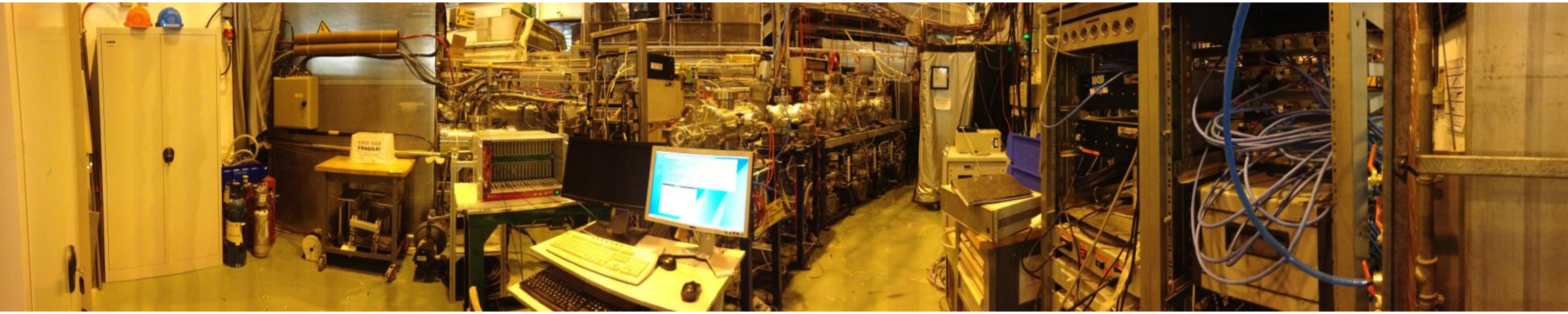
Interesting moments at CRIS this year

Kara M. Lynch
CERN Research Fellow

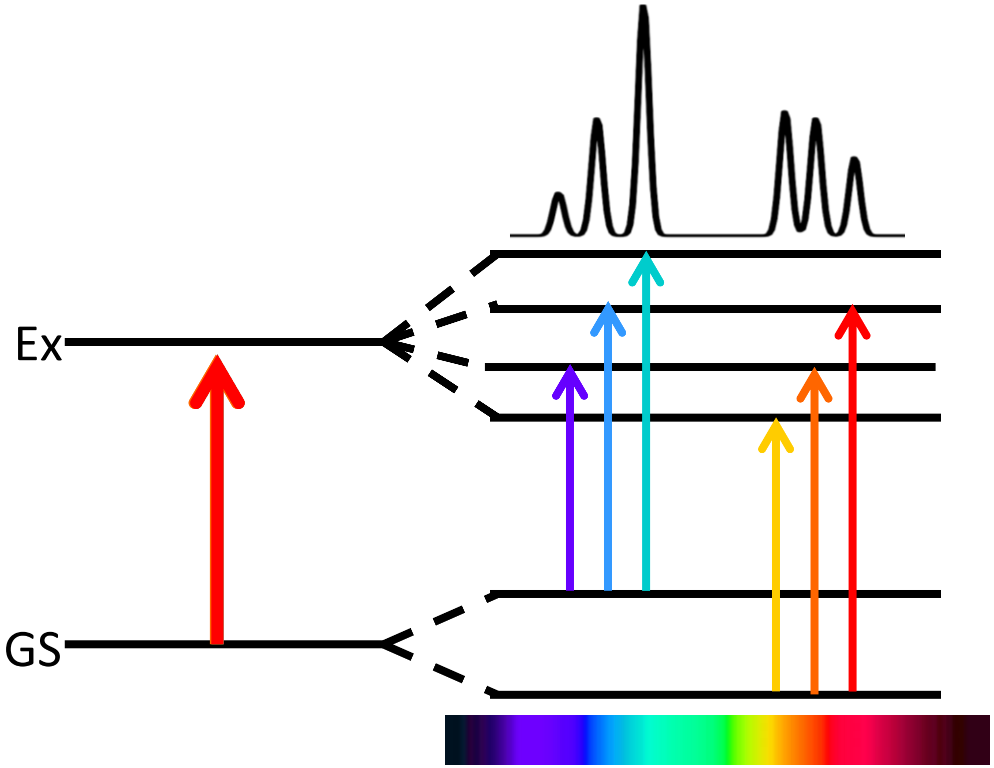
Outline

- Good moments: events that have improved the CRIS setup
  - Achieving high resolution
  - Installation of M2 laser system
  - Installation of Lee laser and Ti:Sa cavities
  - Upgrade of beam line monitoring devices

- Electromagnetic moments: the physics results from such improvements
  - Copper experiment
  - Gallium experiment
  - Francium experiment



Laser spectroscopy



- Probe the hyperfine structure of the energy levels of the electron
  - Scan the laser frequency of the resonant transition
- Nuclear observables extracted with model-independence:

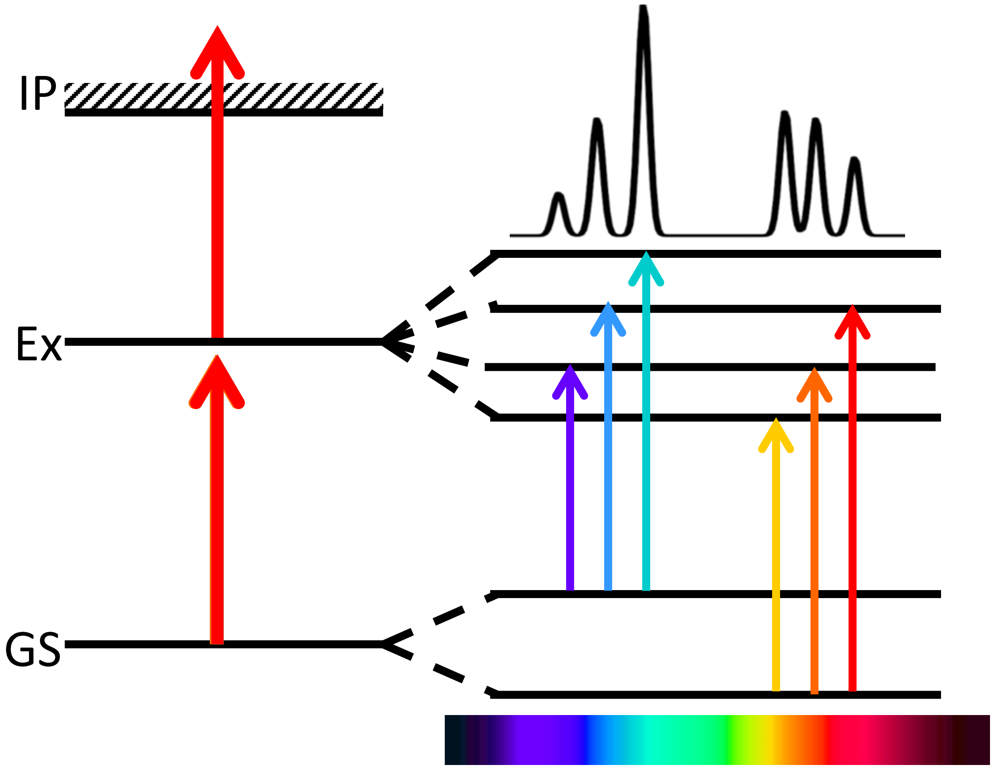
Change in mean square charge radii $\delta\langle r^2 \rangle^{A,A'}$

Magnetic dipole moment μ_I

Electric quadrupole moment Q_S

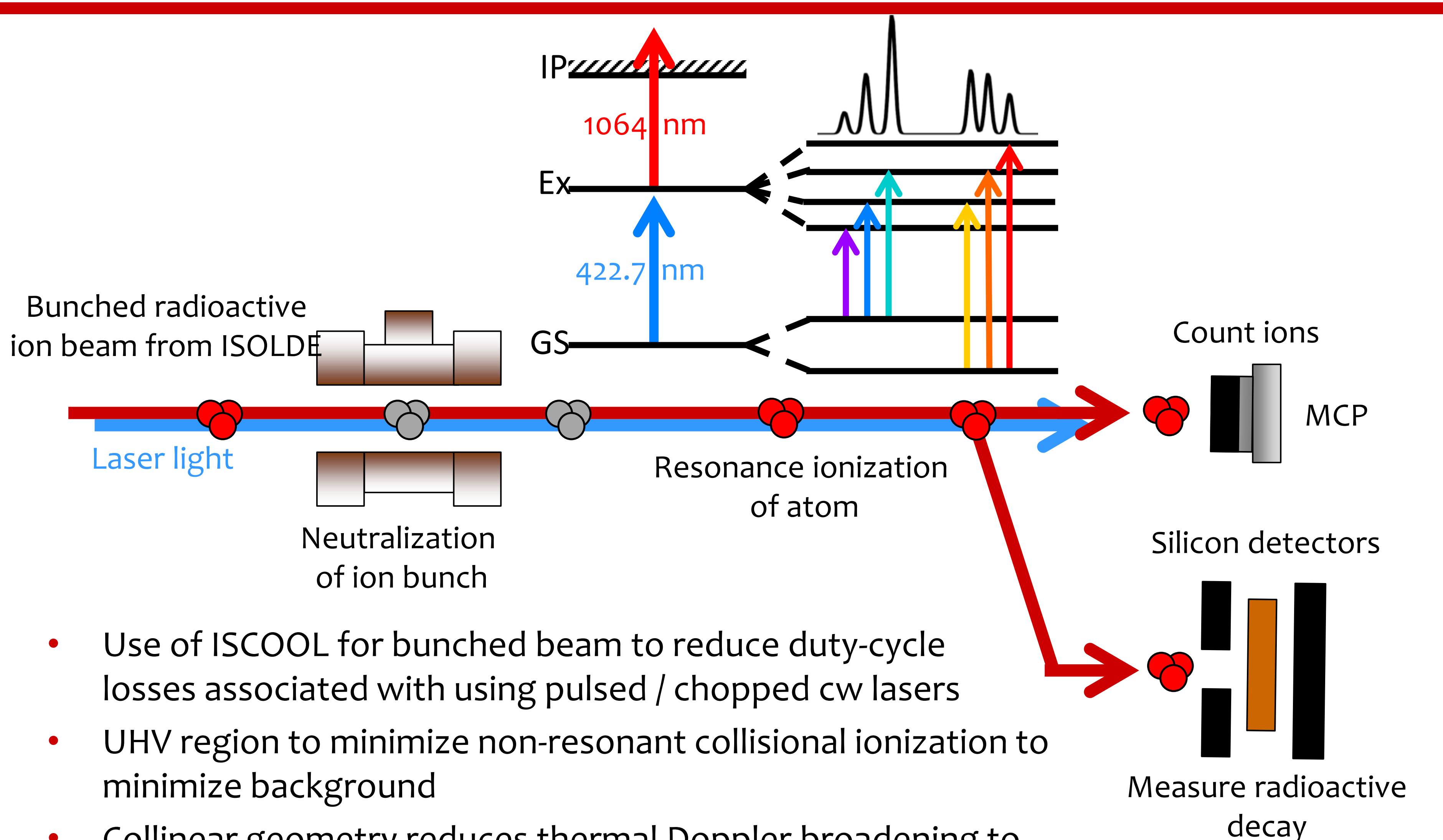
Nuclear spin I

Resonance ionization spectroscopy



- Resonant excitation is followed by an ionization step into the continuum
- When the laser frequency is on resonance with a hyperfine transition, the isotope is resonantly ionized
  - Resonance ionization selects the isotope of interest

