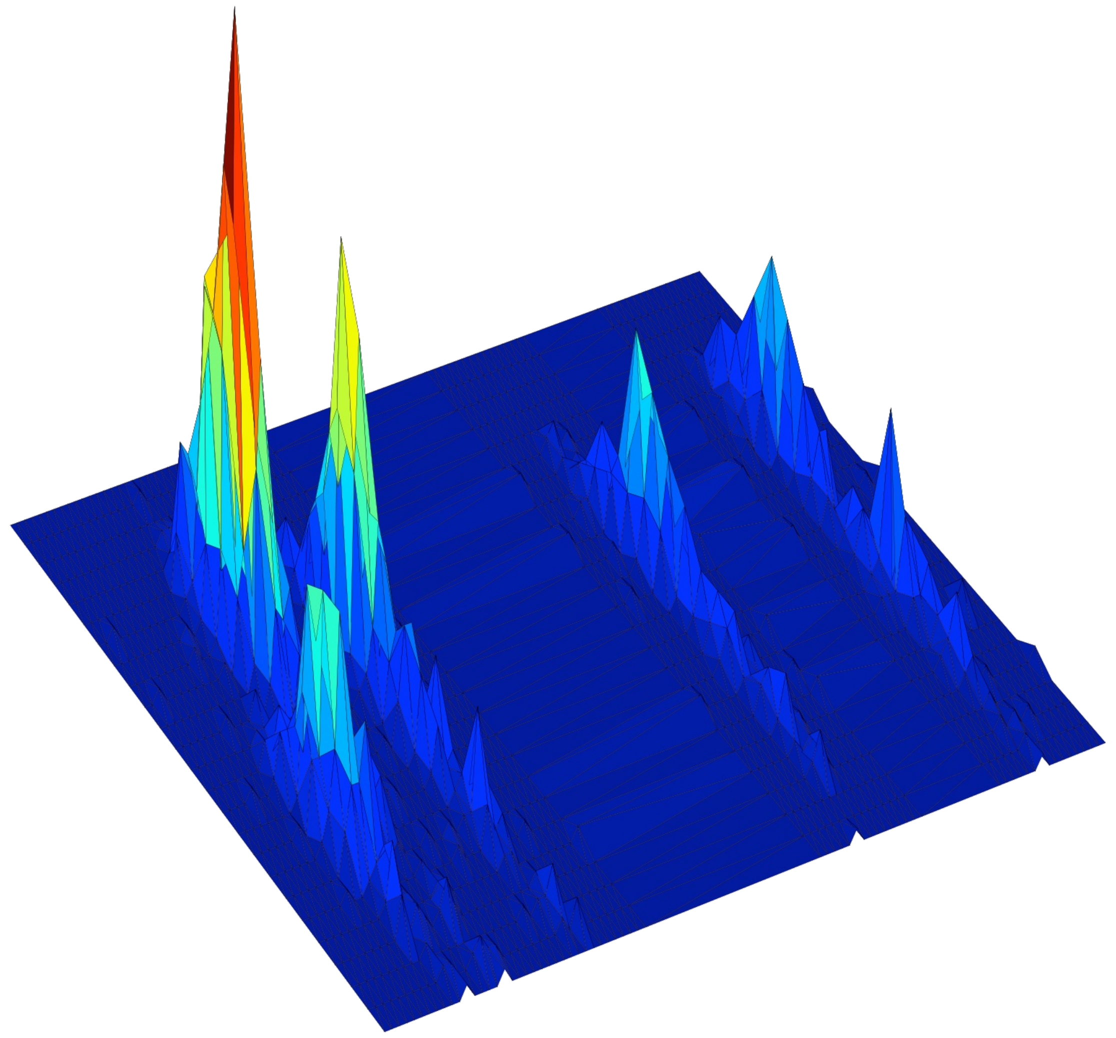
International Nuclear Physics Conference
Adelaide Convention Centre, Australia
11-16 September 2016



Collinear resonance ionization spectroscopy:

From laser spectroscopy to isomer selection

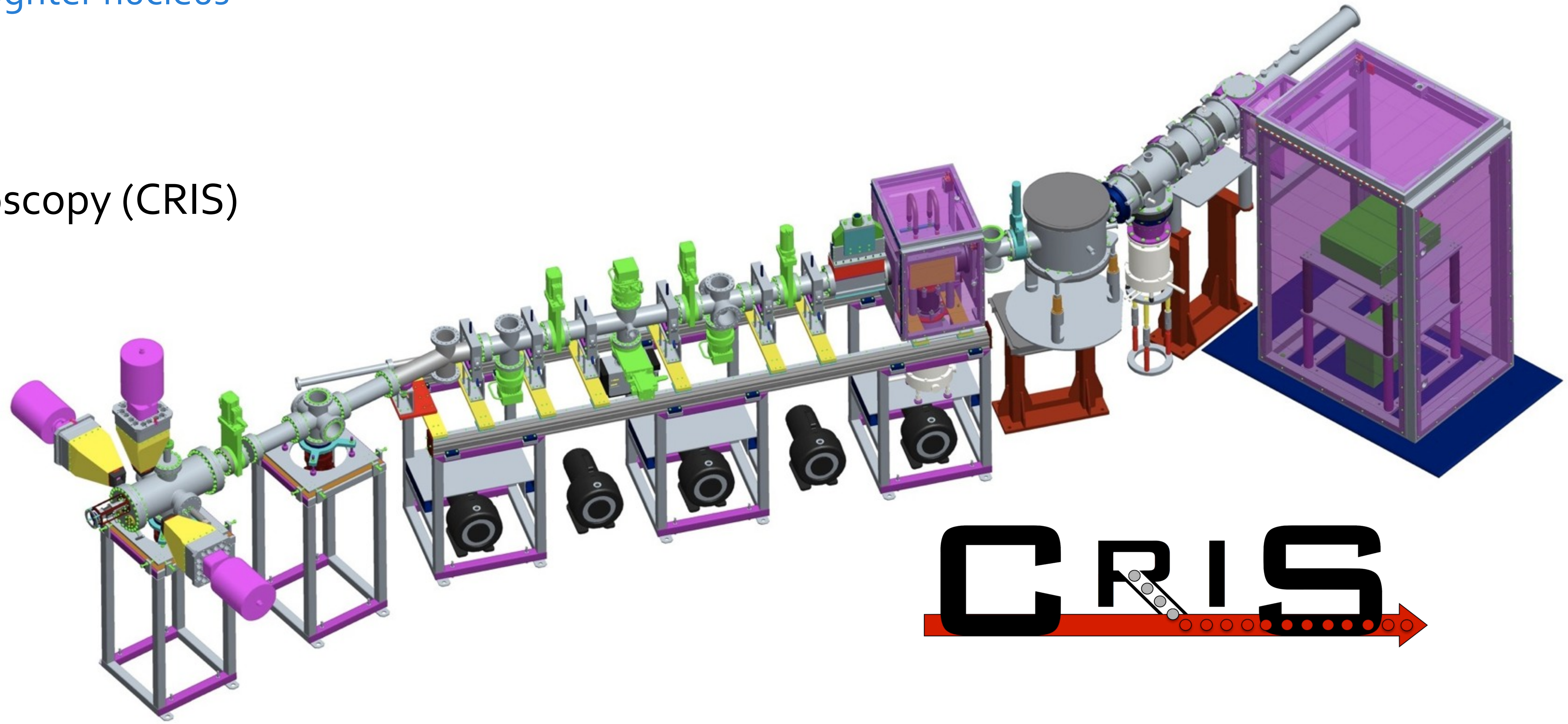
Kara M. Lynch
Research Fellow
CERN

Introduction

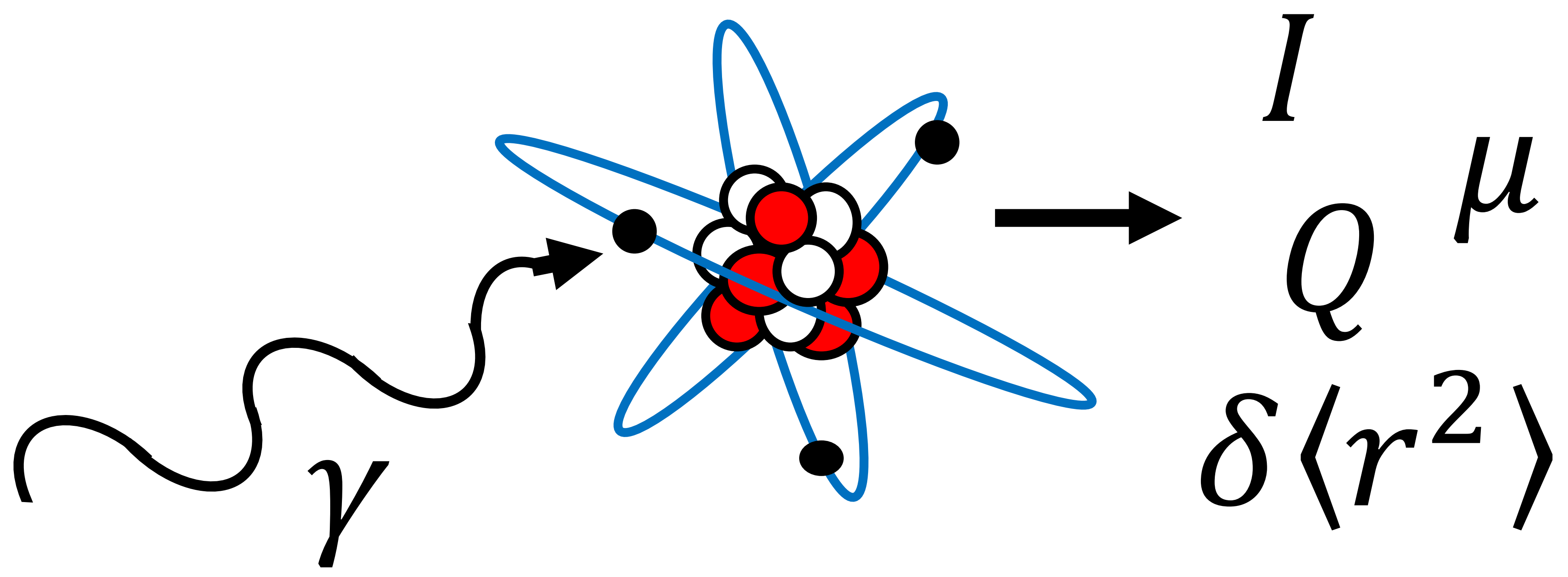
- The CRIS experiment is located at the ISOLDE facility, CERN
  - Laser spectroscopy: spin and moments of parent nucleus
  - Decay spectroscopy: level scheme of daughter nucleus

Introduction

- The CRIS experiment is located at the ISOLDE facility, CERN
  - Laser spectroscopy: spin and moments of parent nucleus
  - Decay spectroscopy: level scheme of daughter nucleus
- Collinear resonance ionization spectroscopy (CRIS)
- The CRIS beam line at ISOLDE
  - The decay spectroscopy station
- Recent results from CRIS experiments
  - Studying neutron-deficient francium
  - Studying gallium, copper and radium
- Summary



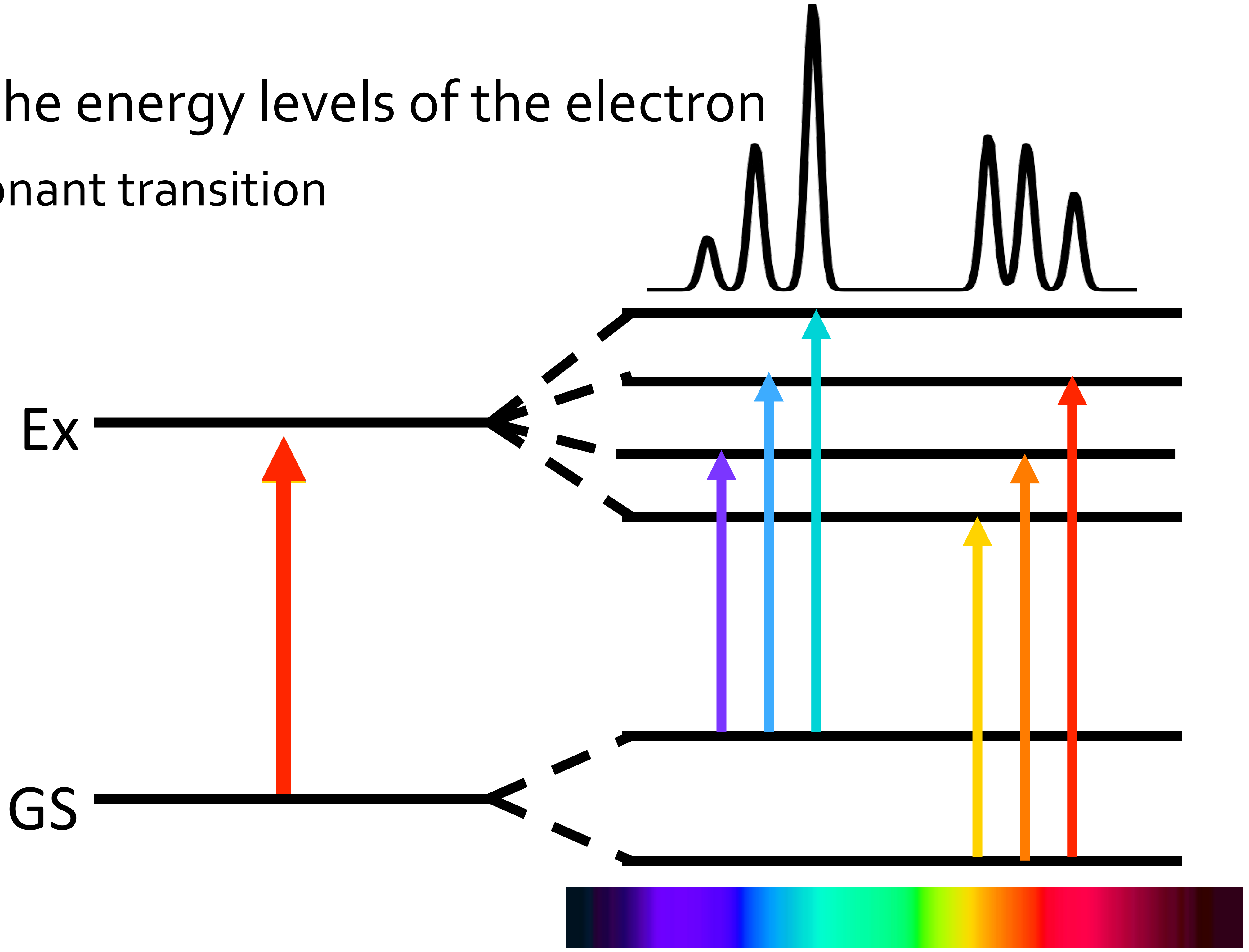
K.T. Flanagan *et al*. CERN-INTC-2008-010 **INTC-P-240** CERN, Geneva (2008)
T.J. Procter *et al.* J. Phys.: Conf. Ser. **381** 1 012070 (2012)

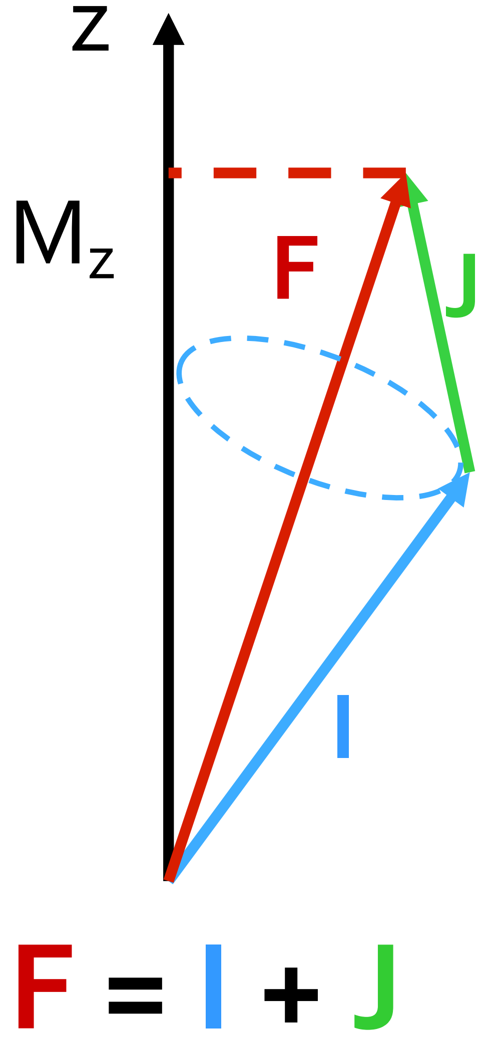


Collinear resonance ionization spectroscopy

Laser spectroscopy

- Probe the hyperfine structure of the energy levels of the electron
  - Scan the laser frequency of the resonant transition

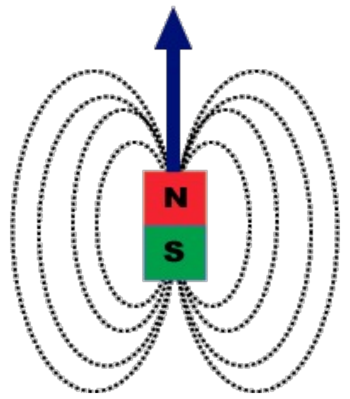




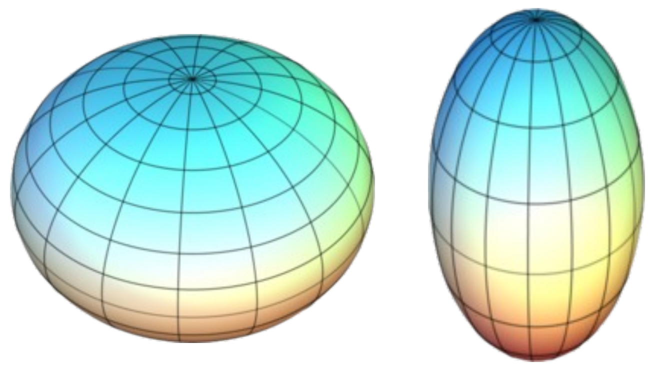
- Nuclear properties extracted with model-independence:

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

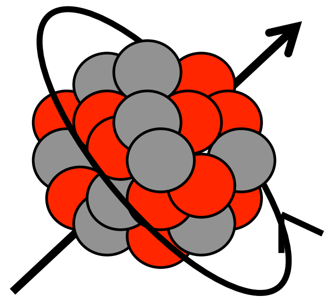
Magnetic dipole moment μ_I



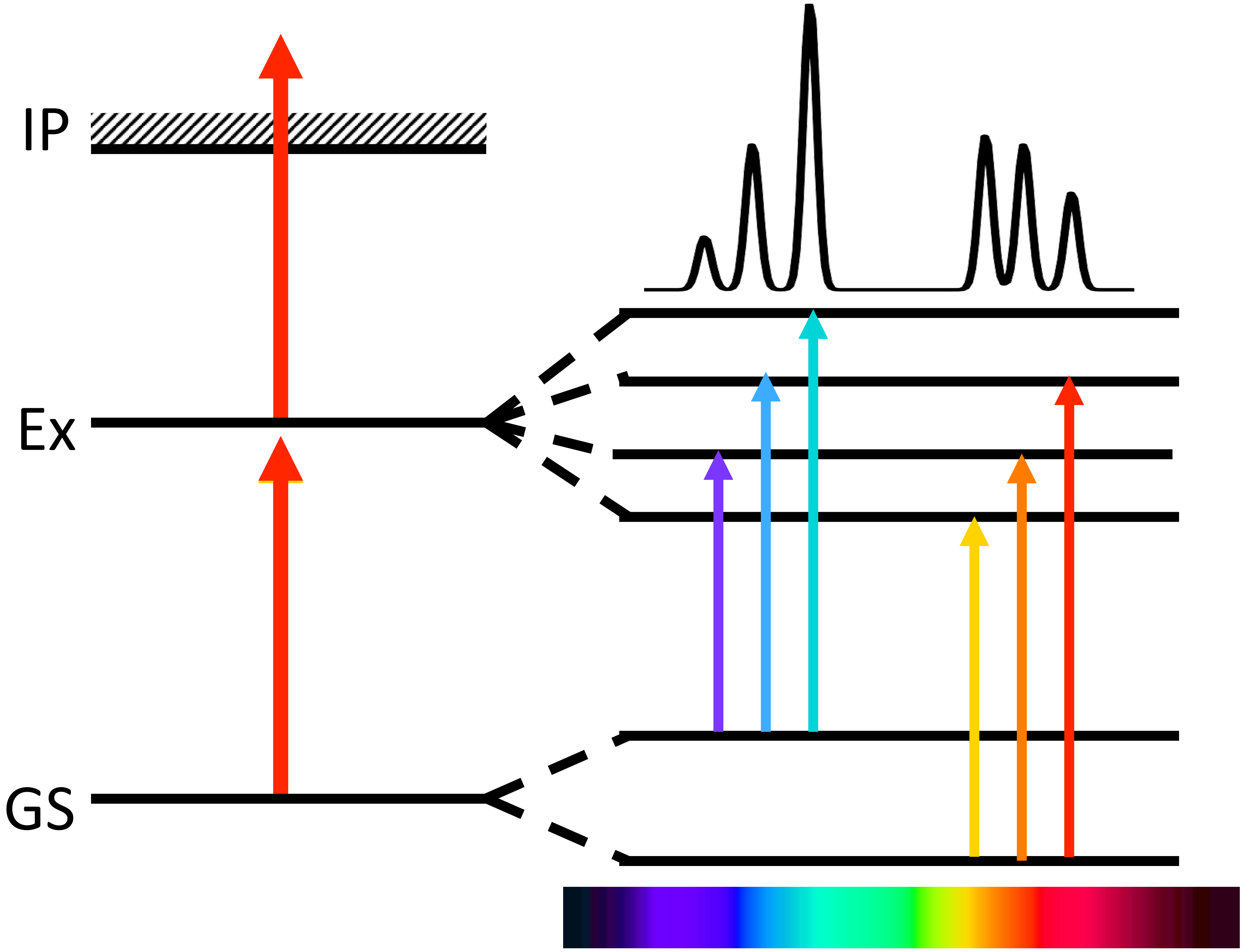
Electric quadrupole moment Q_S



Nuclear spin I

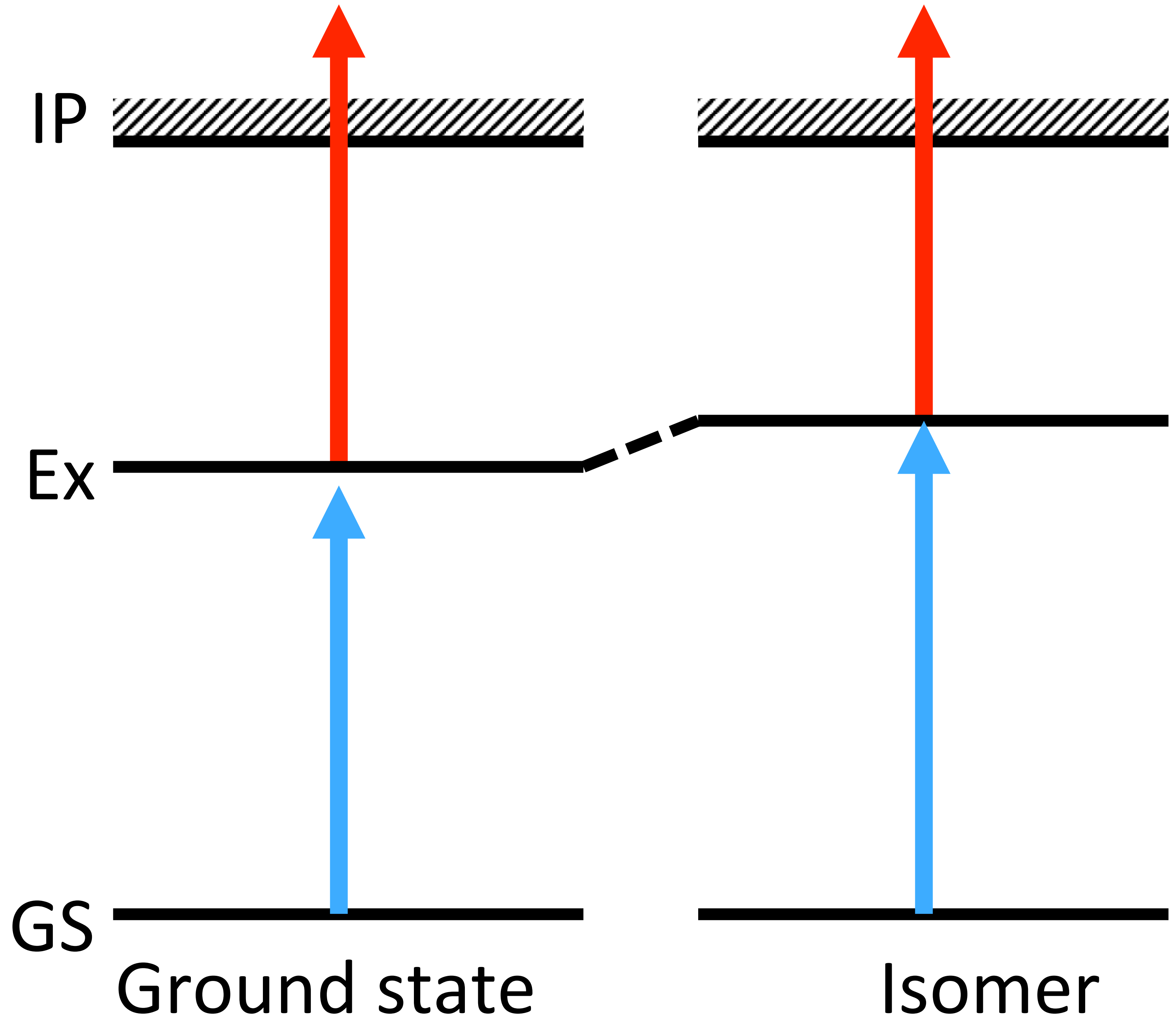


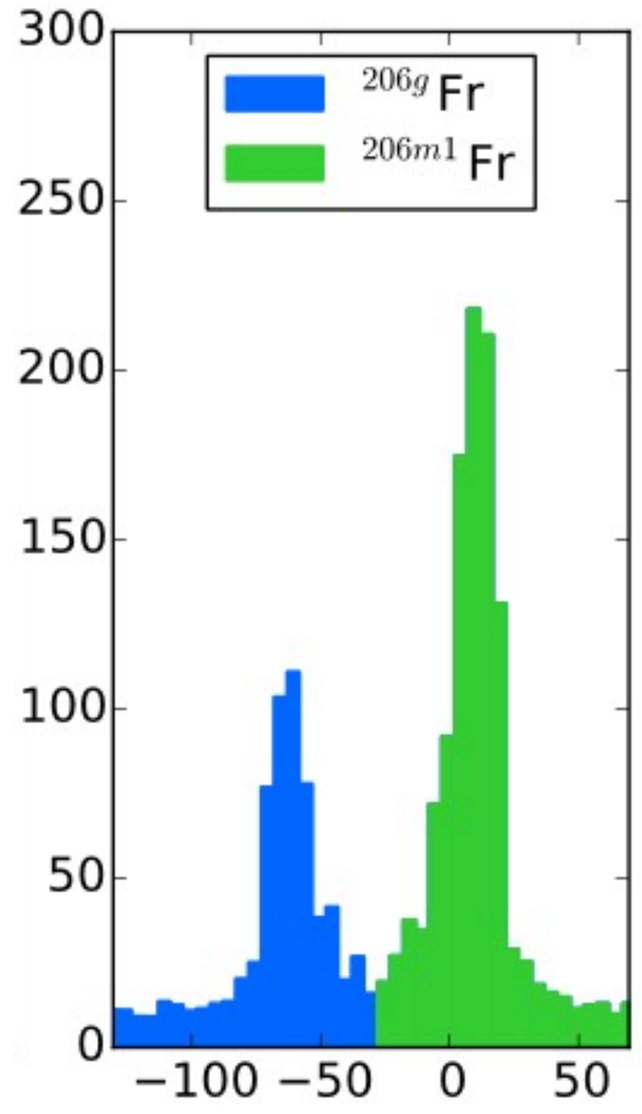
Resonance ionization spectroscopy

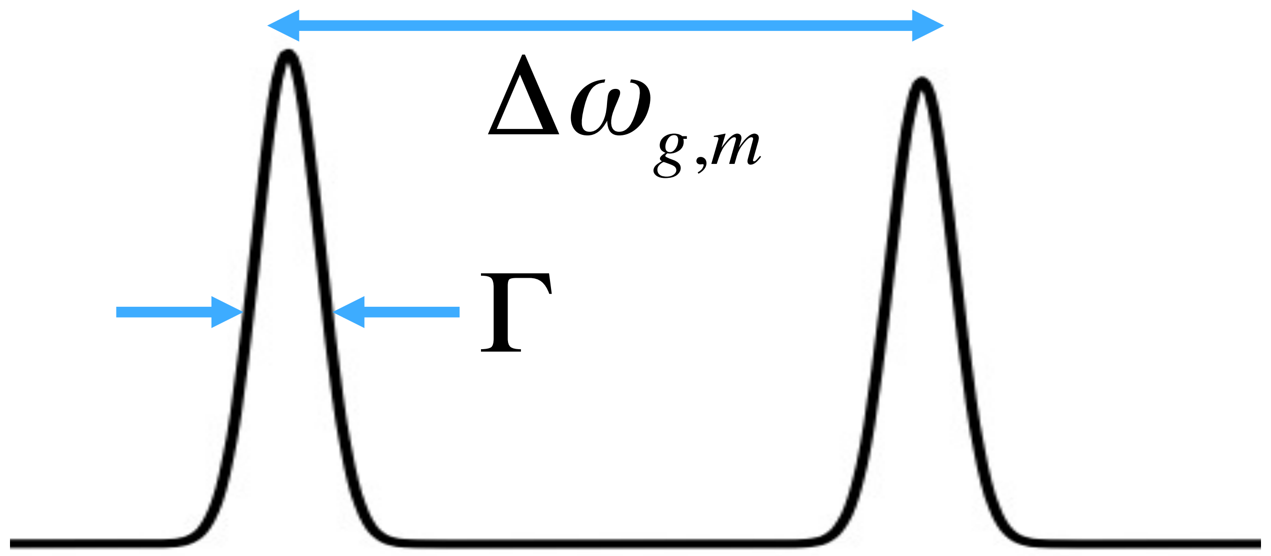


- Resonant excitation is followed by an ionization step into the continuum
  - When the laser frequency is on resonance with a hyperfine transition, the isotope is resonantly ionized
- Resonance ionization selects the isotope of interest
- Using an isotope's hyperfine structure as an atomic fingerprint

