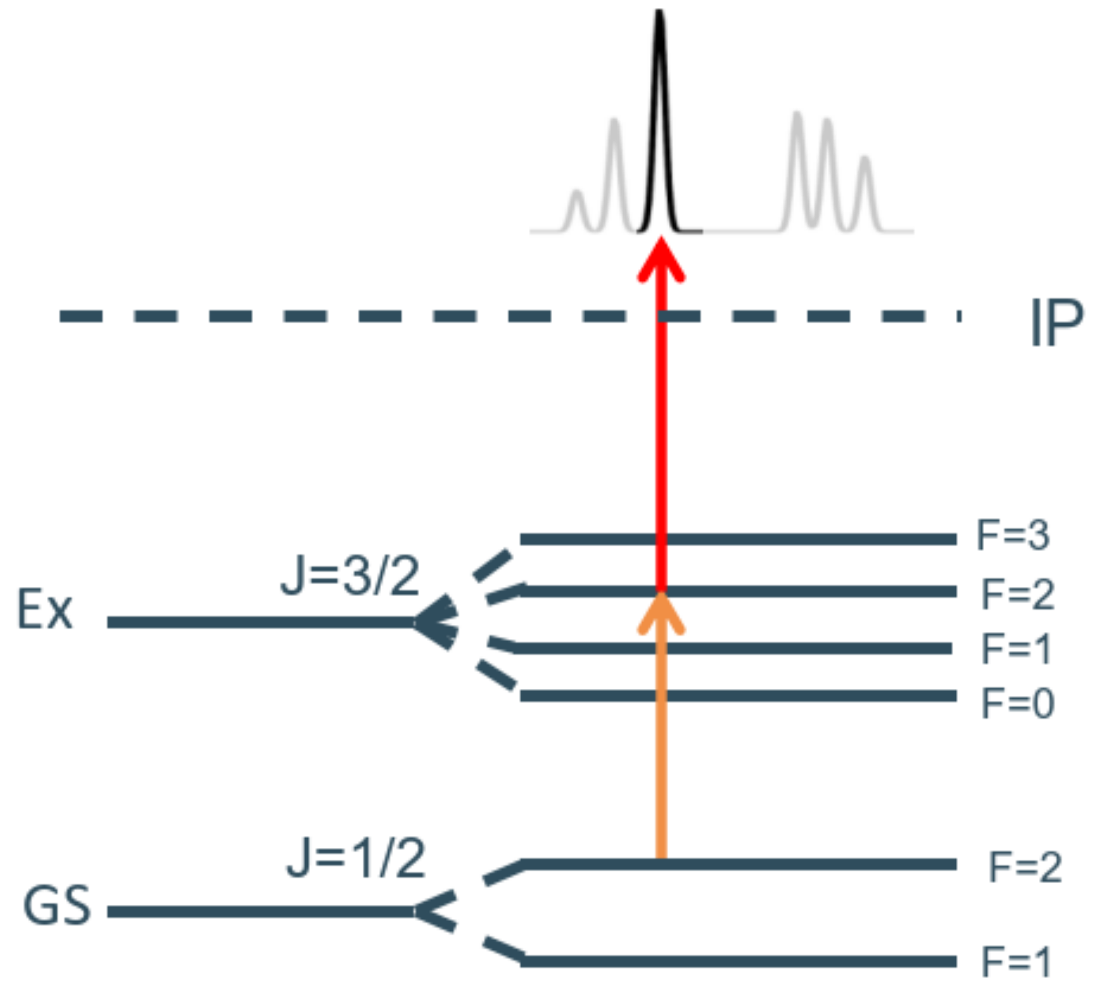
10 years of CRIS

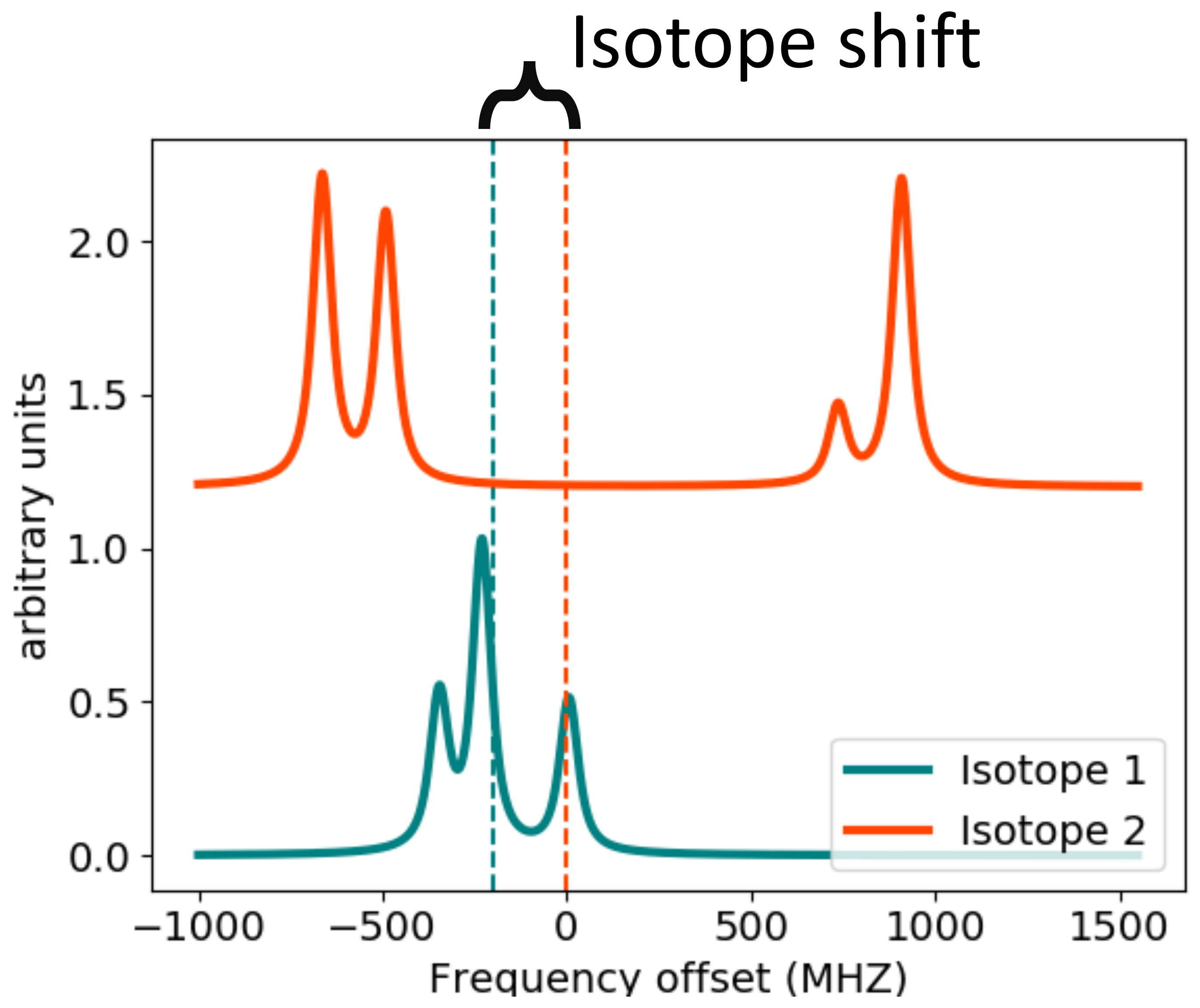
Collinear Resonance Ionization Spectroscopy at ISOLDE

30.11.2022, CERN
ISOLDE Workshop and Users meeting

Ági Koszorús on behalf of the CRIS Collaboration

Laser spectroscopy





- Nuclear spin ***I***
- Magnetic dipole moment ***μ***
- Electric quadrupole moment ***Q***
- Changes in the mean square charge radii ***δ<r²>***

$$\Delta E = A \cdot K/2 + B \cdot \{3K(K+1)/4 - I(I+1)J(J+1)\}/\{2(2I-1)(2J-1)IJ\}$$
$$K = F(F+1)-I(I+1)-J(J+1)$$

$$A = \frac{\mu_I B_J}{IJ}$$

$$B = eQV_{zz}$$

$$\delta\nu^{AA'} = M\frac{m_{A'} - m_A}{m_A m_{A'}} + F\,\delta\langle r^2\rangle^{AA'}$$

Atomic physics

Nuclear physics

Laser spectroscopy experiments at ISOLDE

Familiar presence in the hall:

RILIS + PI-LIST: in-source laser spectroscopy (see talks R. Heinke, K. Chrysalidis)

COLLAPS (see talk P. Plattner, T. Lellinger)

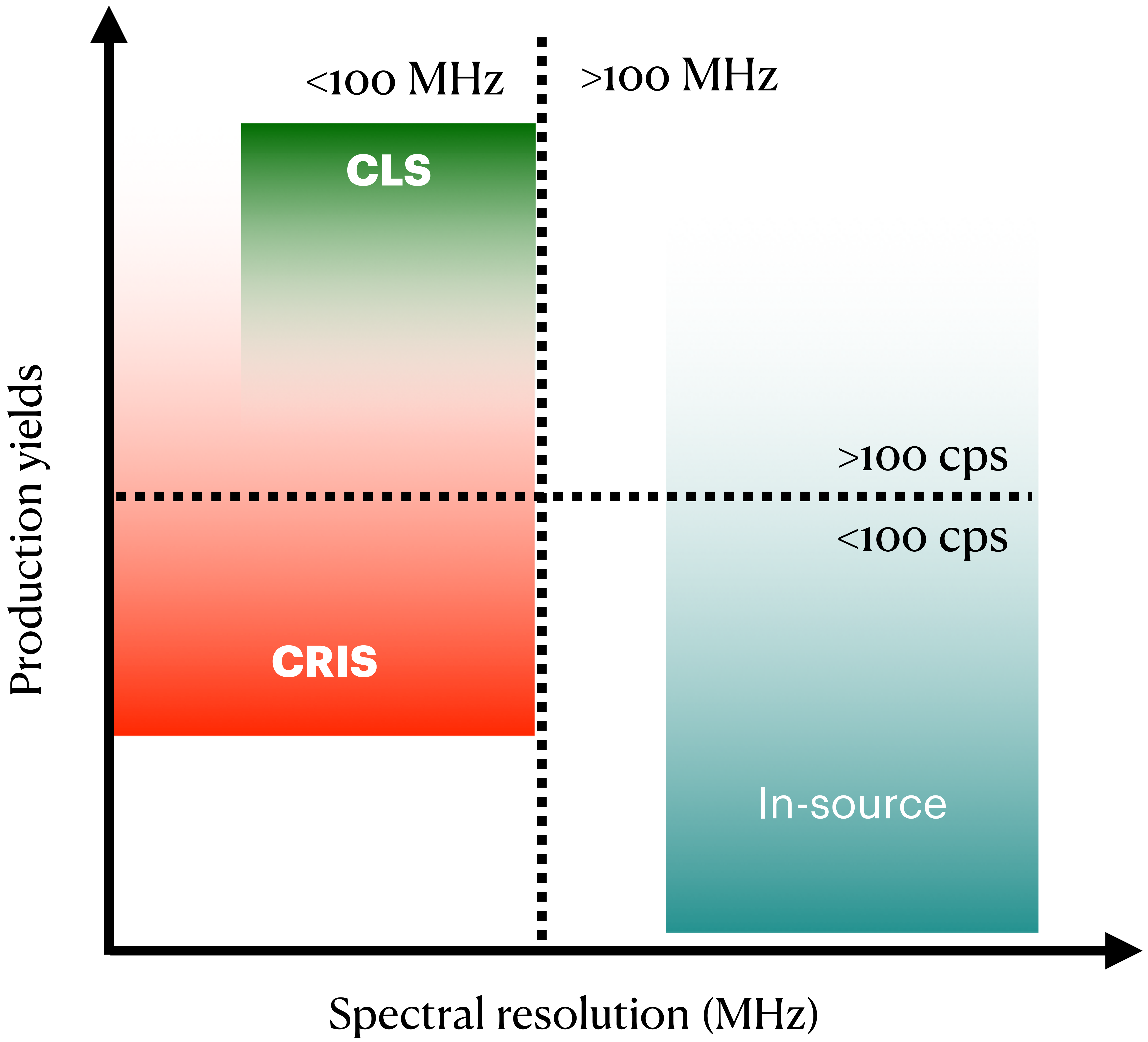
VITO (see talk M. Jankowski)

CRIS (this talk, see talk A. Vernon, talk M. Athanasakis)

Under development:

MIRACLS (see talk by S. Lechner, E. Leistenschneider)