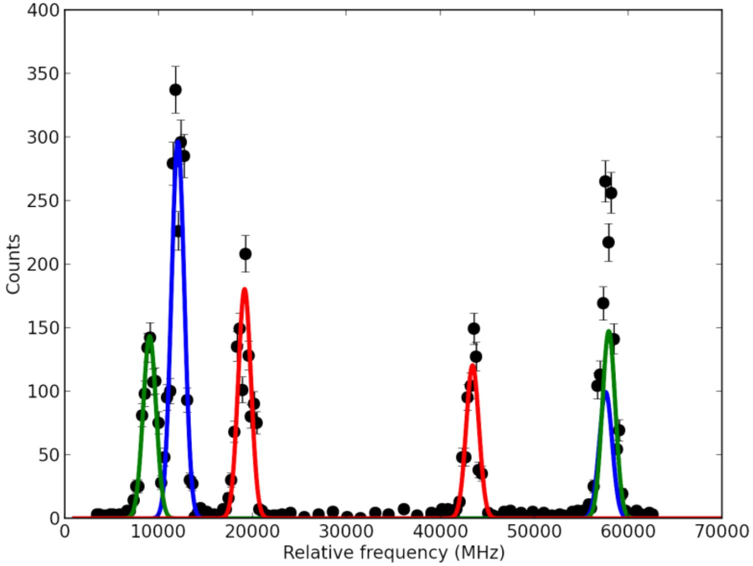
The CRIS technique

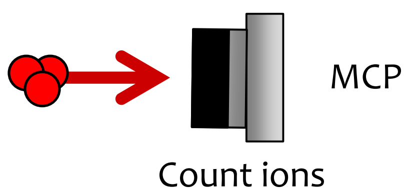


- Use of ISCOOL for bunched beam to reduce duty-cycle losses associated with using pulsed / chopped cw lasers
- UHV region to minimize non-resonant collisional ionization to minimize background
- Collinear geometry reduces thermal Doppler broadening to below natural linewidth of the hyperfine transition (GHz to MHz)

The CRIS technique

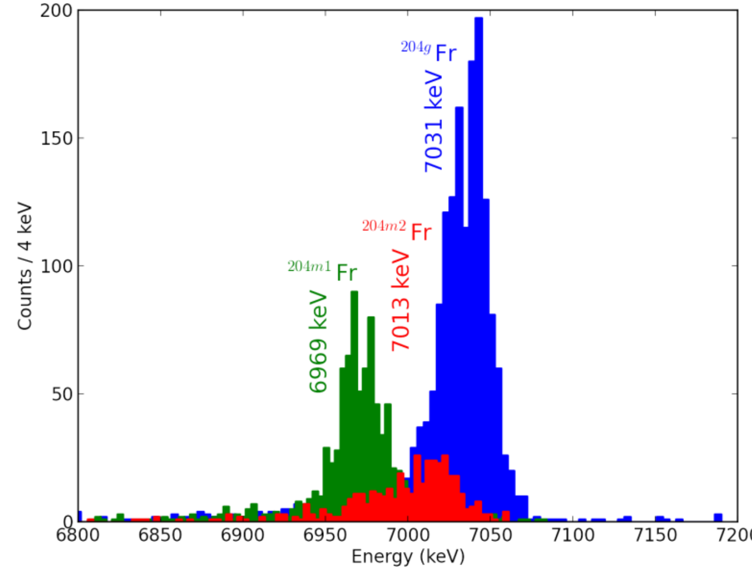
Collinear resonance ionization spectroscopy

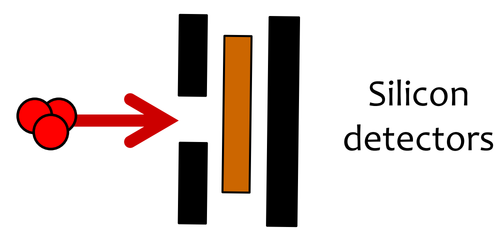




- Sensitivity of technique comes from:
  - Detection of resonant ions
  - Efficient laser ionization
  - Almost background free detection

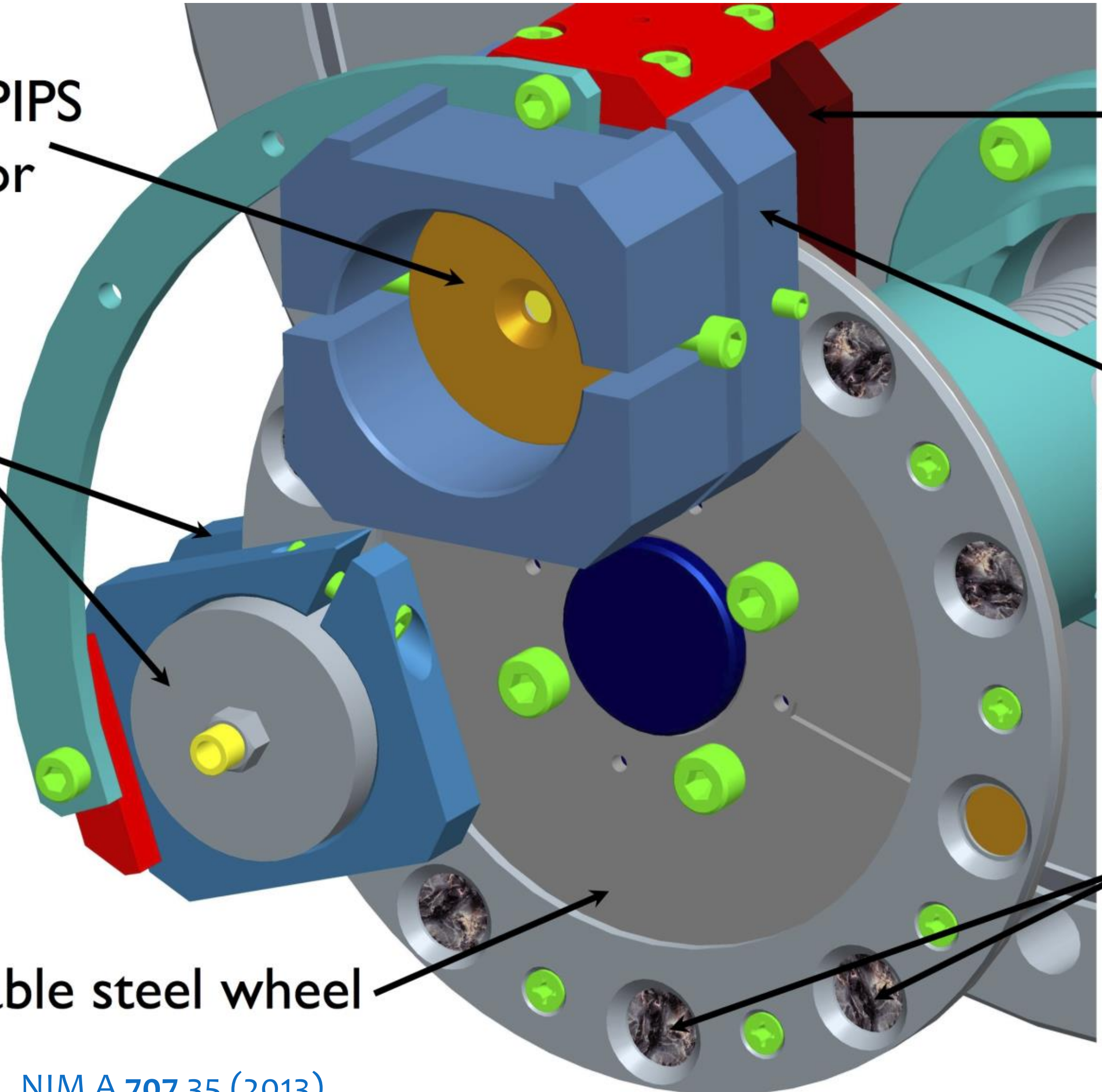
Laser-assisted nuclear decay spectroscopy





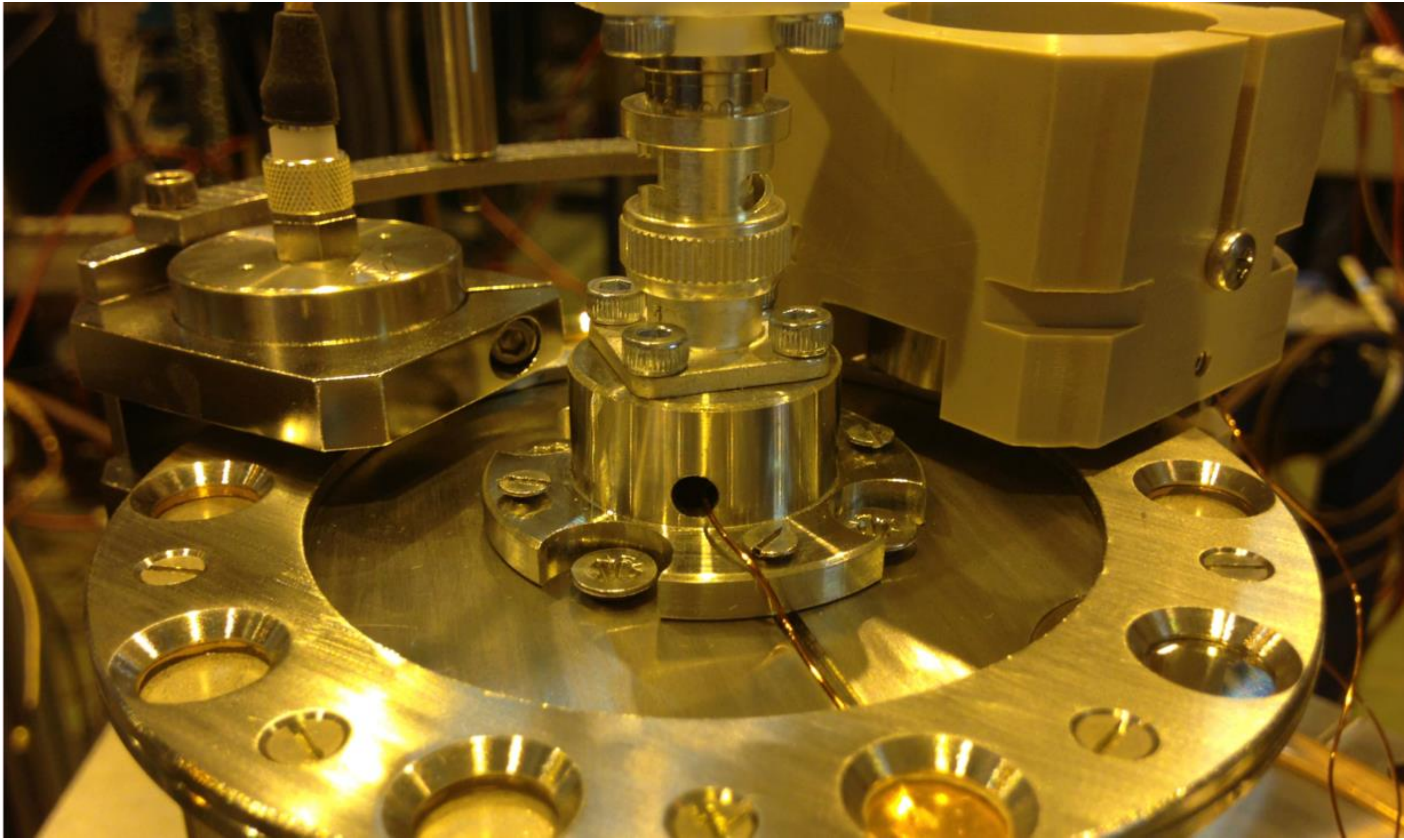
- Implantation of the resonant ions in a carbon foil allows their radioactive decay to be measured
- Provides additional information on the isotope (or isomer) under investigation

The Decay Spectroscopy Station



M.M. Rajabali *et al.*, NIM A **707** 35 (2013)
K.M. Lynch *et al.*, J. Phys.: Conf. Ser. **381** 1 012128 (2012)

