Observation of highly forbidden M1 transition in 7s-8s transition in francium.

Anima Sharma,
University of Manitoba.

WNPPC 2024.

Why are we doing this?

1

❖ To understand the basic building blocks of matter.

❖ Do we understand all fundamental forces?

- Gravity
- Electromagnetism
- Weak interaction
- Strong interaction

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❖ Do we understand all fundamental symmetries?

❖ Parity Conservation in Weak Interaction [1]?

$$^{60}_{27}\mathrm{Co} \rightarrow \, ^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\upsilon}$$

Parity symmetry

$$\mathbf{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}.$$

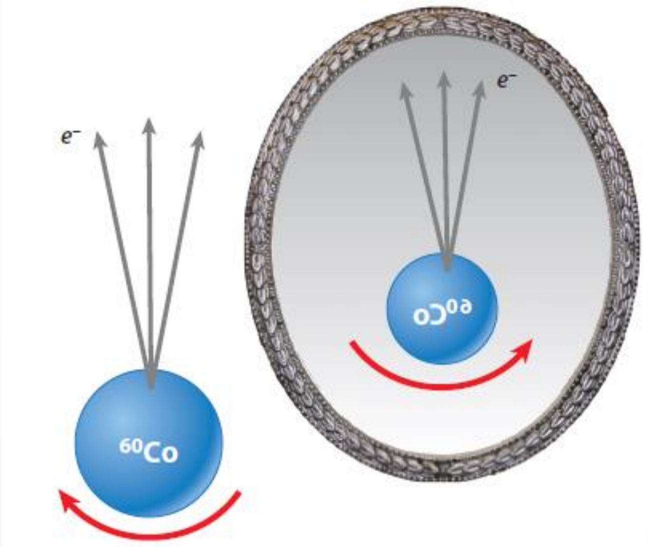

Fig.[ref. 2] Distribution of electrons in the β decay of polarized $^{60}_{27}\mathrm{Co}$ nuclei in C.S. Wu et. al [1].

[1] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. **105**, 1413.
[2] B.M. Roberts, V.A. Dzuba, and V.V. Flambaum, Annu. Rev. Nucl. Part. Sci., 63–86 ,2015.

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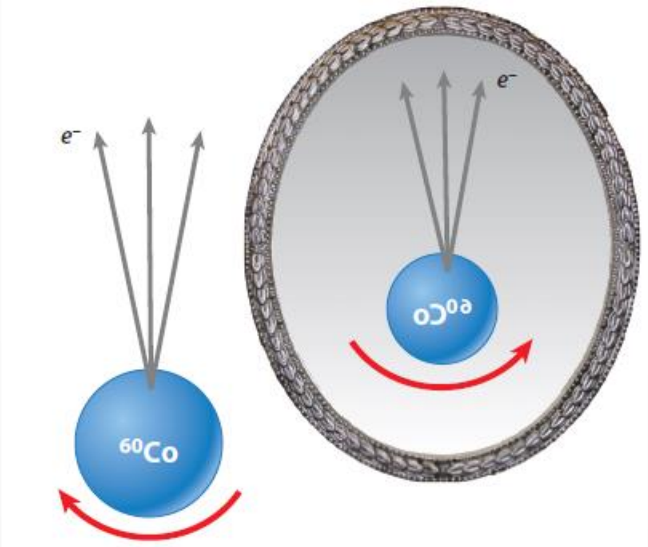

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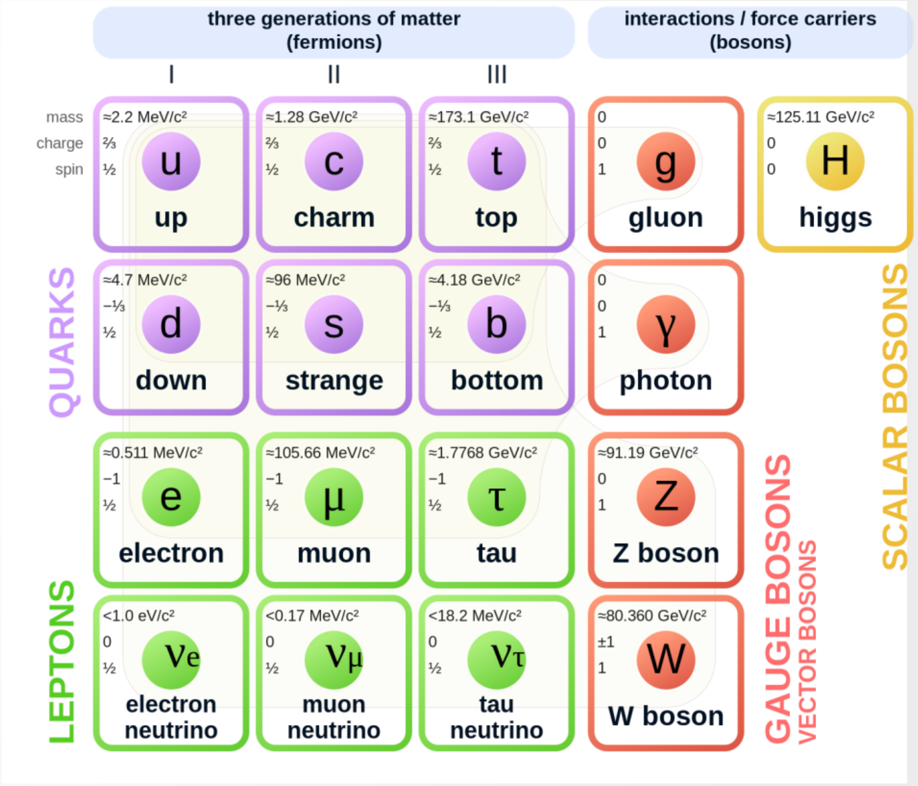
❖ Key to solve the question?

Standard Model of Elementary Particles



Pic. courtesy to Wikipedia.

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Exploring the mediators & physics of weak interaction

- ❖ Weak interaction is not involved directly in atomic processes 👀

⟶ the unified theory of electromagnetic EM (γ) and weak interaction WI (Z^0, $W^\pm$).

Unique signature of weak interaction – parity violation (PV).

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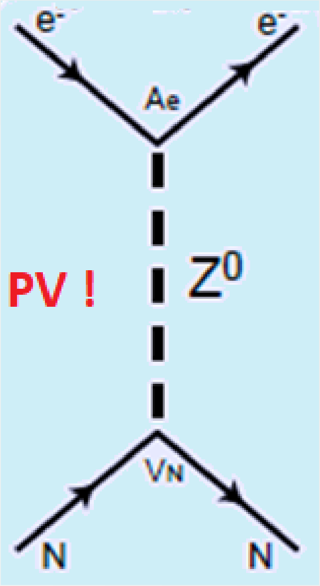
- ❖ Parity violating effect in atoms $\rightarrow$ caused by an interference between EM (γ) and weak amplitudes (heavy intermediate Z^0boson).

Atomic parity violation (APV) arises with PV exchange of Z^0 bosons between atomic electrons and quarks inside the nucleus.

- ❖ Experimentally $\longrightarrow$ APV effect in γ induced transitions between atomic states
$\longrightarrow$ interference of EM and PV transition amplitudes.



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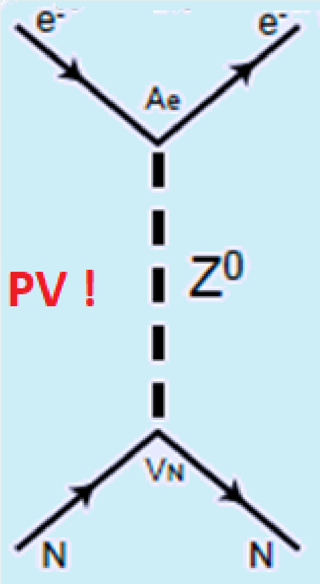


Weak interaction

- Experimentally ⟶ APV effect in γ induced transitions between atomic states
  ⟶ interference of EM and PV transition amplitudes.

- H_{PV} mixes opposite parity atomic states

$|S>_{real} = |S>_{EM} + \delta_{PV}\,|P>_{EM}$,

$<n'S|H_{PV}|nP> \propto Z^3$.