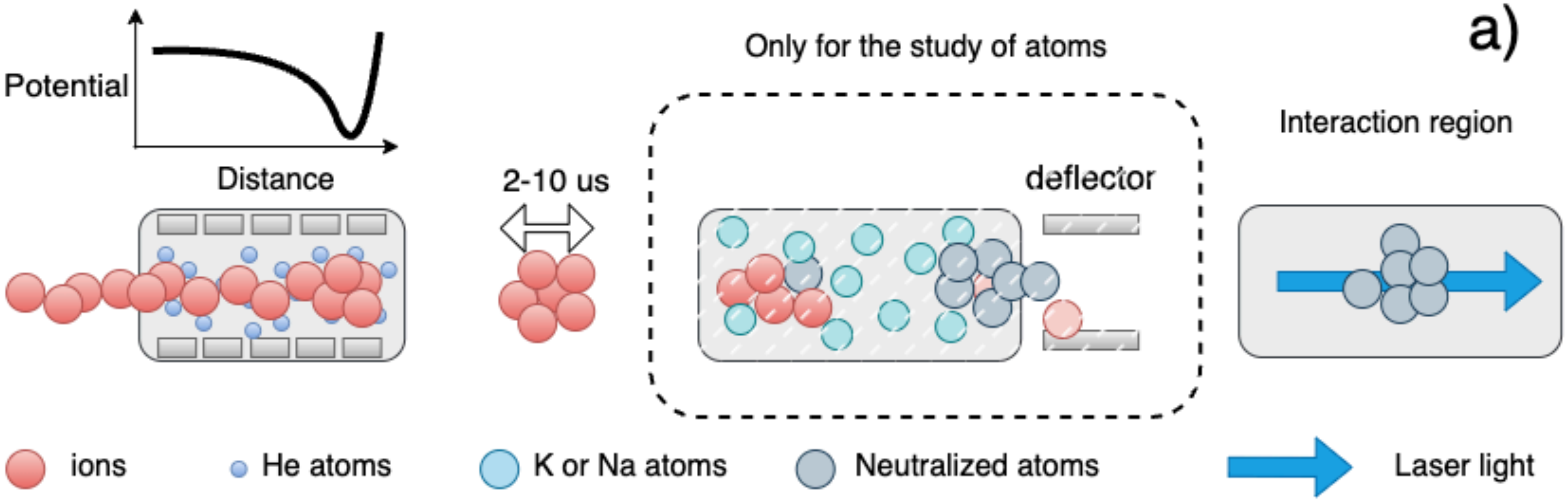
Where does CRIS fit?



Combine the high resolution of collinear laser spectroscopy with the high efficiency of in-source laser spectroscopy!

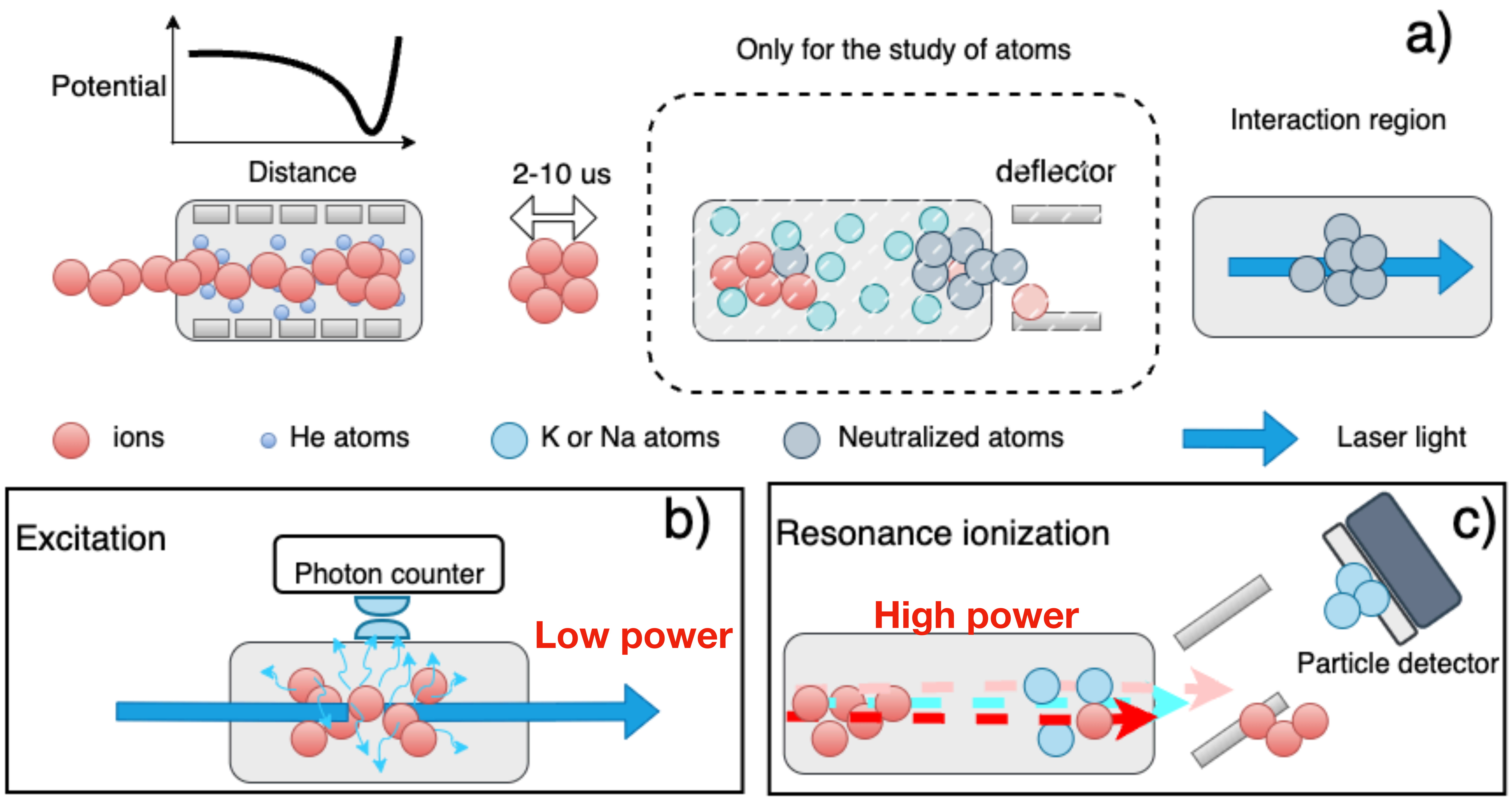
*ROC, beta NMR and many more are not shown

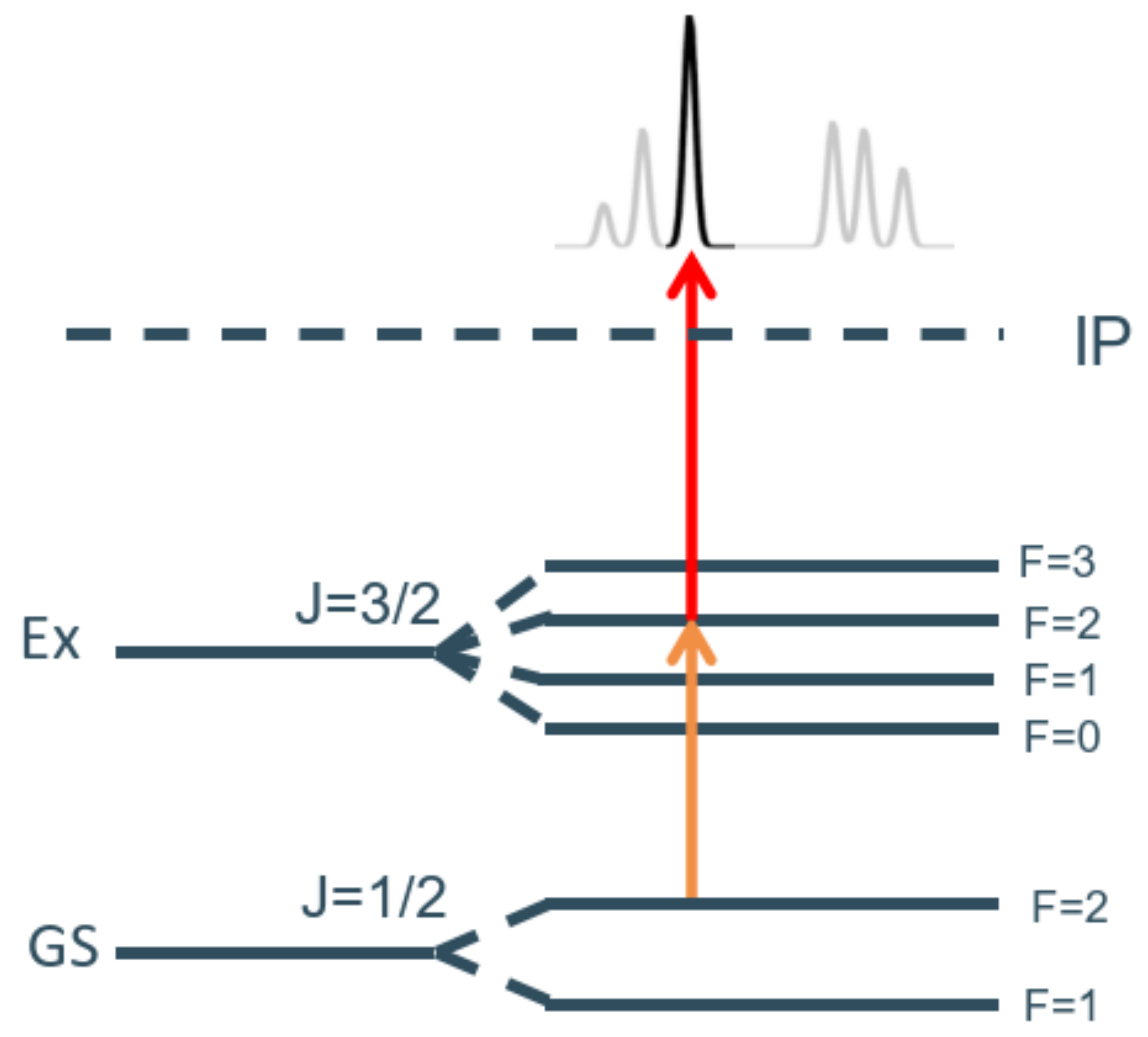
Collinear Laser spectroscopy Techniques



Beam energy:
30-60 keV

Collinear Laser spectroscopy Techniques





- Probing the hyperfine structure using narrowband laser
- Detect the photons following the de-excitation - CLS
- Detect the resonantly laser ionised ion - CRIS

The CRIS beamline

Resonantly and non-resonantly created ions!

Figure made by Jordan R. Reilly

Summer 2012: First results!

