1^{(e)}|JJ\rangle,$$
$$B = 4\langle II|T_2^{(n)}|II\rangle\langle JJ|T_2^{(e)}|JJ\rangle = 2eQ\langle JJ|T_2^{(e)}|JJ\rangle,$$
$$C = \langle II|T_3^{(n)}|II\rangle\langle JJ|T_3^{(e)}|JJ\rangle = -\Omega\langle JJ|T_3^{(e)}|JJ\rangle.$$

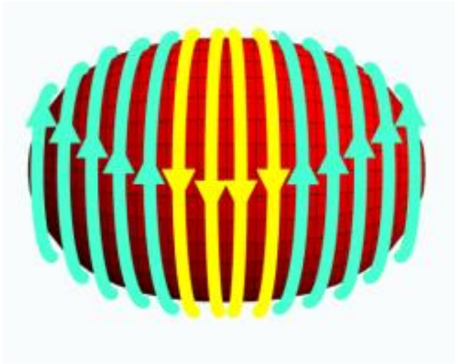
Let’s take another look at the hyperfine structure…

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

Extracting a nuclear moment requires knowledge of the atomic structure of the state in question!



Magnetic dipole



Magnetic octupole

Infinite expansion… Each term is significantly smaller than the previous one.

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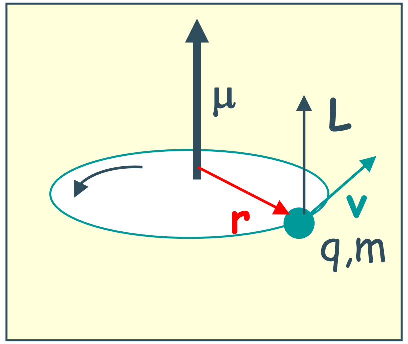
Let's take another look at the hyperfine structure…

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

$$E_F^{(1)} = \sum_k (-1)^{I+J+F} \begin{Bmatrix} J & I & F \\ I & J & k \end{Bmatrix} \times \langle I || M_n^{(k)} || I \rangle \langle J || T_e^{(k)} || J \rangle .$$



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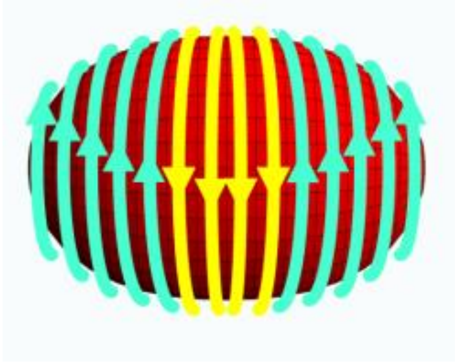

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$$E_F^{(1)} = \sum_k (-1)^{I+J+F} \frac{X_i \begin{Bmatrix} J & I & F \\ I & J & k \end{Bmatrix}}{\begin{pmatrix} I & 1 & I \\ -I & 0 & I \end{pmatrix} \begin{pmatrix} J & 1 & J \\ -J & 0 & J \end{pmatrix}}$$

$$X_1 = IJA$$

$$X_2 = \frac{1}{4} B$$

$$X_3 = C$$

$$X_4 = D$$

…

Nuclear x atomic

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

$$B = 2eQ \times V_{zz}$$

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

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

Ask your friendly neighbourhood atomic theorist what these are

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Unfortunate conventions…

$$X_1 = IJA$$
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$$\ldots$$

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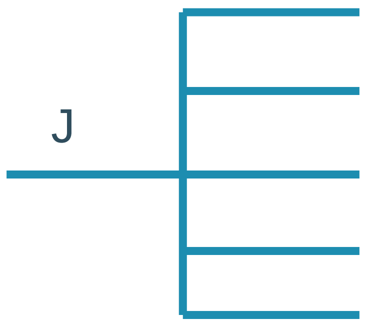

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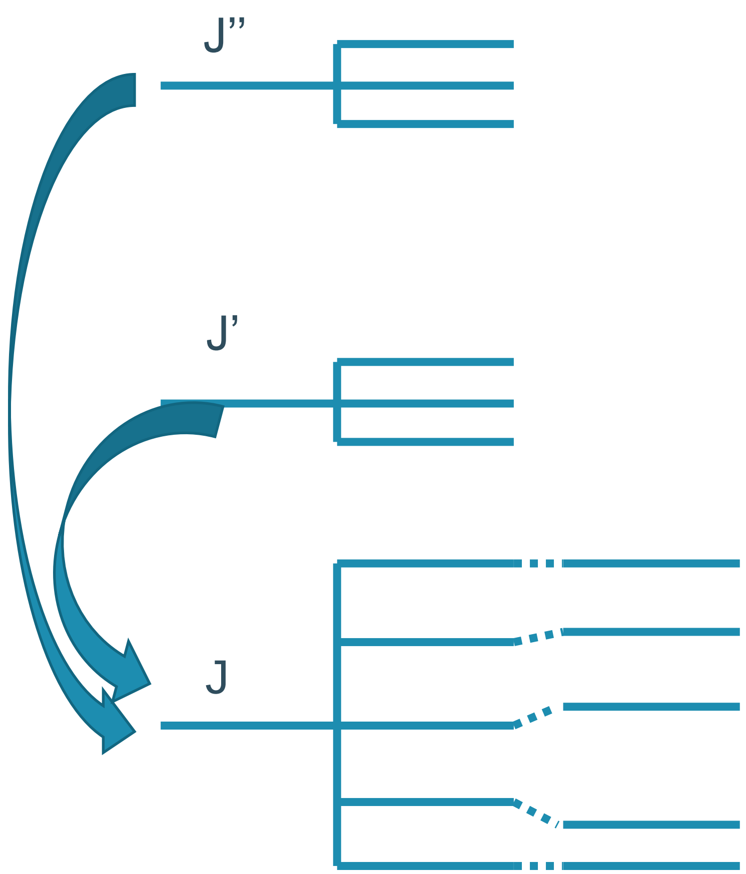
$$E_F^{(2)} = \sum_{J'} \frac{1}{E_J - E_{J'}} \sum_{k_1,k_2} \begin{Bmatrix} F & J & I \\ k_1 & I & J' \end{Bmatrix} \begin{Bmatrix} F & J & I \\ k_2 & I & J' \end{Bmatrix} \times \langle I || M_n^{(k_1)} || I \rangle \langle I || M_n^{(k_2)} || I \rangle \times \langle J' || T_e^{(k_1)} || J \rangle \langle J' || T_e^{(k_2)} || J \rangle ,$$

States with same F of different atomic levels mix



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These expressions may still look a little terrifying, but the stuff related to the angular momenta is actually the easy part.

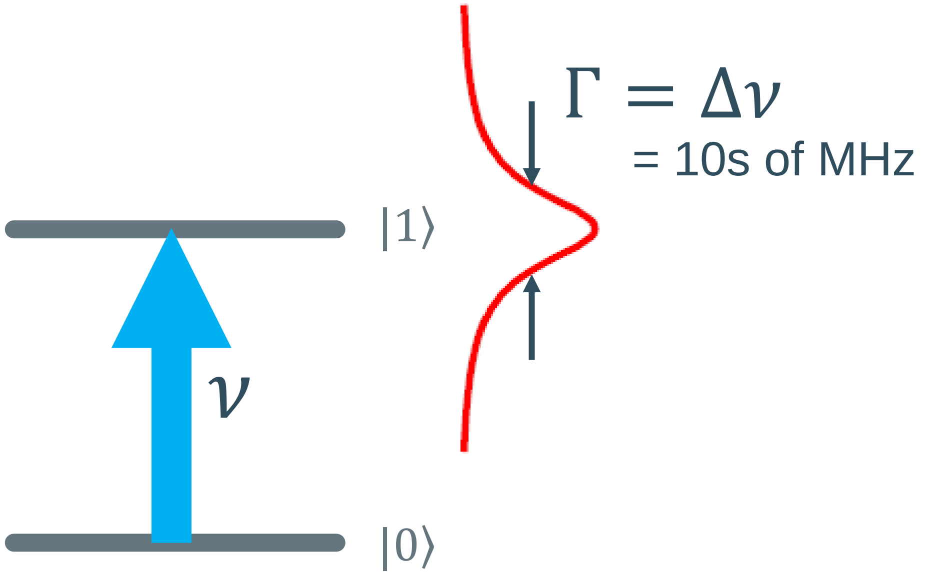
The hard part lies in evaluating the atomic matrix elements!

What is currently holding our experimental resolution/precision back?

+ **Fast** (can be performed on short-lived isotopes ~ ms)

+ **Sensitive** (~ few ions/s)

+ Able to reach natural linewidth of strong transitions



- Very short laser-ion interaction time O(μs) because the beam is in-flight or because of characteristics of the lasers, environment, …

Strong transition

-> Short half-life O(ns)

-> Broad linewidth

Think back to the lecture on penning traps: short measurement time means low precision. It's really just fourier transforms.