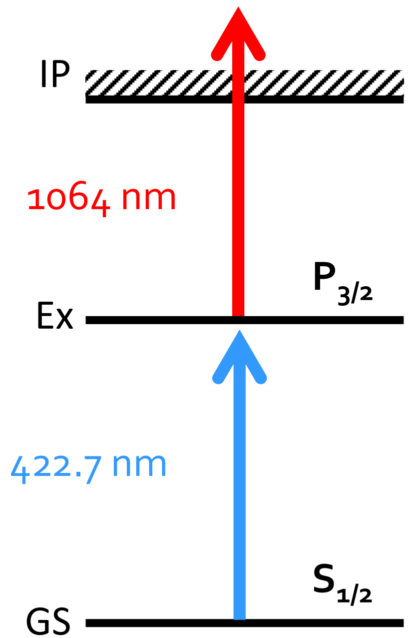
The Decay Spectroscopy Station



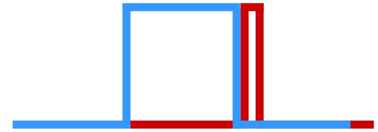
Achieving higher resolution

- Initial Fr experiment used RILIS narrow-band Ti:Sa laser for the 422 nm resonant step
  - Linewidth of 1.5 GHz achieved
  - Enough to resolve lower-state splitting only
    - Extraction of magnetic dipole moments
- New laser system produced frequency-doubled light from COLLAPS’ Matisse Ti:Sa CW laser

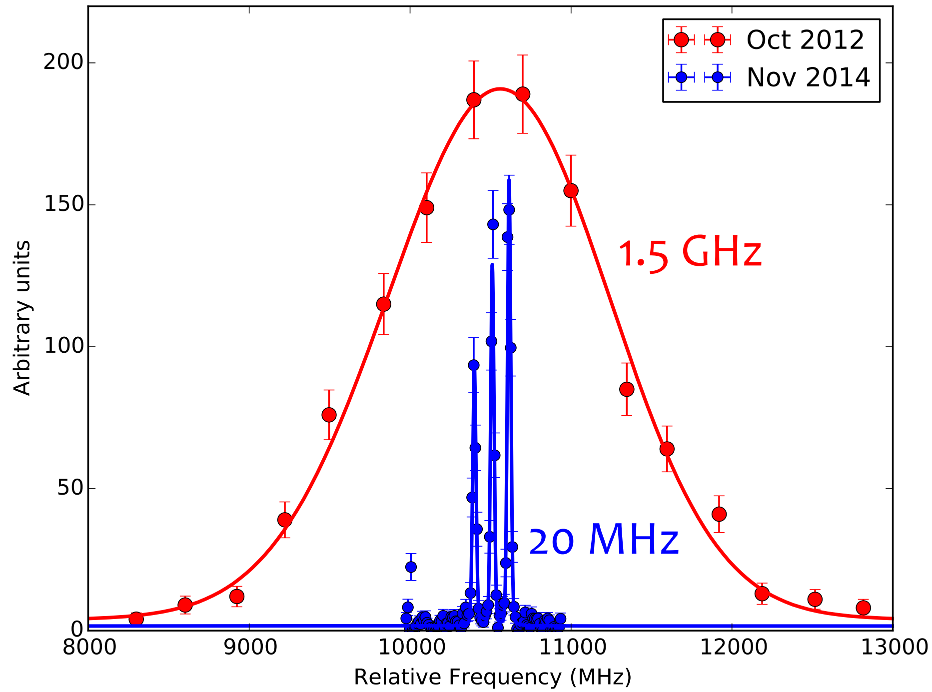
R.P. de Groote, Phys. Rev. Lett. 115 132501 (2015)

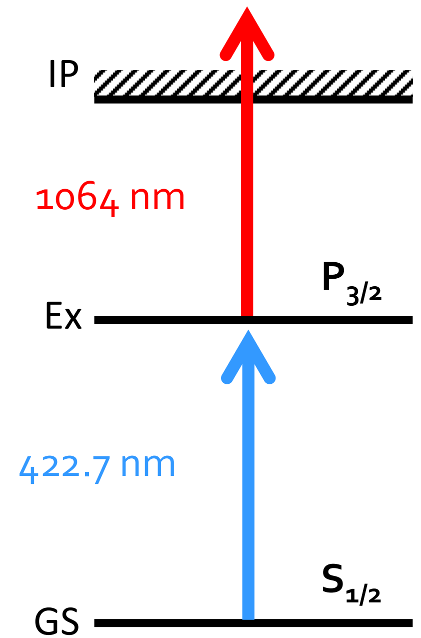


- The 422 nm CW laser light from the Matisse Ti:Sa laser was chopped into pulses of 100 ns
- The 1064 nm ionization step was delayed by 100 ns after start of the 422 nm excitation step
  - Linewidths down to 20 MHz were achieved
  - Upper-state splitting could now be resolved
    - Extraction of quadrupole moments

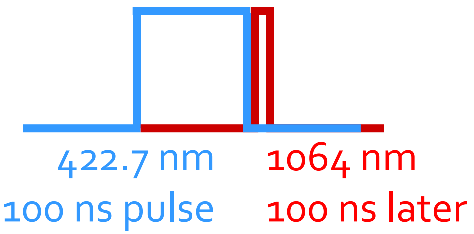


Achieving higher resolution

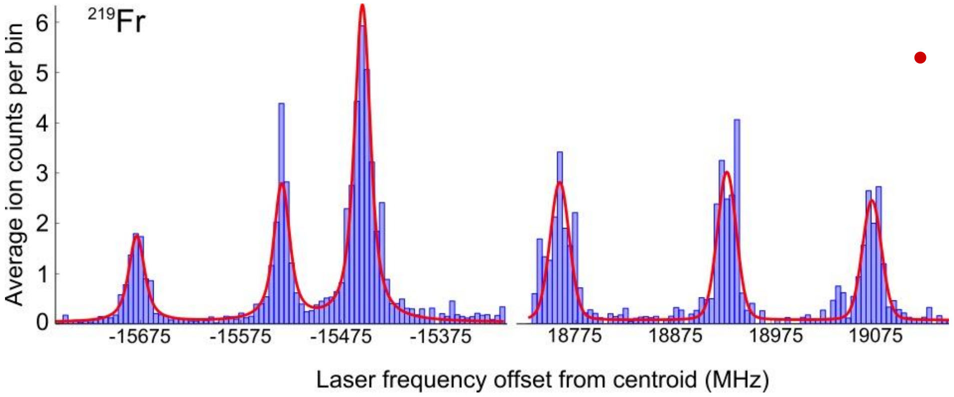




- The 422 nm CW laser light from the Matisse Ti:Sa laser was chopped into pulses of 100 ns
- The 1064 nm ionization step was delayed by 100 ns after start of the 422 nm excitation step
  - Linewidths down to 20 MHz were achieved
  - Upper-state splitting could now be resolved
    - Extraction of quadrupole moments



Poster: Recent results on francium isotopes at the CRIS setup

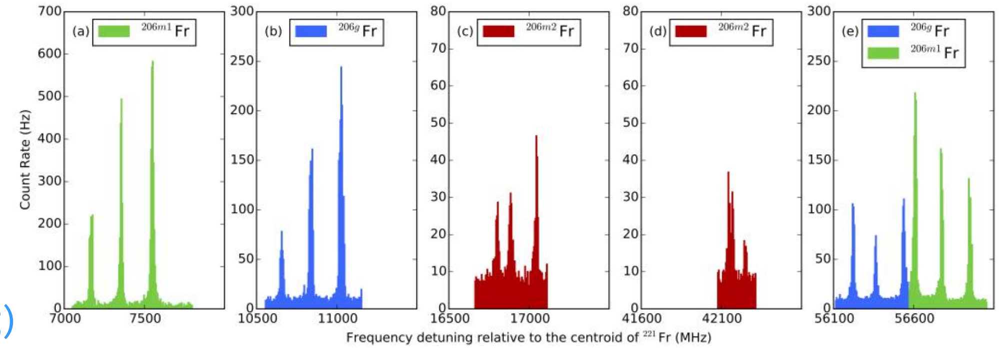


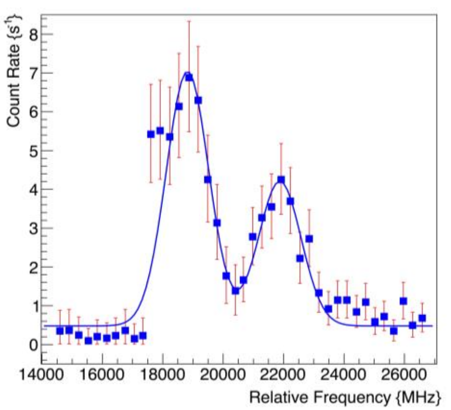
- Quadrupole moment of ^{219}Fr extracted
  - Qs = -1.21(2) eb
  - Linewidth of 20(1) MHz

R.P. de Groote et al., Phys. Rev. Lett. **115** 132501 (2015)

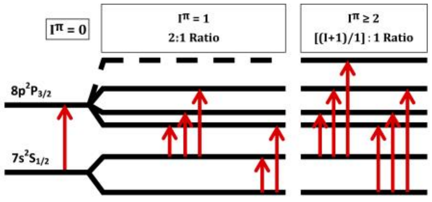
- Hyperfine parameters of $3^{(+)}$, $7^{(+)}$ and $10^{(-)}$ states of ^{206}Fr measured
- Laser-assisted nuclear decay spectroscopy performed on each state
  - Branching ratios of ^{206}Fr and ^{202}At

K.M. Lynch et al., Phys. Rev. C, Submitted (2015)





- Hyperfine structure of ^{214}Fr
  - Shortest-lived isotope (t1/2 = 5 ms) measured with laser spectroscopy on-line
  - Possible due to 200 Hz repetition rate pulsed laser

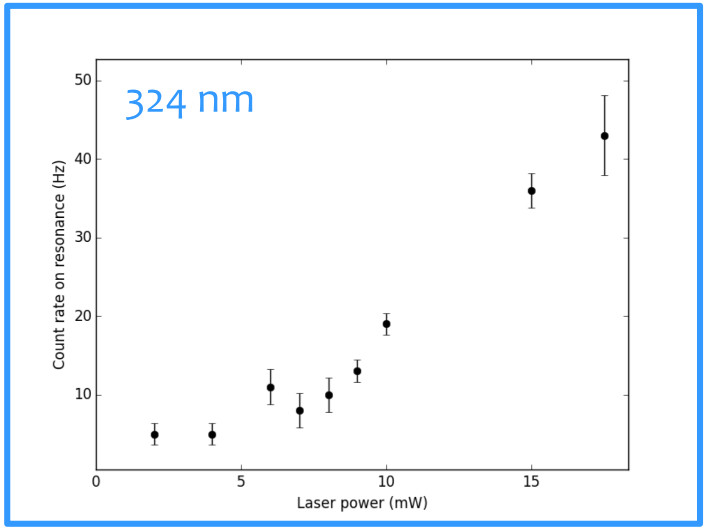


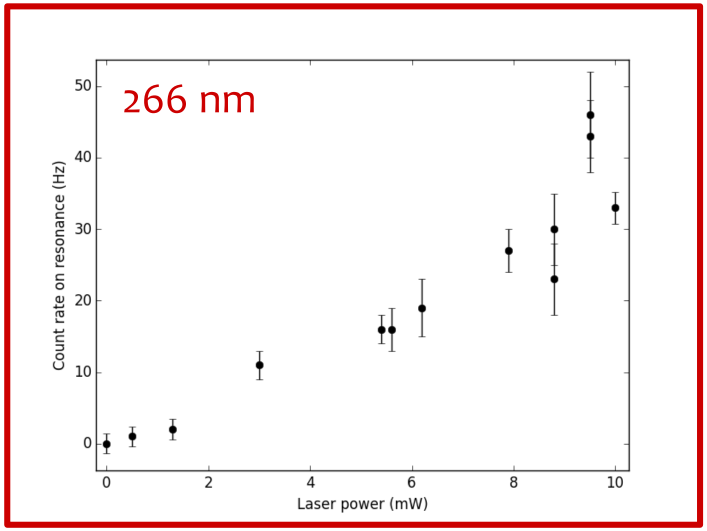
G.J. Farooq-Smith et al., In preparation (2016)