PR… 212501 (2013) PHYSICAL REVIEW LETTERS week ending 22 NOVEMBER 2013

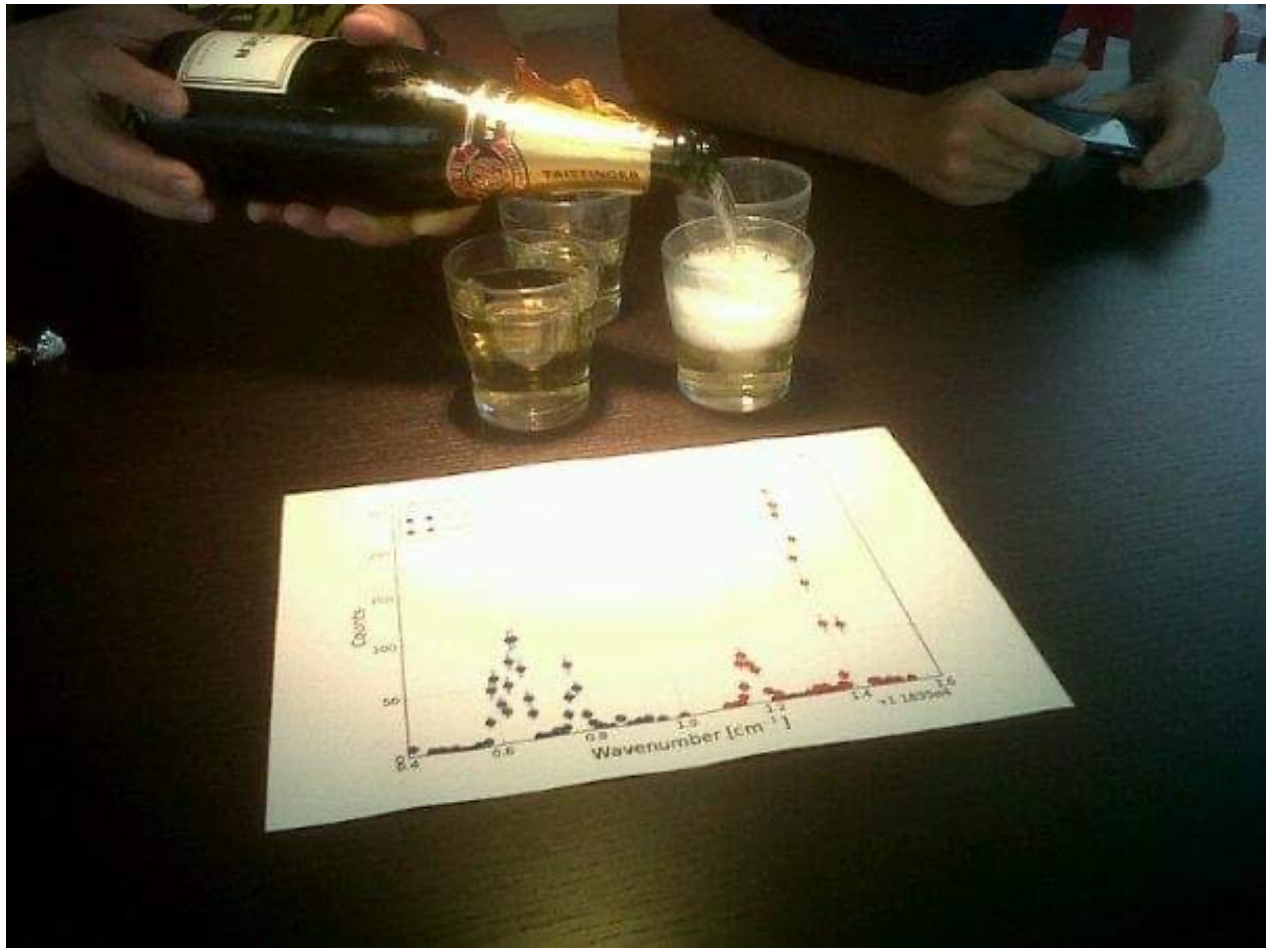
Collinear Resonance Ionization Spectroscopy of Neutron-Deficient Francium Isotopes

K. T. Flanagan,[1,*] K. M. Lynch,[1,2] J. Billowes,[1] M. L. Bissell,[3] I. Budinčević,[3] T. E. Cocolios,[1,2] R. P. de Groote,[3] S. De Schepper,[3] V. N. Fedosseev,[4] S. Franchoo,[5] R. F. Garcia Ruiz,[3] H. Heylen,[3] B. A. Marsh,[4] G. Neyens,[3] T. J. Procter,[1] R. E. Rossel,[4,6] S. Rothe,[4] I. Strashnov,[1] H. H. Stroke,[7] and K. D. A. Wendt[6]

PHYSICAL REVIEW X 4, 011055 (2014)

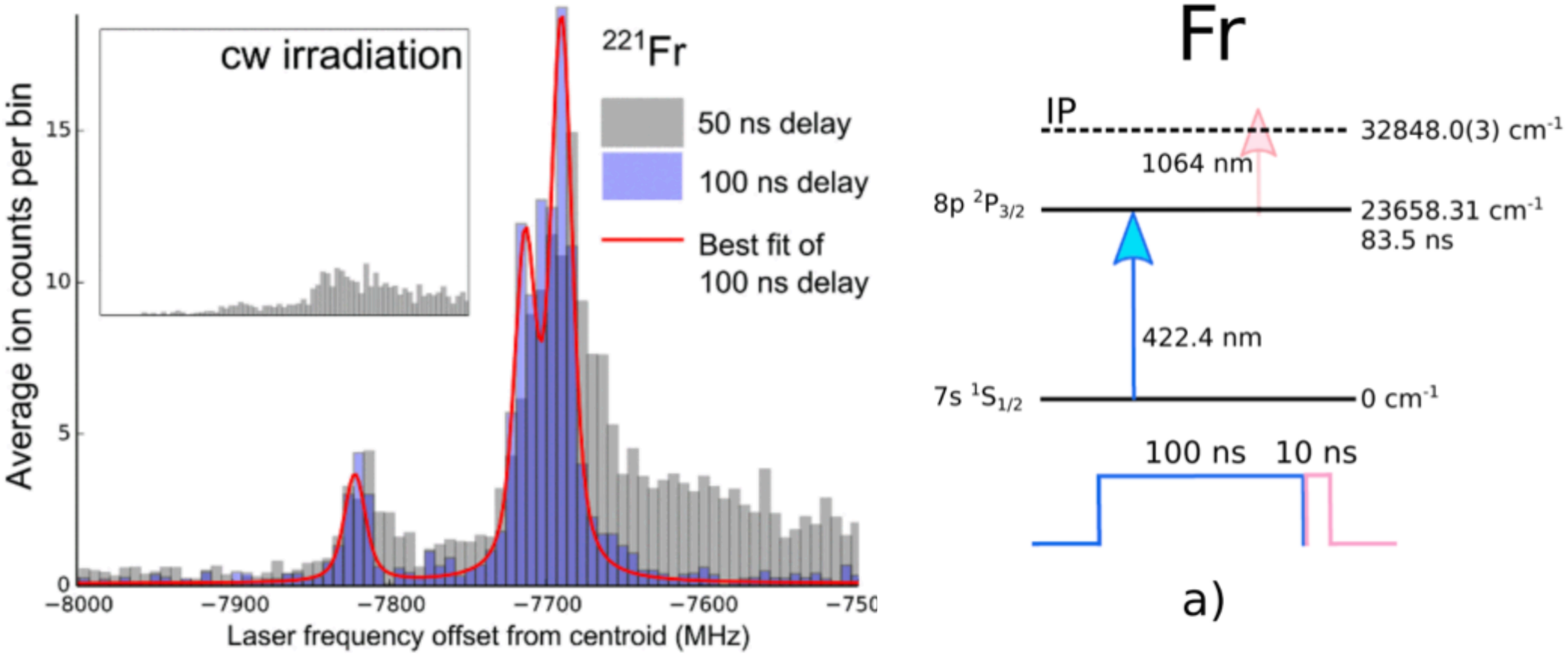
Decay-Assisted Laser Spectroscopy of Neutron-Deficient Francium

K. M. Lynch,[1,2,3,*] J. Billowes,[1] M. L. Bissell,[3] I. Budinčević,[3] T. E. Cocolios,[1,2] R. P. De Groote,[3] S. De Schepper,[3] V. N. Fedosseev,[4] K. T. Flanagan,[1] S. Franchoo,[5] R. F. Garcia Ruiz,[3] H. Heylen,[3] B. A. Marsh,[4] G. Neyens,[3] T. J. Procter,[1,†] R. E. Rossel,[4,6] S. Rothe,[4,6] I. Strashnov,[1] H. H. Stroke,[7] and K. D. A. Wendt[6]



- Measurements were performed on $^{202-231}$Fr
- Laser beam provided by RILIS
- This was the beginning of a rich program on the study of Fr isotopes!

High resolution - delayed ionization



PRL **115,** 132501 (2015) PHYSICAL REVIEW LETTERS week ending 25 SEPTEMBER 2015

Use of a Continuous Wave Laser and Pockels Cell for Sensitive High-Resolution Collinear Resonance Ionization Spectroscopy

R. P. de Groote,[1,*] I. Budinčević,[1] J. Billowes,[2] M. L. Bissell,[1,2] T. E. Cocolios,[2] G. J. Farooq-Smith,[2] V. N. Fedosseev,[3] K. T. Flanagan,[2] S. Franchoo,[4] R. F. Garcia Ruiz,[1] H. Heylen,[1] R. Li,[4] K. M. Lynch,[1,2,5] B. A. Marsh,[3] G. Neyens,[1] R. E. Rossel,[3,6] S. Rothe,[3] H. H. Stroke,[7] K. D. A. Wendt,[6] S. G. Wilkins,[2] and X. Yang[1]

Recipe:

- 1 Long-lived excited state
- 10 mW of pulsed/chopped single-mode light
- 10 mJ of pulsed non-resonant ionisation

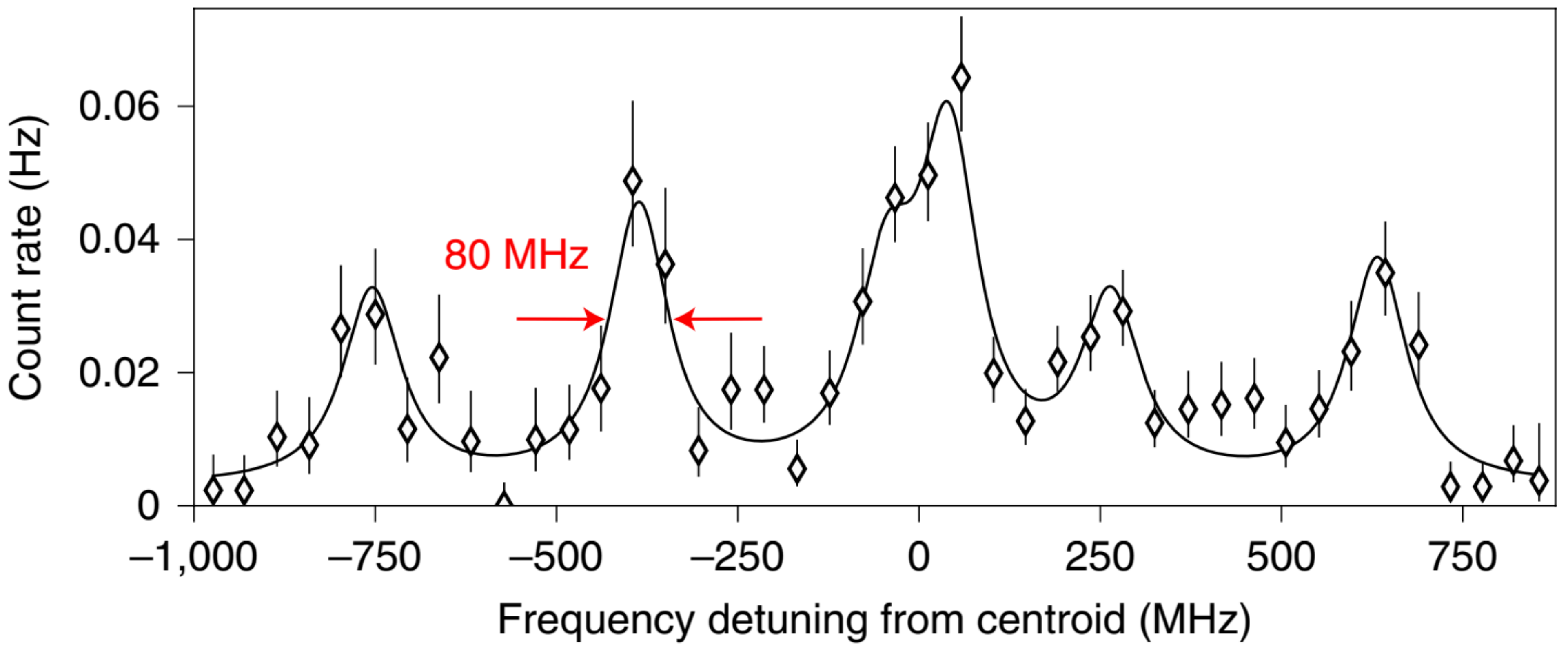
- Apply delayed ionisation:

