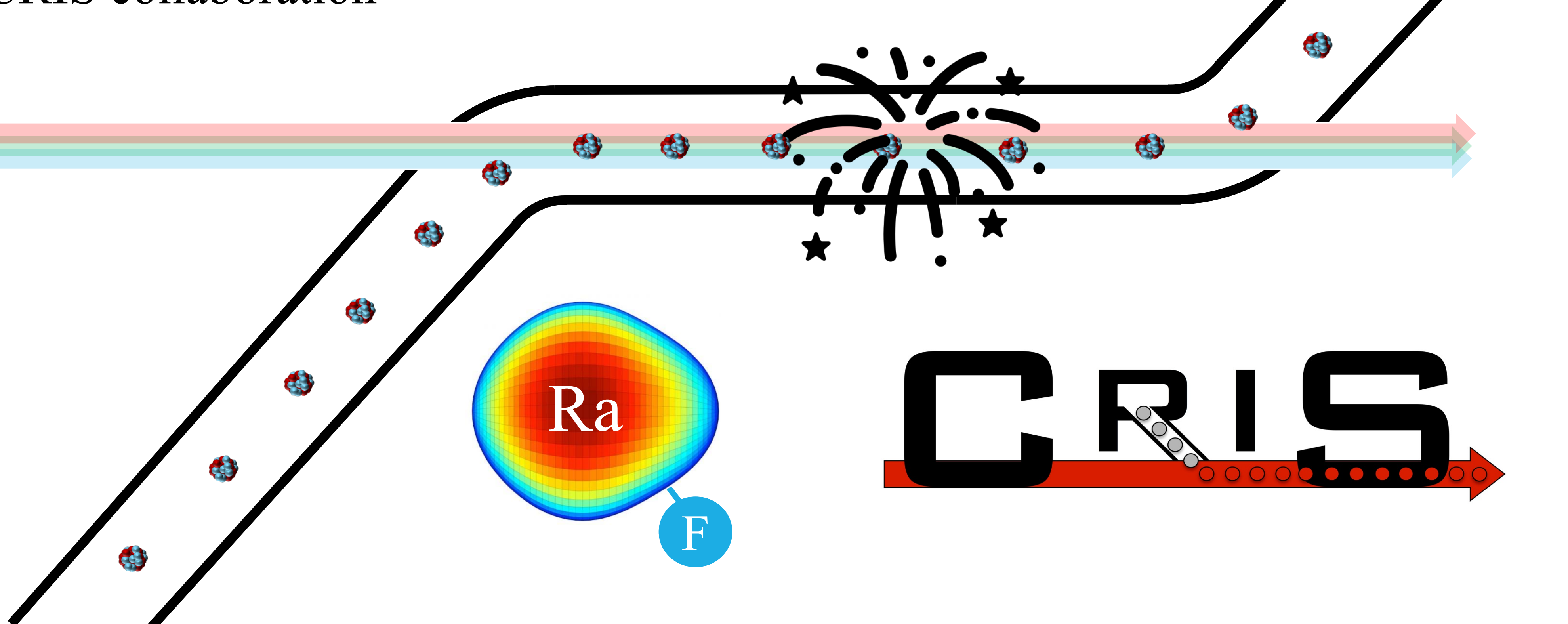
2023 at CRIS

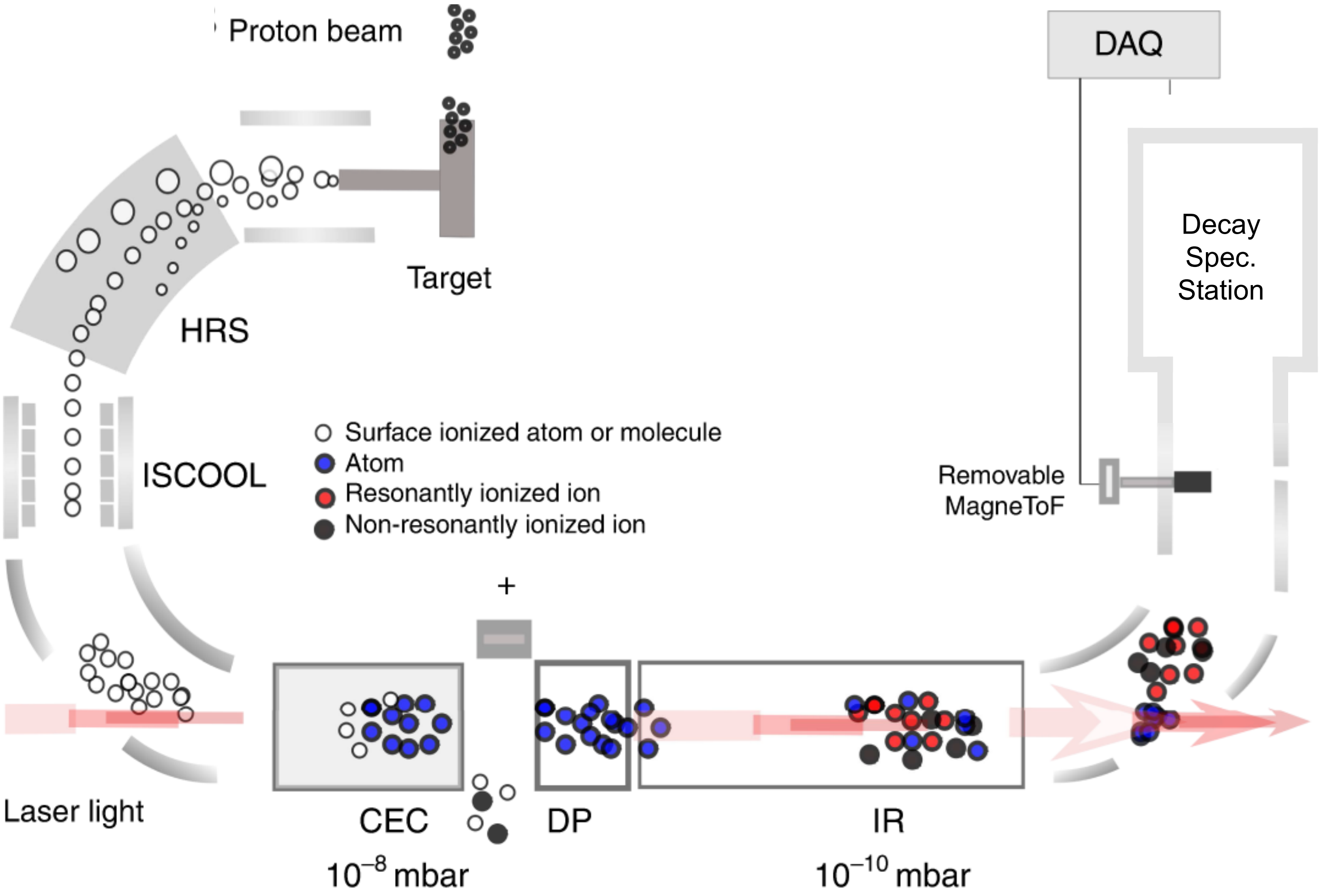
Louis Lalanne
IPHC
on behalf of the CRIS collaboration

ISOL-France
29/05/2023



Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

CRIS : Collinear Resonance Ionization Spectroscopy



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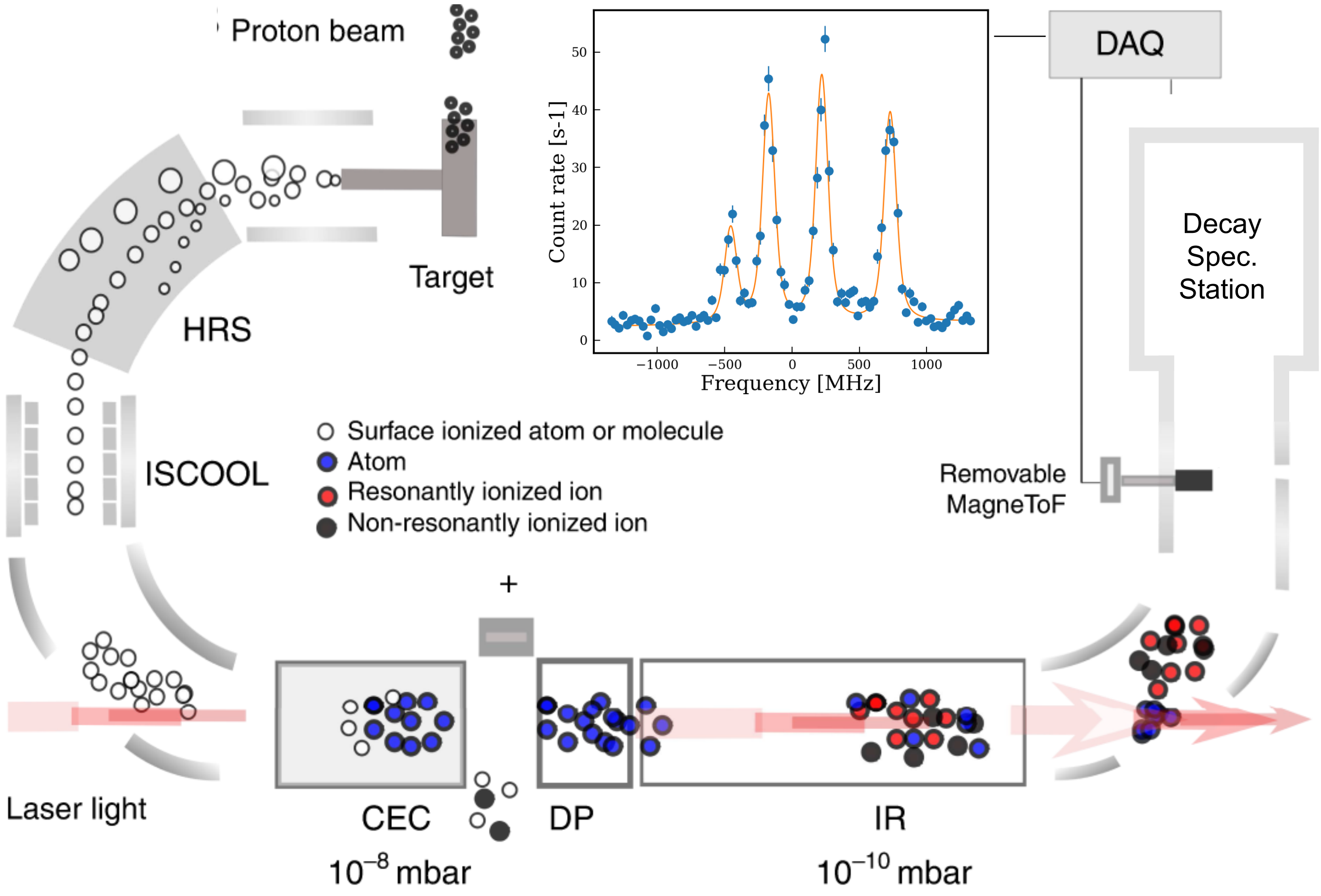

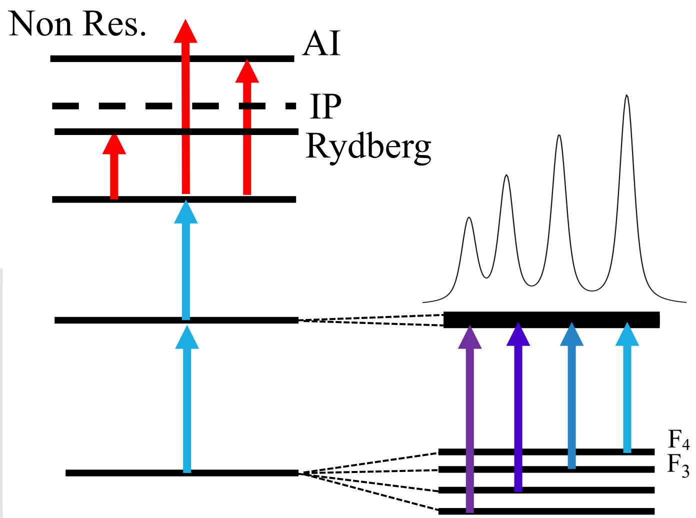

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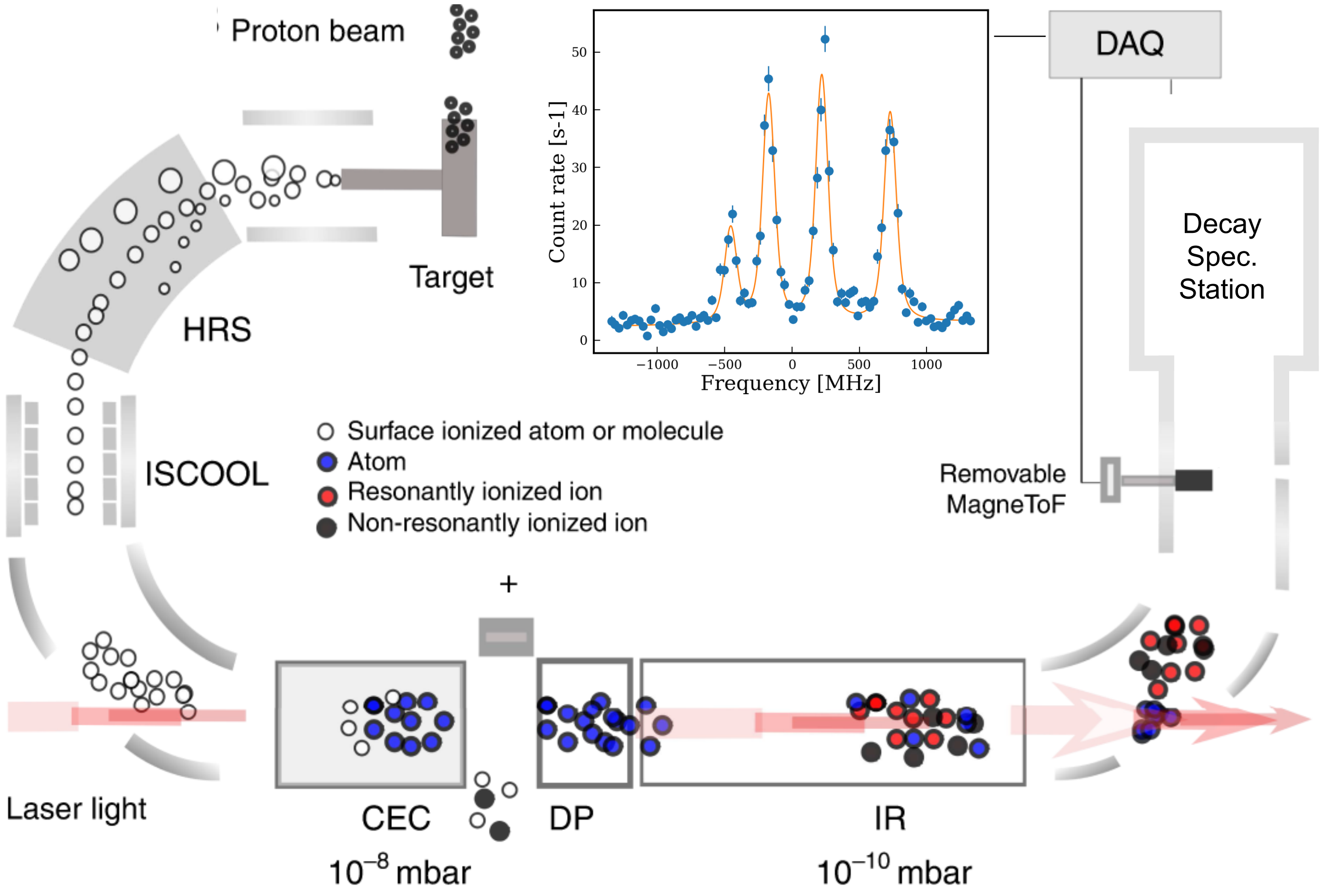
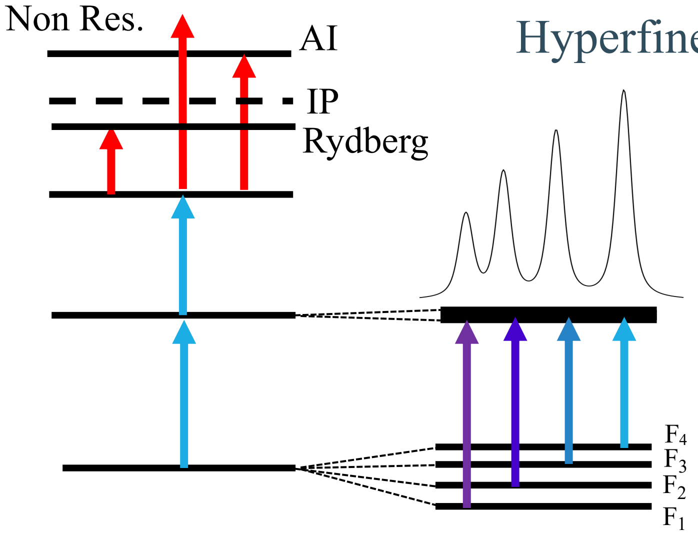




Hyperfine Structure (HFS) :

$$E(F) = kA + k'B$$

$$A = \frac{\mu \, Be(0)}{I.J}$$

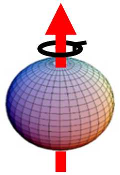
$$B = e\, Q_s V(0)$$

Isotope shift : shift of HFS between two isotopes A and A’

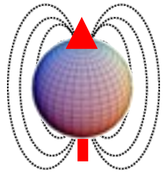
$$\delta\nu_i^{A,A'} = \frac{A - A'}{AA'} M_i + F_i \, \delta\langle r^2\rangle^{AA'}$$

Measuring the HFS :

