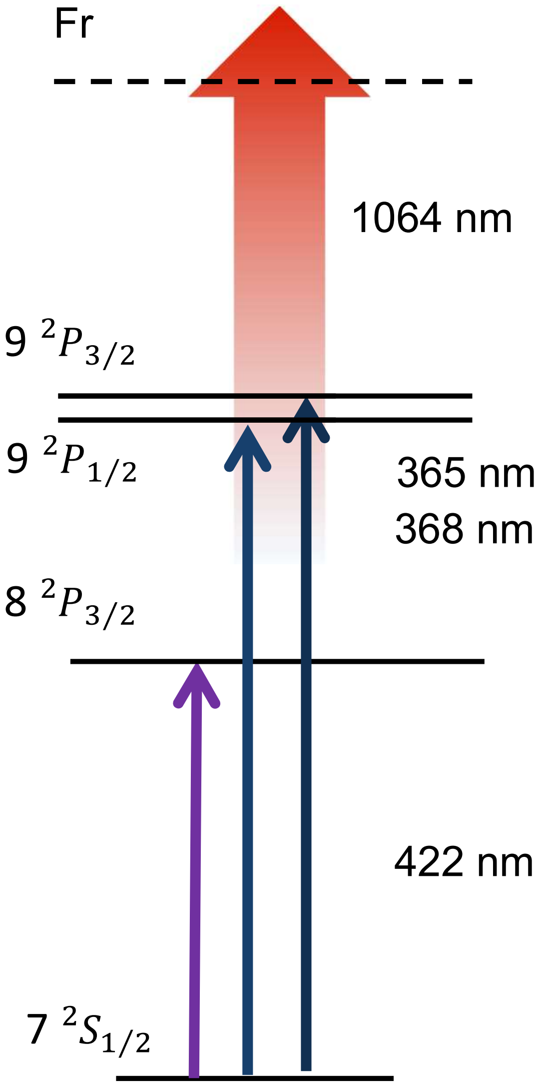
Atomic physics studies of the heaviest alkaline

P. Lassègues, R. P. de Groote, A. Kastberg et al.

Atomic studies in 221 Francium :

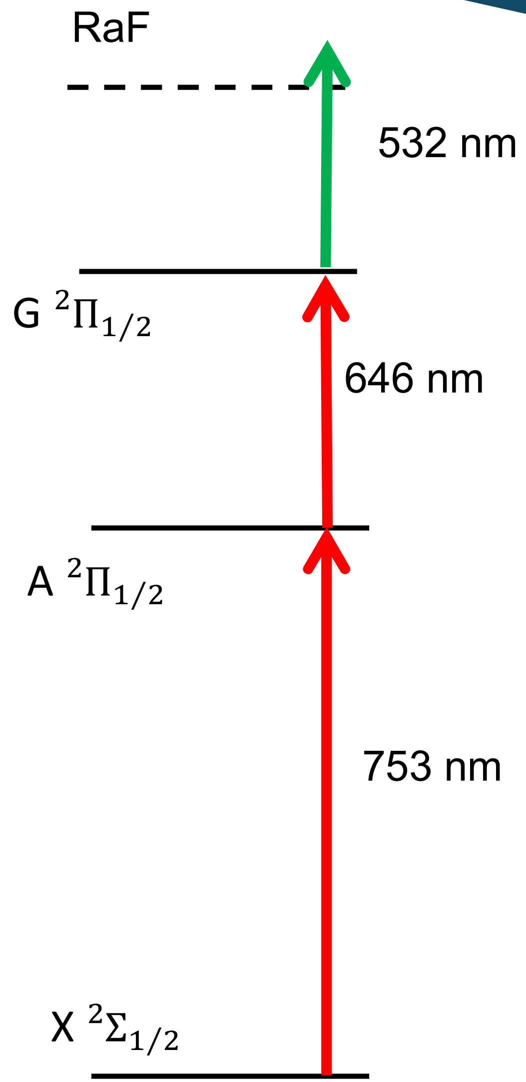
- New **atomic levels** identified in Fr
- **Lifetime** measurements performed for excited *P*-states
- Identified **6D state** (broadband)
- New **Rydberg series** observed

Results December 2023



- Measurements of Energy level
- Measurement of Lifetimes

- 221 Francium : 8 $^2P_{3/2}$, 9 $^2P_{1/2}$, 9 $^2P_{3/2}$
- RaF : A $^2\Pi_{1/2}$



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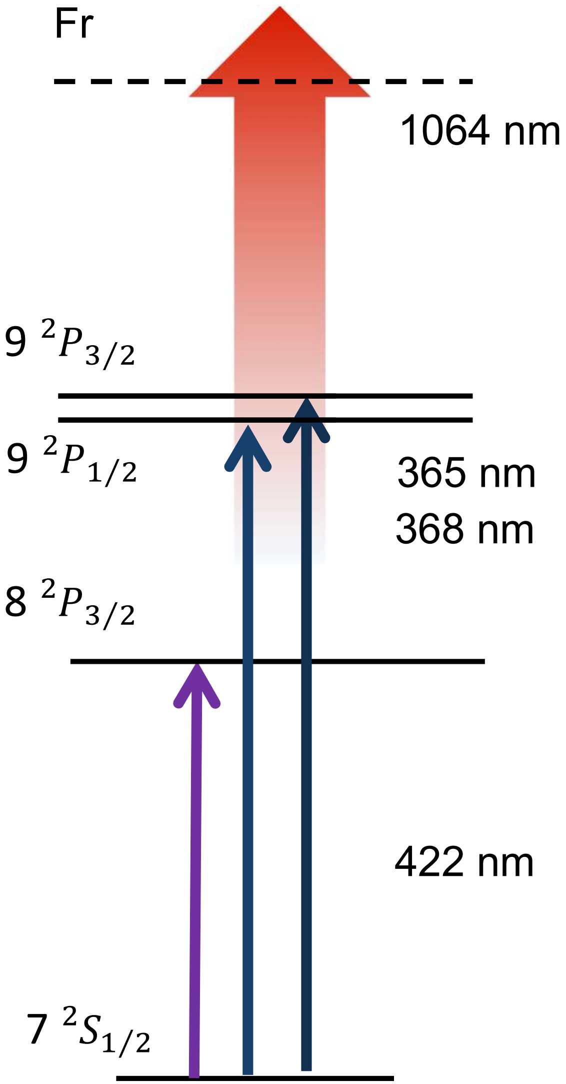
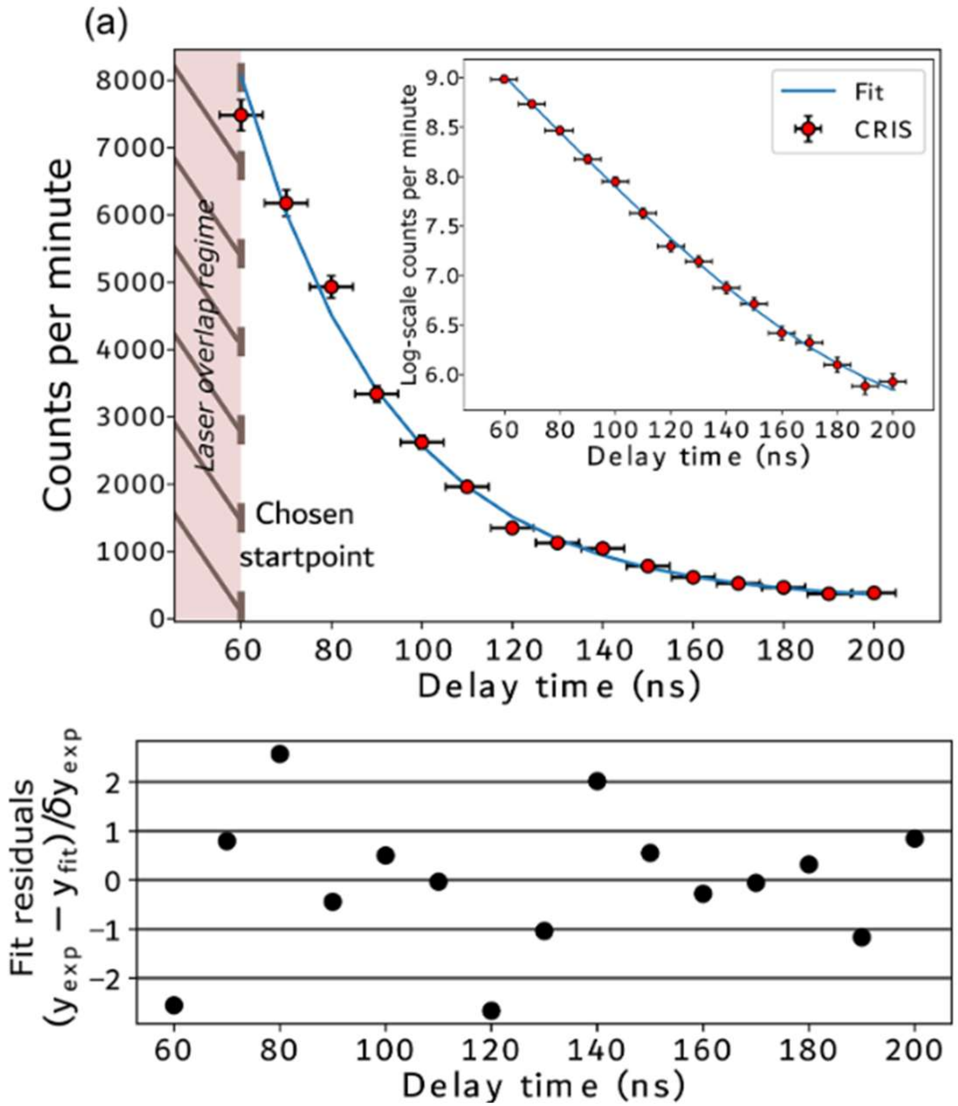
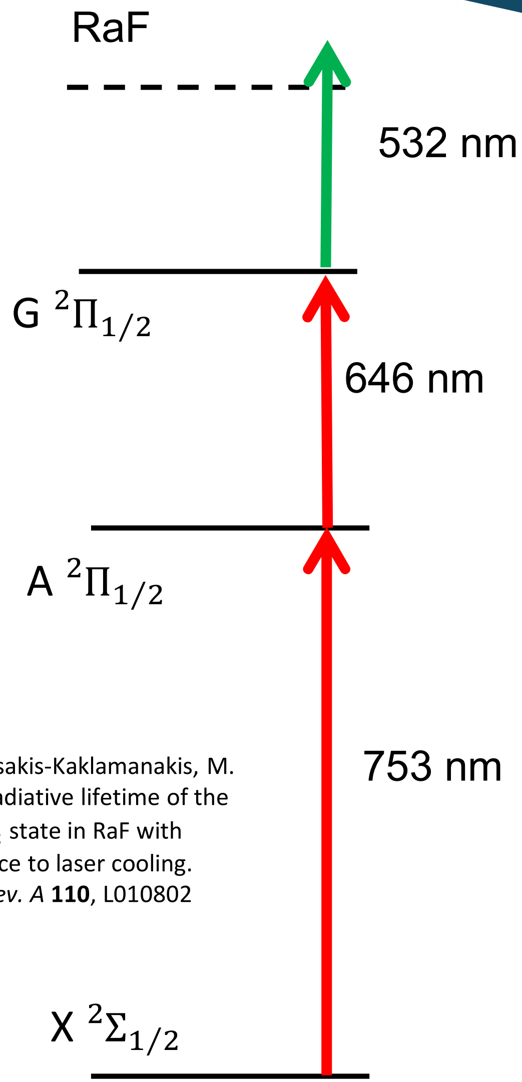


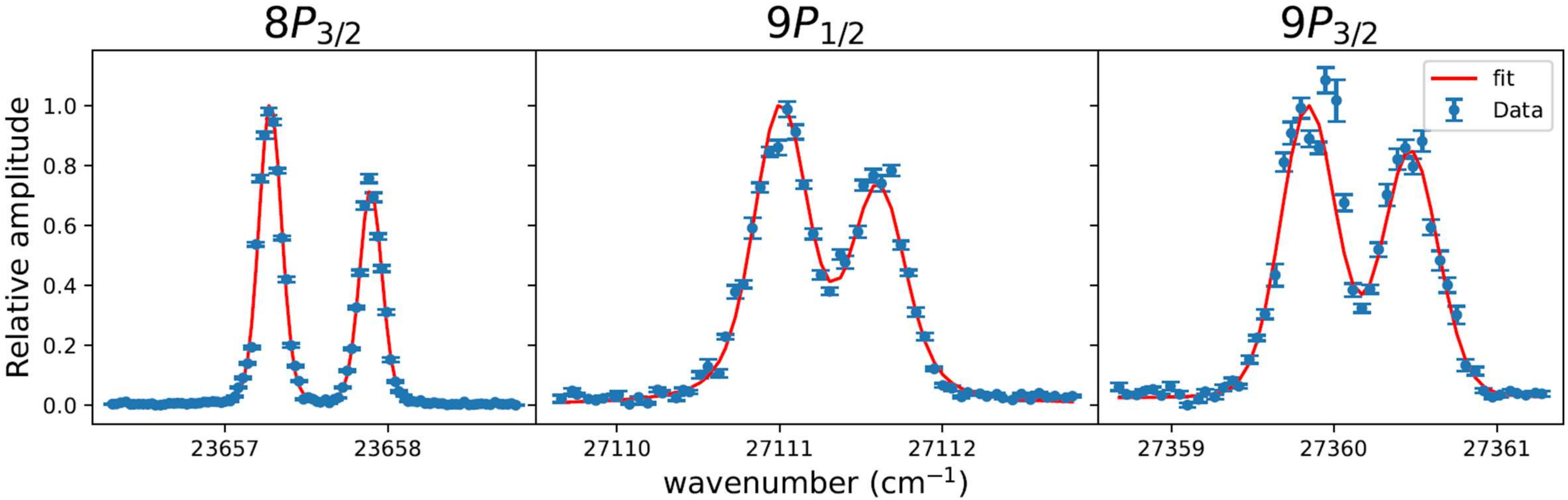


Athanasakis-Kaklamanakis, M. *et al.* Radiative lifetime of the A $^2\Pi_{1/2}$ state in RaF with relevance to laser cooling. *Phys. Rev. A* **110**, L010802 (2024).



Energy Levels

Energy levels



Level	ν (THz)	λ_{vac} (nm)	$\tilde{\nu}$ (cm^{-1})
$8P_{3/2}$	709.235070(35)	422.69829(2)	23657.5354(11)
$9P_{1/2}$	812.774803(147)	368.85058(7)	27111.2491(49)
$9P_{3/2}$	820.235326(159)	365.49566(7)	27360.1054(53)

(Statistical Error)

Energy levels

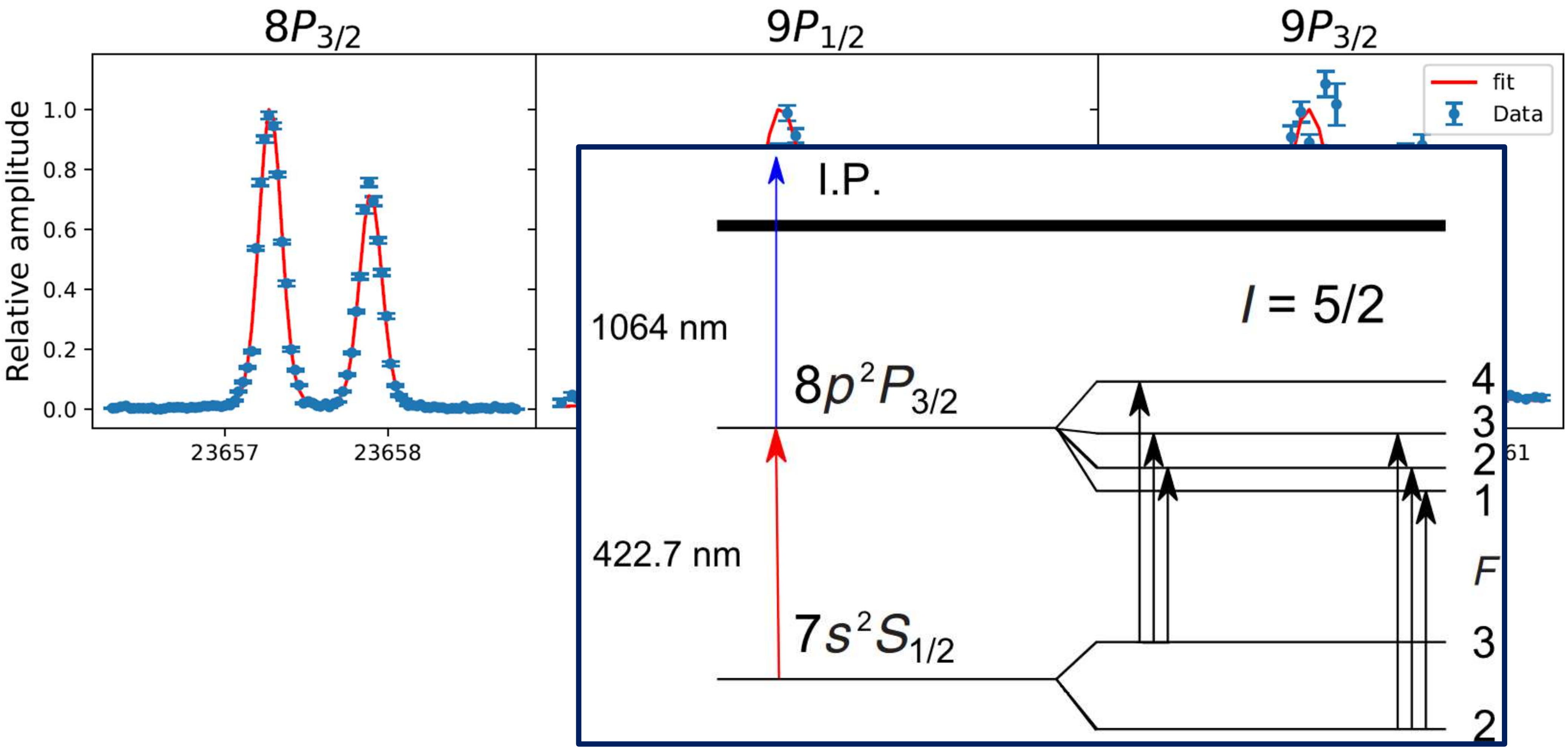


Figure from :Budinčević, I. *et al.* Laser spectroscopy of francium isotopes at the borders of the region of reflection asymmetry. *Phys. Rev. C* **90**,(2014).