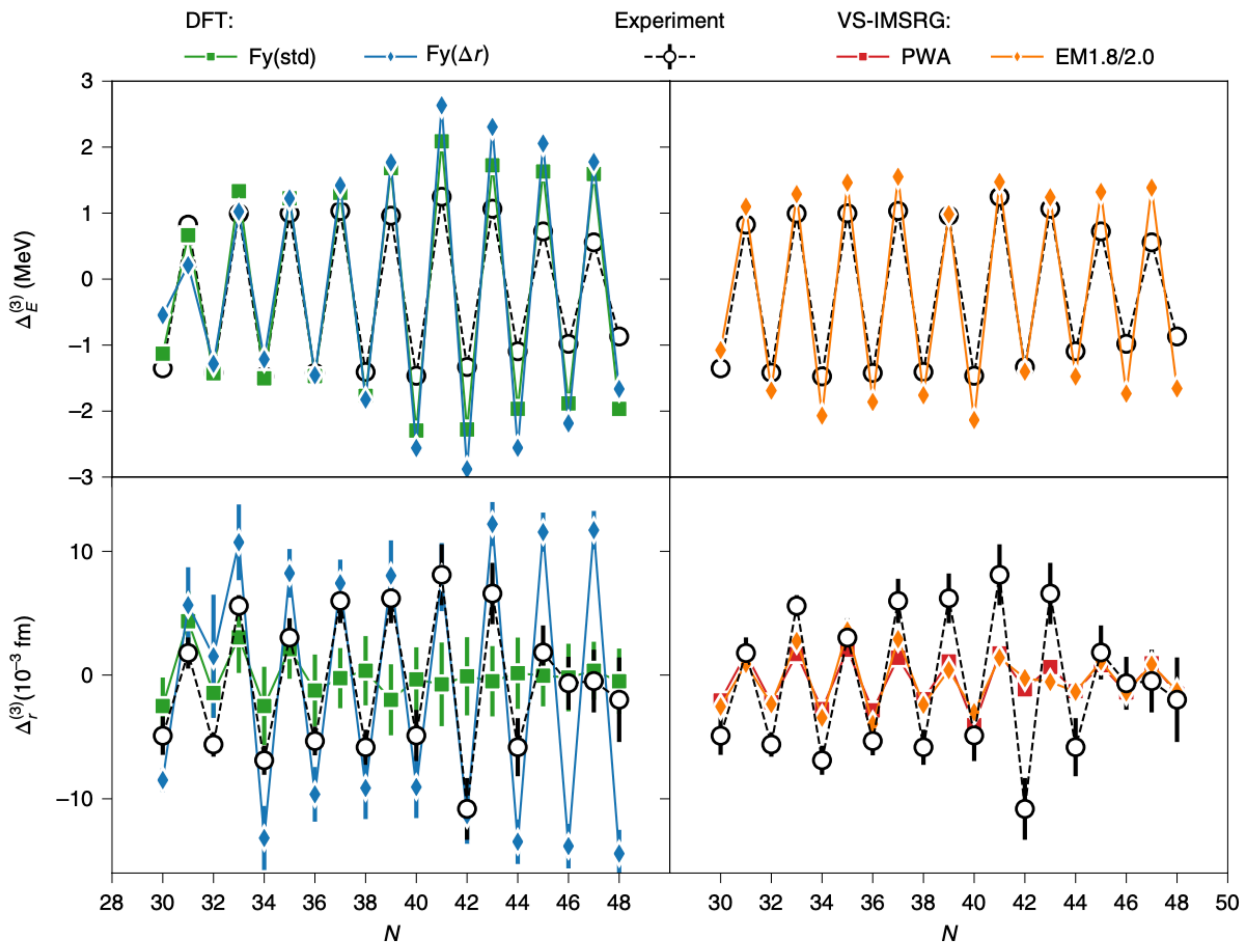
- Final result:

20 MHz resolution! No AC Stark shift! Same efficiency!

=> Weak transitions are the best choice for CRIS.

The merits of high efficiency and zero background





20 ions/s production yield

80 MHz resolution

Absence of background: even weak signals get found

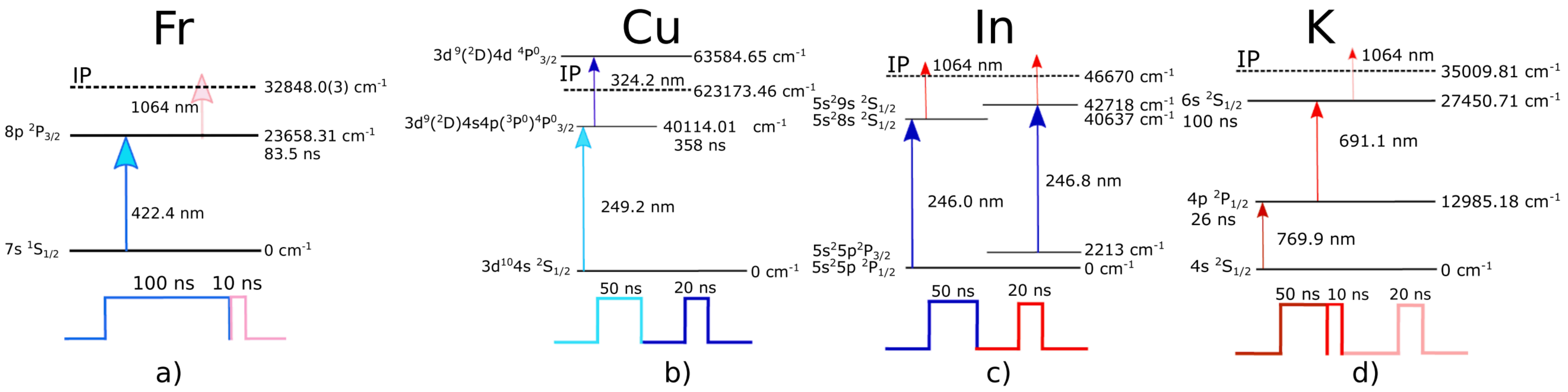
HFS of ^{78}Cu measured in 8h!

- Measurement of nuclear moments in the vicinity of magic Ni:
  - Investigating the robustness of ^{78}Ni
  - Testing large-scale configuration interactions
- Odd-even staggering of the radii and bringing energies
  - Can nuclear DFT and ab-initio theory describe bulk properties and small structure effects?

LETTERS
https://doi.org/10.1038/s41567-020-0868-y
nature physics
Check for updates
OPEN

Measurement and microscopic description of odd–even staggering of charge radii of exotic copper isotopes

High resolution - delayed ionization

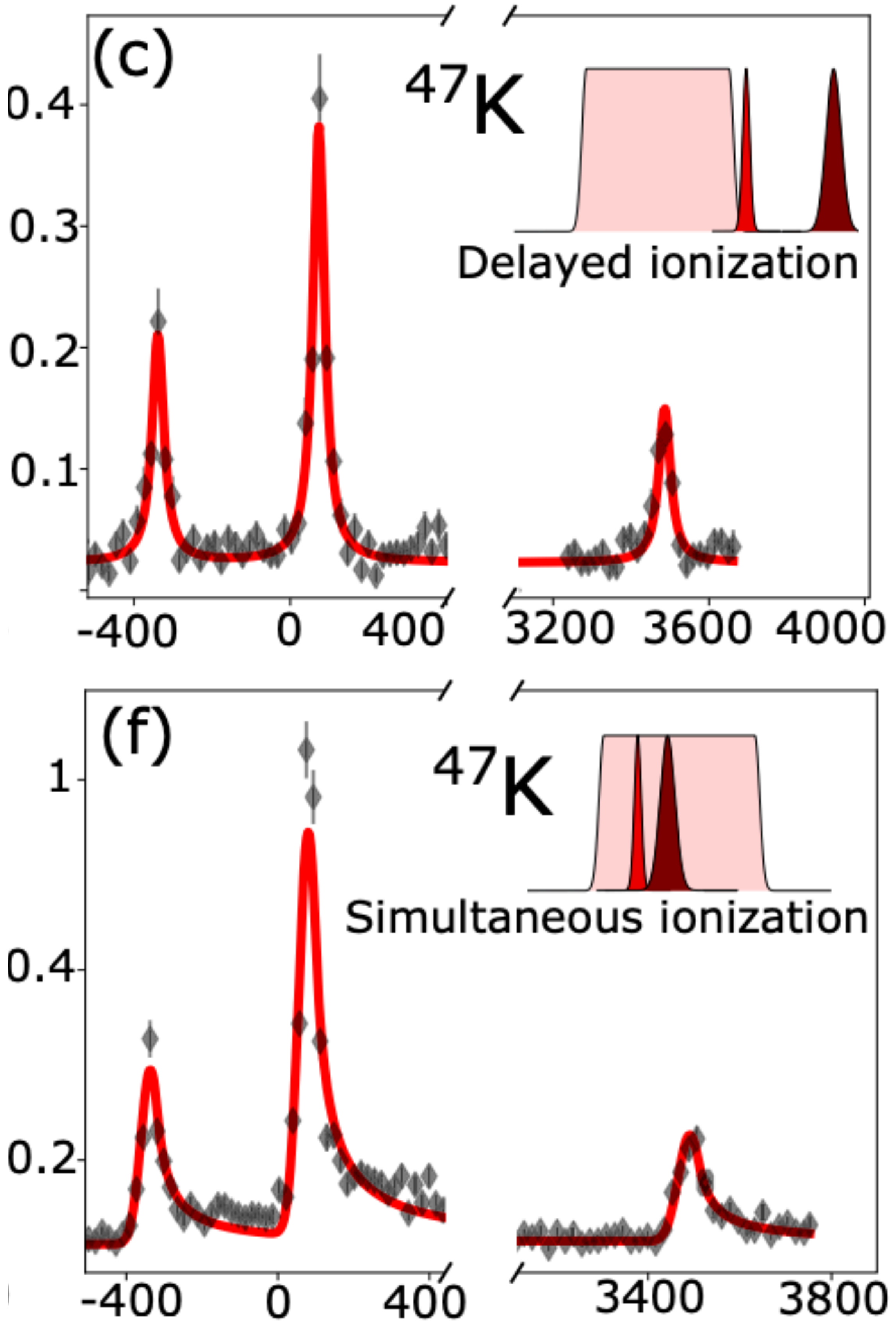


Ideal for long-lived atomic states!

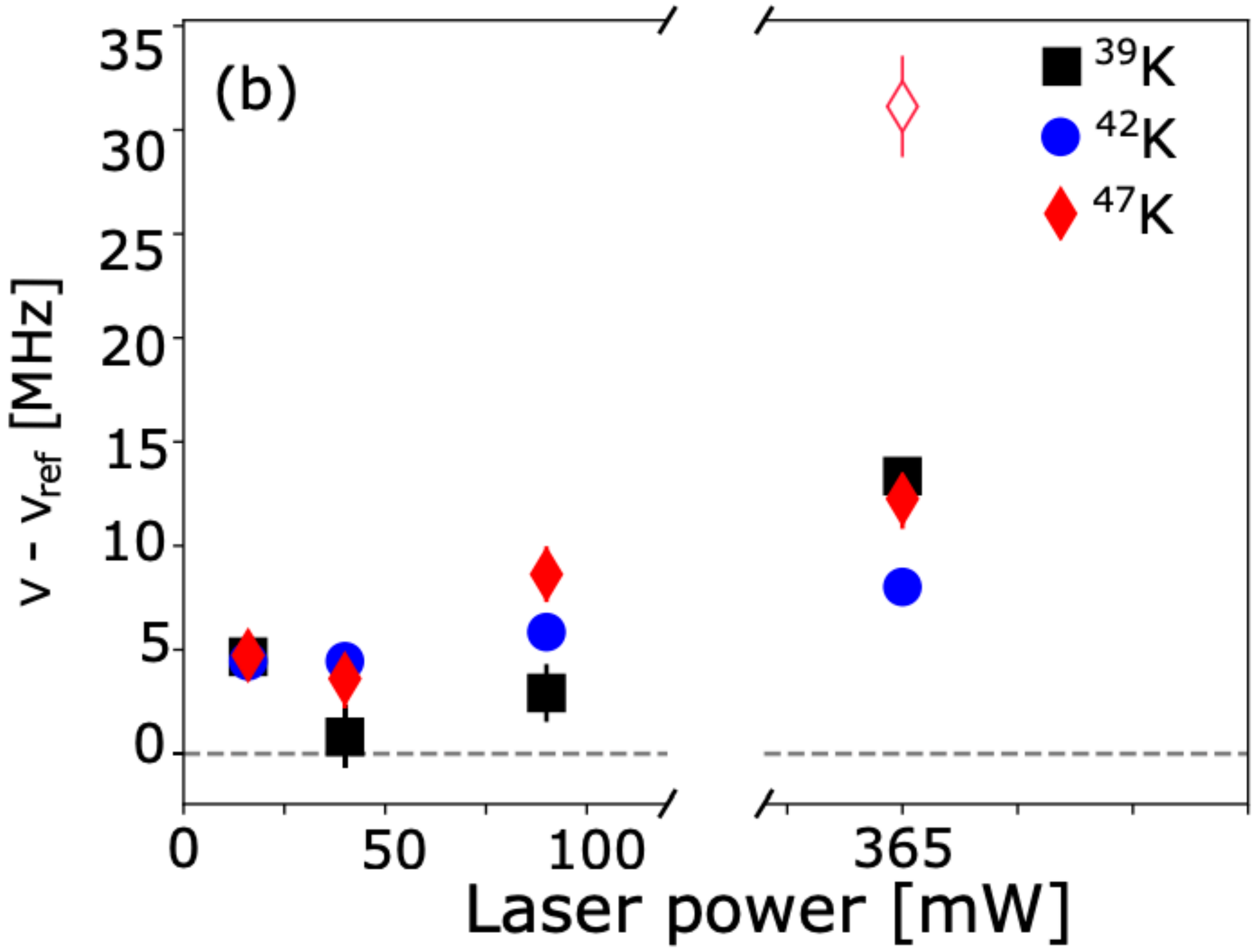
But how about short-lived atomic states?