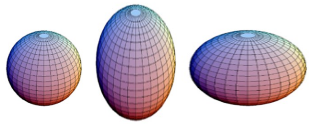
- Nuclear Spin I



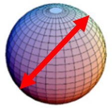
- Magnetic dipole moment μ



- Electric quadrupole moment Q_s



- Changes of charge radii $\delta\langle r^2\rangle$



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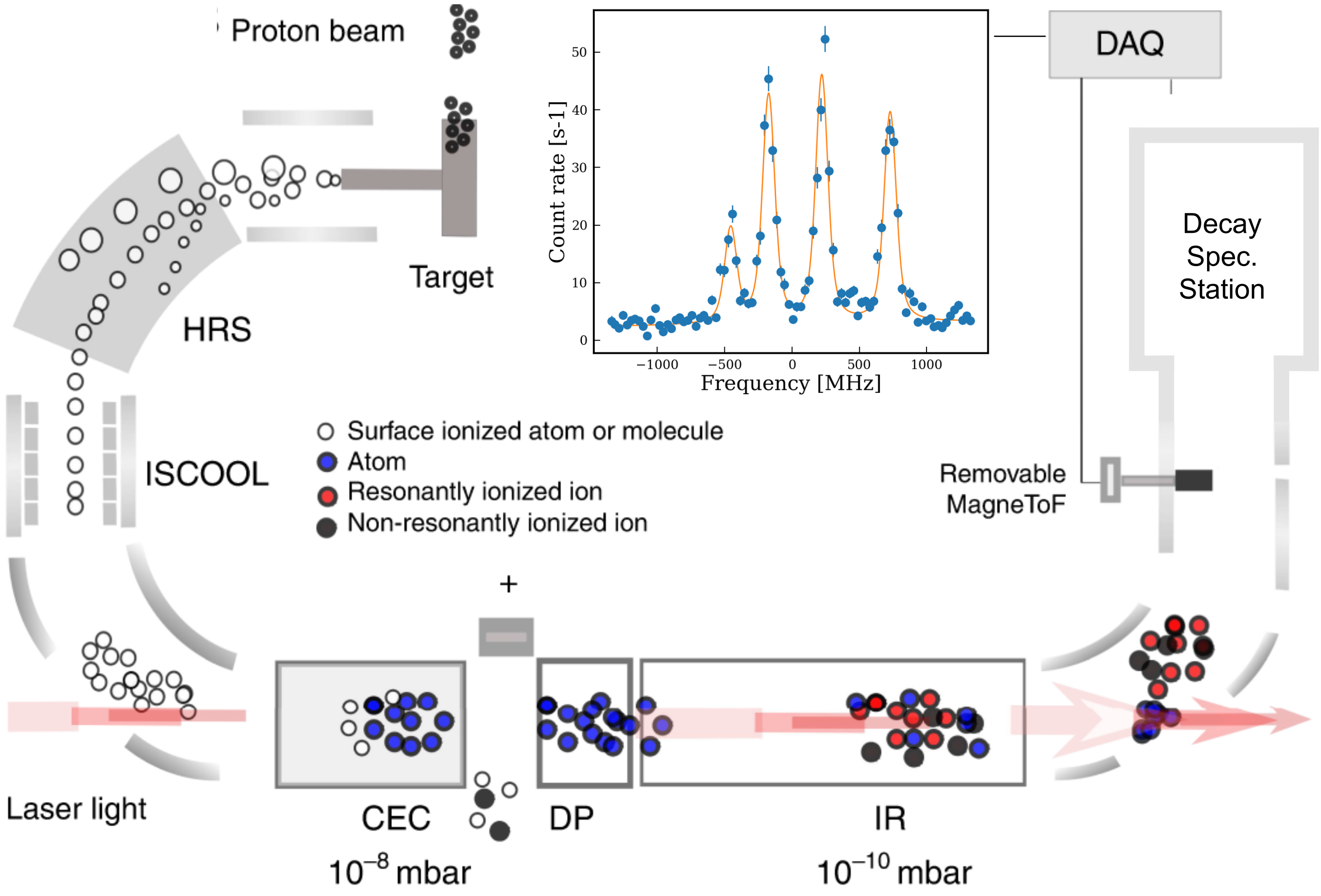

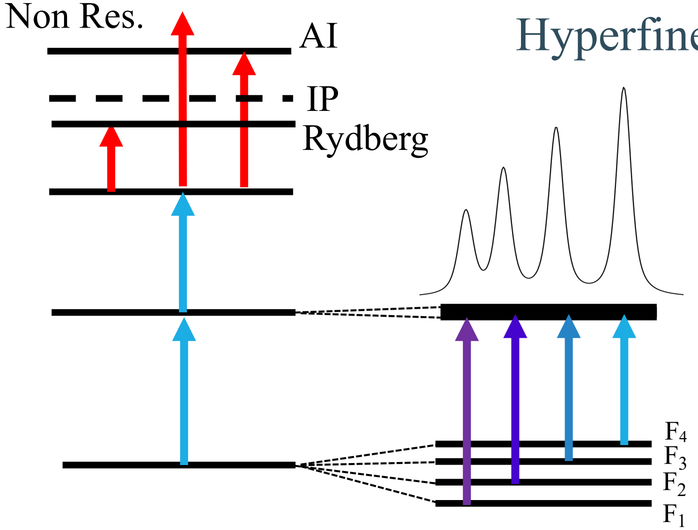

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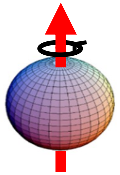

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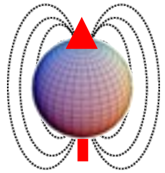

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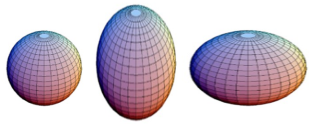

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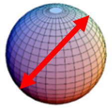
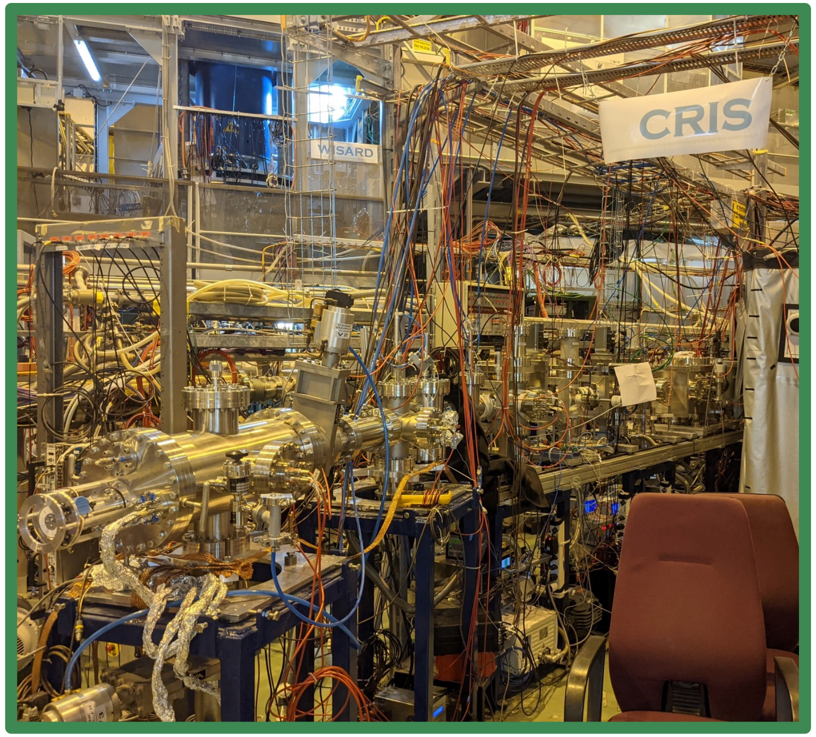


✓ High sensitivity : > few 10 ions/s ✓ High resolution : > 20 MHz

✓ High versality

2023 CRIS upgrade: New End of the Beam Line

Decembre 2022



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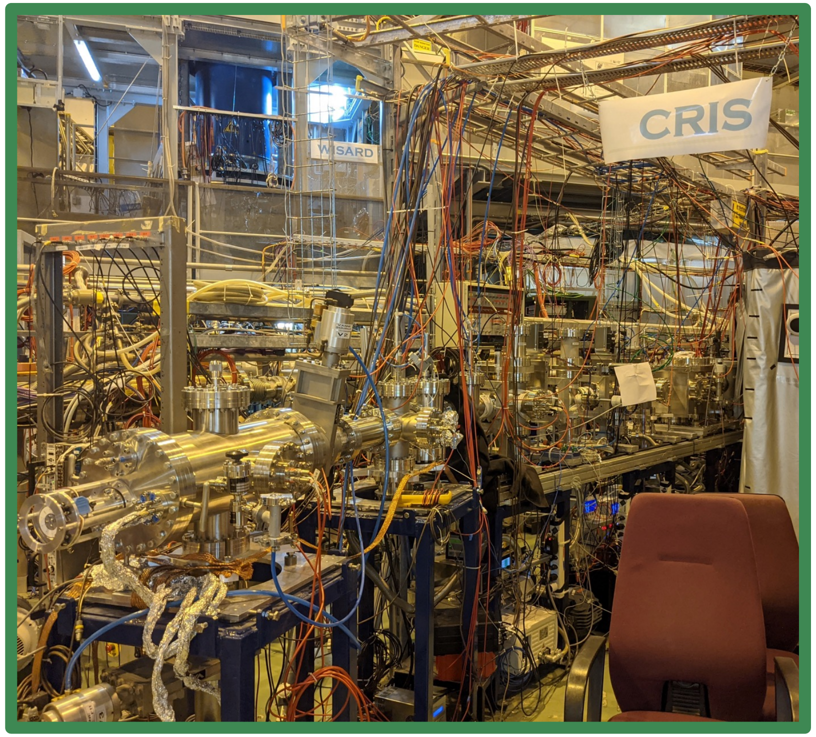
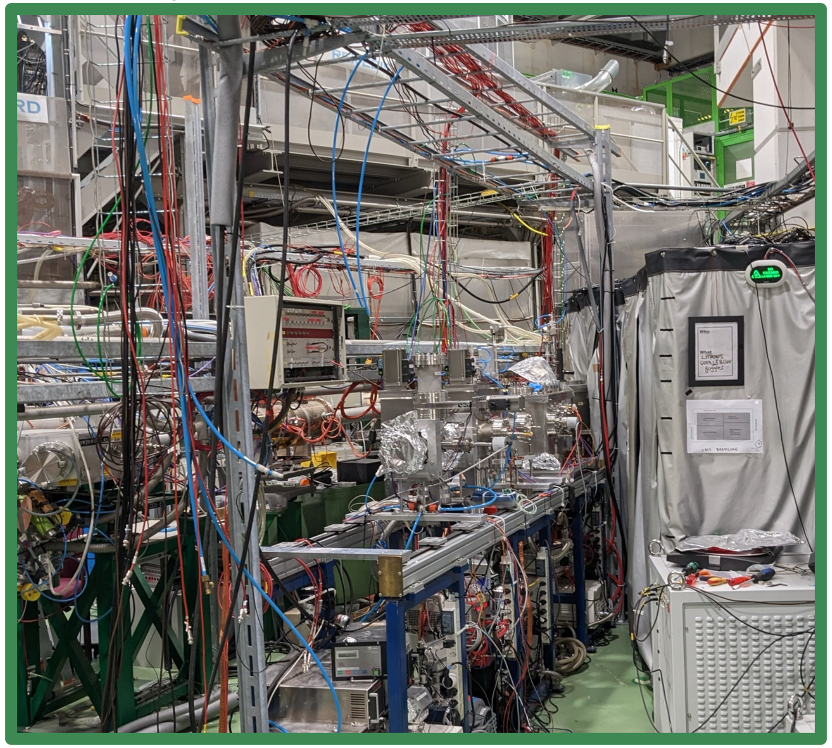


January 2023



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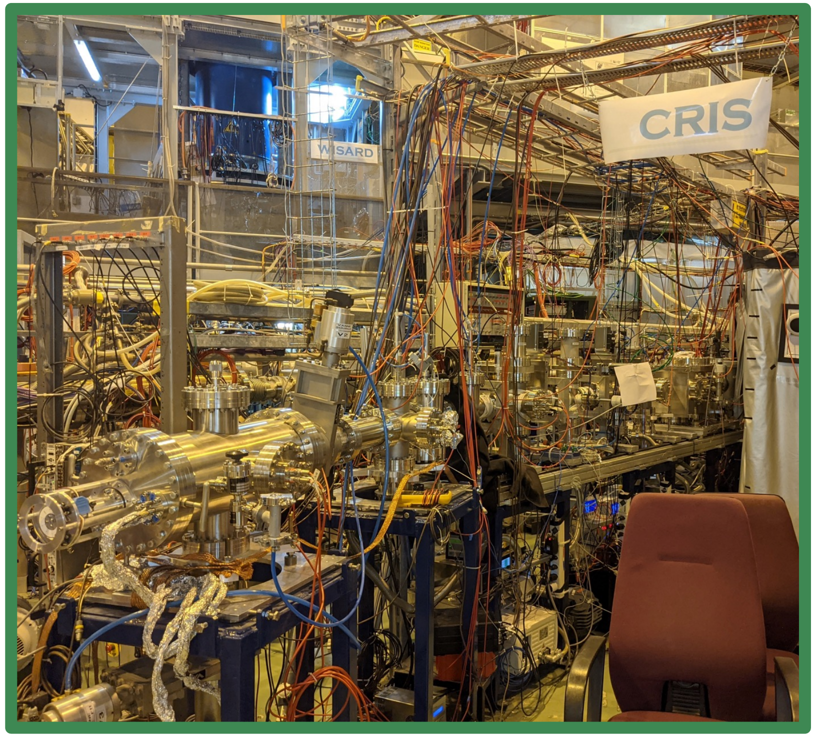

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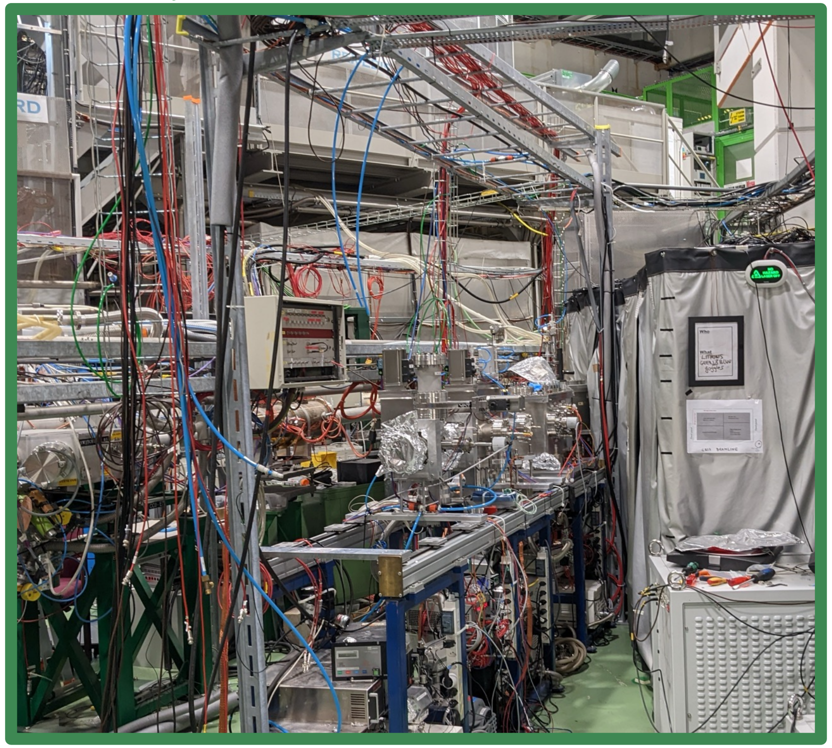
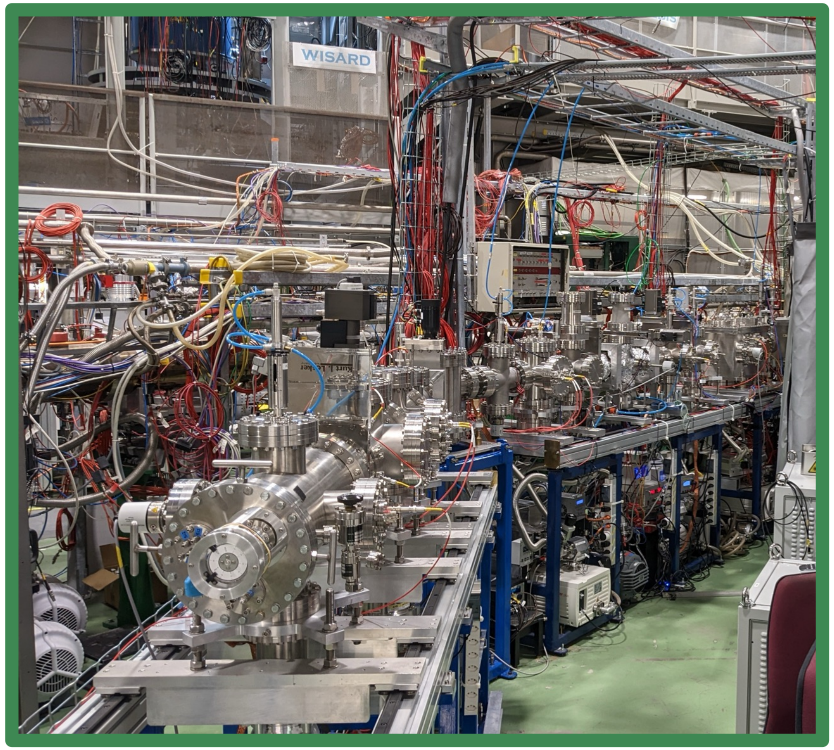