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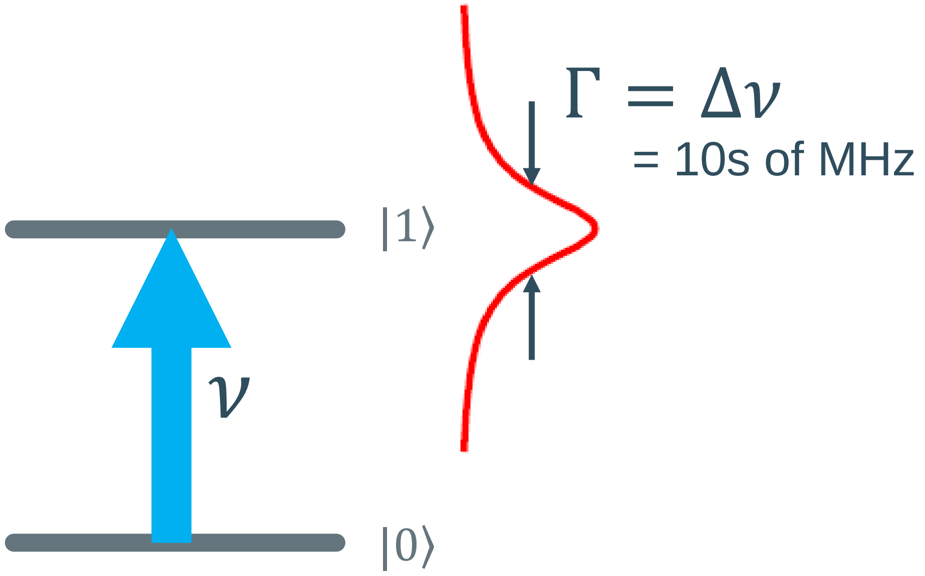

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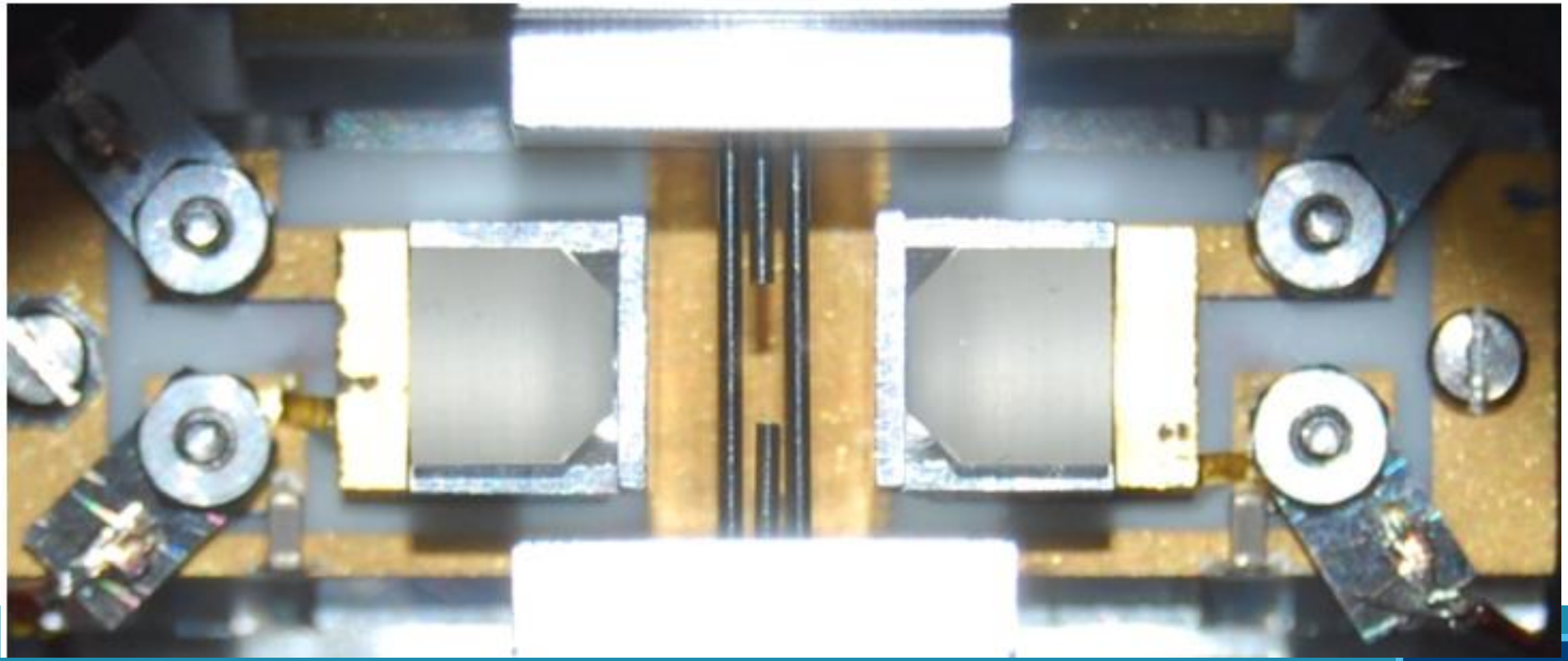
Precision measurements in ion traps

- In order to perform measurements with long interaction times, we need to store atoms or ions into a trap
- After previous lectures, you are all experts in how these work!

- Once in the trap, the ions can be carefully prepared
- Typically Paul traps, but penning traps are also possible.



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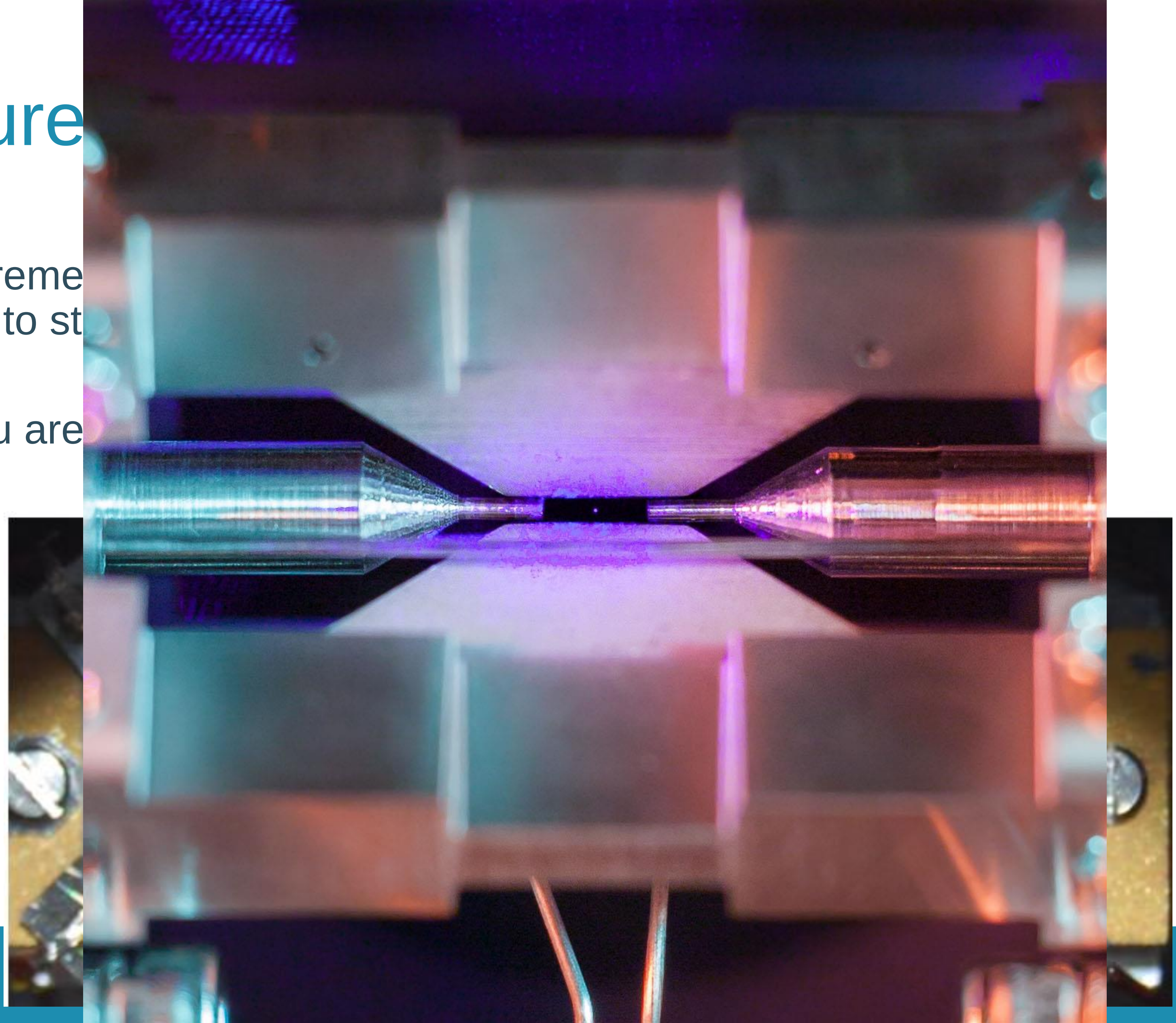
Precision measure

- In order to perform measureme
interaction times, we need to st
ions into a trap
- After previous lectures, you are
how these work!