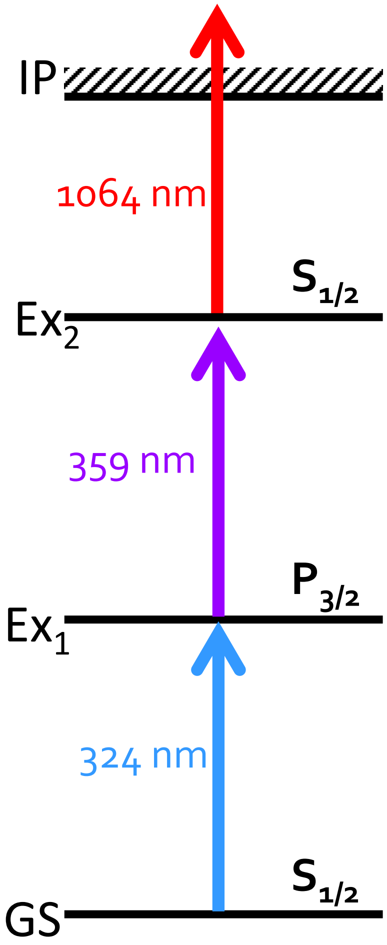
CRIS

IS531: Copper experiment

- Neutron-rich copper isotopes with 1 p outside Z=28 towards N=50
  - Study of the evolution of the shell model with neutron excess
- Litron laser needed to produce 359 nm and 1064 nm broke a week before the experiment
  - RILIS lent us a 20 Hz laser which allowed us to use a different RIS scheme with 266 nm light
- Laser ionization efficiency was only 0.01 %
  - We were not saturated in either step due to the low power of each laser

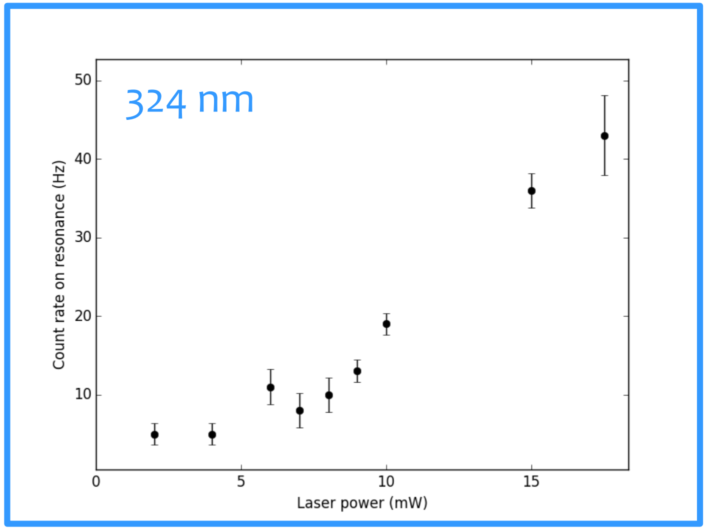


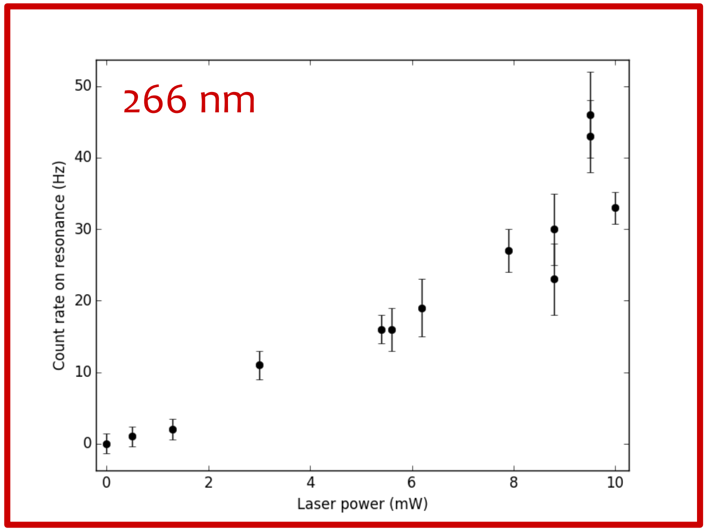


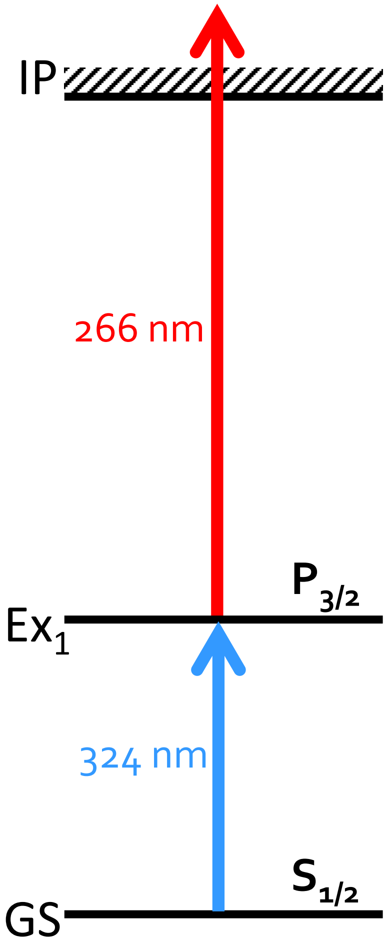


IS531: Copper experiment

- Neutron-rich copper isotopes with 1 p outside Z=28 towards N=50
  - Study of the evolution of the shell model with neutron excess
- Litron laser needed to produce 359 nm and 1064 nm broke a week before the experiment
  - RILIS lent us a 20 Hz laser which allowed us to use a different RIS scheme with 266 nm light
- Laser ionization efficiency was only 0.01 %
  - We were not saturated in either step due to the low power of each laser





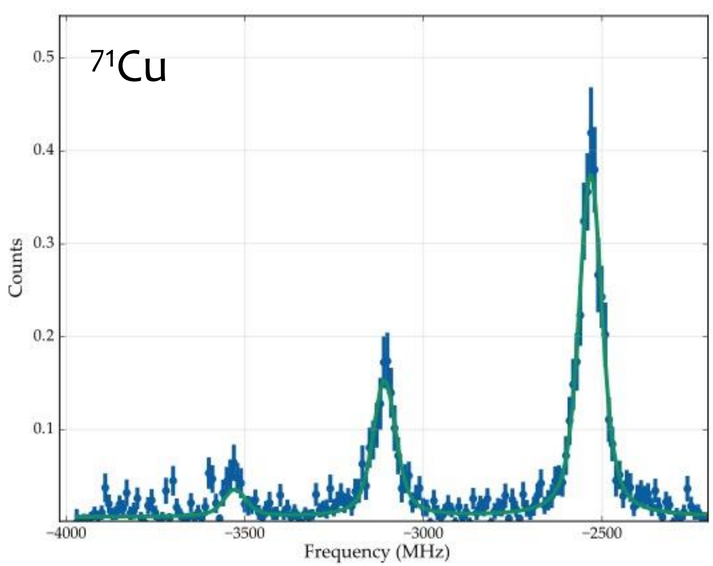


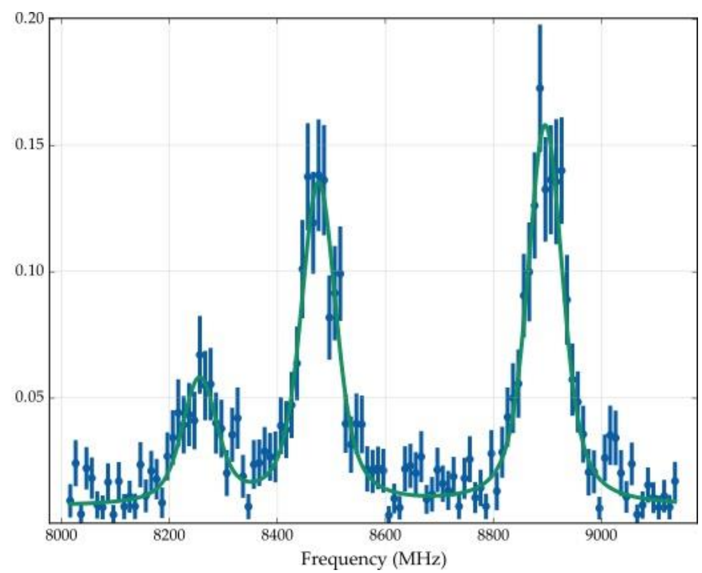
IS531: Copper experiment

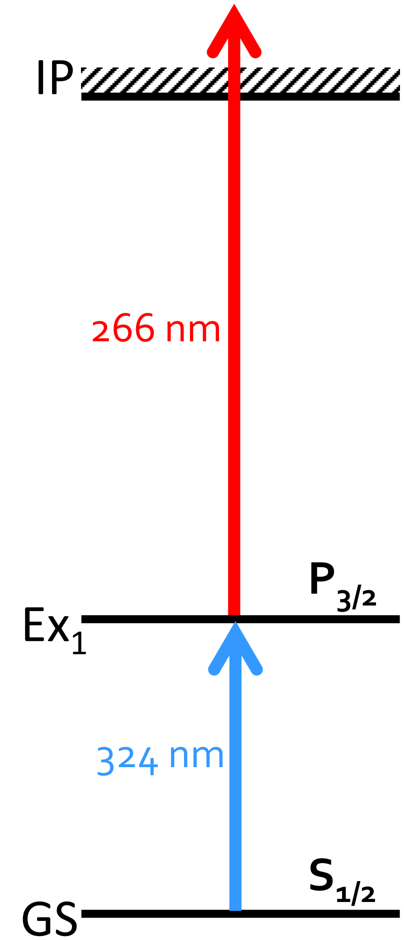
- Limited the exotic isotopes we could measure
  - ^{63}Cu, ^{65}Cu ,^{69}Cu, ^{71}Cu

- Commissioned new Matisse dye laser producing 324 nm light
- Verified that the chopped cw light method worked
  - Achieved resolution of 75 MHz

- Plans to test original and new RIS schemes to find most efficient scheme

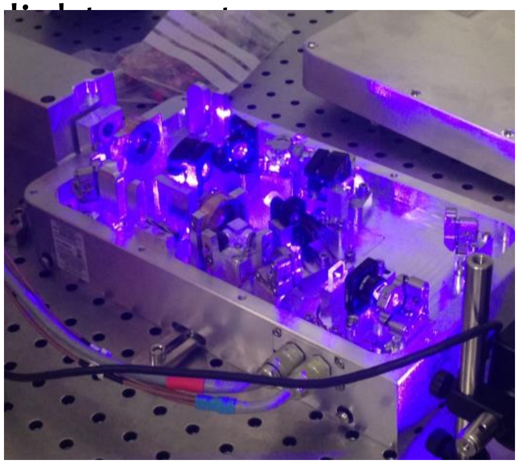






Installation of a new laser system

- Installation of new high-powered, narrow linewidth M2 laser system with large tuning range
  - Sprout pump laser (18 W)
  - SolsTiS Ti:Sa cavity (6 W)
  - ECD-X external frequency doubling cavity (1.5 W)
- Produce