Energy levels – litterature

Level	Ref 1 (NIST) 212 Fr	Exp 221 Fr [we are here]	Ref 2 (BK Sahoo)	Ref 1 (NIST)+IS 221 Fr	$\Delta\tilde{\nu}$ Ref 1	$\Delta\tilde{\nu}$ Ref 2
$8P_{3/2}$	23 658.306(5) [Exp] (1)	23 657.5354(11)	23 667.532 [Theo]	23 657.5288 [Exp]	0,0066 (197 MHz)	9,9966
$9P_{1/2}$	27 118.21(5) [Theo] (2)	27 111.2491(49)	27 121.042 [Theo]	(27 117.4329)	(6,183762)	9,7929
$9P_{3/2}$	27 366.20(5) [Theo] (2)	27 360.1054(53)	27 368.492 [Theo]	(27 365.4229)	(5,317462)	8,3866

Level	Isotope shift (MHz)
$8P_{3/2}$	−23 298.0(8) [Exp] (3)
$9P_{1/2}$	-
$9P_{3/2}$	-

(1) Duong, H. *et al.* First observation of the blue optical lines of francium. *Europhysics Letters* **3**, 175 (1987).
(2) Biémont, E., Quinet, P. & Van Renterghem, V. Theoretical investigation of neutral francium. *Journal of Physics B: Atomic, Molecular and Optical Physics* **31**, 5301 (1998).
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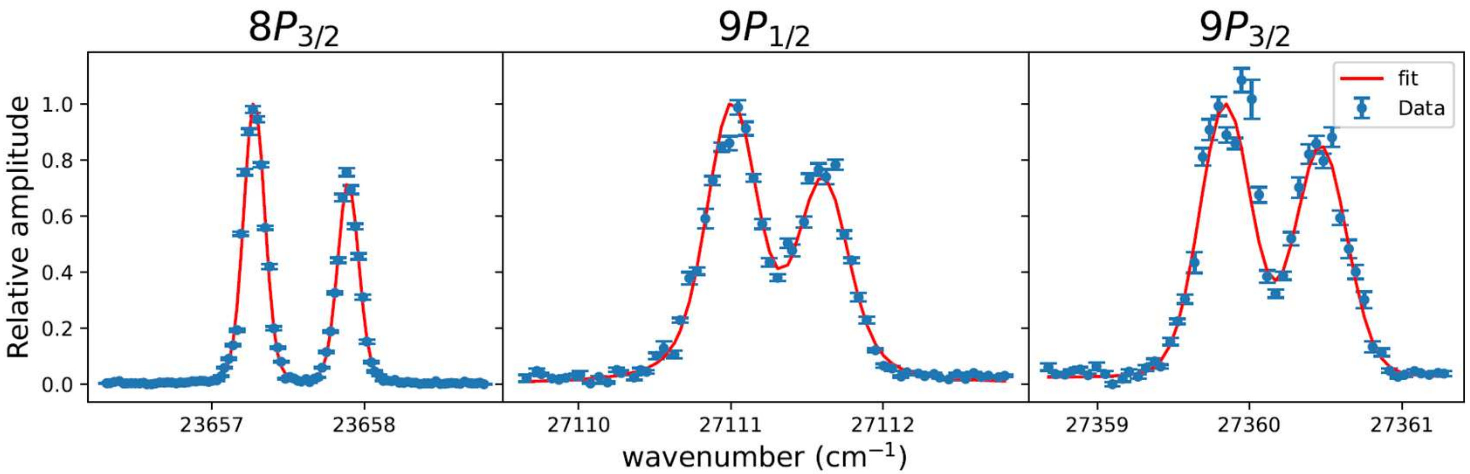
Atomic studies in Fr : Campain 2023



Level	$\tilde{\nu}$ (cm^{-1})
$8P_{3/2}$	23657.5354(11)
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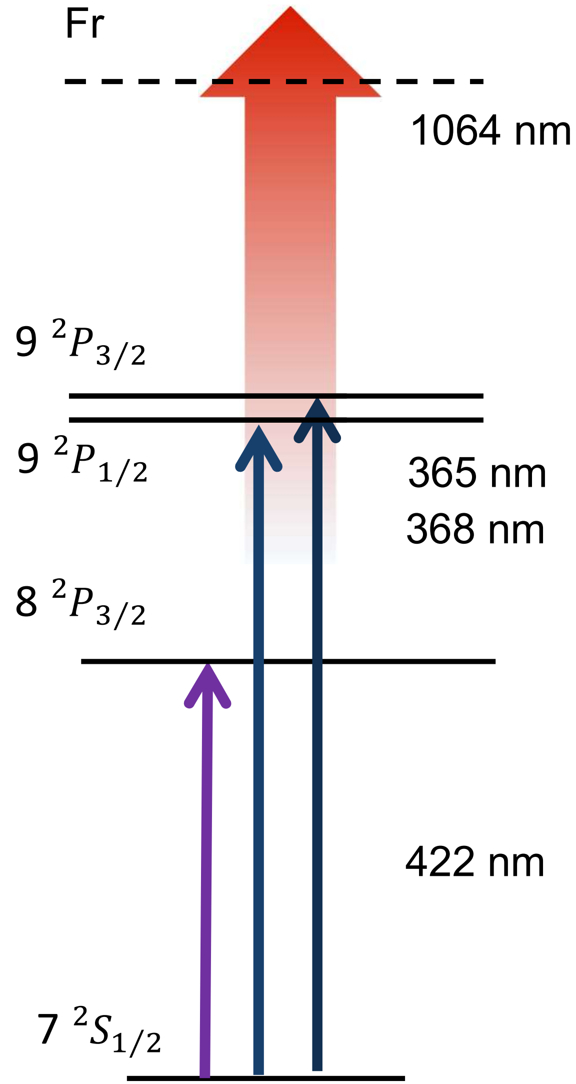
First tests done in 2023:

✓ First identification of $9P_{1/2,\ 3/2,}$



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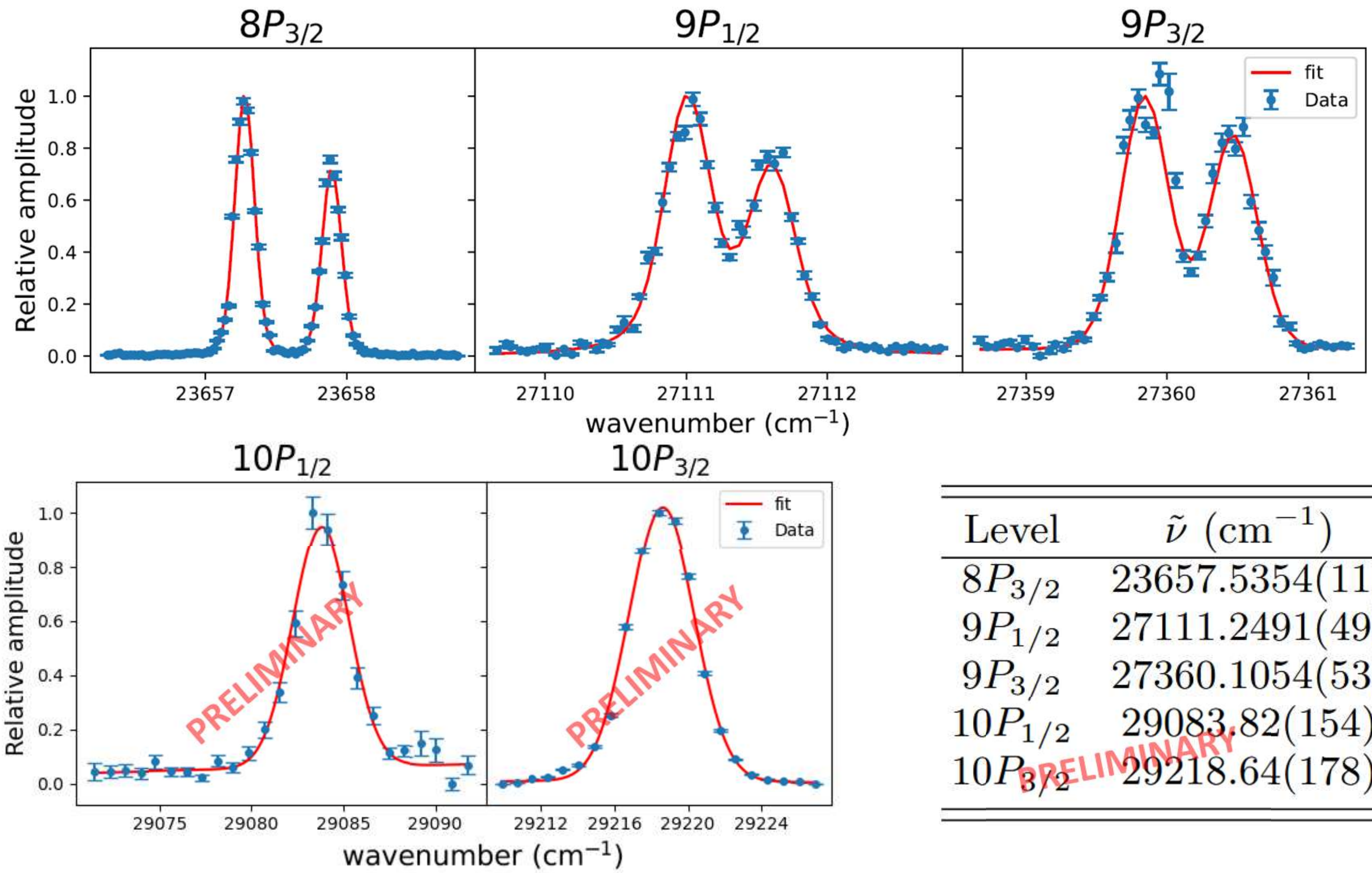

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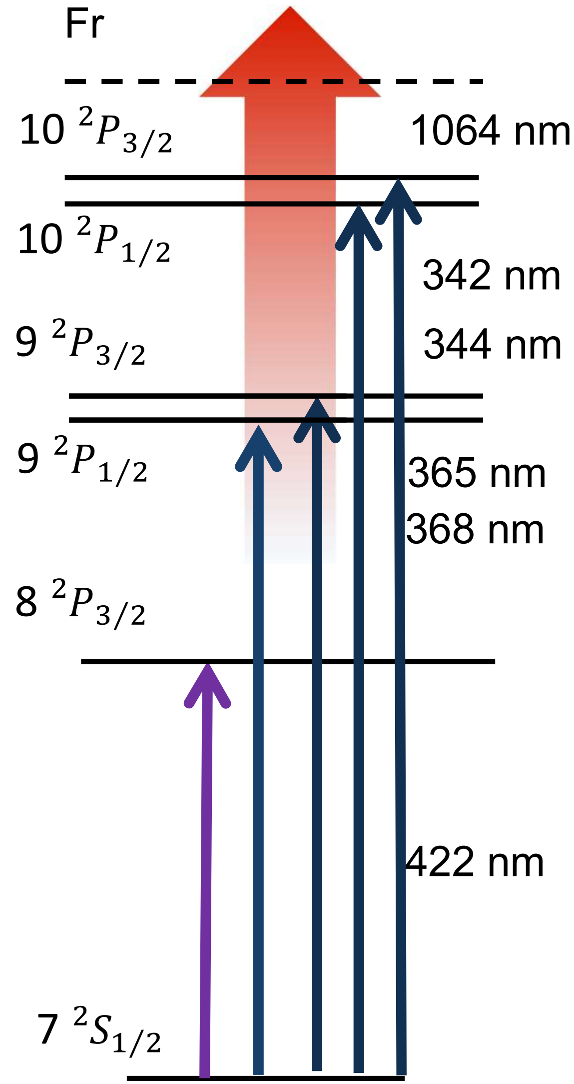
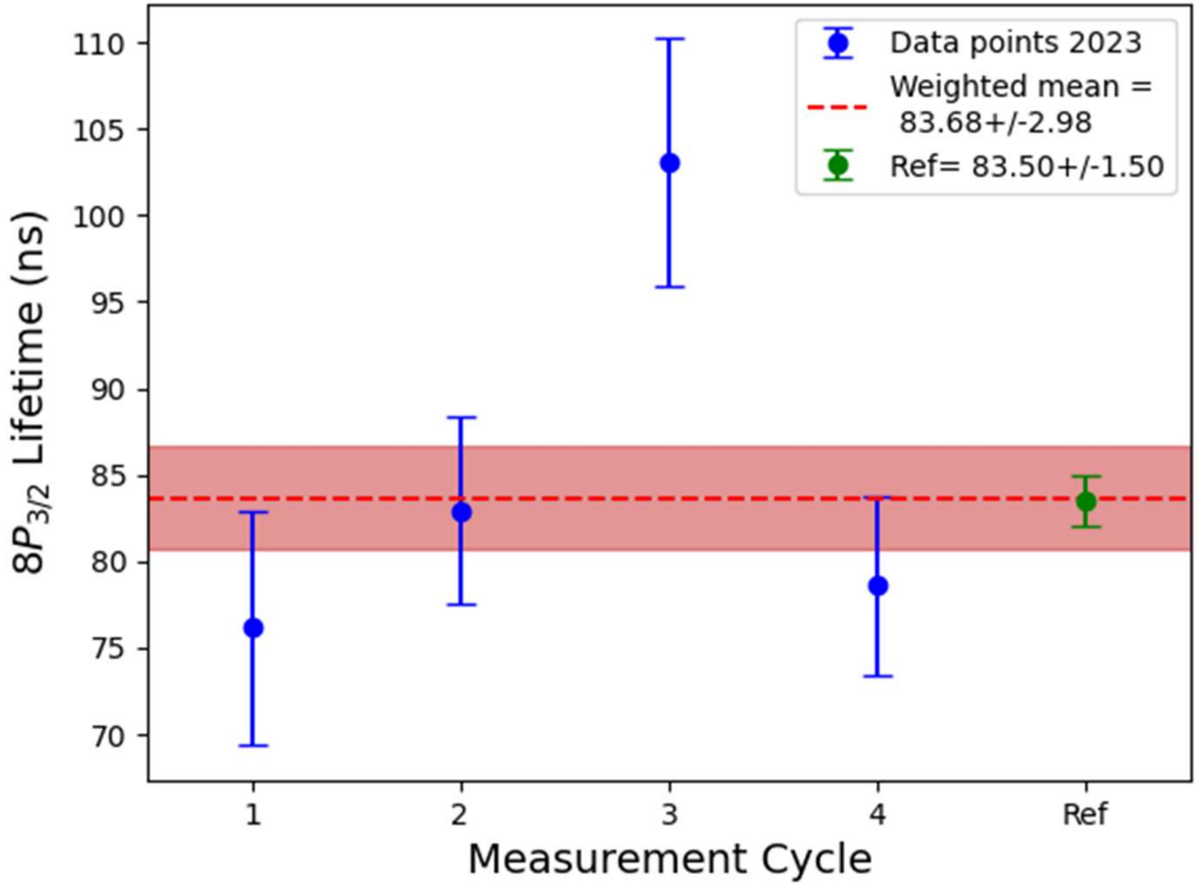
$10P_{1/2}$	29083.82(154)
$10P_{3/2}$	29218.64(178)

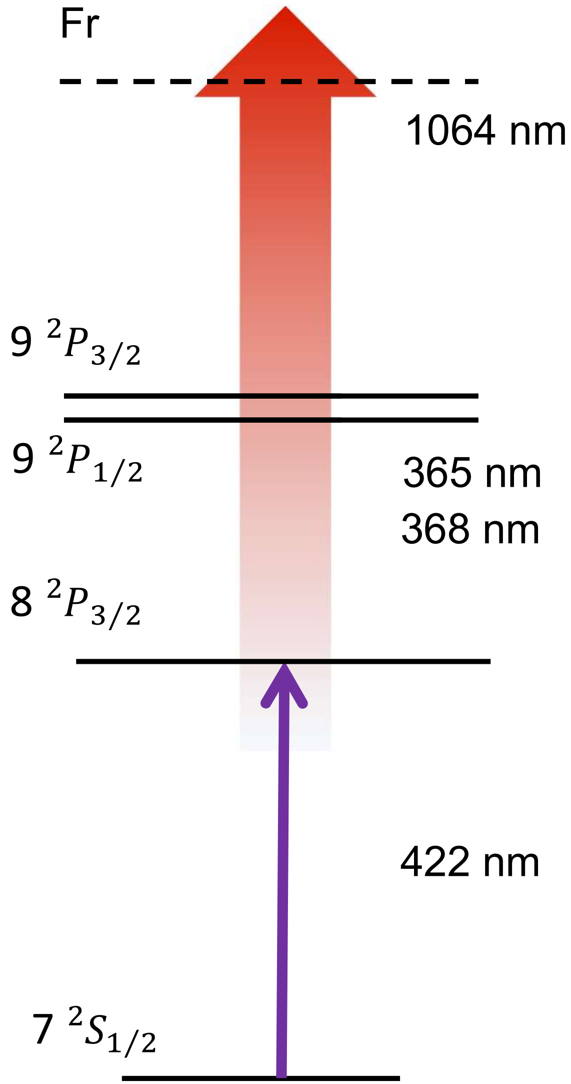
PRELIMINARY



Lifetimes

8p3/2 Lifetime reference





8p3/2 Lifetime reference

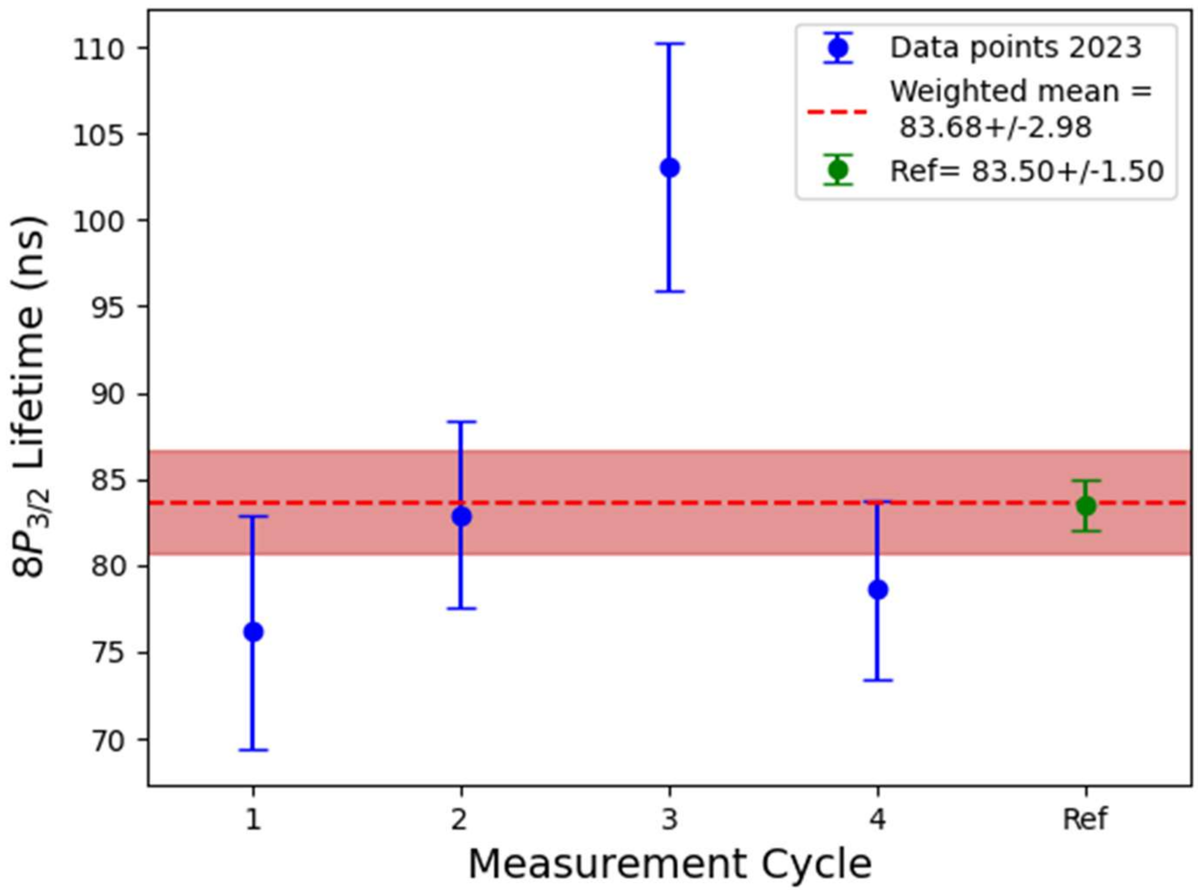


TABLE II. Summary of the details of the different cycles in the lifetime measurement of the 8P3/2 state in Fr. The systematic y-error corresponds to the added uncertainty on the count rate to account for atomic beam fluctuations.

n°	Step timing mod.	ISCOOL ejection delay(μs)	Syst. y-error (%)	$8P_{3_2}$ lifetime (ns) Single fit
1	Ion.	0	3.3	76.15(6.80)
2	Ion.	-0.5	3.4	82.94(5.38)
3	Ion.	+0.5	0.9	103.04(7.17)
4	Exc.	0	4.9	78.60(5.19)
			weighted mean :	**83.68(2.98)**
ref[10]				83.5(1.5)

8p3/2 Lifetime reference

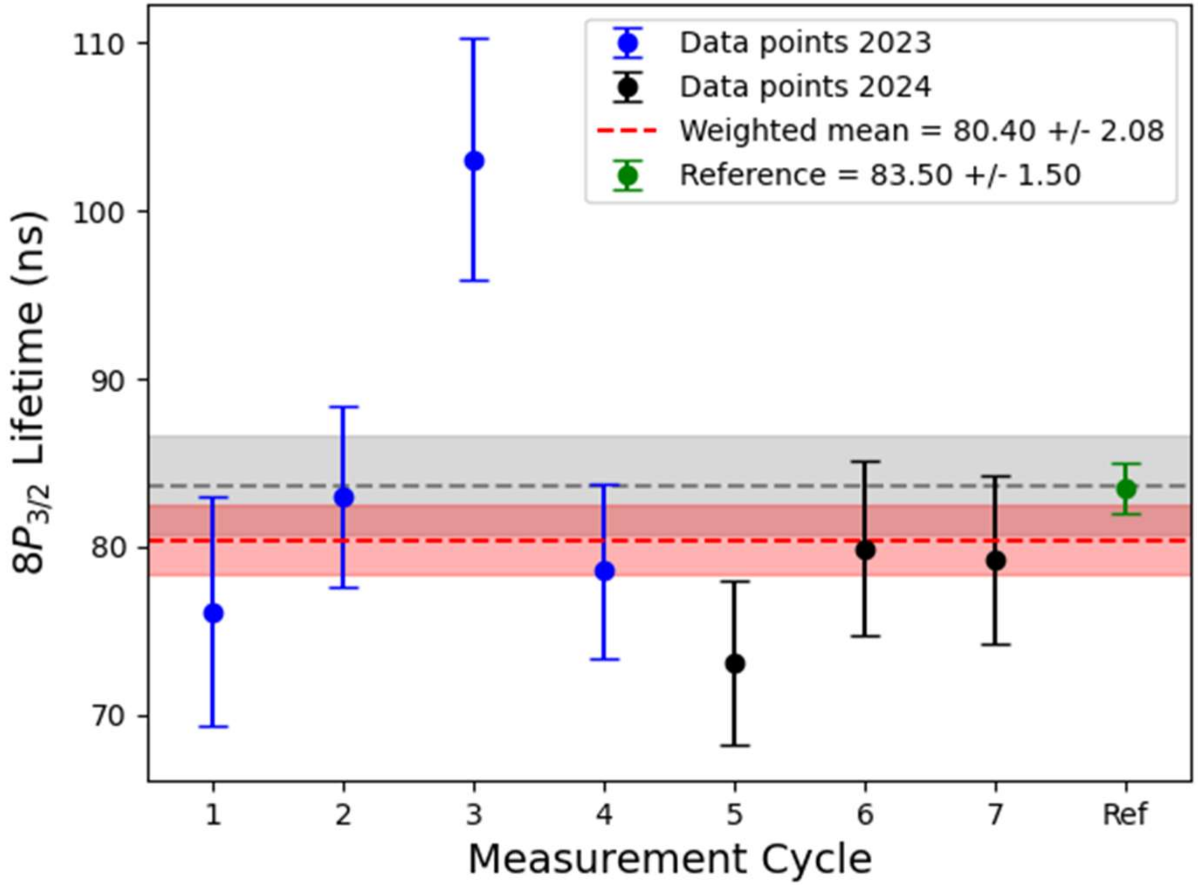


TABLE III. Summary of the details of the different cycles in the lifetime measurement of the 8P3/2 state in Fr. The systematic y-error corresponds to the added uncertainty on the count rate to account for atomic beam fluctuations.