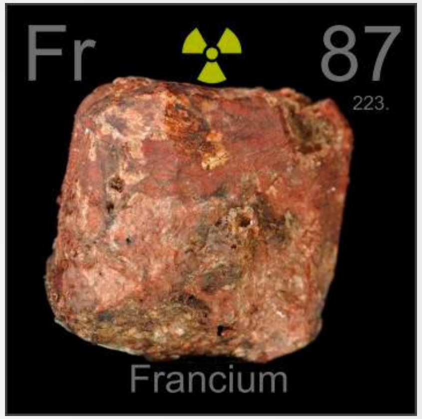
An ideal candidate for APV: Francium

- Z = 87, a heavy nuclei

$$\frac{\delta_{PV}(\mathrm{Fr})}{\delta_{PV}(\mathrm{Cs})} \approx 18$$

Cesium (Z = 55)
Best measurement done so far with 0.35 % accuracy.

Heaviest alkali with simple structure,
Theory calculations can be reliably extracted,
Different isotopes available.



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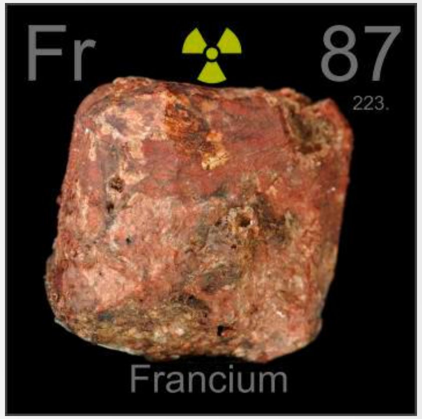

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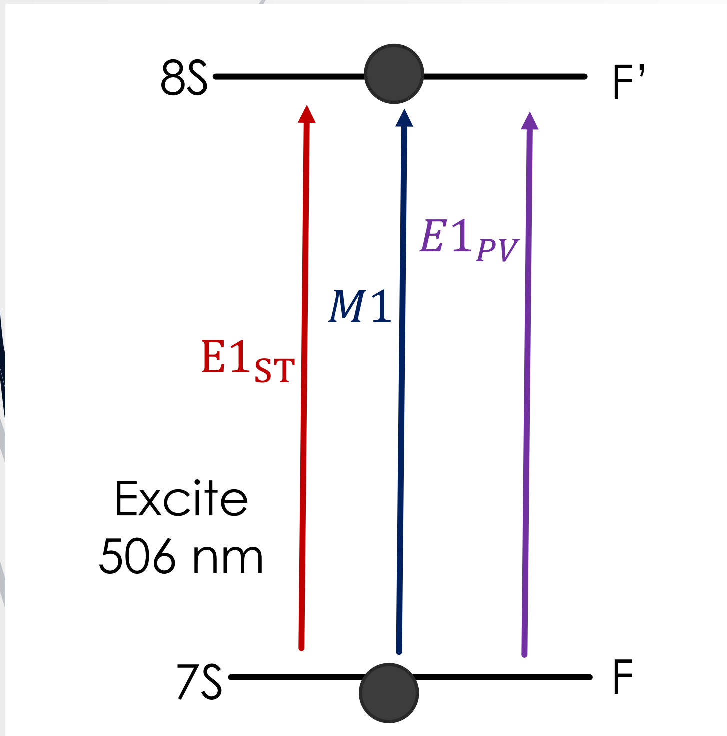

Francium (211)

- ❖ Transition rate, $R_{7S \rightarrow 8S}$

$$R_{7S\rightarrow 8S} \propto |\, E1_{ST} + M1 + E1_{PV}\, |^2$$

$f_{ST} \sim 10^{-10}$,

$f_{M1} \sim 10^{-13}$,

$f_{PV} \sim 10^{-21}$.

Interference signal of $f_{ST} . f_{PV} \approx 16.5$

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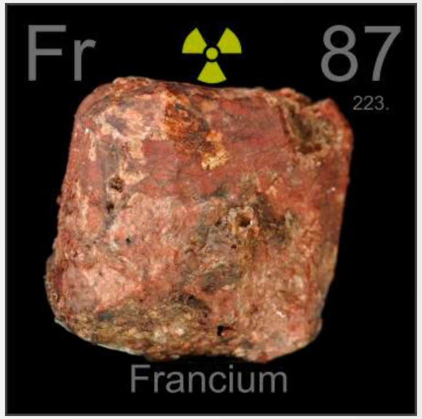

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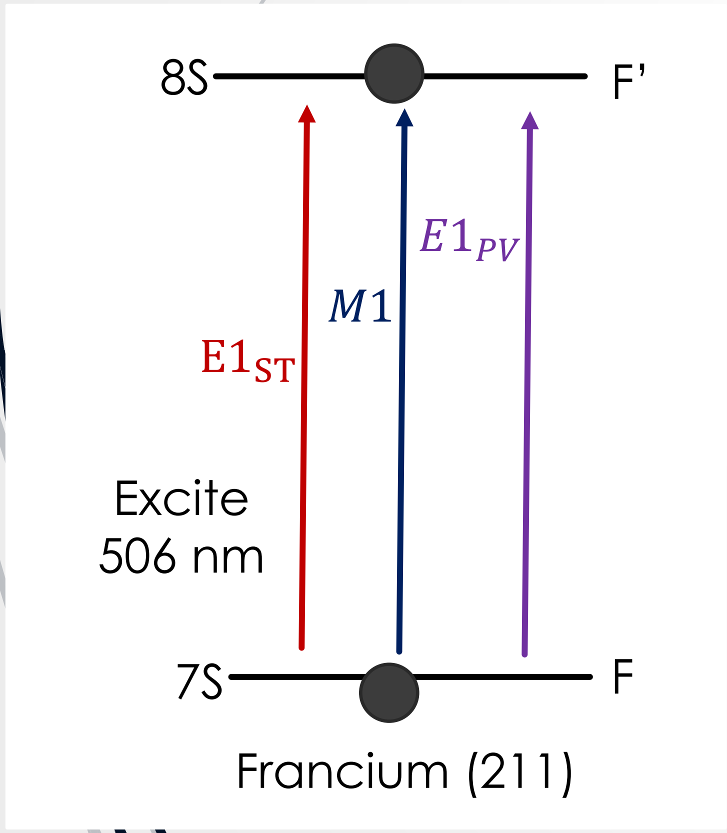

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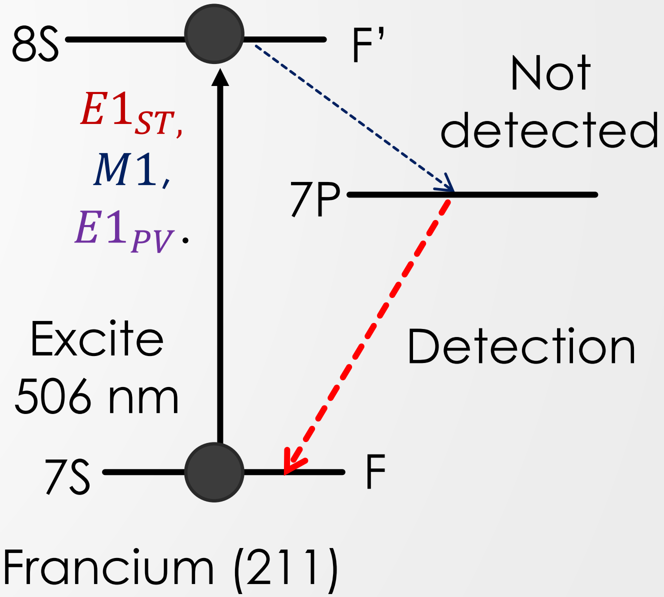

Fig: Our experimental approach.

Francium trapping facility

- No stable isotope → Use a radioactive beam facility → cool and trap atoms in magneto optical trapping (MOT) → suspend 10^5 Fr atoms.