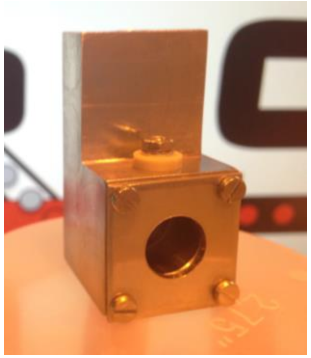


- Laser is remote controlled via network
- Scanning software written and integrated into our data acquisition and control software CRISTAL

T.E. Cocolios et al., NIM B, In Press (2015)

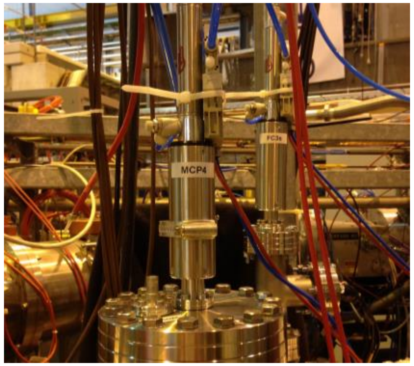
IS571: Gallium experiment

- Commissioning a new laser system
  - New M2 laser system produced 417 nm light
  - Fixed Litron laser produced 1064 nm light
  - Also pumped PDL to produce 639 nm light
- Commissioning new beam-tuning devices
  - New suppressed Faraday cups (with pneumatic control) installed to replace non-suppressed cups on a manual drive
  - New segmented Faraday cup was used to ensure optimum overlap of atom beam with laser beam
  - New MCP was placed closer to interaction region for higher detection/transmission efficiency

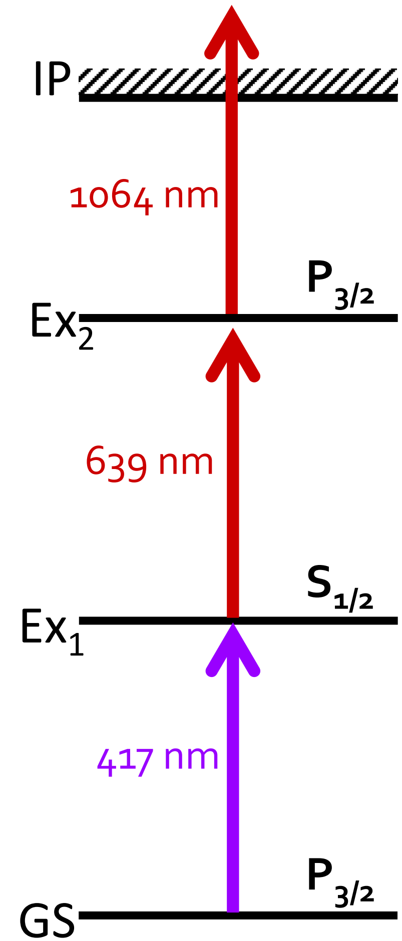


Suppressed FC

Segmented FC

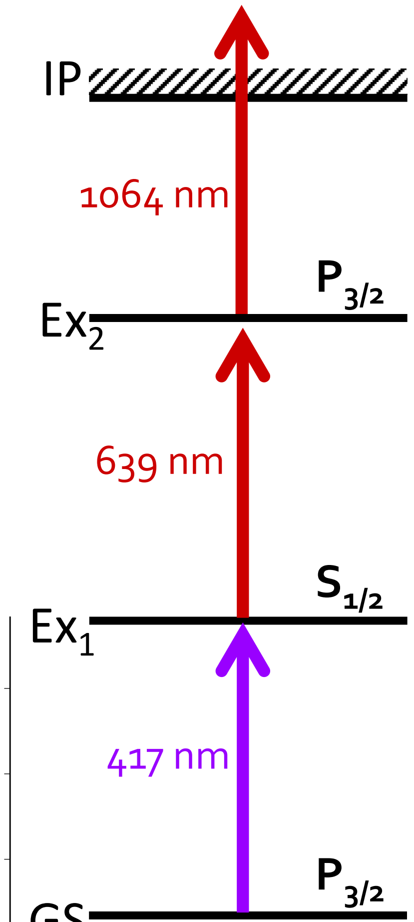


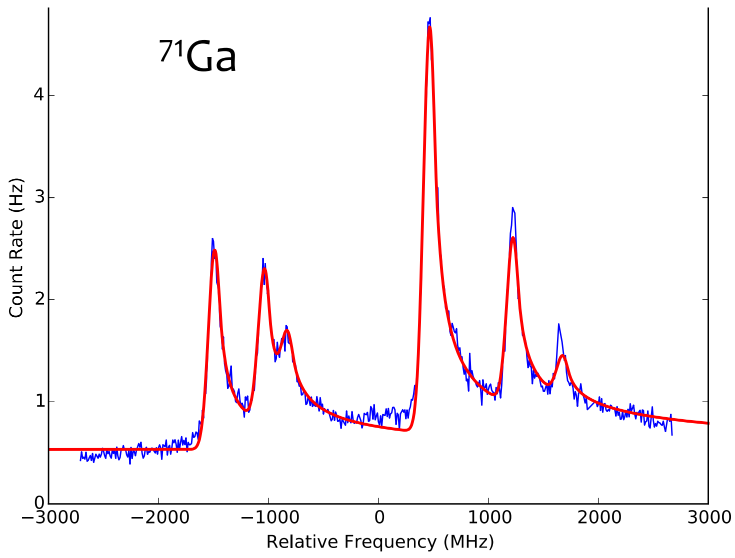
MCP for ion detection

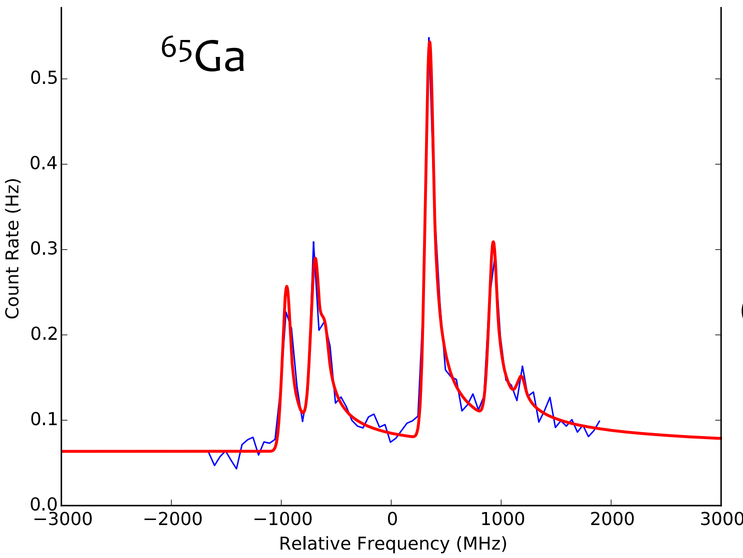


IS571: Gallium experiment

- Study the stability of the nuclear structure beyond the N=50 and Z=28 shell closures
  - Changes in nuclear configuration due to polarization of the core
  - Neutron rich: ^{75}Ga,^{79}Ga,^{80}Ga,^{81}Ga,^{82}Ga
  - Neutron deficient: ^{65}Ga,^{67}Ga
- Neutralization of only 5% - limited our efficiency
- Asymmetric peaks fitted with CrystalBall function
  - Resolution of ~40 MHz
- Data analysis still on going