Selectivity of resonance ionization



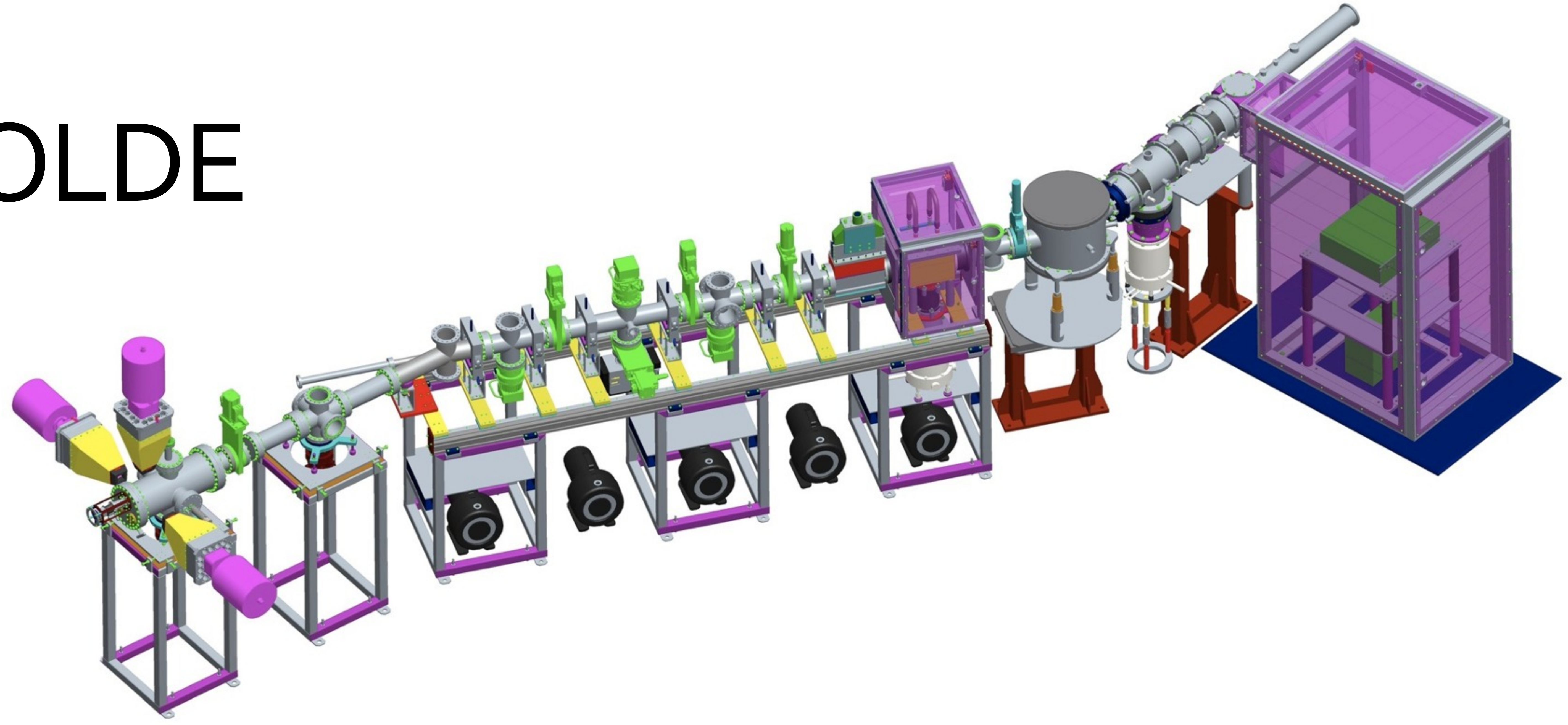




- Selectivity of an isotope is $S = \left(\frac{\Delta\omega_{g,m}}{\Gamma}\right)^2 = \prod S_n$

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

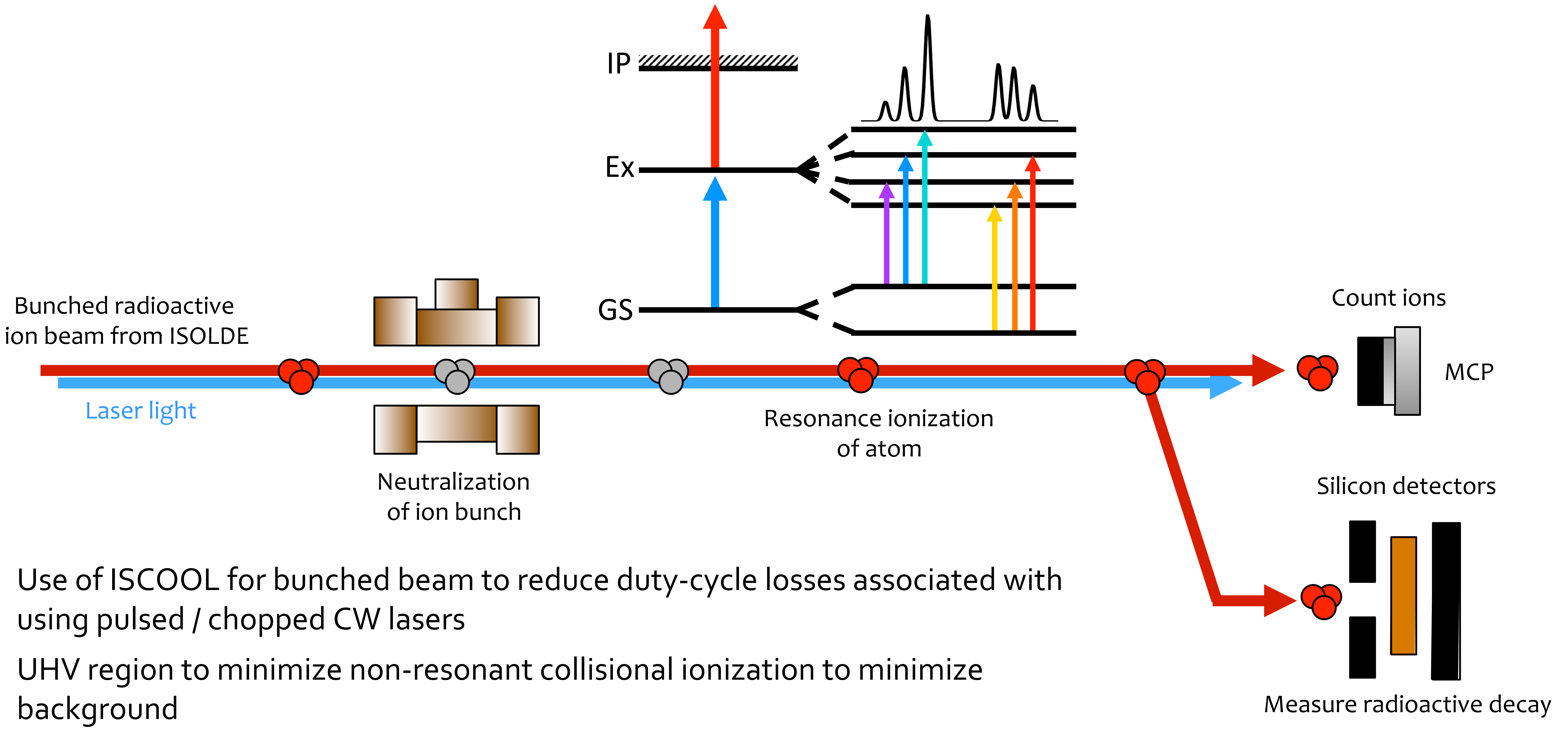
The CRIS beam line at ISOLDE



The ISOLDE Facility

- Radioactive isotopes are created and delivered to the CRIS beam line by:
  - ★ Proton-induced spallation/fission/fragmentation of 1.4 GeV protons impinged upon a thick target
  - ★ Ionization of radioactive products via surface, laser or plasma ionization process
  - ★ Mass separation with HRS
  - ★ Cooling and bunching in ISCOOL at 30 keV
  - ★ Transmission through CA0 to CRIS

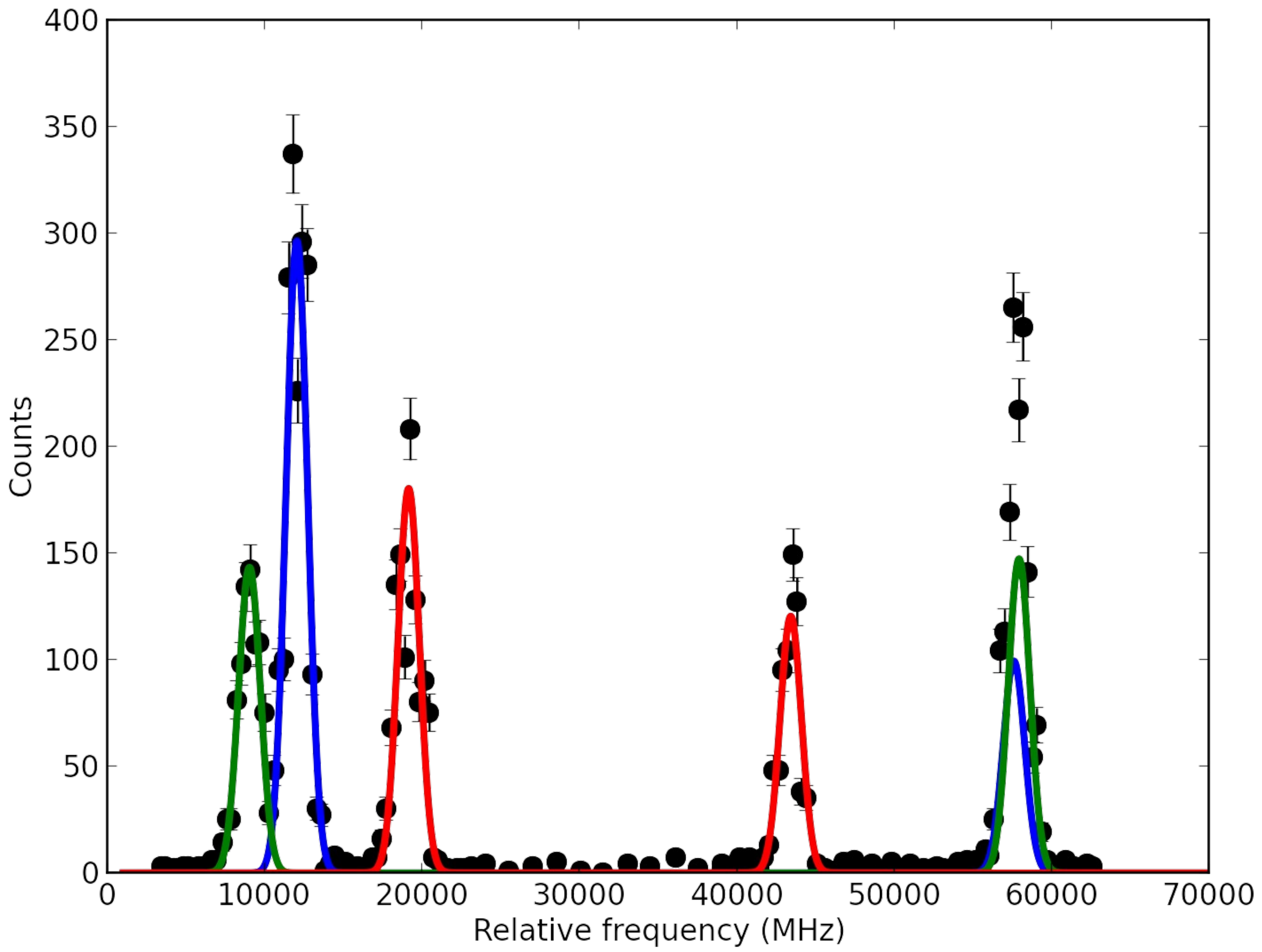
The CRIS technique

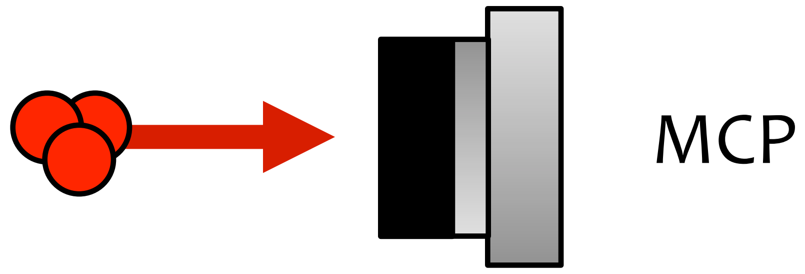


- Use of ISCOOL for bunched beam to reduce duty-cycle losses associated with using pulsed / chopped CW lasers
- UHV region to minimize non-resonant collisional ionization to minimize background
- Collinear geometry reduces thermal Doppler broadening to below natural linewidth of the hyperfine transition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

The CRIS technique

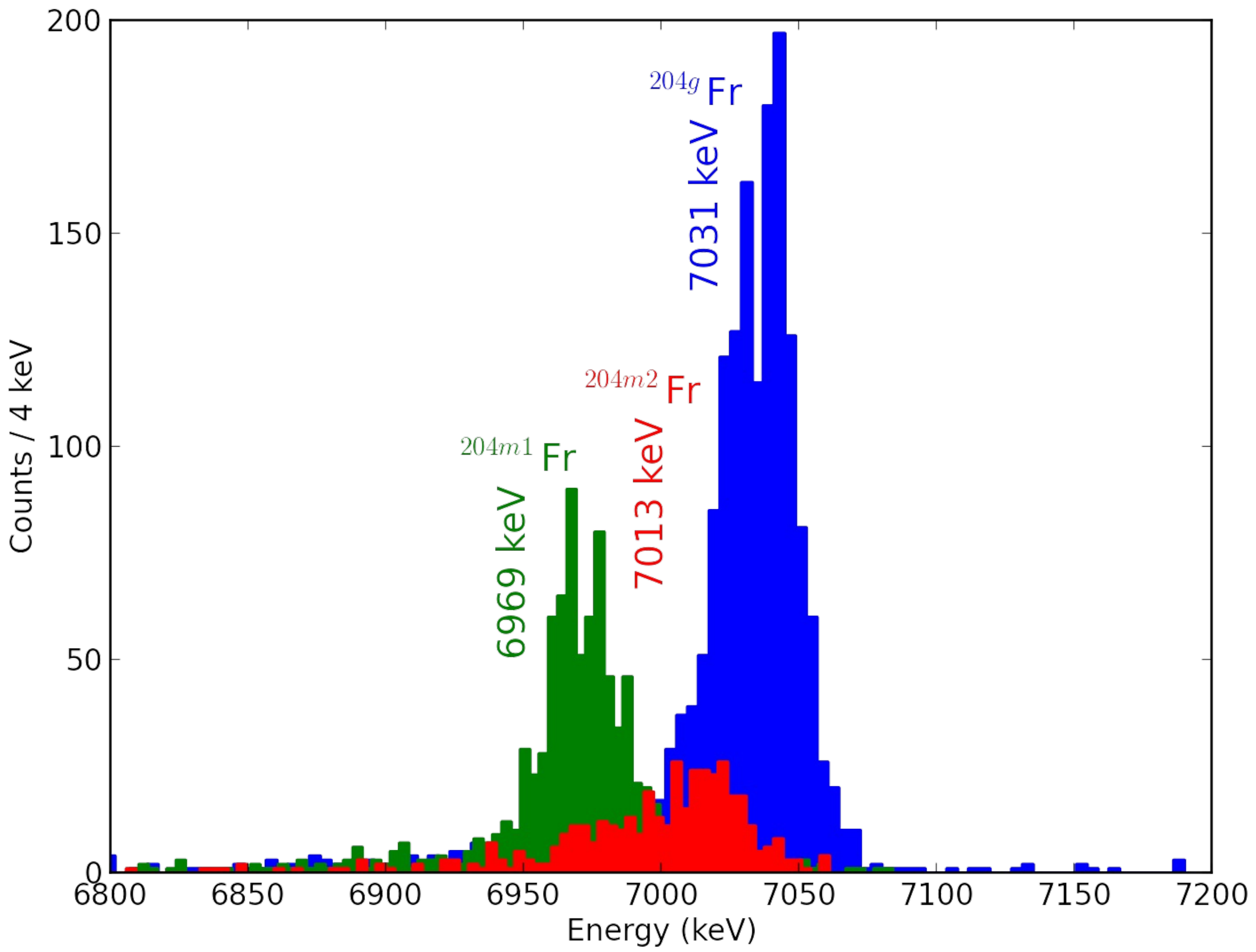
Collinear resonance ionization spectroscopy

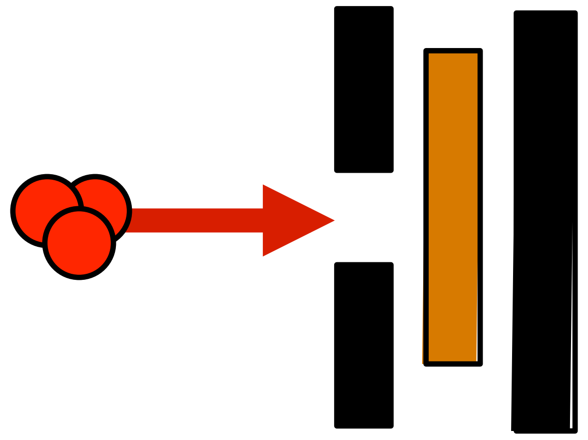




- Sensitivity of technique comes from:
  - Detection of resonant ions
  - Efficient laser ionization
  - Almost background-free detection

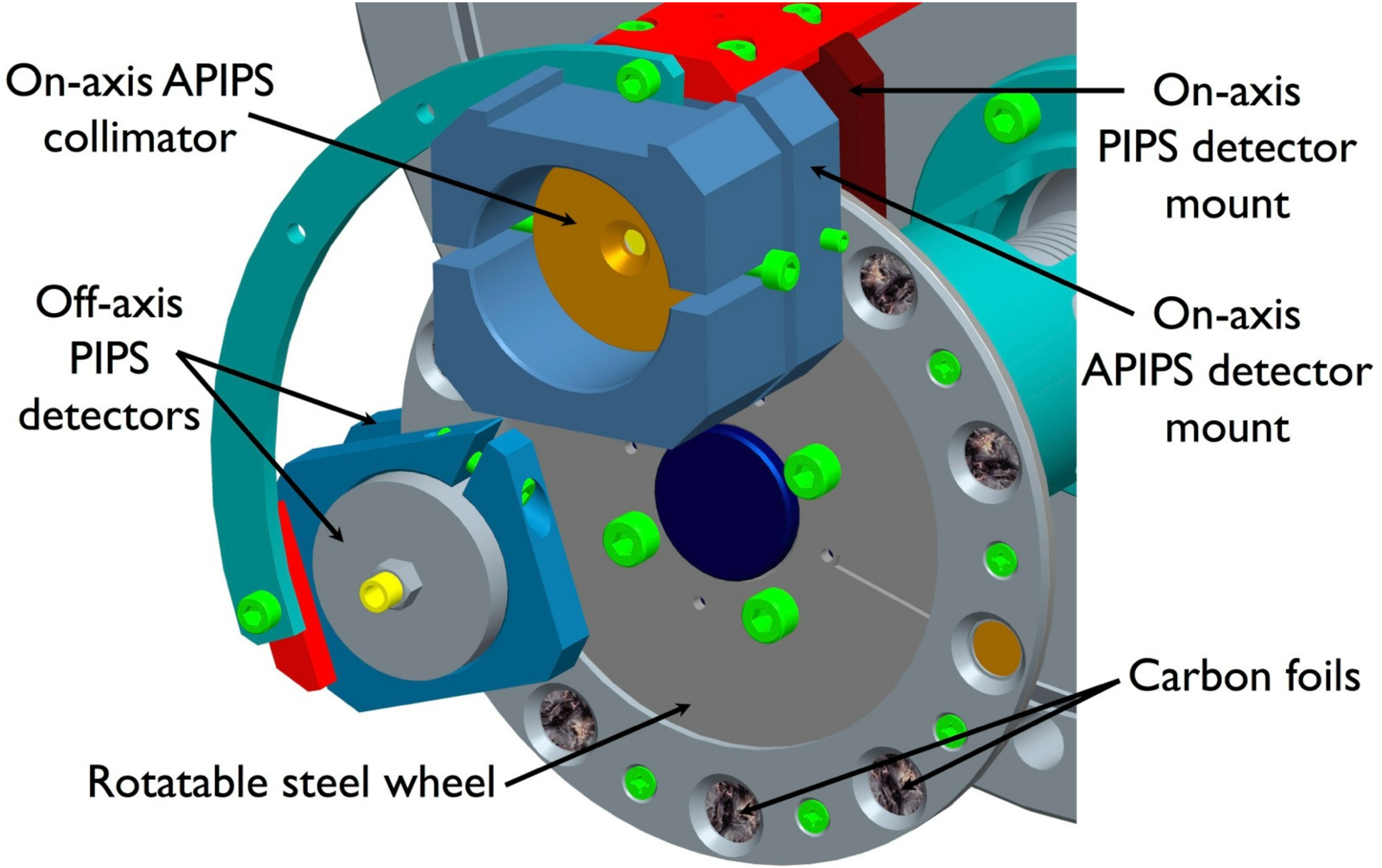
Laser-assisted nuclear decay spectroscopy





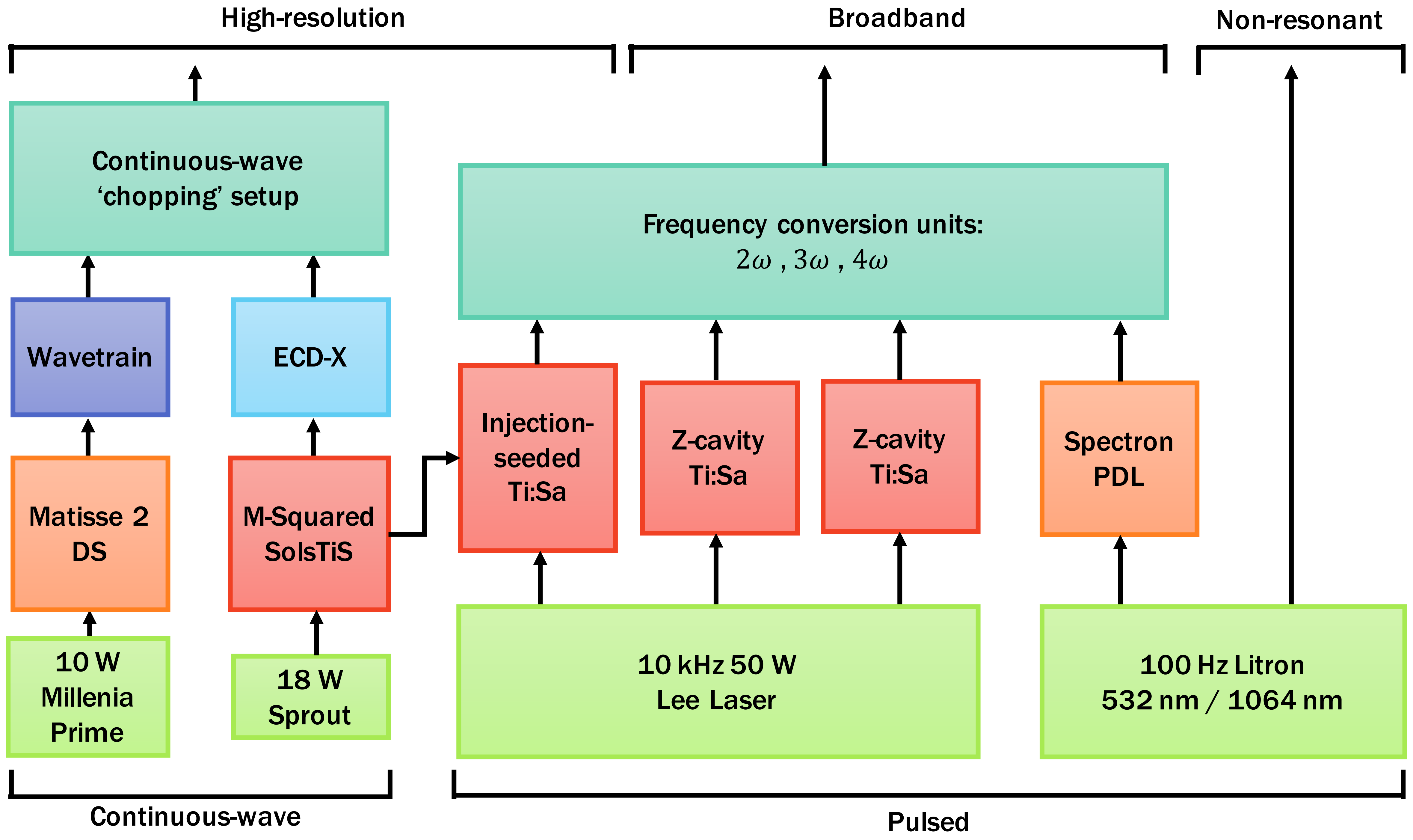
- Implantation of the resonant ions in a carbon foil allows their radioactive decay to be measured
- Provides additional information on the isotope (or isomer) under investigation

The Decay Spectroscopy Station (DSS)

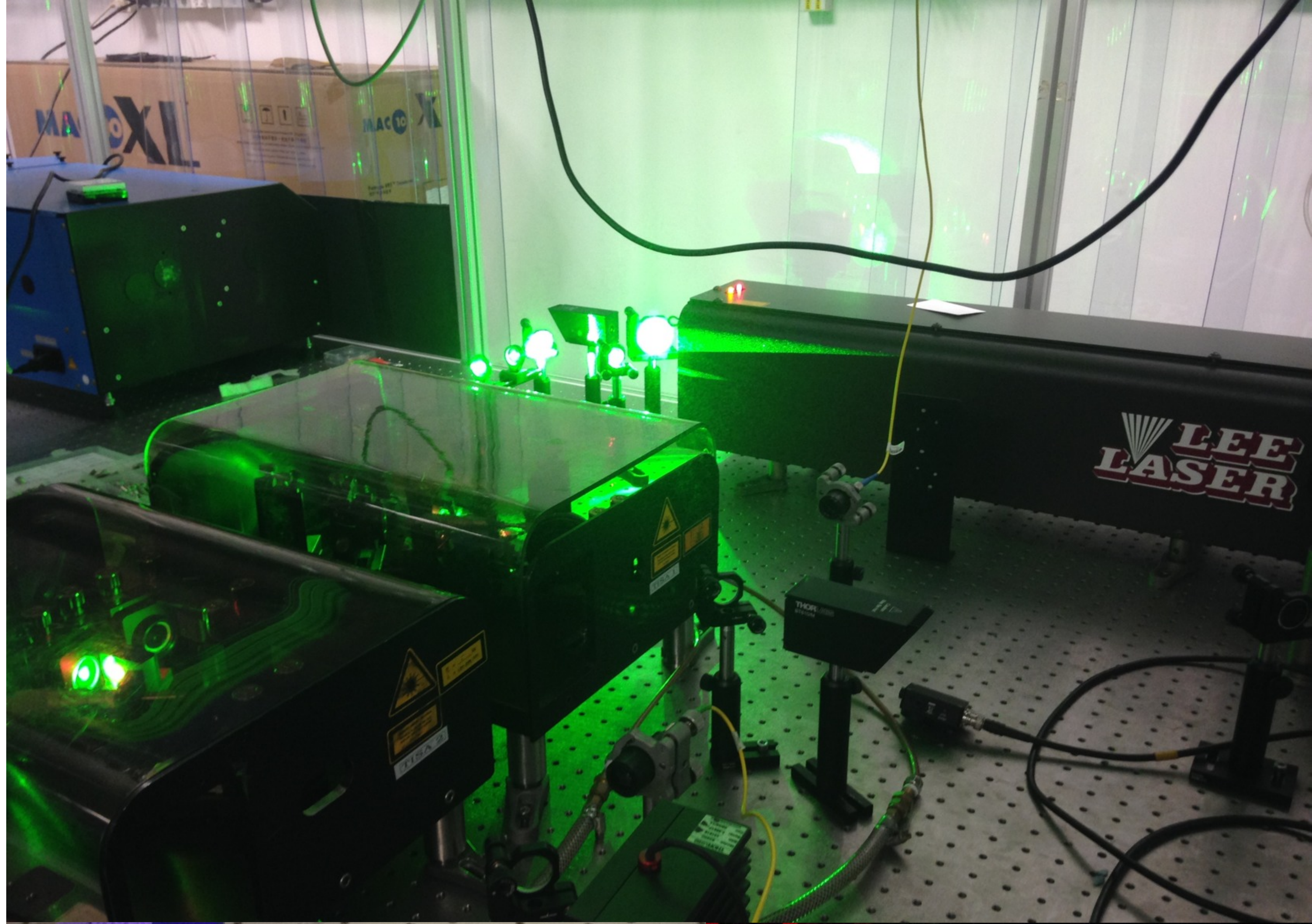


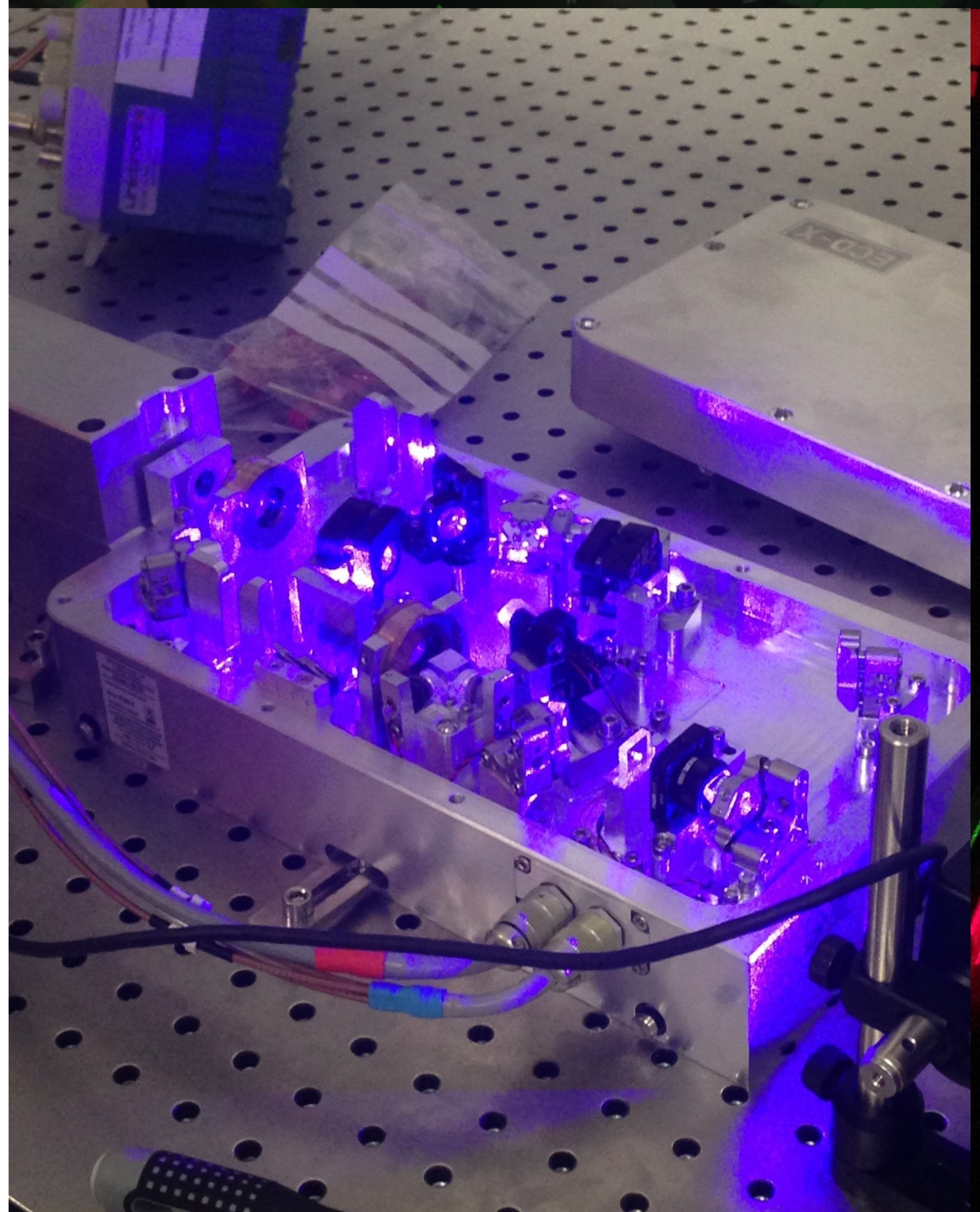
M.M. Rajabali *et al.*, NIM A **707** 35 (2013)
K.M. Lynch *et al.*, J. Phys.: Conf. Ser. **381** 1 012128 (2012)