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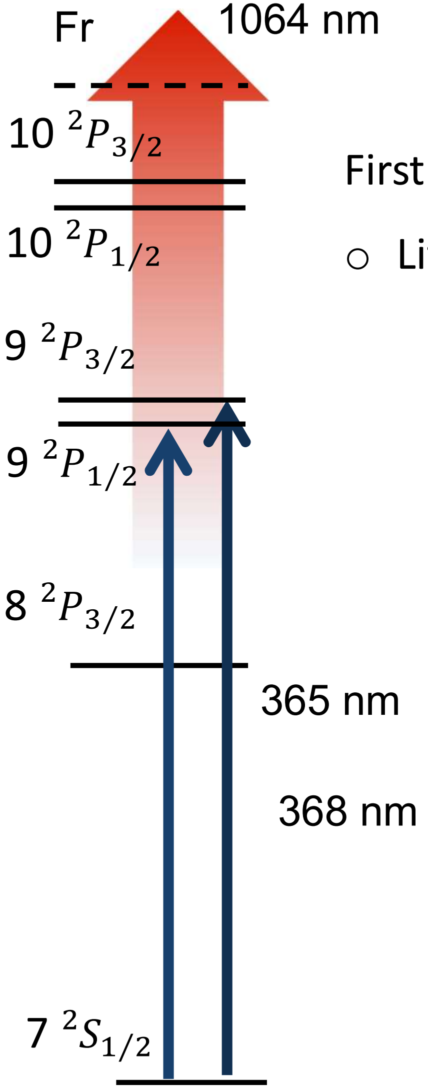
3	Ion.	+0.5	0.9	103.04(7.17)
4	Exc.	0	4.9	78.60(5.19)
5	Ion.	0	2.3	73.09(4.9)
6	Ion.	-0.5	3.0	79.92(5.2)
7	Ion.	+0.5	2.0	79.24(5.0)
			weighted mean :	**80.40(2.08)**
ref[10]				83.5(1.5)

2023 campain : 9P Lifetimes



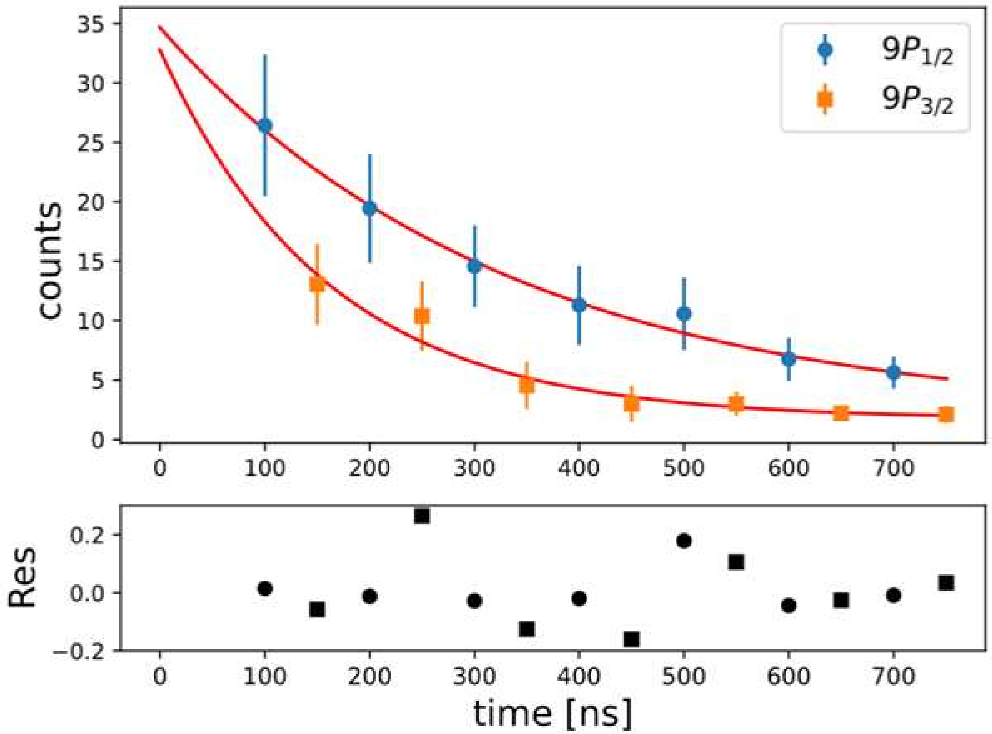
First tests done in 2023:

- Lifetime measurements of $9P_{1/2,\ 3/2}$

  Tentative results, need further measurements

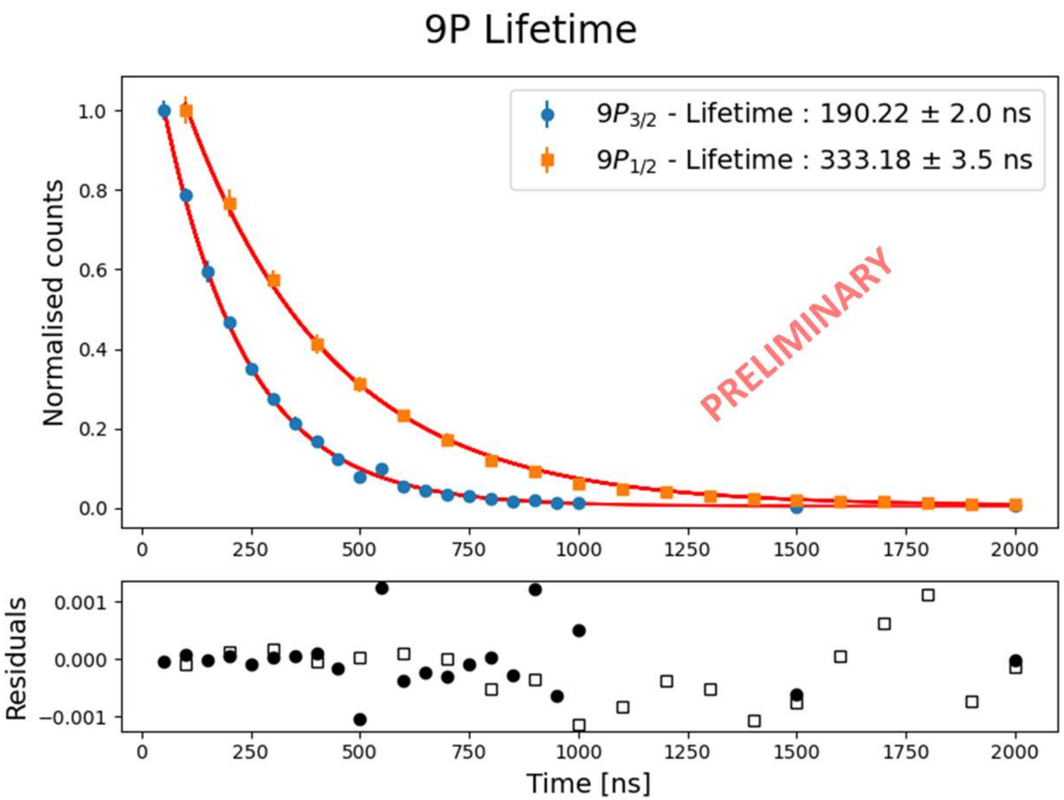
Level	Lifetime(ns)
$9P_{1/2}$	329.3(26.13)
$9P_{3/2}$	159.5(27.74)

2023



Atomic studies in Fr : 9P Lifetimes

2024



2023

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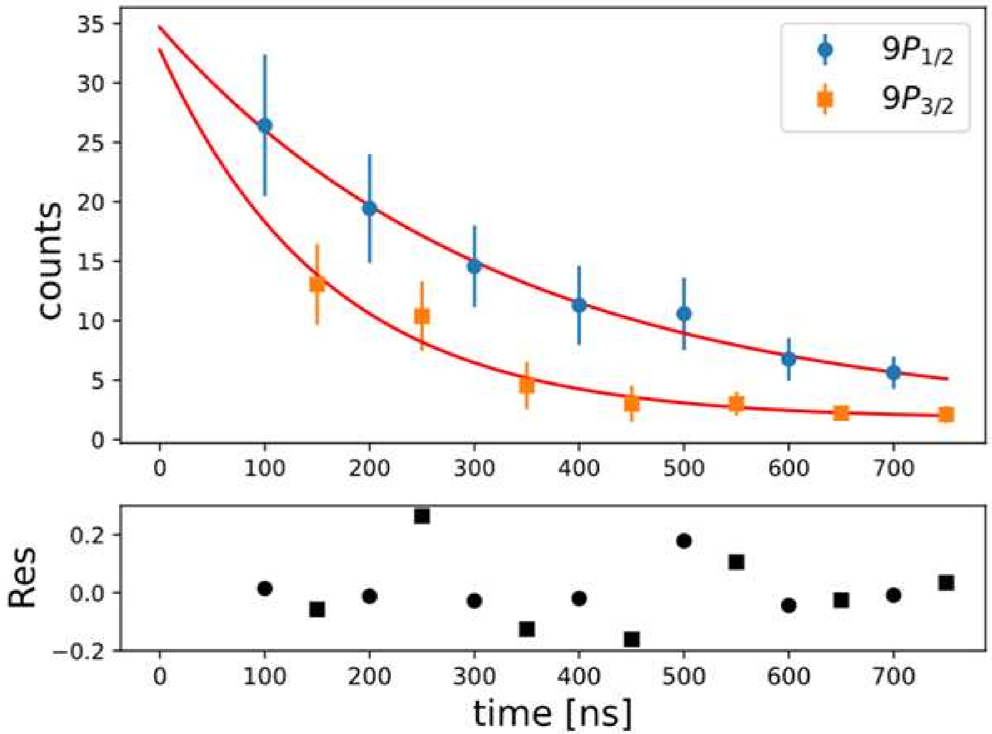
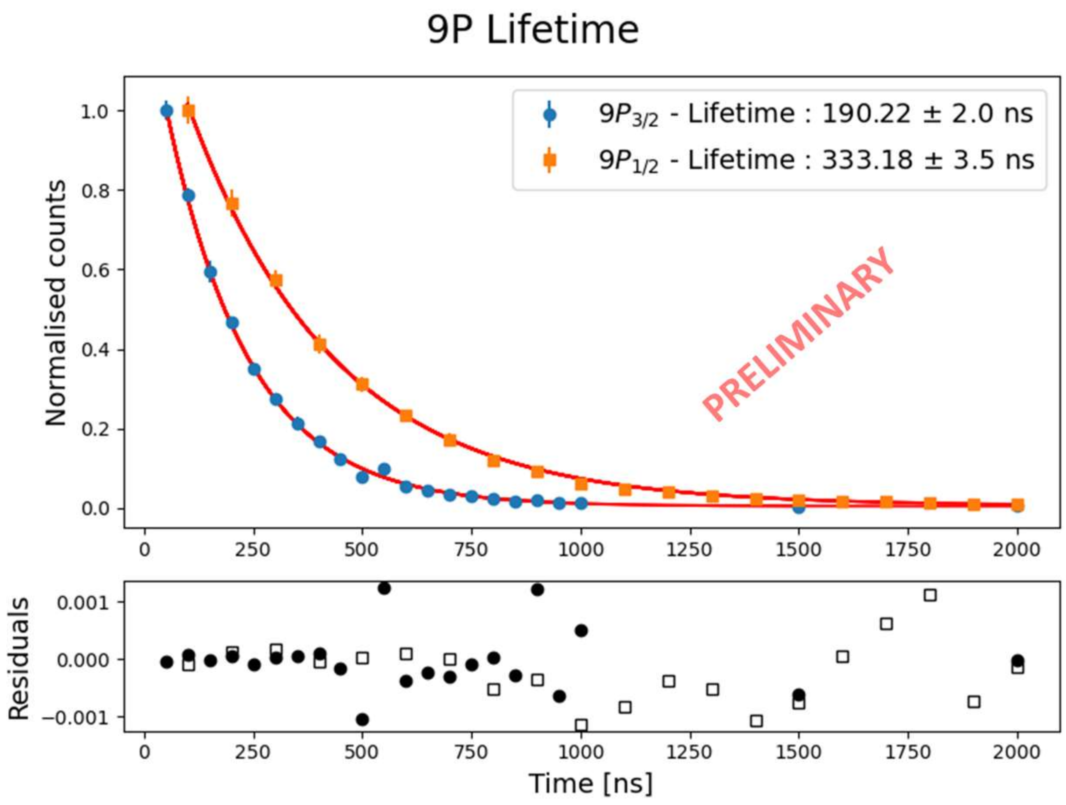
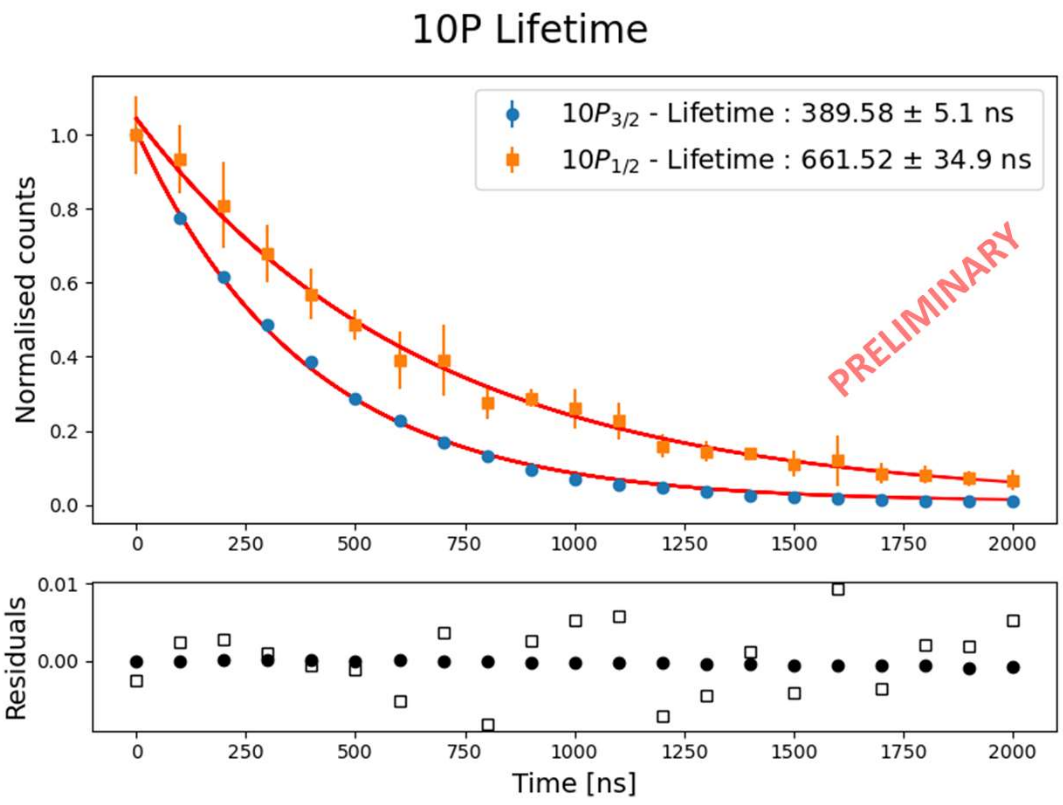


Atomic studies in Fr : Lifetimes





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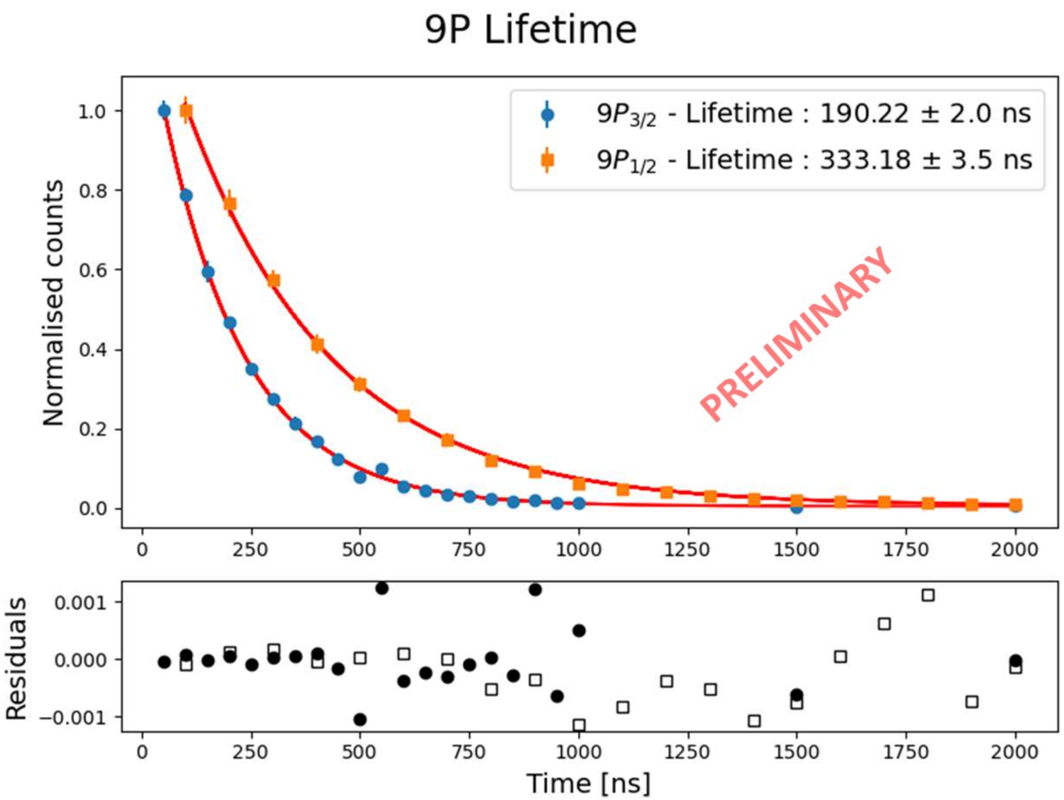
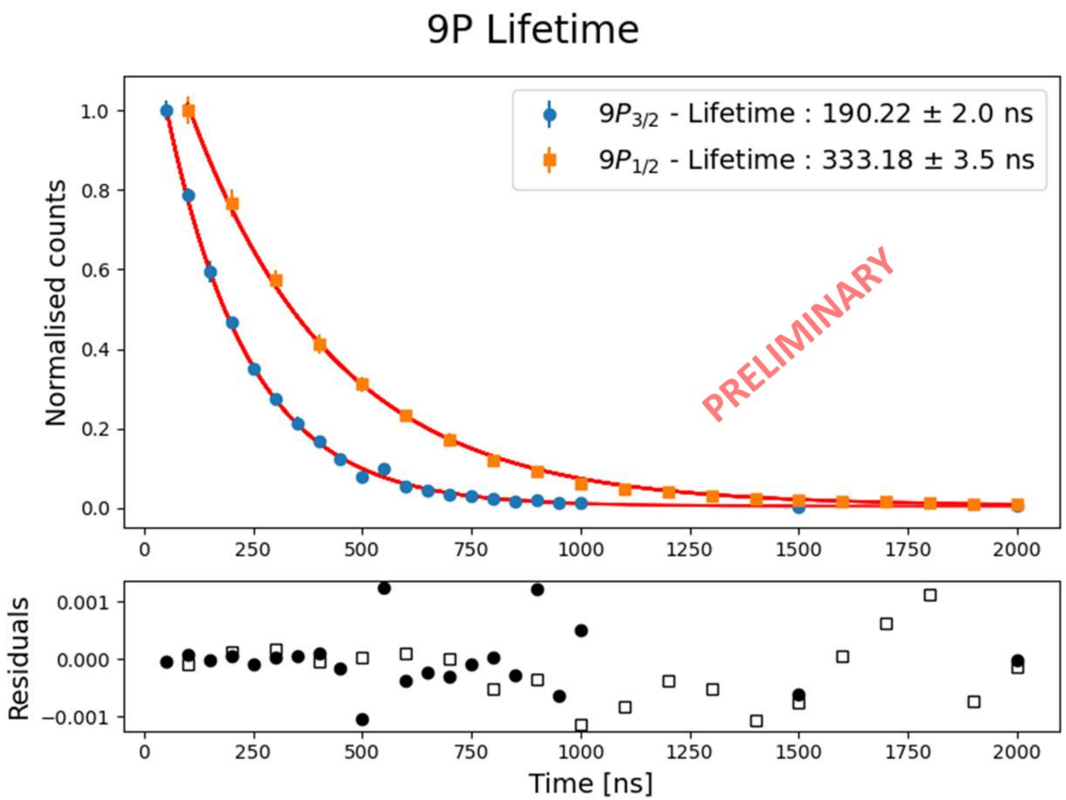