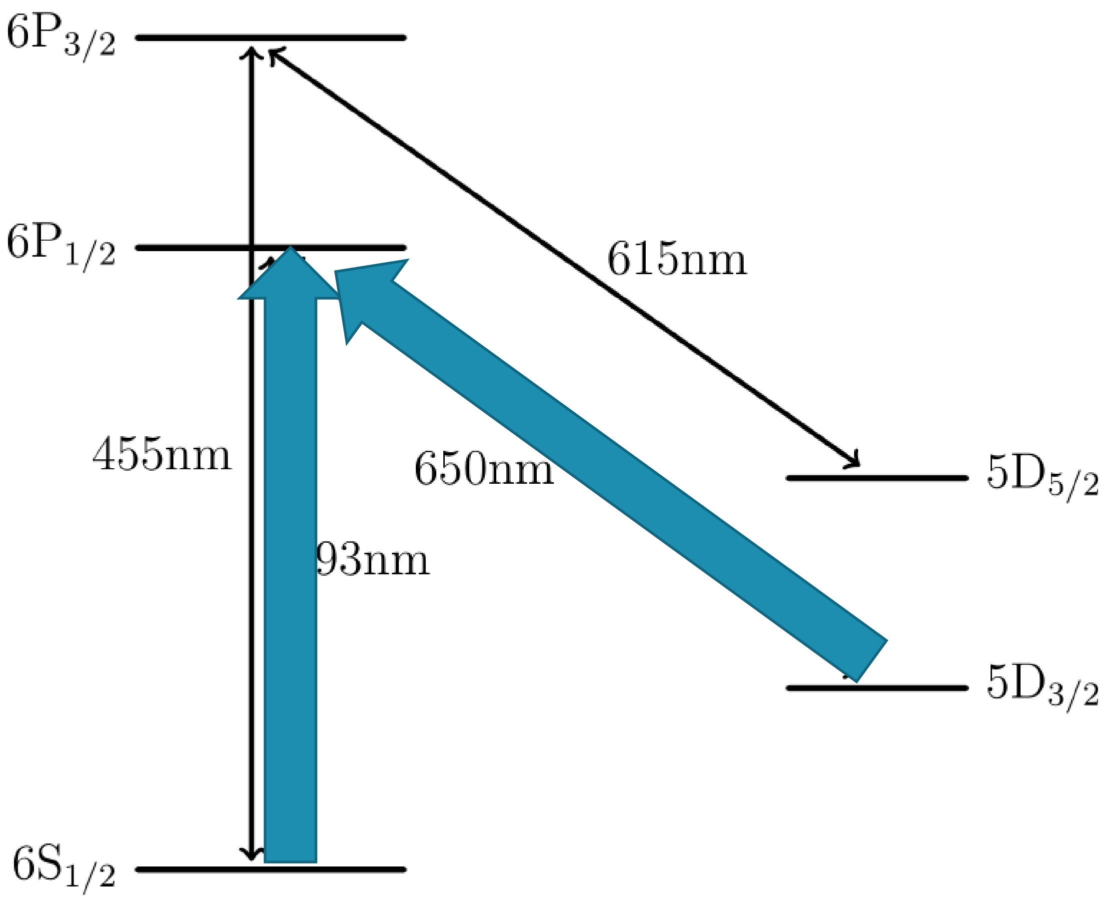
- Once in the trap, the ions can be carefully prepared
- Typically Paul traps, but penning traps are also possible.



Precision measurements in ion traps

- Barium has a simple atomic structure

- By using only two lasers, we can cool the ion down
  - Laser tuned slightly below resonance
  - photon is absorbed when the atom is moving towards the laser
  - Emission is isotropic: net effect means the ion slows down
  - Many cycles: reach temperatures of the order of Kelvin
  - Ask Franziska!



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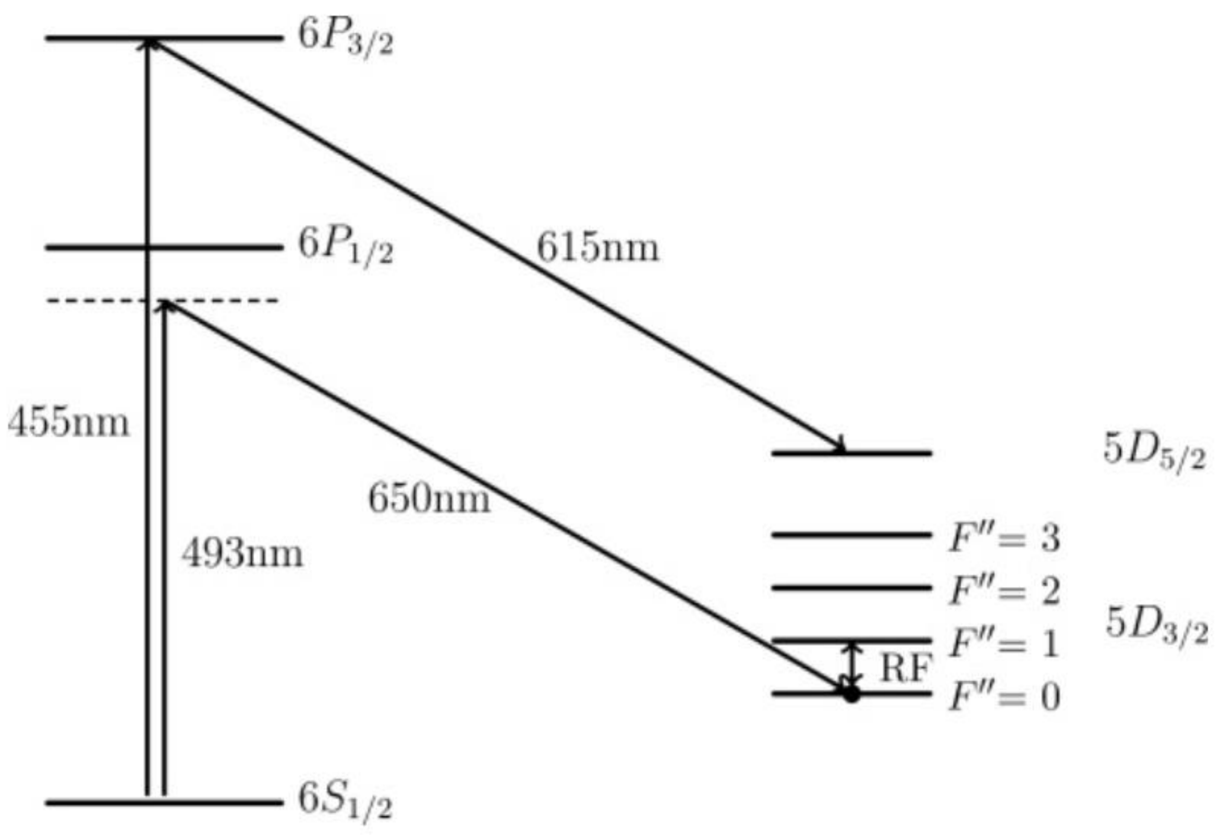
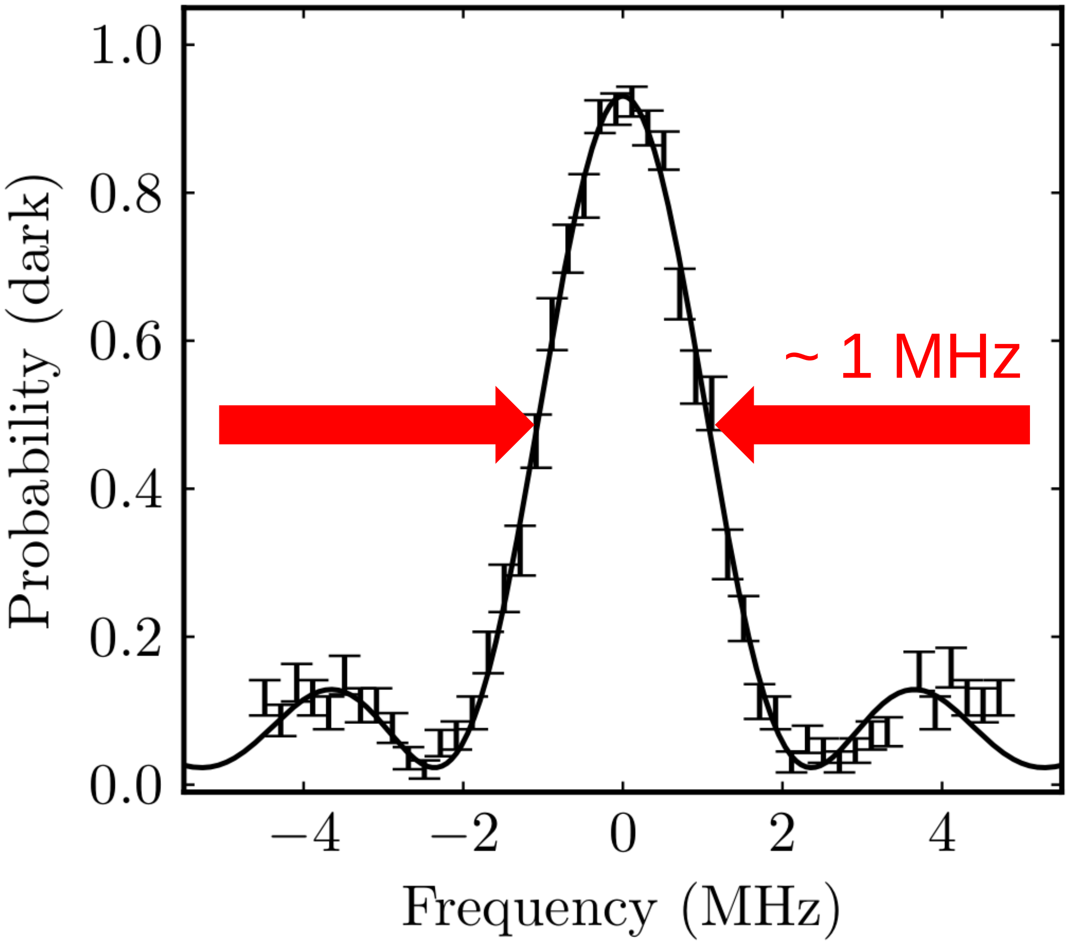
Precision measurements in ion traps

- Barium has a simple atomic structure
- By using only two lasers, we can cool the ion down
- Once the ion has been cooled, precise spectroscopy is possible
  - Radiofrequency excitations can be used to precisely measure splittings of the D states
  - Think of penning traps: long interaction, narrow resonance!