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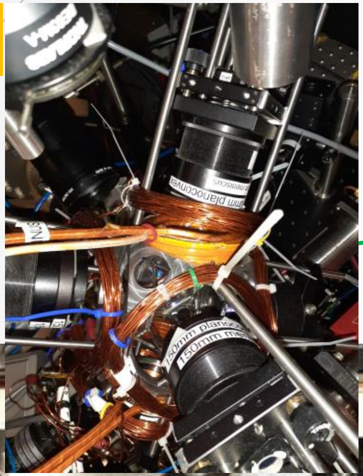

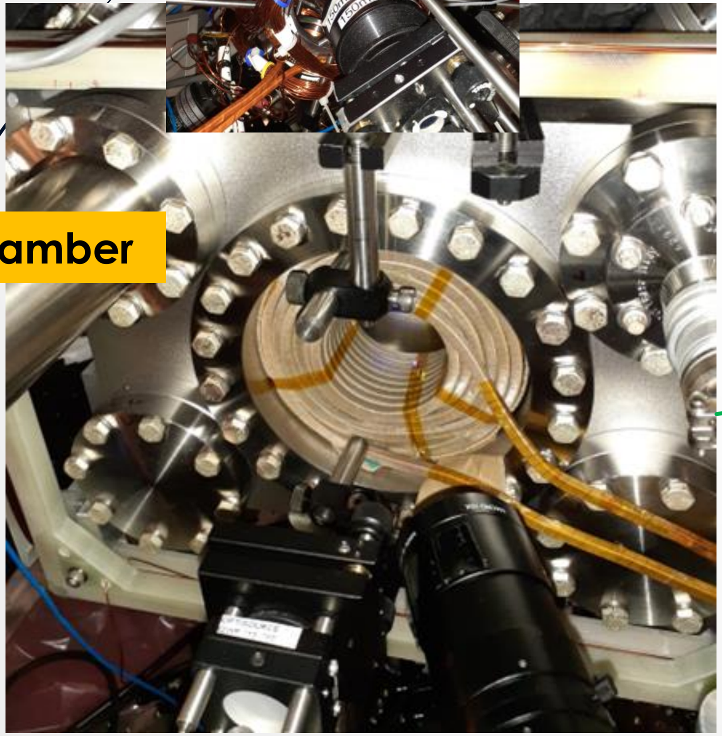

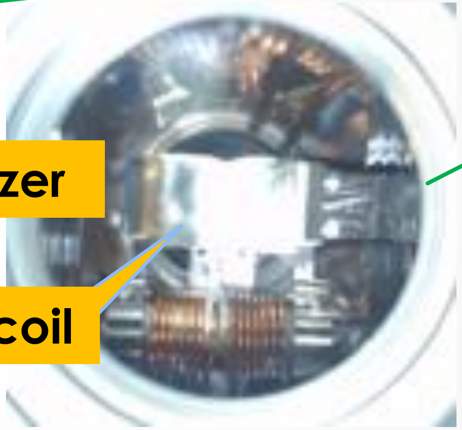

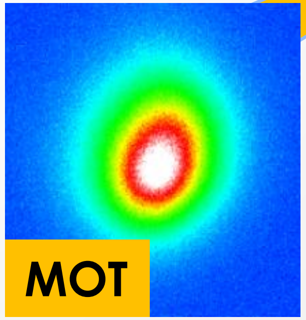

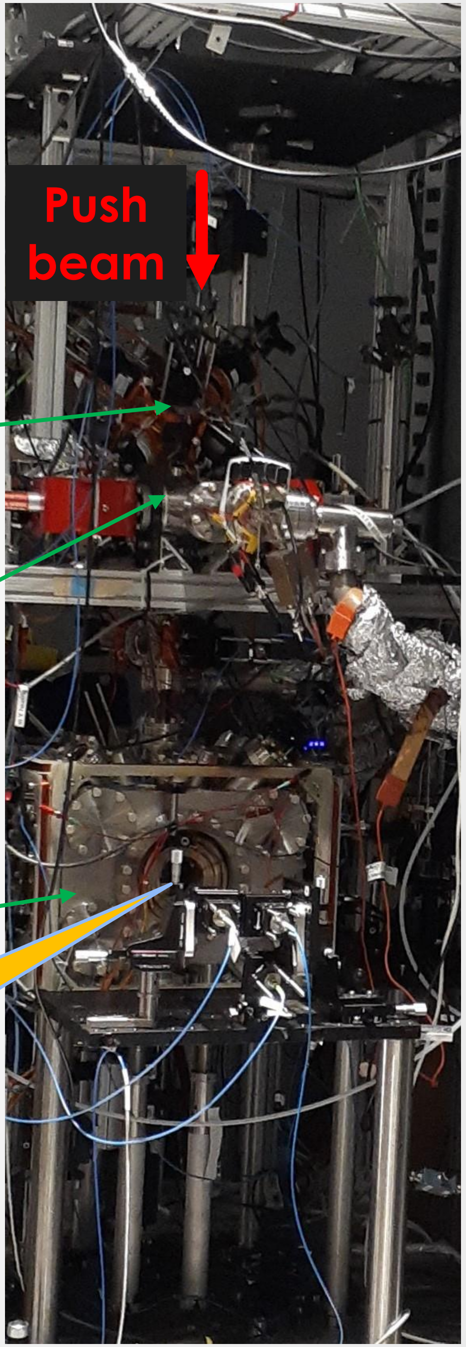

A key contributor to APV: β

- What motivates us to measure M1 ?

Stark induced E1 $|7S_{1/2}, F, m_F> \rightarrow |8S_{1/2}, F', m_{F'}>$

$$E1_{ST}(F', m_{F'}, F, m_F) = \alpha\, E.\epsilon\, \delta_{F'F}\delta_{m_{F'}m_F} + i\beta\,(E \times \epsilon) \cdot <F', m_{F'}|\sigma|F, m_F>$$

m – level dependent term.

APV signature

extract

$$\frac{\Delta R}{R} \propto \frac{\mathrm{Im}(E1_{PV})}{\beta E}$$

measure know

- β is a vector transition polarizability.
  $\Delta F = \pm 1,\ \varepsilon \perp E.$
- β needs to be known accurately to extract $E1_{PV}$,
  - → Can characterize transition by determining α and β,

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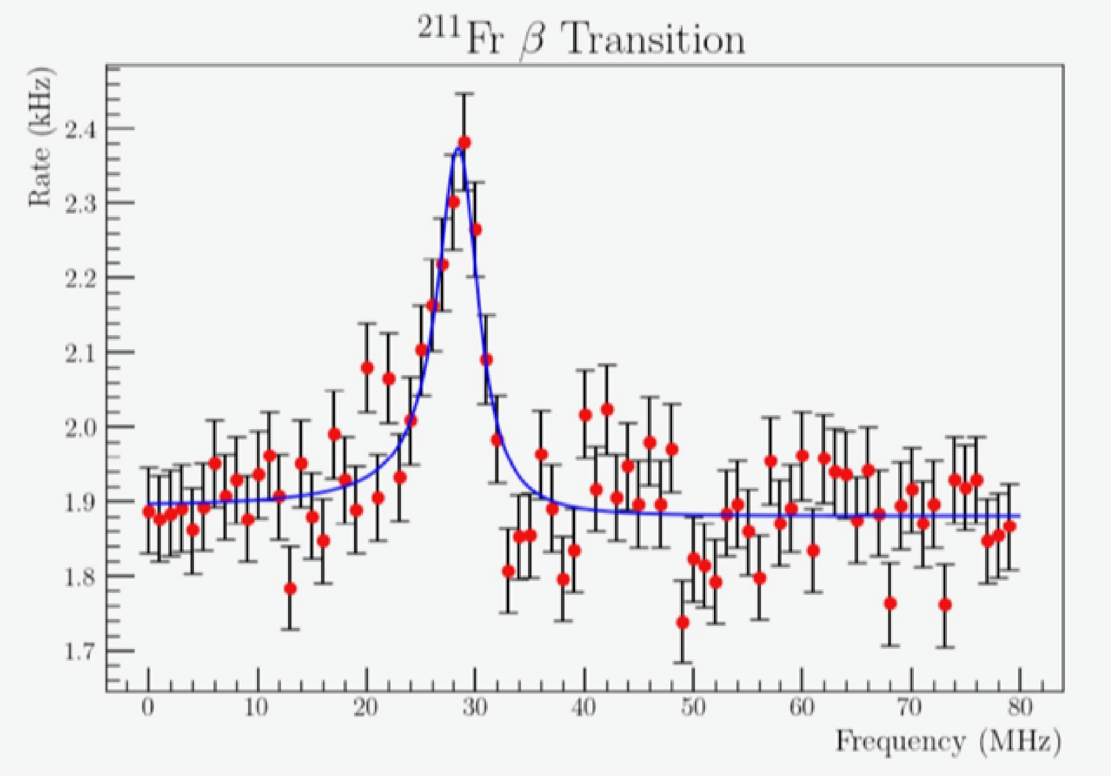

β is measured in 2018 with single, retro-reflected beam of 506 nm.