March 2023



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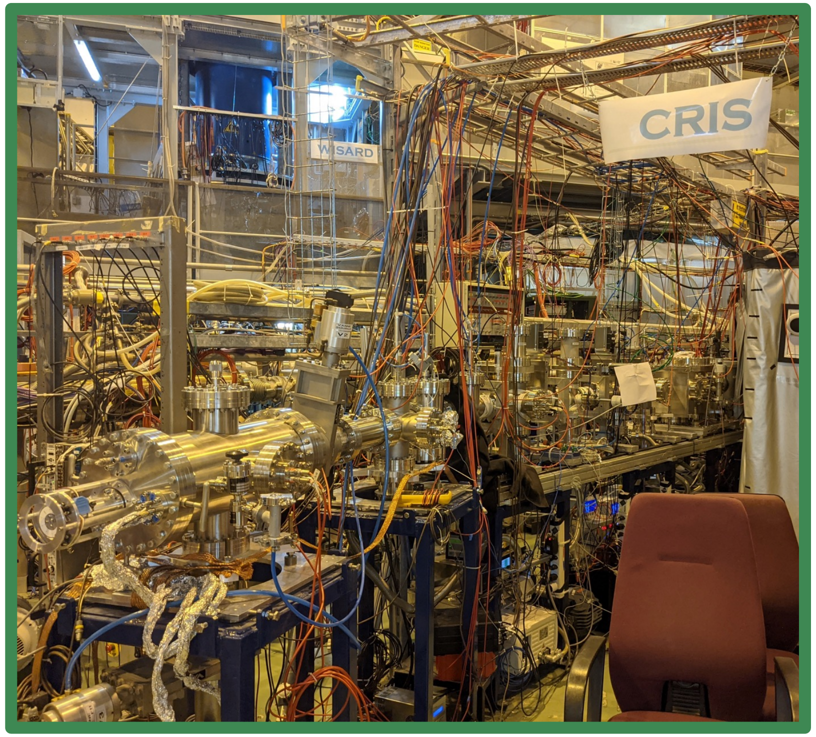

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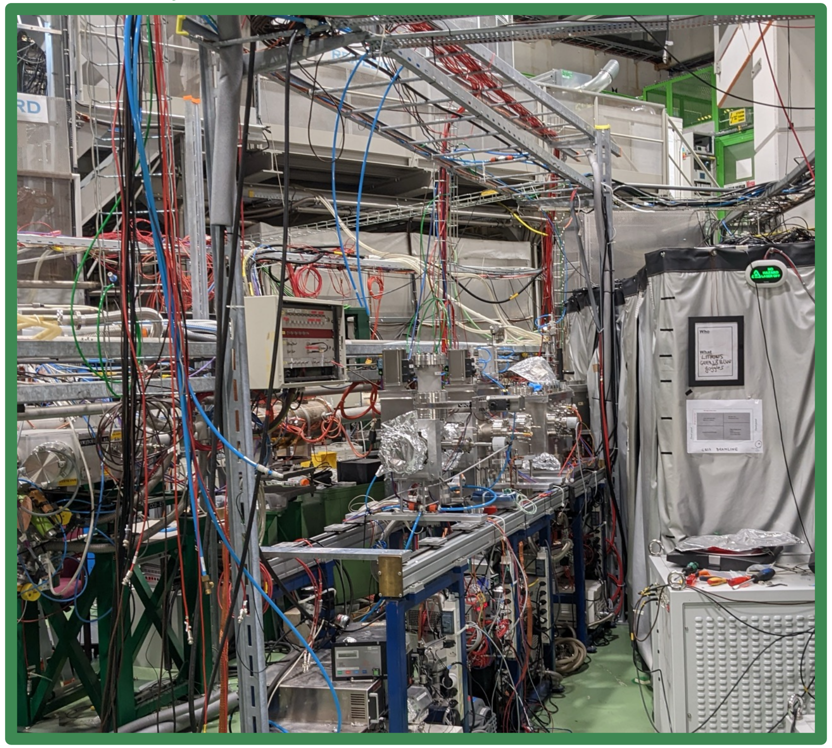

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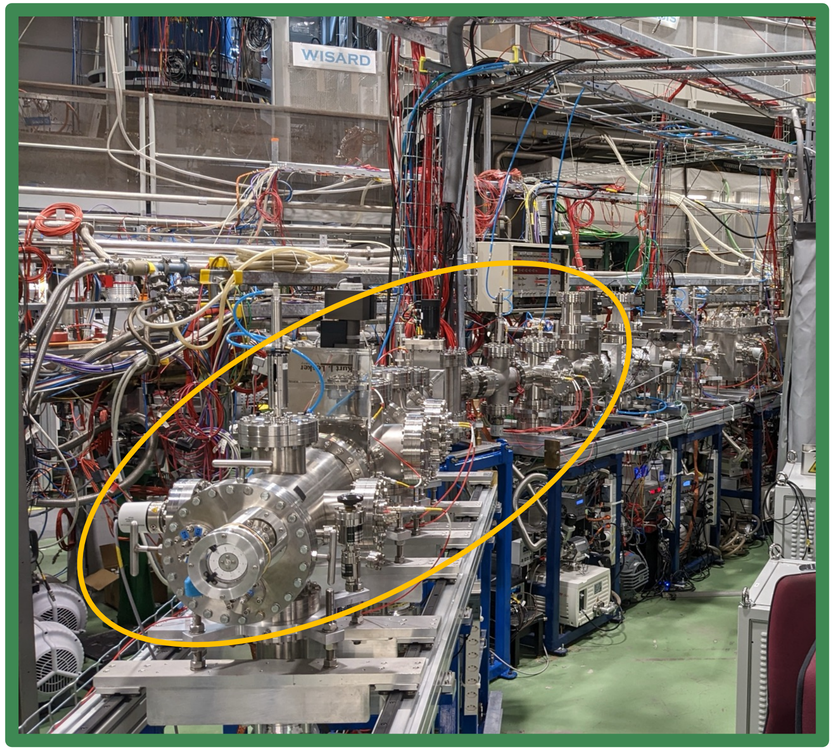


New end of the beam line:

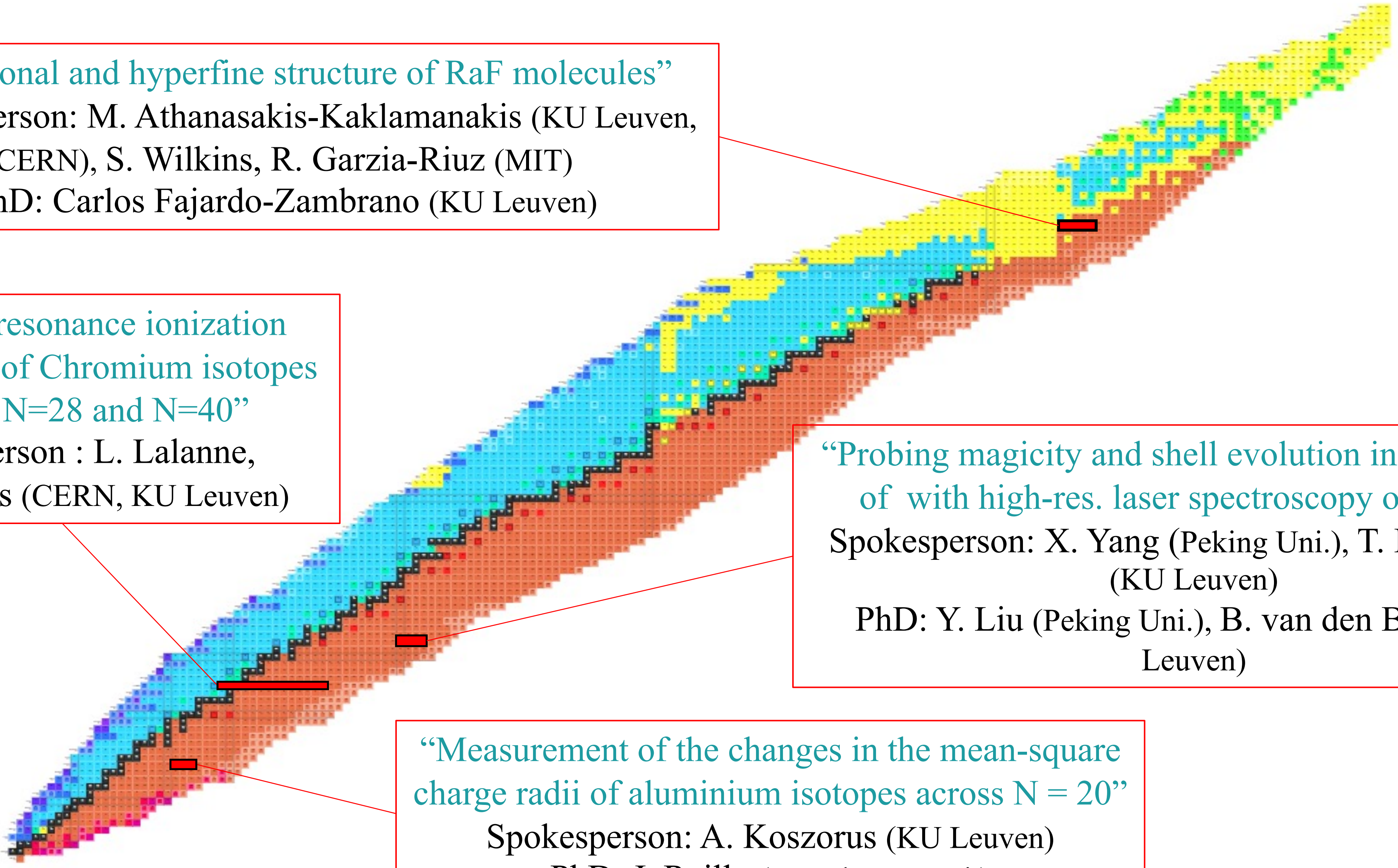
- New field ionization unit
- New bender
- New beam optics

→ Allows Rydberg ionization scheme

→ Beam transport efficiency toward ion detector and decay spectroscopy station improved from 30% to 100%

→ Enable upgrade of the DSS toward a tape system

The 2023 experimental campaigns



"Rotational and hyperfine structure of RaF molecules"

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"Collinear resonance ionization spectroscopy of Chromium isotopes between N=28 and N=40"

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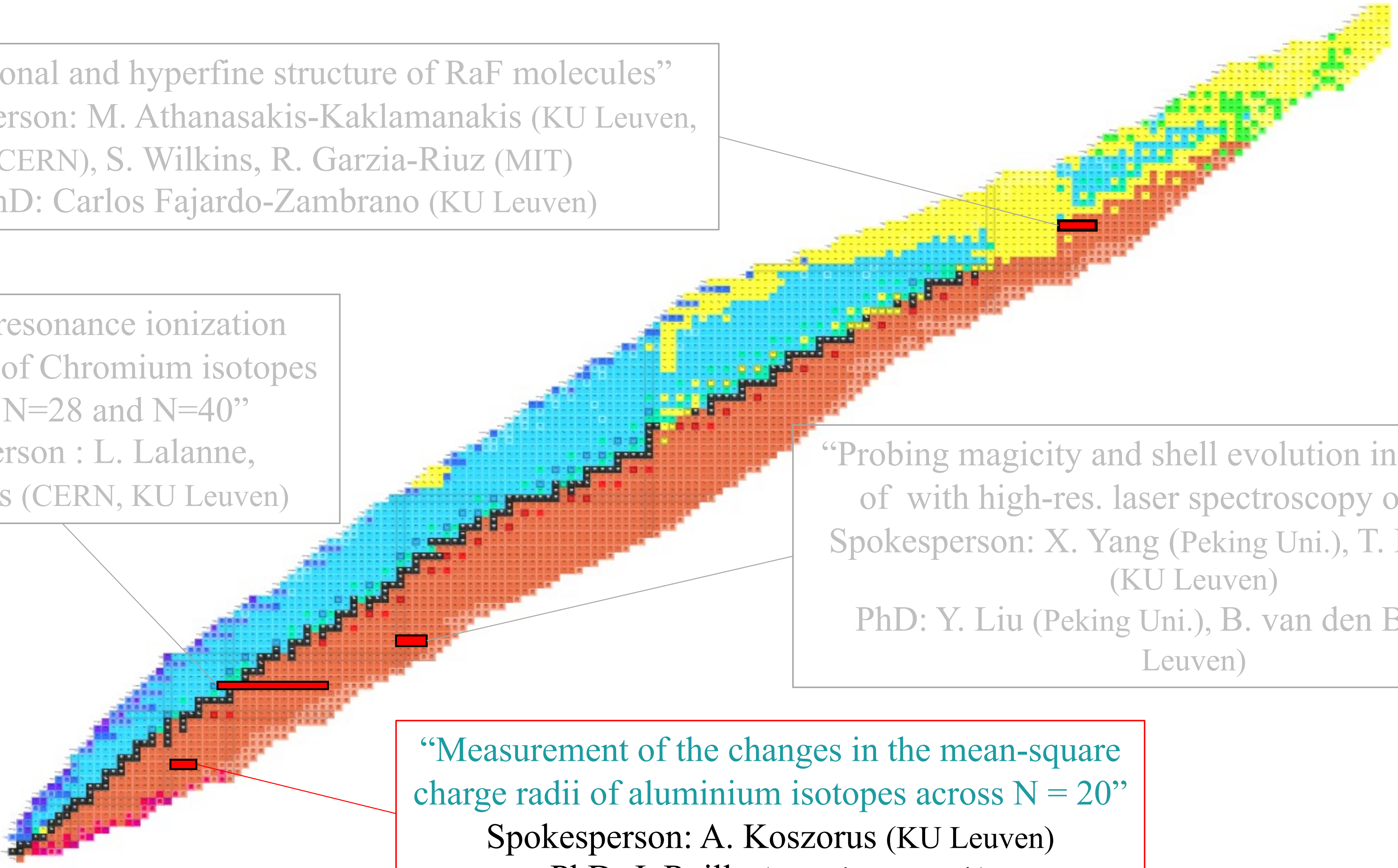

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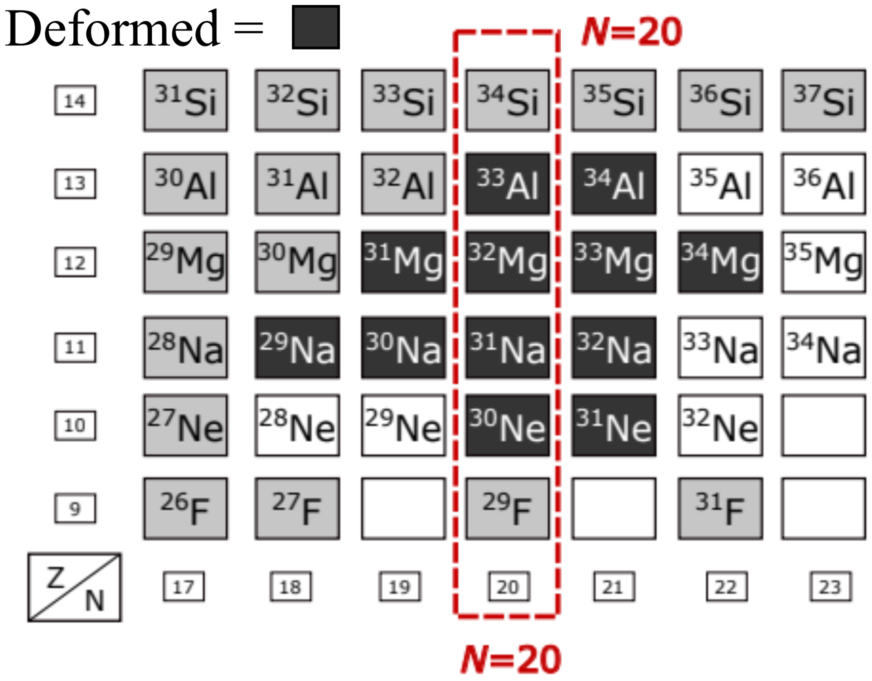
Charge radii of Aluminium isotopes across N = 20

- N=20 Island of Inversion: Strongly mixed and deformed ground state configuration around ^{32}Mg
- ^{33}Al located between strongly deformed ^{32}Mg and spherical ^{34}Si
- Evidence for ^{33}Al g.s. deformation from quadrupole moment [(1)] - Transition into the Island of inversion?