Precision measurements in ion traps

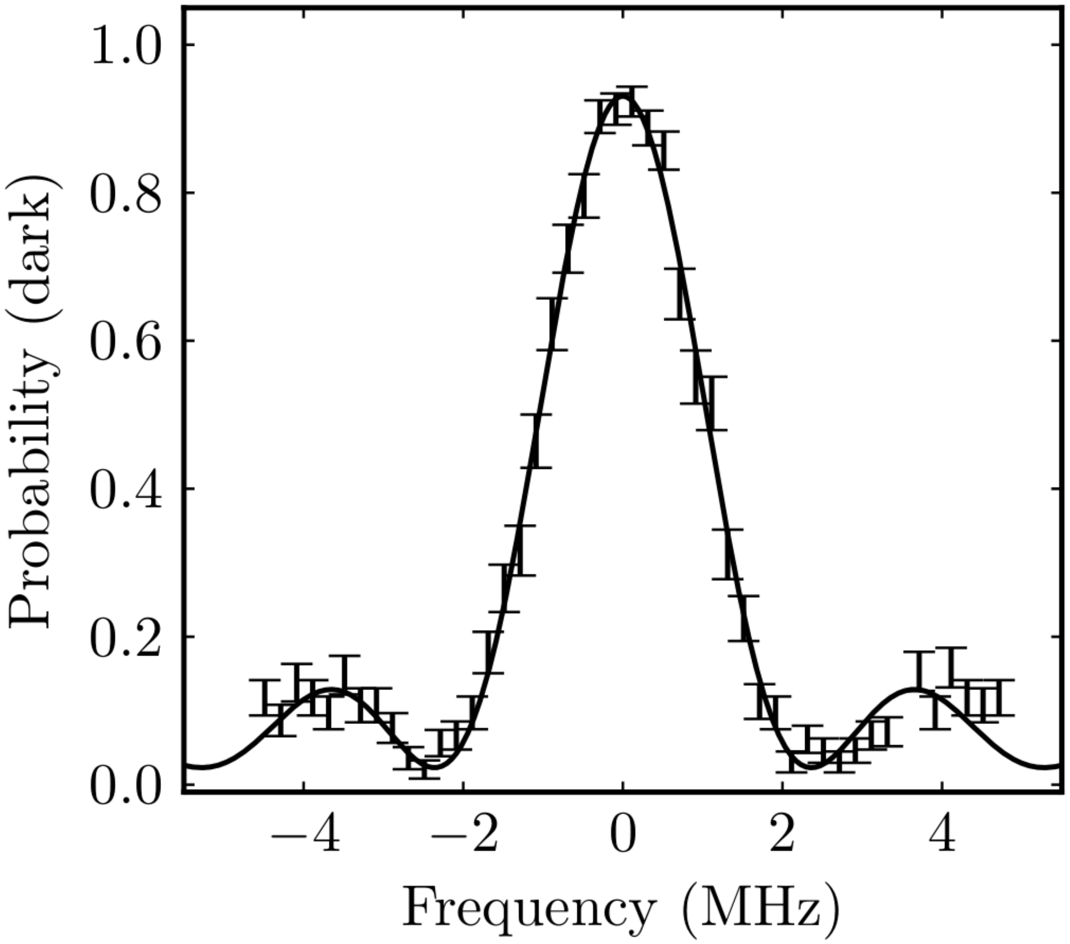


- The atom now sits very still, and can be gently examined with a laser beam

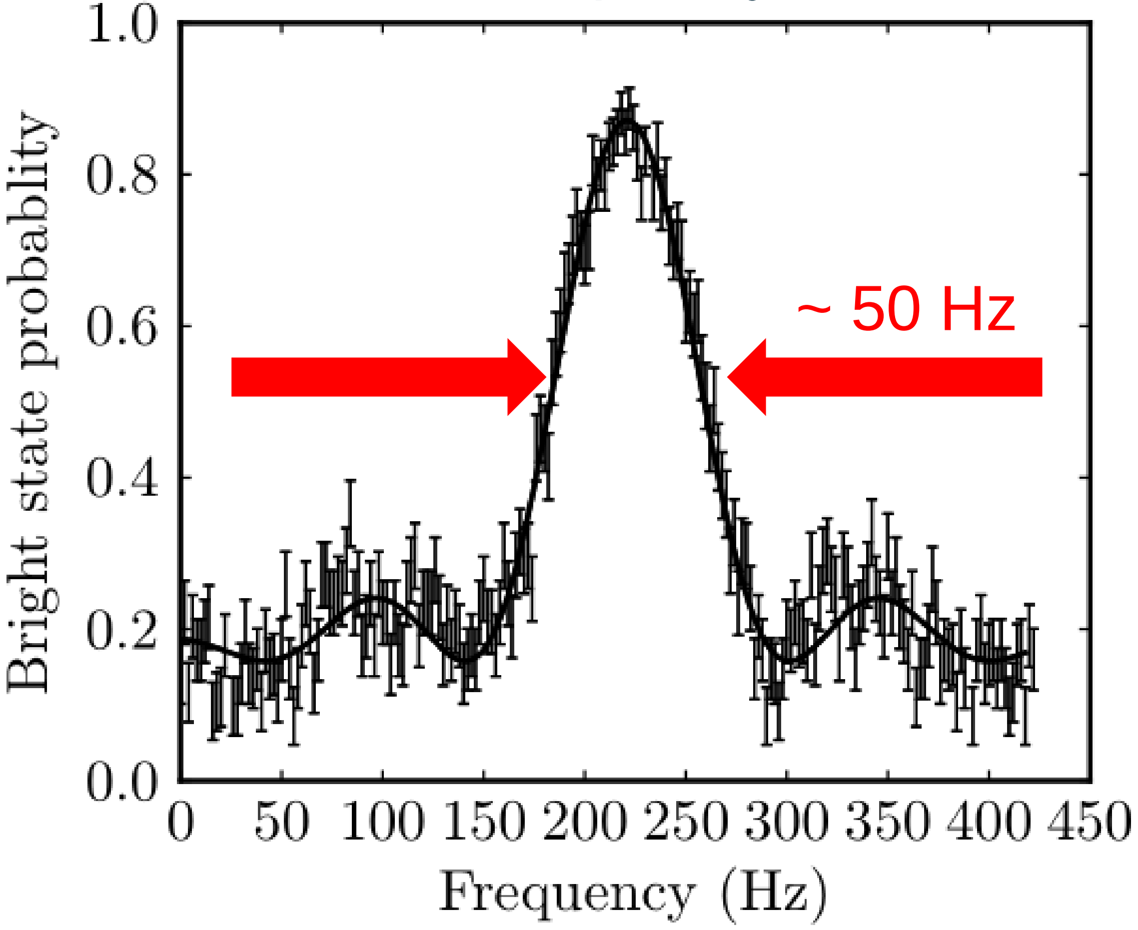
- Scanning over the optical transition…

Optics Express Vol. 20, Issue 19, pp. 21379-21384 (2012)

Precision measurements in ion traps



Direct radiofrequency excitations…



So precise it *Herz.*

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Precision measurements in ion traps

- Combining the data with precise calculations by B. Sahoo
  - Relativistic coupled cluster (CCSD(T) method)
- Consistent value obtained from the two metastable D-states
- Nuclear theory interpretation of the result is yet to be made…

Table 6.2: $5D_{5/2}$ hyperfine coupling constants.

	A (Hz)	B (Hz)	C (Hz)
Uncorr.	−12029724.1(9)	59519566.2(43)	−41.73(18)
η corr.	537(11)	5367(110)	–
ζ corr.	−46.9(12)	587(15)	29.33(75)
Corr.	−12029234(11)	59525520(110)	−12.41(77)

$$\Omega\left({}^{137}\mathrm{Ba}^{+}_{\mathrm{D}_{3/2}}\right) = 0.05057(54)\ (\mu_{\mathrm{N}} \times \mathrm{b}),$$

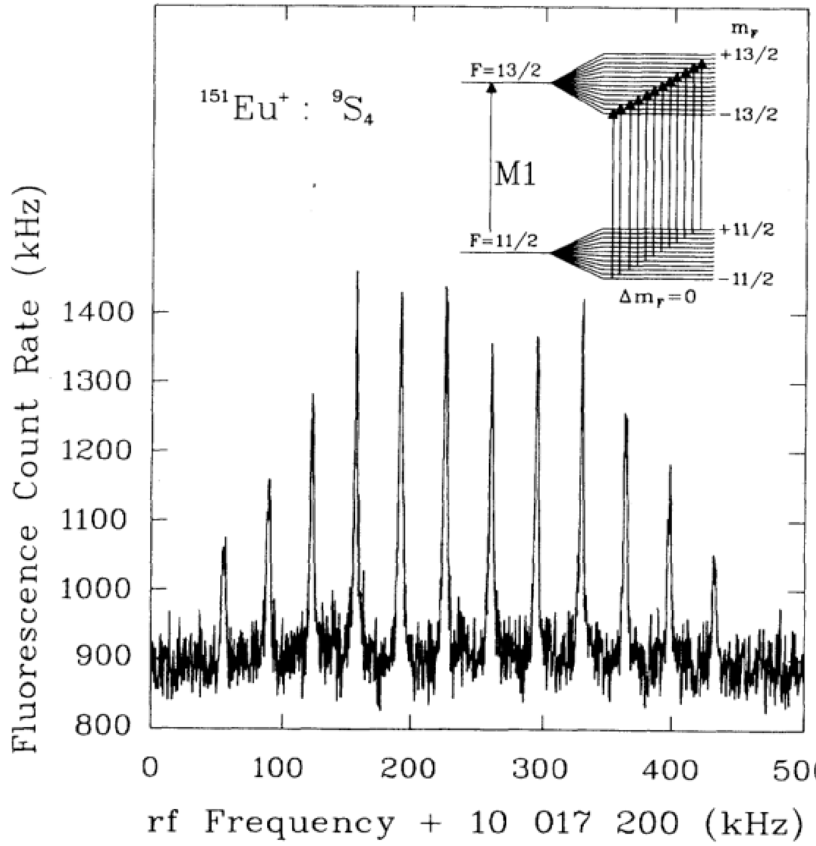
$$\Omega\left({}^{137}\mathrm{Ba}^{+}_{\mathrm{D}_{5/2}}\right) = 0.0496(37)\ (\mu_{\mathrm{N}} \times \mathrm{b}),$$

Optics Express Vol. 20, Issue 19, pp. 21379-21384 (2012)

Precision measurements in ion traps

- The fun doesn't even stop there…
- External B-field: measure zeeman splitting!
  - Direct unambiguous spin assignment

Fit No.	hfs constant	$^{151}Eu^+$ (Hz)	$^{153}Eu^+$ (Hz)	$^{151}Eu^+$:$^{153}Eu^+$
VI	*A*	1 540 297 394(13)	684 565 993(9)	2.250 034 927(35)
	B	−660 862(231)	−1 752 868(84)	0.377 02(13)
	C	26(23)	3(7)	9(22)
	D	−6(5)	−5(2)	1.2(1.1)