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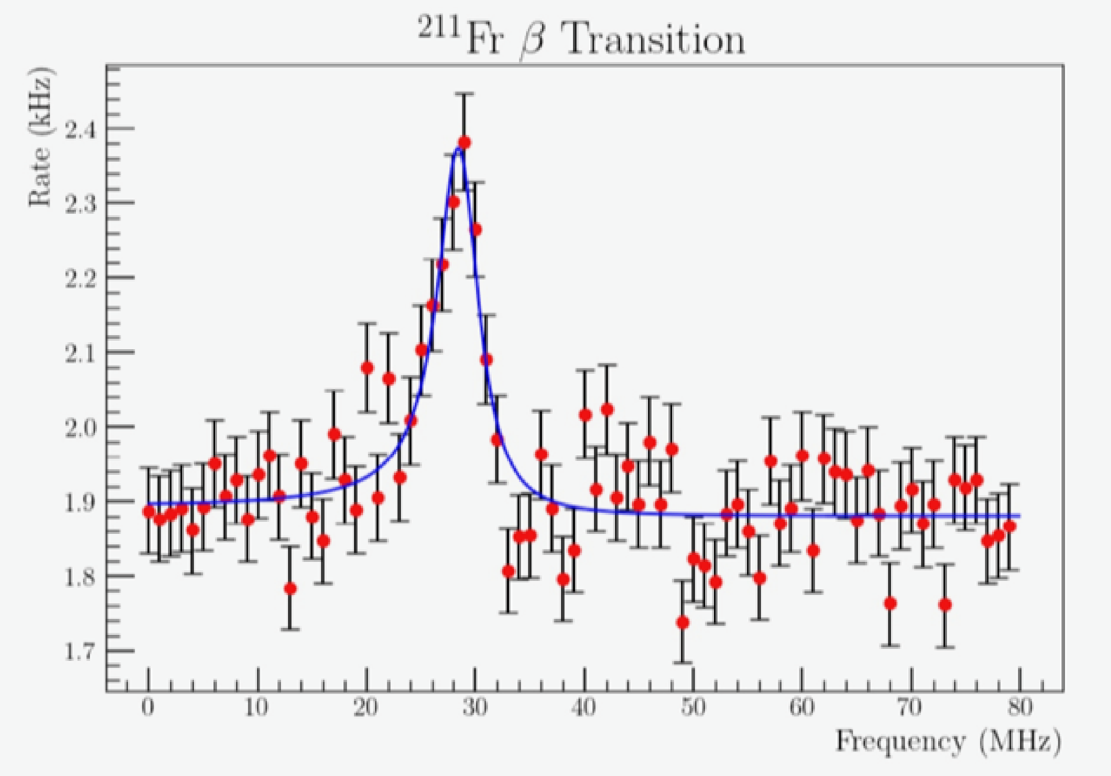

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❖ β needs to be known accurately to extract $E1_{PV}$,

→ Can characterize transition by determining α and β,

→ β can be calibrated via measurement of M1,

→ β and M1 have same m-level dependence,

Understanding of magnetic dipole M1 transition

$$\mathrm{M1}\,(\mathrm{F}',\mathrm{m}' \rightarrow \mathrm{F},\mathrm{m}) = \langle 8\mathrm{S}_{\mathrm{F}',\mathrm{m}'}\,|\vec{\mu}_{\mathrm{M}}.\vec{\mathrm{B}}|\,7\mathrm{S}_{\mathrm{F},\mathrm{m}} \rangle$$

where $\vec{\mu_M} = \vec{\mu_B}\,(\mathrm{g_L L} + \mathrm{g_S S} + \mathrm{g_I I})$, $\vec{\mu_B}$ is Bohr magneton.

(M1 vanishes in non-relativistic approximation because spatial parts of different $nS_{1/2}$ are orthogonal.)

$$\mathrm{M1}\,(\mathrm{F},\mathrm{m} \rightarrow \mathrm{F}',\mathrm{m}') = \mathrm{M1}'\,(\hat{\mathrm{k}} \times \hat{\varepsilon}).\langle \mathrm{F}',\mathrm{m}'|\vec{\sigma}|\,\mathrm{F},\mathrm{m} \rangle$$

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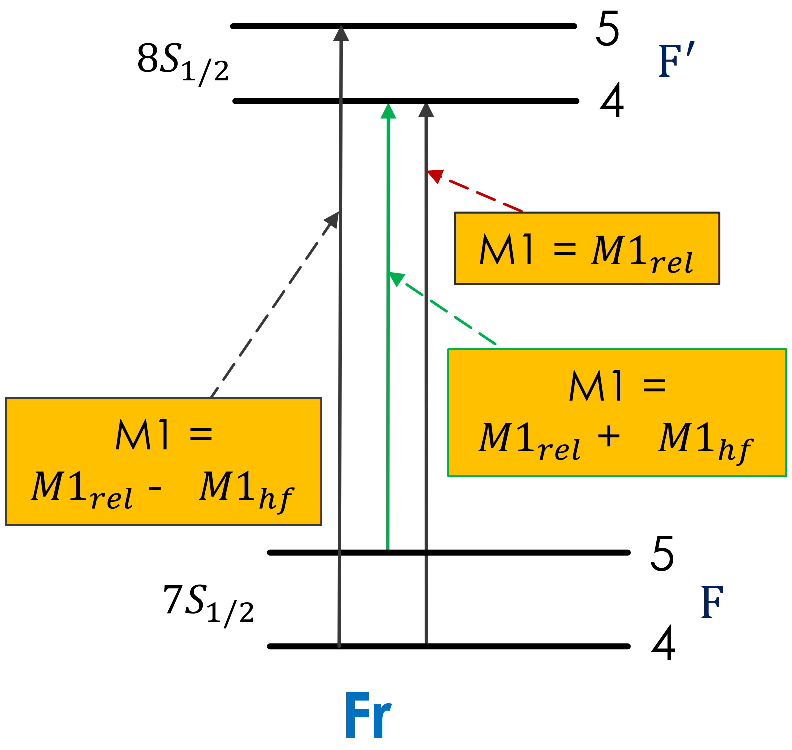
❖ **To measure:** $\mathrm{M1}' \propto \mathrm{M1}_{rel} + (F - F')\,\mathrm{M1}_{hf}.$

where $\mathrm{M1}_{rel}$ is the relativistic and spin orbit effect → *difficult*!
$\mathrm{M1}_{hf}$ is from off-diagonal hyperfine interaction.

$\mathrm{M1}_{hf}$ ~12% contribution to M1′.



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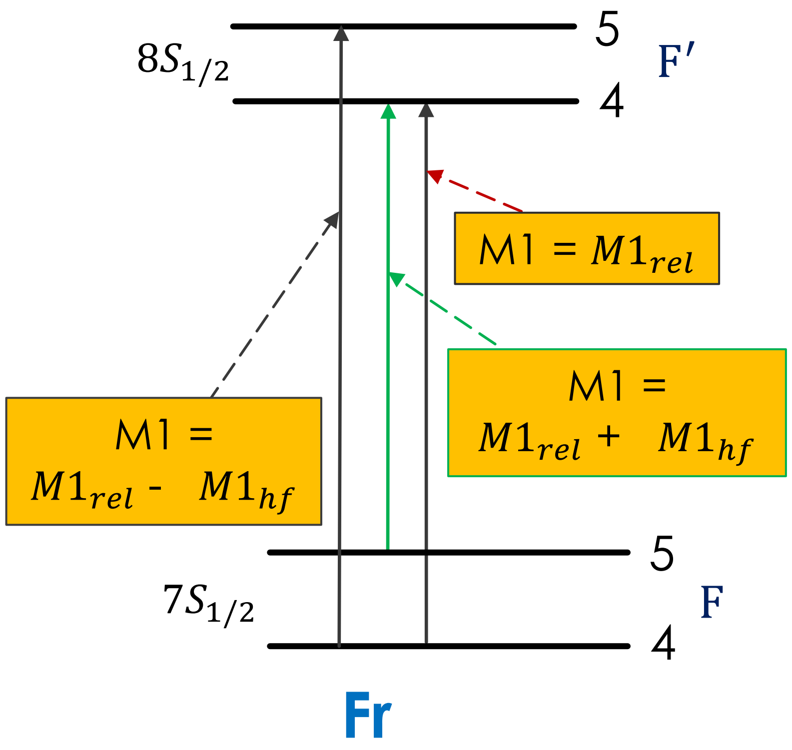
❖ Measure $\frac{\mathbf{M1}}{\boldsymbol{\beta}}$ on $\Delta F = \pm 1$ and know $\mathrm{M1}_{\mathrm{hf}}$
→ to calibrate $\boldsymbol{\beta}$ and $\mathrm{M1}_{\mathrm{rel}}$.