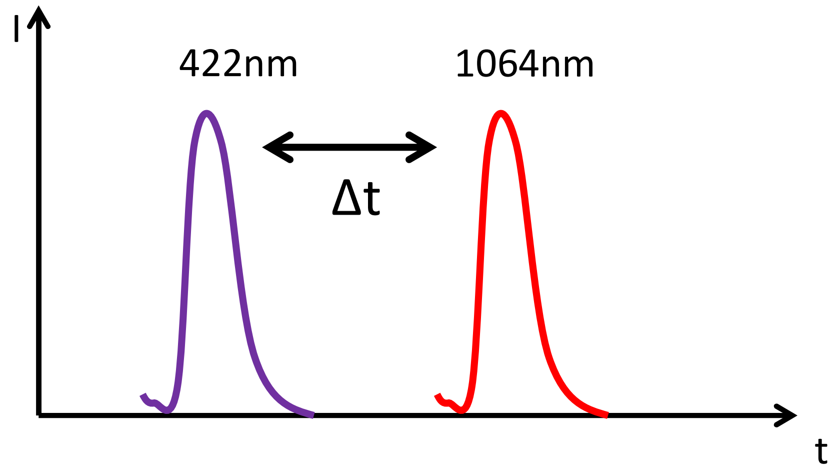
Possible Variations for final results:

Atomic studies in Fr : Lifetimes



Possible Variations for final results:

- Laser Overlap regime



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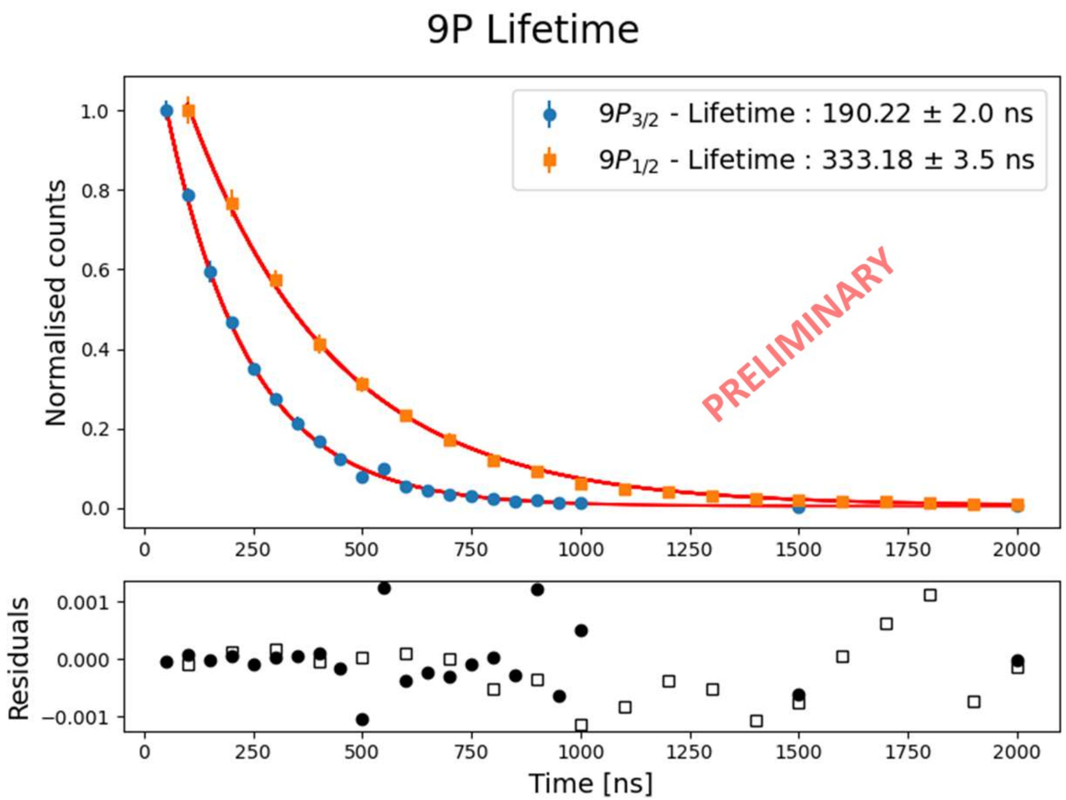

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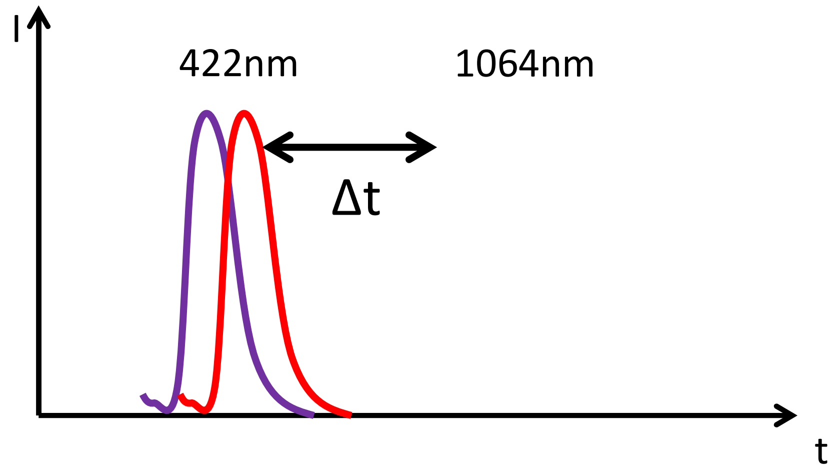

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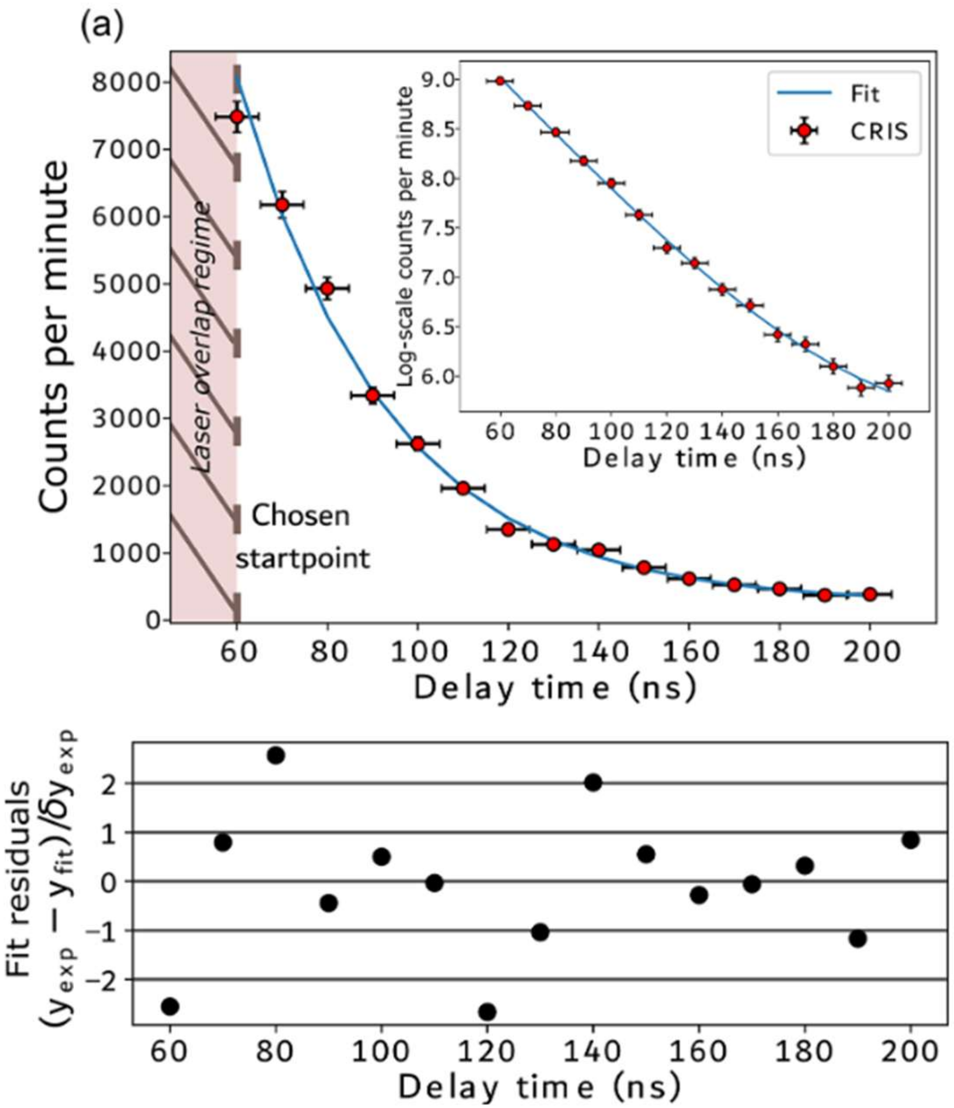

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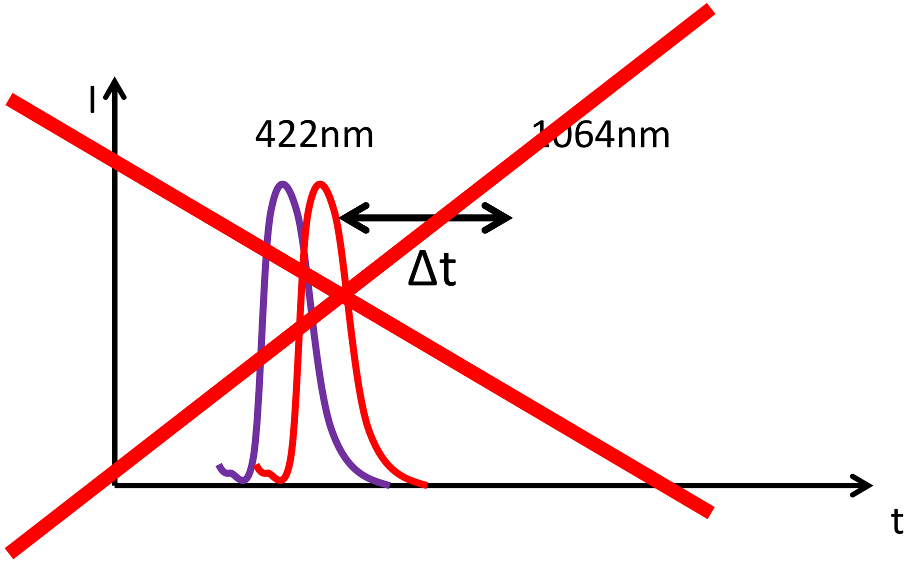

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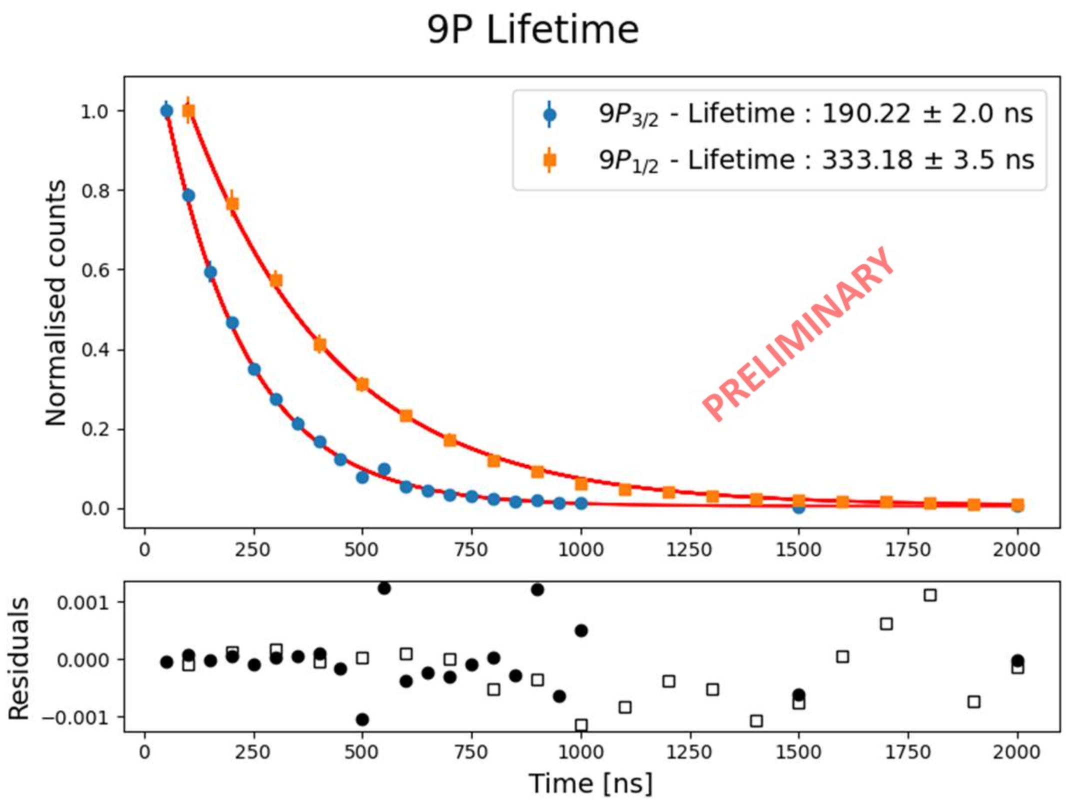
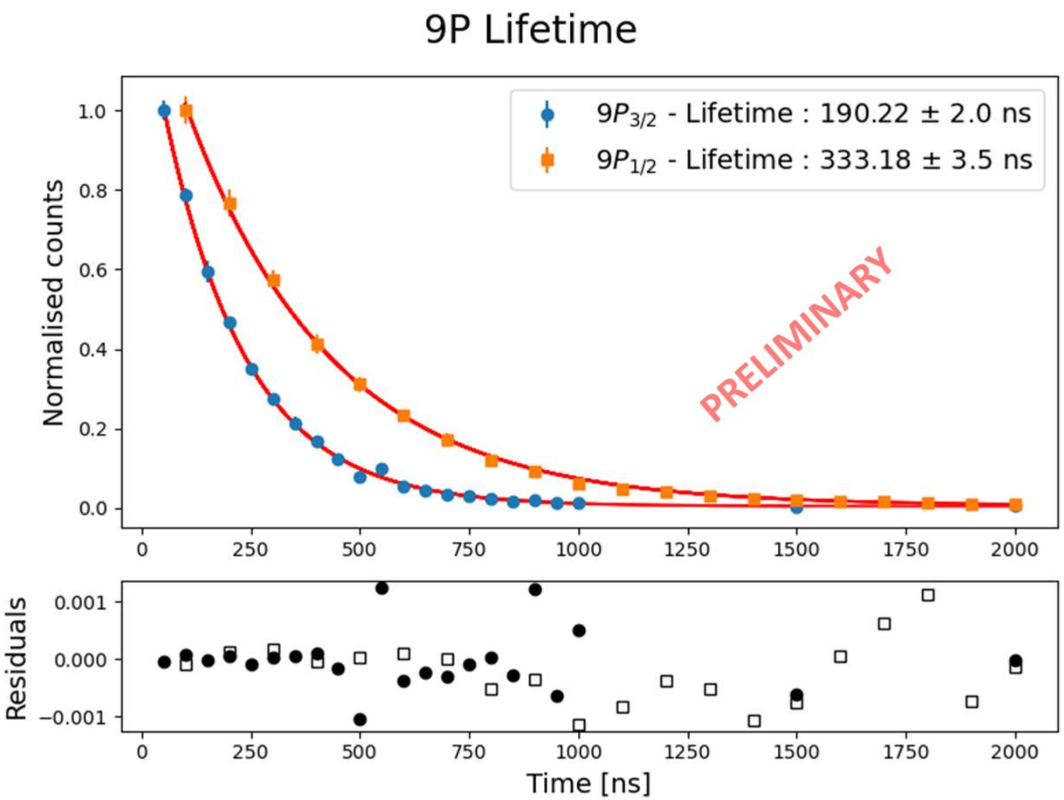


Possible Variations for final results:

- Laser Overlap regime
- Background Measurements

Atomic studies in Fr : Lifetimes



Possible Variations for final results:

- Laser Overlap regime
- Background Measurements

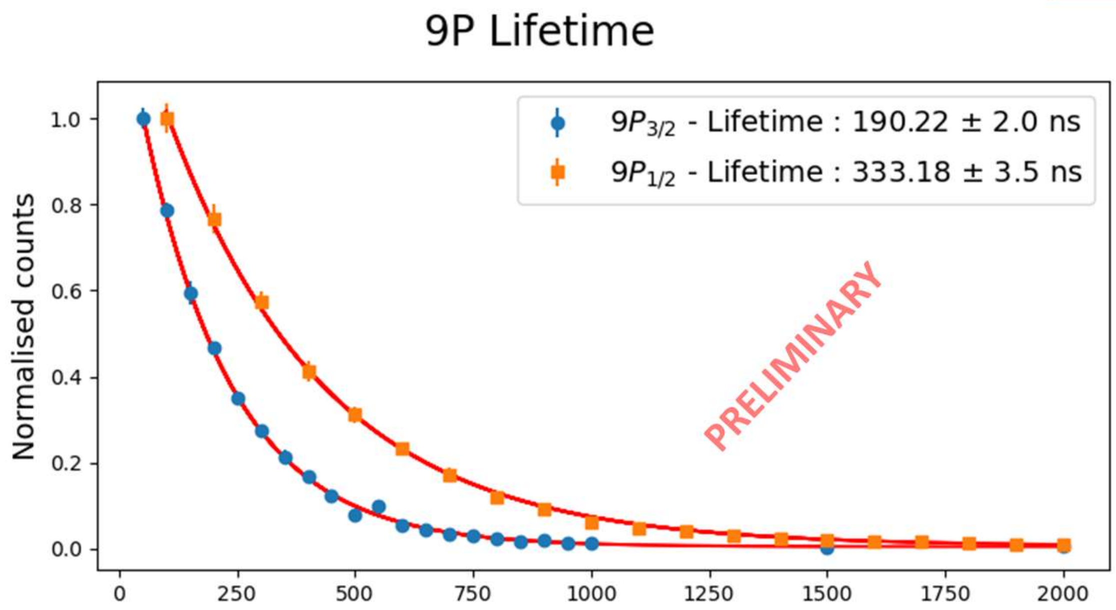
$$f(x) = Ae^{-B} + C$$

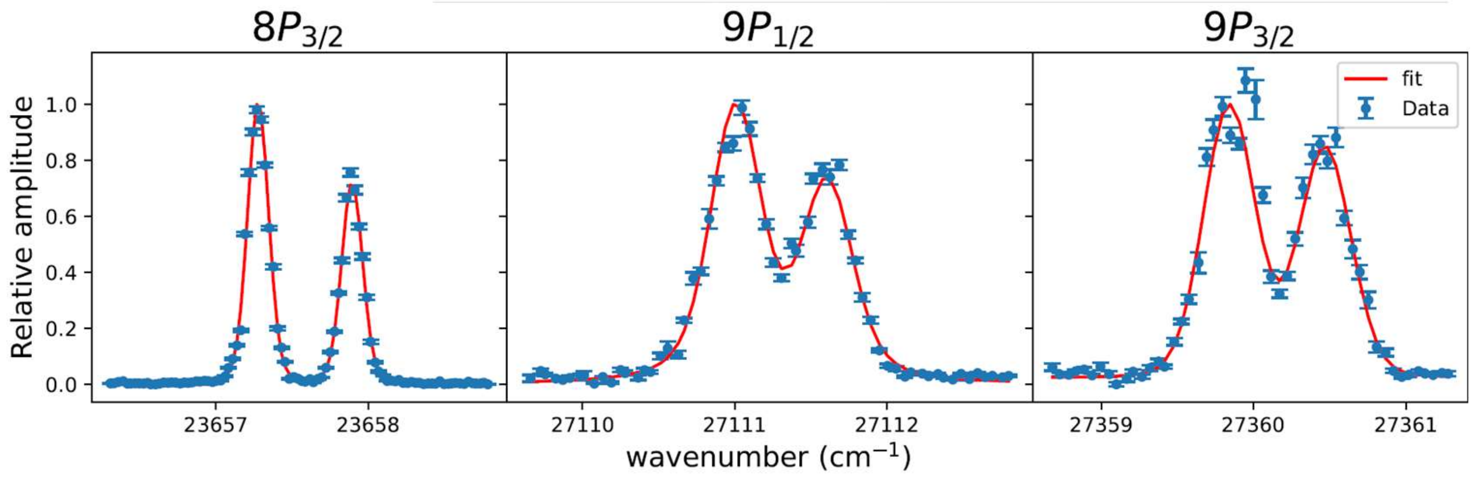
Scan	Lifetime measurement of 10P32
2695	Beamgate close (after 45min of lifetime measurement). Lasers off
2696	OPO on, trili off
2697	OPO off, trili on
2698	OPO off, trili off

Atomic studies in Fr :

High interest for theoretical model :

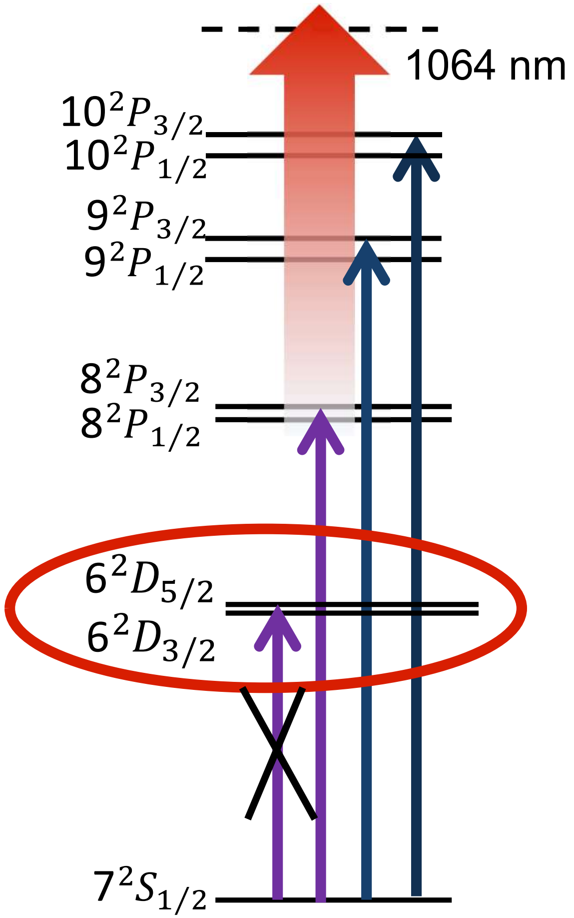
- Matrices elements used to constrain model to determine polarisability
- Publication in preparation with the collaboration of Theoretician team of B.K Sahoo





Main Objective

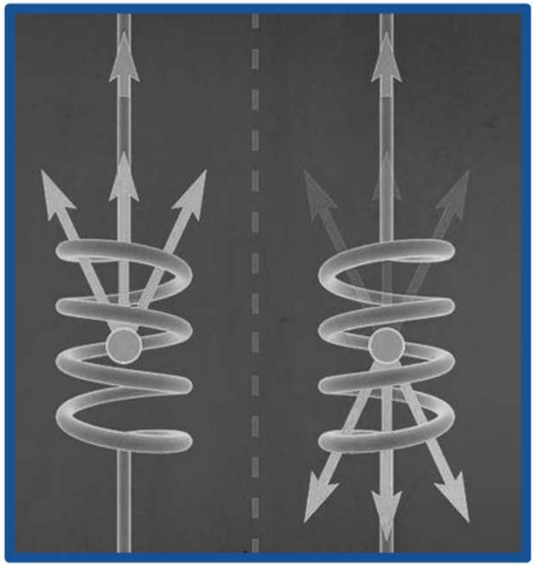
General motivation – Parity non-conservation



Towards the measurements of Parity non-conservation (PNC) in Fr

To date: Most accurate measurement performed on $6\ ^2S_{1/2} \rightarrow 7\ ^2S_{1/2}$ transition in Cs, relative uncertainty of 0.35 %.

Predicted PNC amplitude in the $7\ ^2S_{1/2} \rightarrow 6\ ^2D_{3/2,5/2}$ transitions in Fr: more than 50 times larger

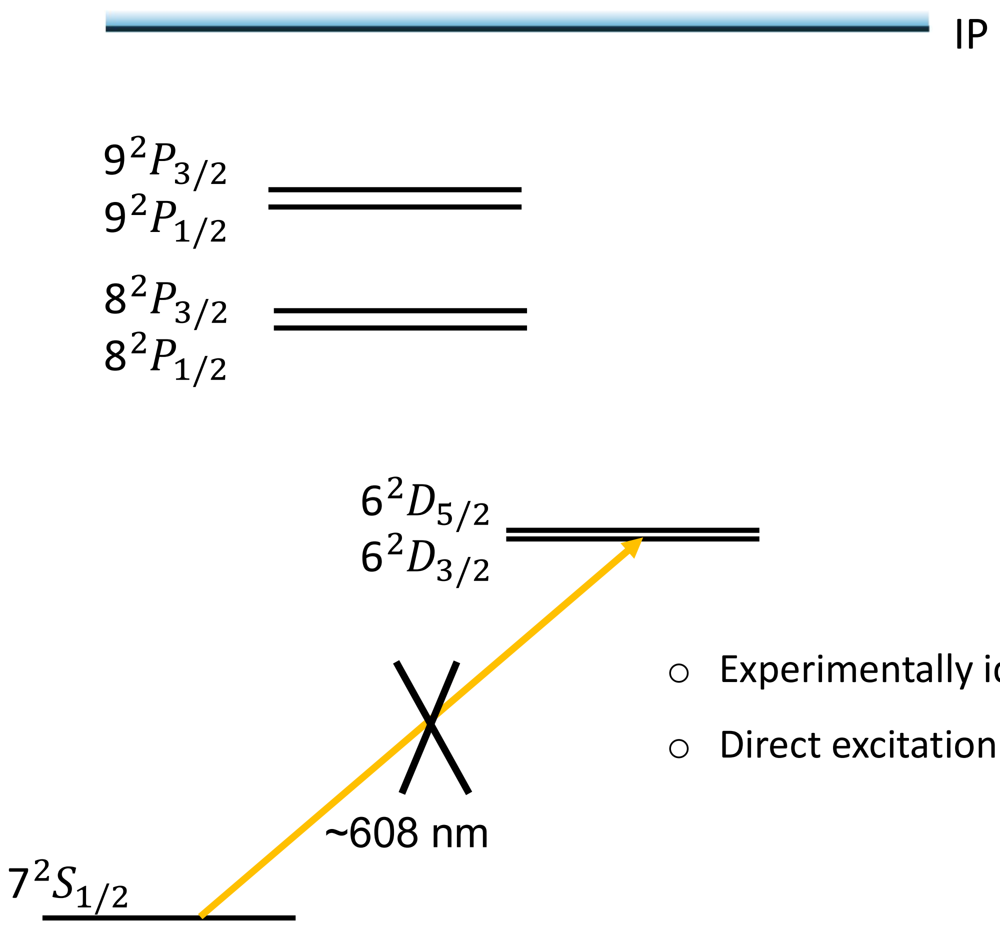


« Parity non-conservation » Artistic rendition of the Wu experiment - **Aleksandra Sokół**

[1] Wood, C. S., S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, et C. E. Wieman. « Measurement of Parity Nonconservation and an Anapole Moment in Cesium ». *Science* 275, nº 5307 (1997)

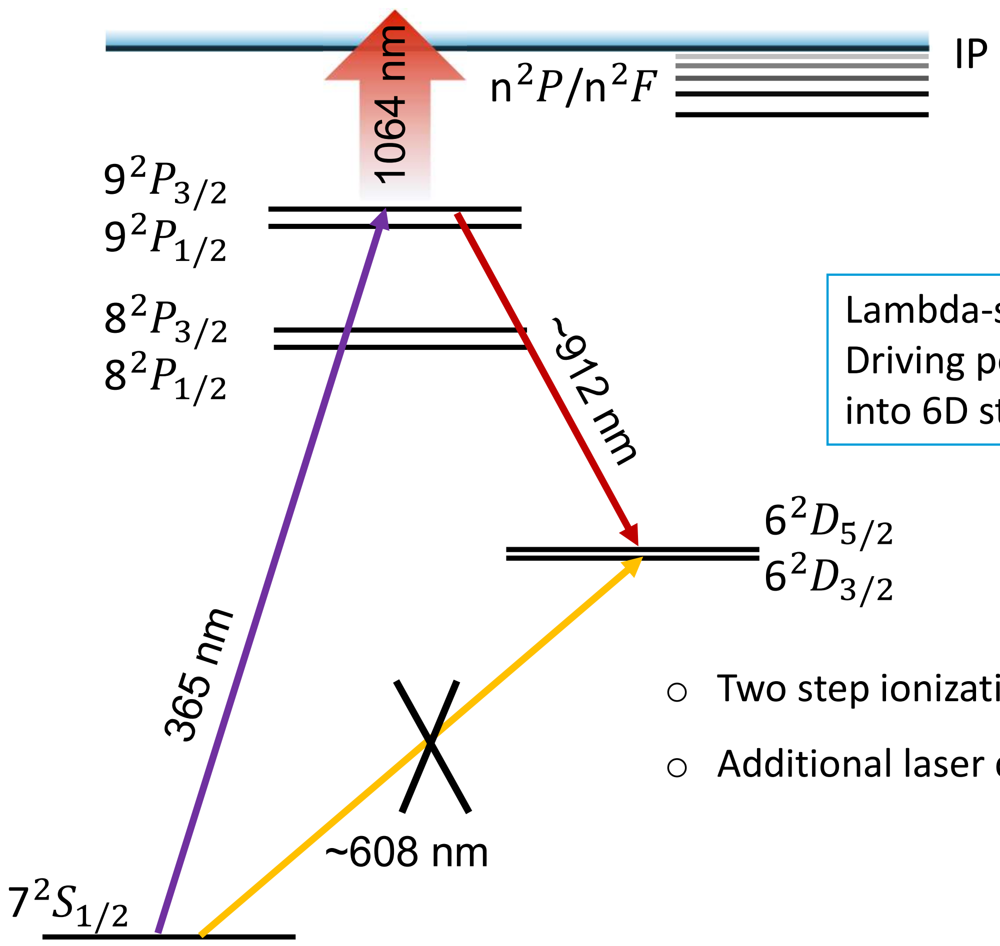
[2] Roberts, B. M., V. A. Dzuba, et V. V. Flambaum. « Parity nonconservation in Fr-like actinide and Cs-like rare-earth-metal ions ». *Phys. Rev. A* 88, nº 1

Atomic 6D-states in neutral Fr



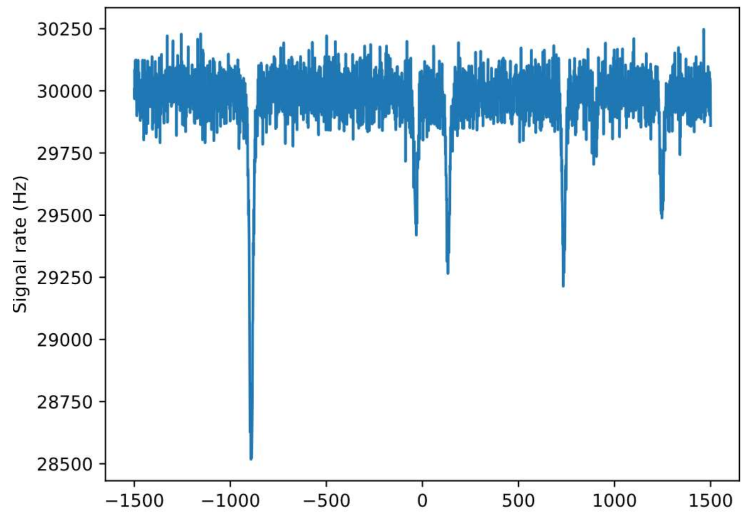
- Experimentally identifying the 6D levels
- Direct excitation forbidden → need different route

Atomic 6D-states in neutral Fr



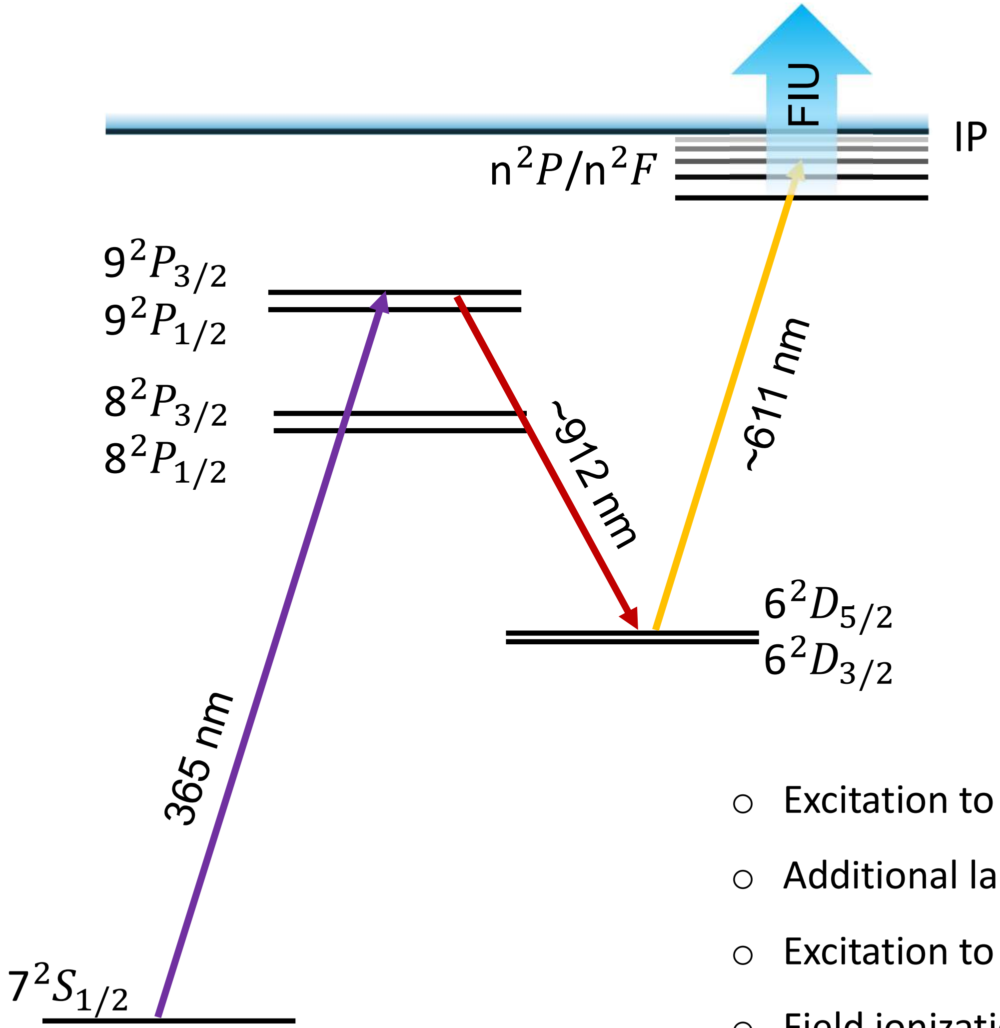
Lambda-scheme: Driving population into 6D states via 9P

Simulated spectra of the $8P_{1/2} \rightarrow 6D_{3/2}$ transitions



- Two step ionization scheme → detect laser ions
- Additional laser driving depopulation into the 6D state → dip in ion rate

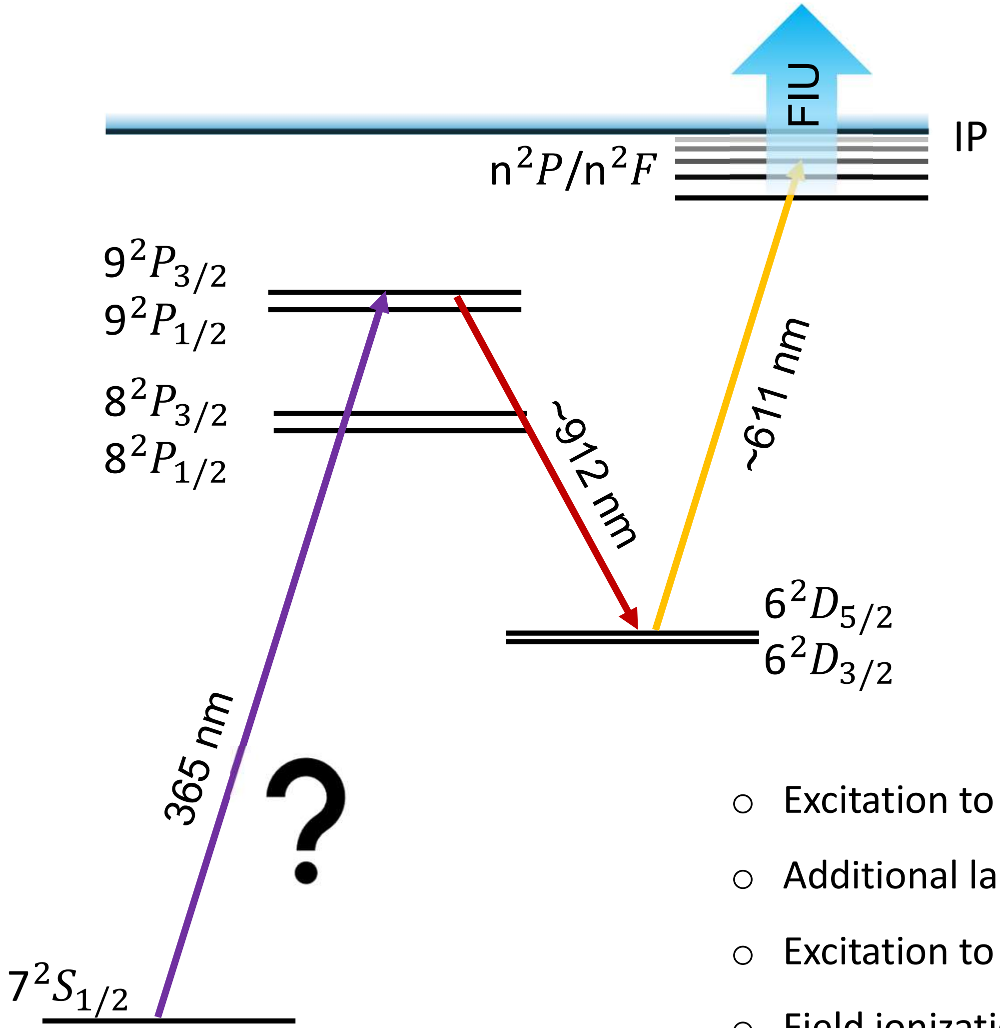
Atomic 6D-states in neutral Fr



N-scheme:
4 steps Ionization

- Excitation to 9P lvl
- Additional laser driving depopulation into the 6D state → dip in ion rate
- Excitation to Rydberg states (+plus bonus of characterizing Rydberg series)
- Field ionization = previous new developments necessary