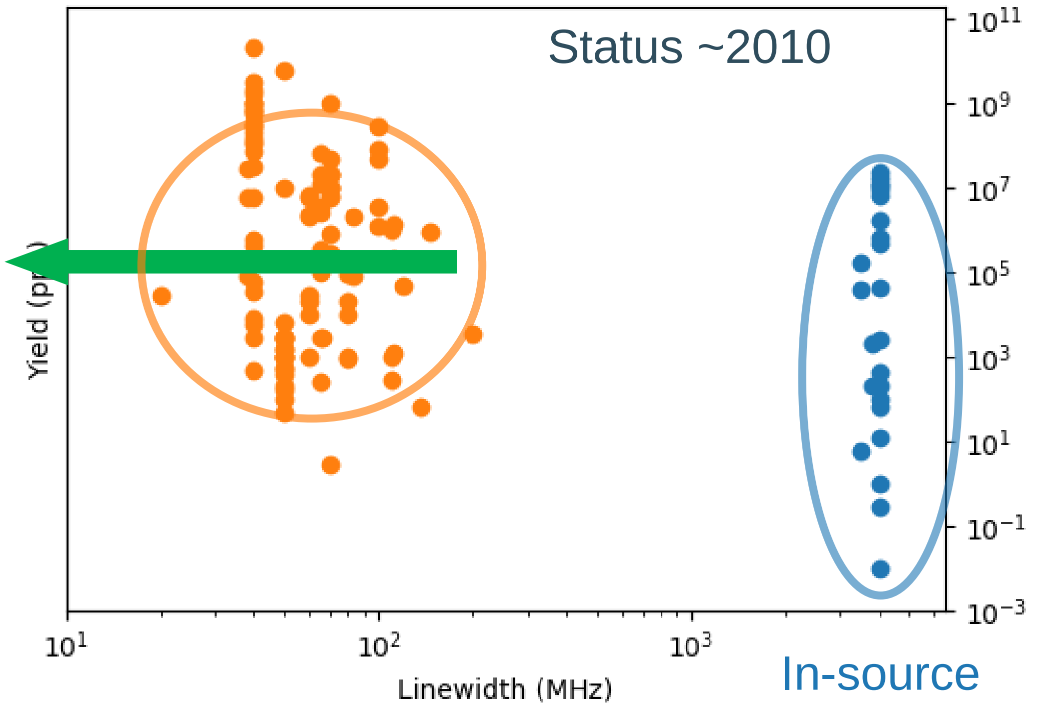


O. Becker et al, PRA vol 45, 5, 1993

Outline/conclusion

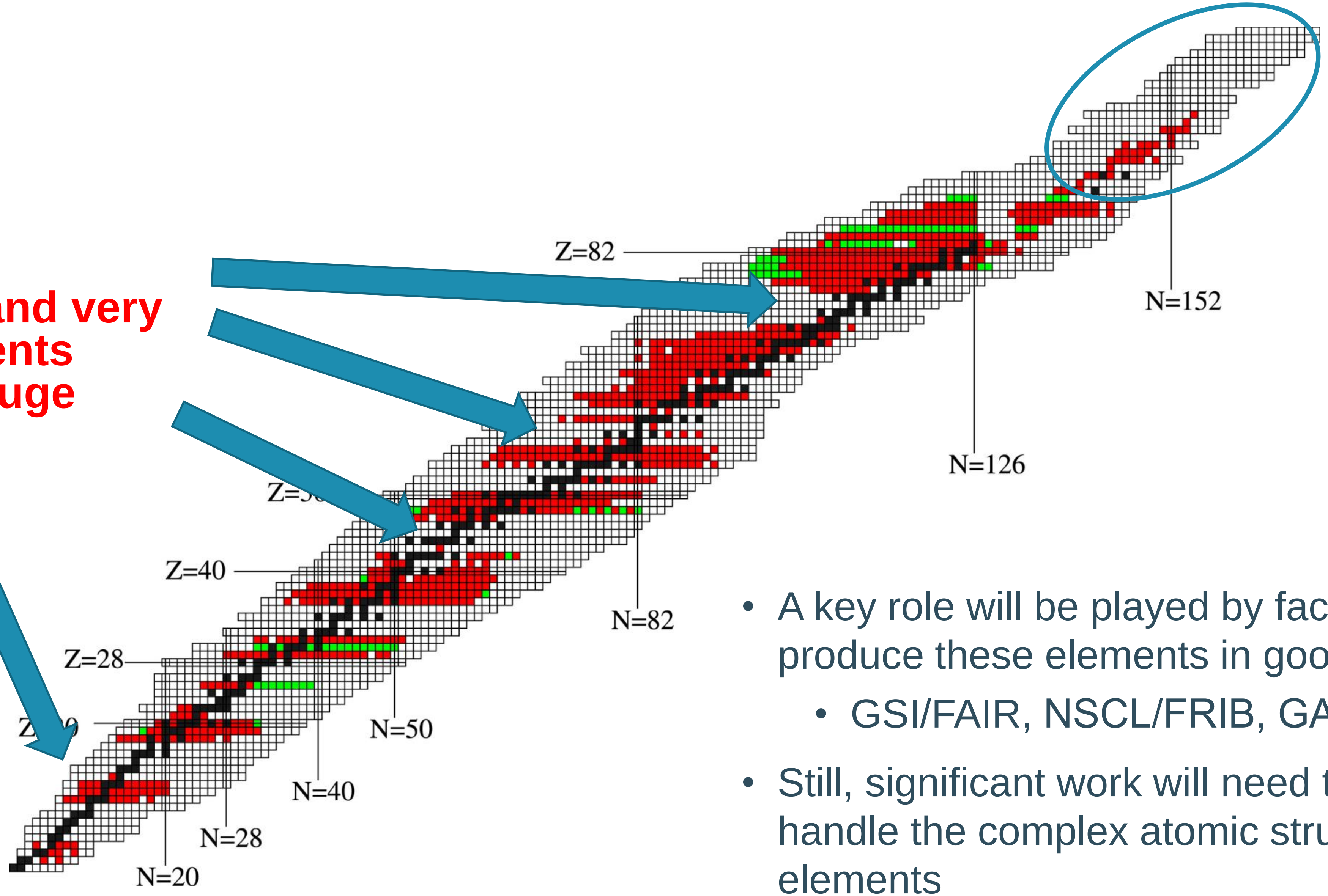
- Optical spectroscopy for nuclear structure research
- Pushing to lower production cross sections
  - in-source laser spectroscopy of silver
- When more precision is needed: collinear fast-beam laser spectroscopy
  - Laser spectroscopy of zinc
- When *even more* precision is needed: beyond conventional optical spectroscopy
  - Future directions?
- Missing third axis: elements which are difficult to extract, and/or have complex atomic structure

Predominantly collinear fast-beam experiments



In-source experiments

Refractory elements and very light elements remain a huge challenge



- A key role will be played by facilities who can produce these elements in good quantities!
    - GSI/FAIR, NSCL/FRIB, GANIL, …
- Still, significant work will need to be done to handle the complex atomic structure of these elements

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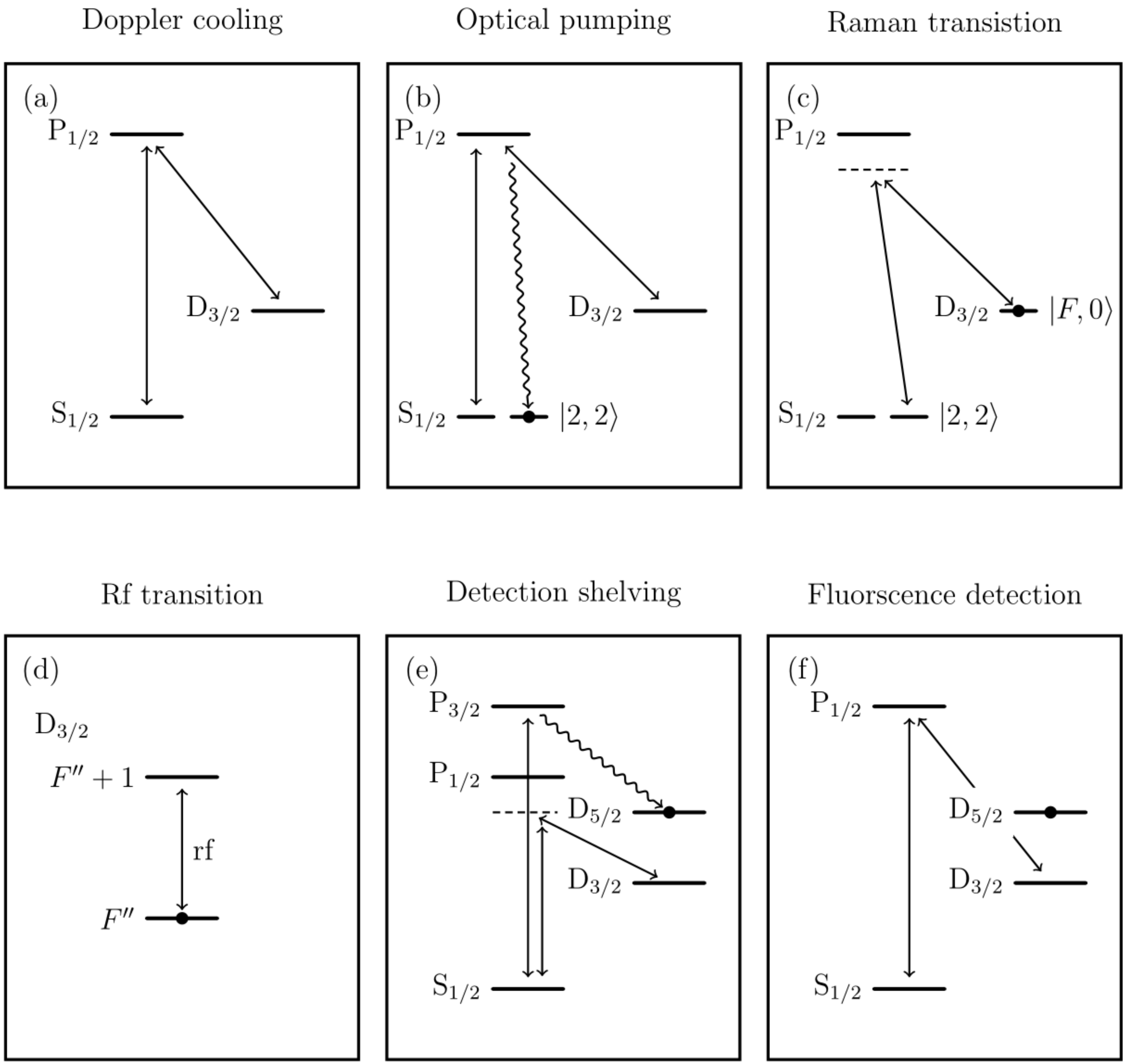
Doppler cooling
Optical pumping
Raman transistion
(a)
P1/2
D3/2
S1/2
(b)
P1/2
D3/2
S1/2
|2, 2⟩
(c)
P1/2
D3/2
|F, 0⟩
S1/2
|2, 2⟩
Rf transition
Detection shelving
Fluorscence detection
(d)
D3/2
F'' + 1
rf
F''
(e)
P3/2
P1/2
D5/2
D3/2
S1/2
(f)
P1/2
D5/2
D3/2
S1/2