CRIS laser laboratory

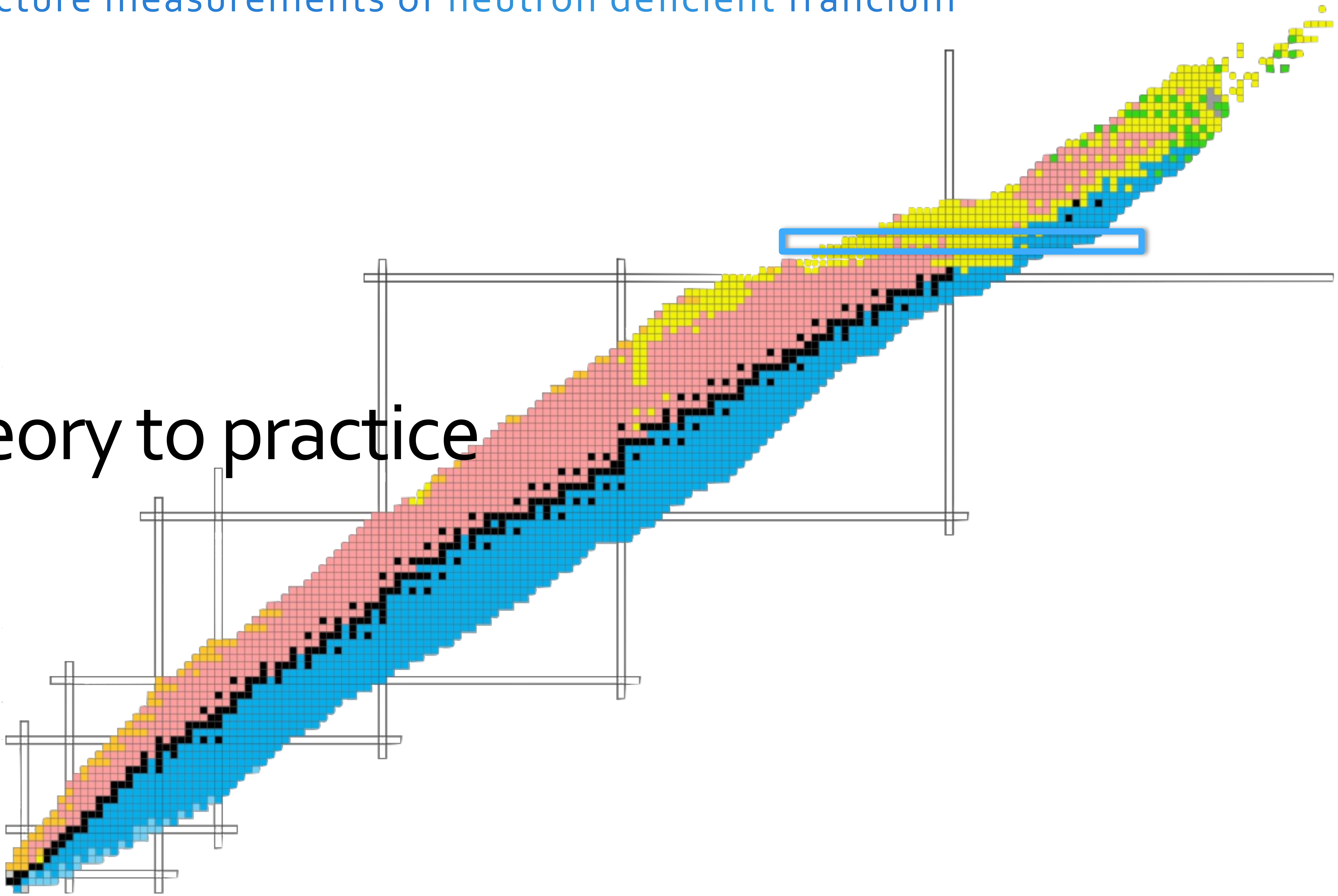


- Located in next to ISOLDE facility in new building
  - Fibre-couple or mirror-couple light downstairs to the beam line
- Installation of new laser systems to increase the available wavelengths for RIS schemes
  - M2 Ti:Sa laser and frequency-doubling cavity
  - Matisse dye laser and frequency-doubling cavity
  - Industrial 10 kHz Nd:YAG Lee laser
  - 2Ti:Sa cavities (Mainz) and injection-seeded Ti:Sa system (Jyväskylä)
  - 200 Hz Nd:YAG Litron laser
  - Spectron pulsed-dye laser





From theory to practice



CRIS timeline

- 2008: Proposal for CRIS submitted to ISOLDE and n-ToF committee (INTC)
- 2010: CRIS beam line constructed and installed at ISOLDE
- 2011: First radioactive beam through CRIS
- 2012: Collinear resonance ionization spectroscopy (low resolution) of Fr
- Laser-assisted nuclear decay spectroscopy of 202,204Fr
- 2013: CERN Long shutdown 1
- 2014: Collinear resonance ionization spectroscopy (high resolution) of Fr
- Laser-assisted nuclear decay spectroscopy of 206,218Fr
- 2015: Collinear resonance ionization spectroscopy (high resolution) of Fr, Ga, Cu
- 2016: Collinear resonance ionization spectroscopy (high resolution) of Cu, Ra

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Proposal to the ISOLDE and N-ToF Experiments Committee (INTC)

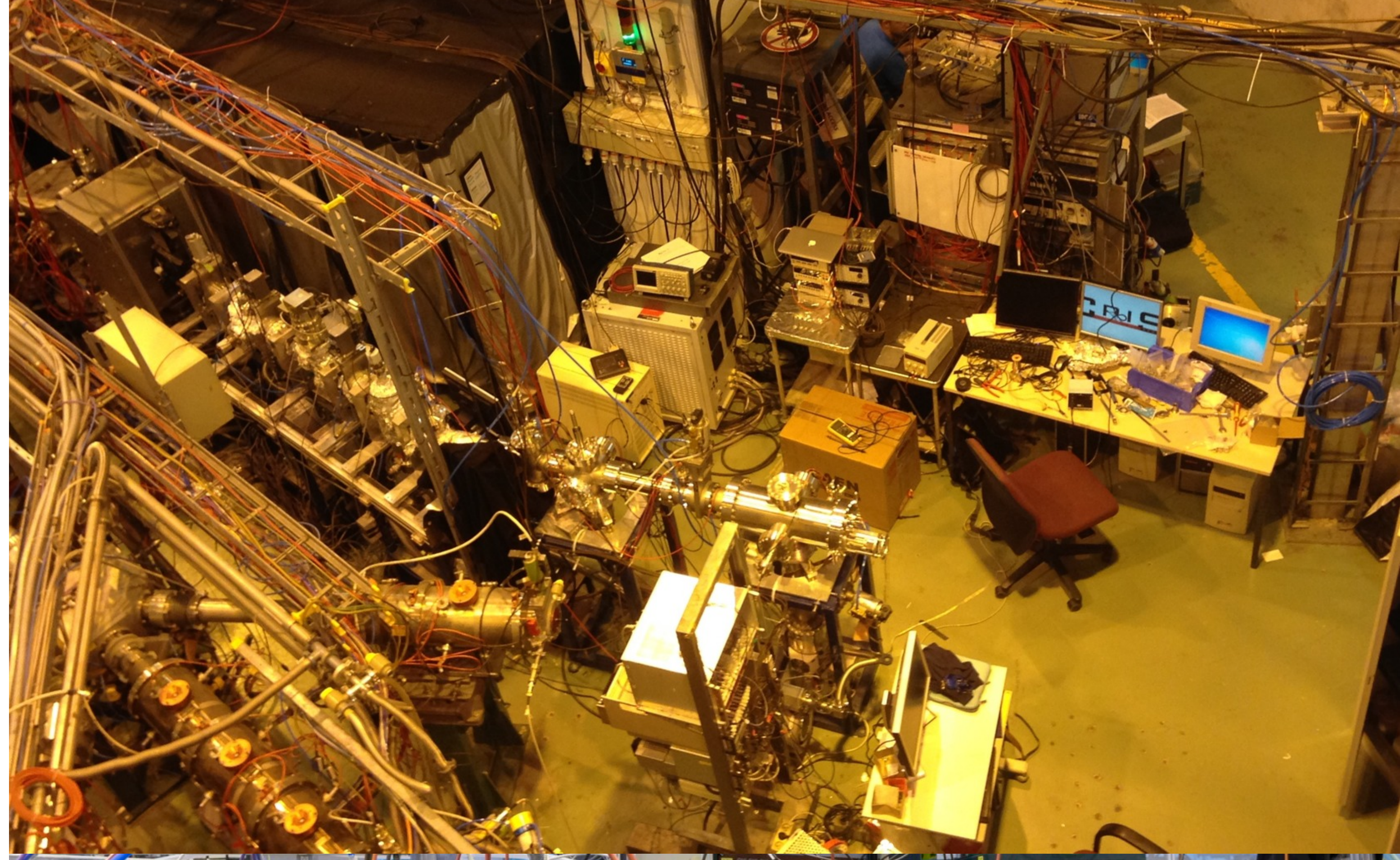
Collinear resonant ionization laser spectroscopy of rare francium isotopes.

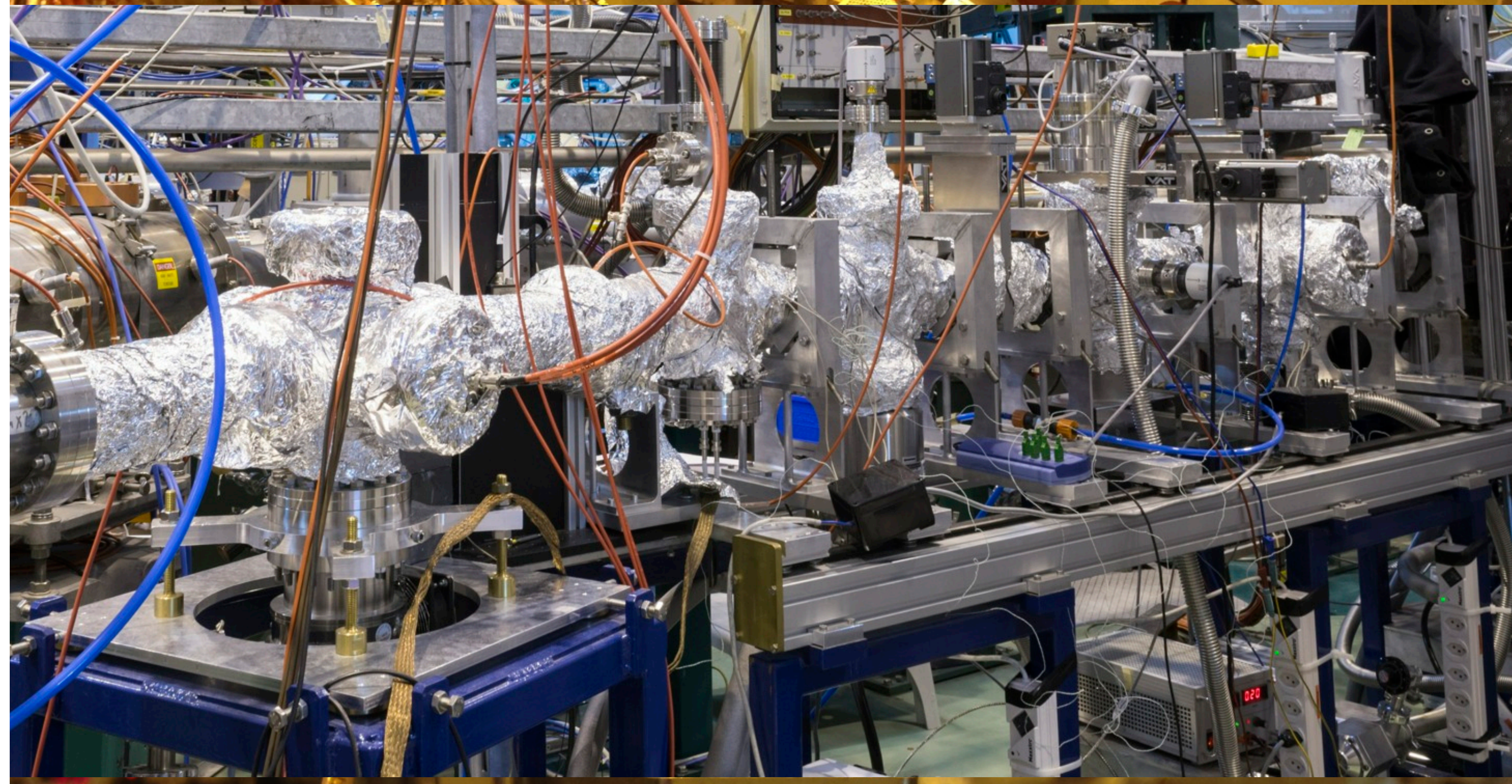
J. Billowes[1], F. Le Blanc[2], M. Bissell[3], P. Campbell[1], B. Cheal[1], K. T. Flanagan[2], D.H. Forest[4], E. Mane[1], G. Neyens[3], M. De Rydt[3], H.H. Stroke[5], B. Tastet[2], G. Tungate[4] and P. Vingerhoets[3]

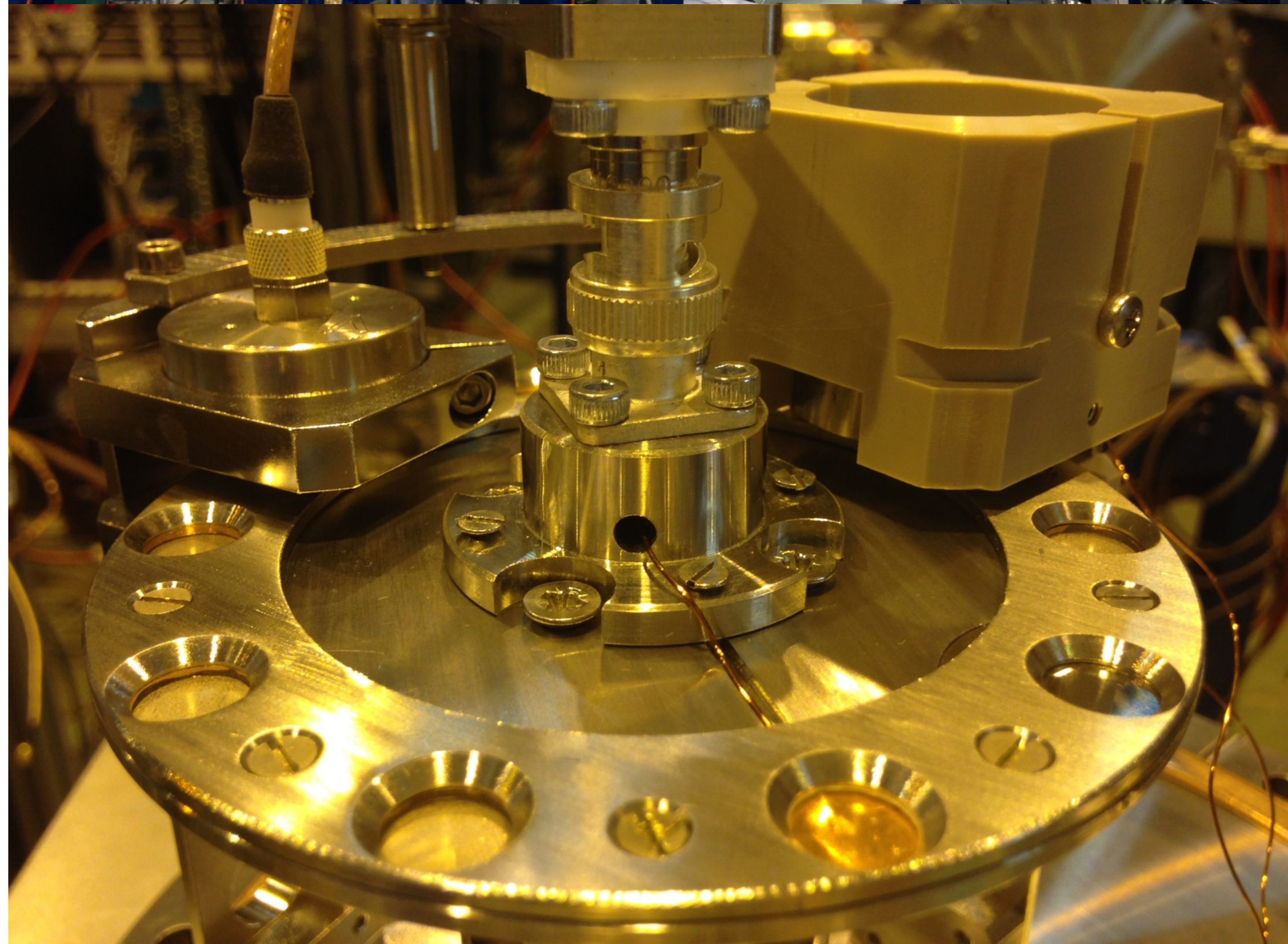
1. Nuclear Physics Group, School of Physics and Astronomy, The University of Manchester, M13 9PL, UK.
2. IPN Orsay, 15 Rue G Clemenceau, 91406, Orsay Cedex, France.
3. IKS, K.U.Leuven, B-3001, Leuven, Belgium.
4. School of Physics and Astronomy, The University of Birmingham, B15 2TT, UK.
5. Department of Physics, New York University, 4 Washington Place, New York, NY 10003, USA.

Spokesperson: K. T. Flanagan
Contactperson: M. Bissell

This programme requests in total 33 shifts of radioactive beam, which will be spread over several runs for a period of two years, commencing 2009.

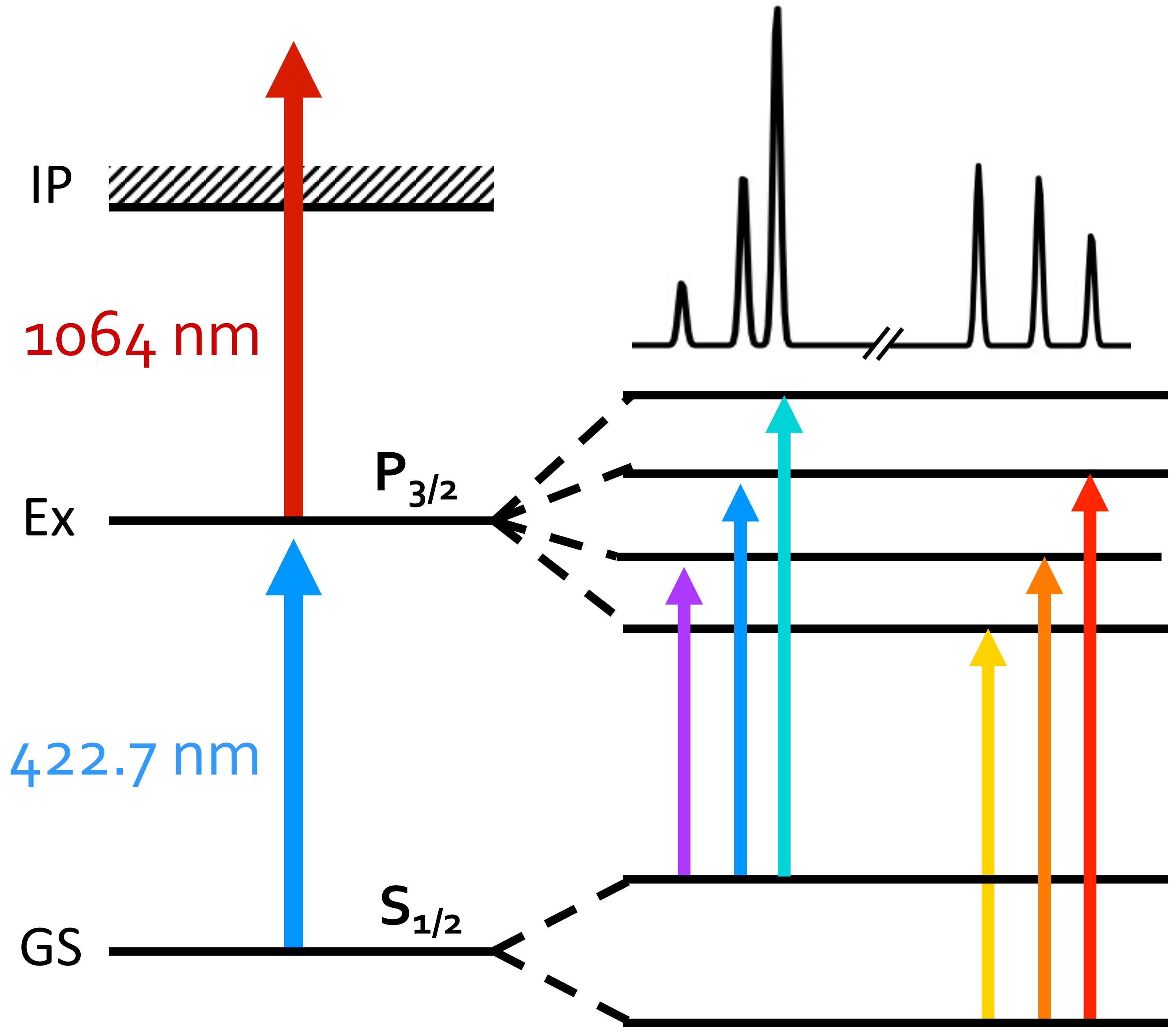


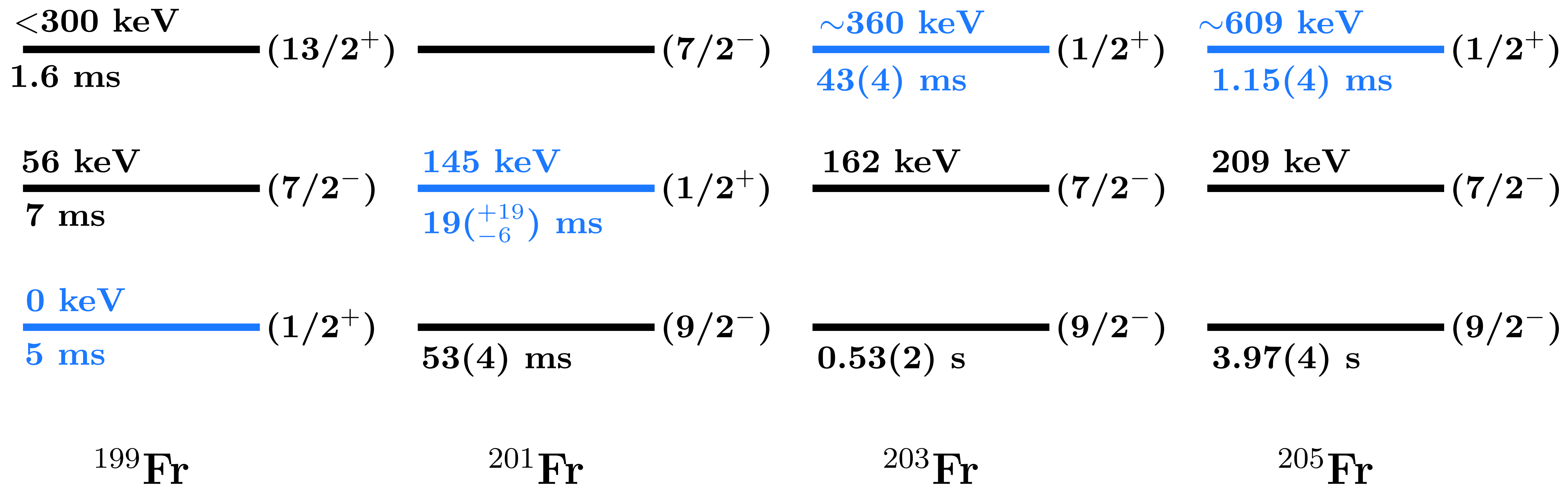




Neutron-deficient francium

- First experimental campaign at CRIS
- Study of evolution of nuclear structure towards ^{199}Fr
  - Reduction in energy of proton intruder state $(\pi s_{1/2}^{-1})$ ½+ in this region of the nuclear chart
  - $(\pi s_{1/2}^{-1})$ ½+ proton intruder state becomes the ground state in ^{195}At and ^{185}Bi
  - Suggestion that ^{199}Fr has I= ½$^{+}$ ground state spin with an associated large deformation
- Study of isotope/isomer shifts and electromagnetic moments will characterise this region