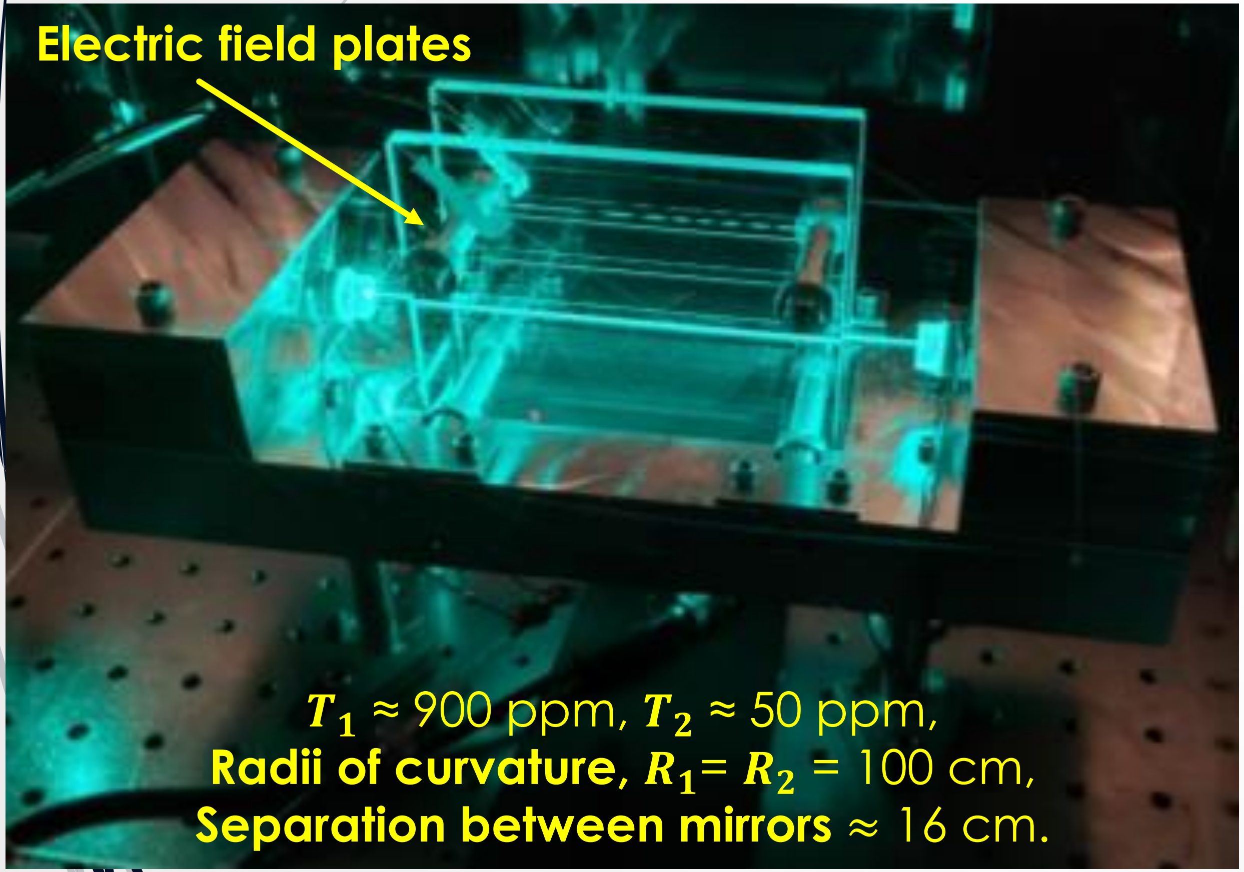


Known hyperfine splitting

$$\mathrm{M1}_{\mathrm{hf}} = \frac{\sqrt{\Delta\omega_{7s}\Delta\omega_{8s}}}{\omega_{7s-8s}}\,\mu_B$$