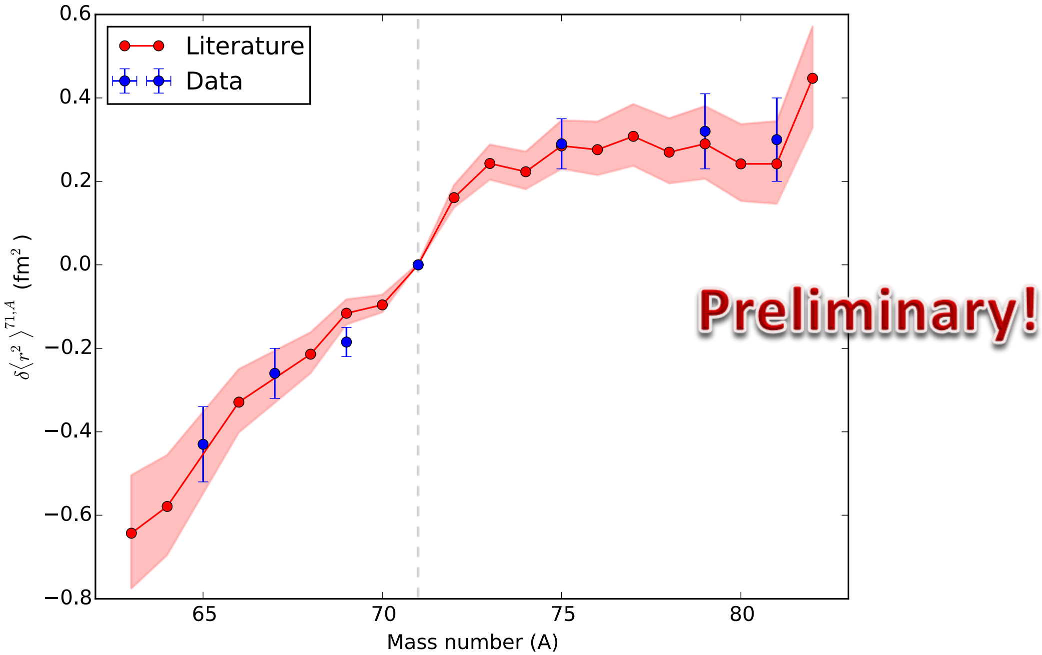


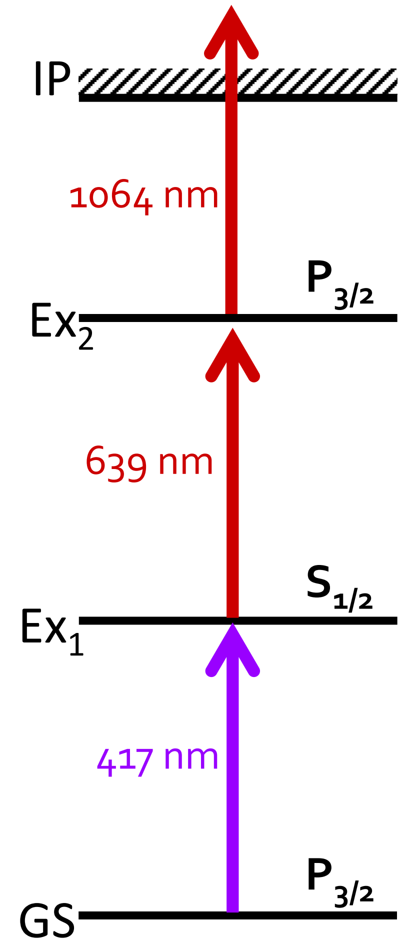




IS571: Gallium experiment

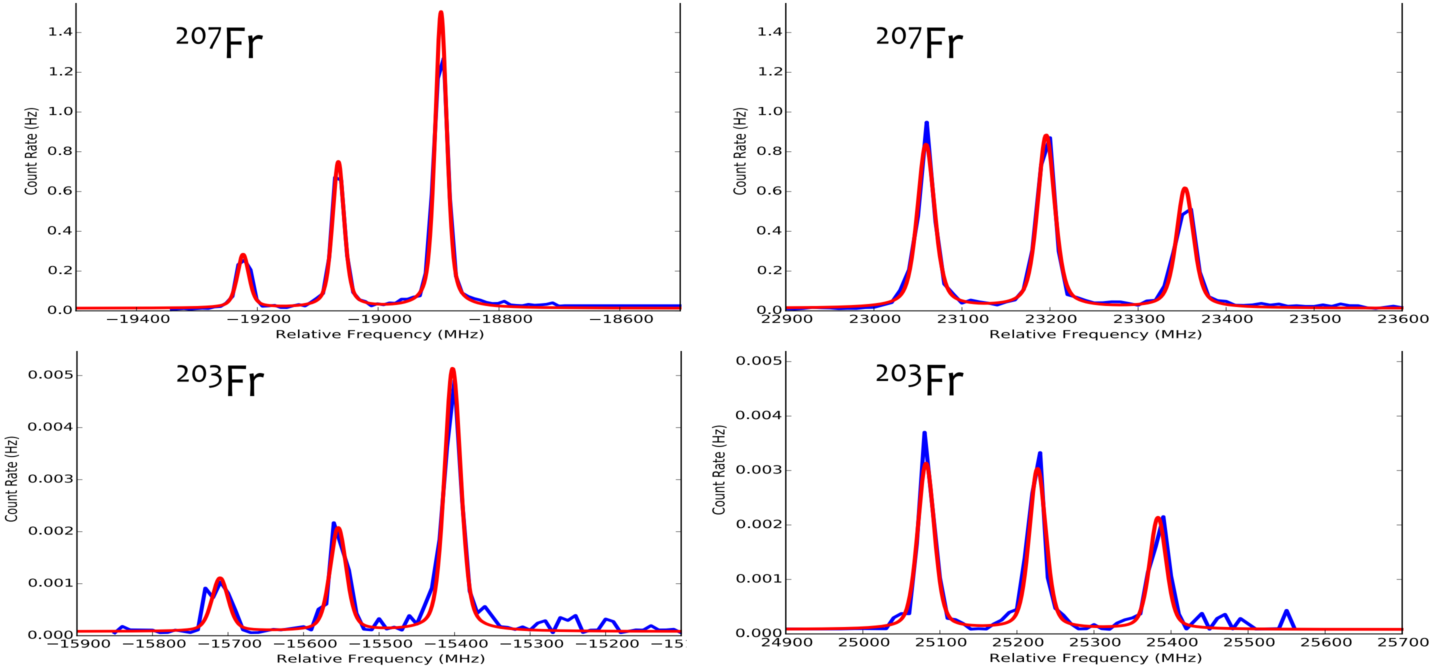
- Study the stability of the nuclear structure beyond the N=50 and Z=28 shell closures
  - Changes in nuclear configuration due to polarization of the core
  - Neutron rich: ^{75}Ga, ^{79}Ga, ^{80}Ga, ^{81}Ga, ^{82}Ga
  - Neutron deficient: ^{65}Ga, ^{67}Ga
- Neutralization of only 5% - limited our efficiency
- Asymmetric peaks fitted with CrystalBall function
  - Resolution of ~40 MHz

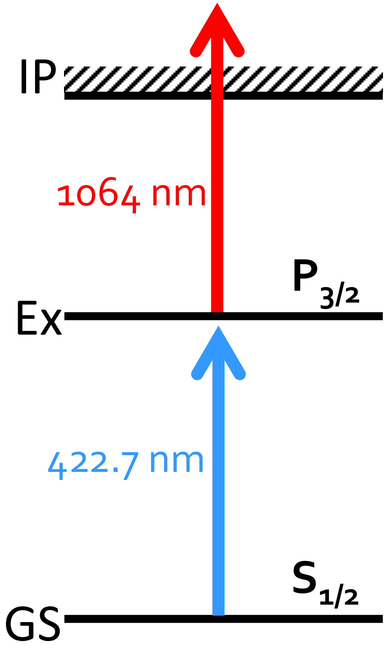




IS471: Francium experiment

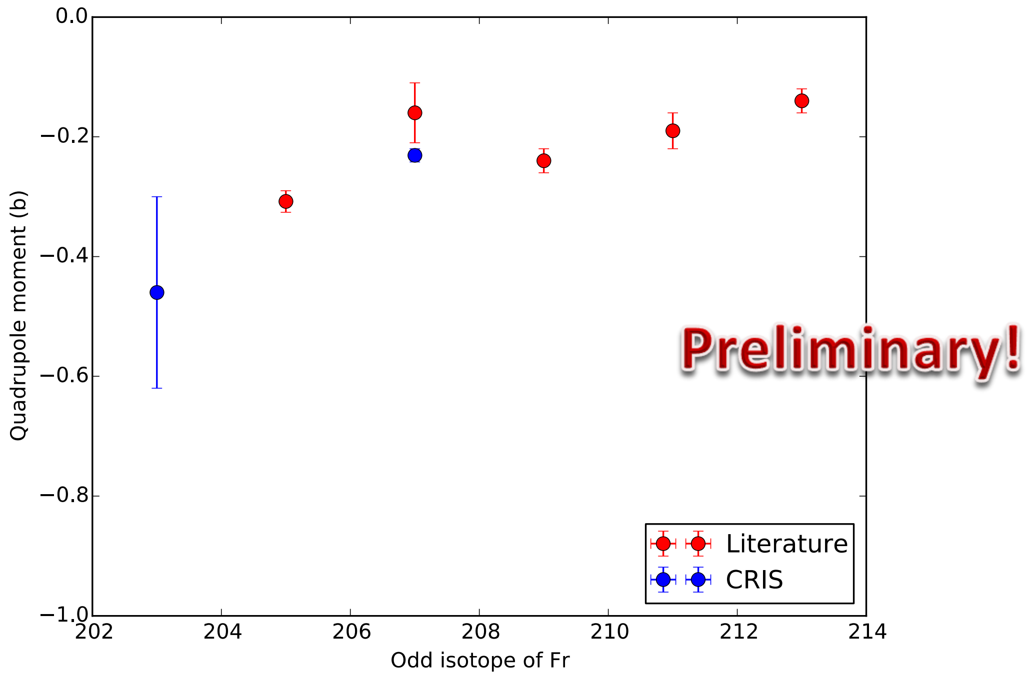
- Last ISOLDE beam time (2-days)
- Use of new M2 laser system to produce 422 nm light
  - Resolution of ~25 MHz
- Re-measurement of quadrupole moment of ^{207}Fr disagrees with literature
- First measurement of quadrupole moment of ^{203}Fr
  - Yield of only 1000/s
- Data analysis is ongoing

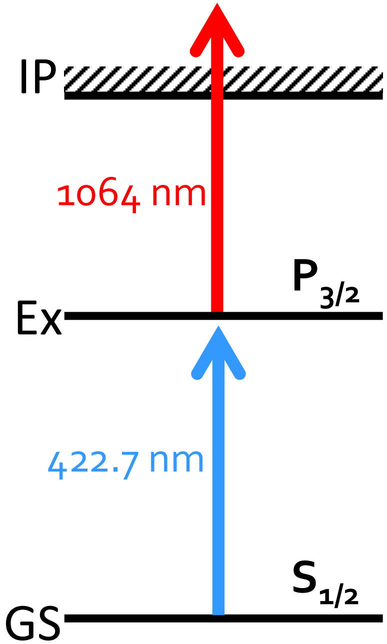




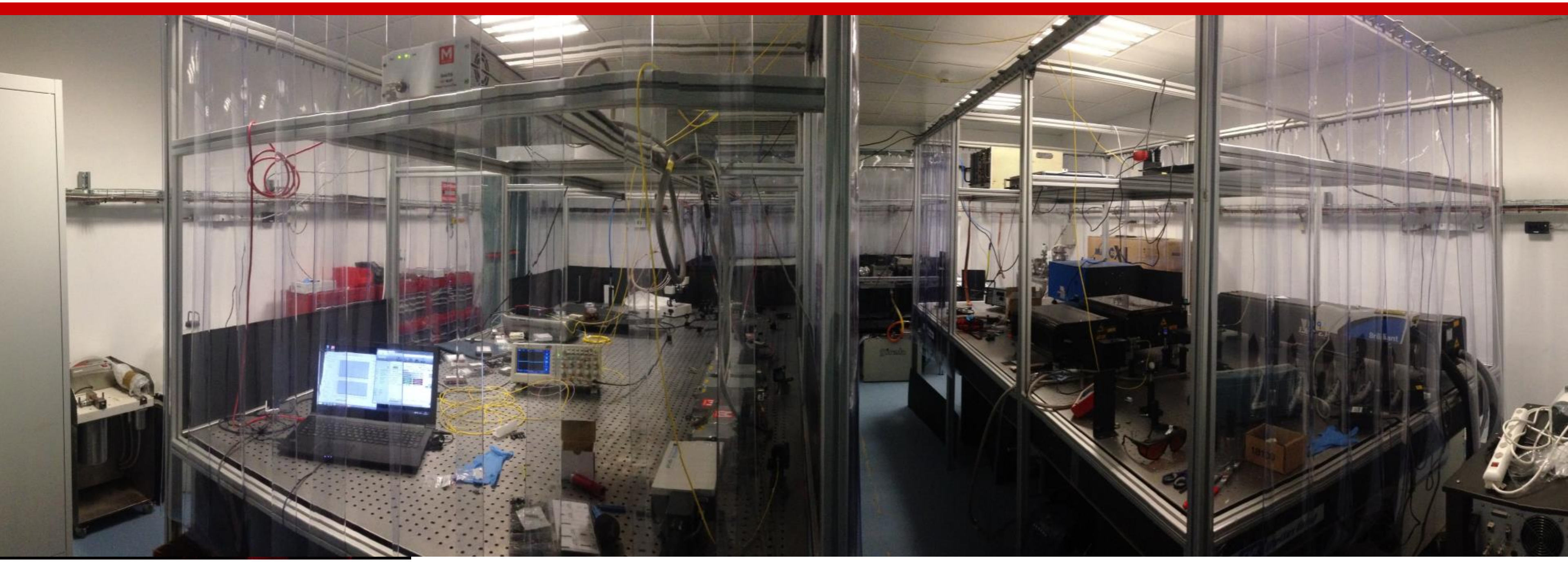
IS471: Francium experiment

- Opportunistic 2-day beam time 3 weeks ago
- Use of new M2 laser system to produce 422 nm light
  - Resolution of ~25 MHz
- Re-measurement of quadrupole moment of ^{207}Fr disagrees with literature
- First measurement of quadrupole moment of ^{203}Fr
  - Yield of only 1000/s
- Data analysis is ongoing