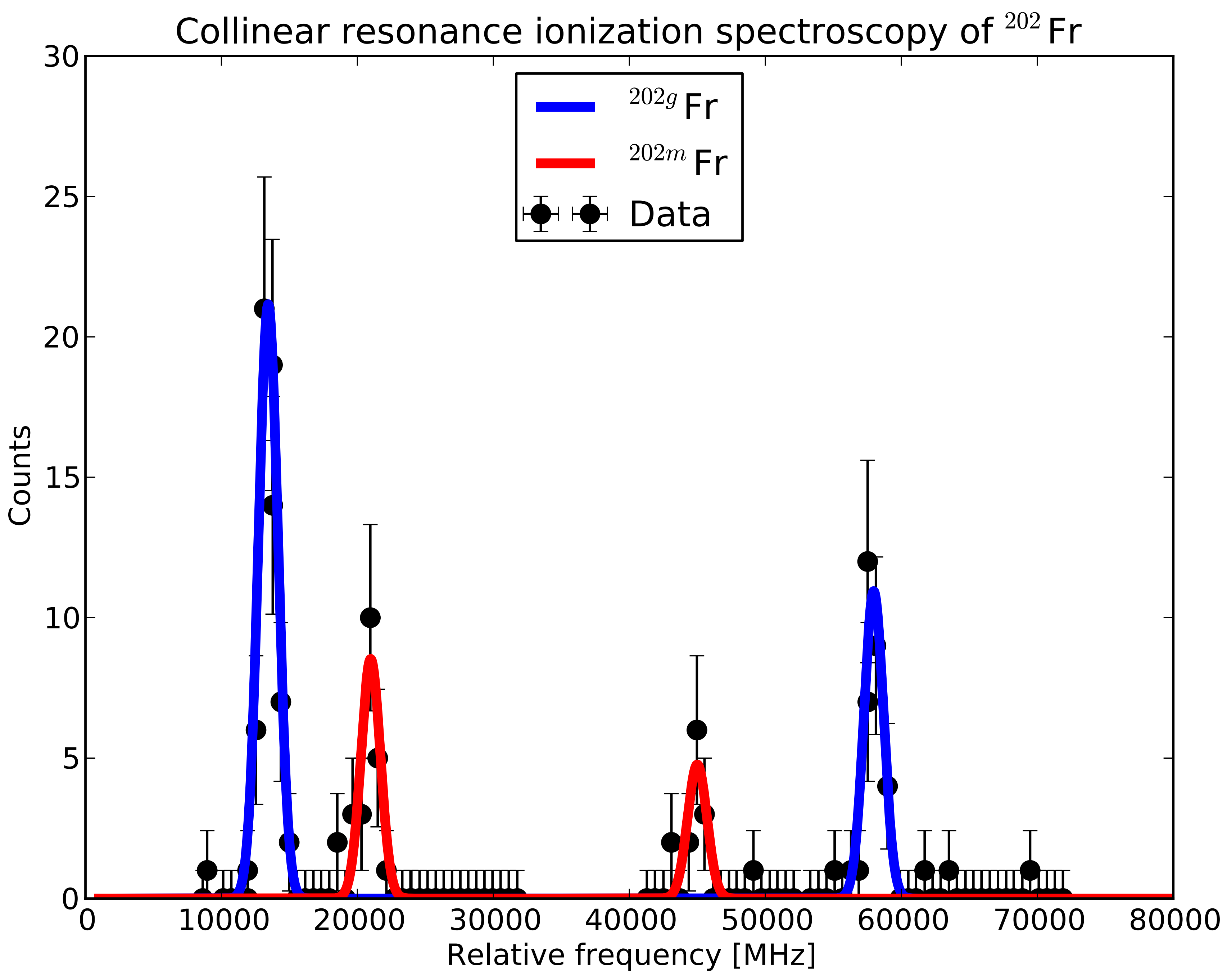


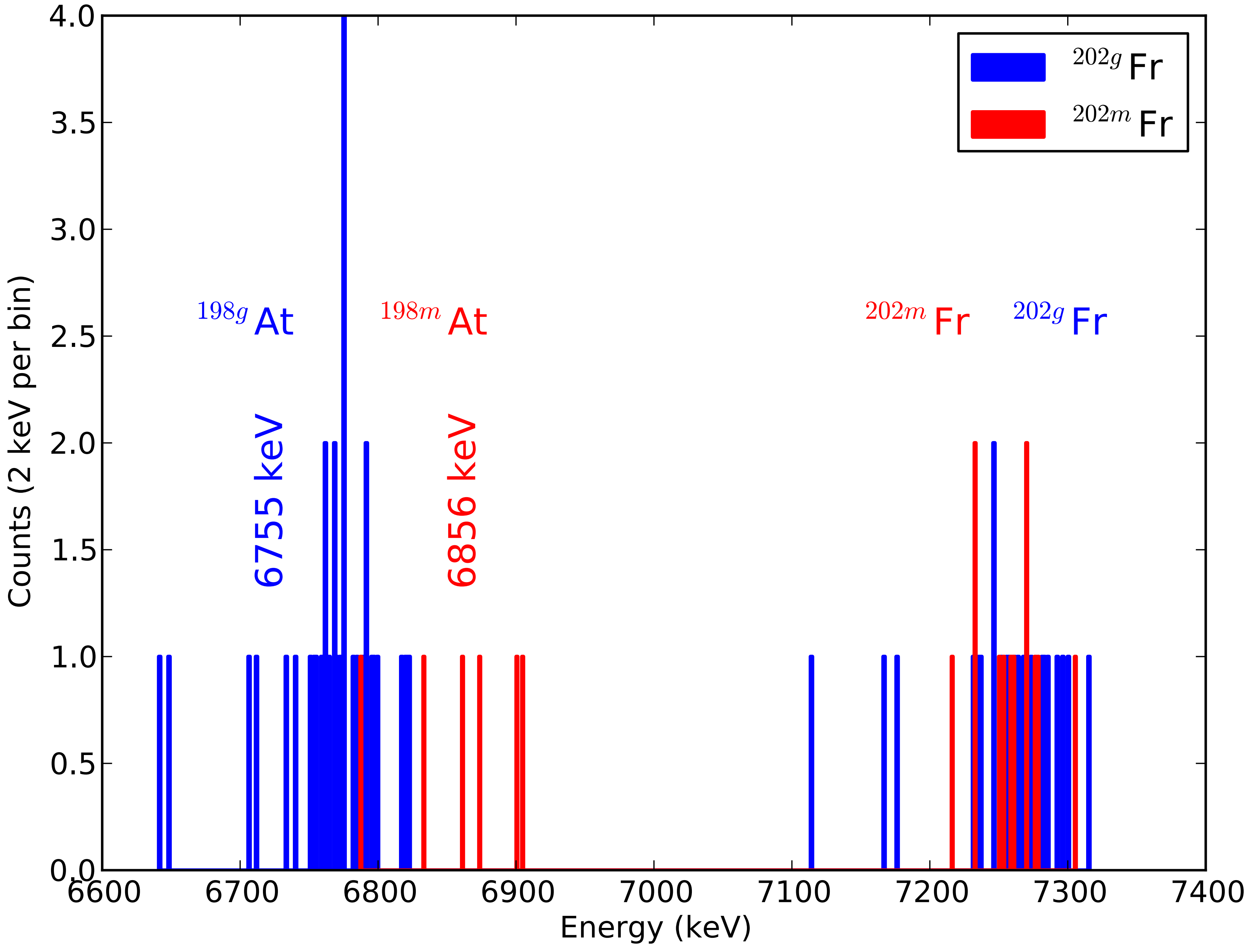


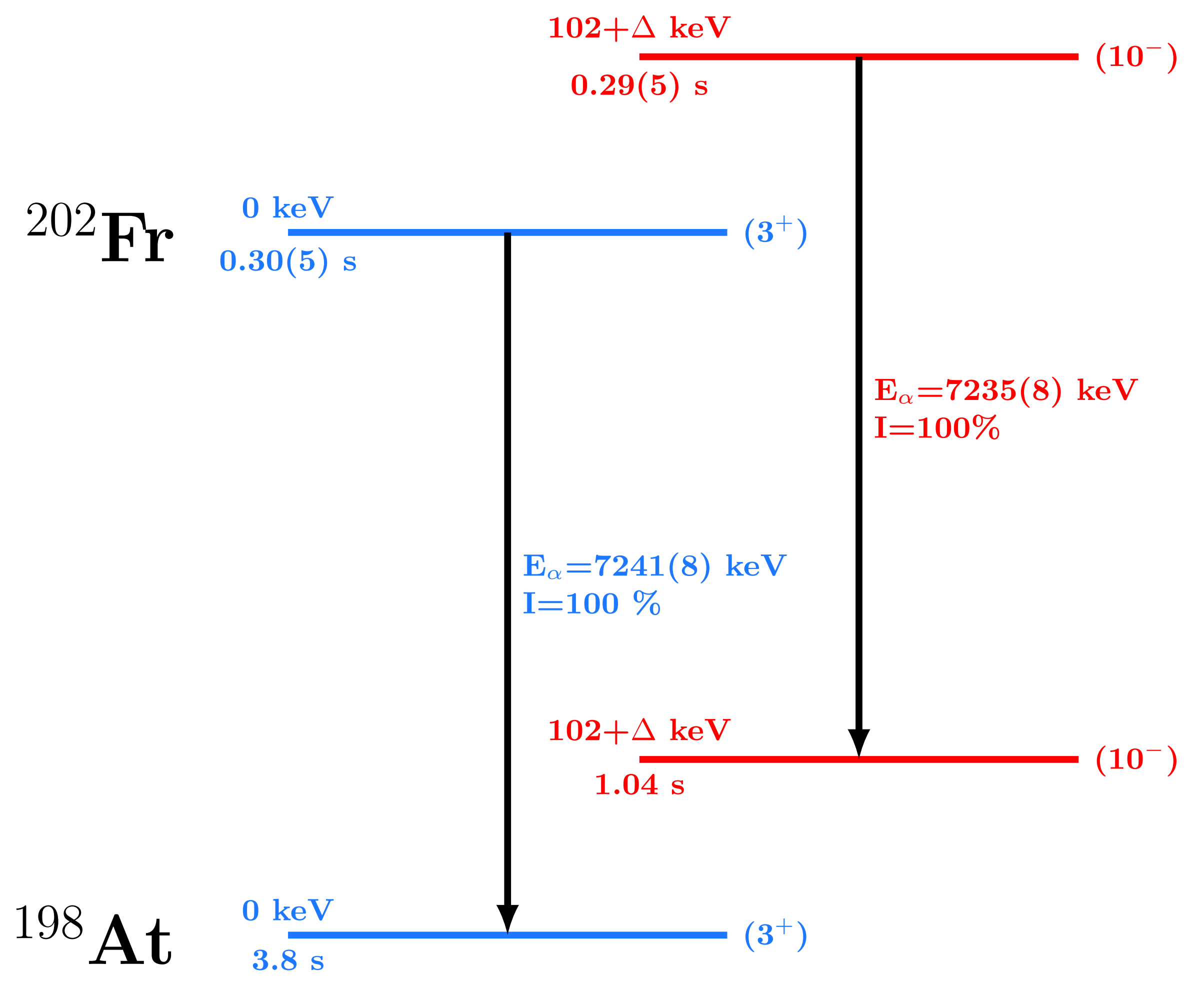
- Resonance ionization scheme:
  - 422 nm: Doubled light from M2 Ti:Sa system
  - 1064 nm: Light from Litron laser

J. Uusitalo *et al.*, Phys. Rev. C **71** 024306 (2005)
U. Jakobsson *et al.*, Phys. Rev. C **85** 014309 (2012)

Collinear resonance ionization spectroscopy of ^{202}Fr



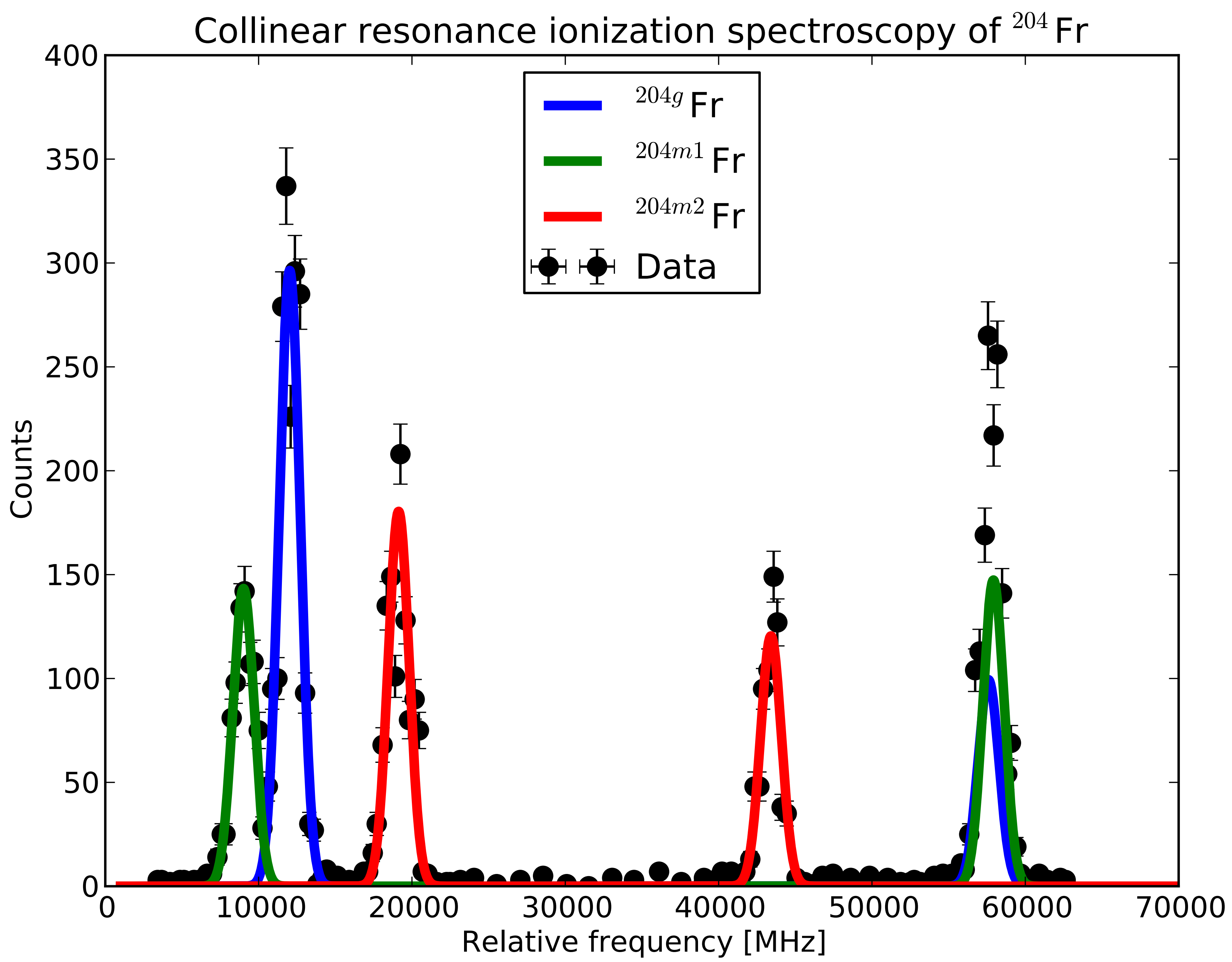


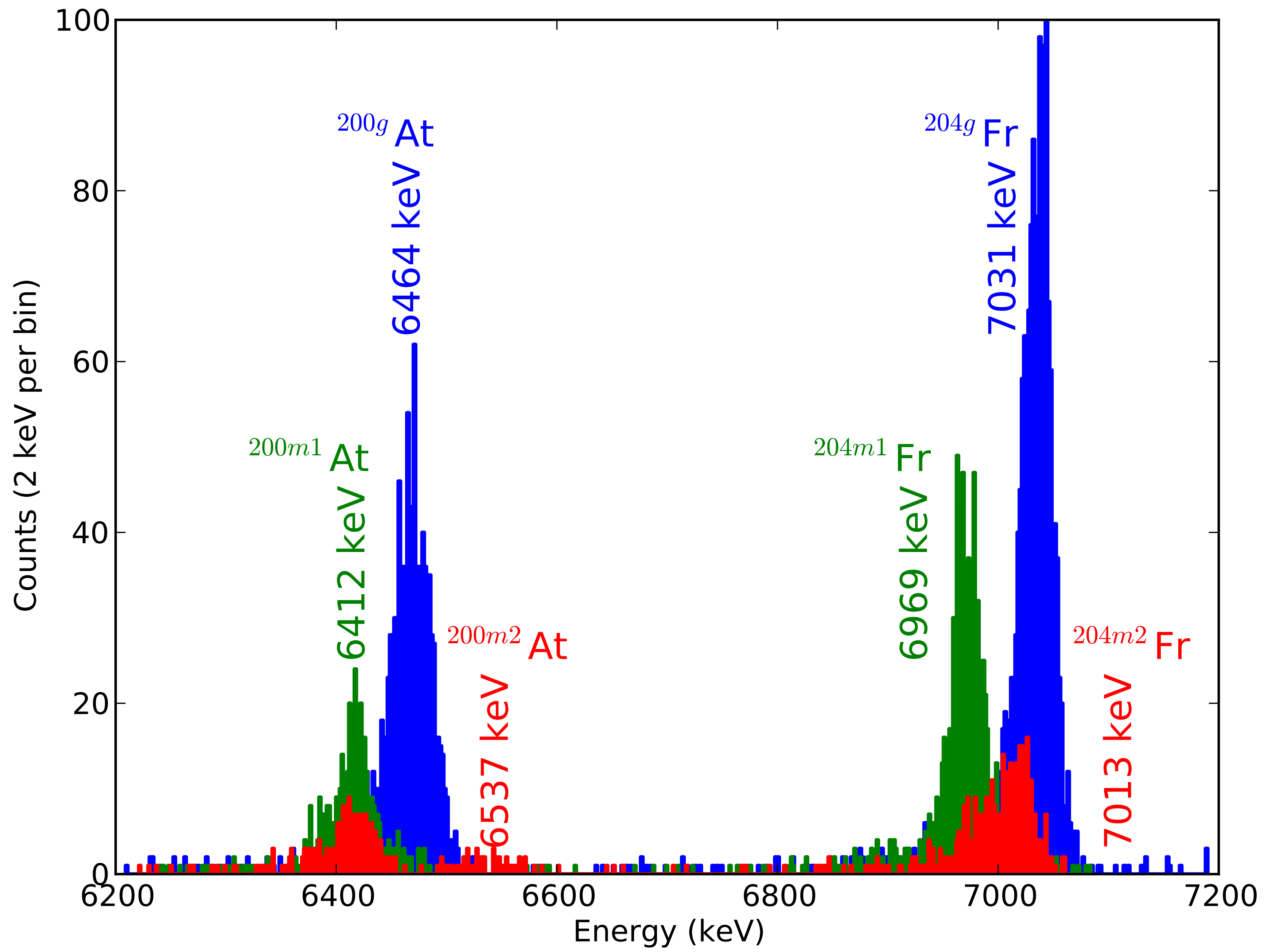


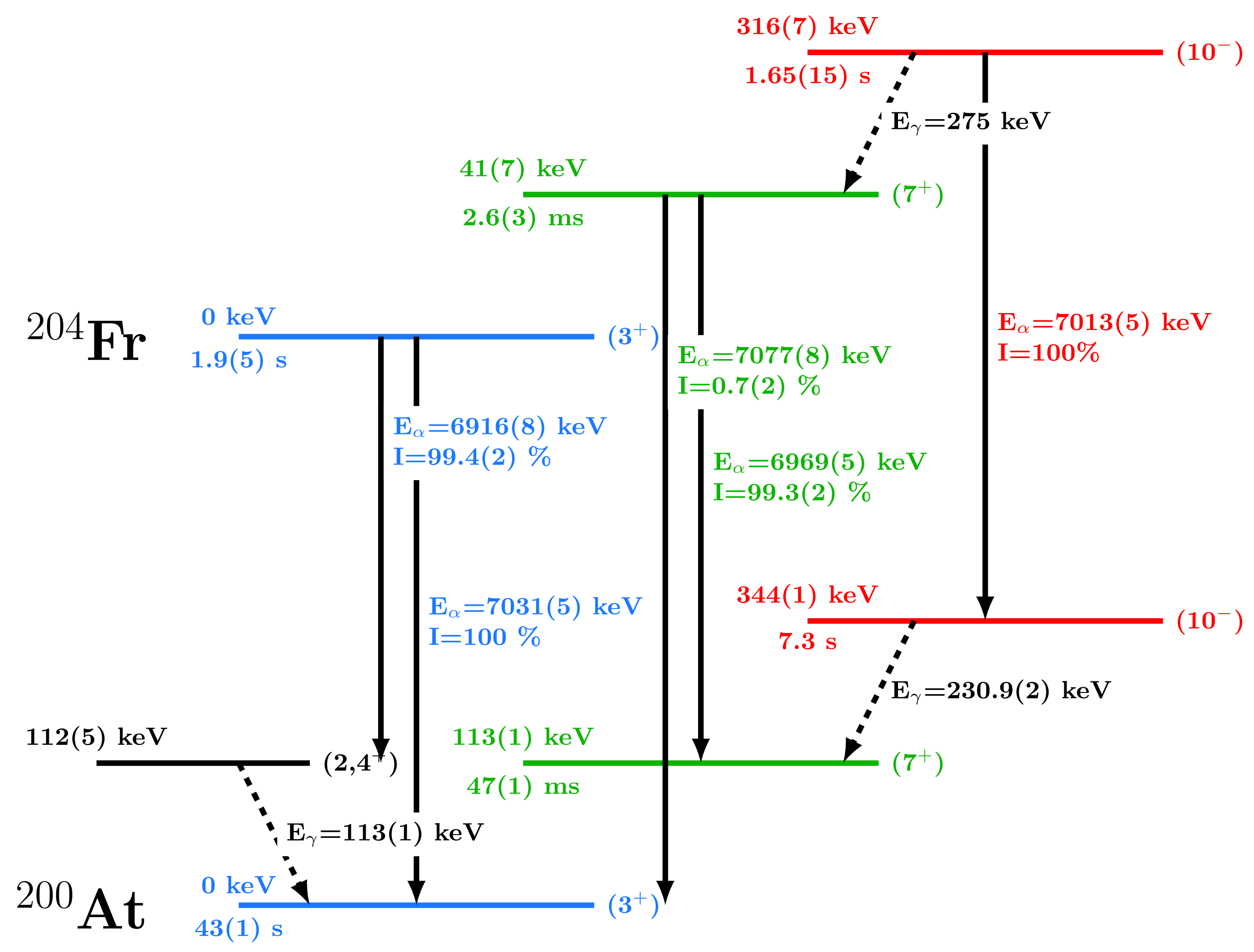
- Identity of hyperfine-structure resonances determined by alpha-decay energy
- Yield estimated to be 100 atoms/s
- Total experimental efficiency estimated to be 1%

K.M. Lynch *et al.*, Phys. Rev. X **4** 011055 (2014)

Collinear resonance ionization spectroscopy of ^{204}Fr



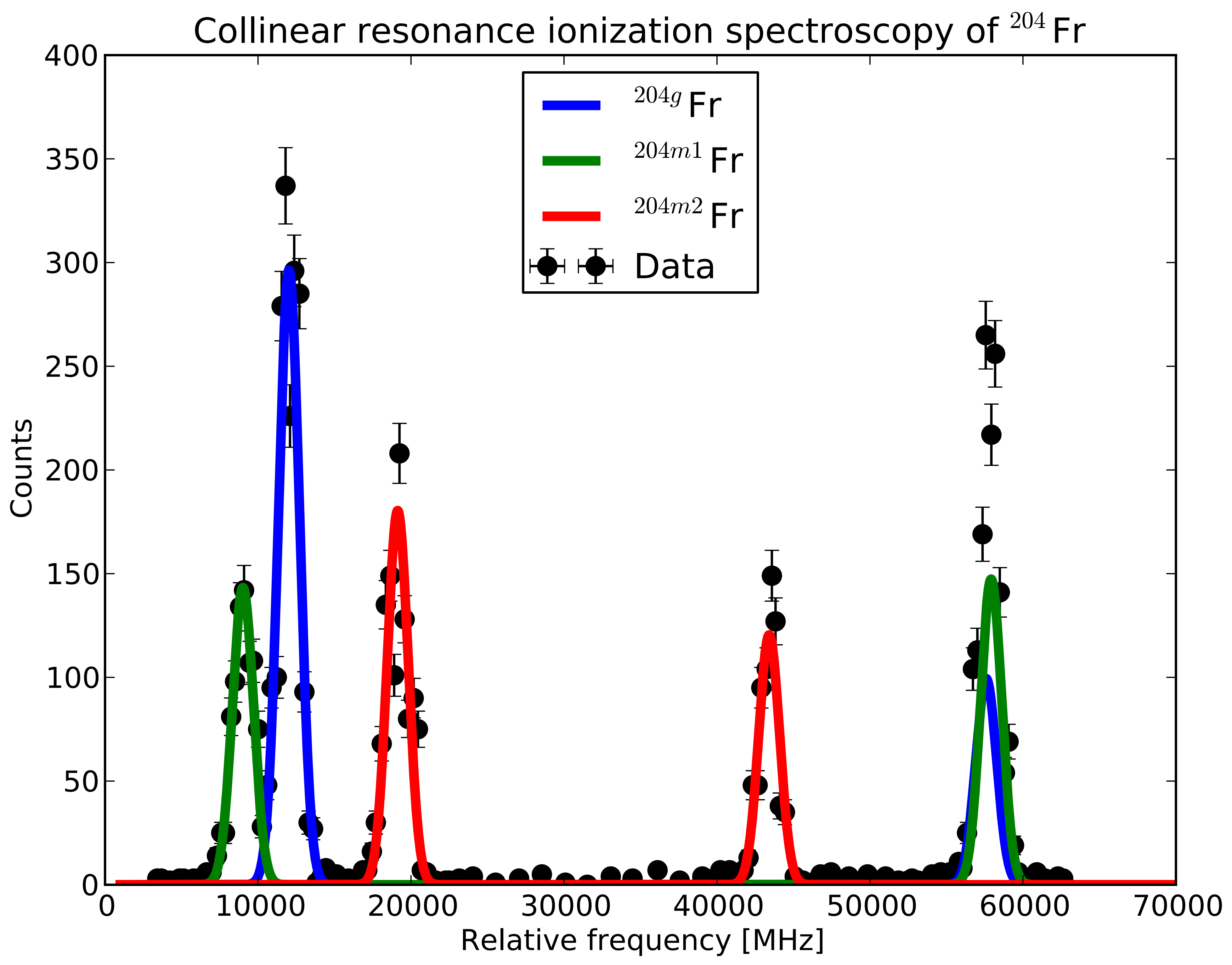


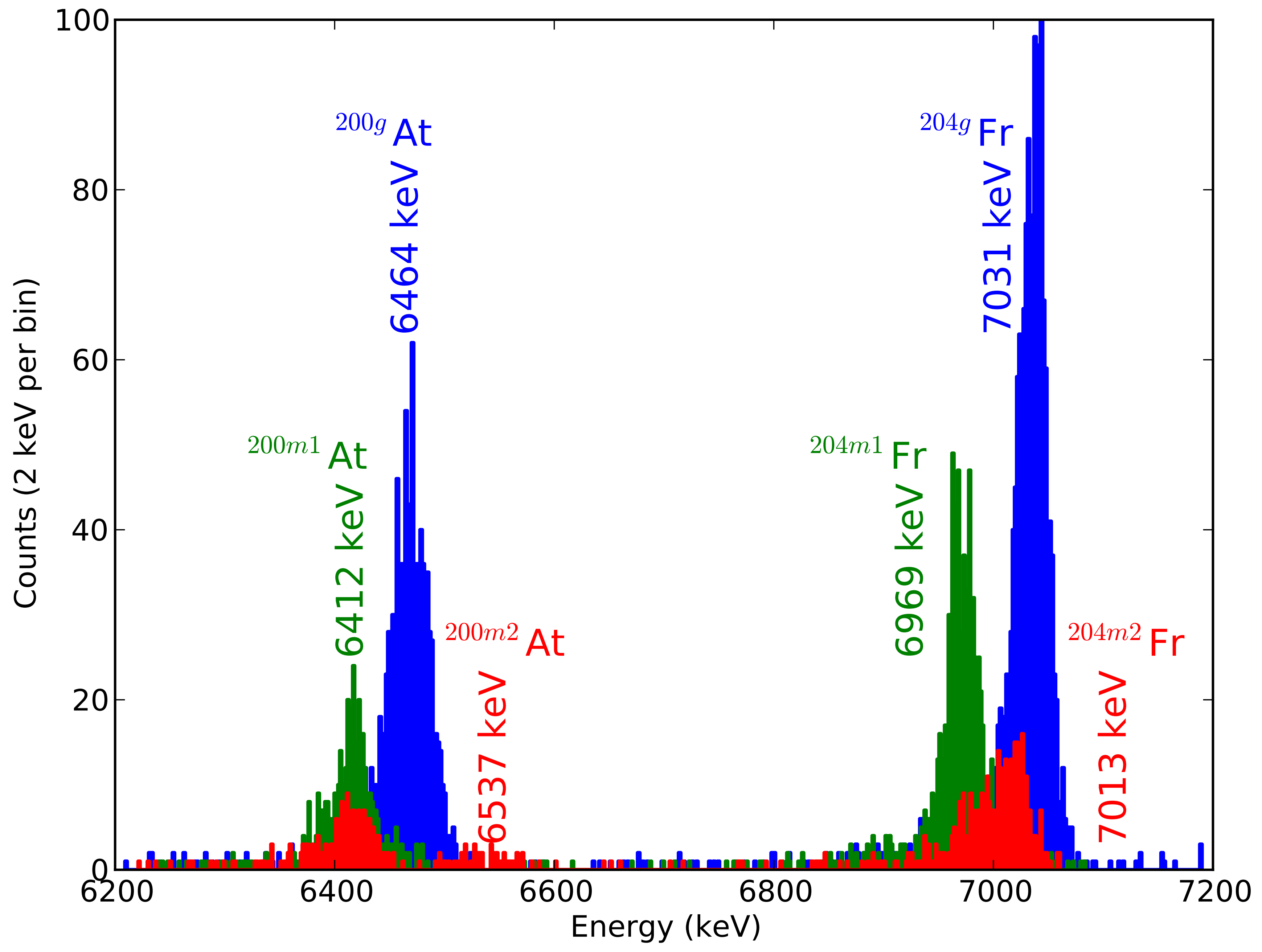


- Identity of hyperfine-structure resonances determined by alpha-decay energy

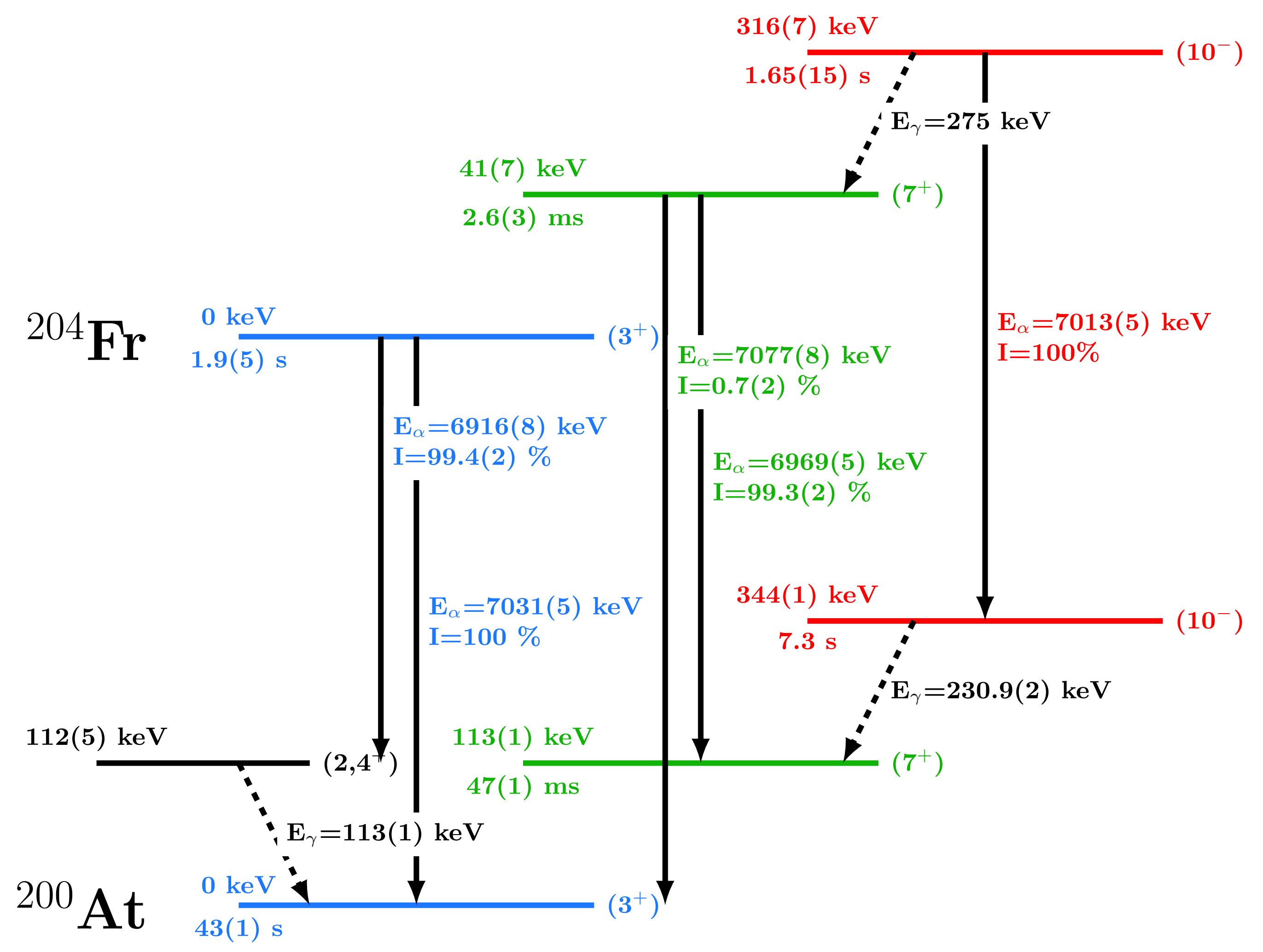
 K.M. Lynch *et al.*, Phys. Rev. X **4** 011055 (2014)