(1) Heylen et al., PHYSICAL REVIEW C **94**, 034312 (2016)

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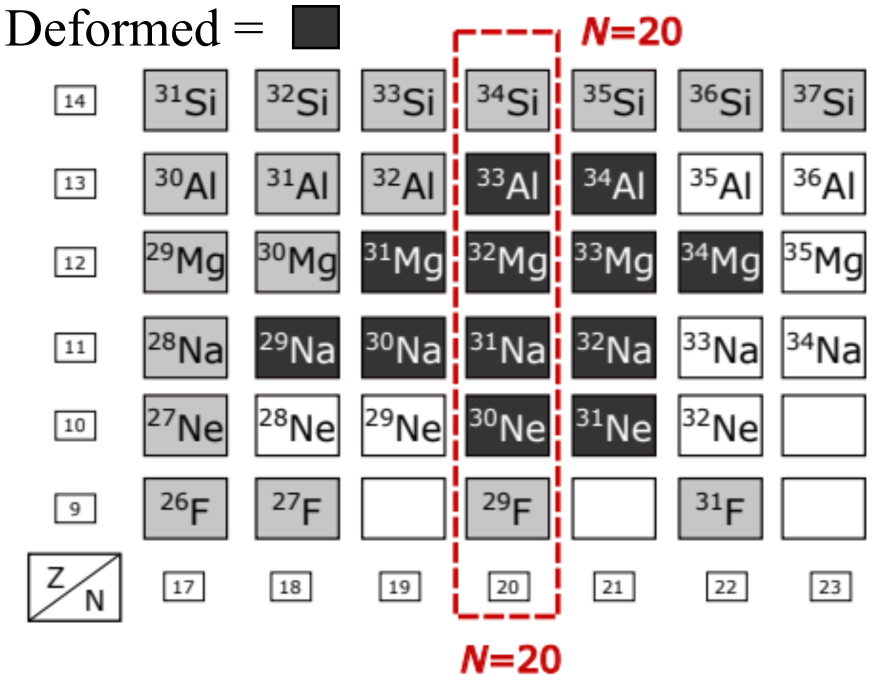
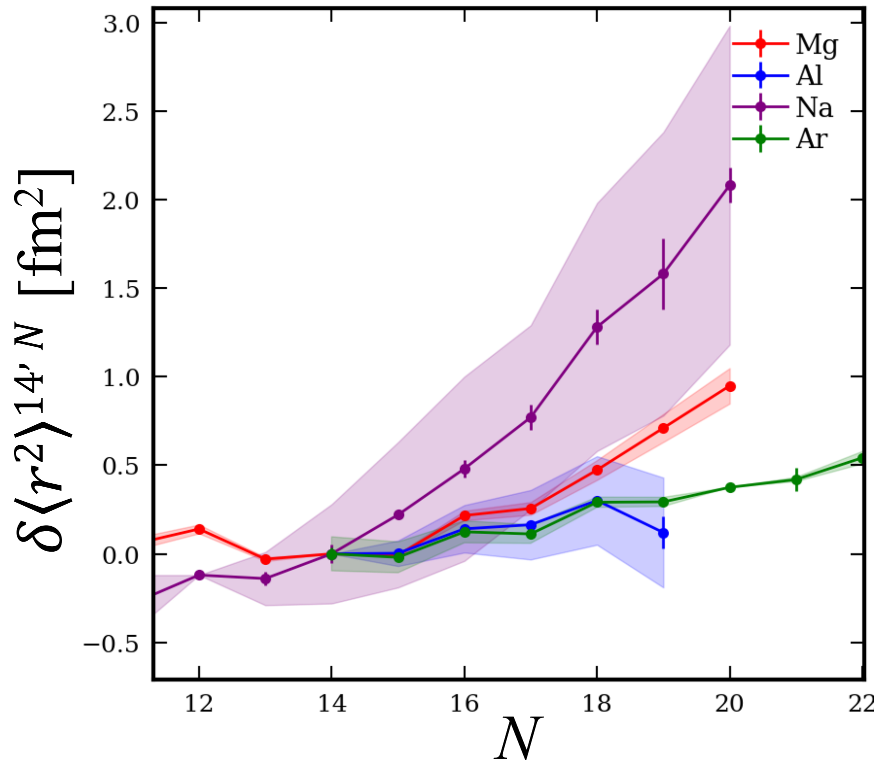




- Large increase in charge radii towards the $N = 20$ shell closure is observed for **Na** and **Mg**
- Previous measurements of Al radii display an unexpected decrease in $\delta\langle r^2\rangle$ between ^{31}Al and ^{32}Al (2)

(1) Heylen et al., PHYSICAL REVIEW C **94**, 034312 (2016)

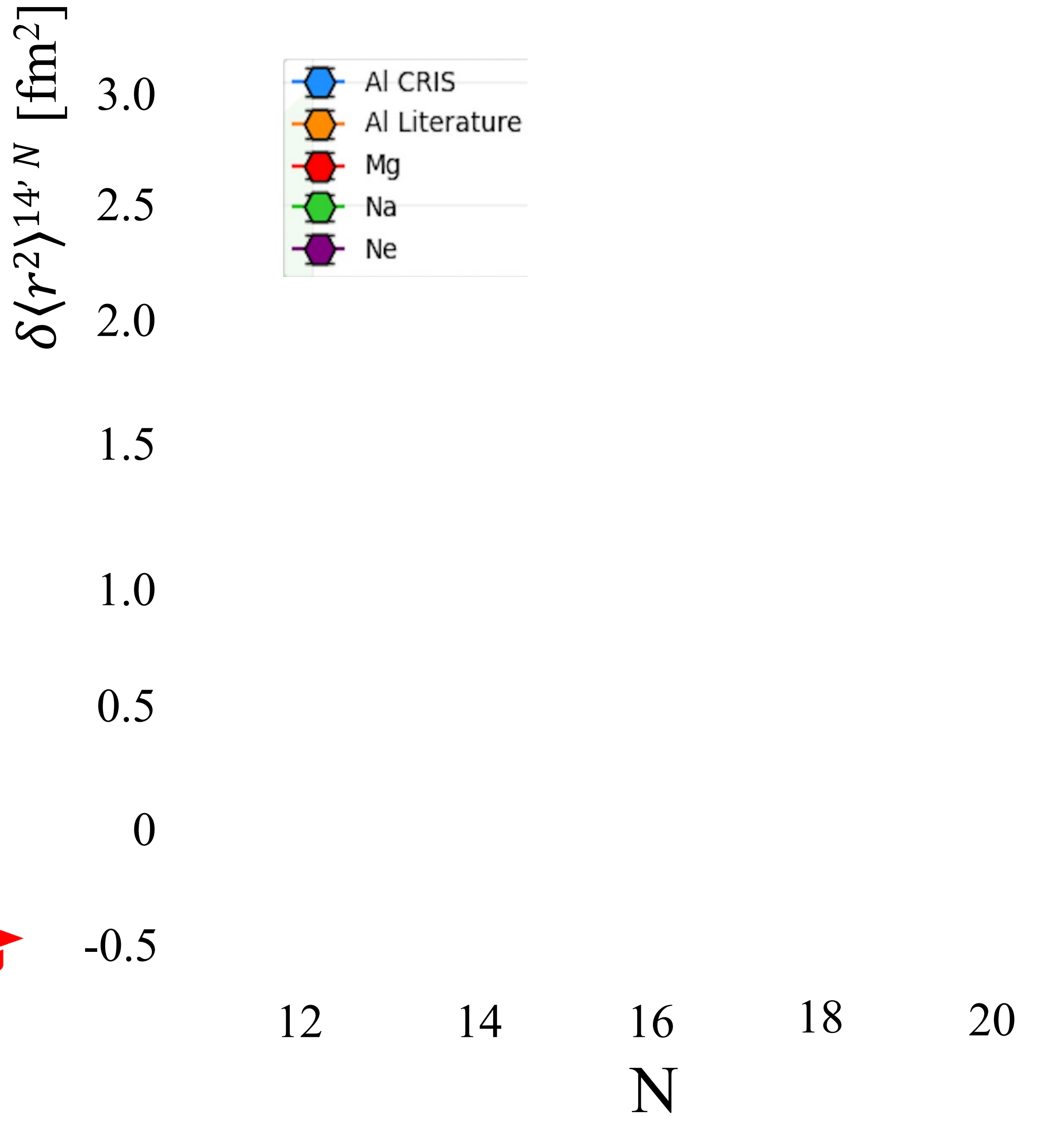
(2) Heylen et al., PHYSICAL REVIEW C **103**, 014318 (2021)

Charge radii of Aluminium isotopes across N = 20

- Two runs: 2022 ($^{27\text{-}32}$Al) and 2023 ($^{33\text{-}34}$Al)
- First laser spectroscopy measurement across N=20 in the IoI
- $^{27\text{-}31}$Al in agreement with previous measurements
- Sudden radii increase in ^{32}Al, in contradiction with previous measurement. No sign of intruder structure in literature. To be investigated
- $^{32\text{-}34}$Al steeper upwards trend toward and crossing $N = 20$, similar to Na and Mg

  → Signature of the N=20 IoI in Al

Analysis and plots from Jordan Reilly



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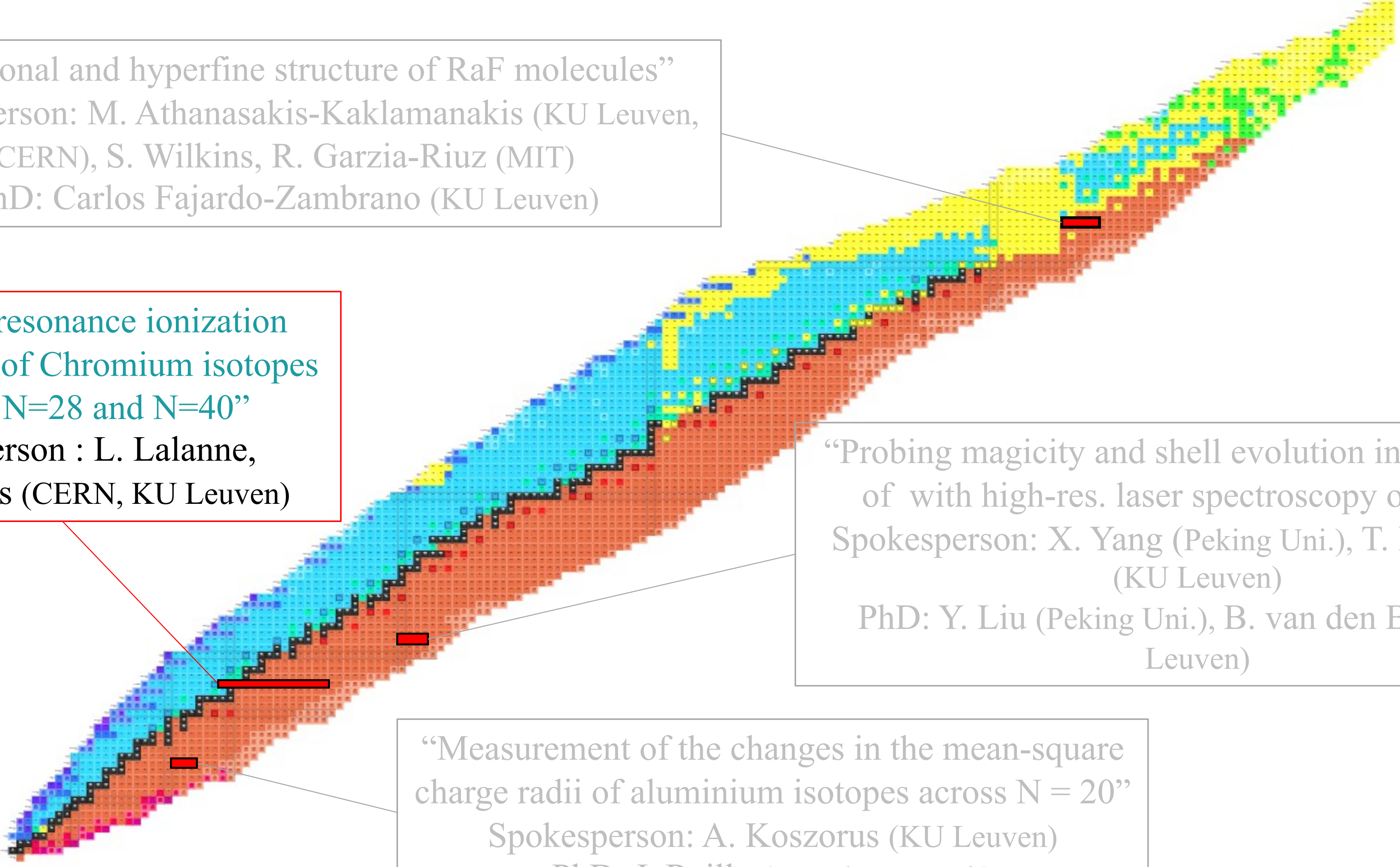

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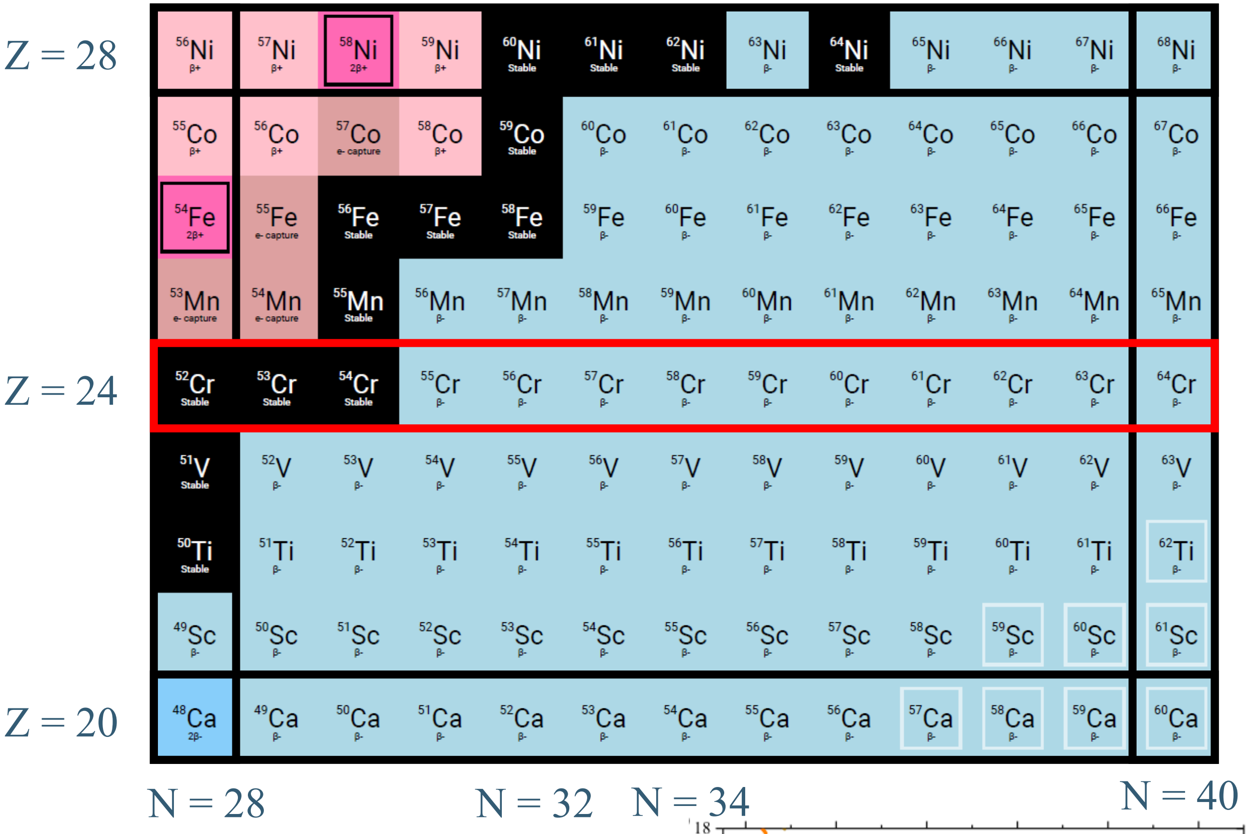
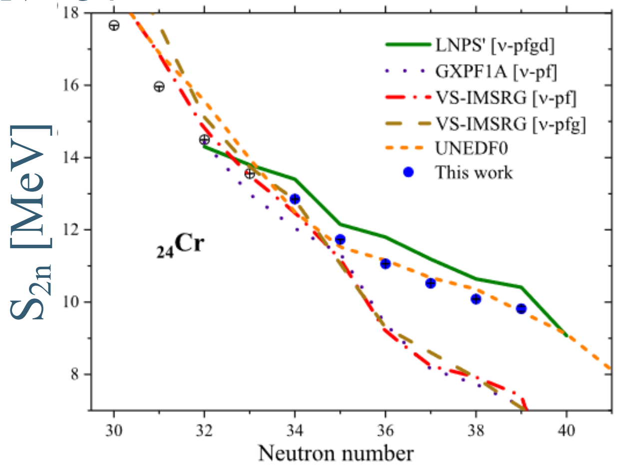
The N=40 Island of Inversion and the Cr isotopes

The Cr isotopes:

- Half filled $f_{7/2}$ → strongest *p-n* collectivity
- Mass : increase of collectivity from *N*=34 onward [(1)]
- Radii of Mn (*Z*=25): suggested onset of deformation around *N*=35 [(2)]
- ^{64}Cr is the predicted center of the *N*=40 Island of Inv.
- No firm assignment of g.s. spins
- No radii or moments known outside stability





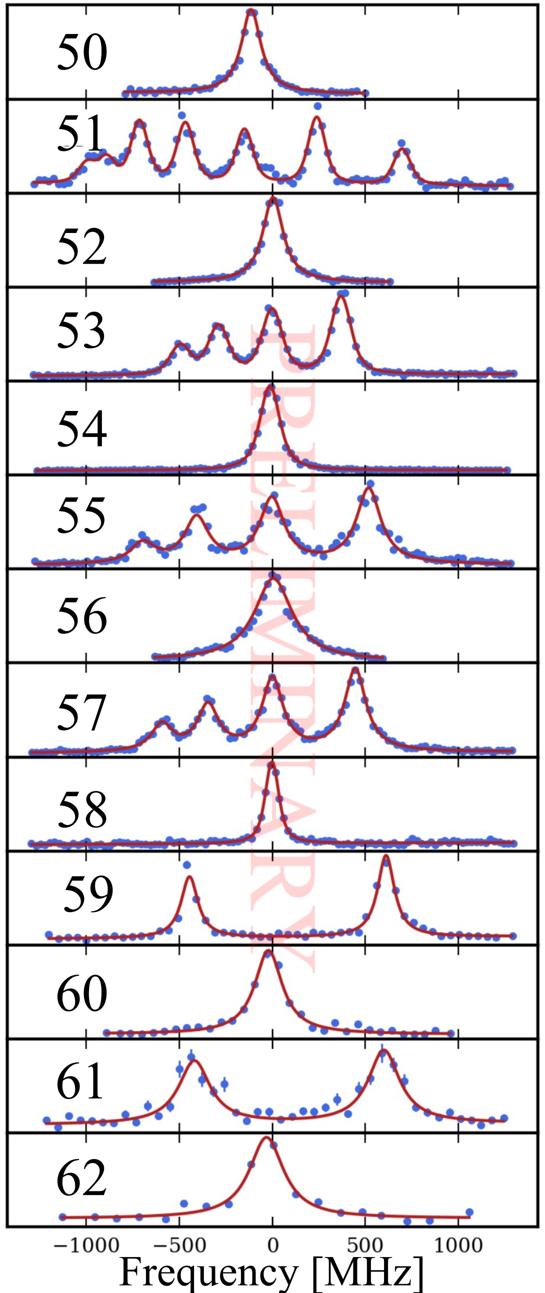
Goals:

- Firm spin assignment outside stability
- Better understand the structure of the odd-*A* Cr ground states
- Investigate the structural changes along the chain and the formation of the N=40 IoI

(1) M. Mougeot *et al.*, PRL **120**, 232501 (2018)

(2) H. Heylen *et al.*, PRC **94**, 054321 (2016)

Cr Results: spins of odd-*A* Cr isotopes



I Lit:
7/2$^-$
3/2$^-$
3/2$^-$
(3/2)$^-$
(1/2)$^-$
(5/2)$^-$

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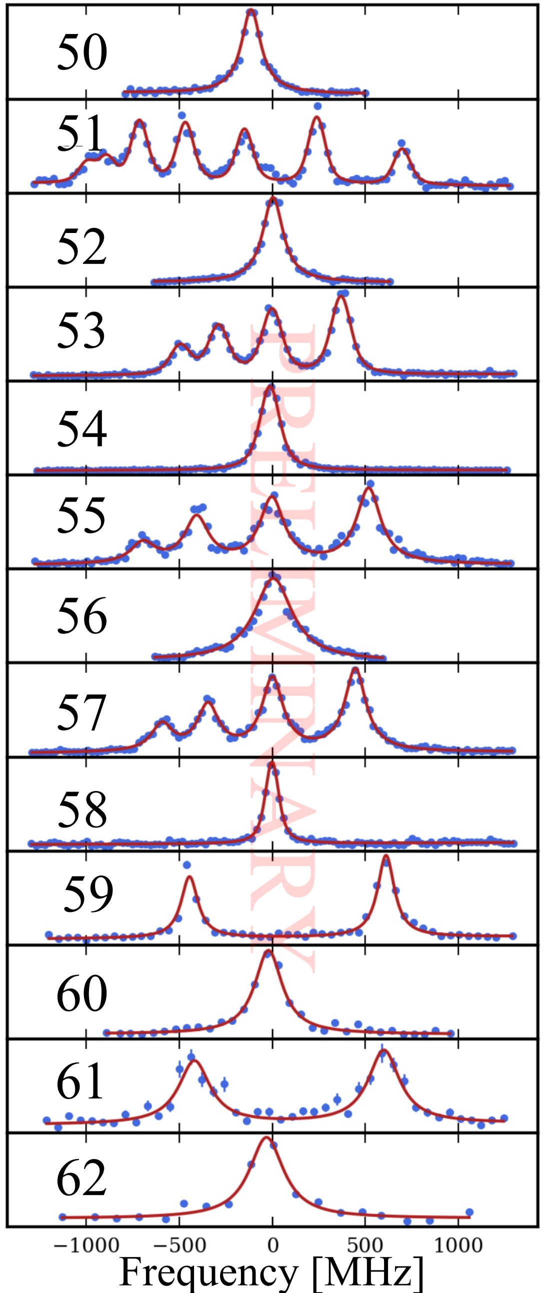

I Lit:	*I* CRIS:
$7/2^-$	$7/2^-$
$3/2^-$	$3/2^-$
$3/2^-$	$3/2^-$
$(3/2)^-$	$3/2^-$
$(1/2)^-$	$1/2^-$
$(5/2)^-$	$1/2^-$

- ^{57}Cr and ^{59}Cr spins confirmed to be 3/2 and 1/2, respectively
- First firm spin assignment of ^{57,59,61}Cr

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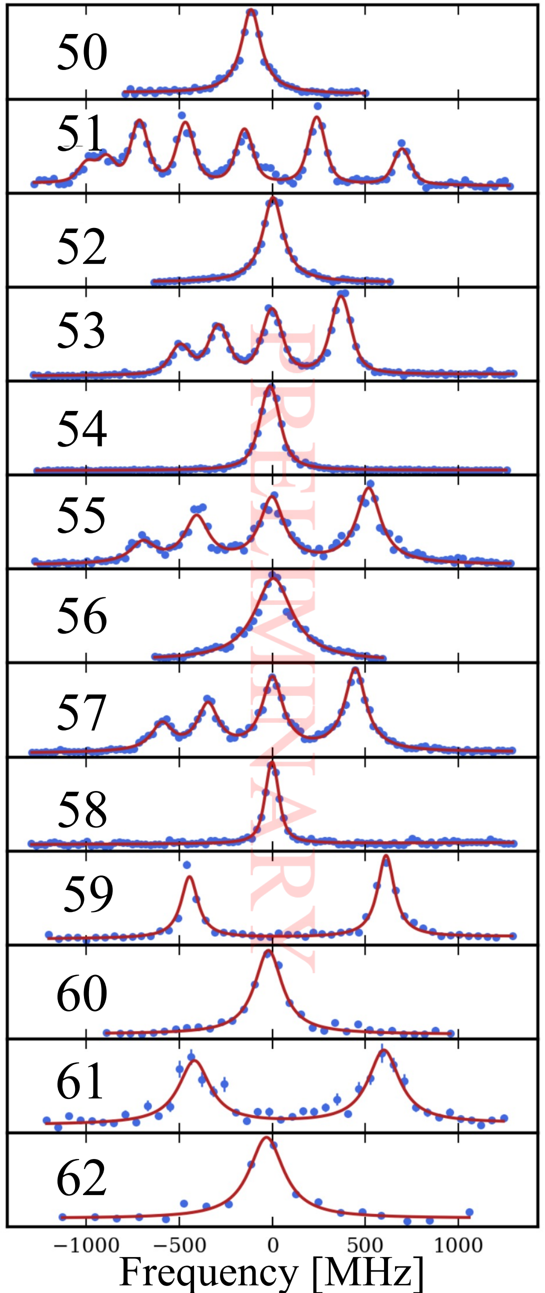

I Lit:	*I* CRIS:
$7/2^-$	$7/2^-$
$3/2^-$	$3/2^-$
$3/2^-$	$3/2^-$
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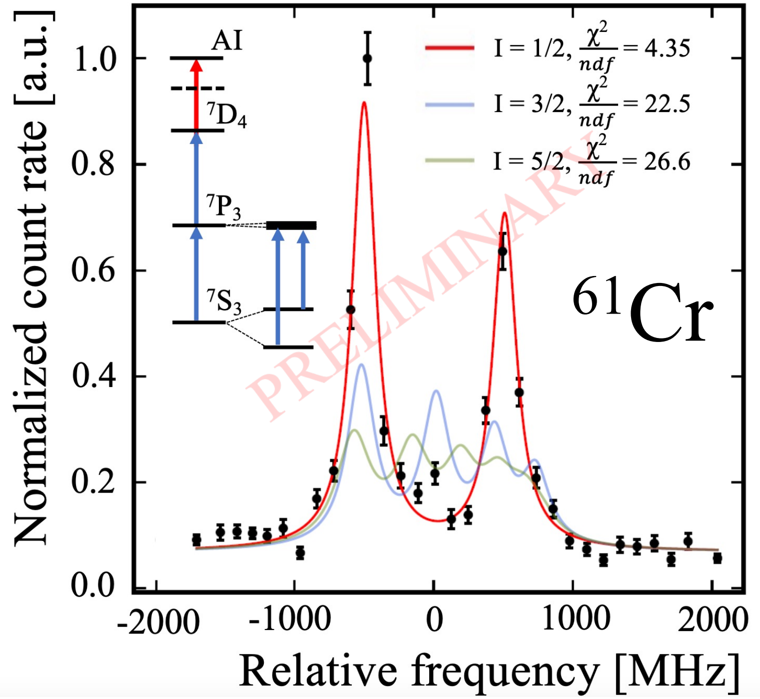

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→ Large consequences on the interpretation of beta decay data

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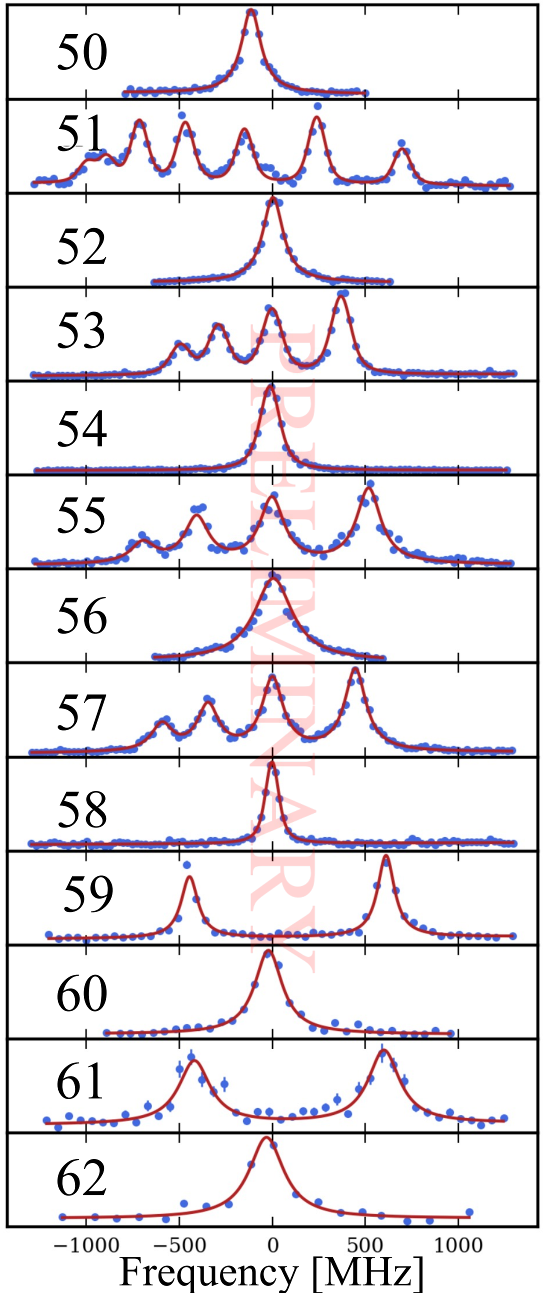
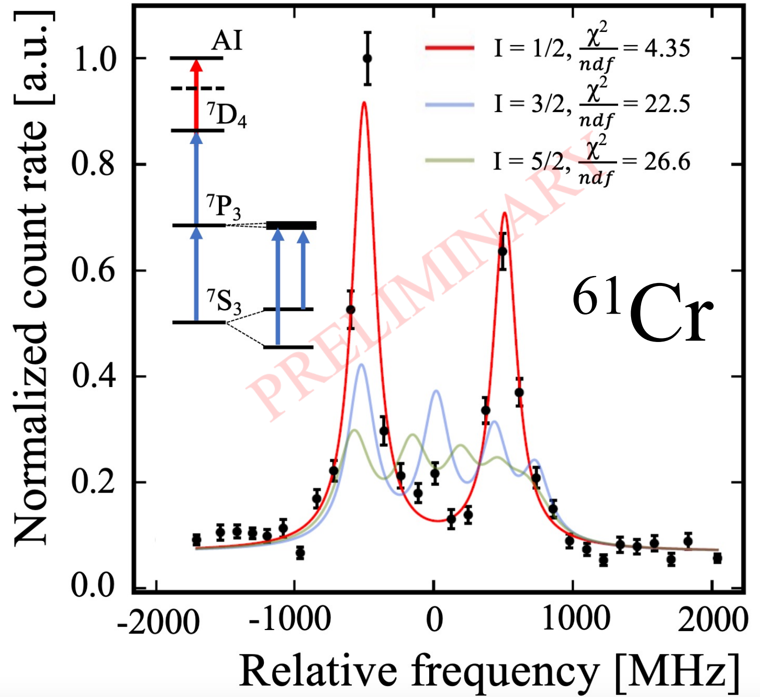
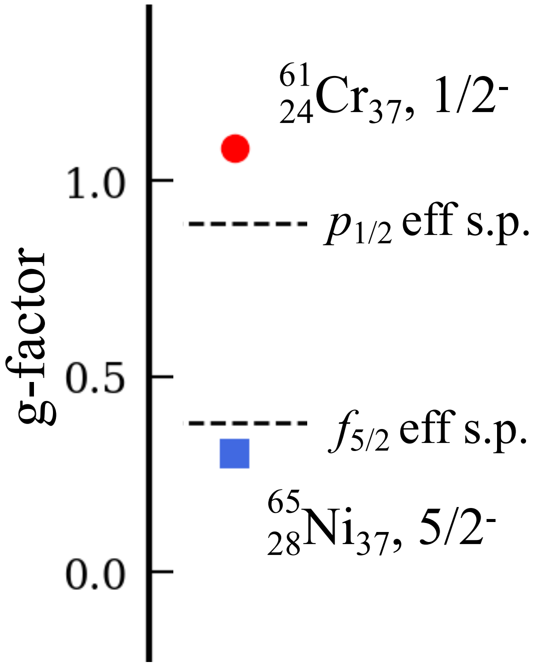


	I Lit:	*I* CRIS:
51	$7/2^-$	$7/2^-$
53	$3/2^-$	$3/2^-$
55	$3/2^-$	$3/2^-$
57	$(3/2)^-$	$3/2^-$
59	$(1/2)^-$	$1/2^-$
61	$(5/2)^-$	$1/2^-$





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- Spin ^{61}Cr found to be 1/2 , disagrees with 5/2 assignment from literature

→ Large consequences on the interpretation of beta decay data

- Magnetic dipole moment : ^{61}Cr neutron $p_{1/2}$ config

→ Evolution along N=27 isotones

Cr Results: Charge radii of Cr isotopes

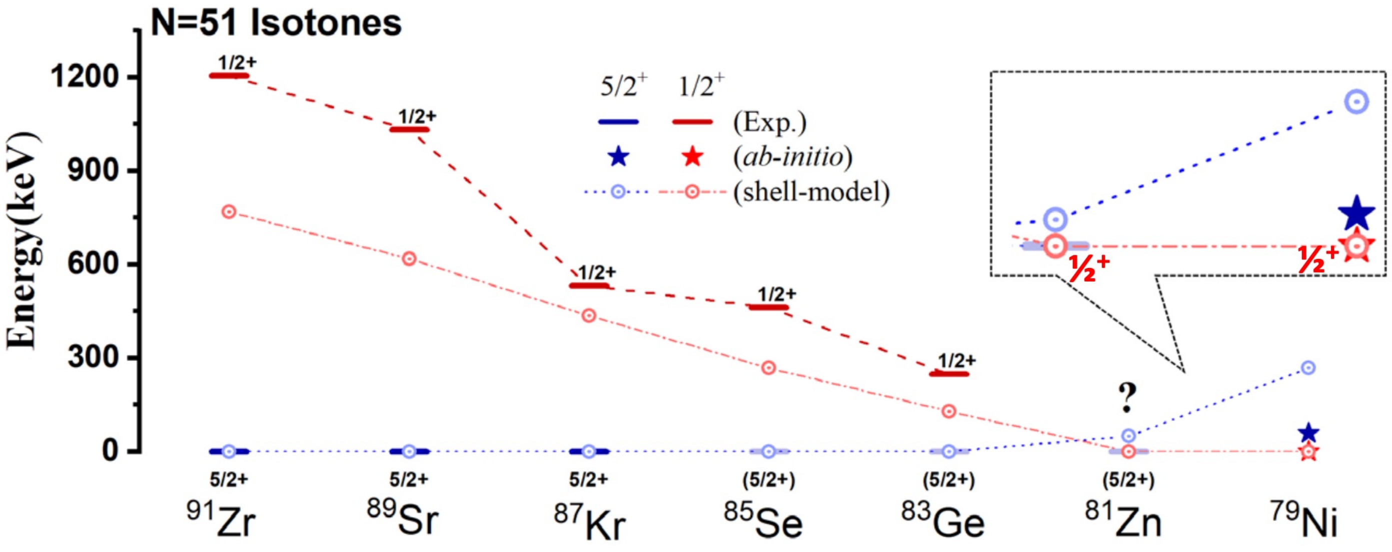
$$\delta\nu_i^{A,A'} = \frac{A - A'}{AA'} M_i + F_i \, \delta\langle r^2\rangle^{AA'}$$

- F and M determined from King plot using model independent absolute radii values [1] (muonic+e^- scat.)
- Strong kink observed at N=28, in good agreement with literature
- Steep increase of the Cr charge radii between N=28 and N=32 following closely the Ca trend
  → Z independent behaviour
- Clear change of slope at N=34 between deformed Cr, and spherical Ni
- Strong odd-even staggering of the Cr radii for N>34

Signature of the emergence of intruder configurations toward the N=40 Island of Inversion

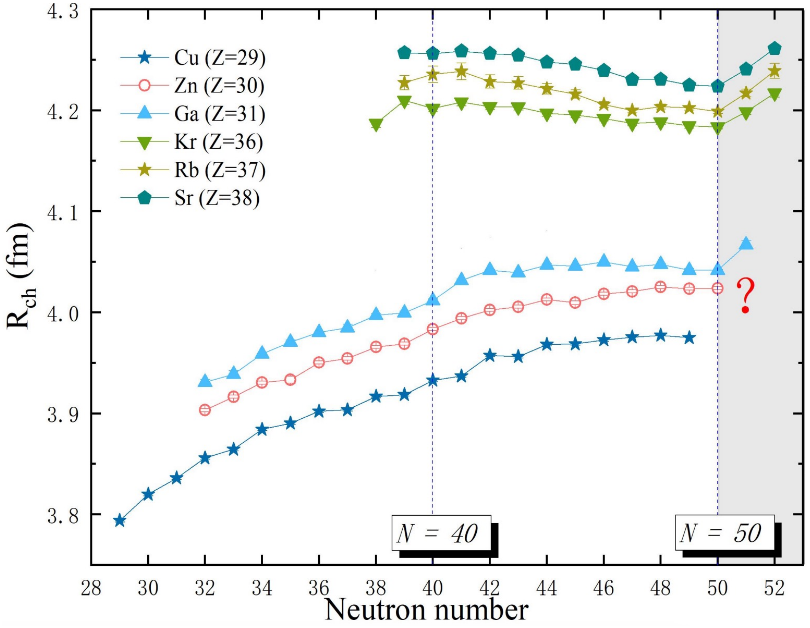
(1) J. W. Lightbody et al., PRC 27, 1 (1983)