Atomic 6D-states in neutral Fr



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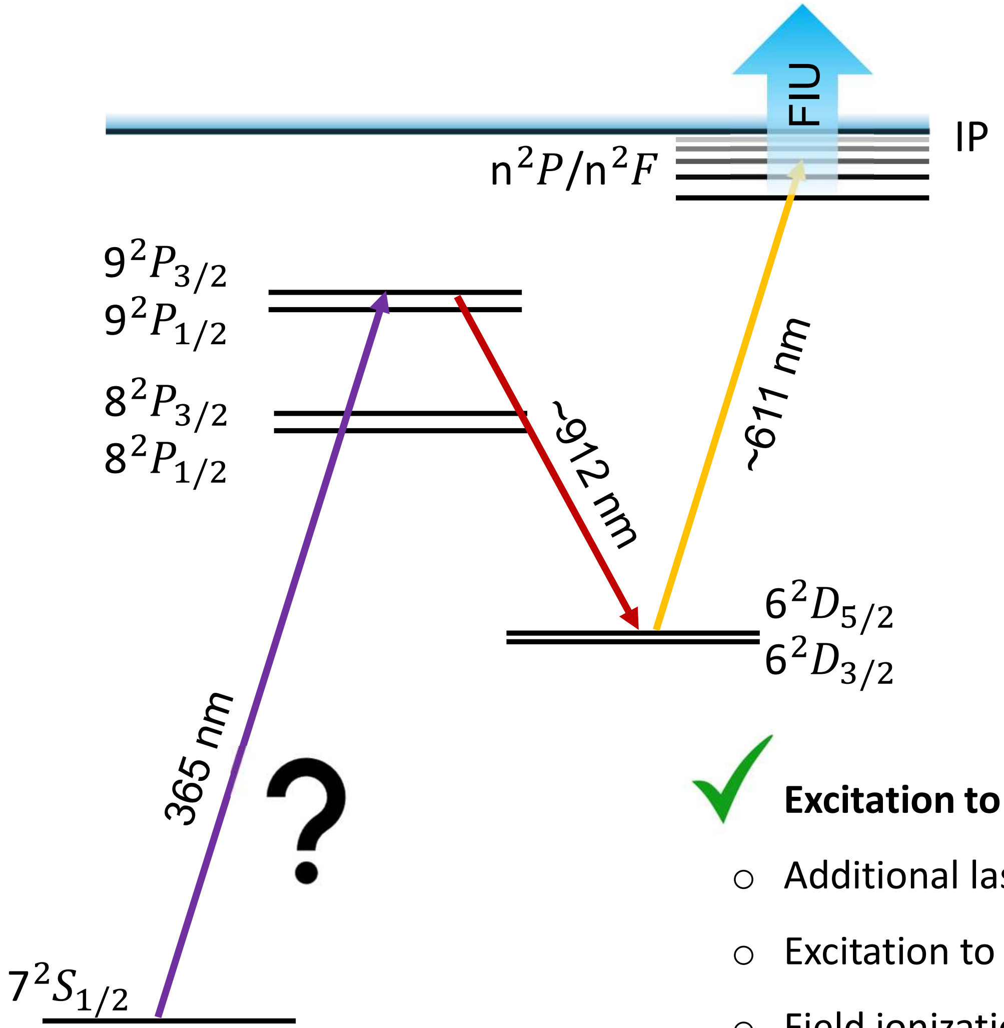

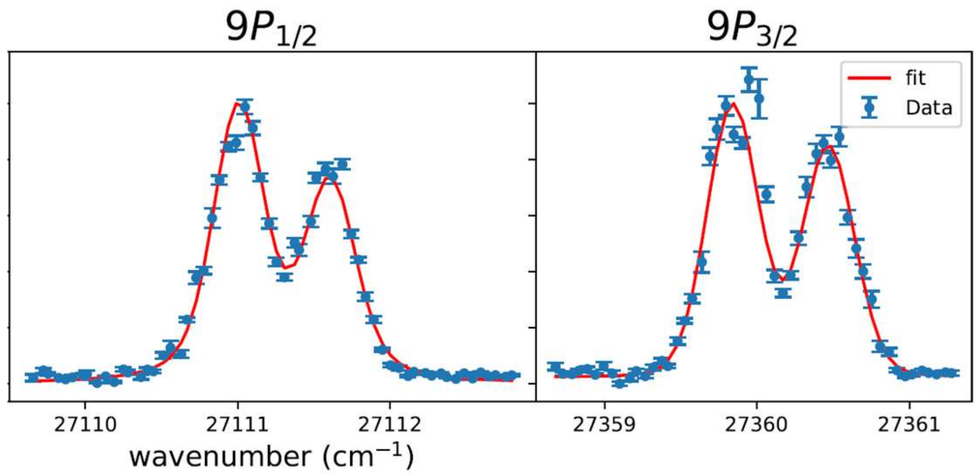

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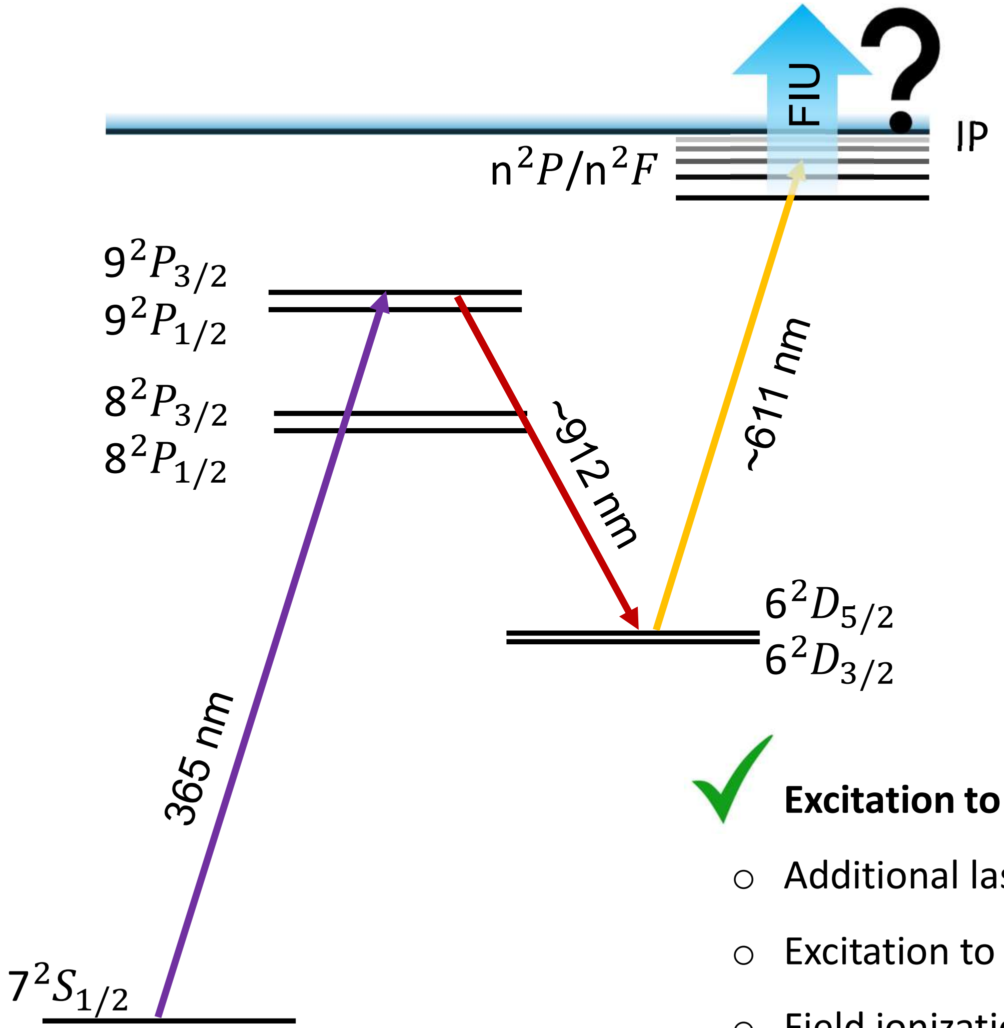

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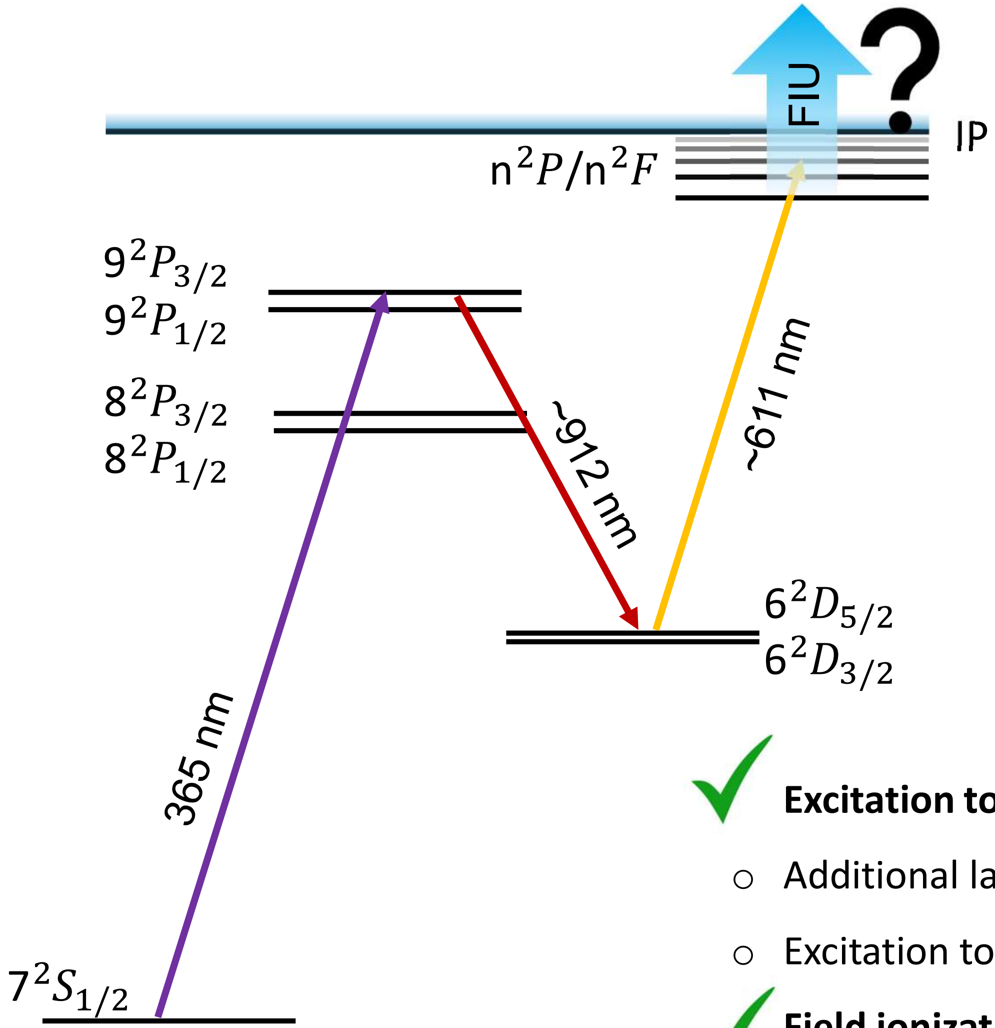
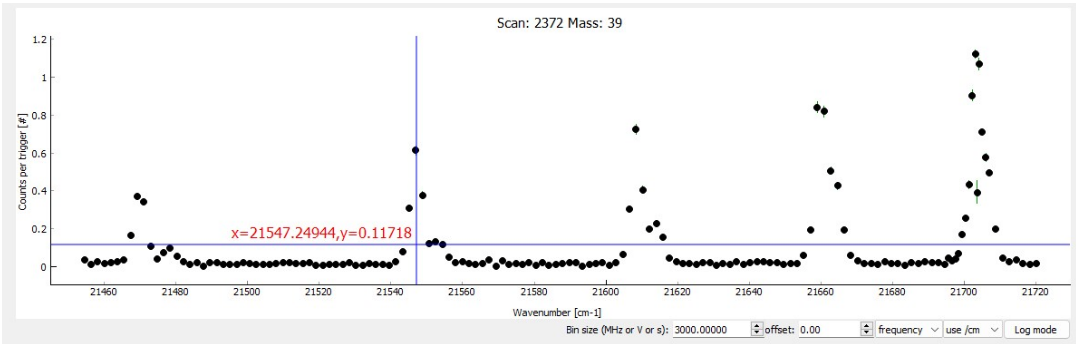
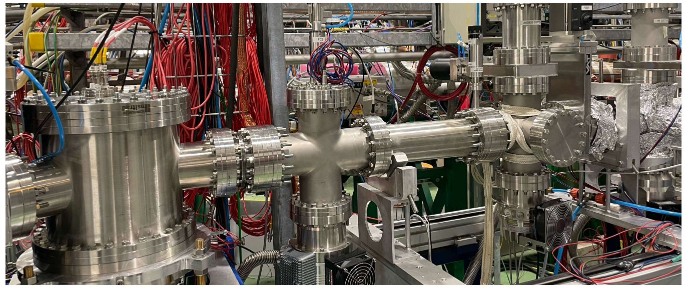
Atomic 6D-states in neutral Fr







✓ **Excitation to 9P lvl**

- Additional laser driving depopulation into the 6D state → dip in ion rate
- Excitation to Rydberg states (+plus bonus of characterizing Rydberg series)

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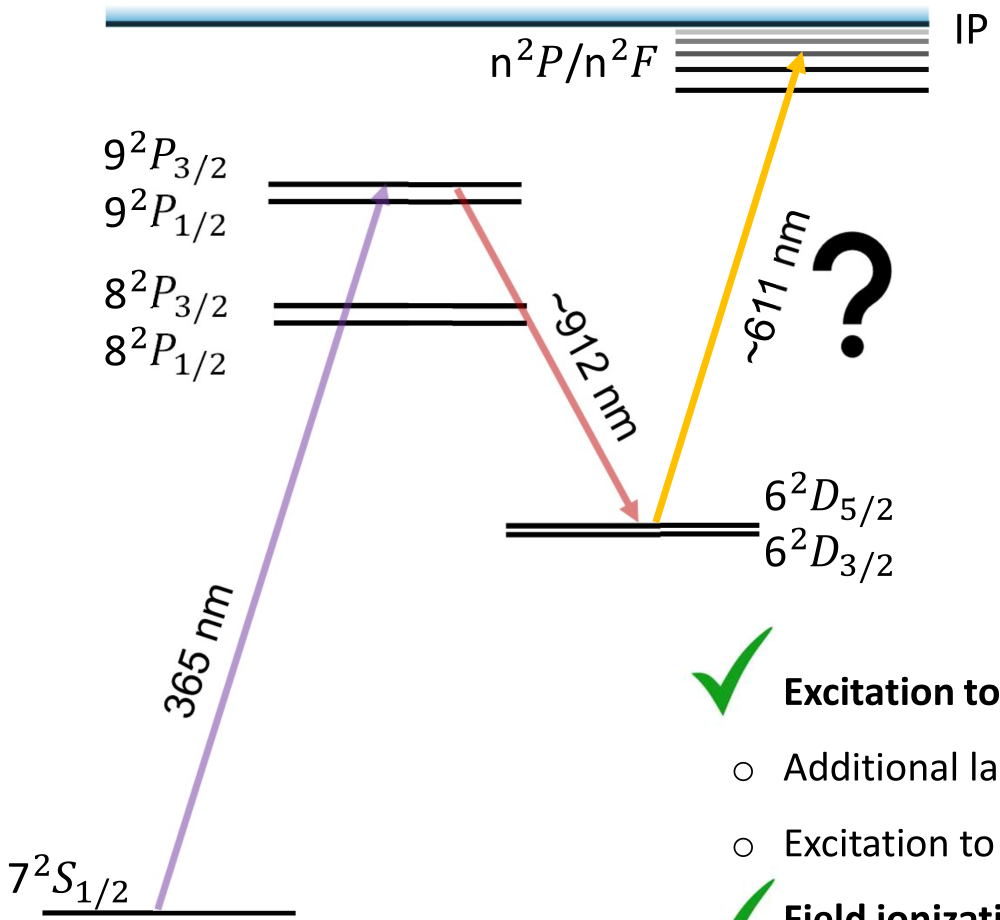

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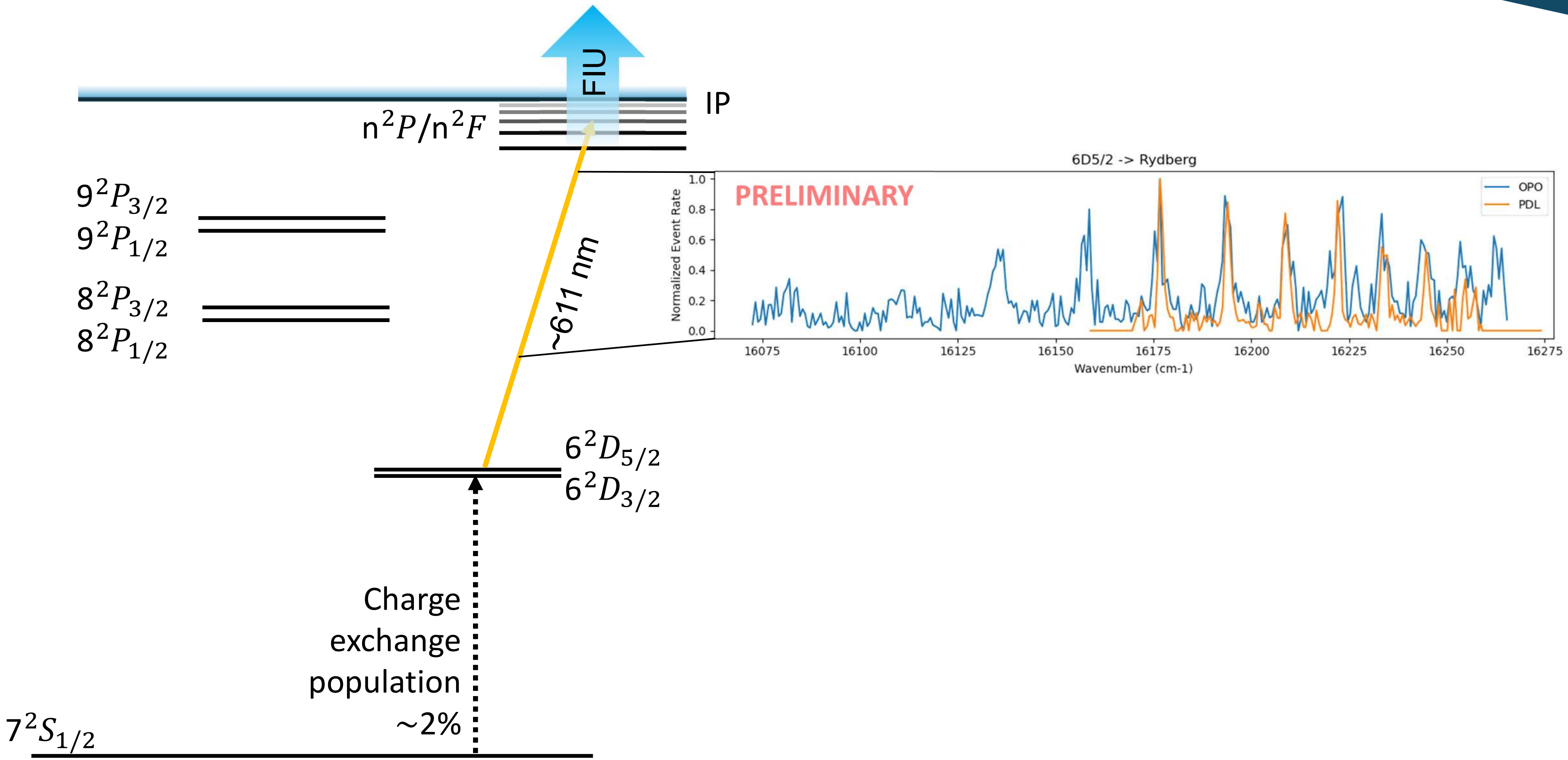