—> Potassium experiment at CRIS accepts the challenge.

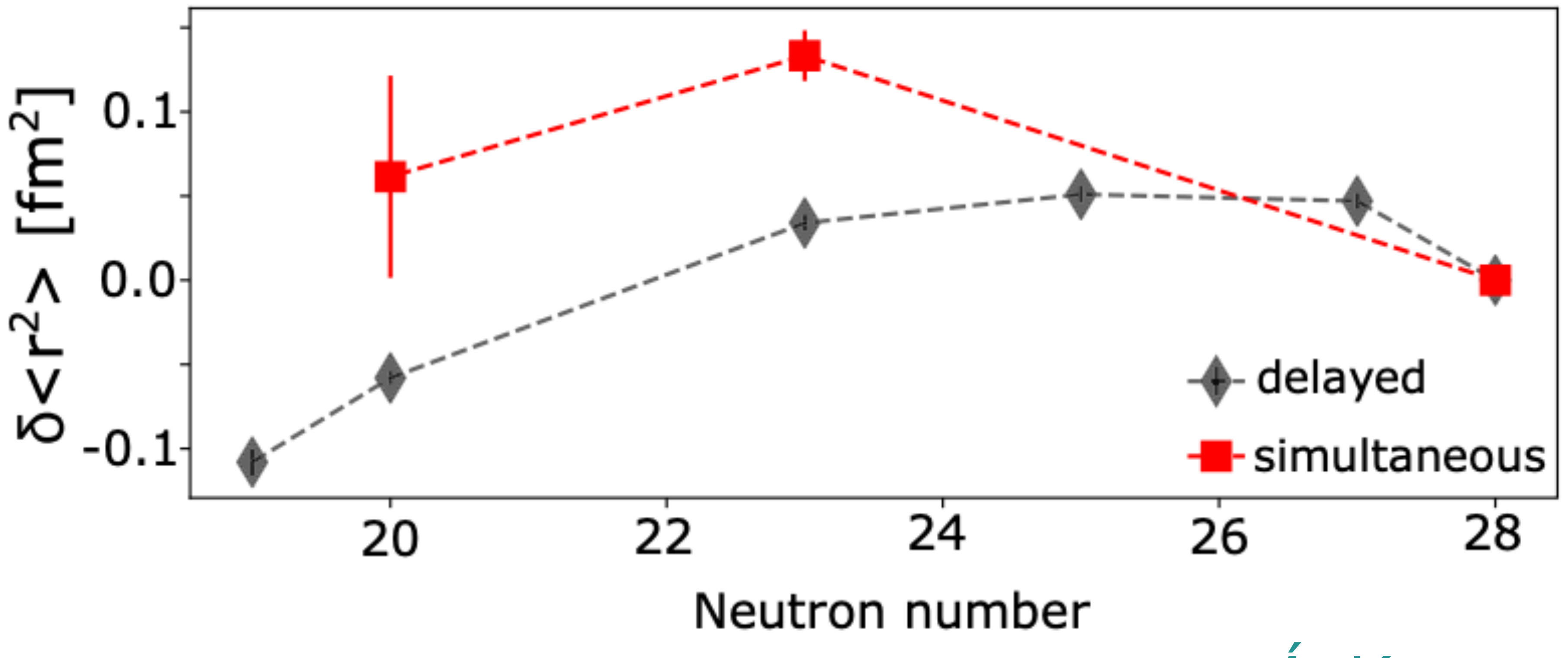
Precision spectroscopy with high-power lasers?



Use of high-energy laser pulses leads to line-shape distortions. Delayed ionization removes this, but affects the efficiency.



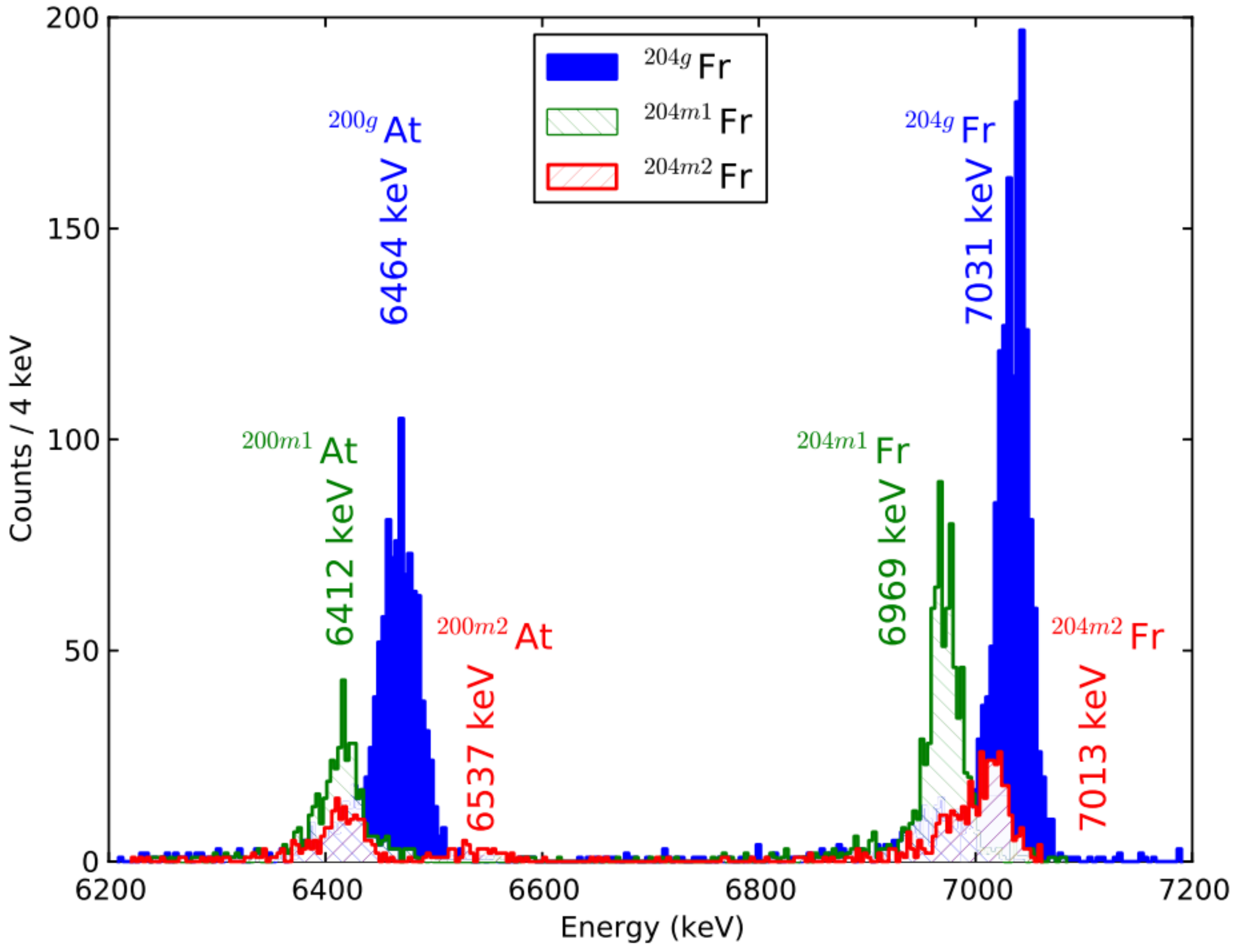
The effect of high laser power, and timing of the laser pulses was carefully investigated.