Collinear resonance ionization spectroscopy of ^{204}Fr



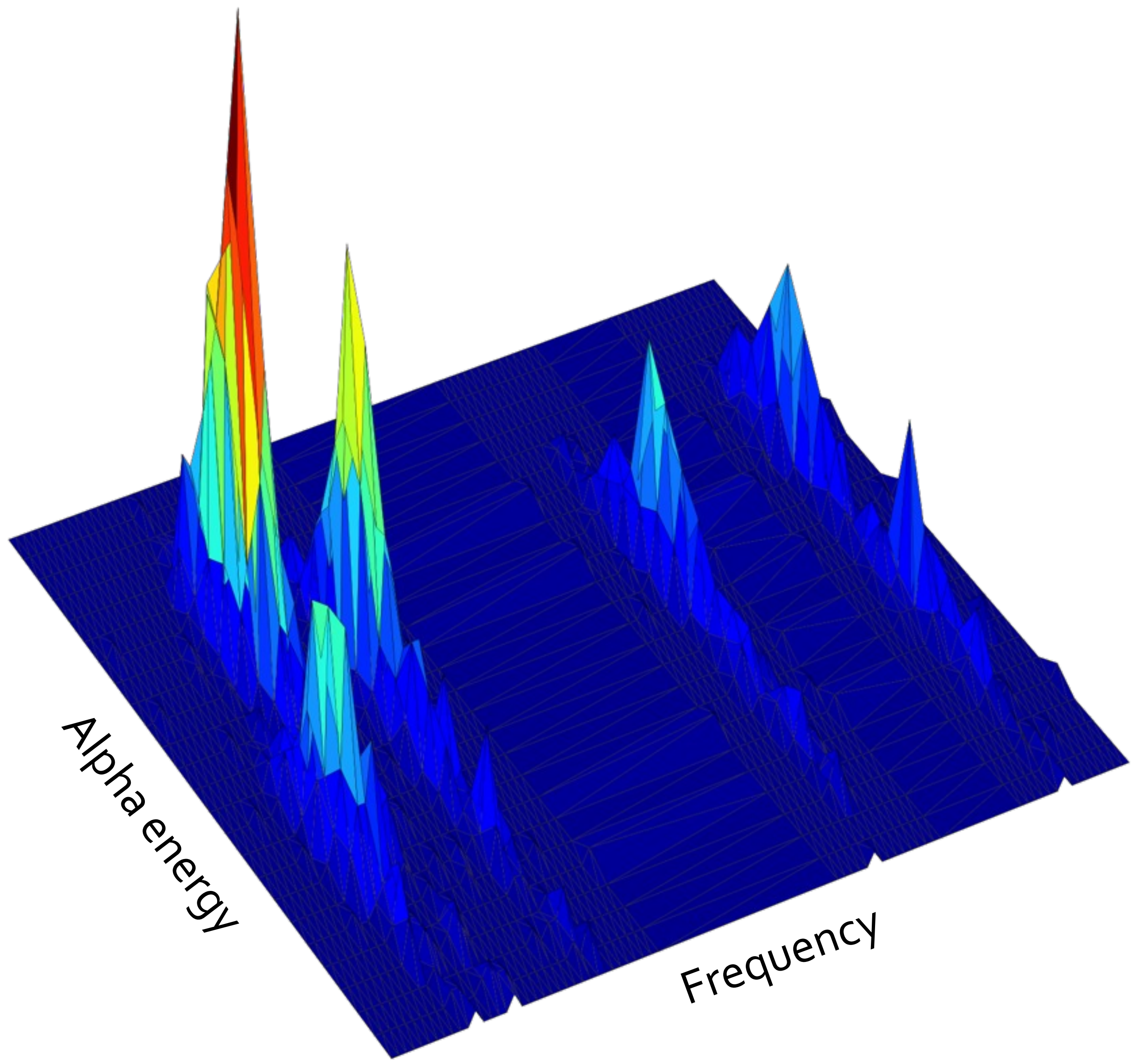


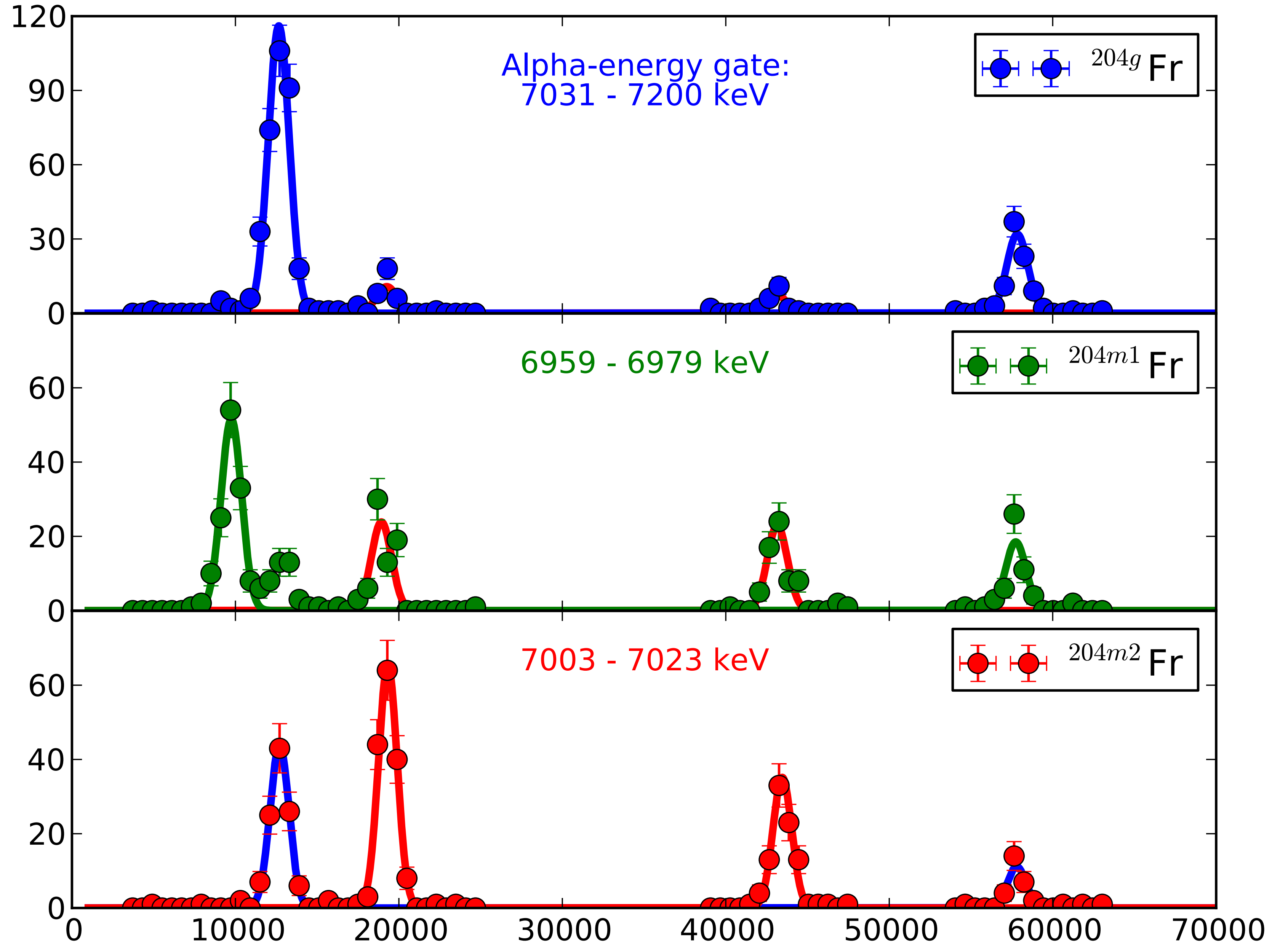
- The HFS of ^{204}Fr was scanned across
  - Decay measurement was taken every frequency step
- Gate on energy of alpha particle to enhance hyperfine structure of $3^{(+)}$, $7^{(+)}$ and $10^{(-)}$ states of ^{204}Fr
- Alpha-tagging allows hyperfine-structures to be disentangled



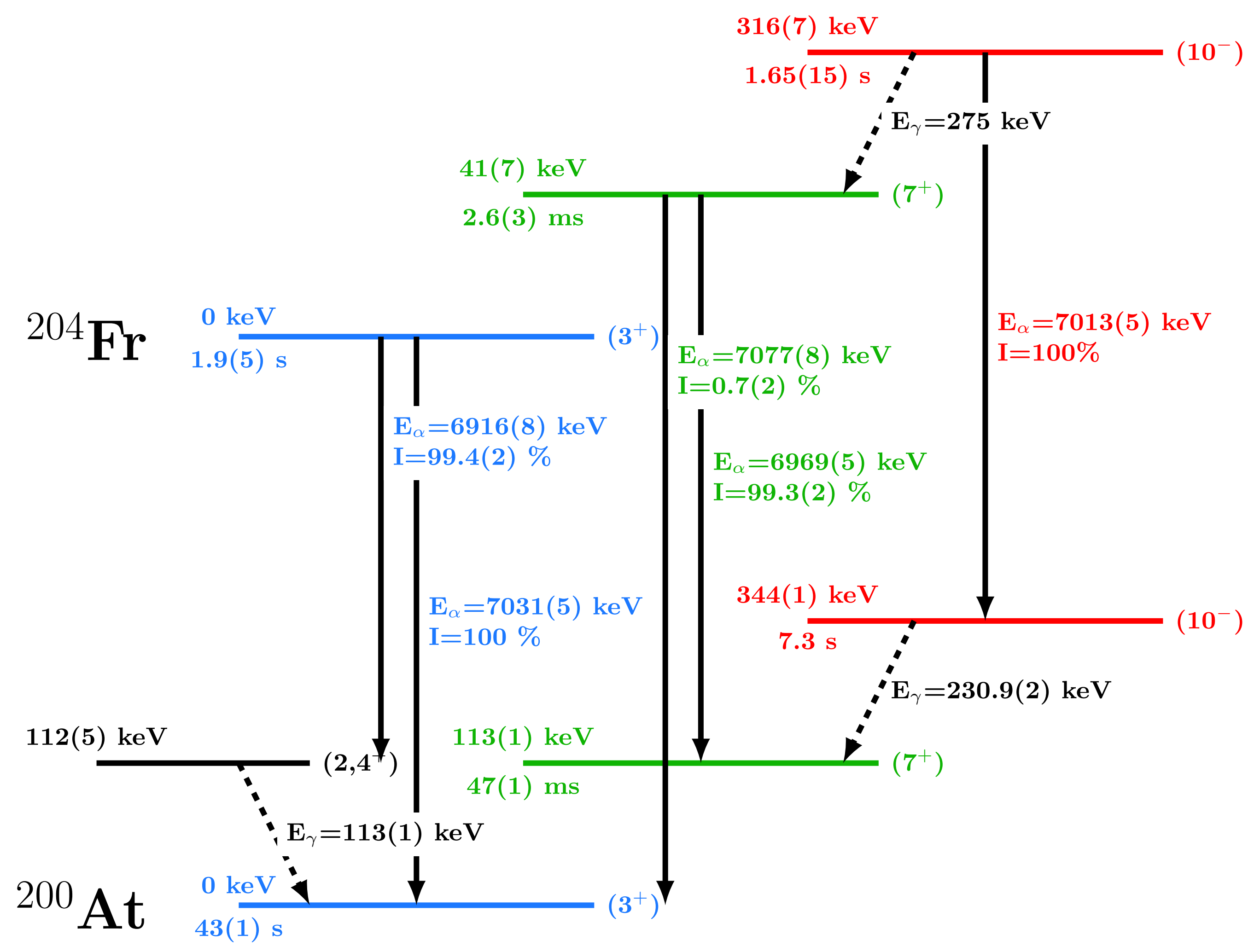
K.M. Lynch *et al.*, Phys. Rev. X **4** 011055 (2014)

Collinear resonance ionization spectroscopy of ^{204}Fr





- The HFS of ^{204}Fr was scanned across
  - Decay measurement was taken every frequency step
- Gate on energy of alpha particle to enhance hyperfine structure of ^{204g}Fr, ^{204m1}Fr and ^{204m2}Fr isomers
- Alpha-tagging allows hyperfine-structures to be disentangled



 K.M. Lynch *et al.*, Phys. Rev. X **4** 011055 (2014)

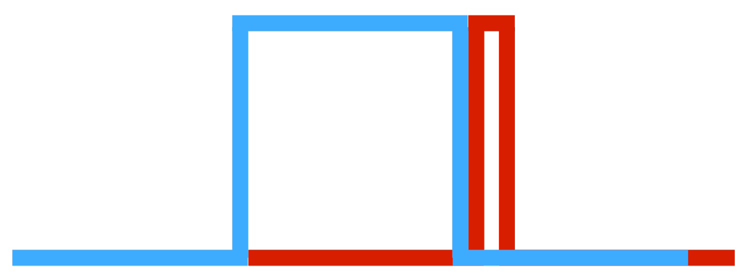
Evolution of resolution

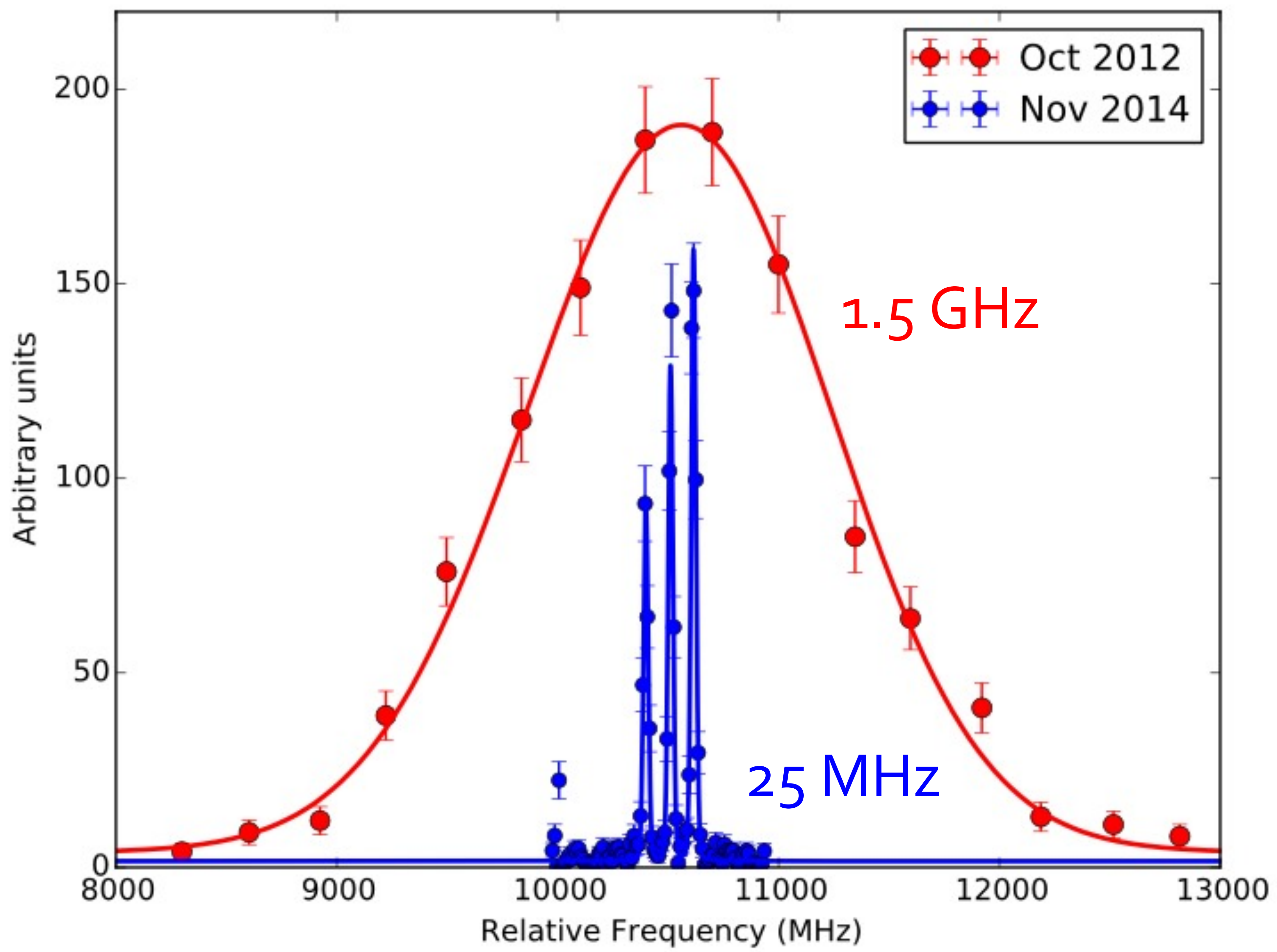
October 2012
- Fibre-coupled light from narrow-band Ti:Sa laser (RILIS)

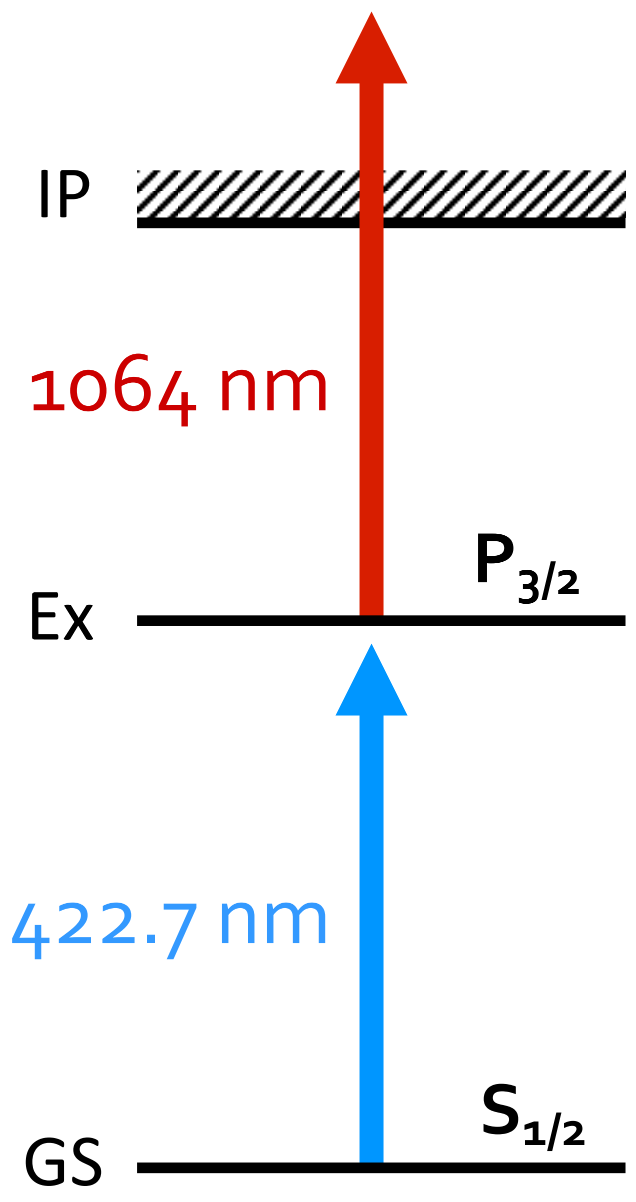
November 2014
- CW laser light from Matisse Ti:Sa laser (COLLAPS) was chopped into pulses

November 2015
- CW laser light from new M2 Ti:Sa laser (CRIS) was chopped into pulses

- The 1064 nm ionization step was delayed after start of the 422 nm excitation step
- Smaller linewidths were achieved
- Upper-state splitting could now be resolved
- Extraction of quadrupole moments

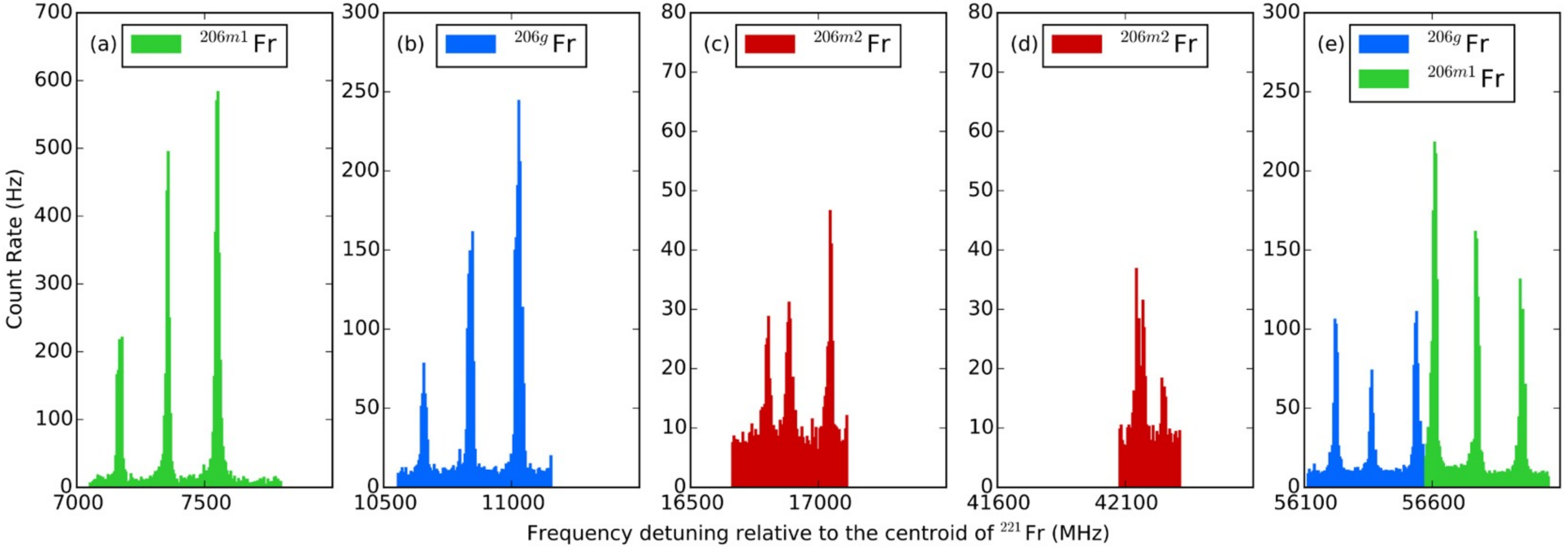


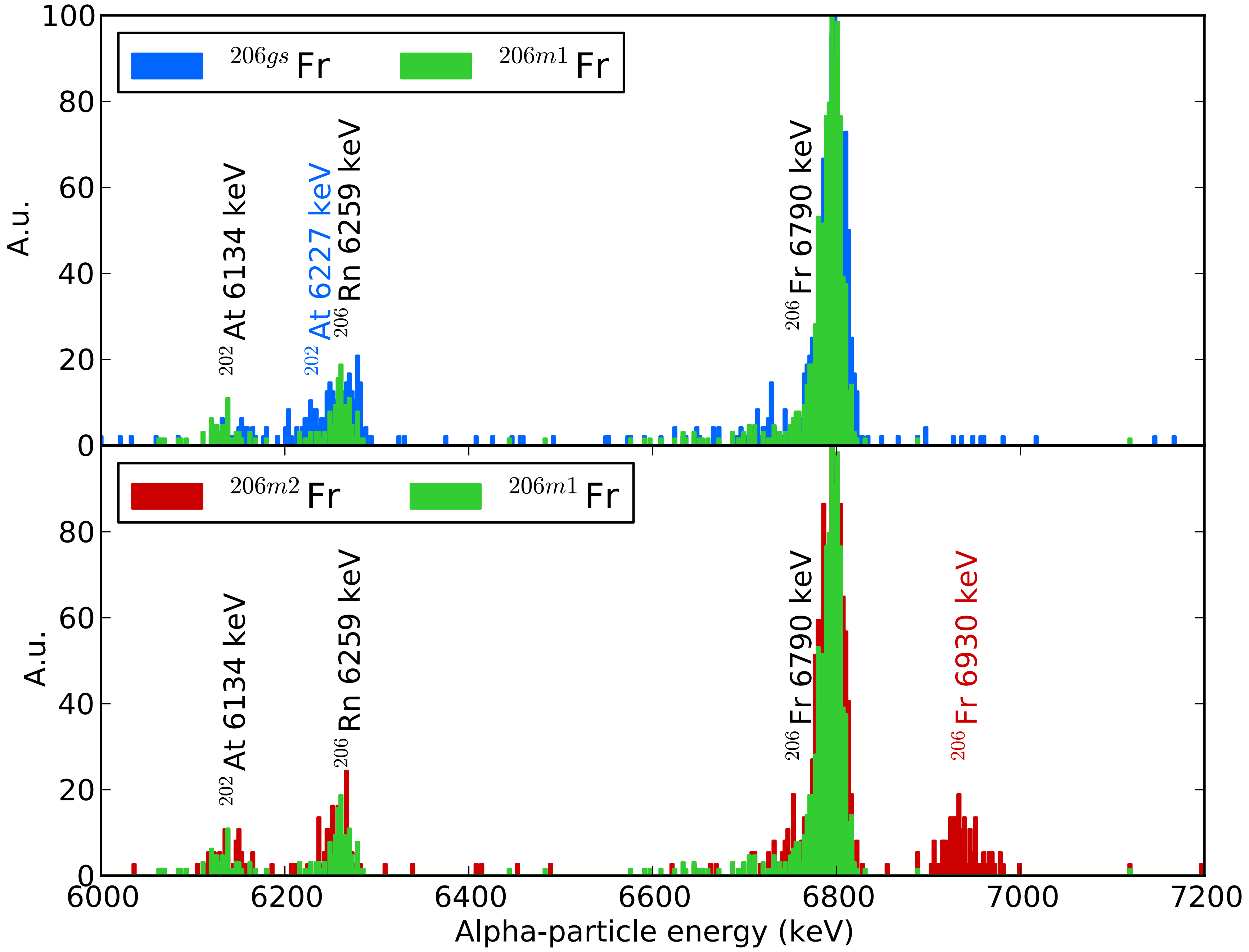


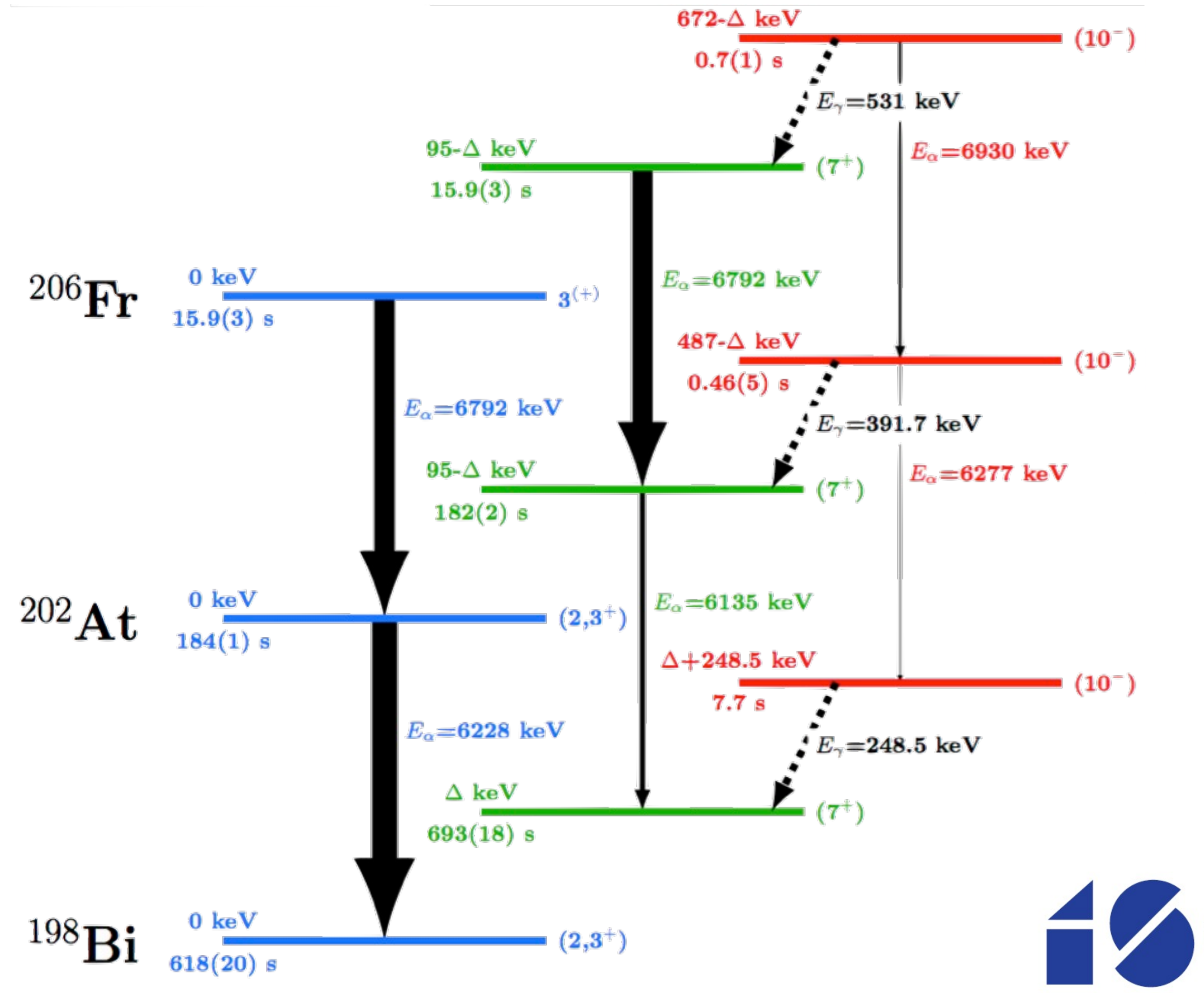


R.P. de Groote et al., Phys. Rev. Lett. **115** 132501 (2015)

Collinear resonance ionization spectroscopy of ^{206}Fr





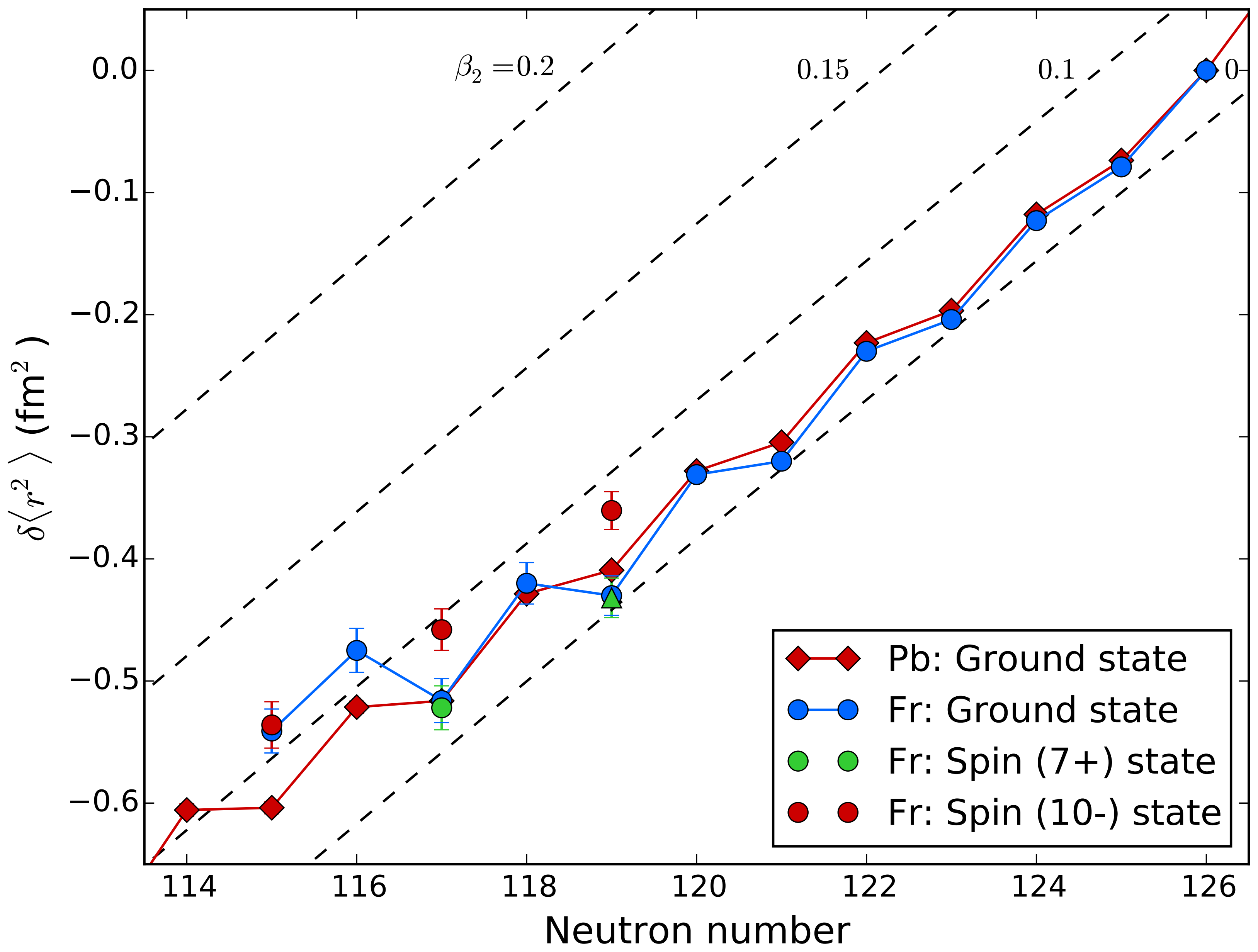


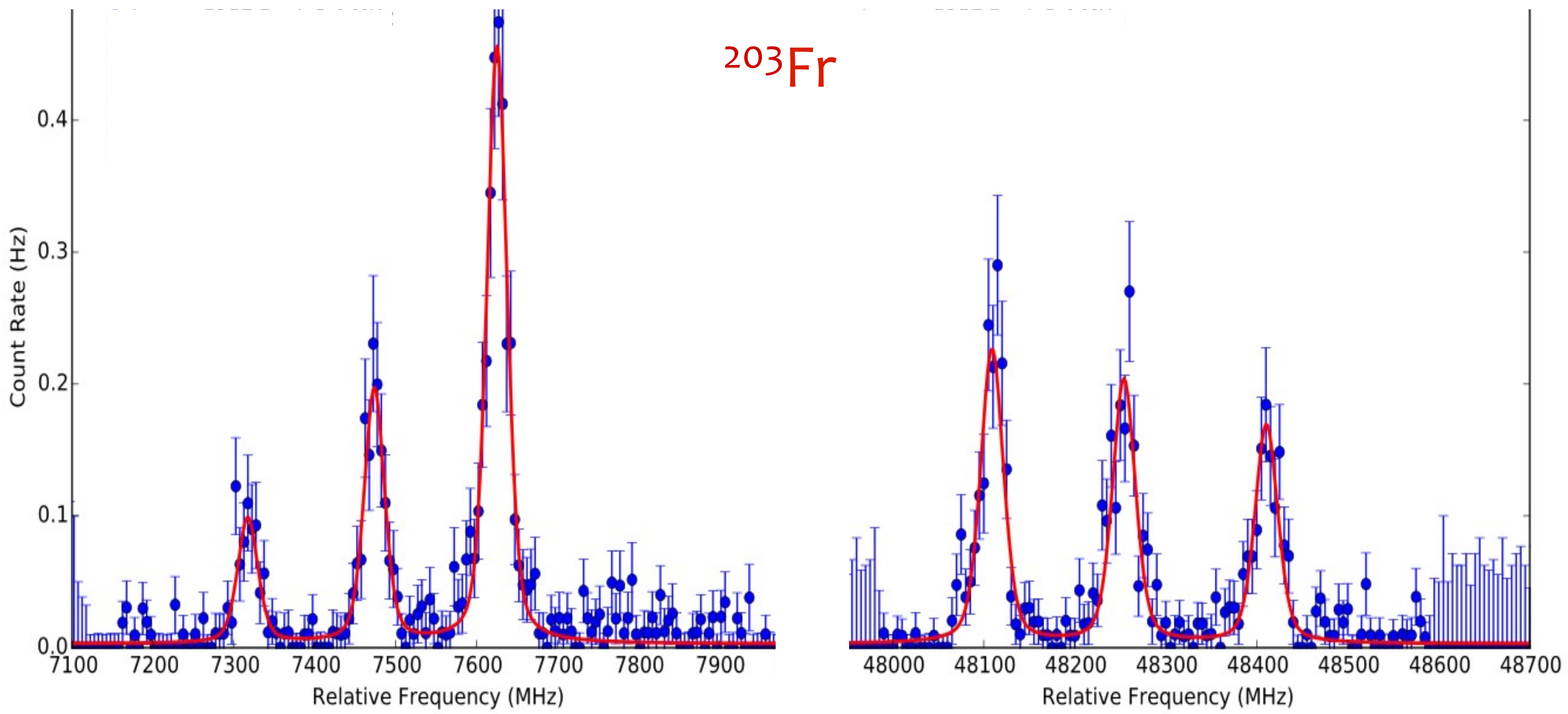
- Hyperfine structure of 3(+), 7(+) and 10(-) states of ^{206}Fr measured
- Laser-assisted nuclear decay spectroscopy performed on each state
- Branching ratios of ^{206}Fr and ^{202}At