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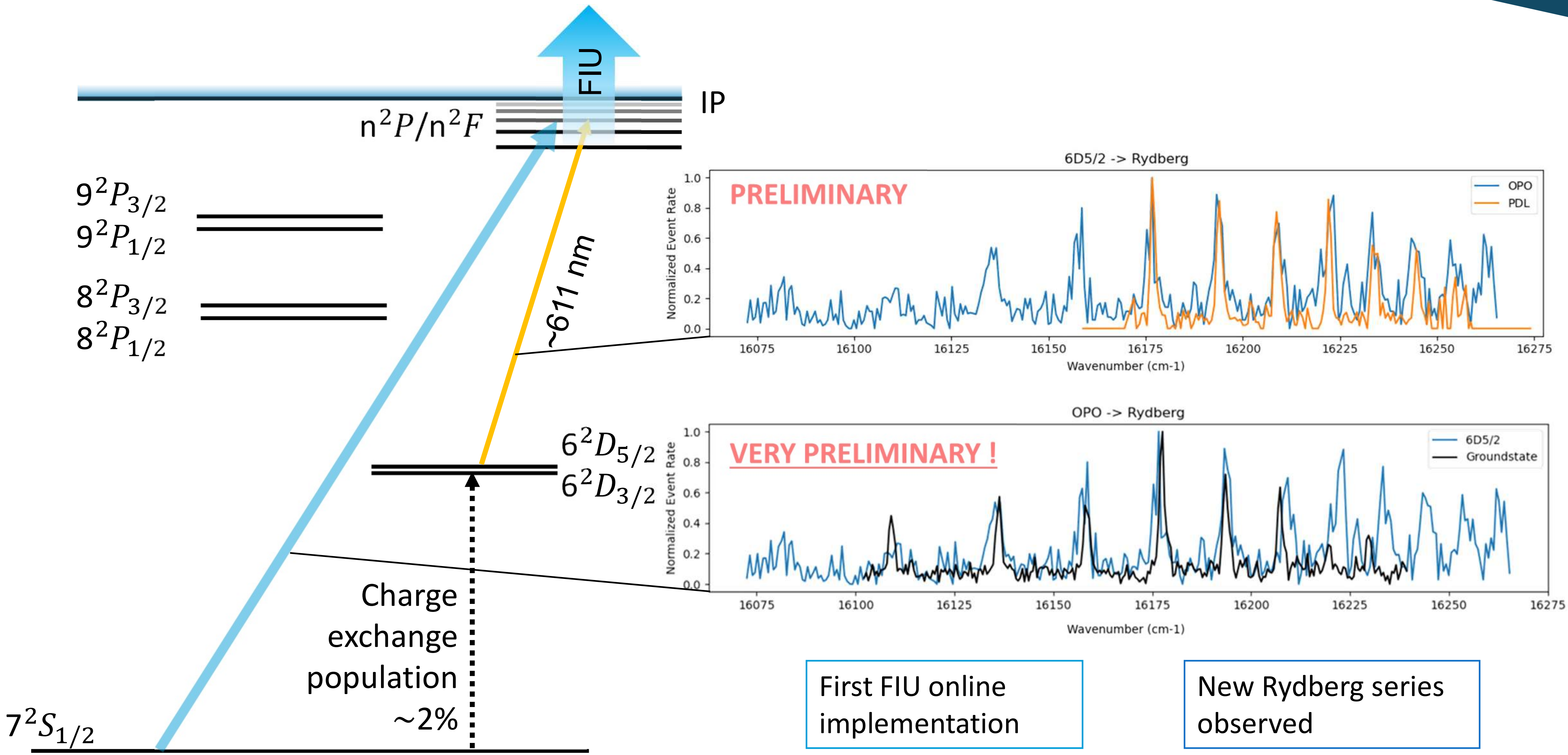
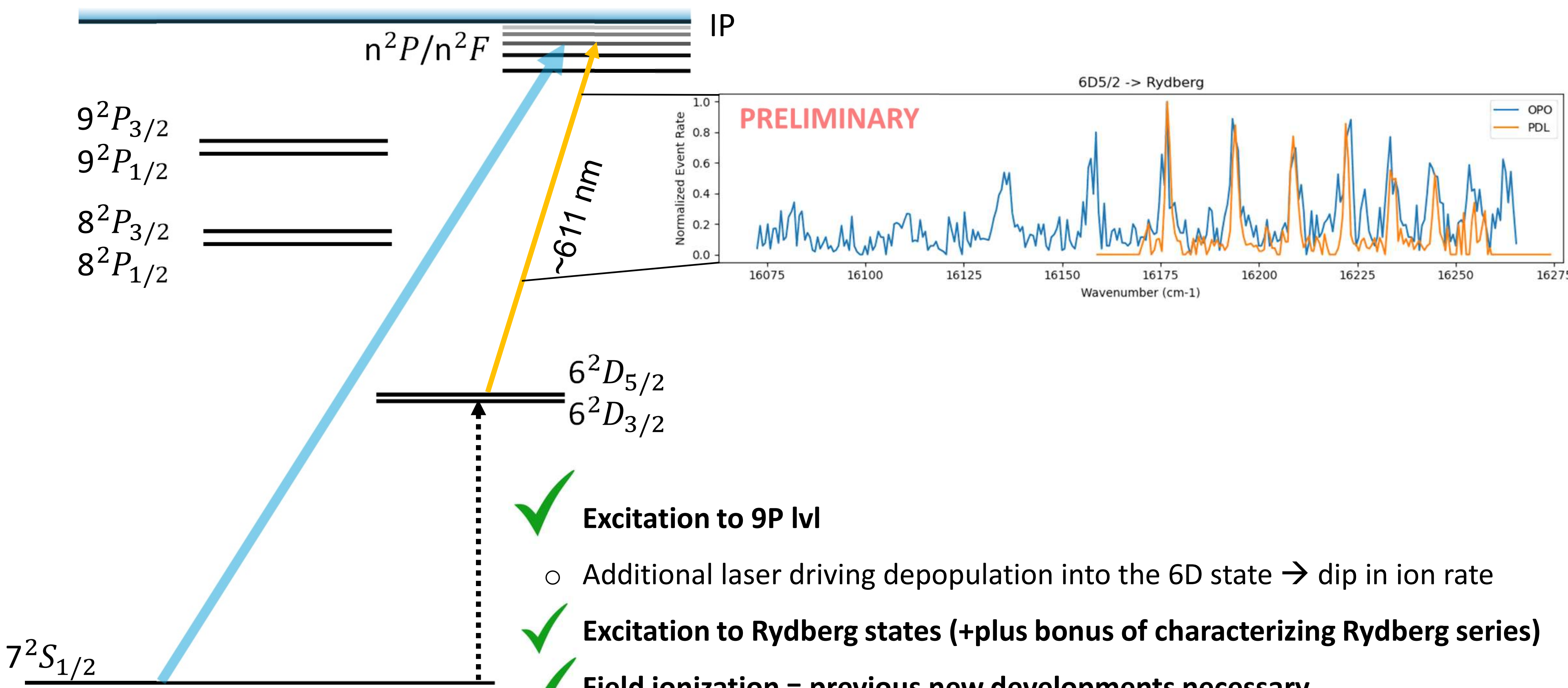


First FIU online implementation

New Rydberg series observed

Atomic 6D-states in neutral Fr



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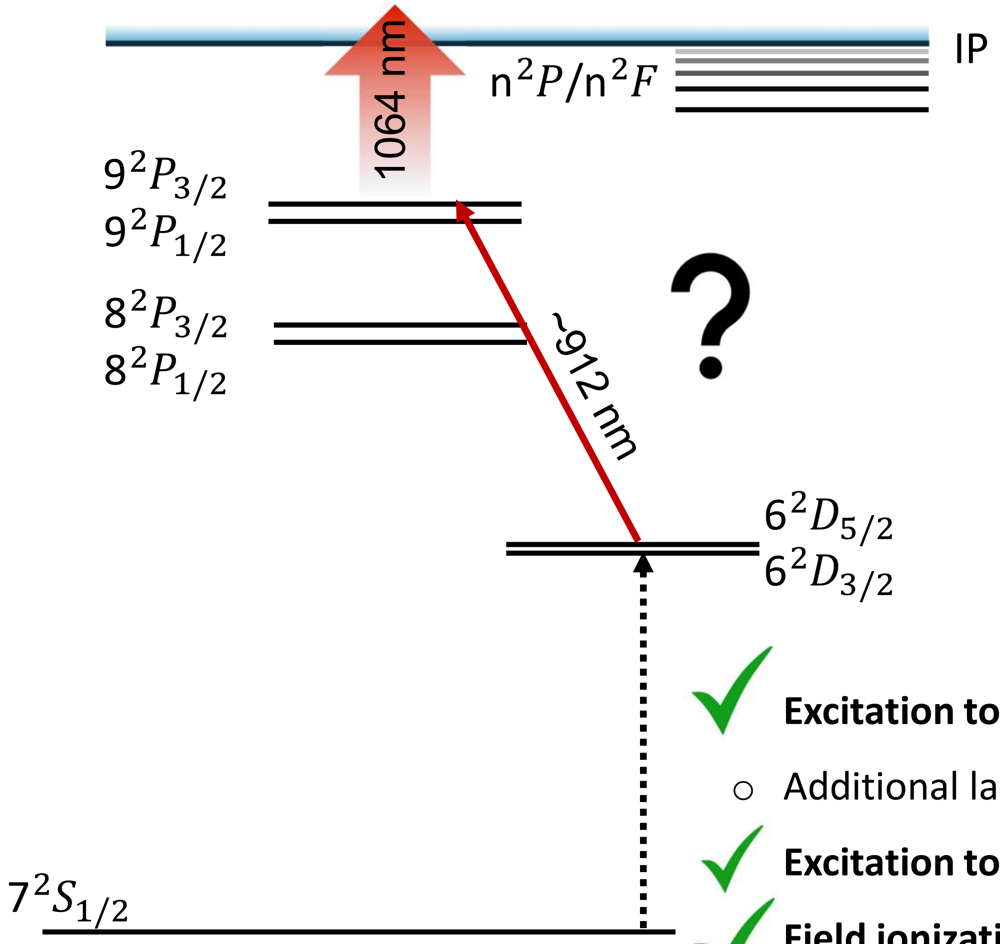
Lifetime measurements of $6D_{5/2}$



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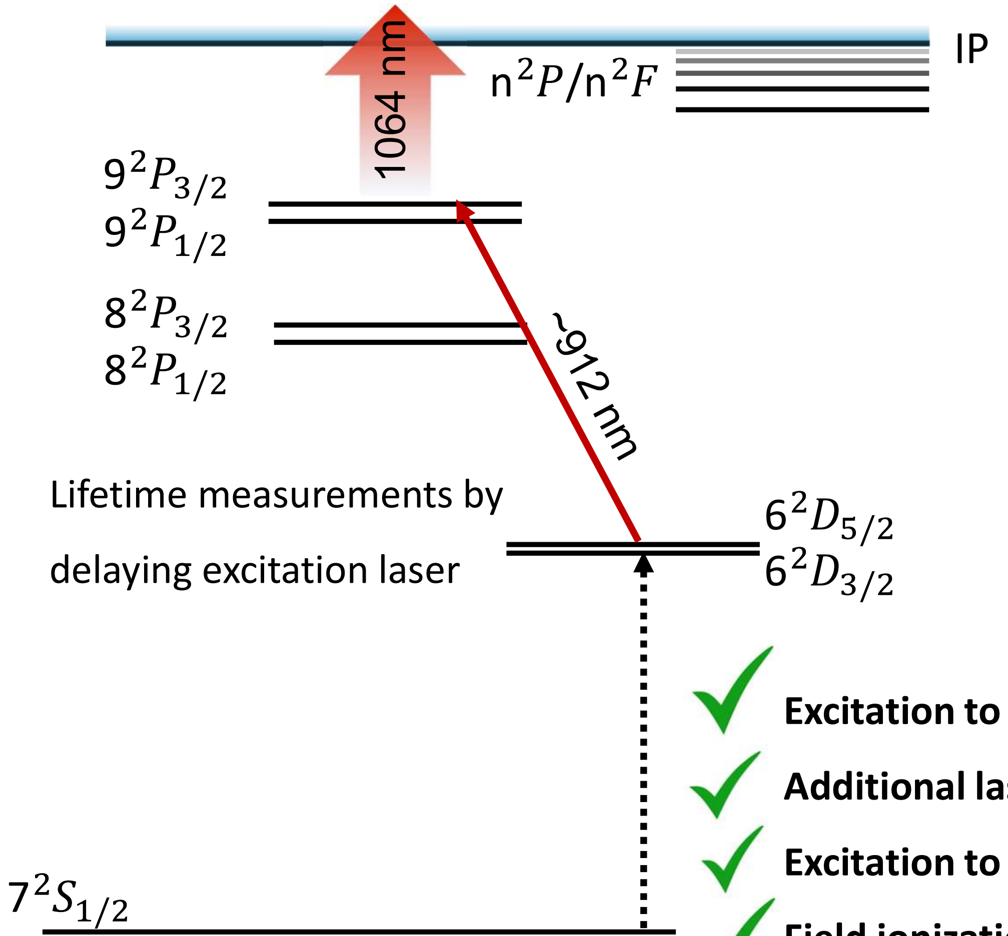
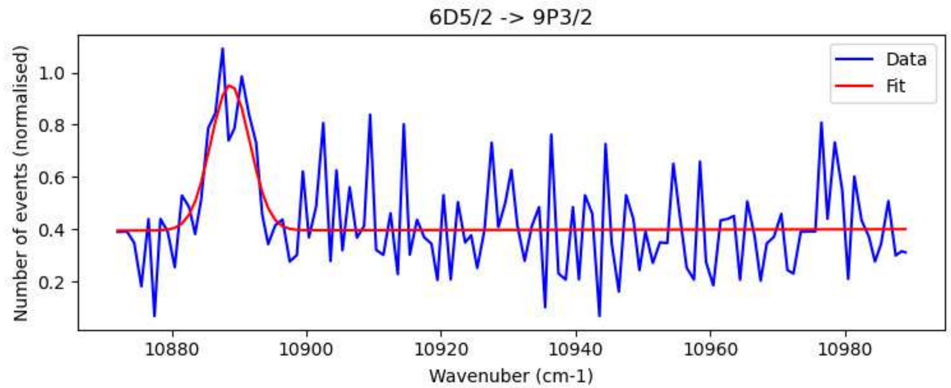


Lifetime measurements by delaying excitation laser



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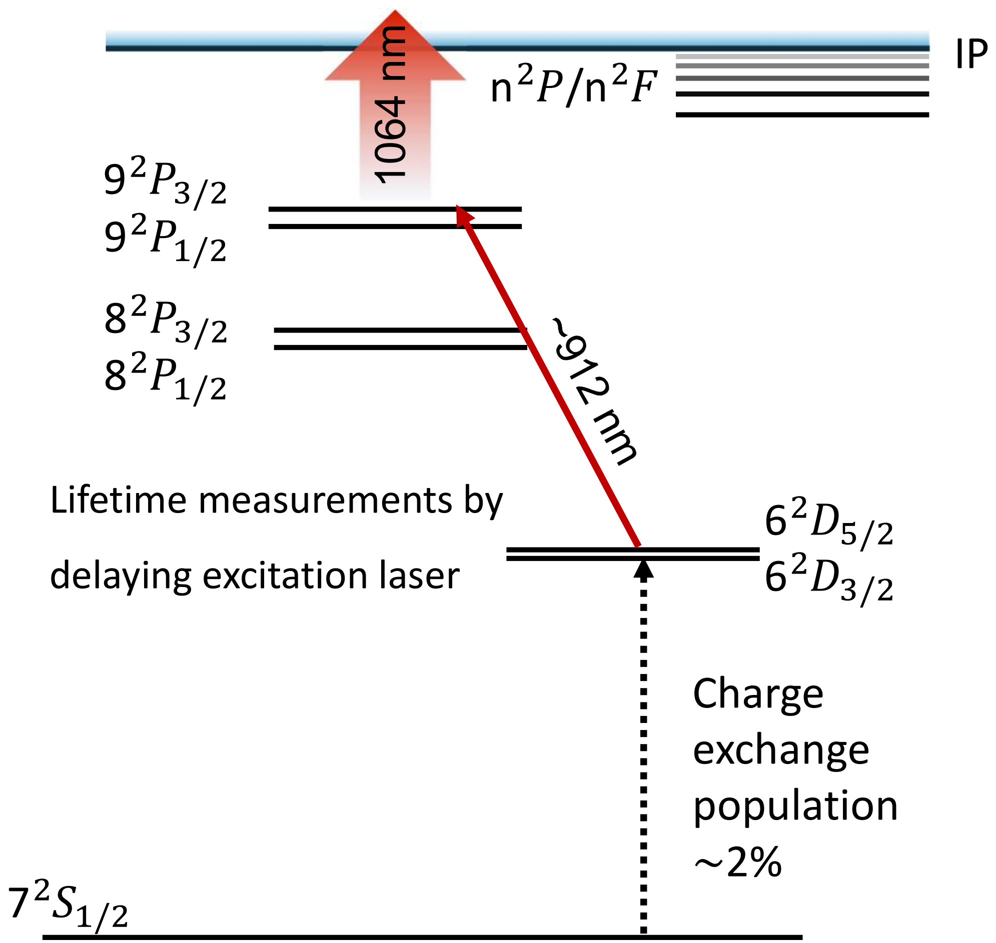
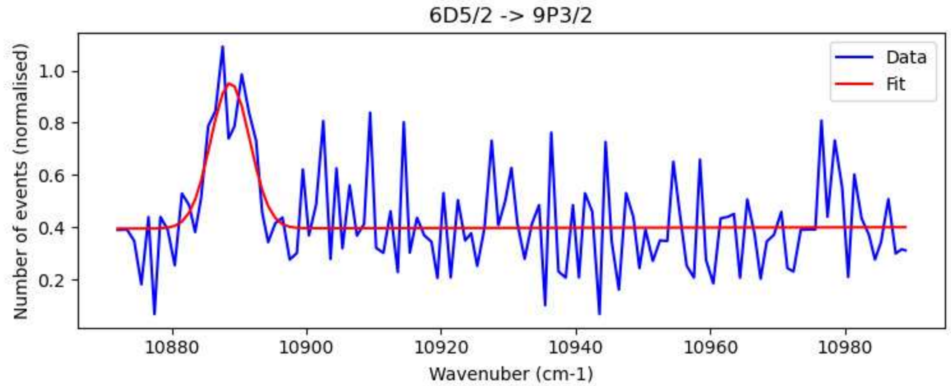
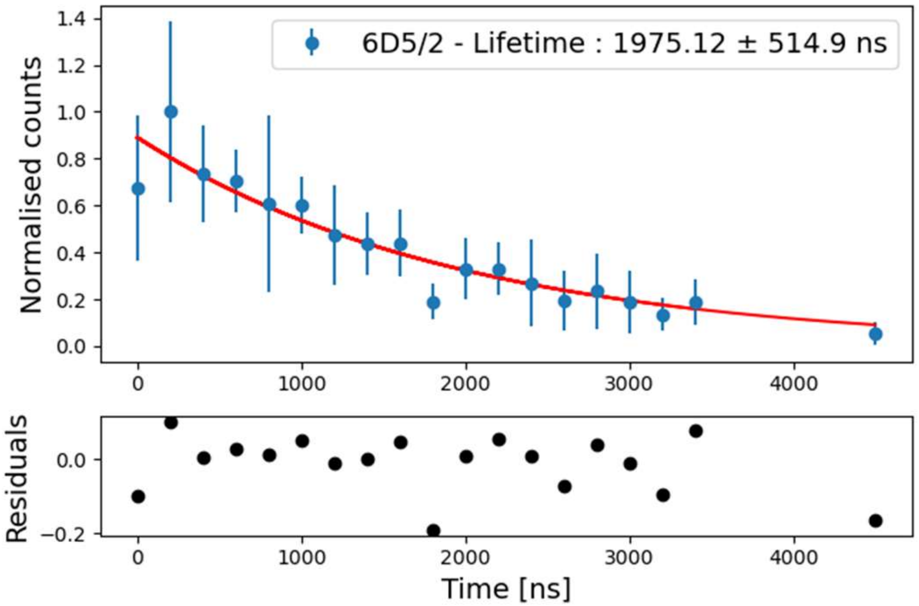
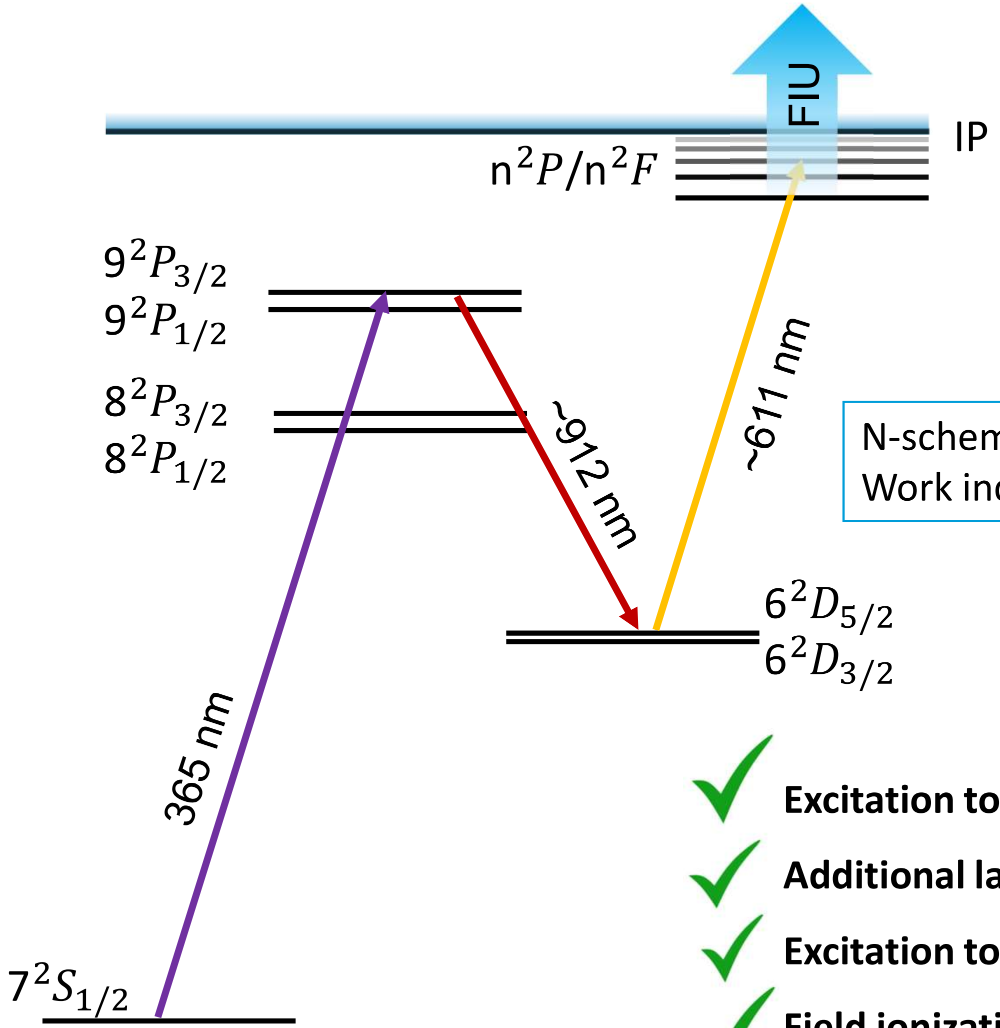