Longer interaction times… trapping!

- Inject nuclei into an atom or ion trap
- Then, very long interaction times (seconds or more!) are possible
  - Drive forbidden optical transitions (linewidths << kHz)
  - Directly excite electrons within one atomic level
    (J, F, mF) → (J, $F^{(')}$, $m_F^{(')}$)

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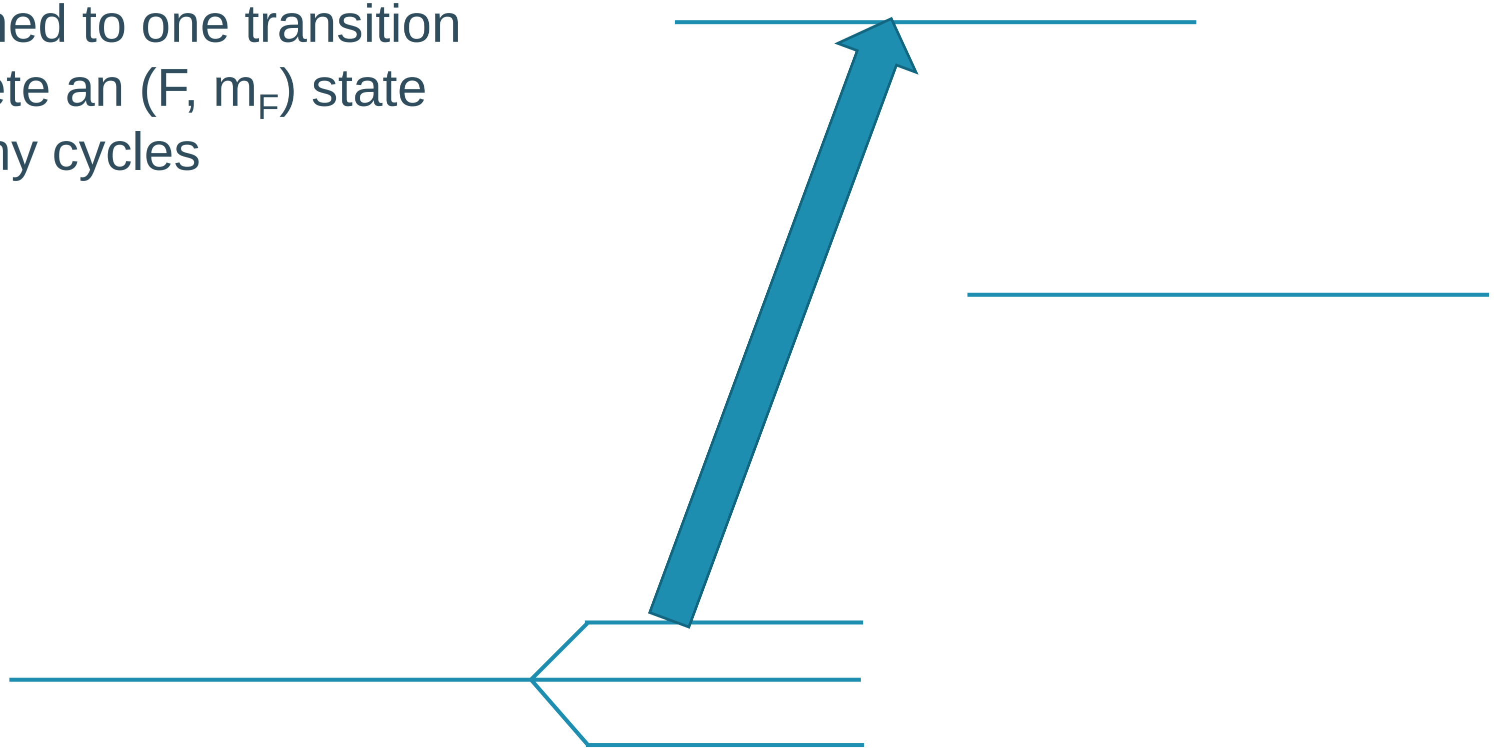
Longer interaction times… trapping!

Measurement principle:

- Laser tuned to one transition will deplete an (F, m_F) state after many cycles



KU LEUVEN

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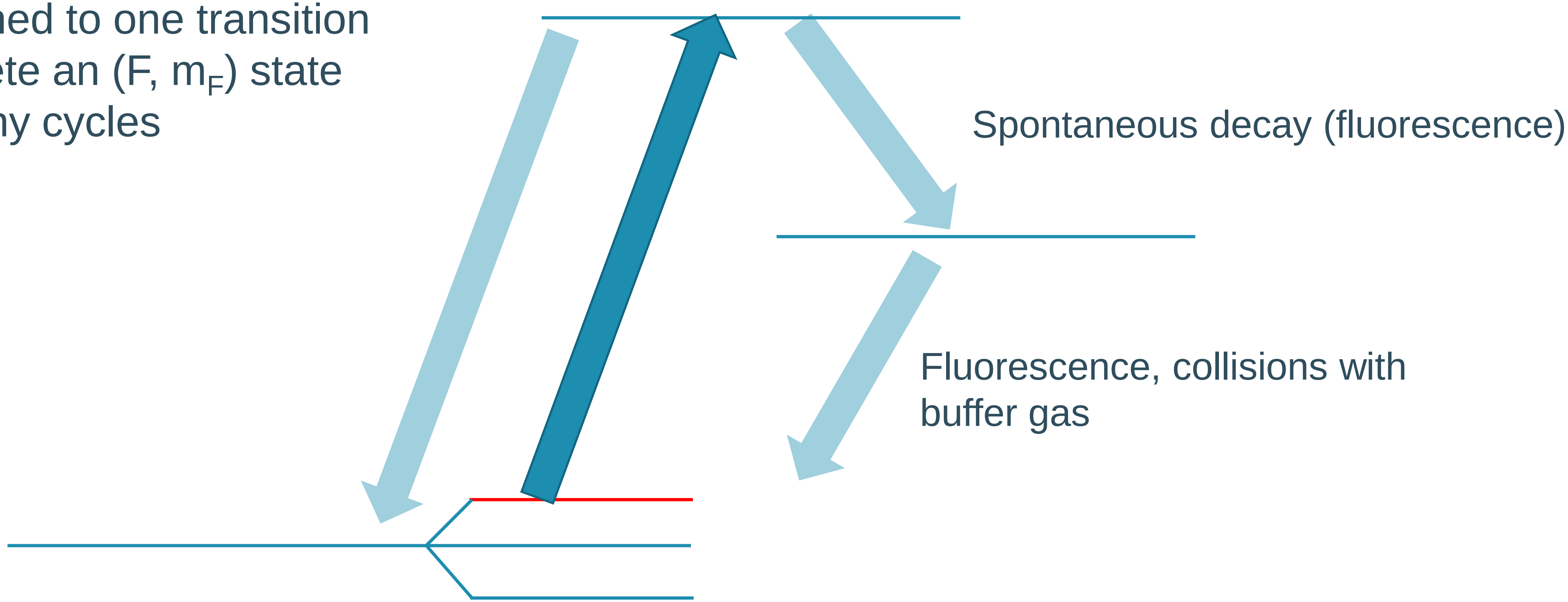
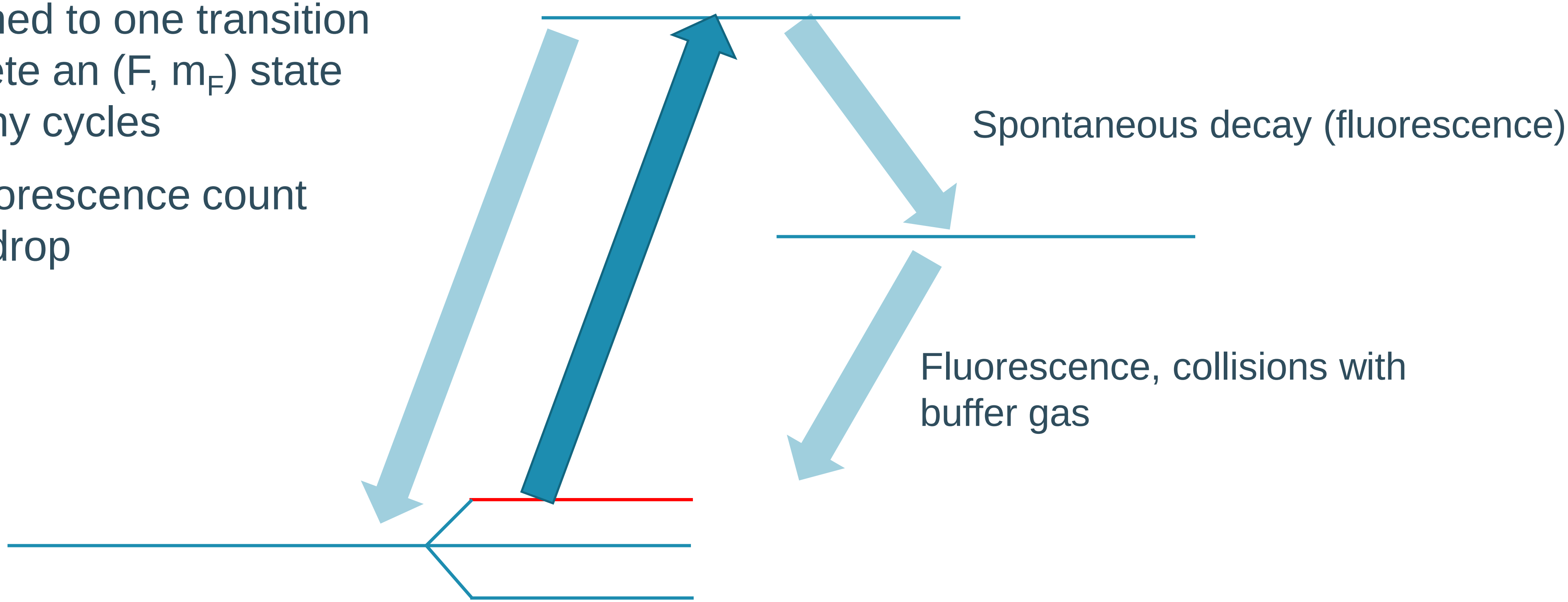