K.M. Lynch et al., Phys. Rev. C, **93** 014319 (2016)

Change in mean-square charge radii

$$\delta\upsilon^{AA'} = M\frac{A'-A}{AA'} + F\delta\langle r^2\rangle^{AA'}$$



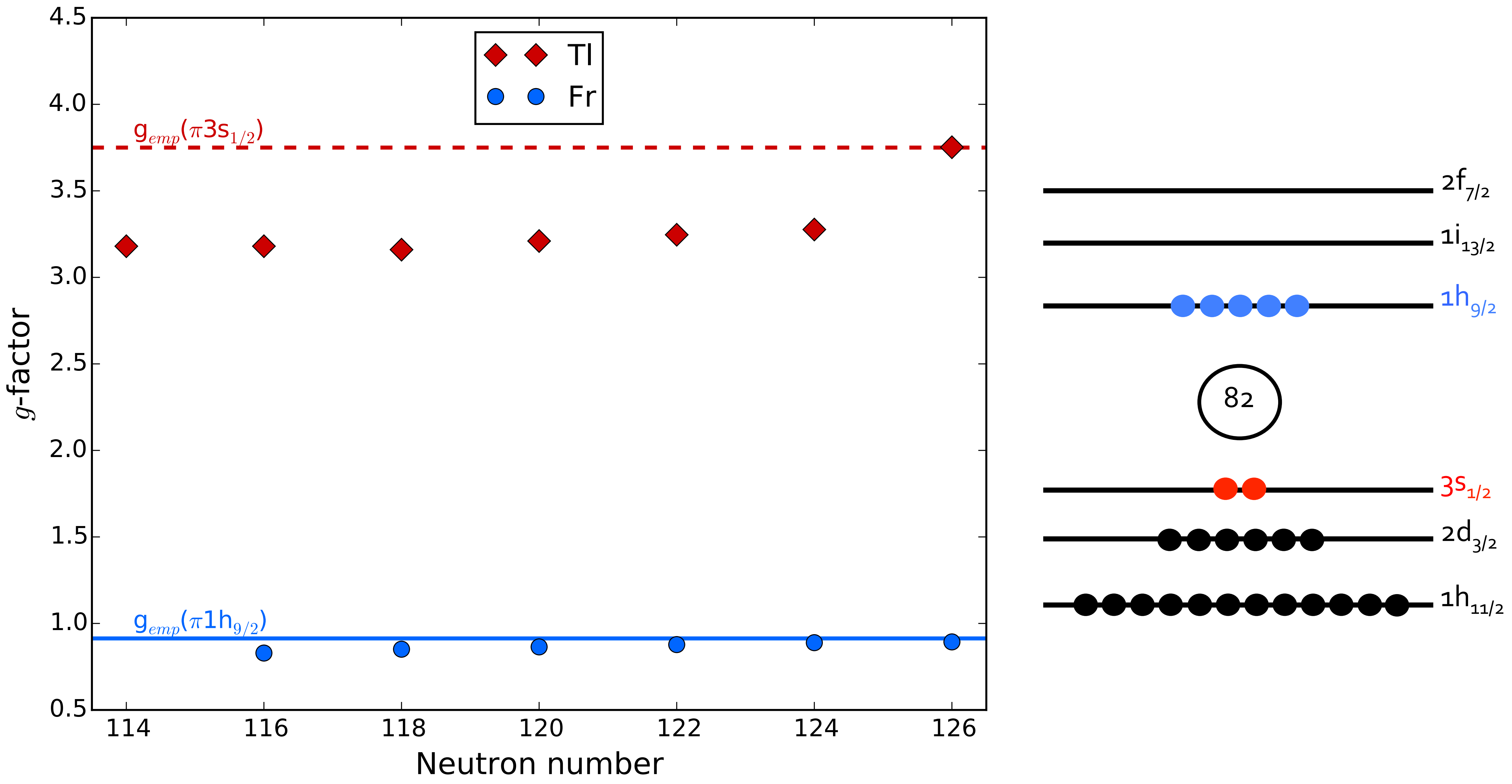


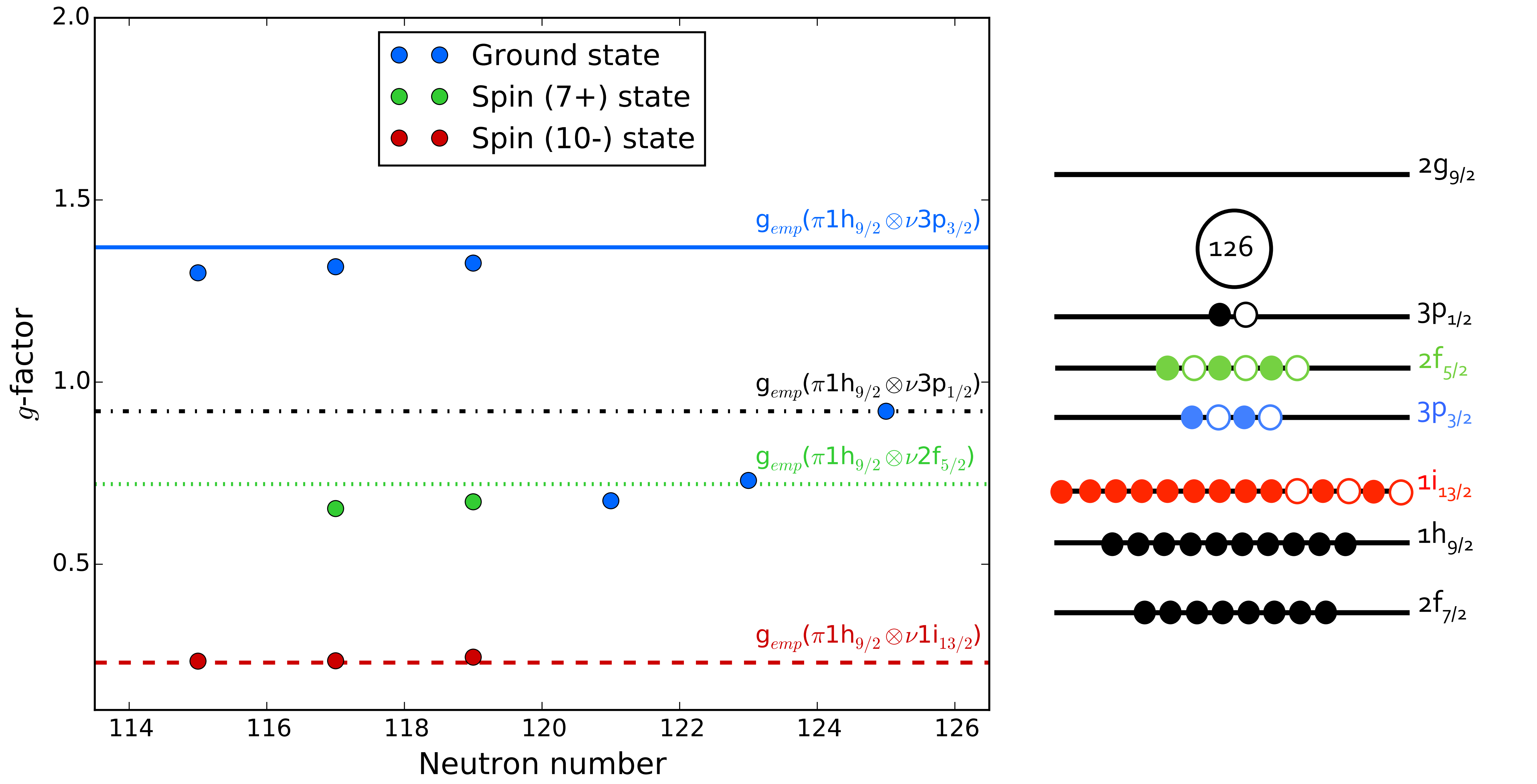
- Deviation from Pb (Z=82) charge radii trend at ^{203}Fr (N=116)
  - Marks onset of collective behaviour
  - Measure quadrupole moment to determine static deformation

- First measurement of quadrupole moment of ^{203}Fr
- Searched for ½+ isomer ($t_{1/2}$= 60 ms) but ran out of time
- Data analysis ongoing…

g-factors

$$g = \frac{\mu_I}{I}$$





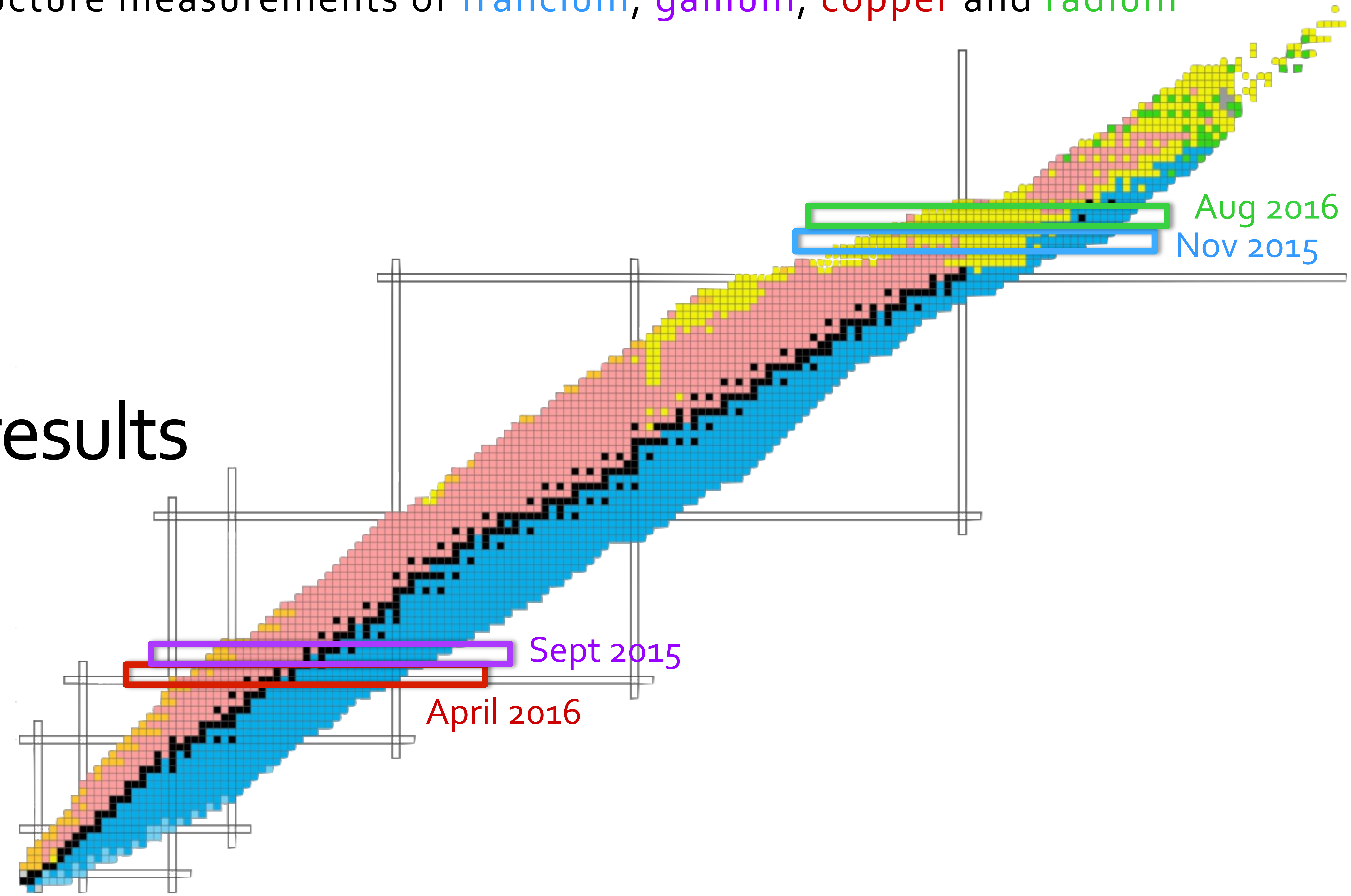
- Ground state $(\pi 1h_{9/2})$ configuration down to ^{203}Fr
  - Proton intruder state $(\pi 3s_{1/2})$ not yet inverted with the ground state

- Ground state configuration of ^{202,204}Fr determined to be $(\pi 1h_{9/2})(\nu 3p_{3/2})$
  - Configuration in literature is $(\pi 1h_{9/2})(\nu 2f_{5/2})$ based on Fr-At-Bi alpha-decay systematics
  - Initially a choice between $(\pi 1h_{9/2})(\nu 2f_{5/2})$ and $(\pi 1h_{9/2})(\nu 3p_{3/2})$ in the literature

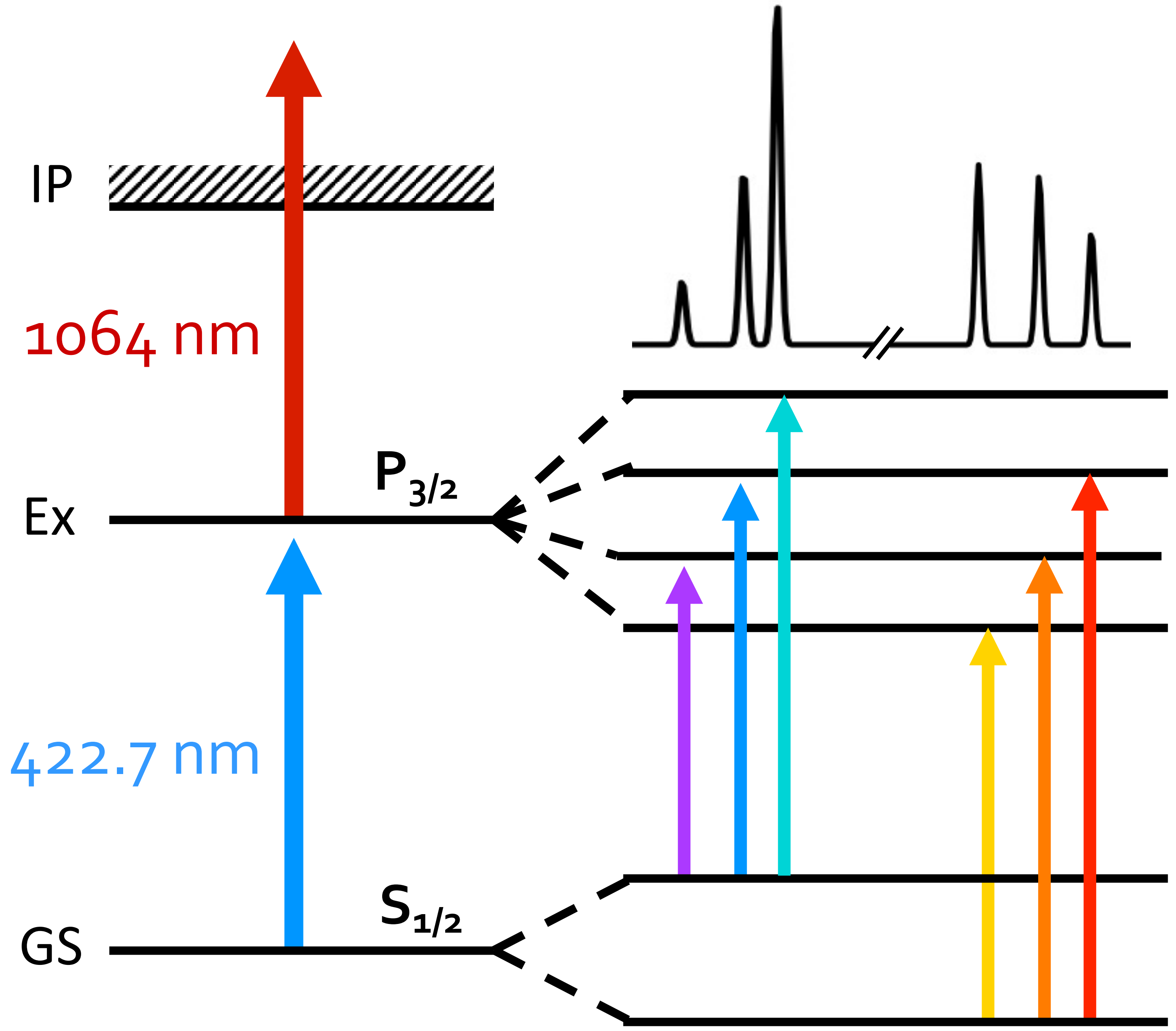
K.T. Flanagan *et al.*, Phys. Rev. Lett. **111** 212501 (2013)
K.M. Lynch *et al.*, Phys. Rev. X **4** 011055 (2014)
S. Zhu, F. Kondev, NDS 109, 699 (2008)
P. Van Duppen et al., NP A 529, 268 (1991)

Hyperfine-structure measurements of francium, gallium, copper and radium

Recent results

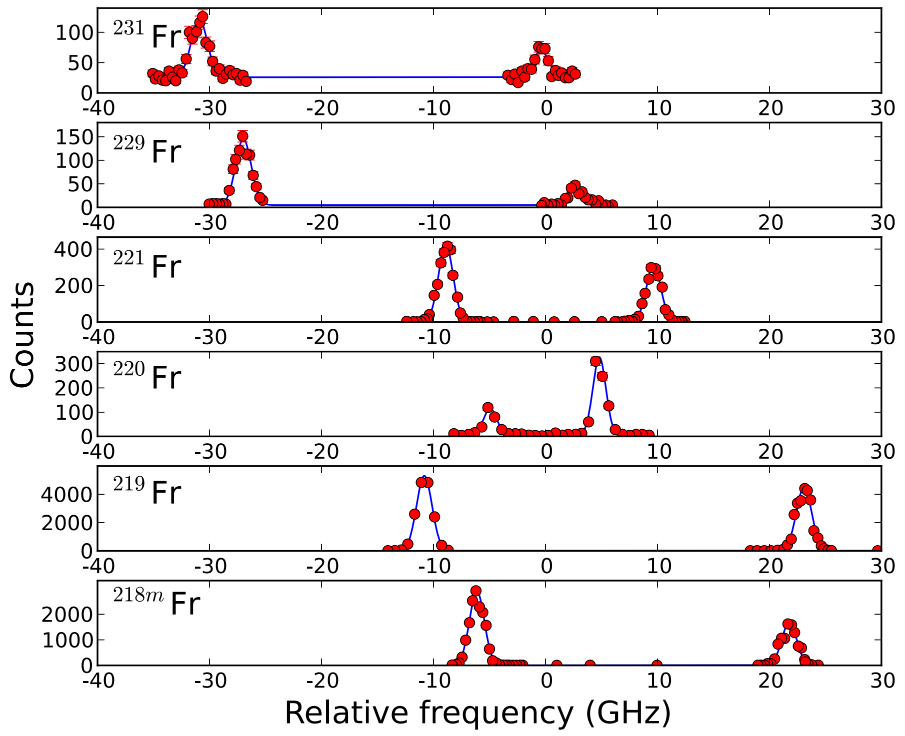


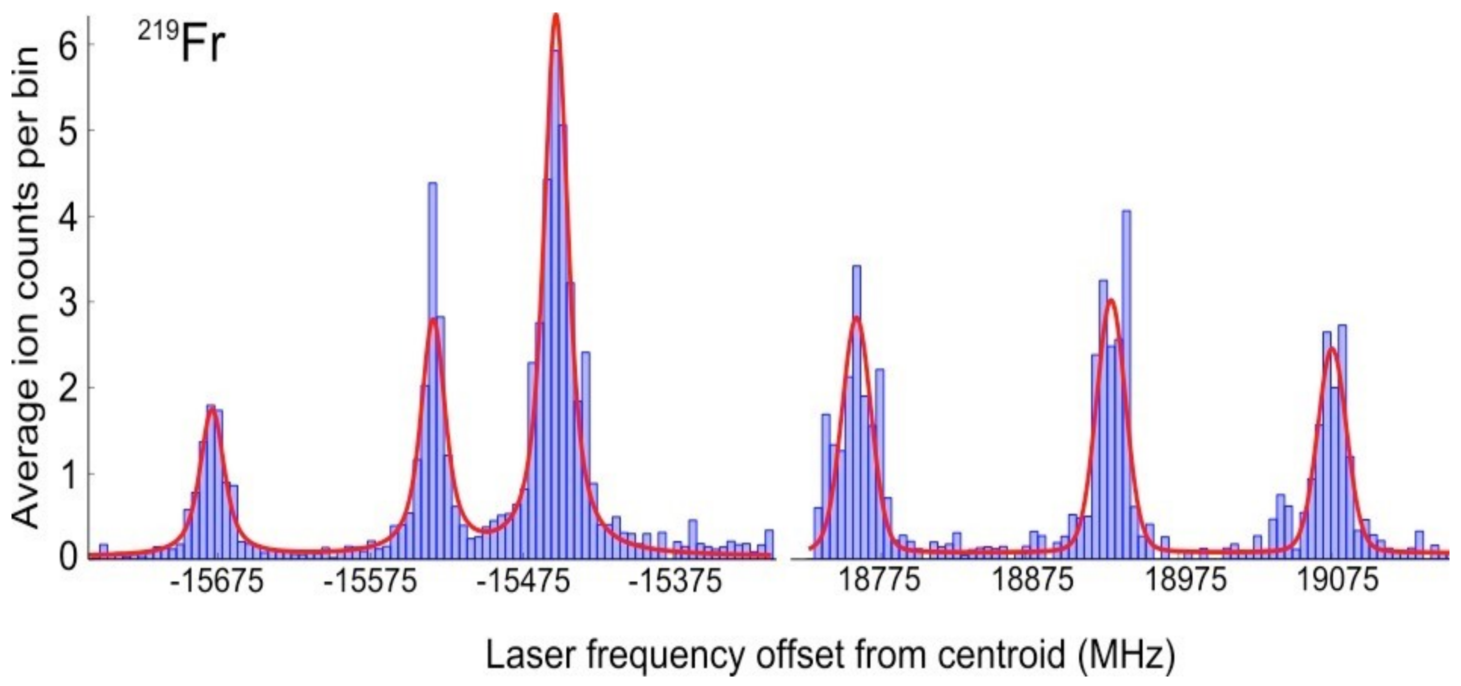
Neutron-rich francium



- Neutron-rich isotopes at border of reflection asymmetry
  - Spin of ^{229,231}Fr suggest gs is proton-intruder orbital

I. Budincevic et al., Phys. Rev. C **90** 014317 (2014)



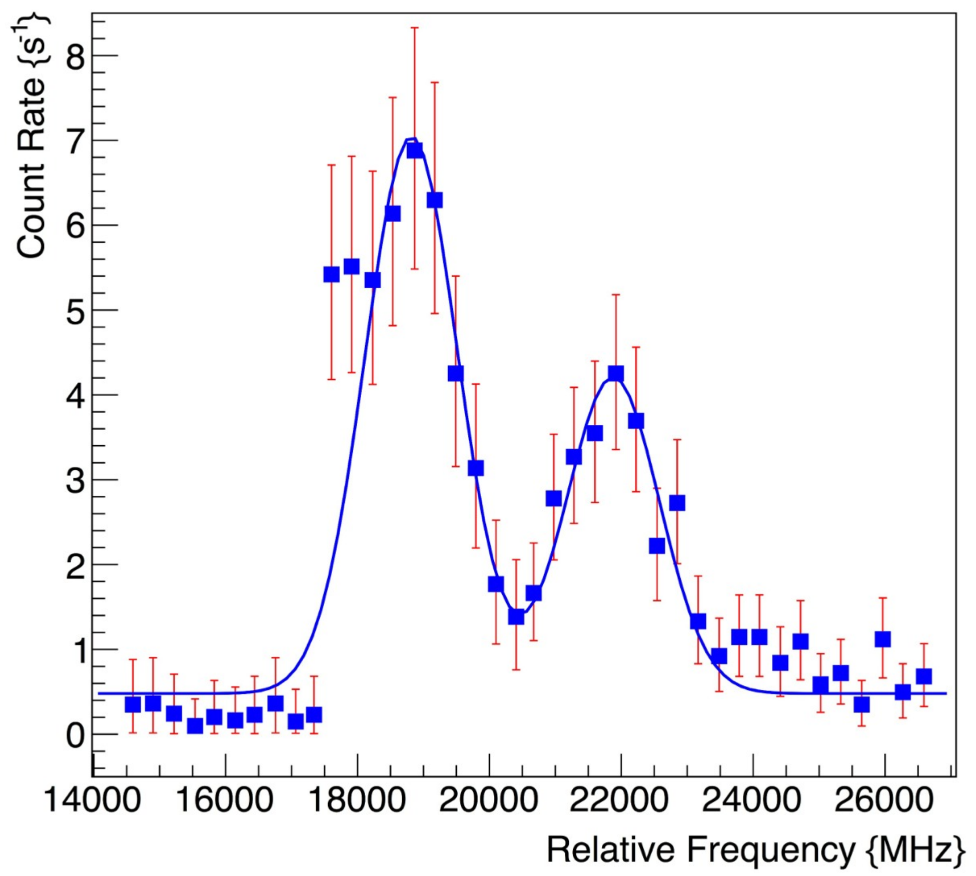


- Quadrupole moment of ^{219}Fr extracted
  - Qs = -1.21(2) eb
  - Linewidth of 20(1) MHz

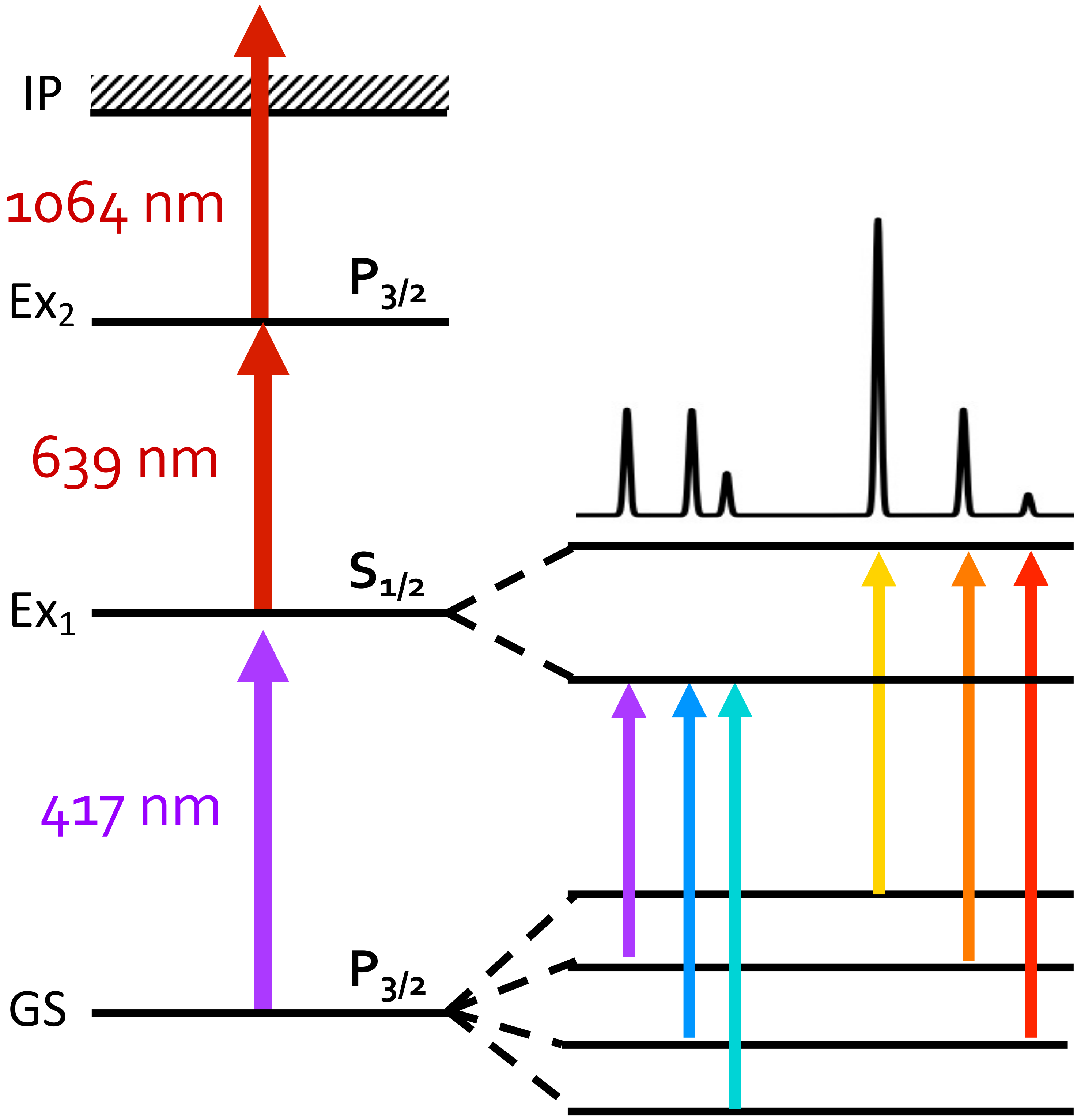
R.P. de Groote et al., Phys. Rev. Lett. **115** 132501 (2015)