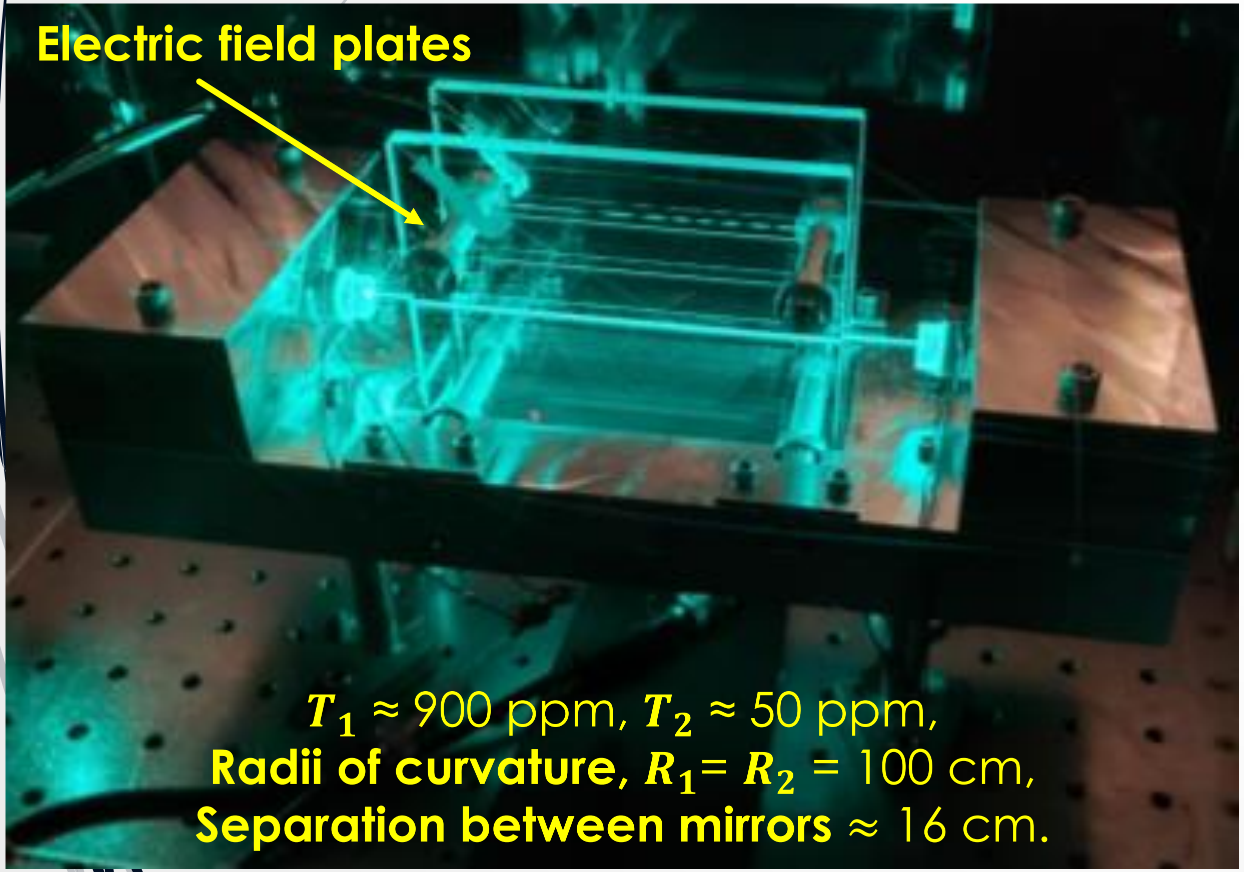
Known 7s-8s transition energy

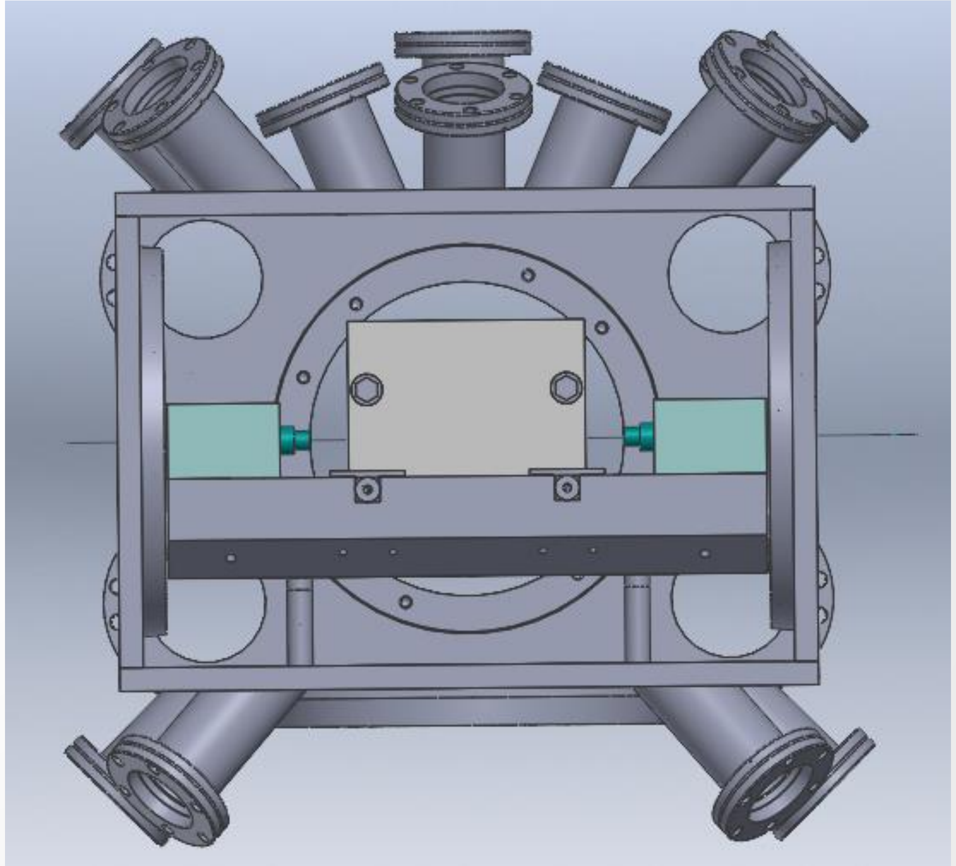
Intensify 506 nm with power build up cavity (PBC)



Intensify 506 nm with power build up cavity (PBC)

- ❖ Spherical mirror resonator → Power build up ~ 4000 ×,
- ❖ UHV compatible → Pound-Drever-Hall → lock the cavity to TEM_{00} mode,
- ❖ Accommodate electric field plates and MOT beams,





Section view of science chamber with PBC.

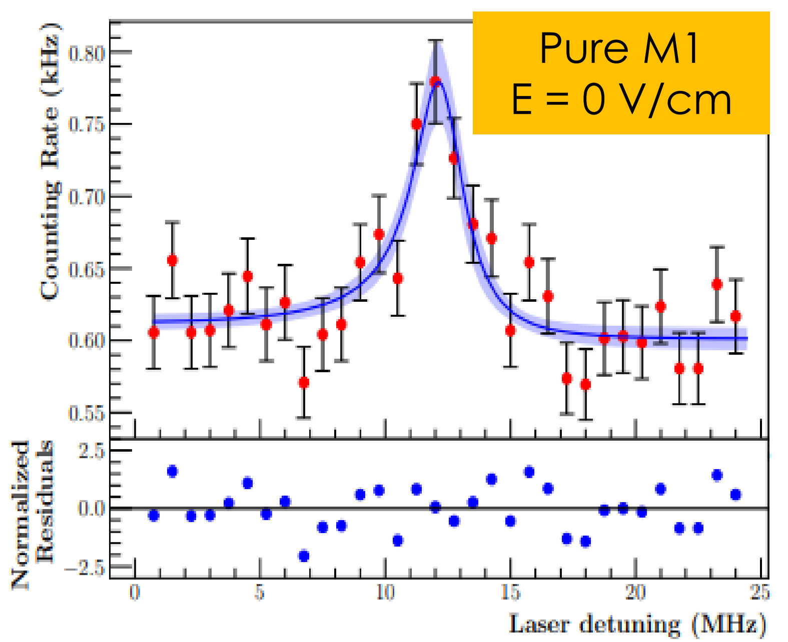
First observation of magnetic dipole M1 transition in 2021

- Unassisted of any 'Stark mixing', E = 0 V/cm.

$$R_{7S\rightarrow 8S} \propto \beta^2 E^2 + (M1_{rel} \pm M1_{hf})^2$$

E = 0 V/cm

- Could only measure $\Delta F = -1$,



7S (F = 5) → 8S (F' = 4) M1 transition taken at 0 V/cm for Fr 211.

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- Combine calculations of β and $M1_{hf}$ to experimentally determine $M1_{rel}$.

TABLE I. A comparison of the relativistic component for the Fr $7s \rightarrow 8s$ reduced $M1$ matrix element between theory and experimental values.

References	$M_{rel}^{RME}(\times 10^{-5}\mu_B/c)$
Theory	
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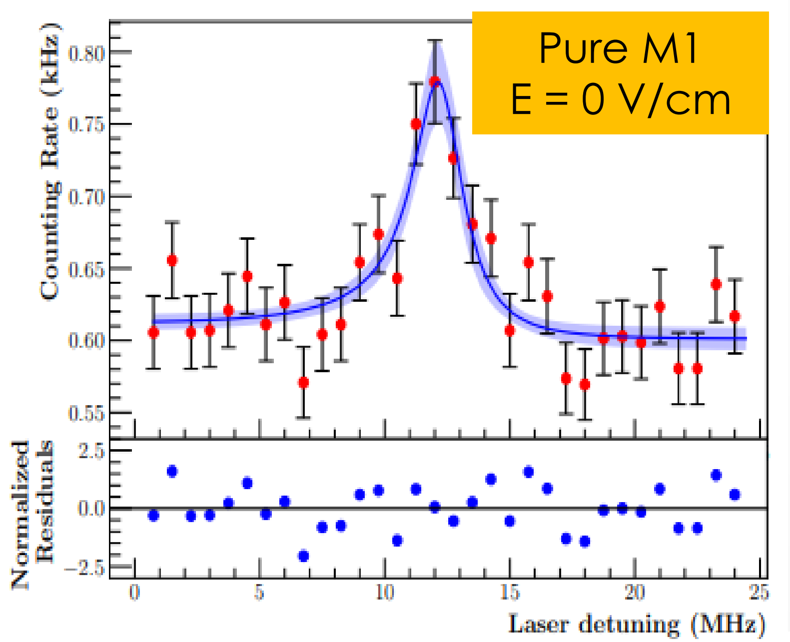
This work	$152(12)_{expt}(1)_{theo}$

*Preliminary results.