Longer interaction times… trapping!

Measurement principle:

- Laser tuned to one transition will deplete an (F, m_F) state after many cycles
- Thus, fluorescence count rate will drop



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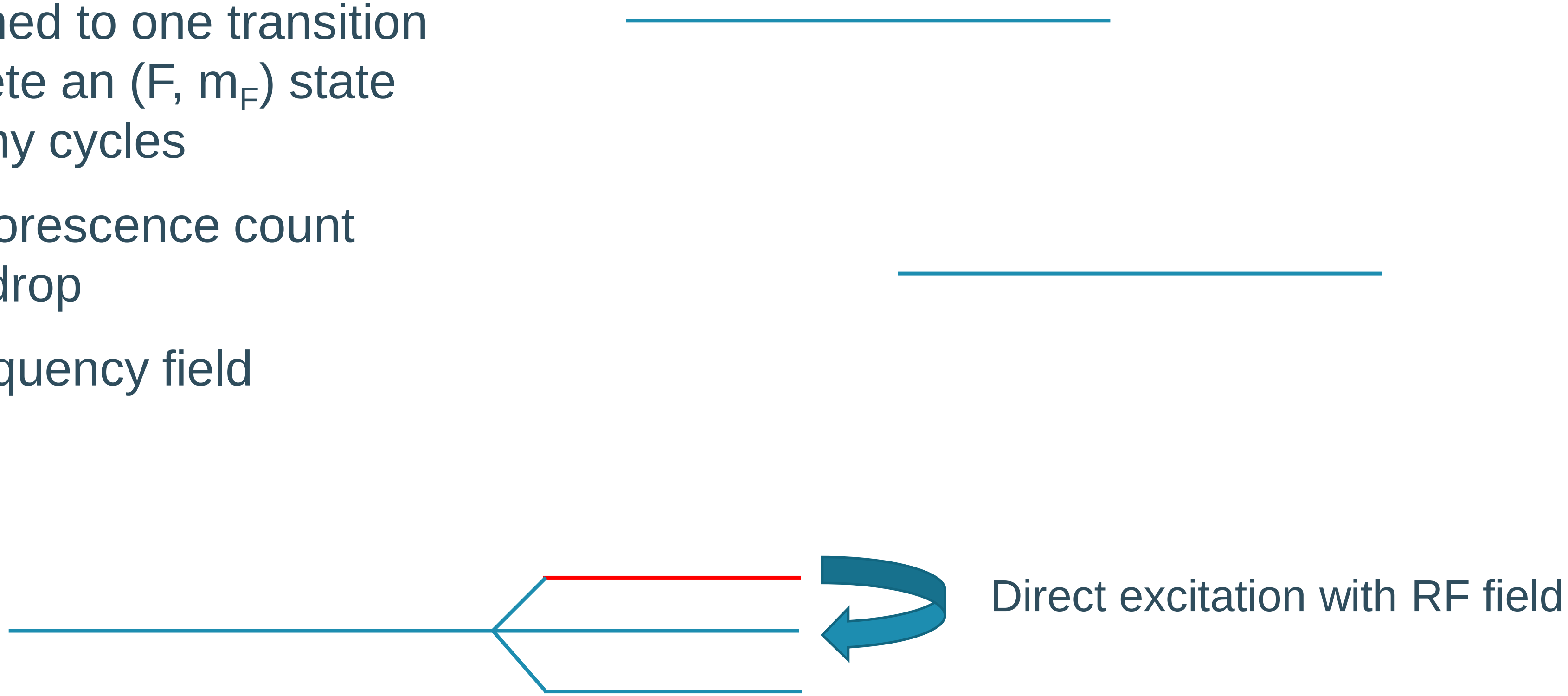
Longer interaction times… trapping!

Measurement principle:

- Laser tuned to one transition will deplete an (F, m_F) state after many cycles
- Thus, fluorescence count rate will drop
- Radiofrequency field



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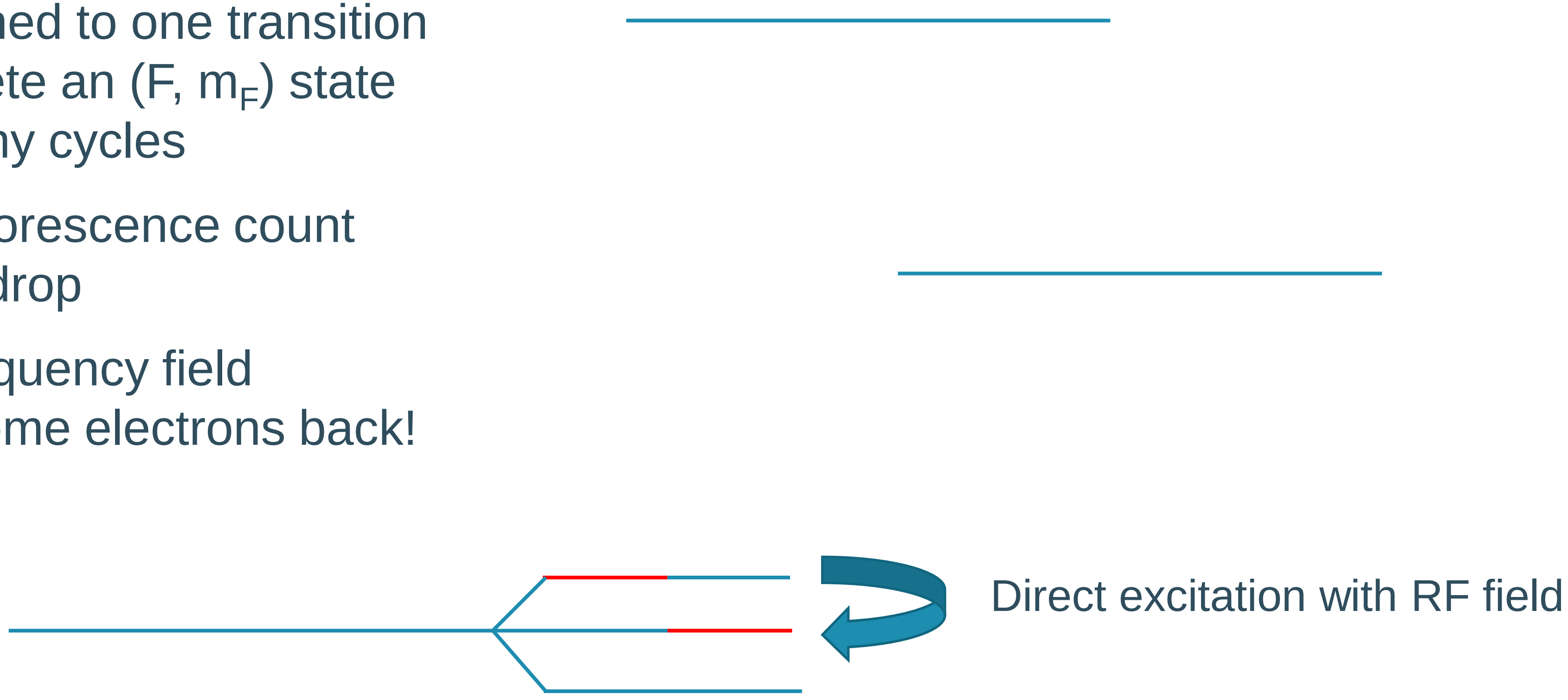
Longer interaction times… trapping!

Measurement principle:

- Laser tuned to one transition will deplete an (F, m_F) state after many cycles
- Thus, fluorescence count rate will drop
- Radiofrequency field brings some electrons back!