- Hyperfine structure of ^{214}Fr
  - Shortest-lived isotope ($t_{1/2}$ = 5 ms) measured with laser spectroscopy on-line
  - Possible due to 200 Hz pulsed laser system

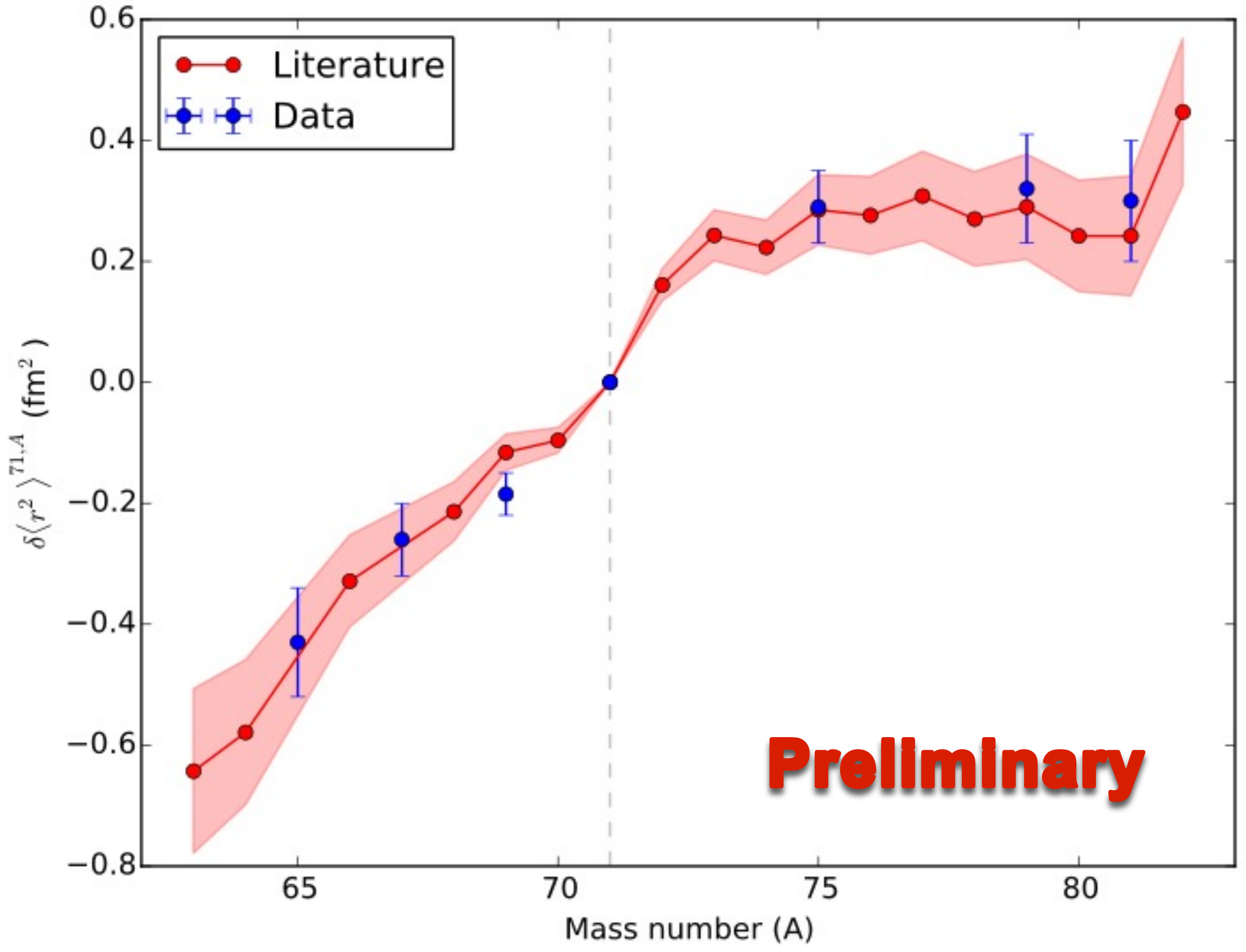
G.J. Farooq-Smith et al., Phys Rev. C, Accepted

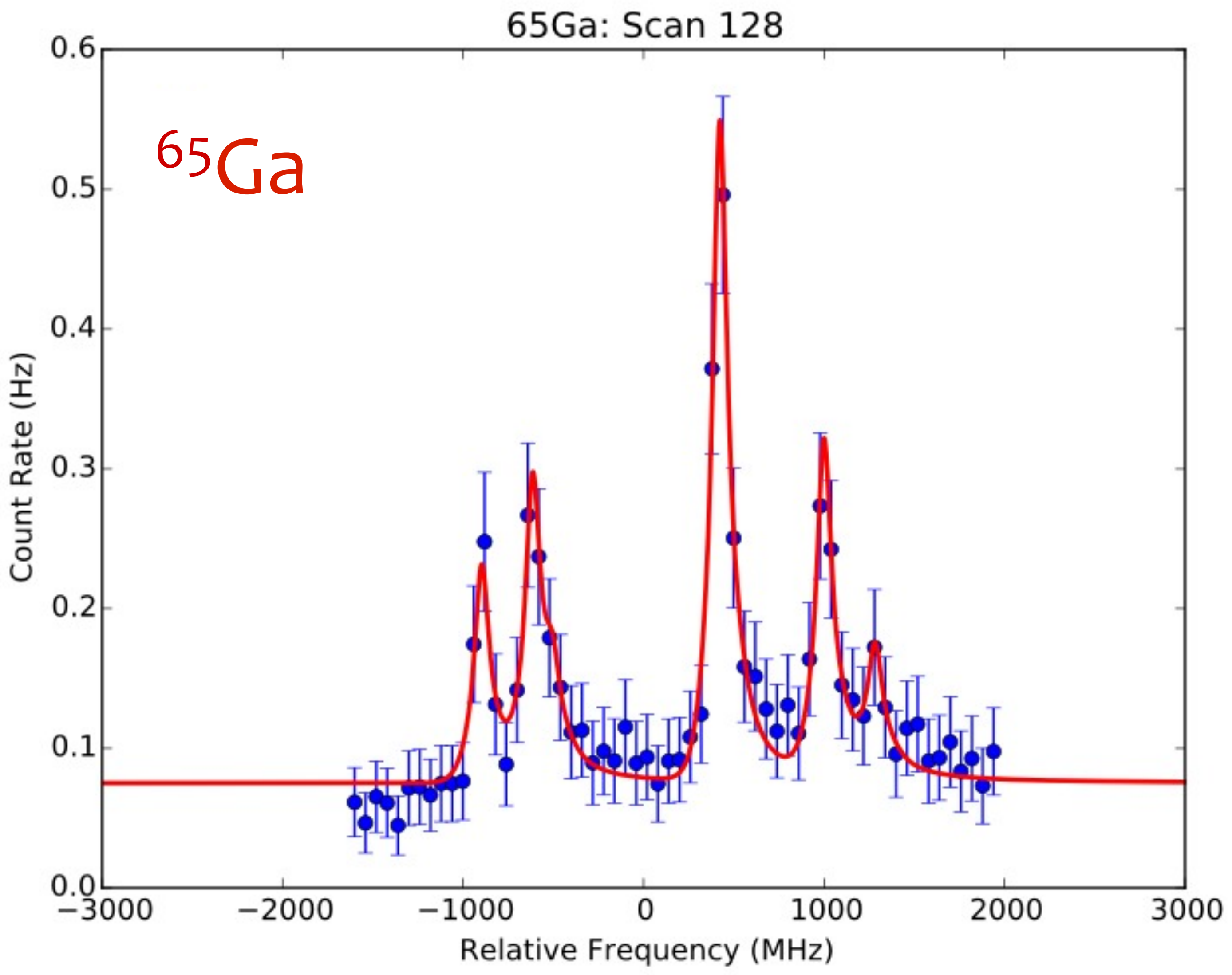


Neutron-rich gallium isotopes

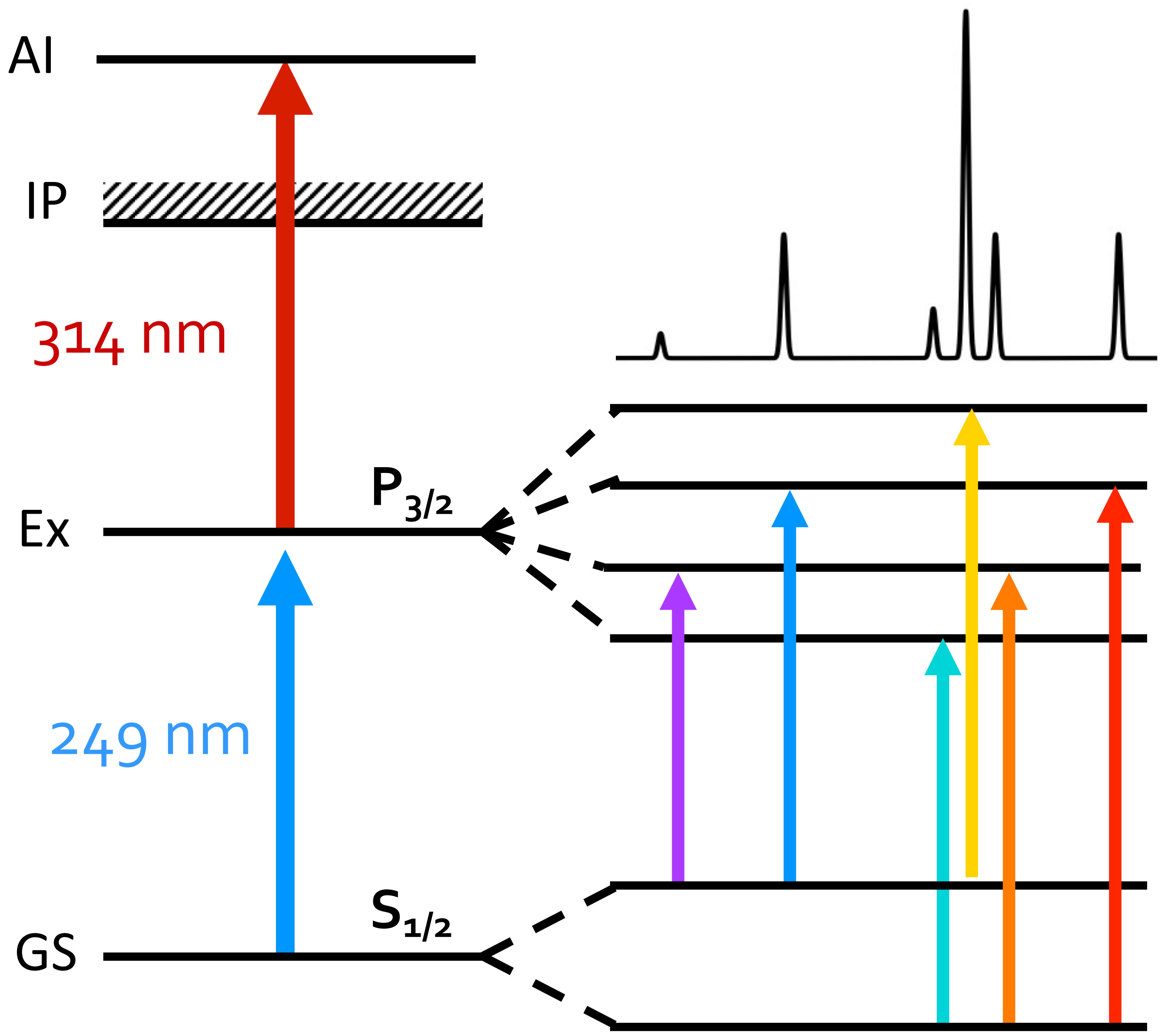


- Study the stability of the nuclear structure beyond the N=50 and Z=28 shell closures
  - Changes in nuclear configuration due to polarization of the core
  - Beta-decay of ^{80g,m}Ga
- Neutralization of only 5% limited our efficiency on the neutron-rich side
  - Neutron rich: ^{75}Ga,$^{79\text{-}82}$Ga
  - Neutron deficient: ^{65}Ga,^{67}Ga
- Data analysis ongoing…



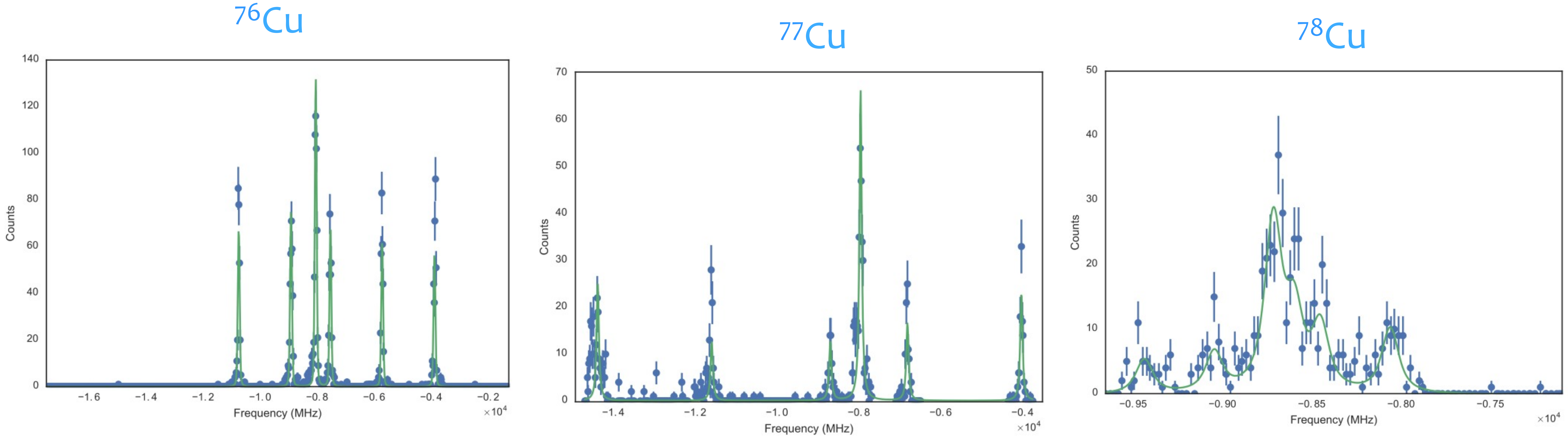


Neutron-rich copper isotopes

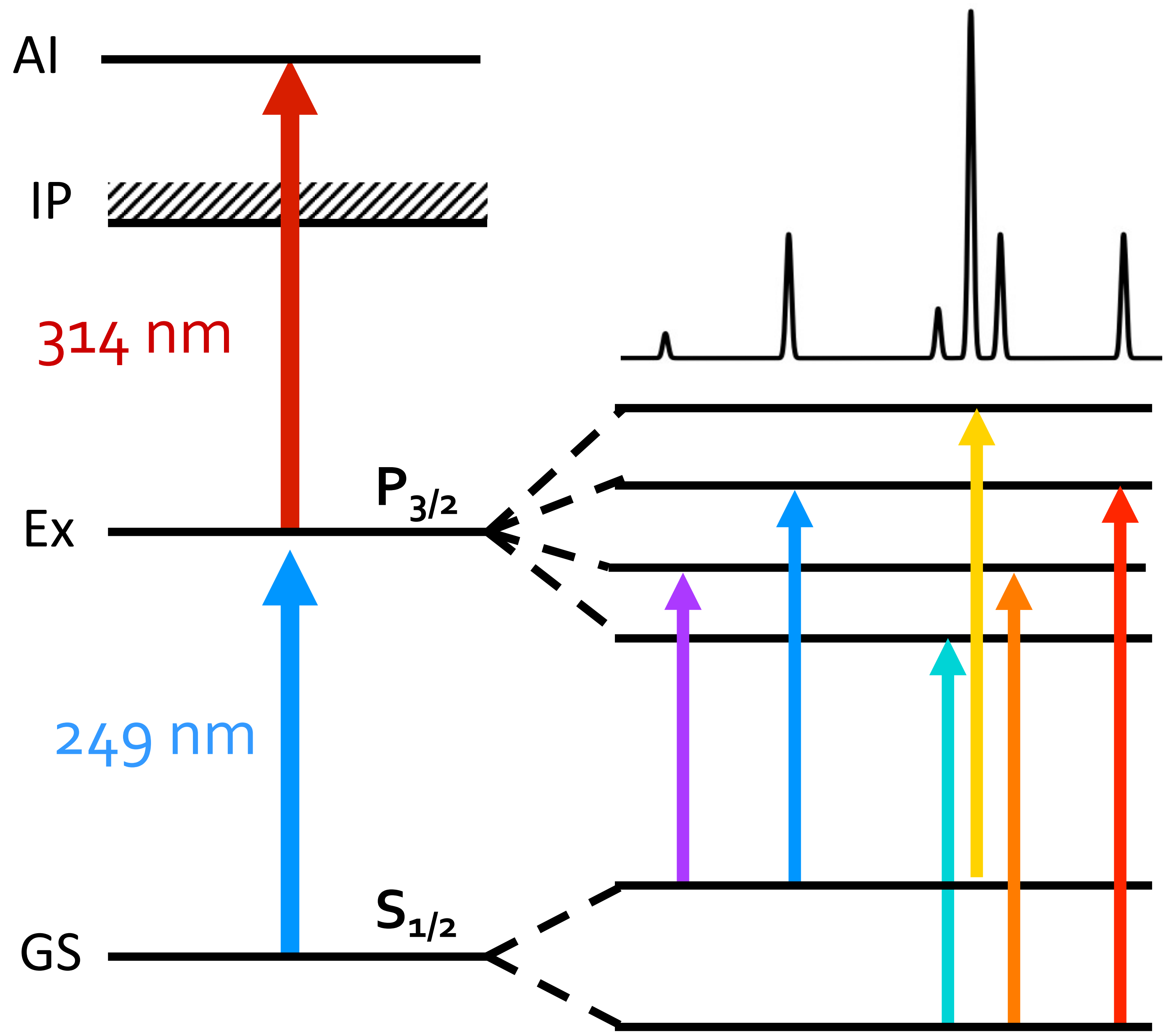


- Neutron-rich copper isotopes with 1 proton outside Z=28 towards N=50
  - Study of the evolution of the shell model with neutron excess
- Study spins, magnetic and quadrupole moments of copper isotopes A=76-78

- ^{75}Cu measured yield of 20,000 ions/s
- Estimated yield of ^{78}Cu of < 20 ions/s
- Data analysis ongoing…

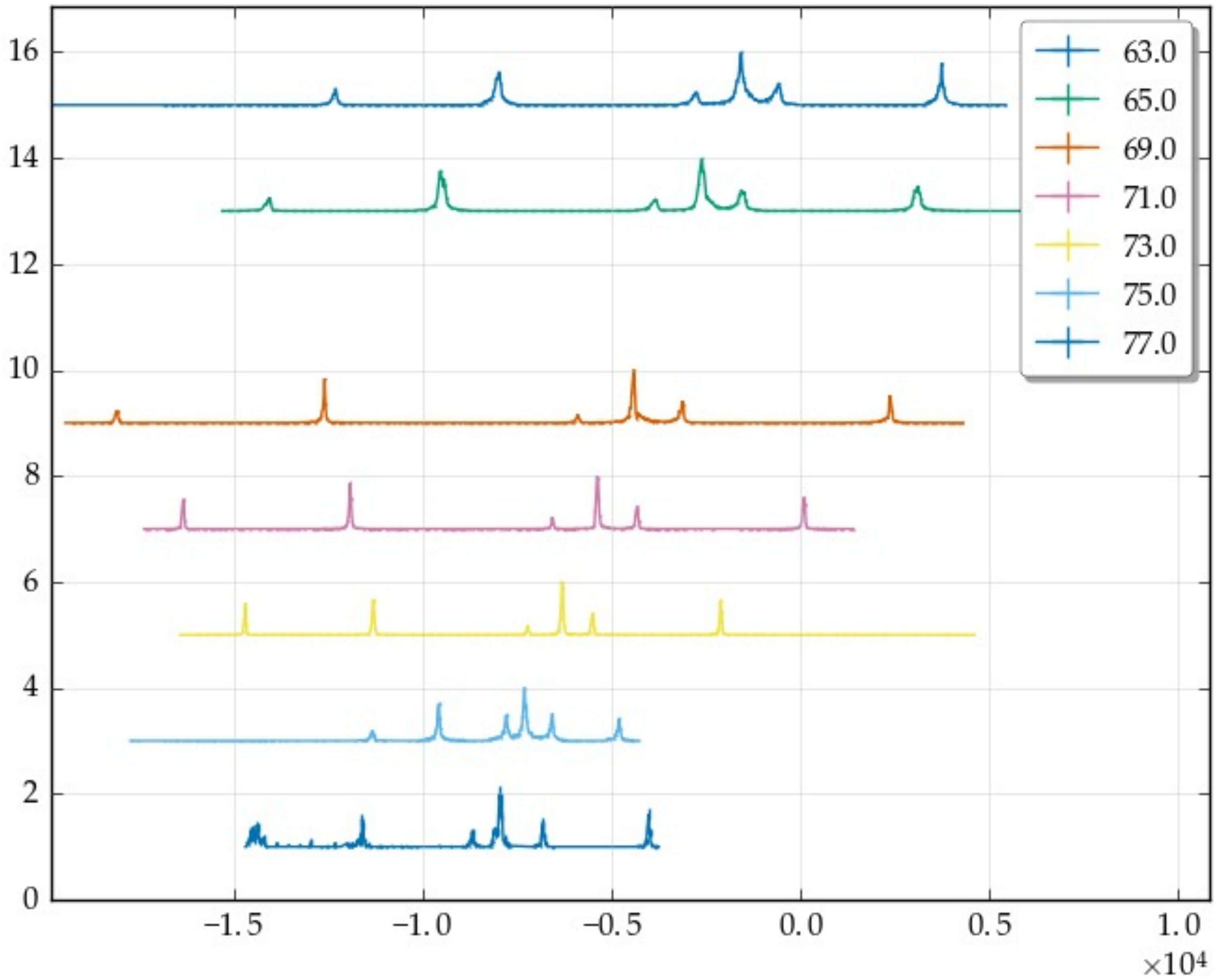


Neutron-rich copper isotopes

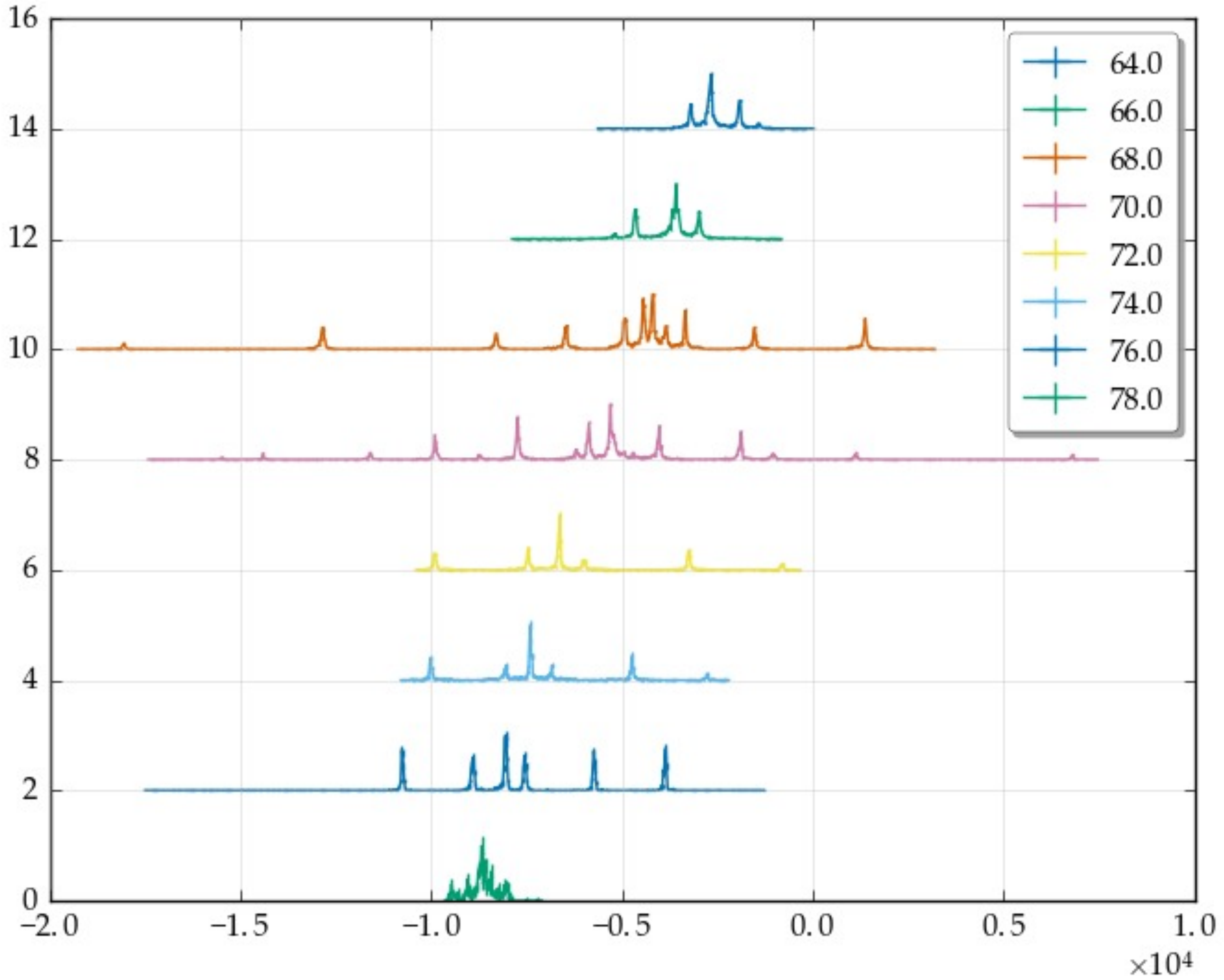


- Neutron-rich copper isotopes with 1 proton outside Z=28 towards N=50
  - Study of the evolution of the shell model with neutron excess
- Study spins, magnetic and quadrupole moments of copper isotopes A=76-78
- Studied $^{63\text{-}66,\ 68\text{-}78}$Cu isotopes