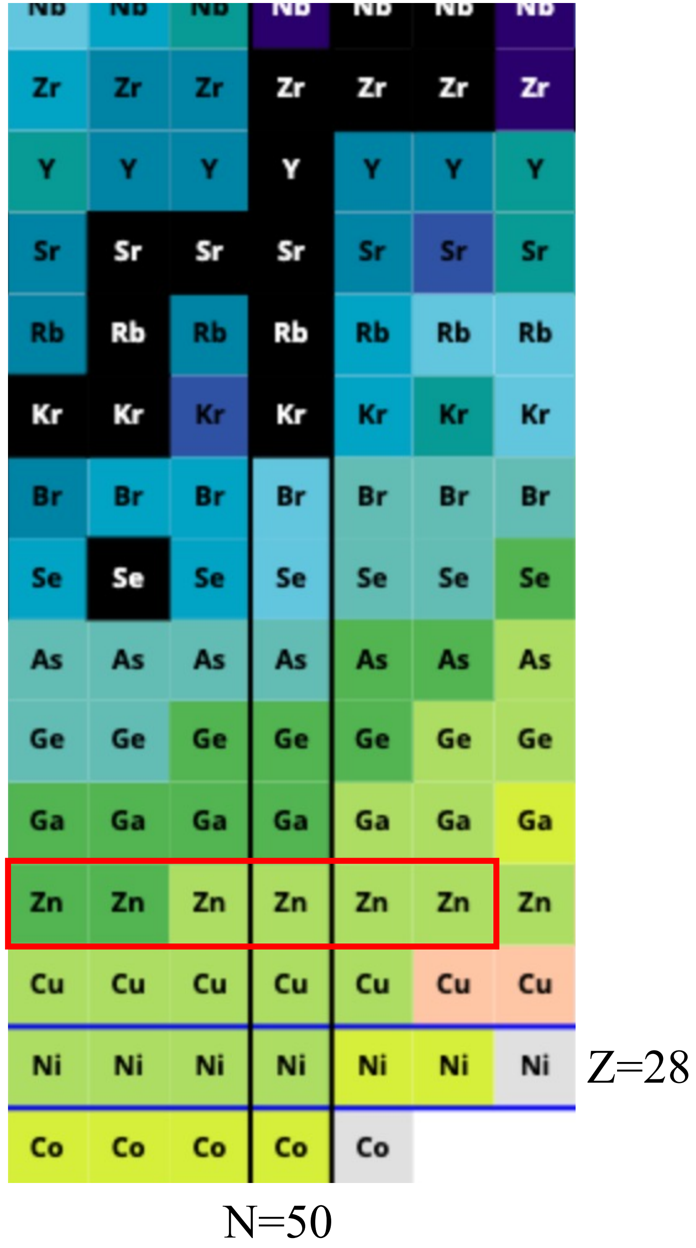
Laser spectrocopy of $^{81,82}Zn$



N = 51 isotones: energy drop of the ½+ state.
→ Inversion in ^{81}Zn?

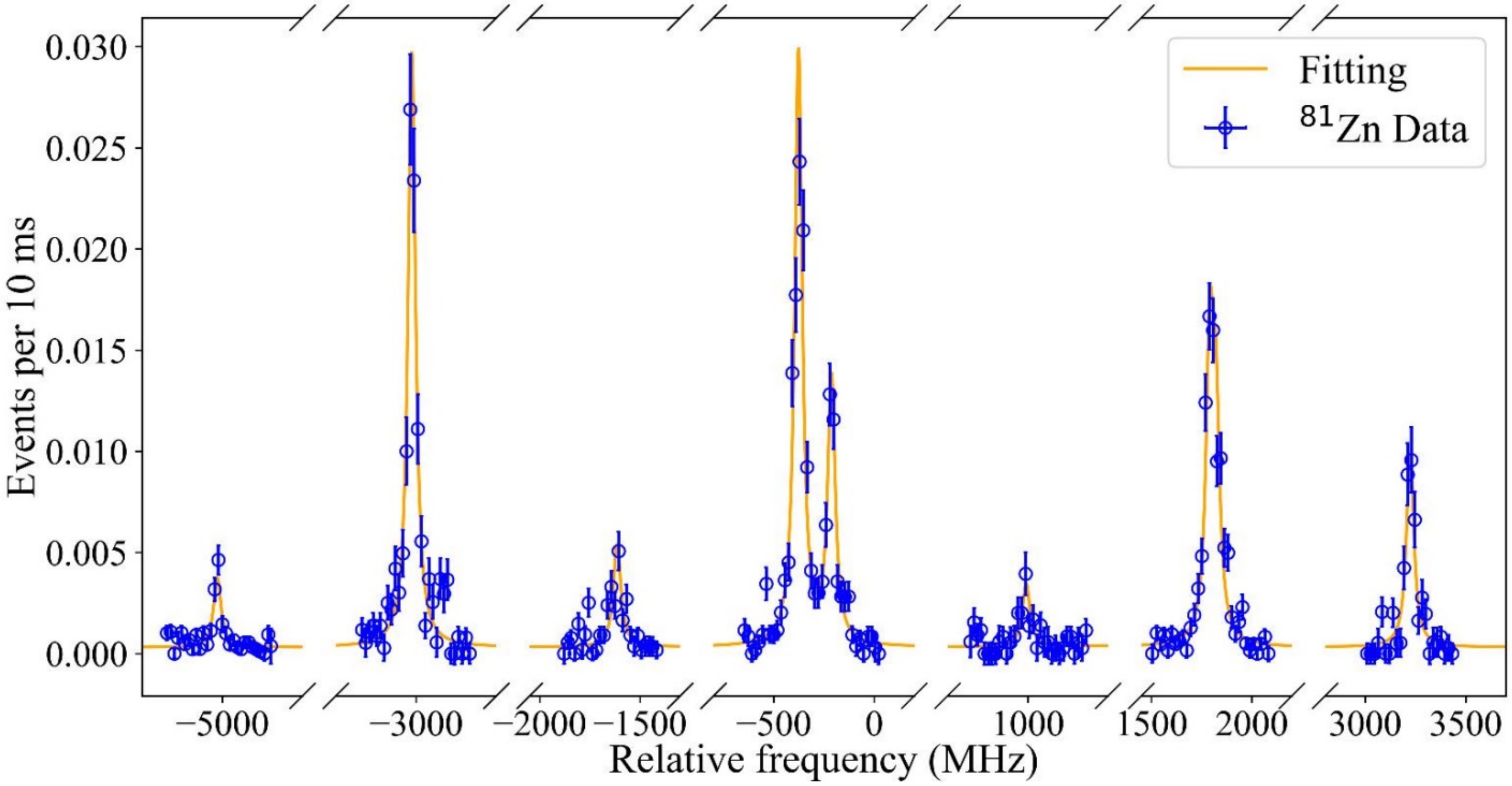
No radii across N = 50 for Z<31
→ N = 50 magic effect in the charge radii of isotopes closed to Ni ?





Laser spectrocopy of $^{81,82}Zn$

^{81}Zn HFS



- Statistical test of HFS models + A parameter ratio for different spin hypothesis

→ Observed 5/2 state in ^{81}Zn

→ no sign for ½ state

Moments of ^{81}Zn

Large scale shell model [1]

ab-initio based on VS-IMSRG[2]
(with two-mesons exchange current[3])

- Significant deformation of ^{81}Zn g.s.
- ^{81}Zn moments well reproduced by SM
- Ab-initio fails to describe deformed ground states

[^{87}Krμ, Q_s]: M. Keim et al., Nucl. Phys. A, 586, 219 (1995). [^{89}Srμ, Q_s]: F. Buchinger et al., Phys. Rev. C, 42, 2754 (1990).
[^{91}Zrμ]: E. Brun et al., Phys. Rev., 105, 1929 (1957). [^{91}ZrQ_s]:V. Kellö et al., Chem. Phys. Lett., 318, 222, (2000).

[1]J. Li, Phys. Lett. B 840, 137893 (2023).
[2]S. R. Stroberg, *et al*, Phys. Rev.Lett. 118, 032502 (2017).
[3T. Miyagi *et al*., https://arxiv.org/abs/2311.14383.

Laser spectrocopy of $^{81,82}Zn$

- First Zn radii measurement across N=50
- Large kink at N=50
- Steep increase above N=50

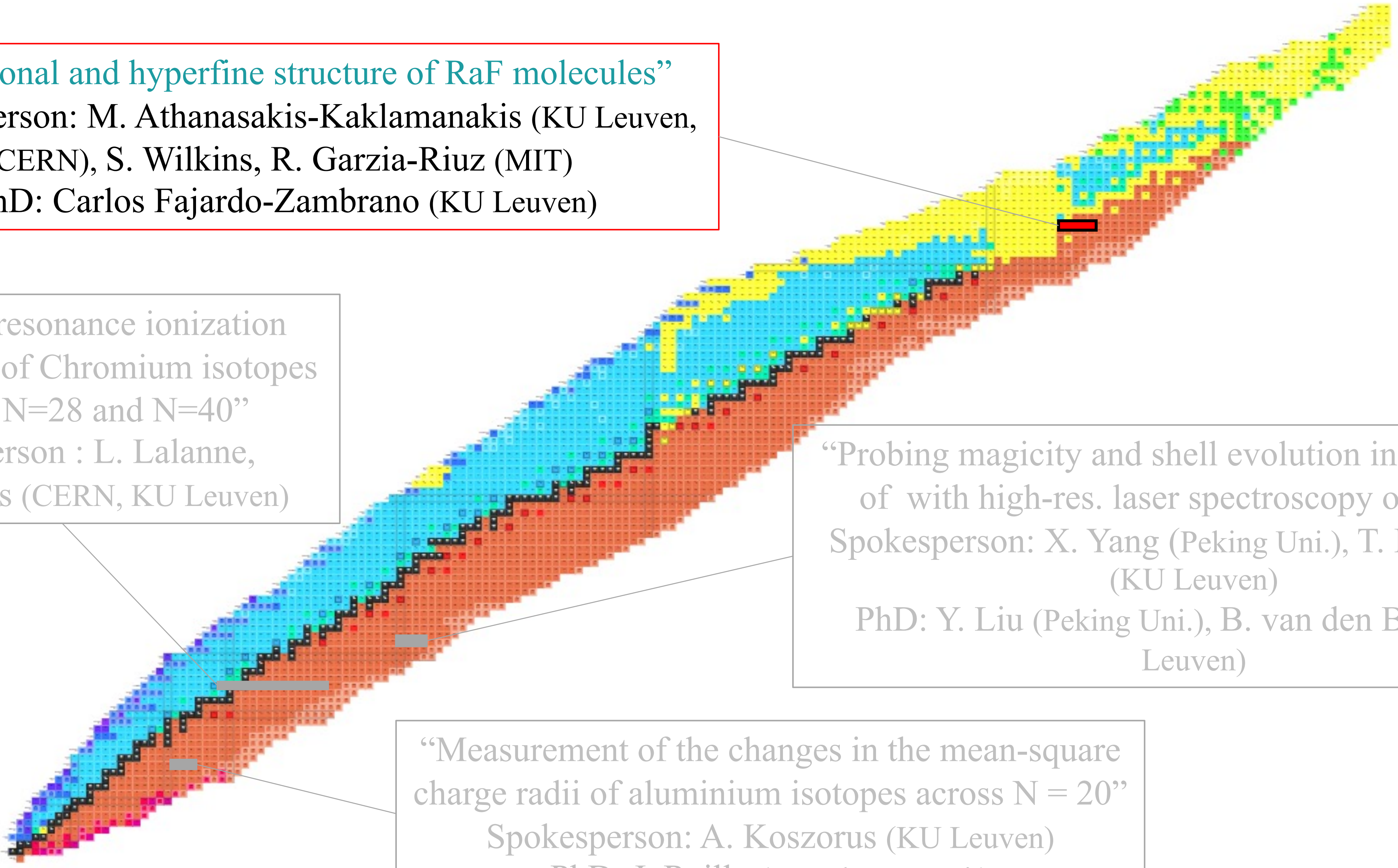
→ Signature for N=50 magicity

Analysis and plots from Yongchao Liu

The 2023 experimental campaigns

"Rotational and hyperfine structure of RaF molecules"
Spokesperson: M. Athanasakis-Kaklamanakis (KU Leuven, CERN), S. Wilkins, R. Garzia-Riuz (MIT)
PhD: Carlos Fajardo-Zambrano (KU Leuven)

"Collinear resonance ionization spectroscopy of Chromium isotopes between N=28 and N=40"
Spokesperson : L. Lalanne, A. Koszorus (CERN, KU Leuven)



"Probing magicity and shell evolution in the vicinity of with high-res. laser spectroscopy of $^{81,82}Zn$"
Spokesperson: X. Yang (Peking Uni.), T. E. Cocolios (KU Leuven)
PhD: Y. Liu (Peking Uni.), B. van den Borne (KU Leuven)

"Measurement of the changes in the mean-square charge radii of aluminium isotopes across N = 20"
Spokesperson: A. Koszorus (KU Leuven)
PhD: J. Reilly (Manchester Uni.)

RaF for *P,T* violation searches

- electron electric dipole moment (eEDM) : asymmetric charge distribution along electron’s spin axis
- Nonzero EDM’s implies the existence of the T,P-violating interactions

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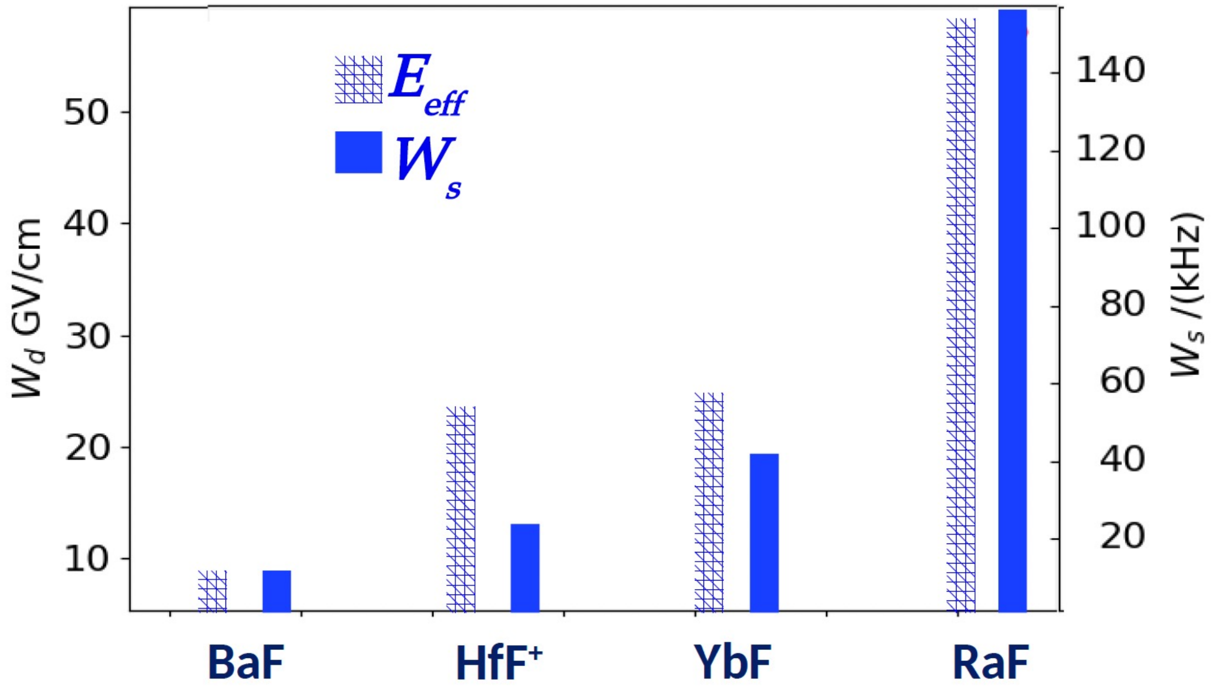

Plot courtesy of R. F. Garcia Ruiz and S. G. Wilkins (MIT)

EDM precision $\propto \tau\, E_{\mathrm{eff}} \sqrt{N}$

Radioactive molecules:

Exceptionally sensitive to P,T-violating moments

$>10^5$ times more sensitive than stable atoms

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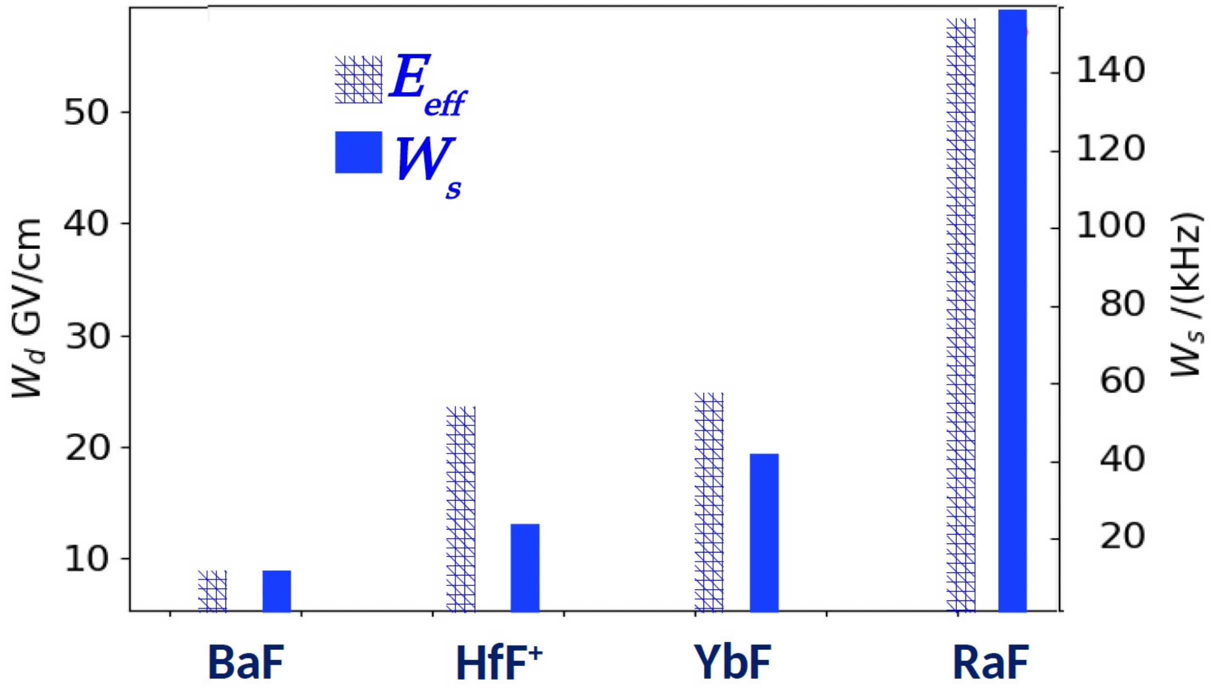

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Laser coolable in neutral trap!