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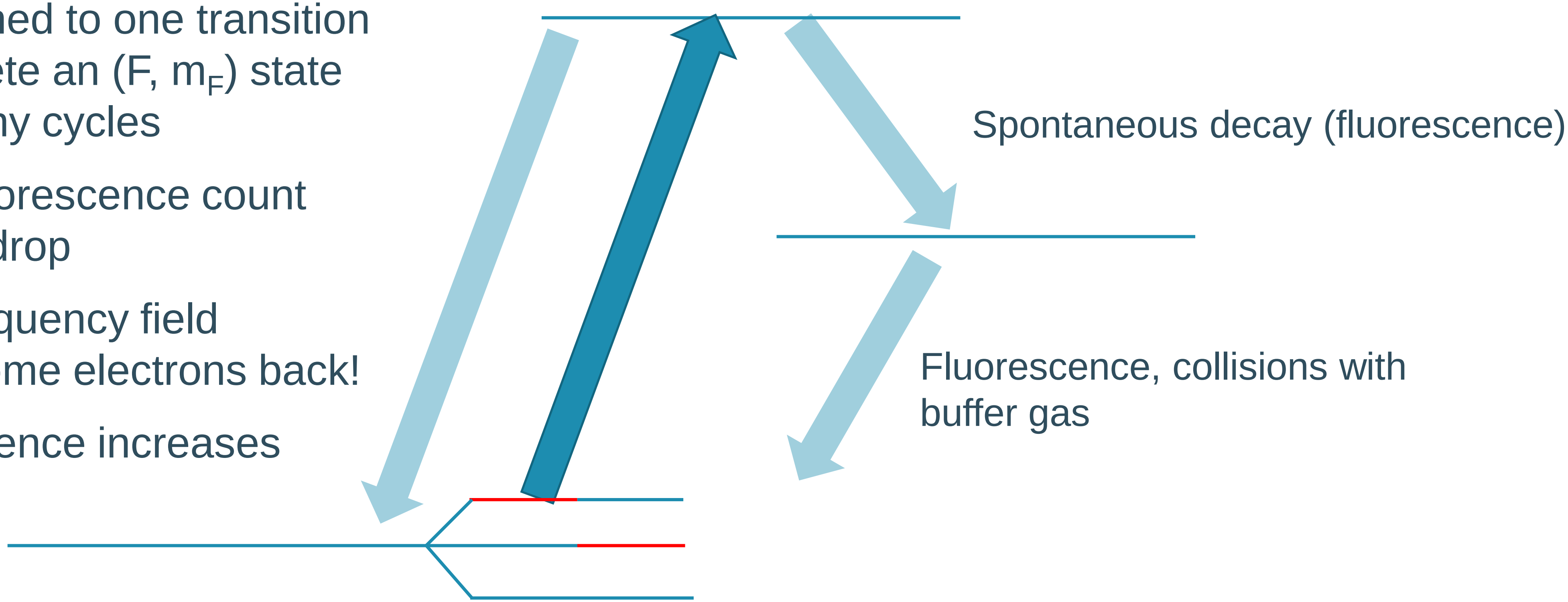
Longer interaction times… trapping!

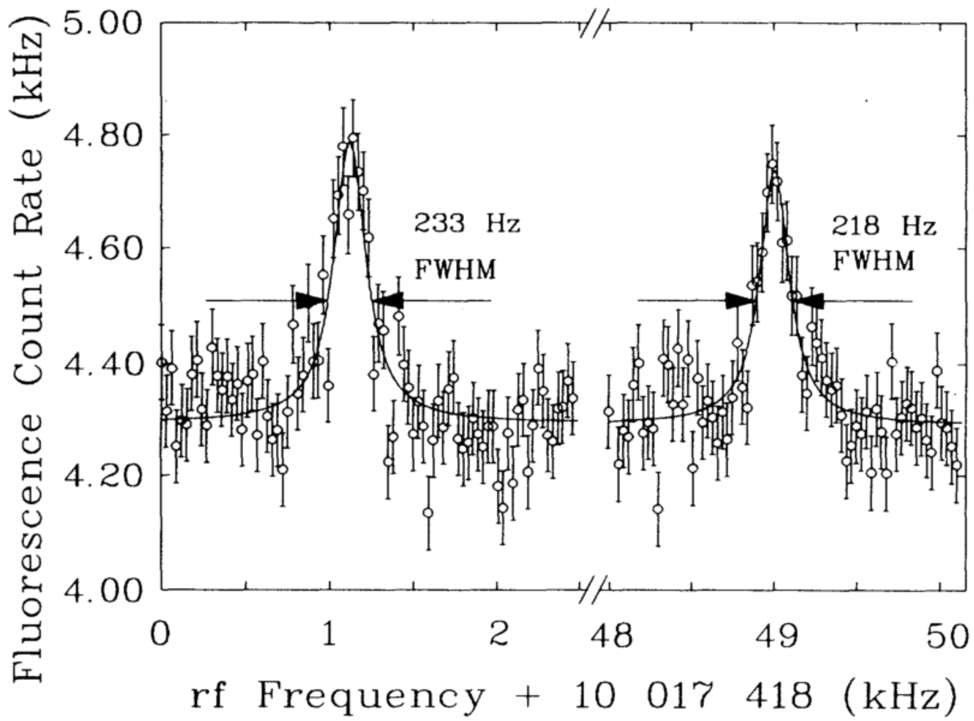
Measurement principle:

- Laser tuned to one transition will deplete an (F, m_F) state after many cycles
- Thus, fluorescence count rate will drop
- Radiofrequency field brings some electrons back!
- Fluorescence increases



Translation of a radiofrequency excitation into an optical signal!
RF on resonance => photons emitted by fluorescence

Longer interaction times… trapping!



O. Becker et al, PRA 48, 5 1993

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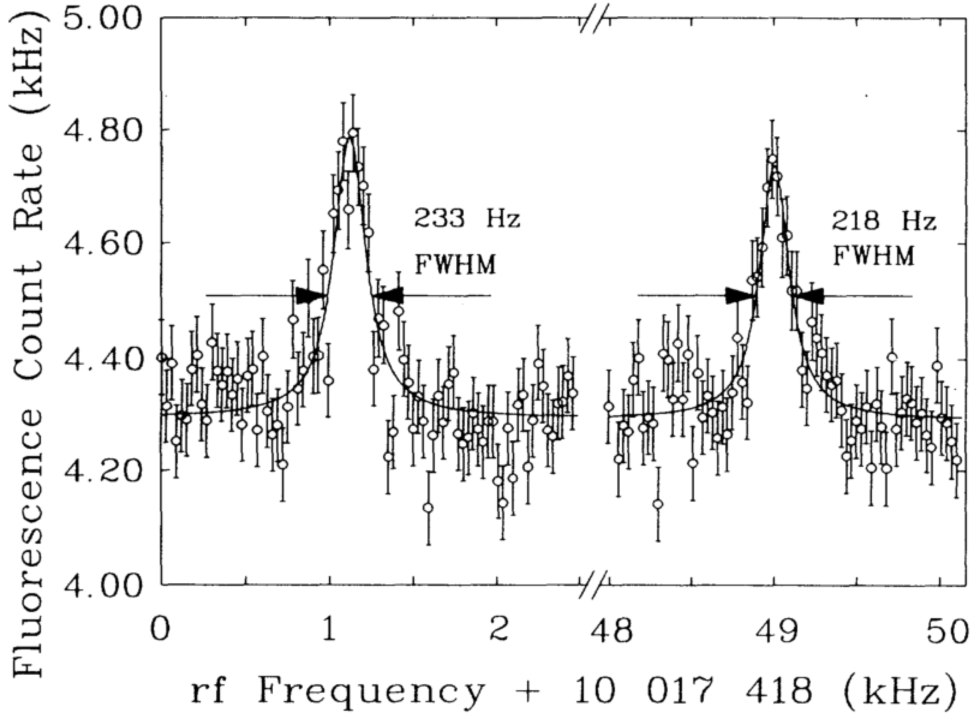
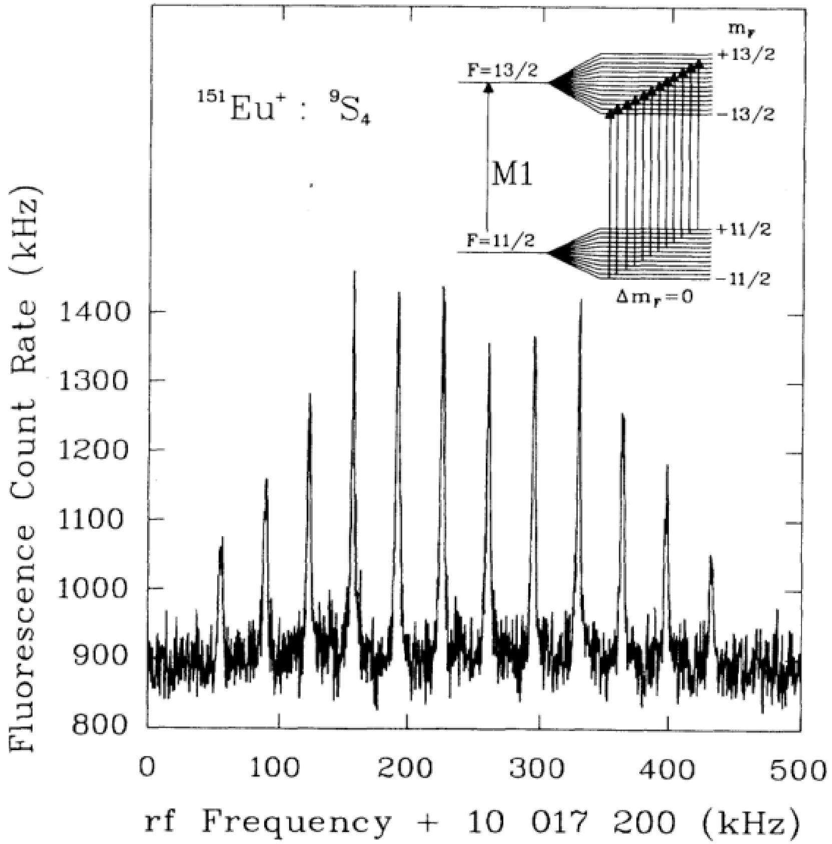
Longer interaction times… trapping!





Add external B-field: resolve Zeeman splitting
Count the peaks, determine nuclear spin…

O. Becker et al, PRA 48, 5 1993

Longer interaction times… trapping!

- Is it all worth the effort?

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