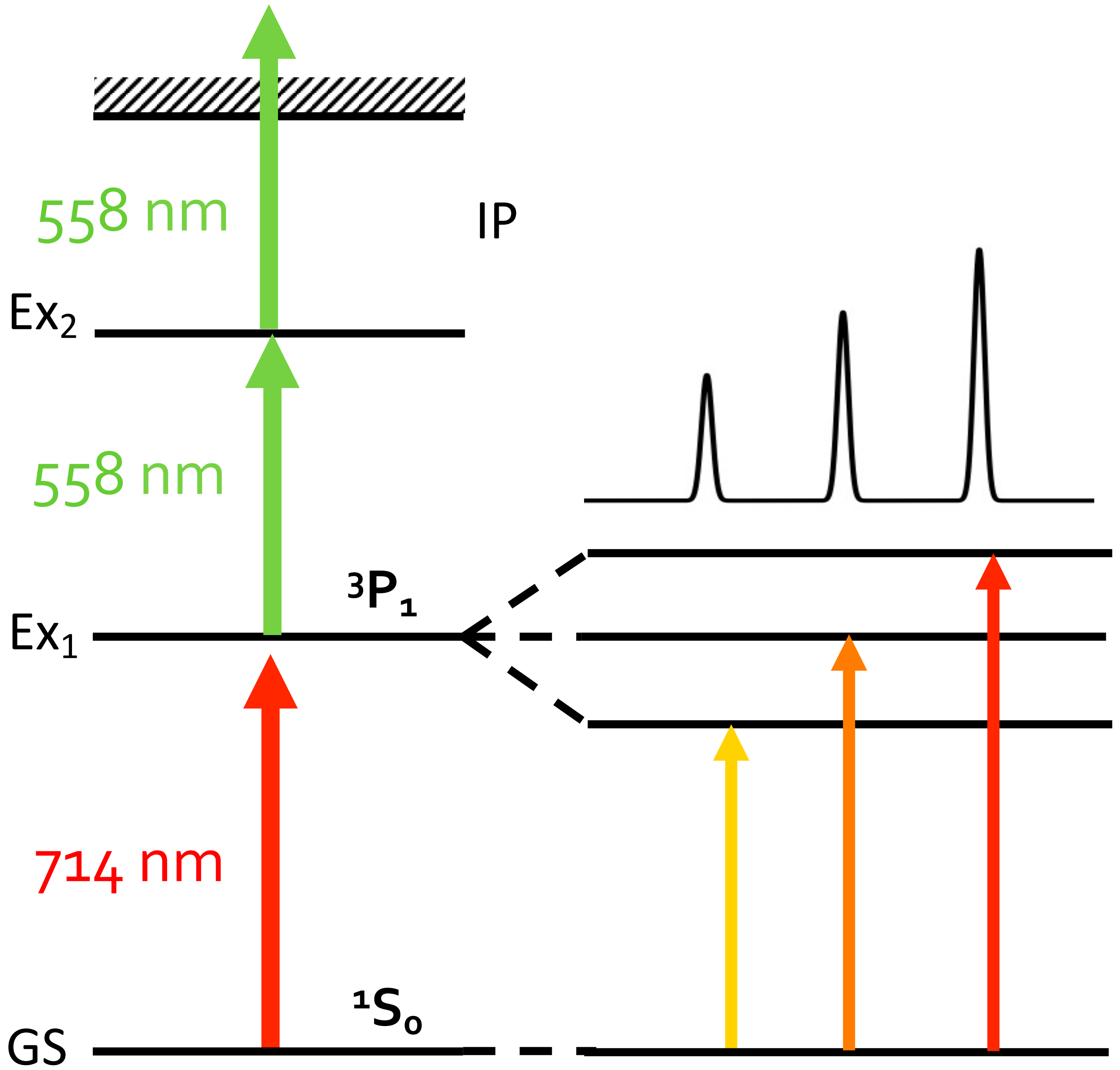
Odd isotopes



Even isotopes



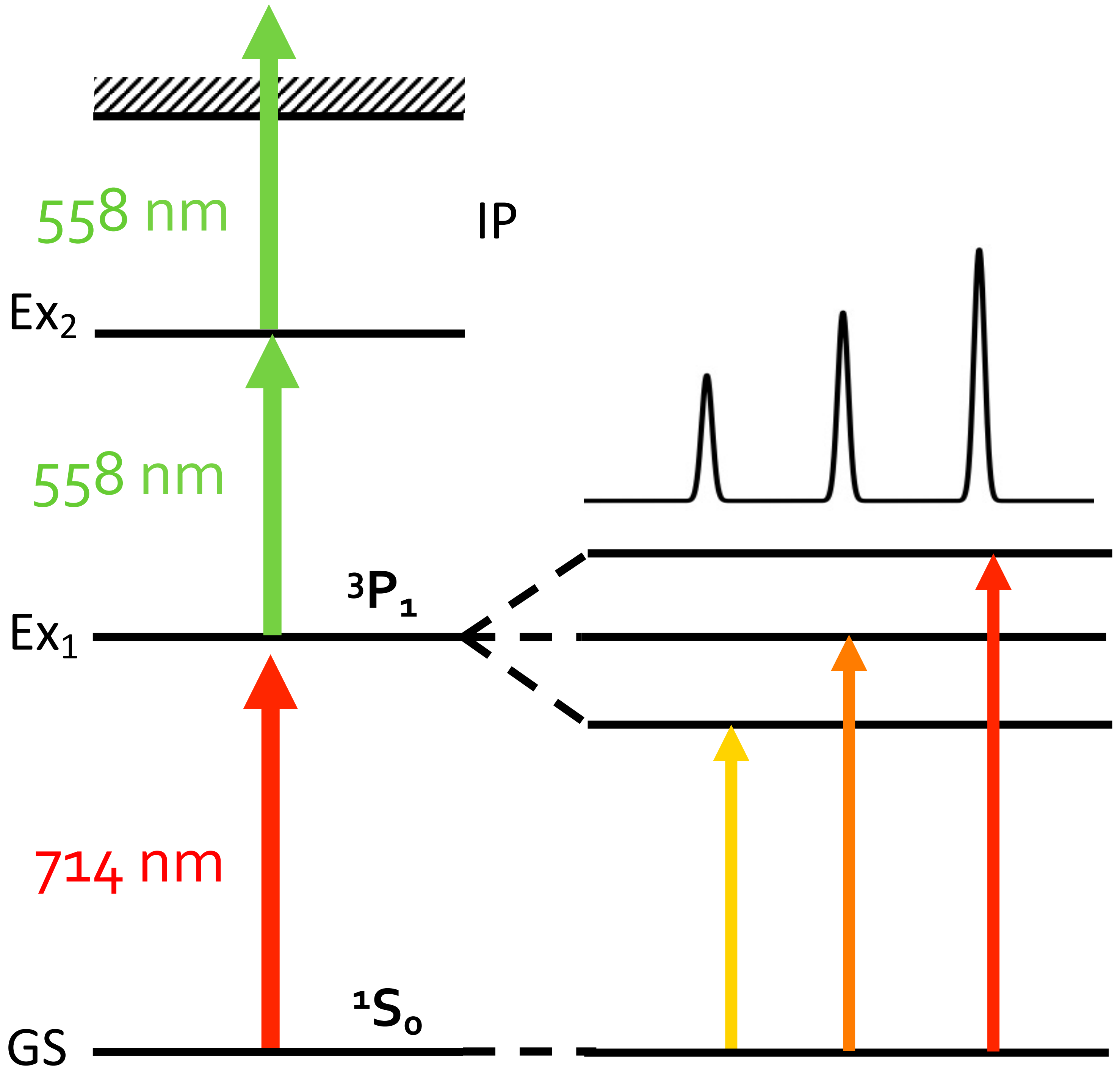
Neutron-deficient radium isotopes



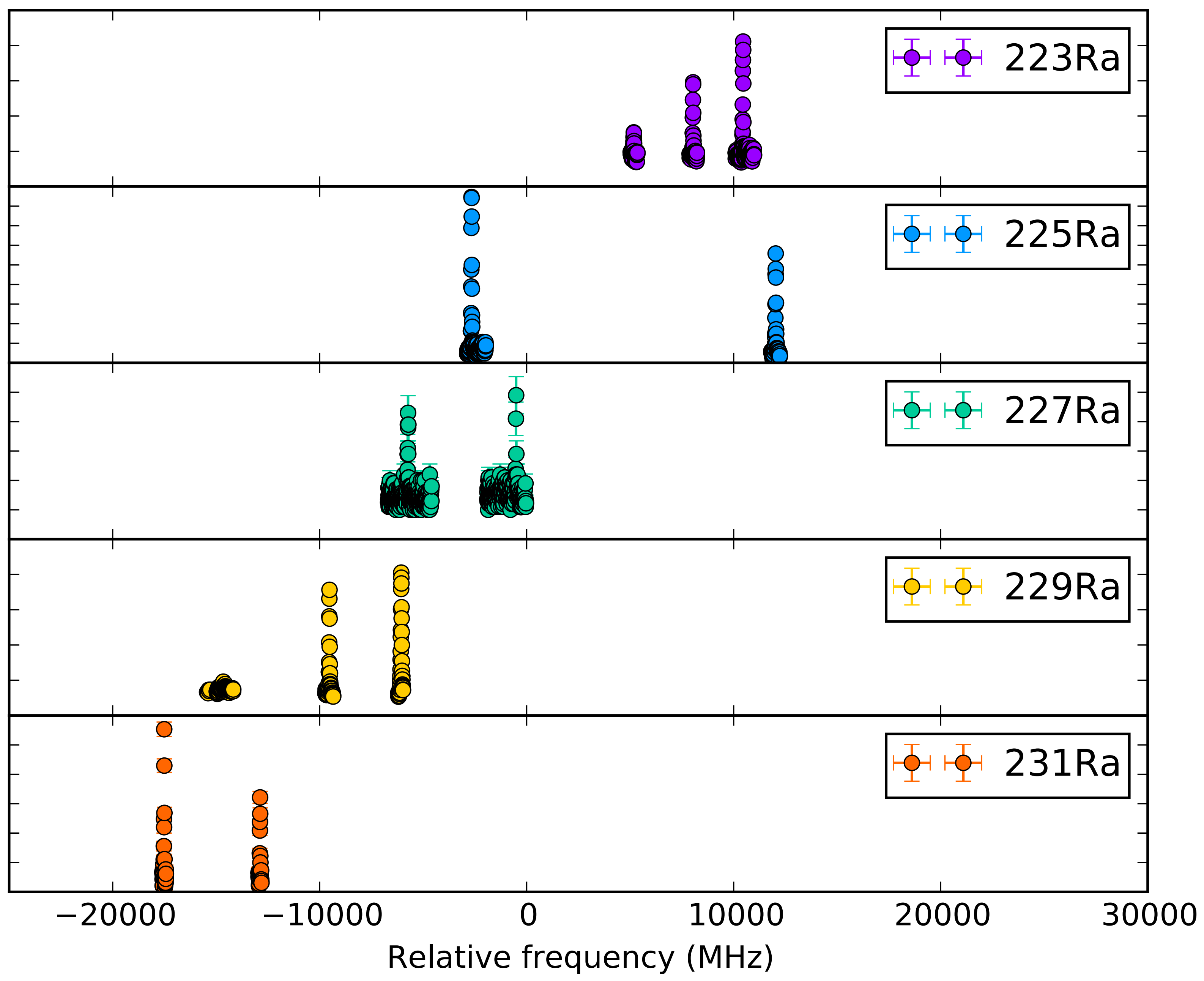
- Experiment performed in August
- Study of evolution of nuclear structure in neutron-deficient radium isotopes
  - Separate contribution of even-Z core from independent proton in francium
  - Investigate charge radii and suggested departure from sphericity
- High background (francium) limited measurements
- Turned attention to neutron-rich radium isotopes
- Studied $^{214,222\text{-}232}$Ra, with hints of resonance for ^{233,234}Ra
  - Narrowband TiSa for high-resolution studies
  - Broadband TiSa for resonance-peak searches
- Resonance ionization scheme:
  - 714 nm: Chopped CW light from Matisse TiSa laser (narrowband)/ Z-cavity TiSa laser (broadband)
  - 558nm: Light from PDL

Neutron-rich radium isotopes

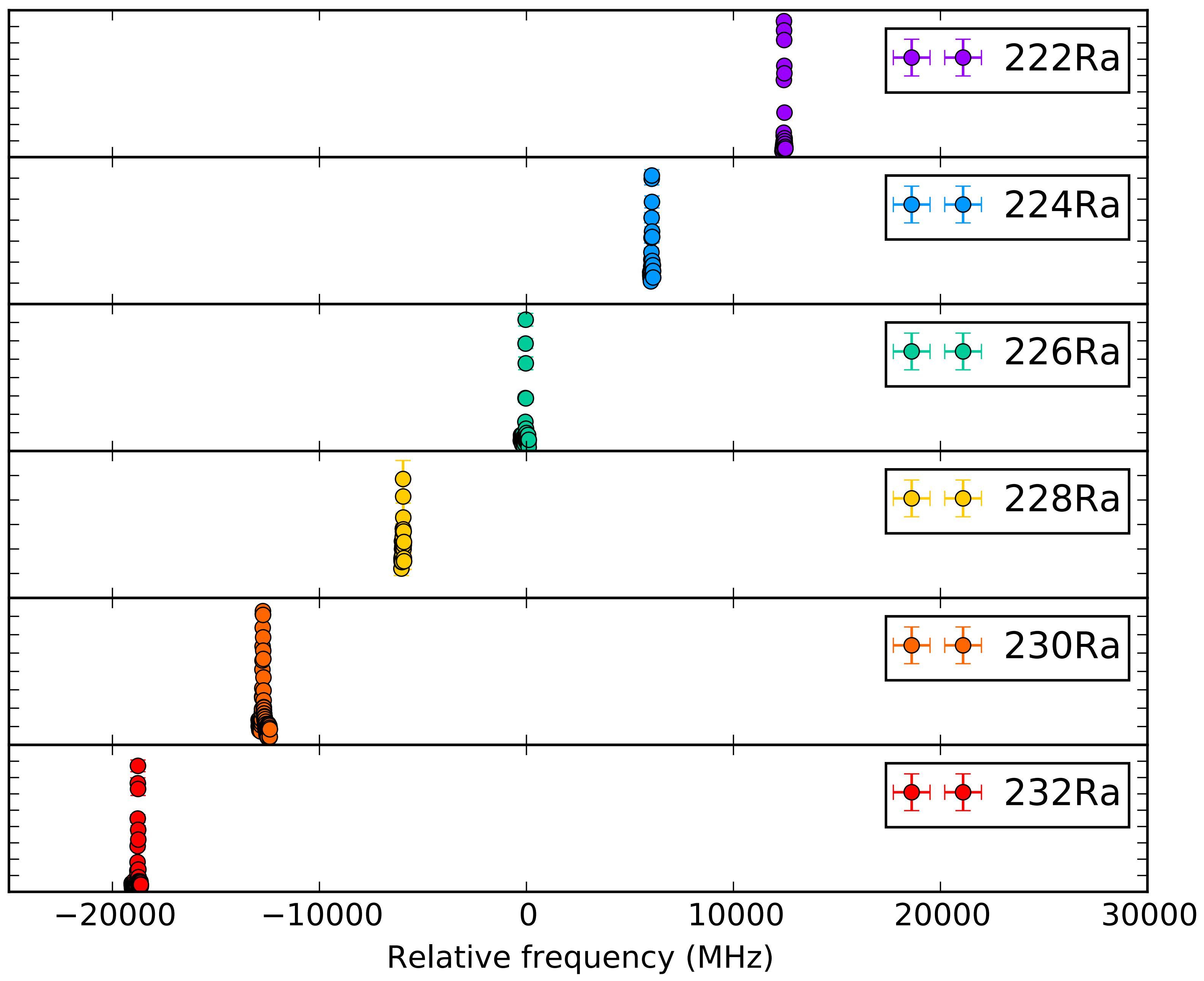
- Experiment performed in August
- Studied $^{214,222-232}$Ra, with hints of resonance for ^{233,234}Ra
- Data analysis just started…



Odd isotopes

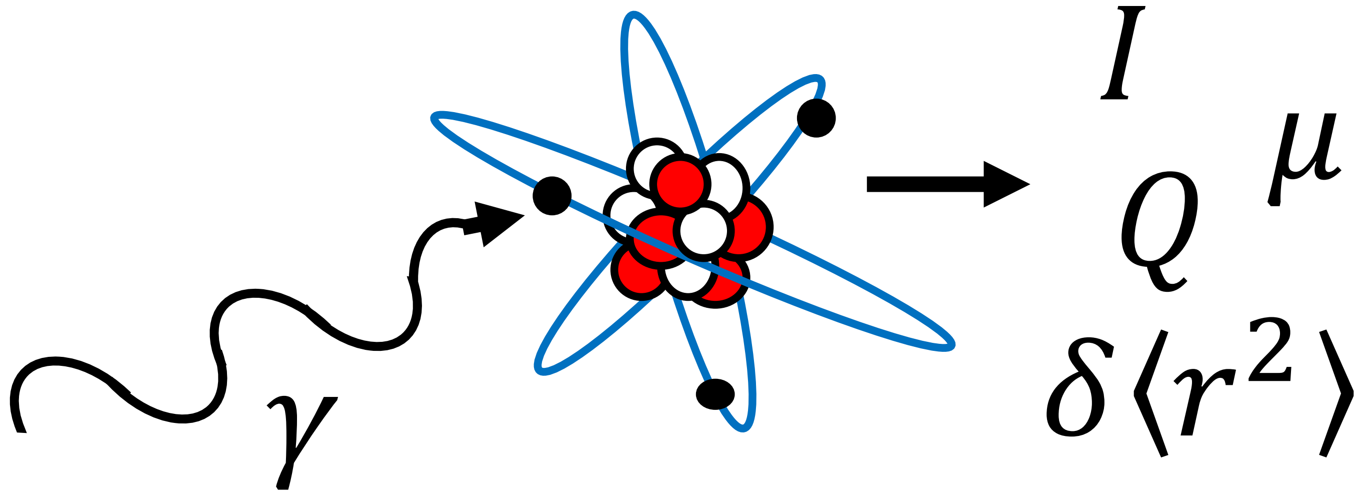


Even isotopes

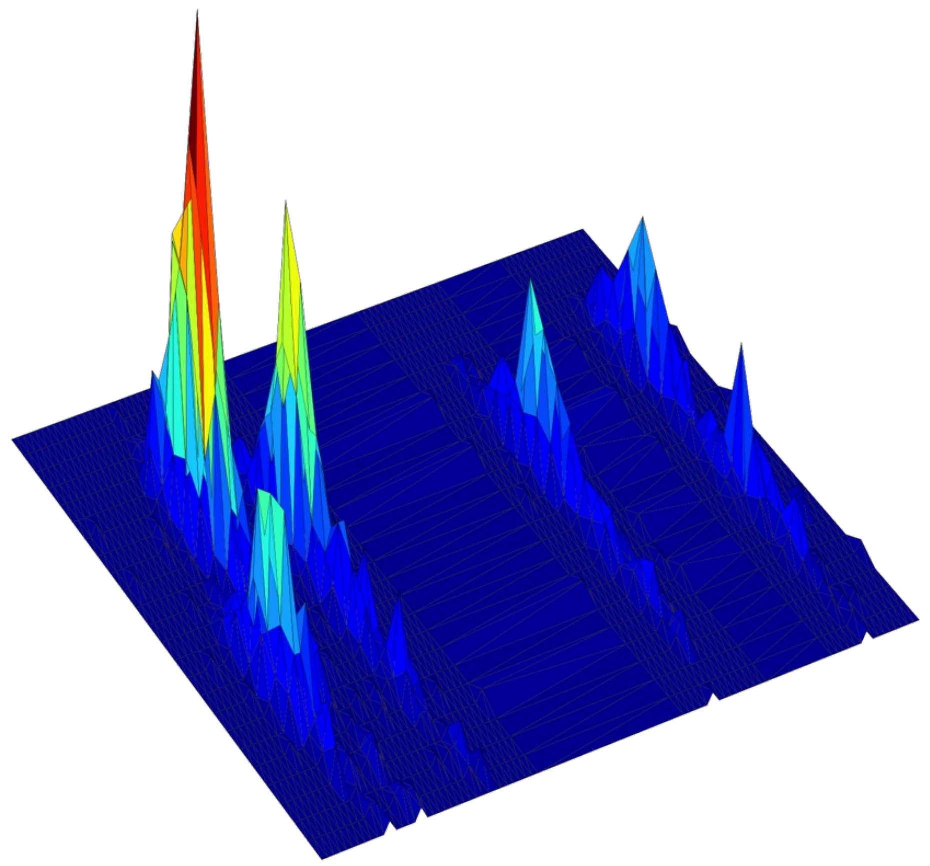


Summary

Summary



- Presented technique of CRIS: collinear resonance ionization spectroscopy
  - Hyperfine structure measurements allow extraction of nuclear properties



- Presence of Decay Spectroscopy Station allows for:
  - Identification of hyperfine-structure peaks
  - Dedicated decay spectroscopy of pure ground and isomeric states
- Demonstration of technique with neutron-deficient francium isotopes
- Recent high-resolution laser spectroscopy studies of Ga, Cu and Ra isotopes

The CRIS Collaboration

MANCHESTER 1824 · CERN · KU LEUVEN · NEW YORK UN · LPSC Grenoble · JOHANNES GUTENBERG UNIVERSITÄT MAINZ

J. Billowes, C. Binnersley, M. L. Bissell, I. Budincevic, T.E. Cocolios, T. Day Goodacre,
R. P. de Groote, G. J. Farooq-Smith, V. N. Fedosseev, K. T. Flanagan, S. Franchoo,
R. F. Garcia Ruiz, W. Gins, H. Heylen, T. Kron, A. Koszorus, K. M. Lynch, B. A. Marsh,
G. Neyens, R. E. Rossel, S. Rothe, H. H. Stroke, A. Vernon, K. D. A. Wendt, S. G. Wilkins, X. Yang

With many thanks to my PhD supervisor, Kieran Flanagan,

My current supervisor, Maria Garcia Borge,

And the IUPAP C12 committee for this wonderful honour.

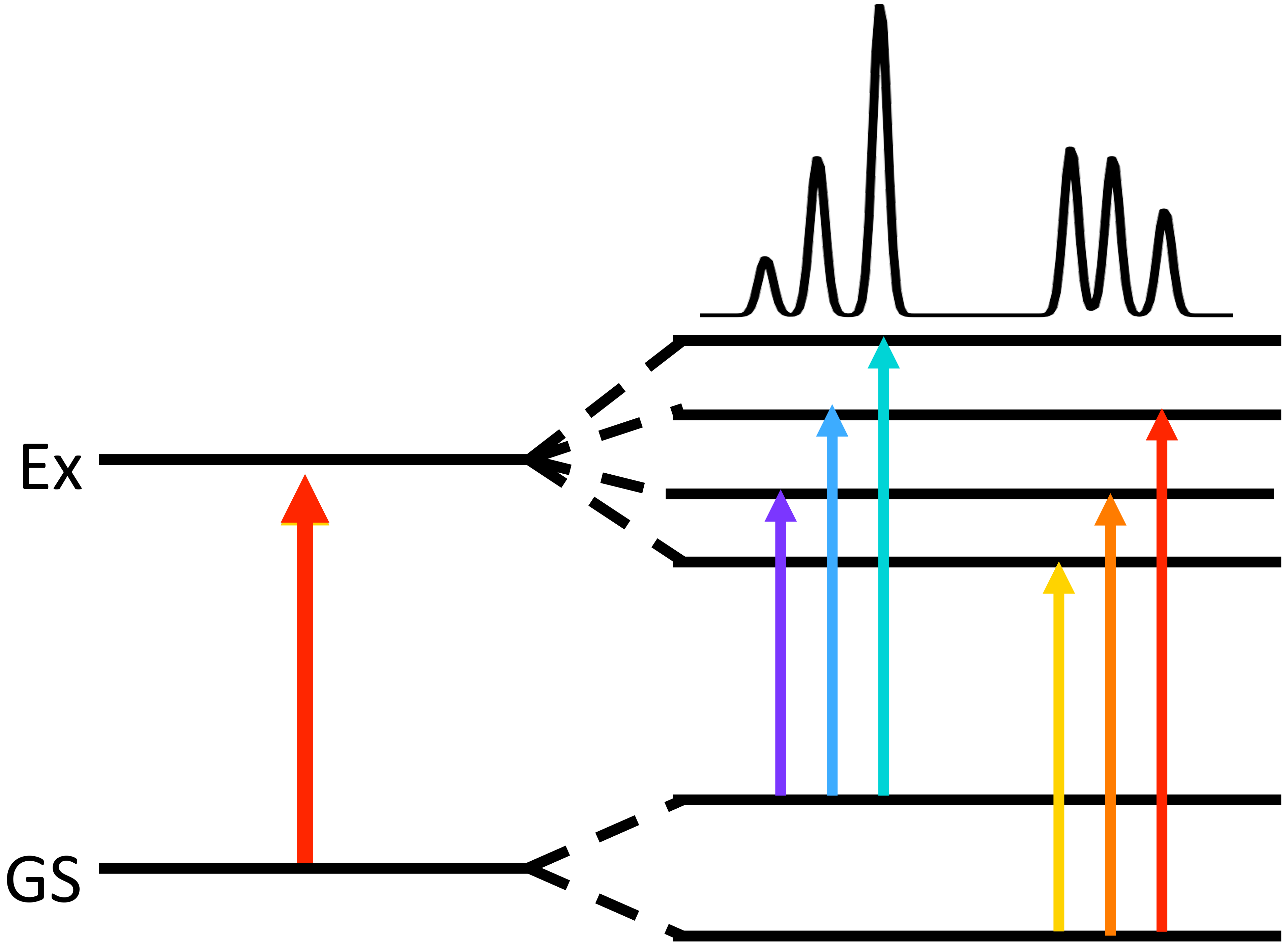
Thanks for your attention!

Fitting the hyperfine structure

- The perturbation of each energy level is given by: $\boxed{\frac{\Delta E}{\hbar} = \alpha A + \beta B}$
- where:

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

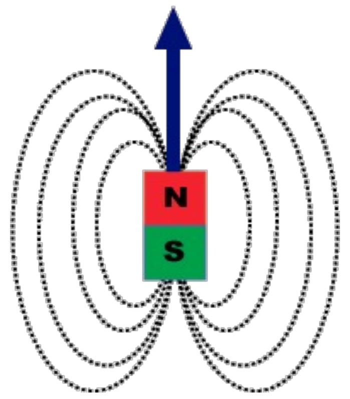
$$K = F(F+1) - I(I+1) - J(J+1)$$



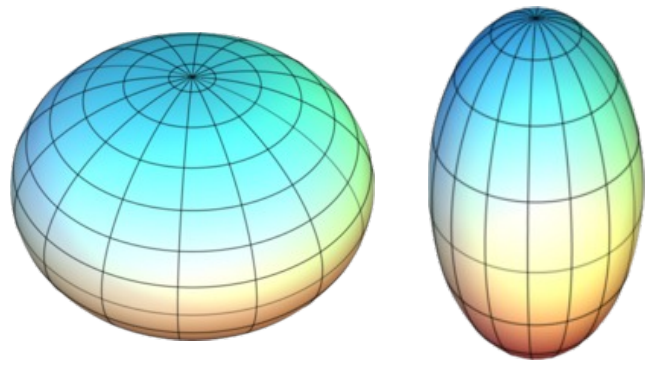
- The frequency of each HF peak is given by: $\boxed{\gamma = \upsilon + \alpha_u A_u + \beta_u B_u - \alpha_l A_l - \beta_l B_l}$
- where $A = \frac{\mu B_0}{IJ}$ $\qquad B = eQ_s \left\langle \frac{\partial^2 V_e}{\partial z^2} \right\rangle$

Isotope shift $\delta\upsilon$

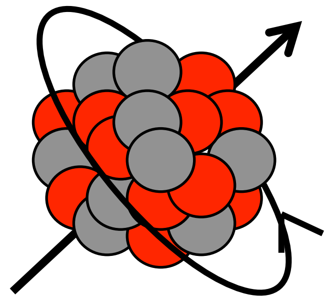
Magnetic dipole moment μ_I



Electric quadrupole moment Q_S



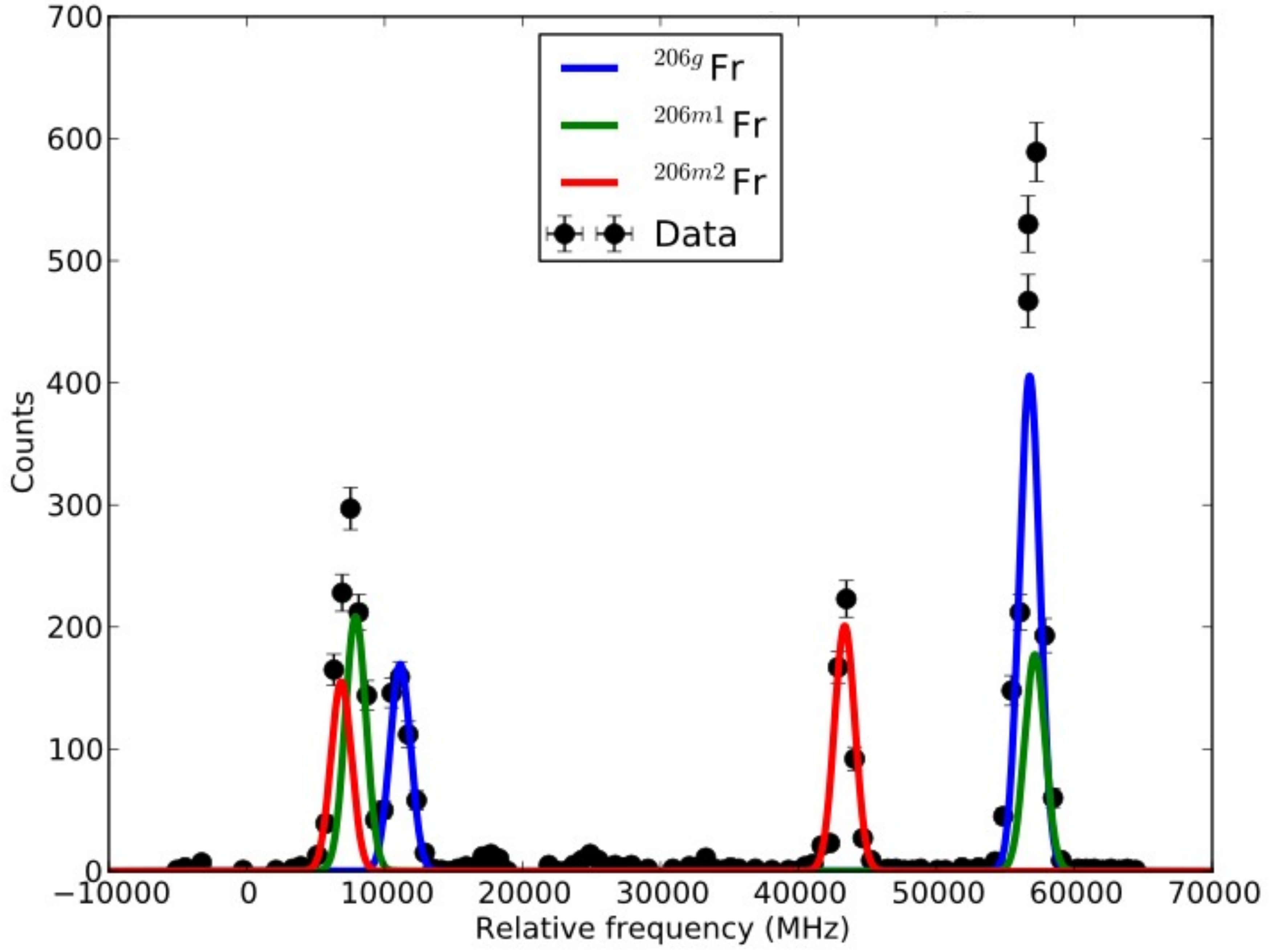
Nuclear spin I

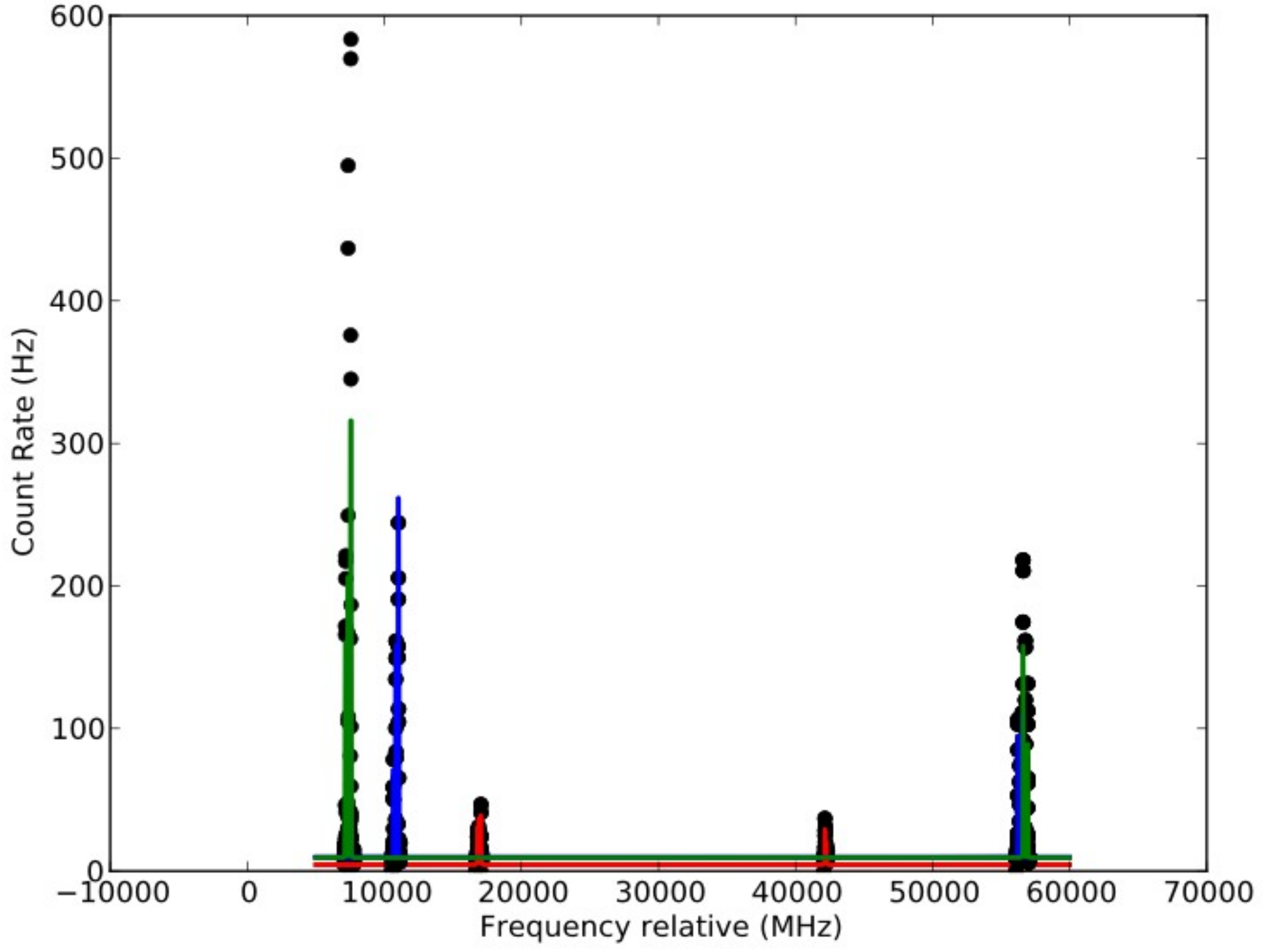


New charge exchange cell

- Current charge exchange cell can only use potassium
  - Limits elements to those with good neutralization cross-section with potassium
- New charge exchange cell can be used with potassium, sodium, rubidium…
  - Choose alkali metal based on isotope under study
- Increase neutralization efficiency

Unambiguous assignment of HFS peaks





- Mis-identification of HFS peak in ^{206}Fr in low-resolution data
  - Missing peak for the ^{206m2}Fr state
- High-resolution studies and laser-assisted decay spectroscopy identified correct structure