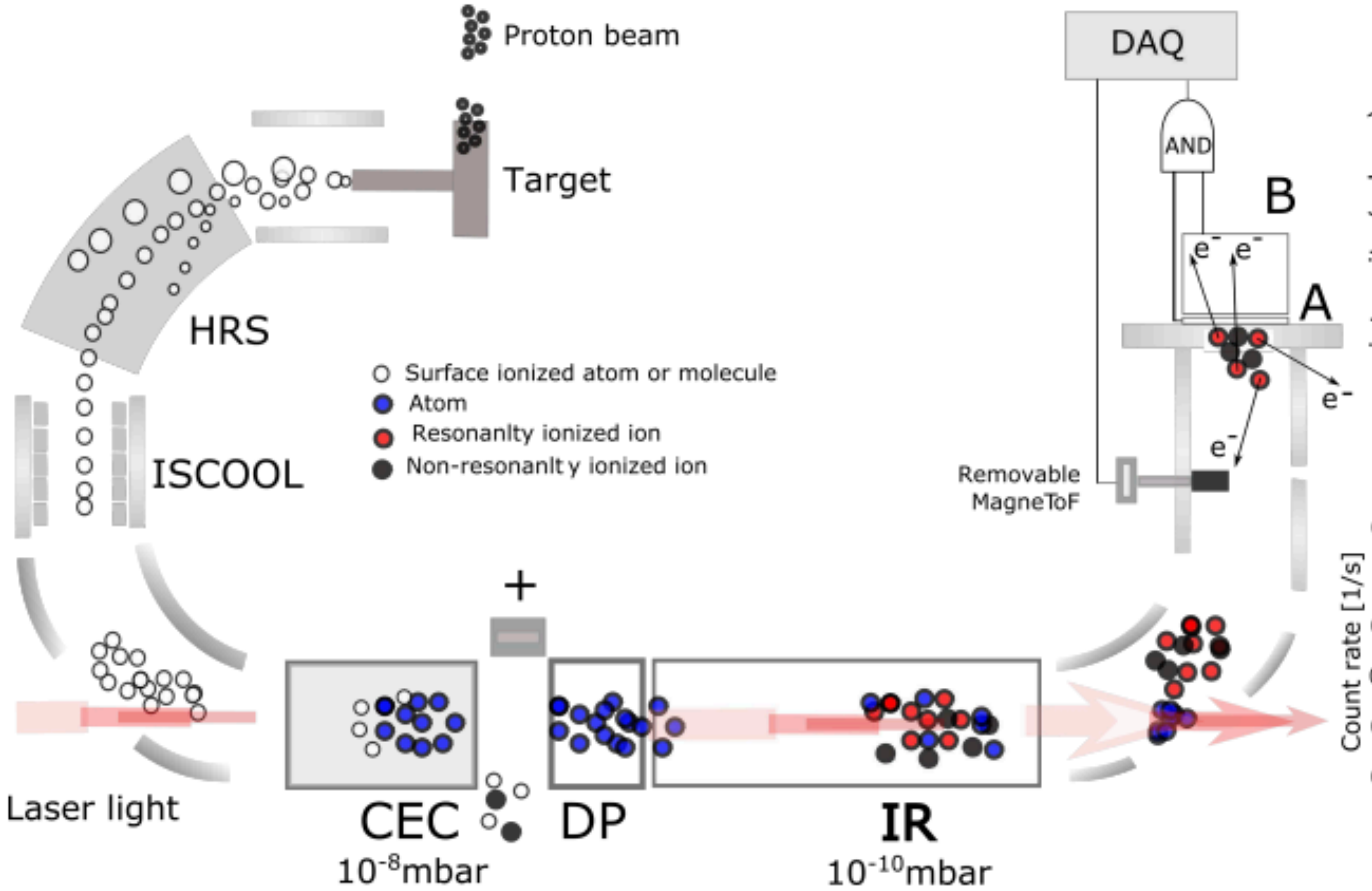


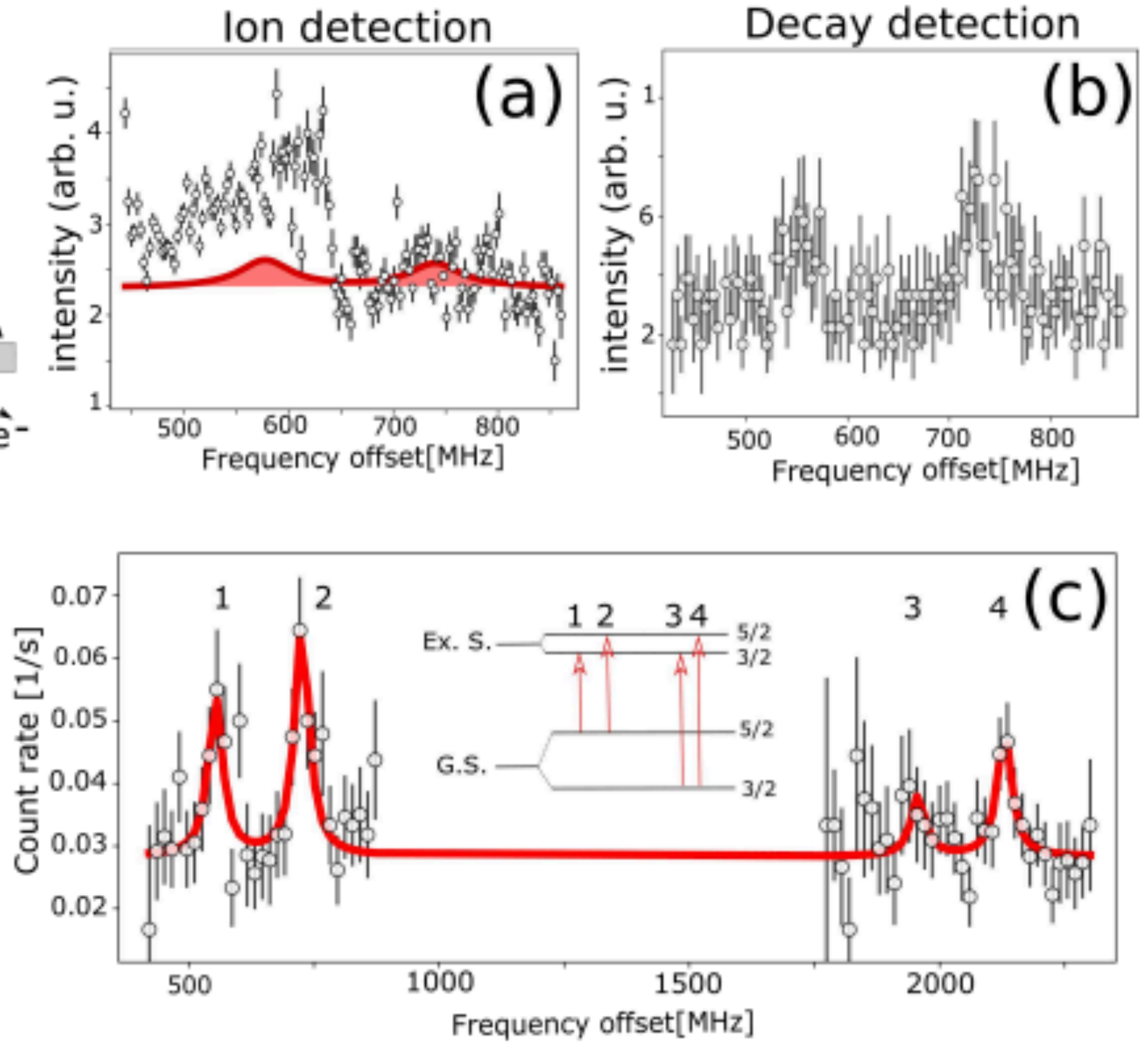
A procedure was developed for correcting the wavelength meter drifts using interferometers, improving the precision of the technique.

Á. Koszorús et al., Phys. Rev. C **100**, 034304 – 2019

Flexible detection: decay tagging for background reduction







PHYSICAL REVIEW X

Decay-Assisted Laser Spectroscopy of Neutron-Deficient Francium

K. M. Lynch, J. Billowes, M. L. Bissell, I. Budinčević, T. E. Cocolios, R. P. De Groote, S. De Schepper, V. N. Fedosseev, K. T. Flanagan, S. Franchoo, R. F. Garcia Ruiz, H. Heylen, B. A. Marsh, G. Neyens, T. J. Procter, R. E. Rossel, S. Rothe, I. Strashnov, H. H. Stroke, and K. D. A. Wendt

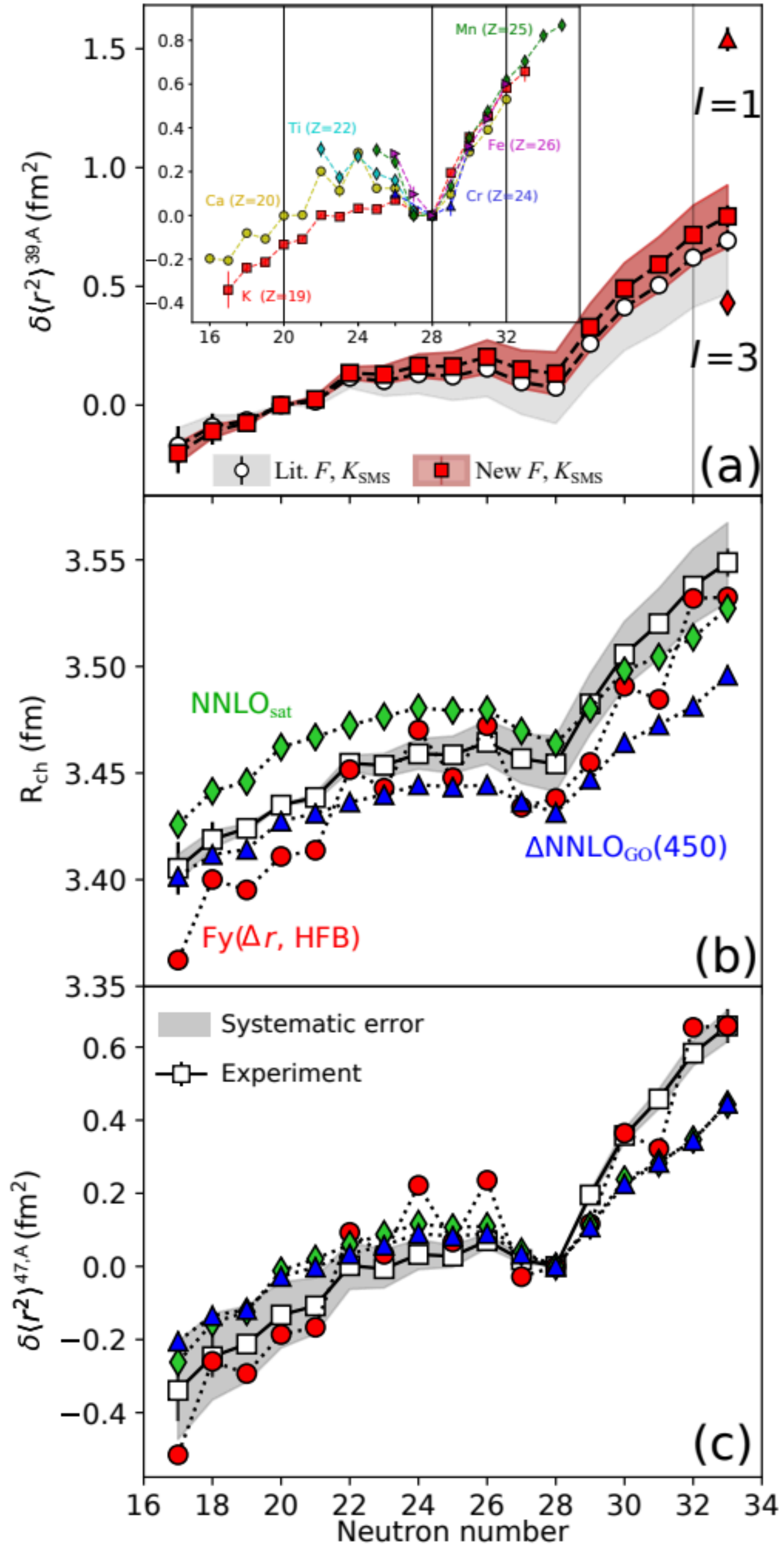
Phys. Rev. X **4**, 011055 – Published 28 March 2014

Physics See Synopsis: Picking Nuclei with Lasers

nature physics LETTERS
https://doi.org/10.1038/s41567-020-01136-5
Check for updates

OPEN

Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of $N = 32$



Charge radii near *N*=32

350 ion/s production rate for ^{52}K
10^6 ion/s isobaric contamination

NNLO_sat fitted to properties of selected nuclei up to *A*=25

NNLO_go new interaction from chiral-effective field theory:

- Explicitly includes the Δ(1232)[1] isobars
- fitted to the properties of *A*≤4 and **nuclear matter properties** (the saturation energy and density, and the symmetry energy of nuclear matter)

Fayans DFT (Δr, HFB) successful for Cu (*Z*=29), Cd (*Z*=48), Sn (*Z*=50), Ca (*Z*=20) and K (Z=19)

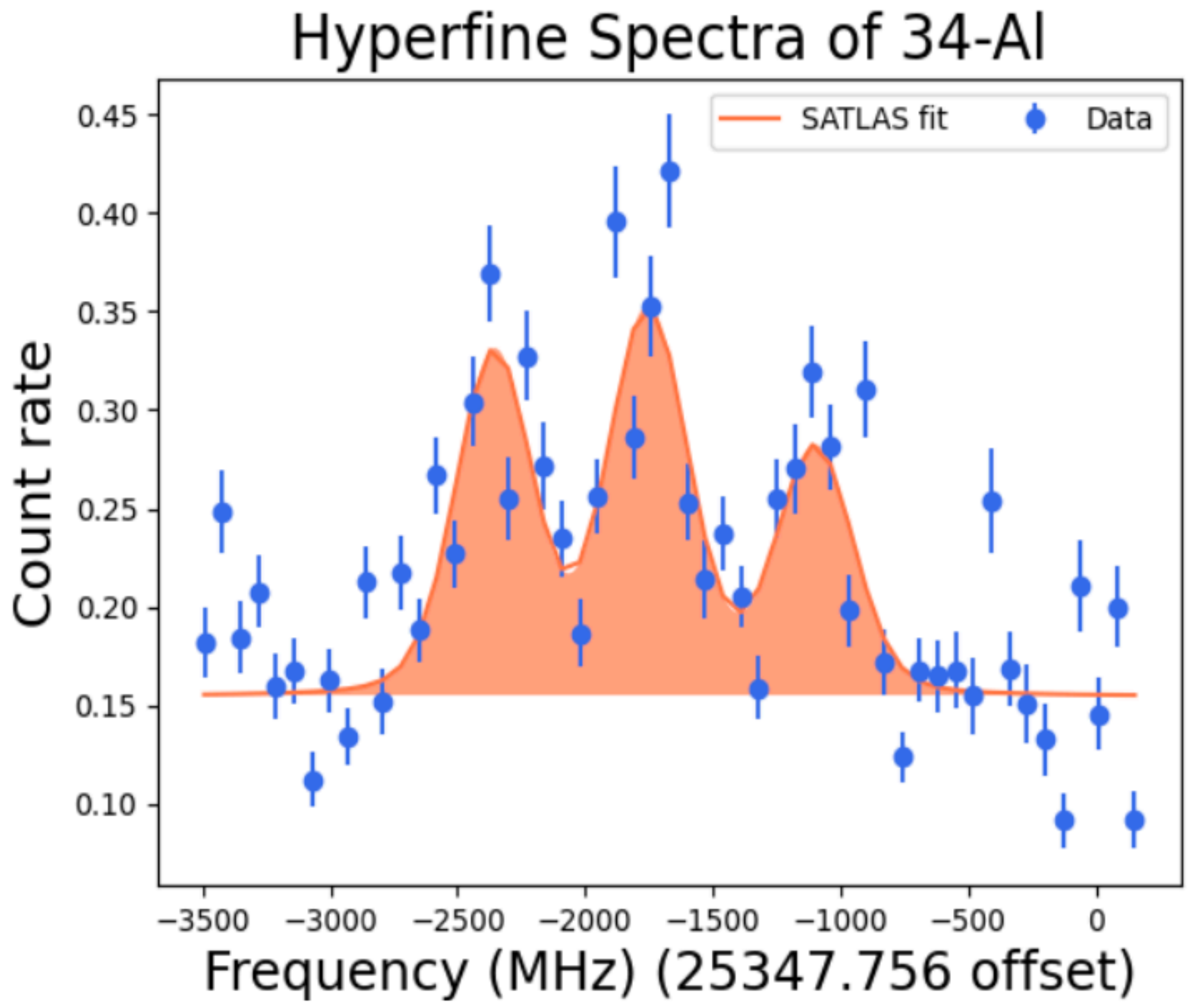
Two ab initio interactions - same results
Missing many-body correlations?