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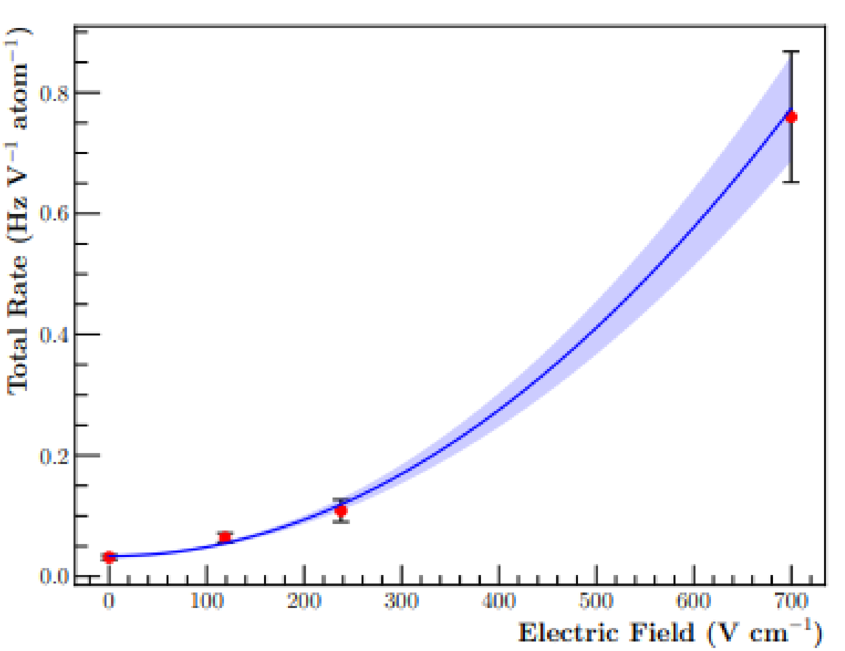

Normalized transition rates vs electric field.

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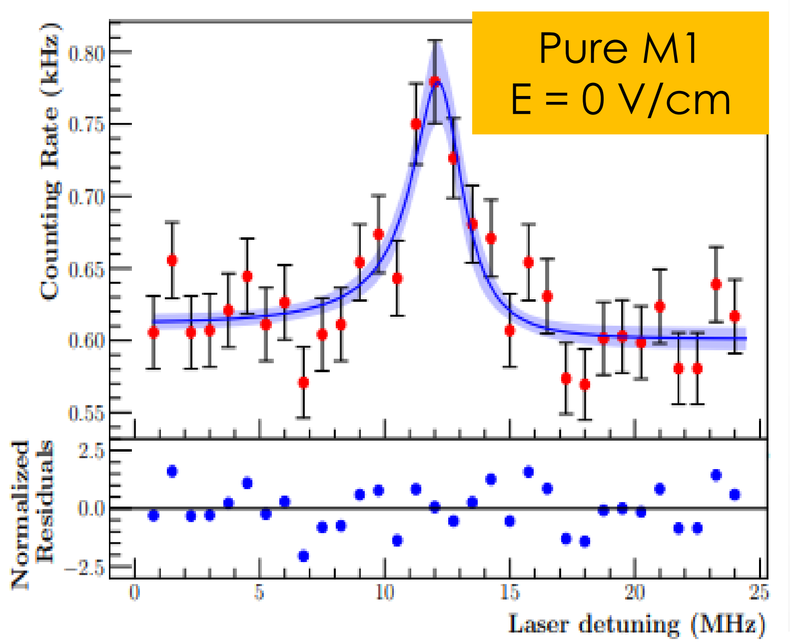

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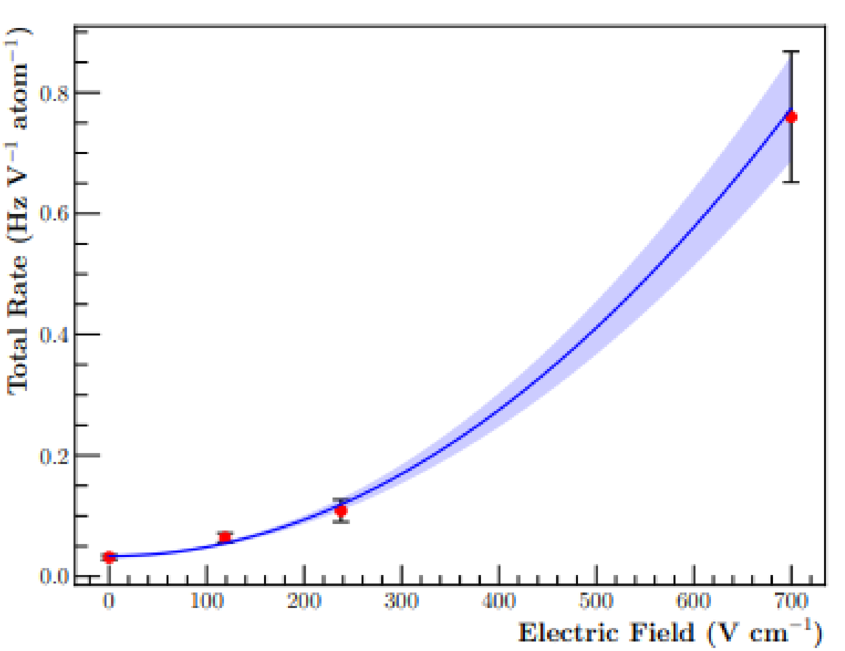


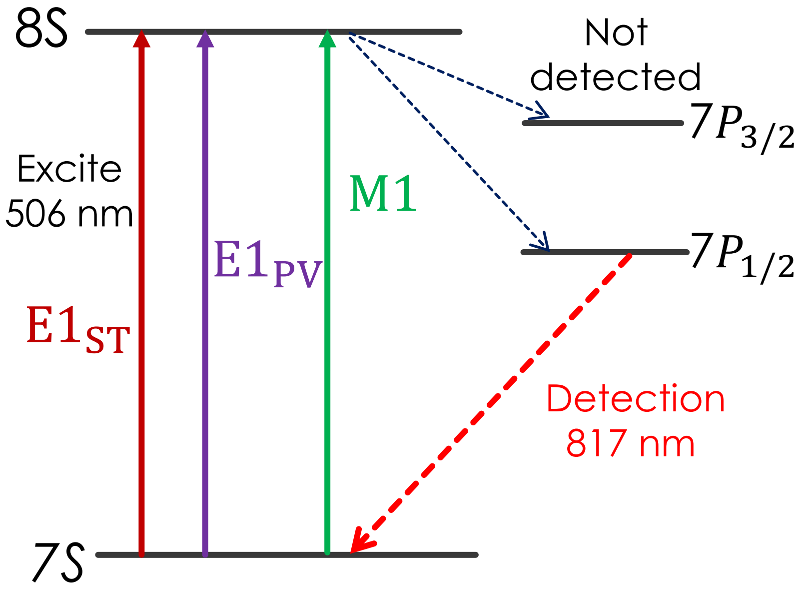
Normalized transition rates vs electric field.

Challenges:

- Saw saturation of transition → hyperfine level pumping.
- → notable % of atoms decay to other HF state → no longer resonant to 506 nm.

Improvements in detection system

❖ Detection system: Photon detection efficiency ≈ 1/4000,
(Solid angle * Filter transmission * Polarizing beam splitter * Quantum efficiency),