Atomic 6D-states in neutral Fr



N-scheme:
Work indirectly !

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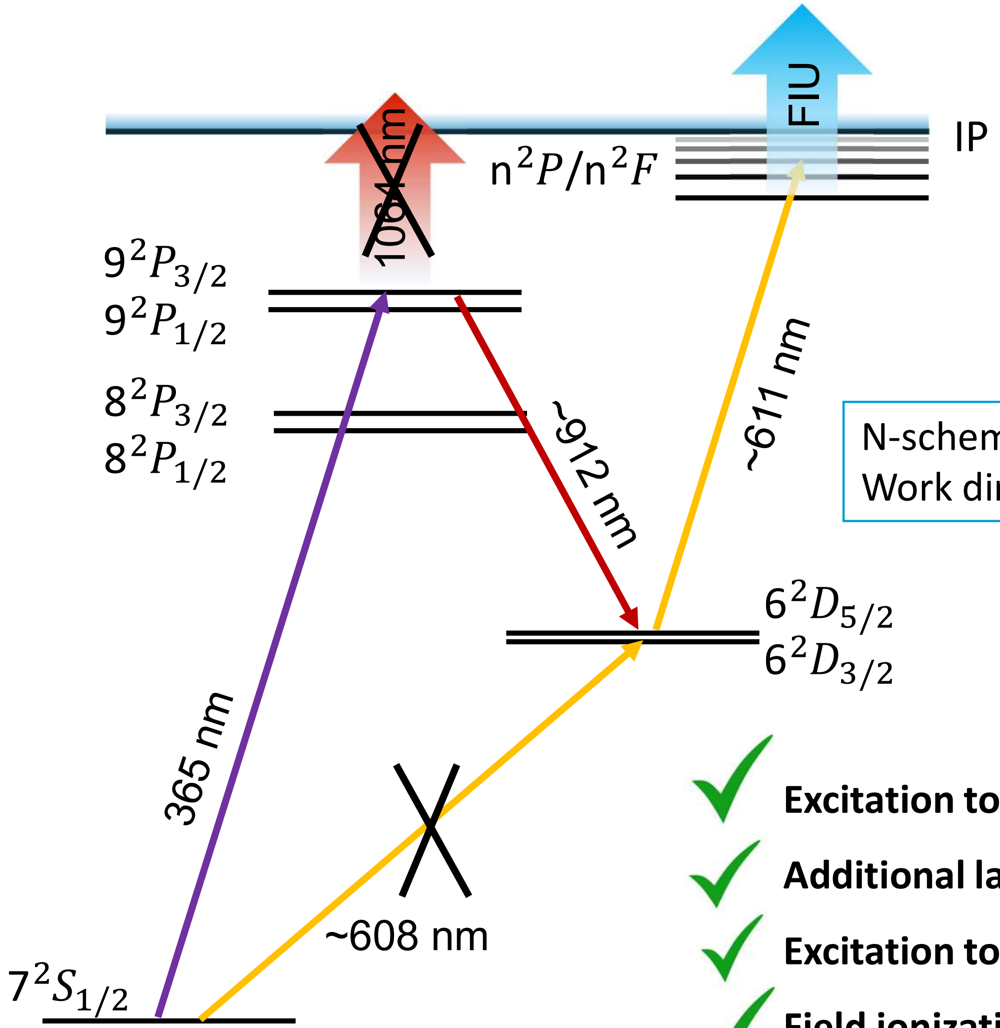
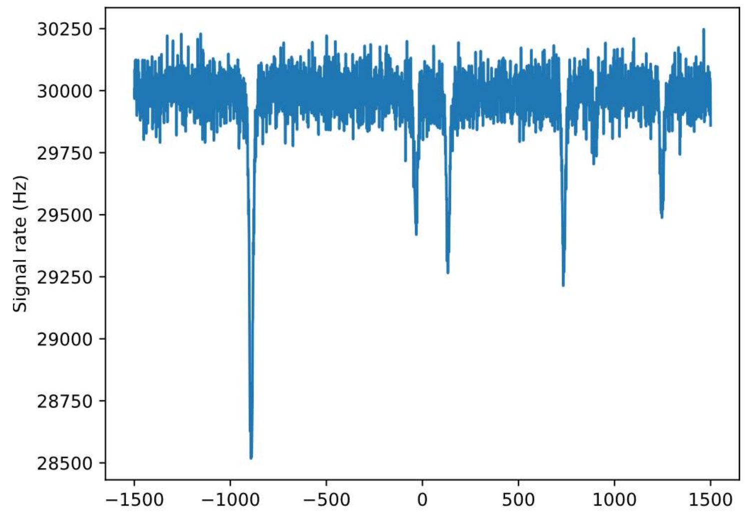


N-scheme:
Work directly ?

Simulated spectra of the $8P_{1/2} \rightarrow 6D_{3/2}$ transitions



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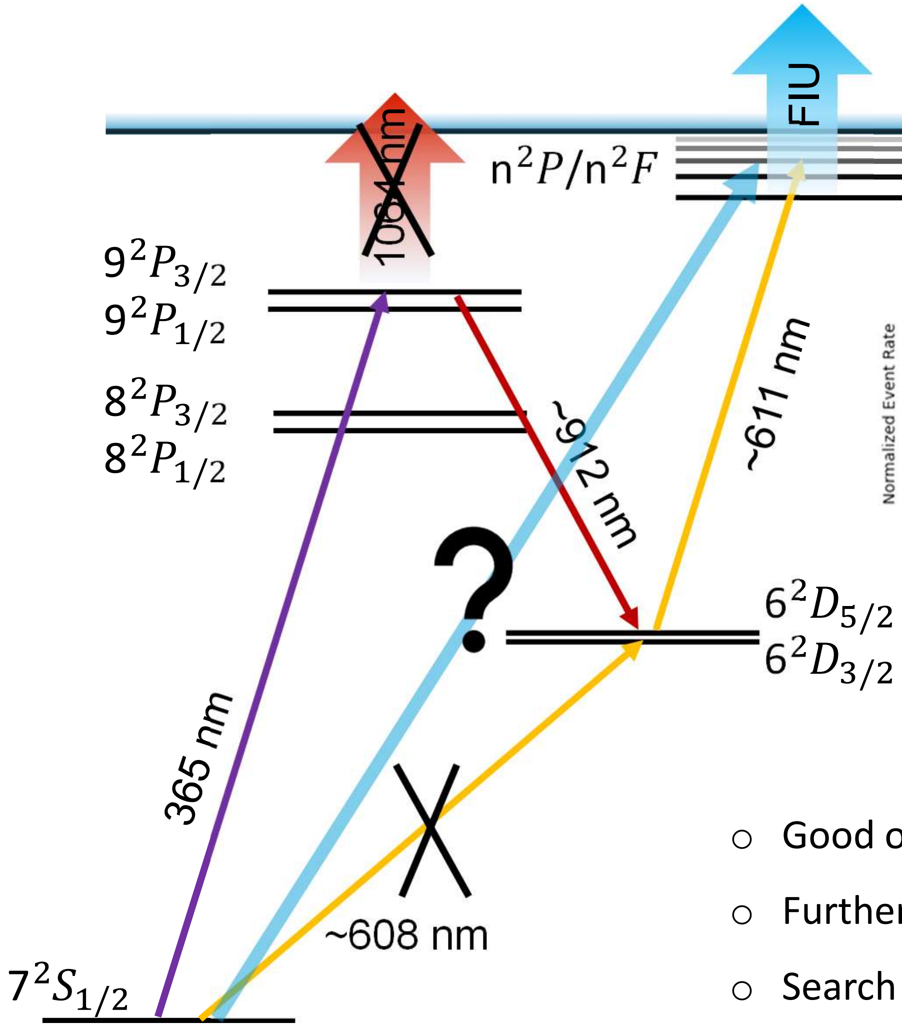
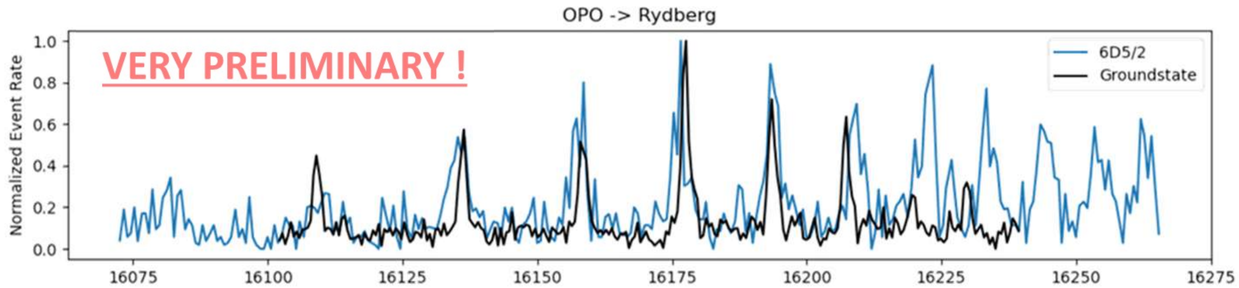
More Atomic measurements in neutral Fr !



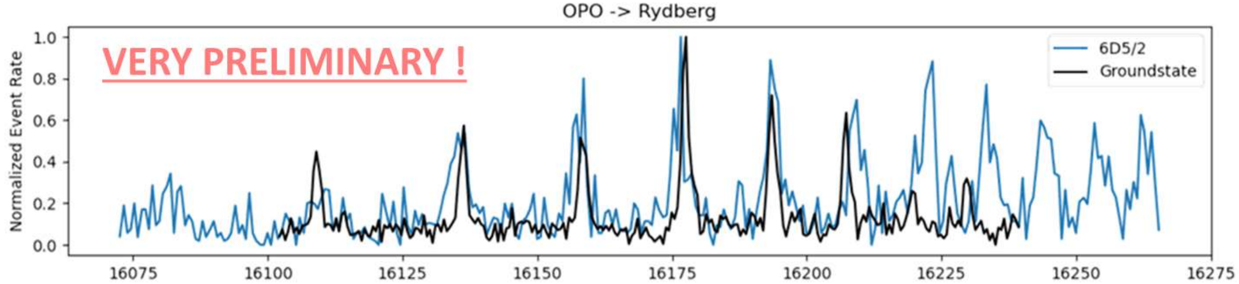


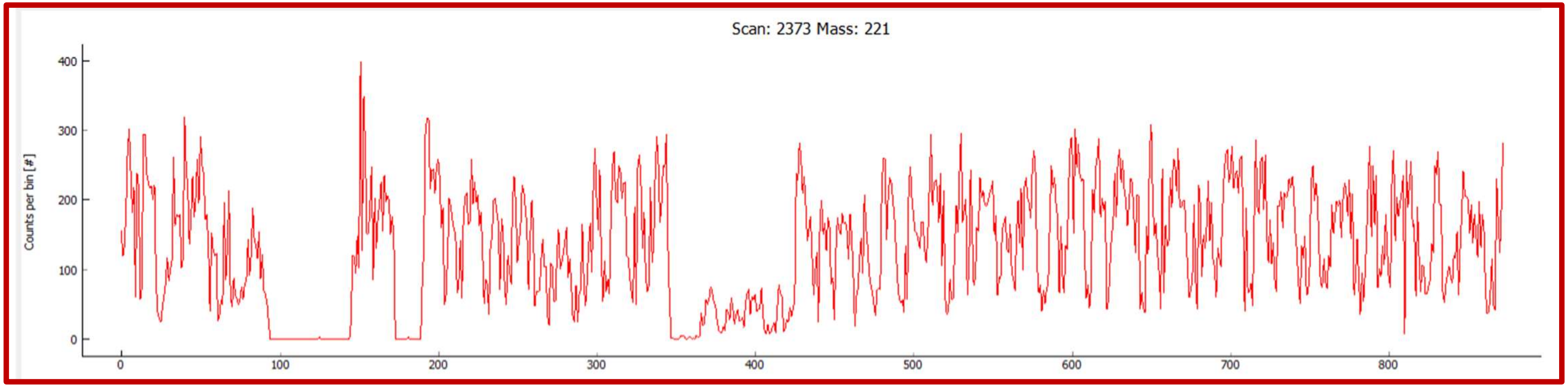
- Good opportunity to Scan all P serie to IP
- Further tests on λ and N Scheme
- Search for D level Fine and Hyperfine structure

More Atomic measurements in neutral Fr !

Fluctuations of the Beam:

- Unable to do High precision Spectroscopy
- At least 2 shifts losts
- Same problem during Antimony ? And Gold ?

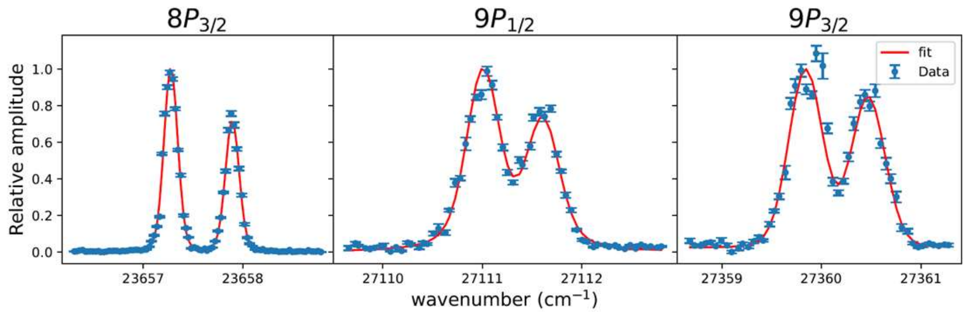


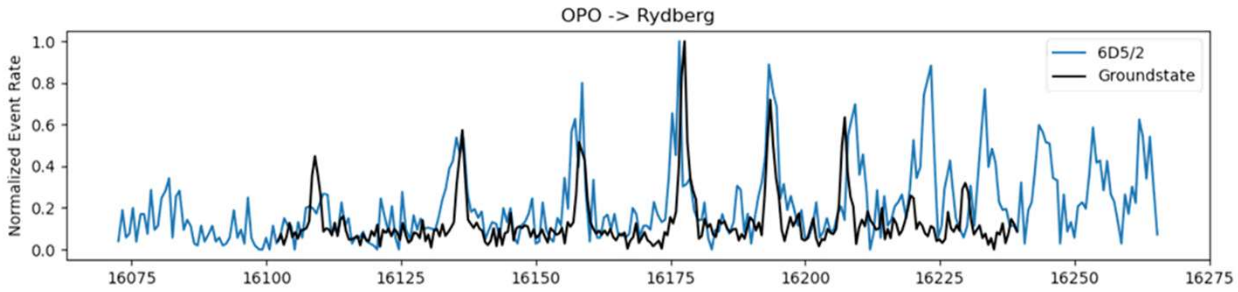


Conclusion

Atomic studies in 221 Francium :

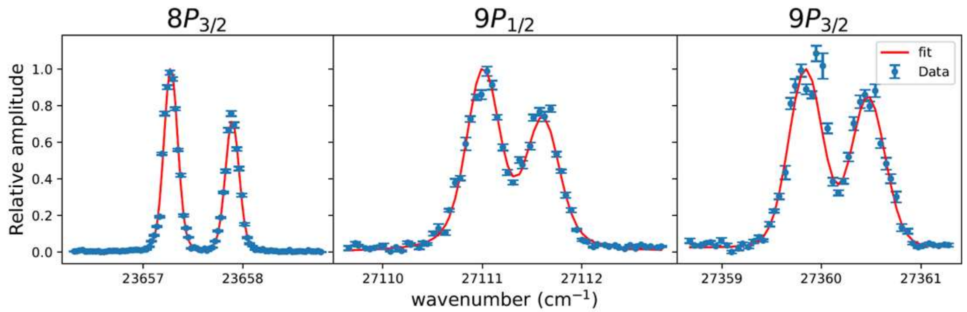
- New **atomic levels** identified in Fr
- **Lifetime** measurements performed for excited *P*-states
- Identified **6D state** (broadband)
- New **Rydberg series** observed

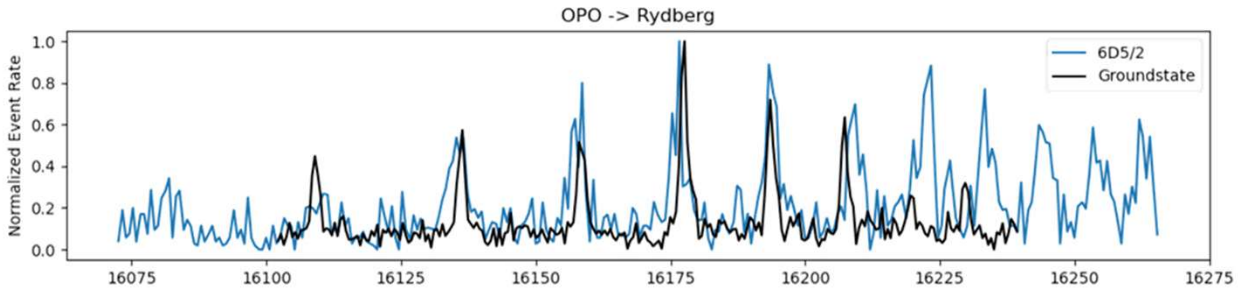




Outlook

- More measurements to be done on 6Ds
- Scan Rydberg series further for unambiguous identification
- More precise lifetime measurements
- Ionization potential
- Hyperfine structure of 6Ds





With 6D identification: first stepping stone towards high-precision studies

Acknowledgments

CRIS collaboration

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sck cen

IPHC
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STRASBOURG