[1] A Ekström, G Hagen, TD Morris, T Papenbrock, PD Schwartz
Physical Review C 97 (2), 024332

nature physics LETTERS
https://doi.org/10.1038/s41567-020-01136-5
Check for updates

OPEN
Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of *N* = 32

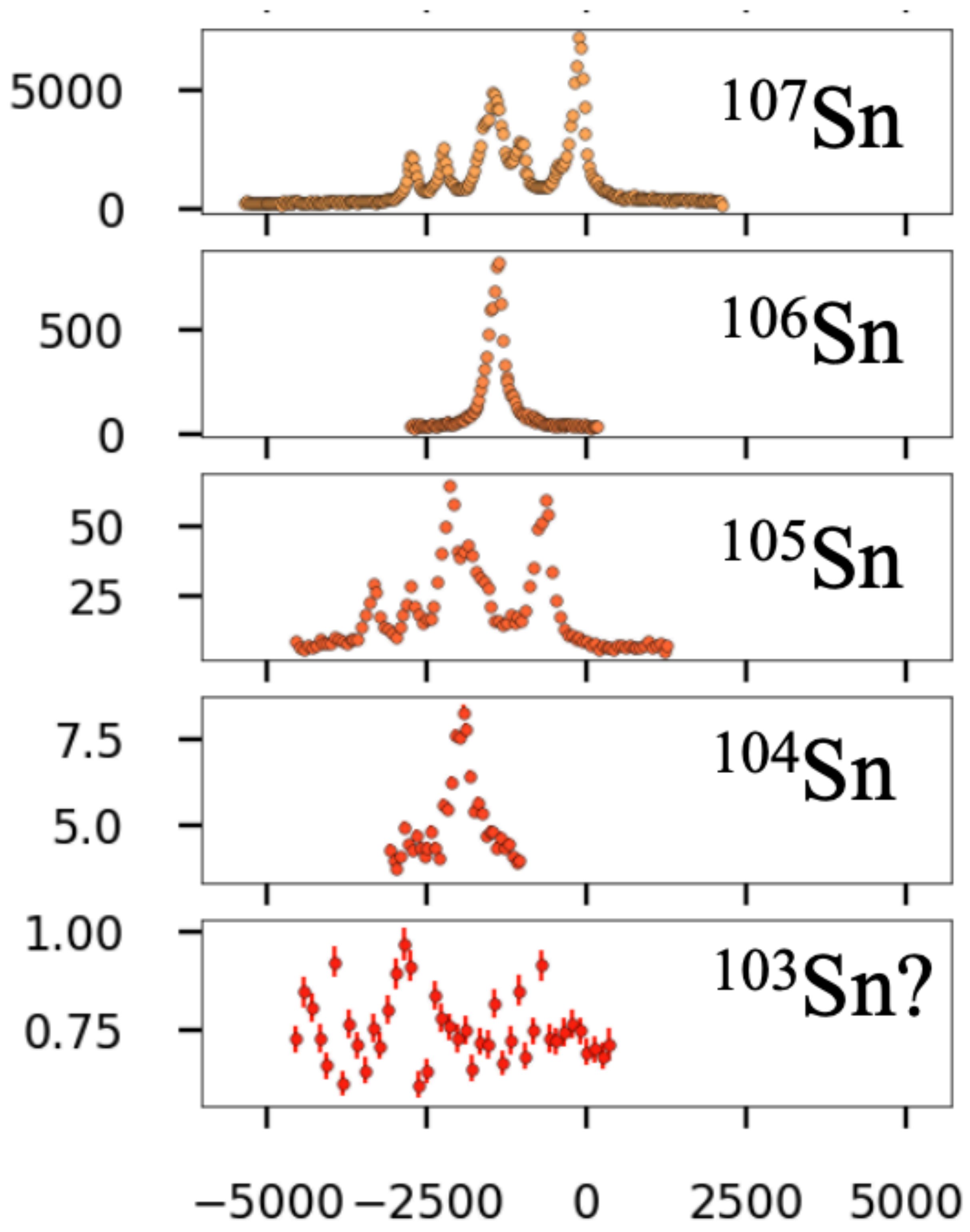
Going even lighter, even less production: ^{33,34}Al

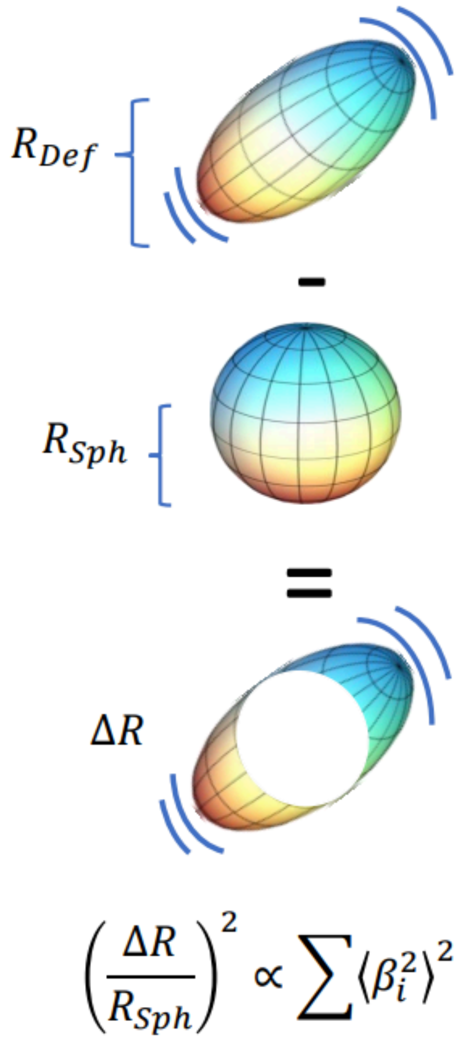


150 ions/second

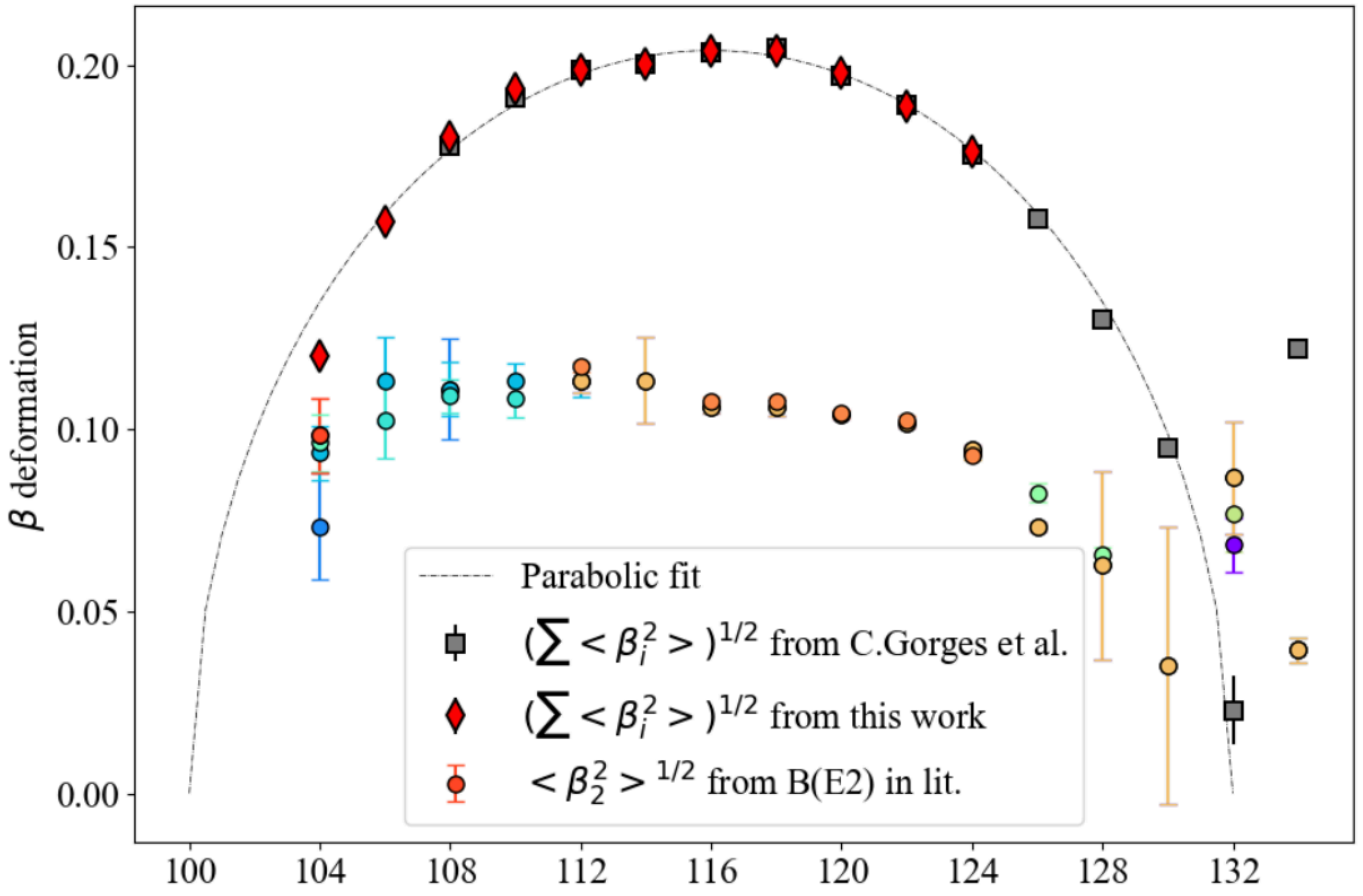
- Experiment performed 2022
- Literature: up to ^{32}Al (see also talk P. Plattner)
- Aim at CRIS: push beyond N=20
- Challenging experiment; after many days of hard work the experimental efficiency and resolution were under full control
- ^{33,34}Al: in 1 day!
- Next experiment: improve statistics, push to ^{35}Al
- Analysis ongoing. See poster J. Reilly!

Exploring shell closures in the Sn (Z=50) region





Collectivity along the tin chain



Figures from the tac of F.P-Gustafffson ISODLE workshop 2020

Publication in preparation (F. Parnefjord Gustafssonet al)

nature

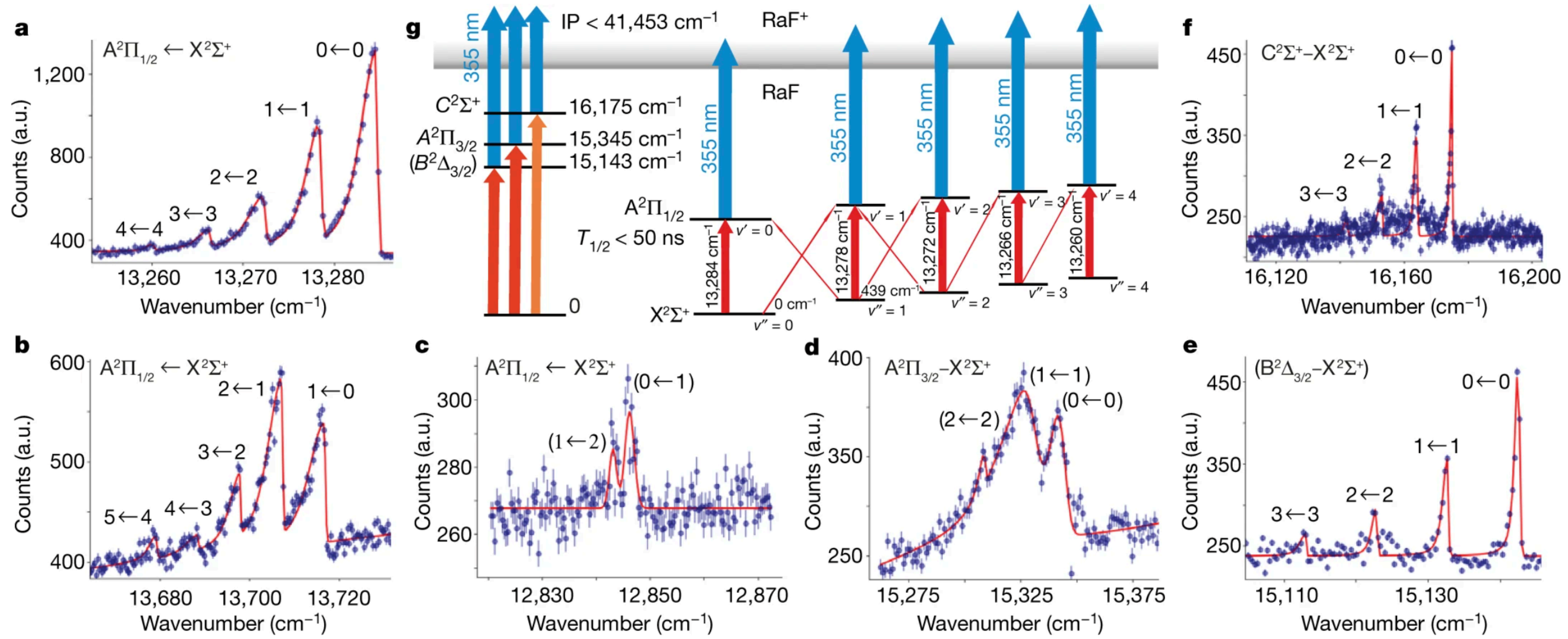
Article | Published: 13 July 2022

Nuclear moments of indium isotopes reveal abrupt change at magic number 82

Indium (Z=49): see talk A. Vernon

Silver (Z=47): see poster B. Van Den Borne

Molecular spectroscopy at CRIS!



nature

Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

PHYSICAL REVIEW LETTERS **127,** 033001 (2021)

Editors' Suggestion | Featured in Physics

Isotope Shifts of Radium Monofluoride Molecules

S. M. Udrescu,[1,*] A. J. Brinson,[1] R. F. Garcia Ruiz,[1,2,†] K. Gaul,[3] R. Berger,[3,‡] J. Billowes,[4] C. L. Binnersley,[4] M. L. Bissell,[4] A. A. Breier,[5] K. Chrysalidis,[2] T. E. Cocolios,[6] B. S. Cooper,[4] K. T. Flanagan,[4,7] T. F. Giesen,[5] R. P. de Groote,[8] S. Franchoo,[9] F. P. Gustafsson,[6] T. A. Isaev,[10] Á. Koszorús,[6] G. Neyens,[2,6] H. A. Perrett,[4] C. M. Ricketts,[4] S. Rothe,[2] A. R. Vernon,[4] K. D. A. Wendt,[11] F. Wienholtz,[2,12] S. G. Wilkins,[1,2] and X. F. Yang[13]

- Innate high efficiency of CRIS enables measurements of complex systems
- Large number of energy levels and density is not a showstopper!
- See talk on molecular spectroscopy M. Athanasakis
- First publications in molecular theory as well! (M. Athanasakis, accepted for publication in PRX!)