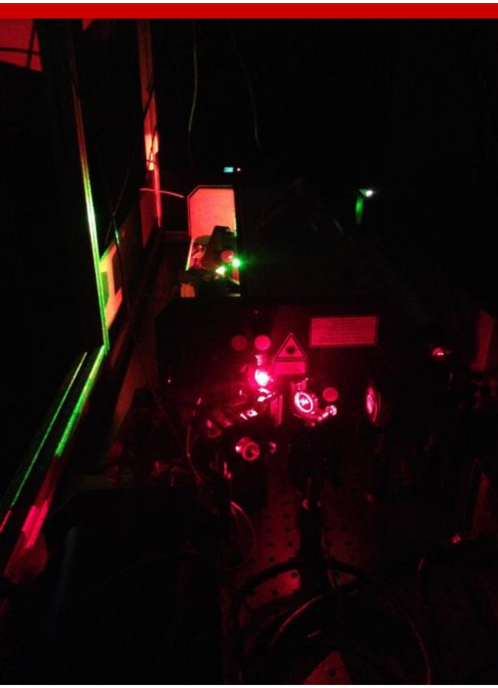


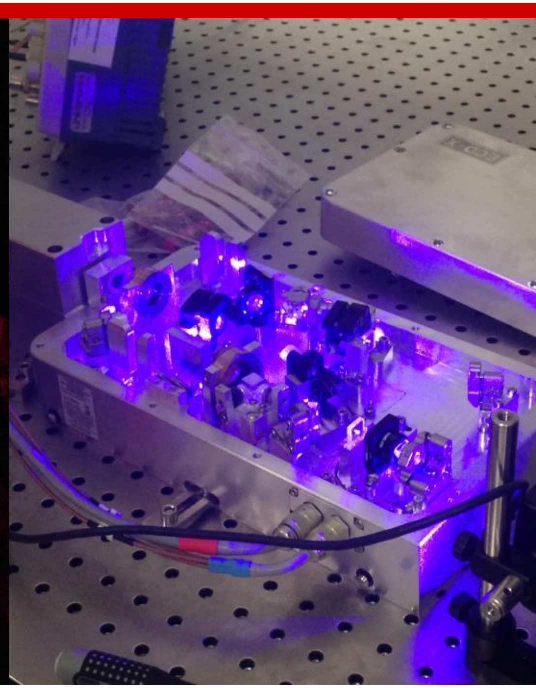
CRIS laser laboratory

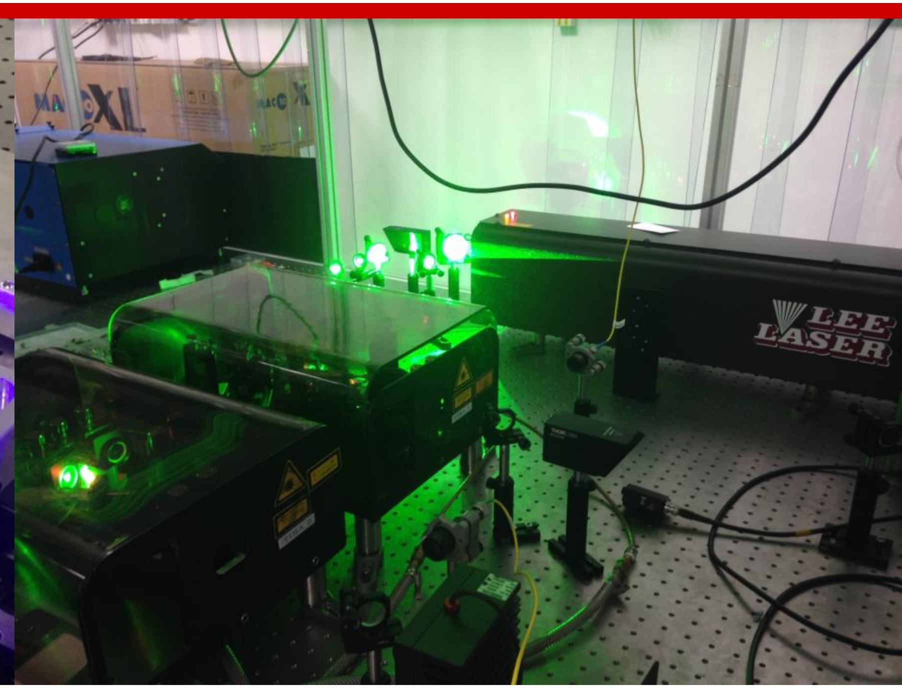


- Increasing the available wavelengths we can produce for RIS schemes
    - M2 Ti:Sa laser and frequency-doubling cavity
    - Matisse dye laser and frequency-doubling cavity
    - Industrial Nd:YAG laser and Ti:Sa cavities
    - 200 Hz Nd:YAG laser and pulsed-dye laser
- Fibre couple light downstairs to the beam line

CRIS laser laboratory

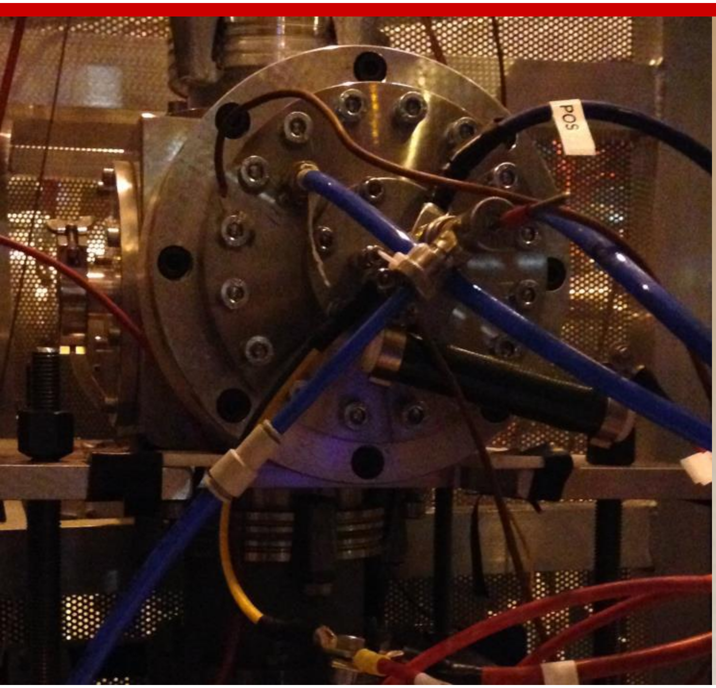


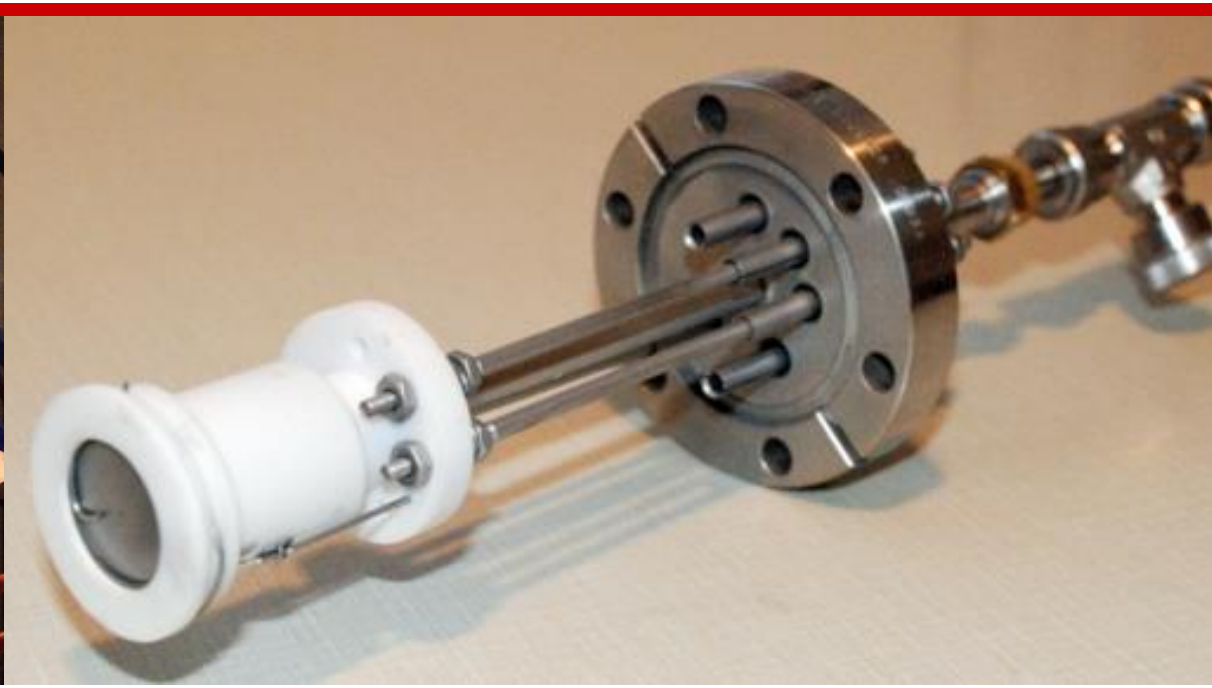




- Increasing the available wavelengths we can produce for RIS schemes
  - M2 Ti:Sa laser and frequency-doubling cavity
  - Matisse dye laser and frequency-doubling cavity
  - Industrial Nd:YAG laser and Ti:Sa cavities
  - 200 Hz Nd:YAG laser and pulsed-dye laser
- Fibre couple light downstairs to the beam line

CRIS Ion Source

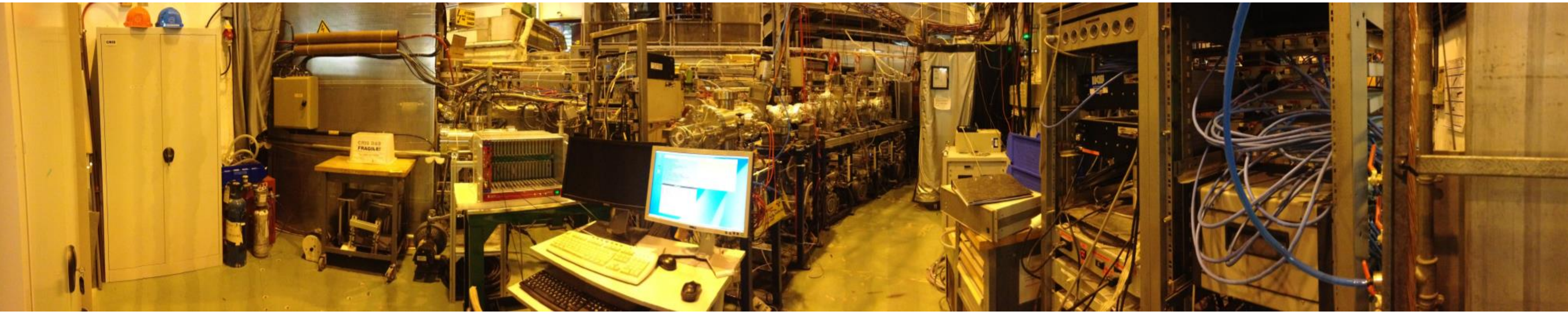




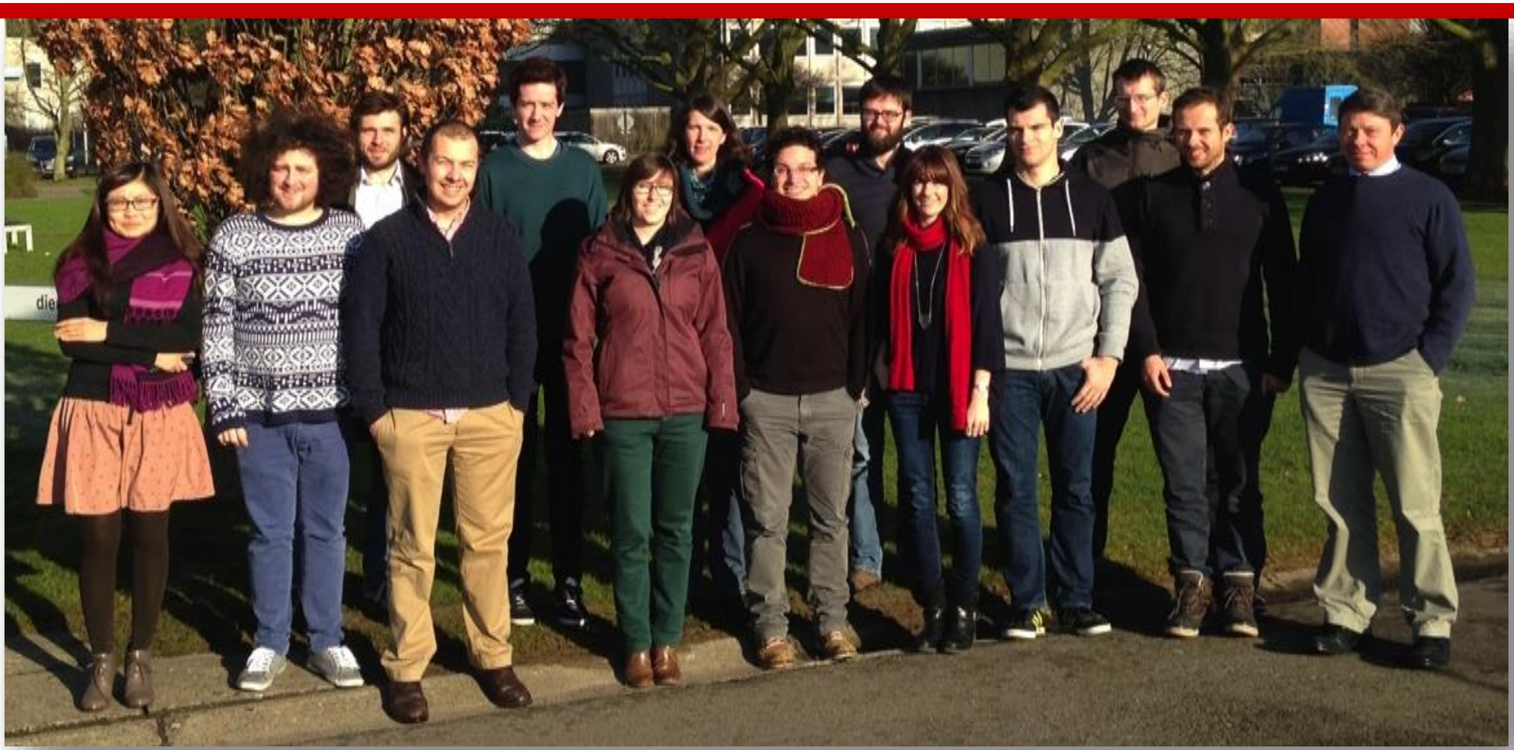
- Surface ion source replaced by a new plasma ion source
- Able to produce a larger range of ion beams
- Installed a few weeks ago and commissioned
- Allows testing of resonance ionization schemes offline
  - Choose most efficient scheme ahead of online experiment
- First tests will be with K and Cu