↓

Very long coherence time τ

and number density N

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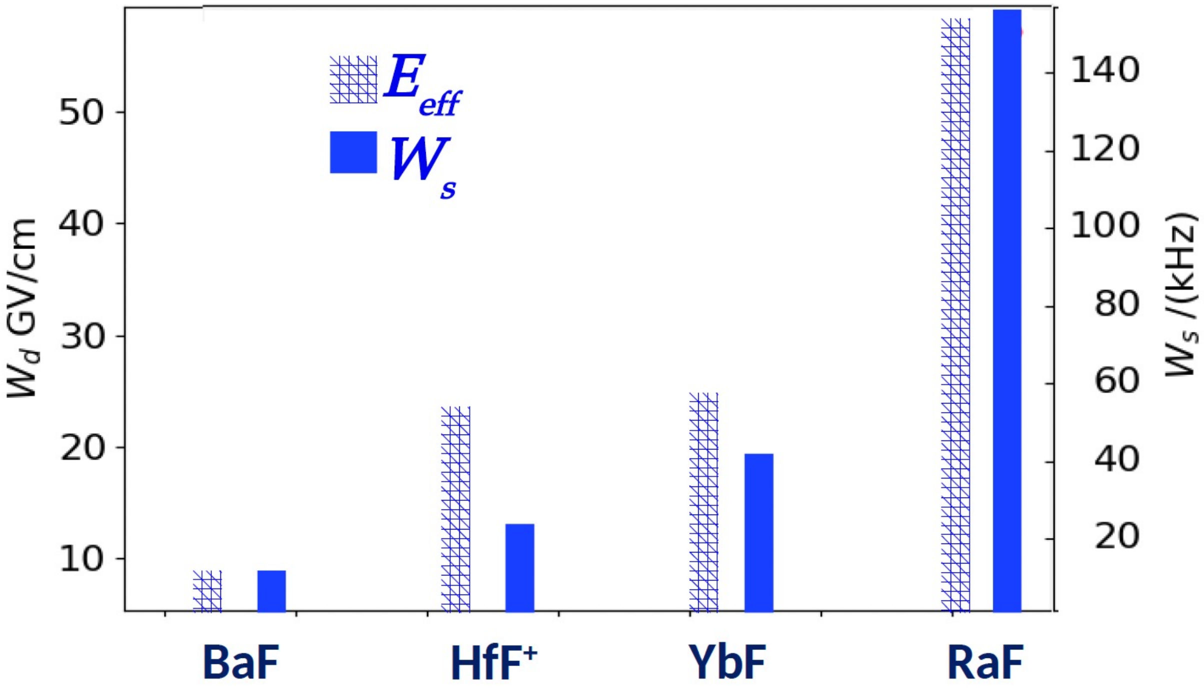

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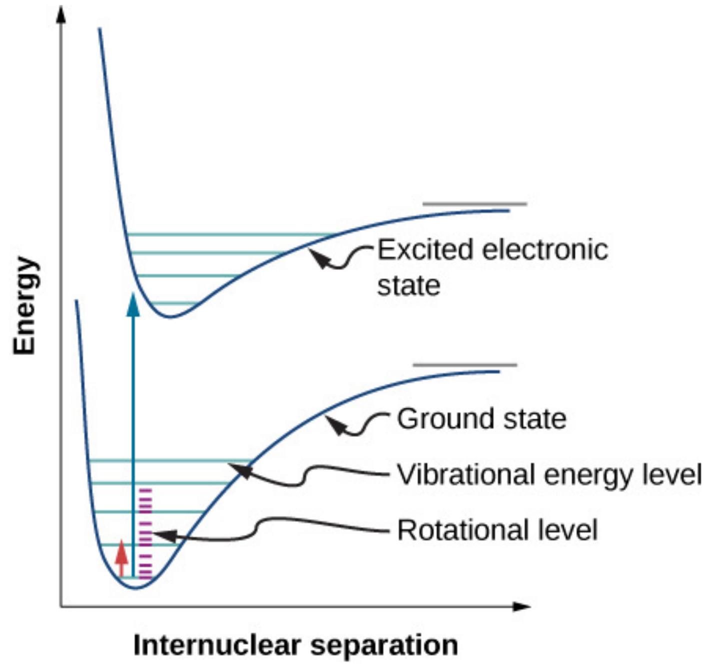
➔ RaF is one of the most promising system for *P,T* violation searches

High-resolution spectroscopy of RaF

The Hamiltonian of RaF:

$$\hat{H}^{\mathrm{RaF}} = \hat{H}_{\mathrm{el}} + \hat{H}_{\mathrm{vib}} + \hat{H}_{\mathrm{rot}} + \hat{H}_{\mathrm{hfs}} + \cdots + \hat{H}_{P,T}$$



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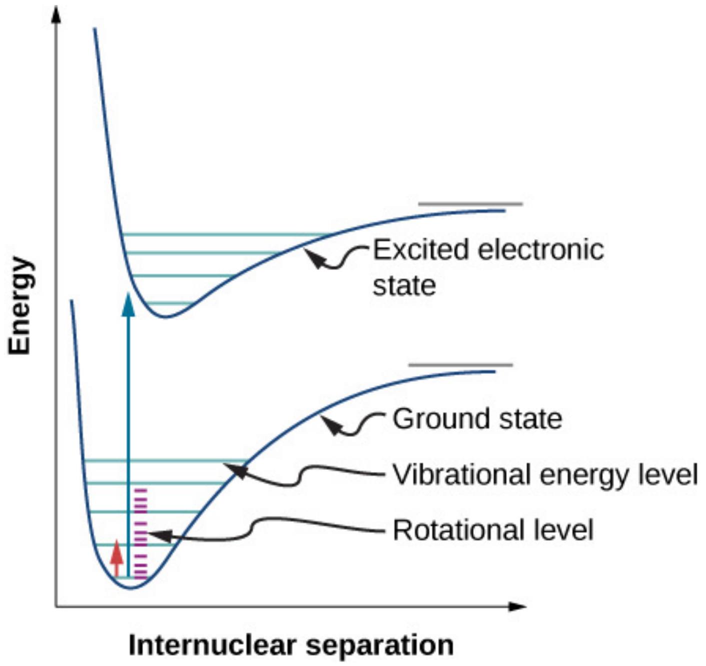
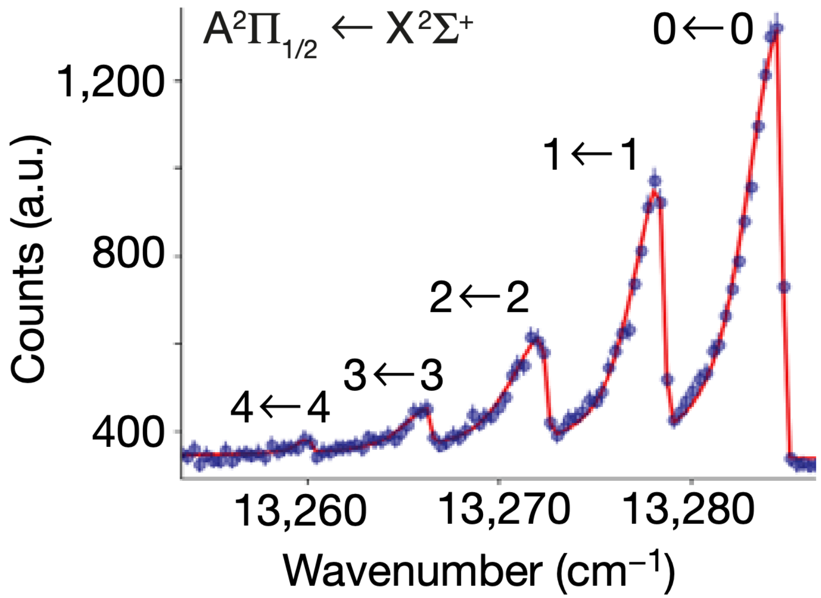
Electronic and vibrational structure

CRIS 2018

Nature 581, 396 (2020)





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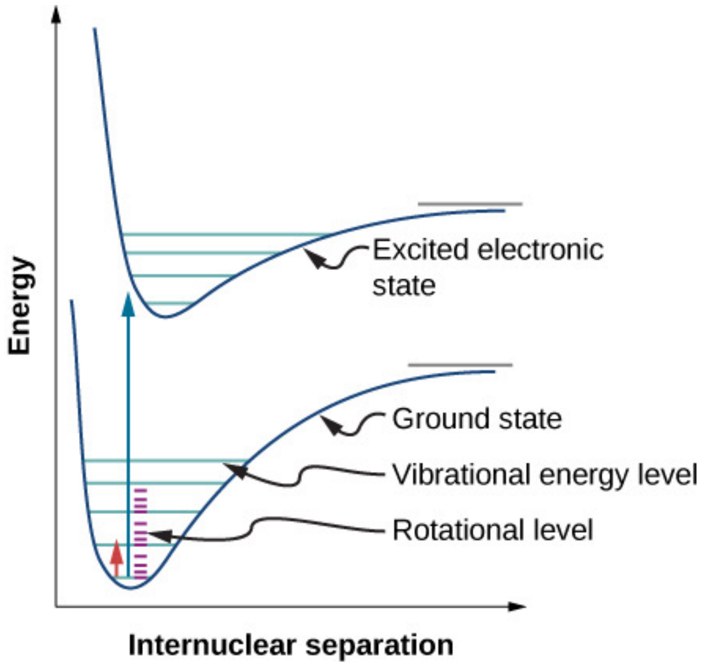
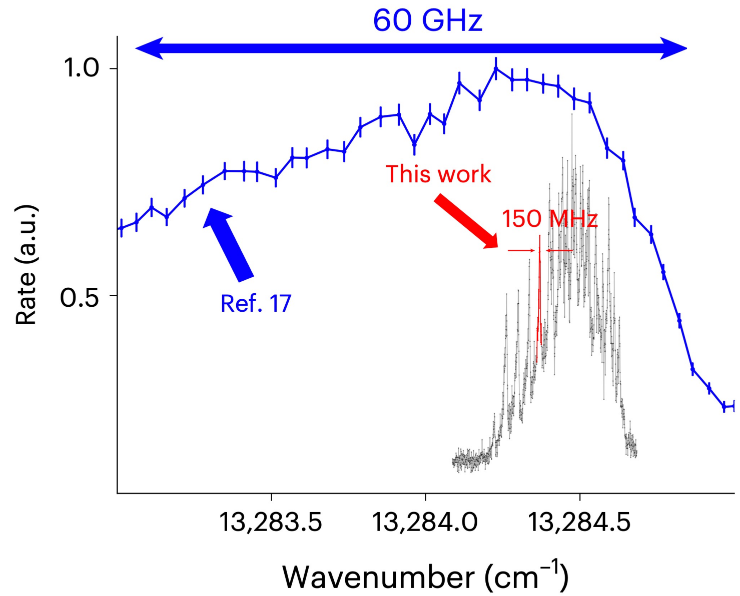
PRL 127, 033001 (2021) arXiv:2308.14862, submitted (2023)





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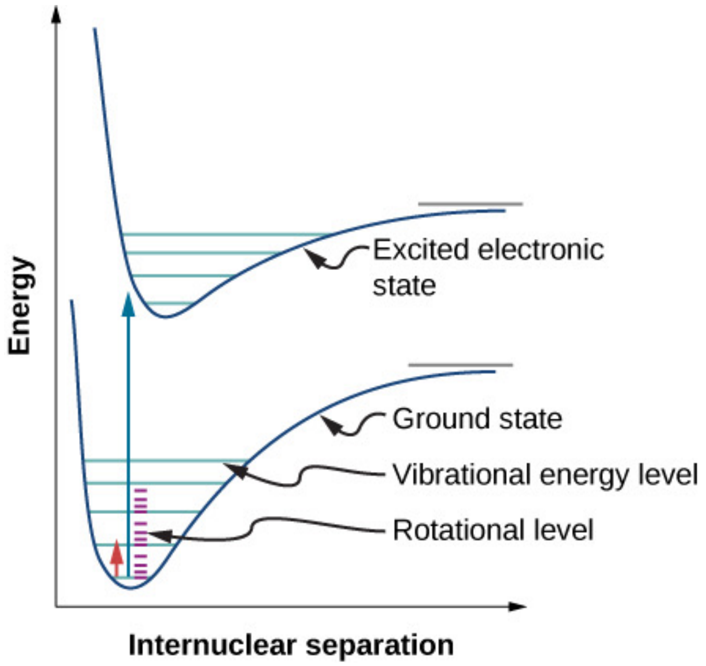

Electronic and vibrational structure
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Nature 581, 396 (2020)

Rotational structure
CRIS 2021

Nature Physics **20**, 202–207 (2024)

Electric quadrupole interaction
CRIS 2023

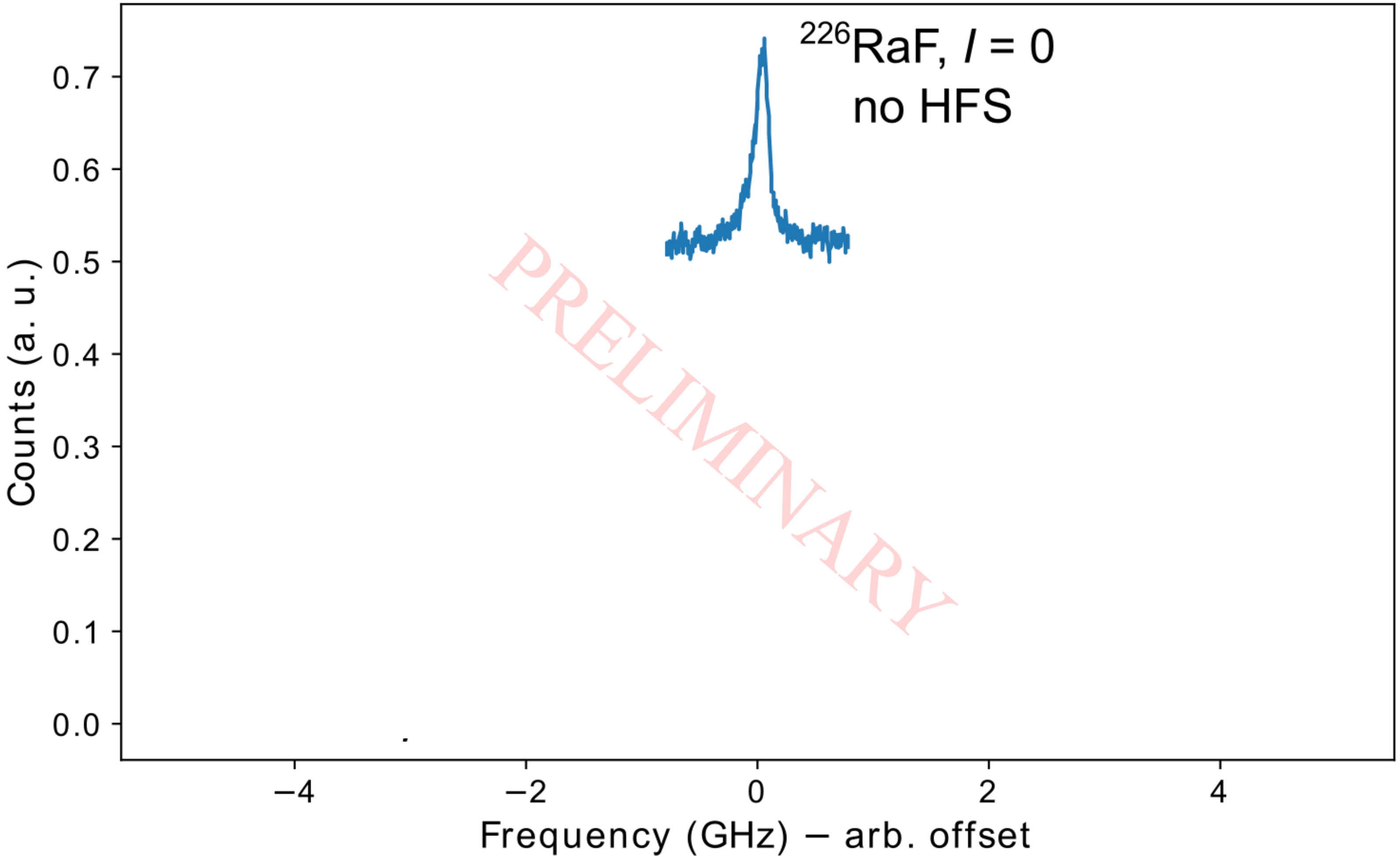
Magnetic dipole interaction
CRIS 2021/2023

PRL 127, 033001 (2021)

arXiv:2308.14862, submitted (2023)

arXiv:2311.04121, submitted (2023)