Sensitivity

Finding the most efficient way to turn an optical resonance into an ion signal

- Extensive suite of laser systems for broad wavelength coverage
- Develop methods to handle both strong and weak transitions effectively
- Develop atomic and molecular expertise!
- Dedicated offline program to fully explore all options!

Selectivity

Finding the needle in the haystack: separating the ions of interest from the contamination.

- decay tagging
- Ultra-high vacuum to avoid collisional ionization
- Smart laser ionization scheme development (Rydberg ionisation, auto-ionising states)
- Future ideas; injecting ions into RFQ+MRTOF for mass cleaning?

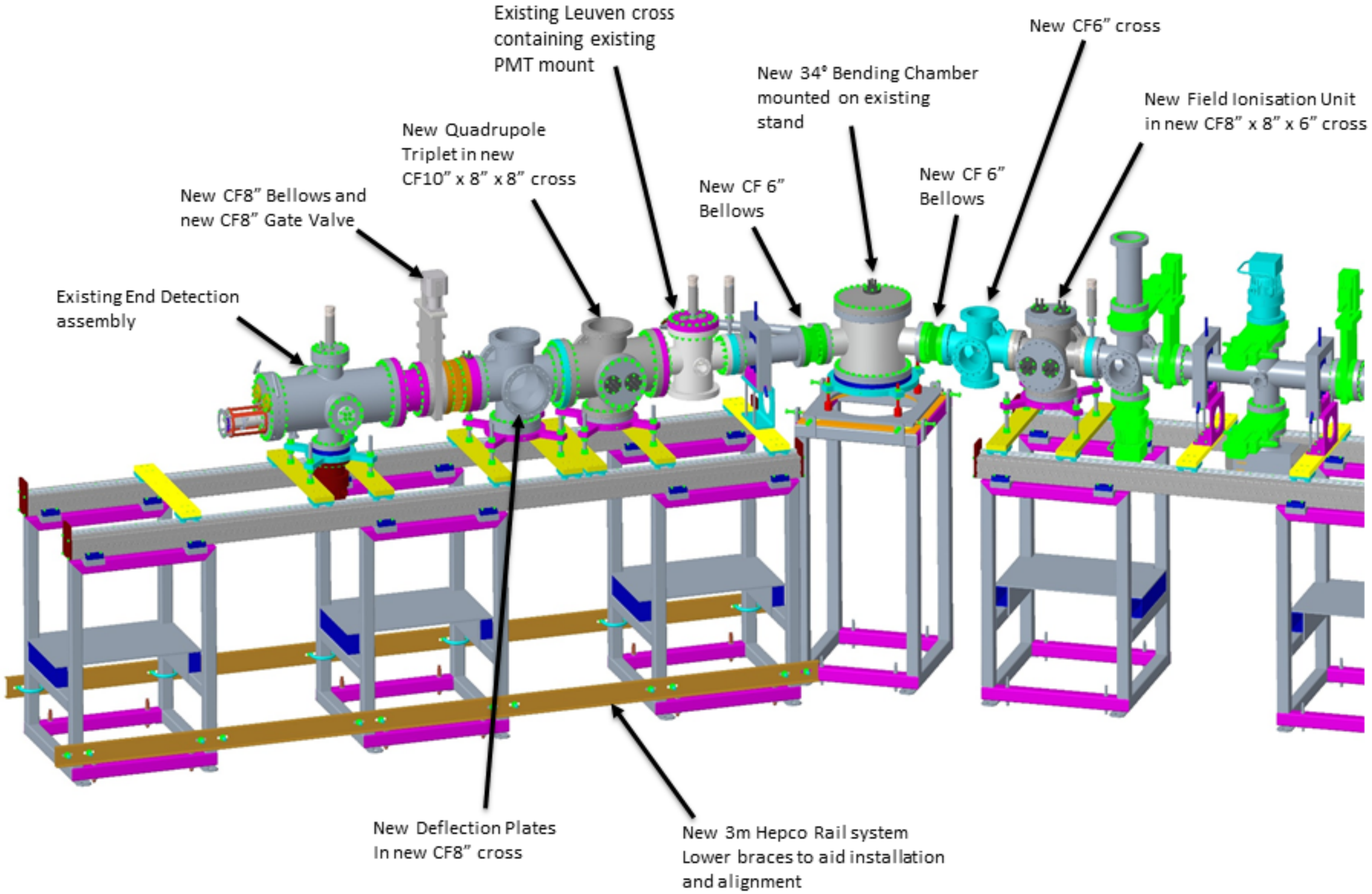
Precision

Finding ways to make the measurements count - precision, accuracy, systematics!

- Understand the physics of laser-atom interactions
- Explore both familiar and new tools: wavemeters, interferometers, Doppler tuning, …
- Dedicated offline program to fully characterise the method!

Never stop growing, learning, improving!

Future plans: beamline upgrade



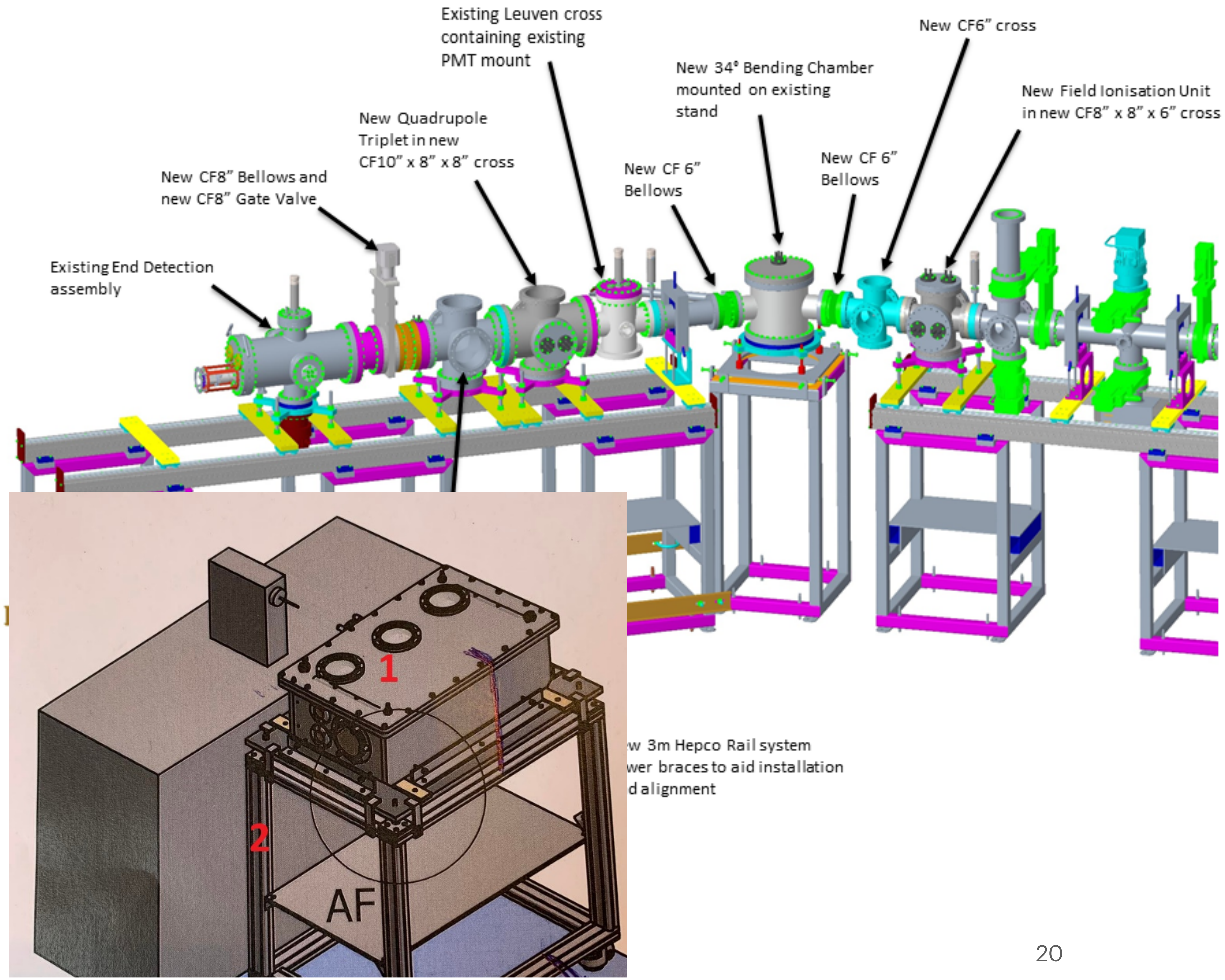
- Stepwise excitation to high-lying Rydberg levels
- These Rydberg levels can be ionised by applying a moderately large electric field
  - Reduction of background due to smaller ionization region
- Advantage: does not require high power lasers to ionize
  - Eliminates systematics which currently require attention
- Demonstrated offline with stable indium

scientific reports

Laser spectroscopy of indium Rydberg atom bunches by electric field ionization

A. R. Vernon, C. M. Ricketts, J. Billowes, T. E. Cocolios, B. S. Cooper, K. T. Flanagan, R. F. Garcia Ruiz, F. P. Gustafsson, G. Neyens, H. A. Perrett, B. K. Sahoo, Q. Wang, F. J. Waso & X. F. Yang

Future plans: beamline upgrade



- New decay station
- Optimised for beta detection
- Tape station to remove activity buildup
- Under construction and testing

Worldwide adoption of the CRIS method!

- After pioneering work at ISOLDE, CRIS beamlines are being installed in other laboratories!

  - University of Jyvaskyla: low-energy, small footprint CRIS setup

  - NSCL/FRIB: BECOLA setup extended with ion detection and pulsed lasers

  - Ultra-trace analysis spin-off company at University of Manchester

ARTEMIS ANALYTICAL

In summary

- 10 years since the first resonance!
- Best resolution: 20 MHz using delayed ionisation (Fr)
- Best efficiency: 20 ions/s production rate ^{78}Cu (measured in 8h!)
- Precision around 1 MHz
- Versatility:
  - Study of atomic physics, nuclear physics, quantum chemistry
  - Particle detection: ion counting of decay detection
- Continuous upgrades to improve the technique!
- First laser spectroscopy of radioactive molecules!

Active projects

- Neutron-rich $^{33\text{-}35}Al$ (see poster J. Reilly!)
- Exotic silver isotopes near neutron shell closures (see poster B. Van Den Borne!)
- Molecular spectroscopy of AcF (experiment currently running!)
- Neutron-rich indium beyond N=82
- Negative ion measurements of radioactive isotopes
- Laser spectroscopy of zinc (poster of Yongchao Liu)
- …
- … and many more plans in the making!

Thank you for your attention!

KU LEUVEN

MANCHESTER 1824

PEKING UNIVERSITY 1898

UNIVERSITAS GOTHOBURGENSIS 1891

CERN

fwo

UKRI Science and Technology Facilities Council

erc

Local members at CRIS missing from the picture (past and present): Ronald.F. Garcia Ruiz, Xiaofei Yang, Youngchao Liu, Yang, Kara Lynch, Adam Vernon, Shane Wilkins, Cory Binnersley, Gregory J. Farooq-Smith, Chris Ricketts, F. Parnefjord Gustafsson