Summary

- Three experiments ran this year, achieving high resolution laser spectroscopy with new chopped-cw light method
  - Copper
  - Gallium
  - Francium
- Focused effort to increase the available wavelengths for RIS schemes
  - Installation of new M2 Ti:Sa laser system
  - Installation of industrial Nd:YAG laser and Ti:Sa cavities
- Installation of new Faraday cups and MCP to improve beam tuning through CRIS line
- New ion source with allow for off-line testing and optimization of RIS schemes with our new laser systems



The CRIS Collaboration



J. Billowes, M. L. Bissell, I. Budincevic, T. E. Cocolios, R. P. De Groote, G. Farooq-Smith, V. N. Fedosseev, K. T. Flanagan, S. Franchoo, R. F. Garcia Ruiz, H. Heylen ,T. Kron, K. M. Lynch, B. A. Marsh, G. Neyens, T. J. Procter, R. E. Rossel, S. Rothe, R. Li, H. H. Stroke, K. D. A. Wendt, S. Wilkins, X. Yang

Thanks for your attention!

Fitting the hyperfine spectra

- The perturbation of each energy level is given by:

$$\frac{\Delta E}{\hbar} = \frac{K}{2}A + \frac{3K(K+1) - 4I(I+1)J(J+1)}{8I(2I-1)J(2J-1)}B$$

where

$$K = F(F+1) - I(I+1) - J(J+1) \qquad A = \frac{\mu B_e}{IJ} \qquad B = eQ_s\left\langle \frac{\partial^2 V_e}{\partial z^2} \right\rangle$$

- The frequency of each HF peak is given by:

$$\gamma = \nu + \alpha_u A_u + \beta_u B_u - \alpha_l A_l - \beta_l B_l$$

where

$$\alpha = \frac{K}{2} \qquad \beta = \frac{3K(K+1) - 4I(I+1)J(J+1)}{8I(2I-1)J(2J-1)}$$

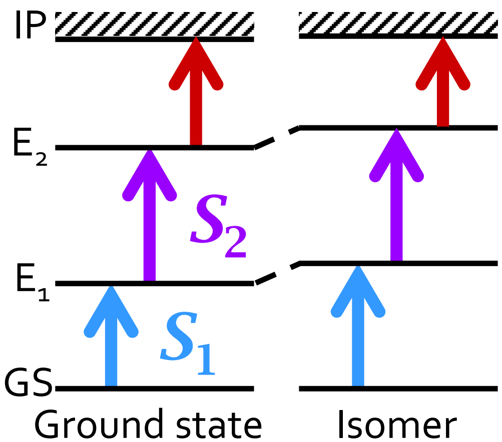
- The centroid and hyperfine factors can be determined from the hyperfine spectrum using a χ^2 minimization fitting routine

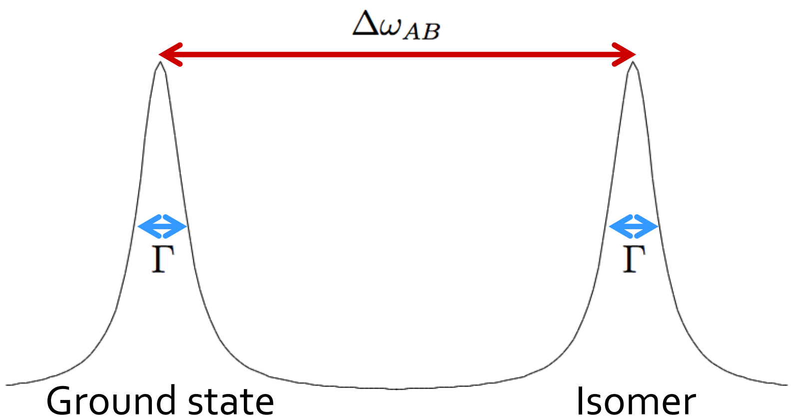
Selectivity of resonance ionization

- When the laser frequency is on resonance with a hyperfine transition, the isotope is resonantly ionized
    - Resonance ionization selects the isotope of interest

Selectivity of an isotope is:

$$S = \left(\frac{\Delta\omega_{AB}}{\Gamma}\right)^2$$





$$S = S_1 \times S_2 \qquad S = \Pi\, S_n$$

The higher the number of excitation steps, the greater the selectivity

- Analogous to the mass resolution in mass spectrometry

Experiments in 2015

- Copper
- Measure spins, magnetic moments and quadrupole moments of $^{76\text{-}78}Cu$
  - Cu has 1 proton outside Z=28 to test evolution of shell model with neutron excess
  - Proton acts as probe for orbitals above closed shell
  - Provide information on the rigidity of the core and the effect of the neutron excess on the neutron and proton orbitals

- Gallium
- Measure hyperfine structure and half-lives of neutron-rich gallium isotopes: $^{>80}Ga$
  - Study stability of nuclear structure beyond N=50 and Z=28

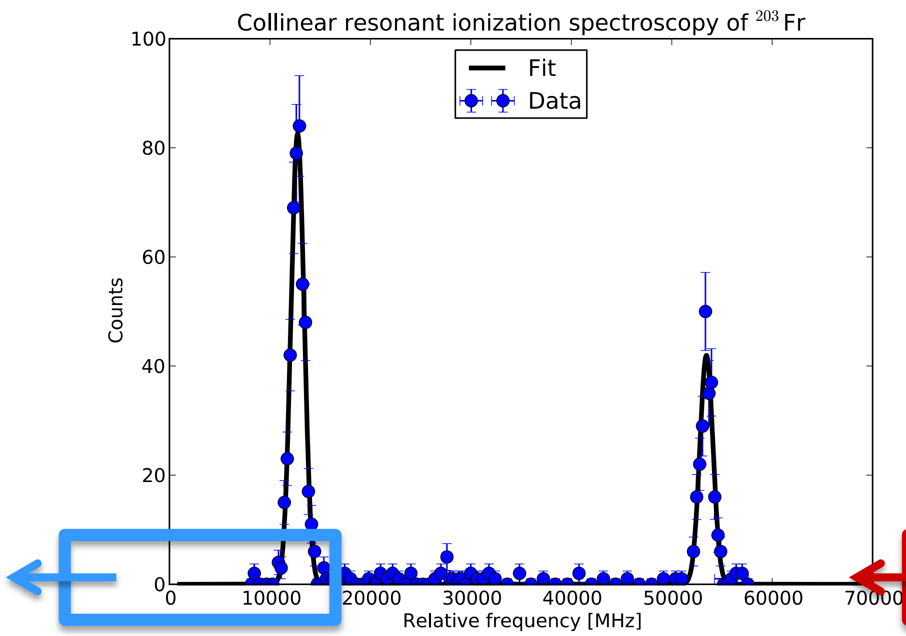
- Francium
- Measure hyperfine structure of neutron-deficient isotopes: $^{207,203,203m}Fr$
  - Investigate the change in nuclear structure with moments and charge radii
  - Study evolution of the $(\pi s_{1/2}^{-1})$ ½+ proton intruder state

In search of ^{203m}Fr

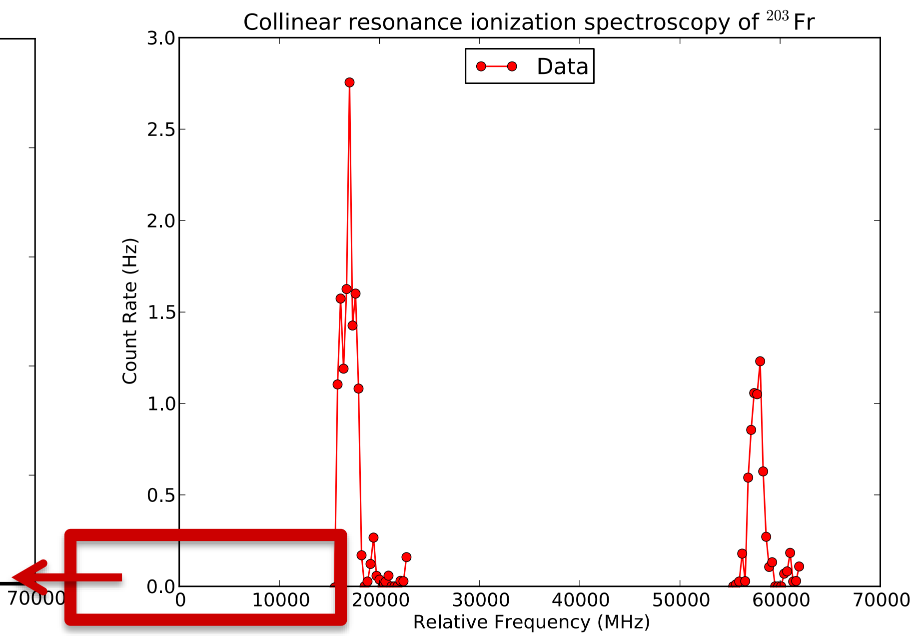
- Searched for the 60 ms isomeric state in ^{203}Fr in 2014
  - Used low-resolution mode (using RILIS lasers) as the state is (1/2)+
  - Unfortunately did not see an hint of the isomeric state in the time
- Searched again in 2015 in high-resolution mode but without success

Isotope of Fr	Half life	Spin
203g	0.55 s	(9/2) -
203m	60 ms	(1/2) +
201g	62 ms	(9/2) -
201m	19 ms	(1/2) +

October 2012



November 2014



Total experimental efficiency

$$\varepsilon_{\text{Total}} = \varepsilon_{\text{Transmission}}\ \varepsilon_{\text{Neutralization}}\ \varepsilon_{\text{Laser ionization}}\ \varepsilon_{\text{Detection}}$$

- $\varepsilon_{\text{Transmission}}$ = 40% - 70 %
- $\varepsilon_{\text{Neutralization}}$ = 50% - 70 % (Fr), 70 % (Cu), 5-20 % (Ga)
- $\varepsilon_{\text{Laser ionization}}$ = Highly dependent on RIS scheme, laser power density and atom-laser beam overlap
- $\varepsilon_{\text{Detection}}$ = ~ 30%