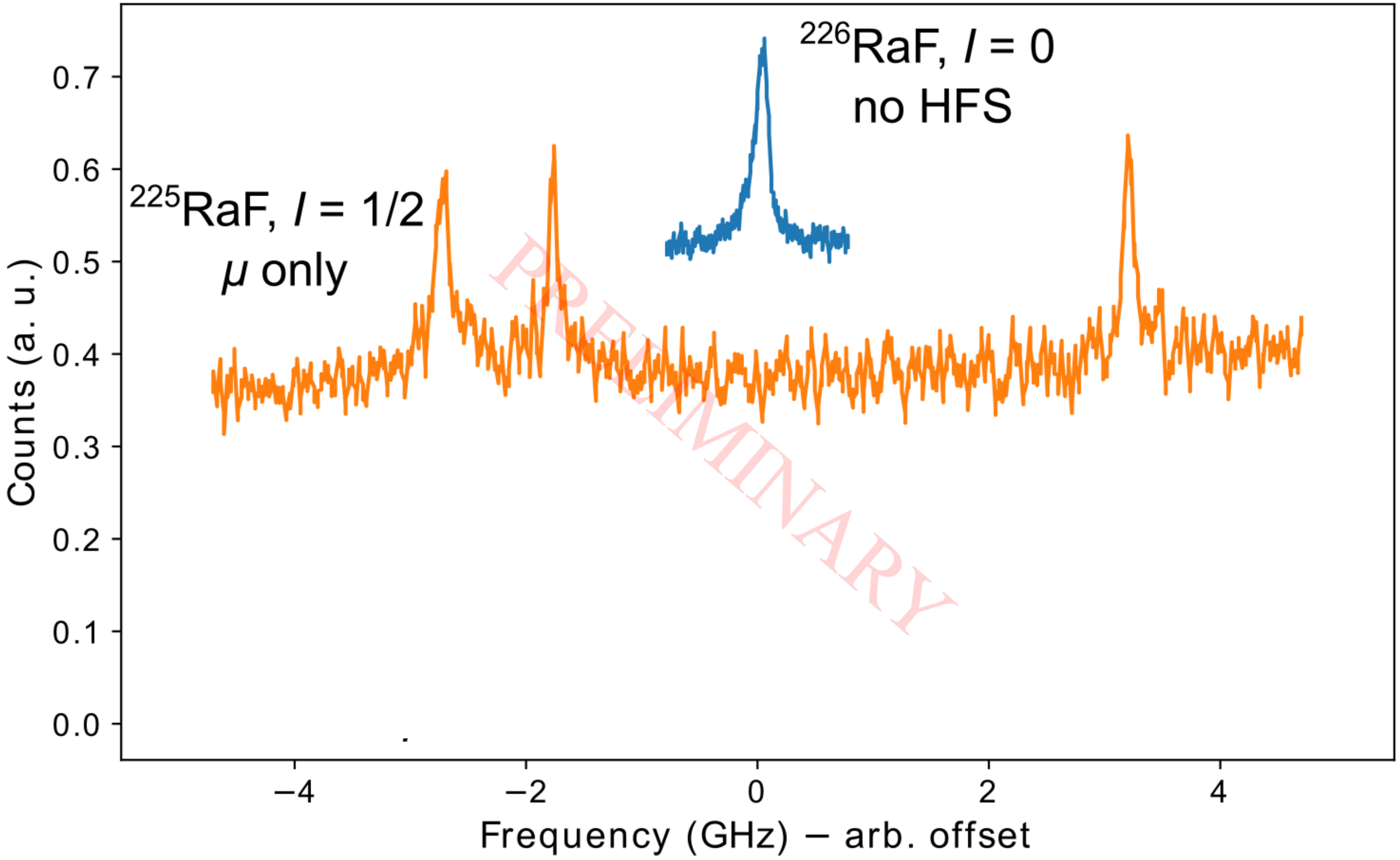
High-resolution spectroscopy of RaF



2023 RaF:

- High res. spec. of ^{226}RaF

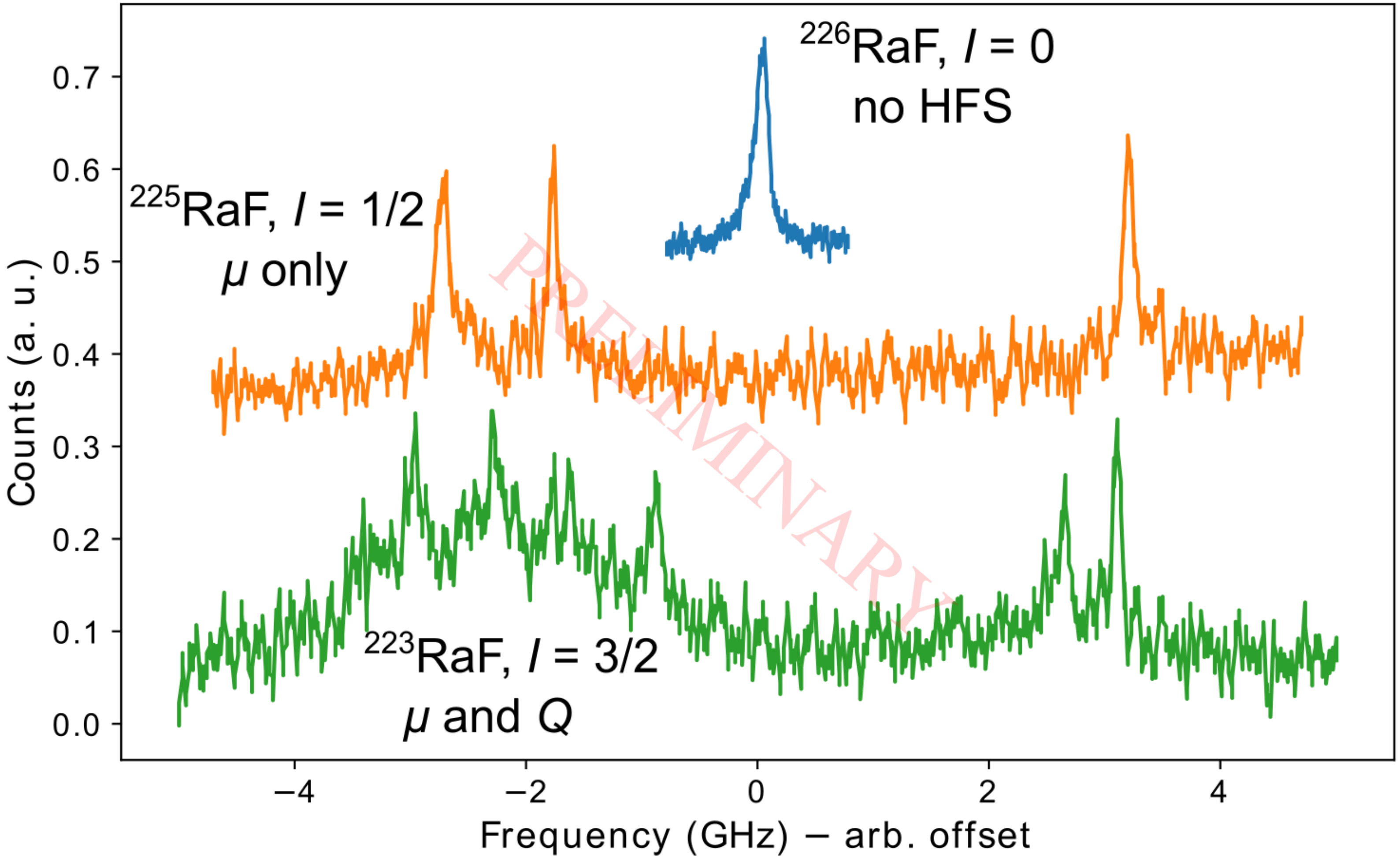
High-resolution spectroscopy of RaF



2023 RaF:

- High res. spec. of ^{226,225}RaF

High-resolution spectroscopy of RaF



2023 RaF:

- High res. spec. of ^{226,225,223}RaF
- First measurement of the hyperfine structure of ^{223}RaF

→ Analysis ongoing for the first measurement of an electric quadrupole moment in a radioactive molecule

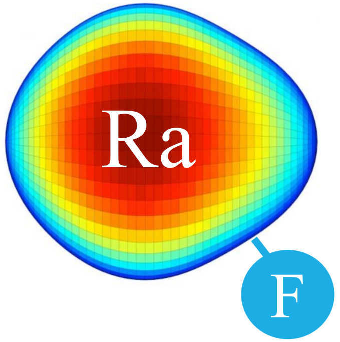
Analysis and slides from Michail Athanasakis-Kaklamanakis

Conclusion

2023 @ CRIS

- Two major upgrades: New end of the beam line and new Decay spectroscopy station succesfully commisioned
- Charge radii of neutron rich Aluminium isotopes across *N*=20 in the Island of inversion
- Spin, radii and magnetic dipole moment of neutron rich Chromium isotopes from *N*=26 to *N*=38, entering the *N*=40 Island of Inversion

- Spin, Radii and moments of ^{81,82}Zn across *N*=50 in the vicinity of ^{78}Ni
- Hyperfine and ro-vibrational structure of ^{223,225,226}RaF and first determination of a quadrupole moment in radioactive molecule



The 2023 CRIS Collaboration

MANCHESTER 1824
The University of Manchester

KU LEUVEN

CERN

O. Ahmad, M. Au, **M. Athanasakis-Kaklamanakis**, J. Berbalk, C. Bernerd, K. Chrysalidis, T. E. Cocolios, R. van Duyse, R. P. de Groote, C. Fajardo-Zambrano, K. T. Flanagan, S. Franchoo, R. F. Garcia Ruiz, R. Heinke, M. Heines, D. Hanstorp, P. Imgram, Á. Koszorús, **L. Lalanne**, P. Lassegues, R. Lica, J. Lim, **Y. Liu**, K. Lynch, R. Mancheva, **A. McGlone**, W. Mei, G. Neyens, L. Nies, A. Raggio, **J. Reilly**, S. Rothe, E. Smets, **B. van den Borne**, J. Warbinek, J. Wessolek, S. Wilkins, X. F. Yang

Massachusetts Institute of Technology

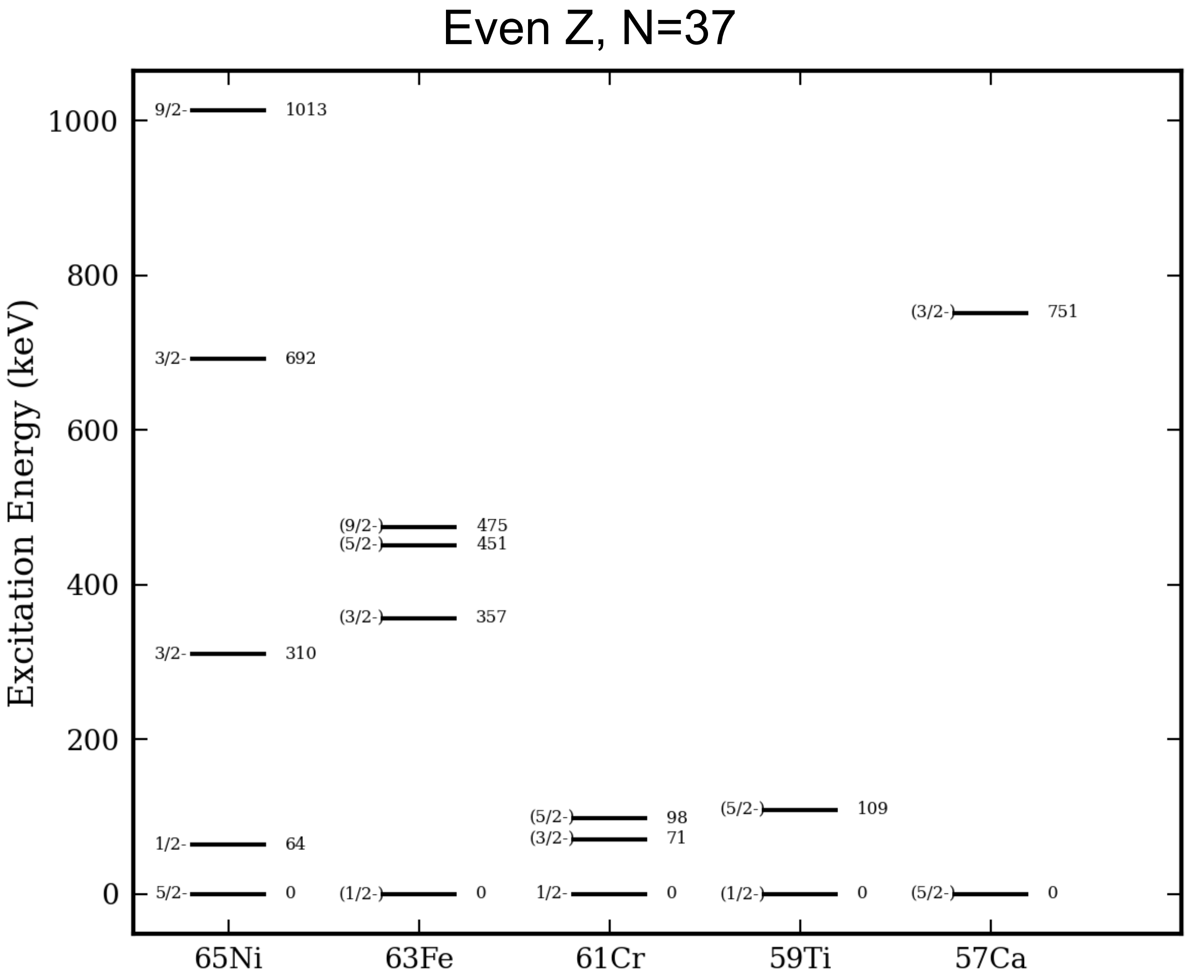
北京大學 PEKING UNIVERSITY

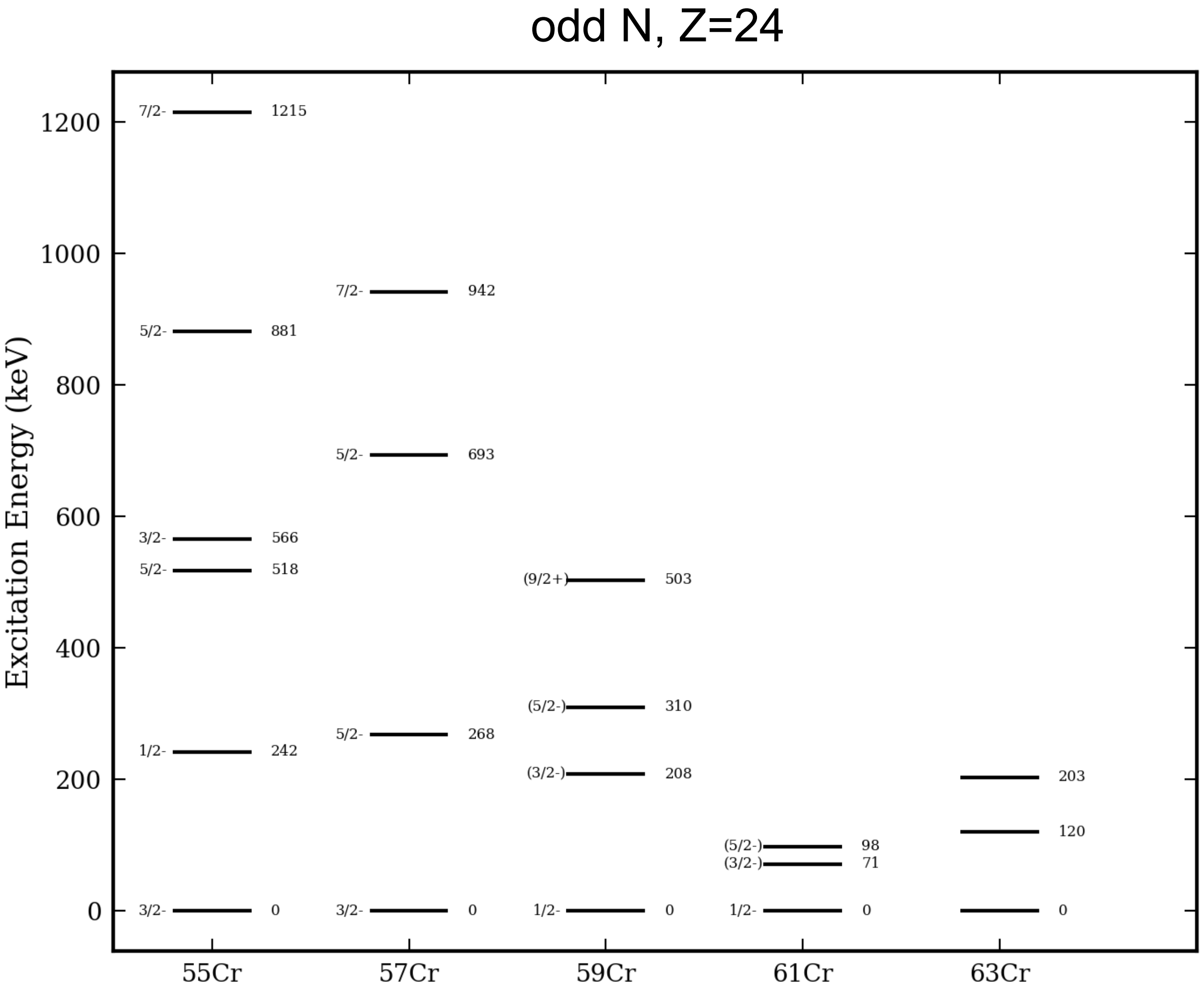
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

UNIVERSITY OF GOTHENBURG

THANK YOU FOR YOUR ATTENTION

Spectro systematic





The ½-, 3/2-, 5/2- triplet coexist at low energies in all nuclei of the region. 61Cr seems to be the most condensed structure