$7S \rightarrow 8S$

Fr 211

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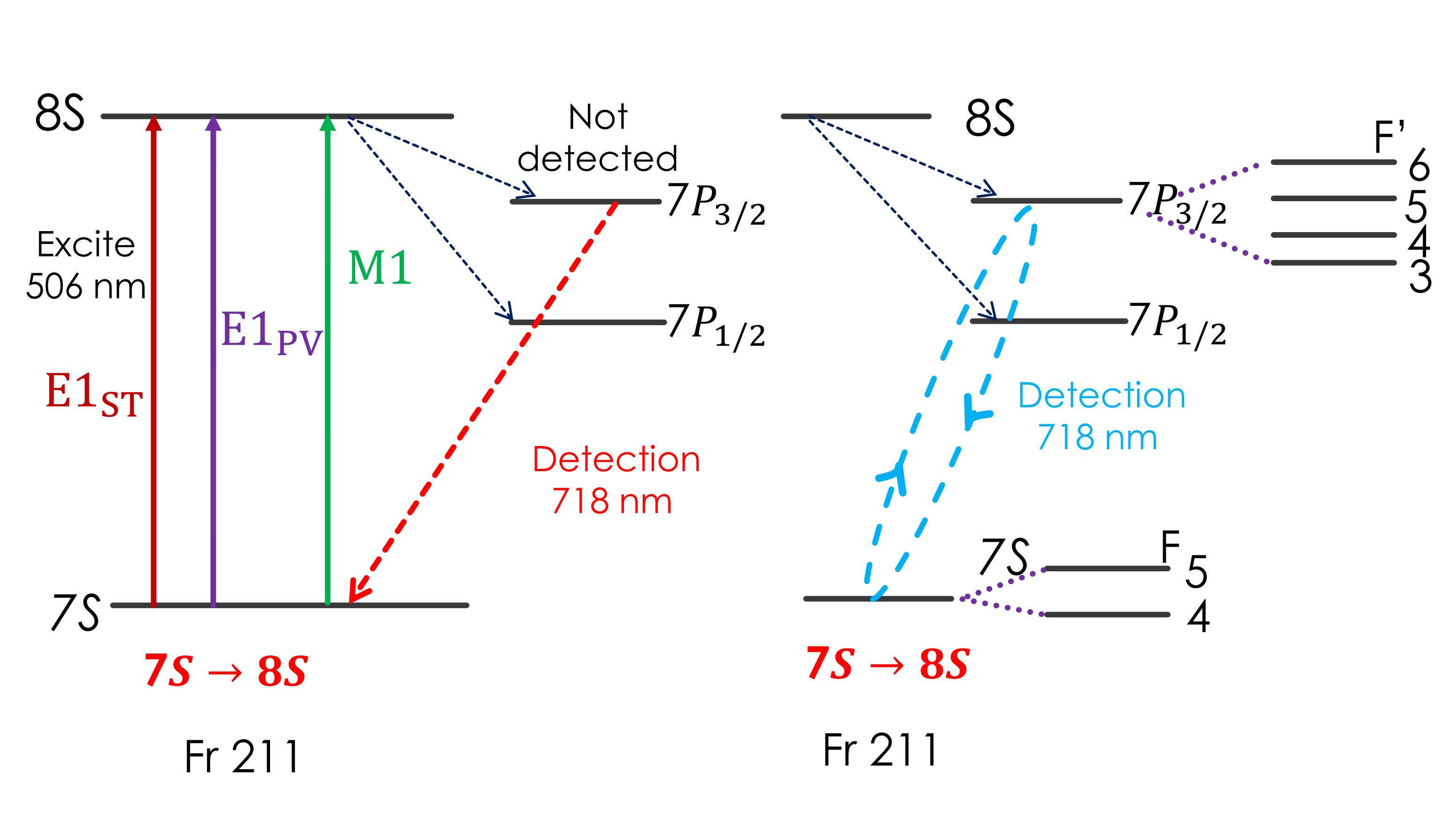

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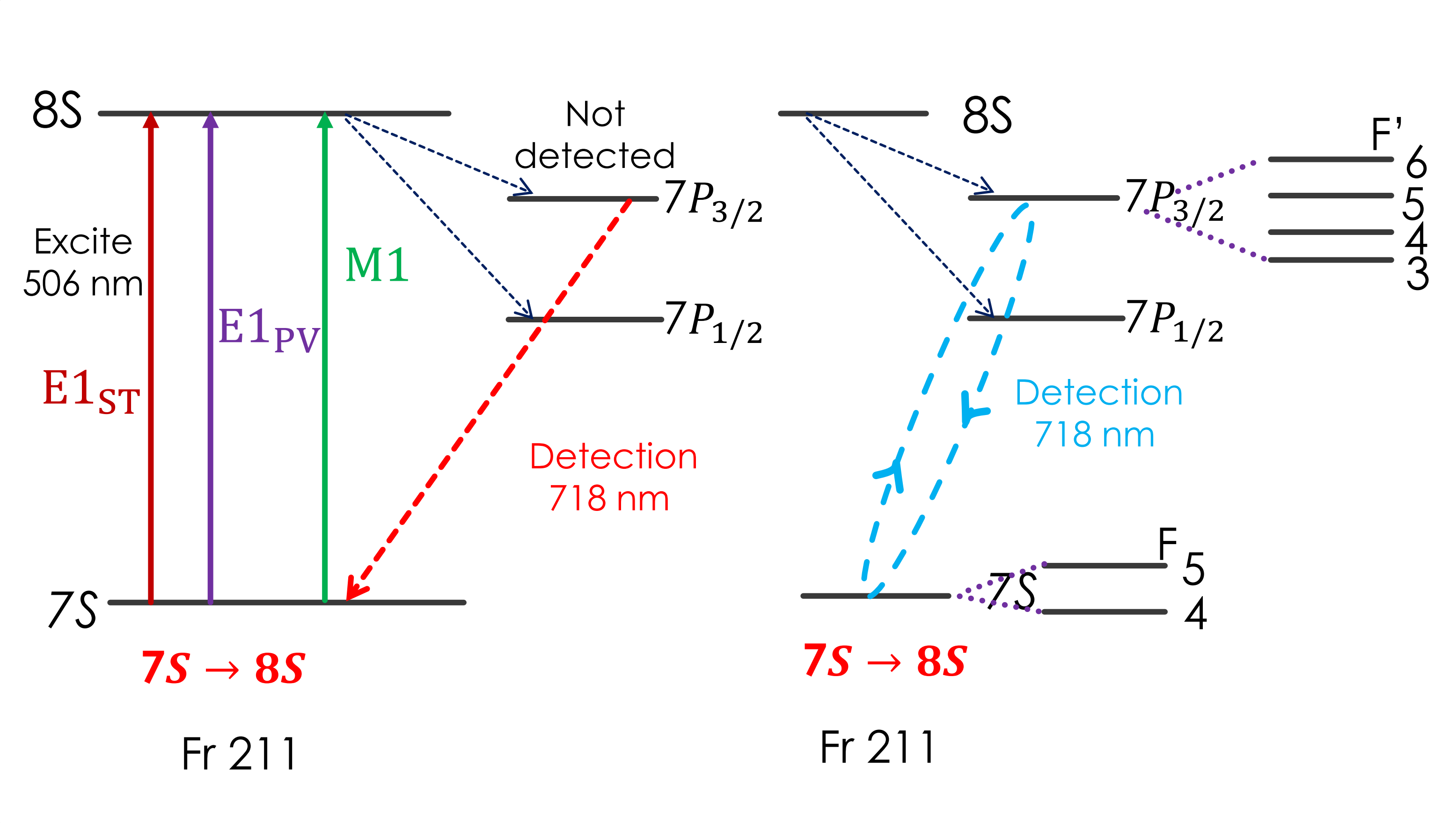
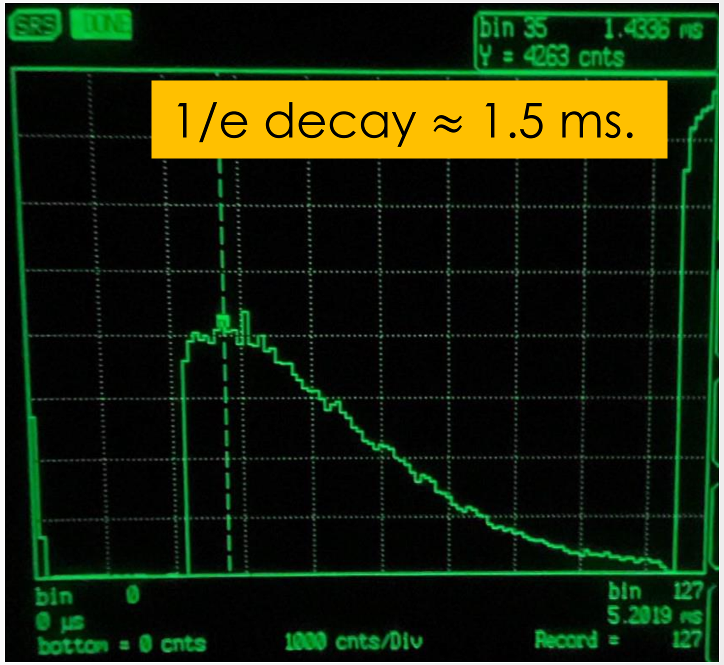
  (Solid angle * Filter transmission * Polarizing beam splitter * Quantum efficiency),
  → Upped from the photomultiplier tube to SiPM,
- ❖ Burst signal: Bursting of photons on D2 cycling transition,
  → estimated cycling of ~ 16000 photons in ~ 1.3 ms for Fr 211.





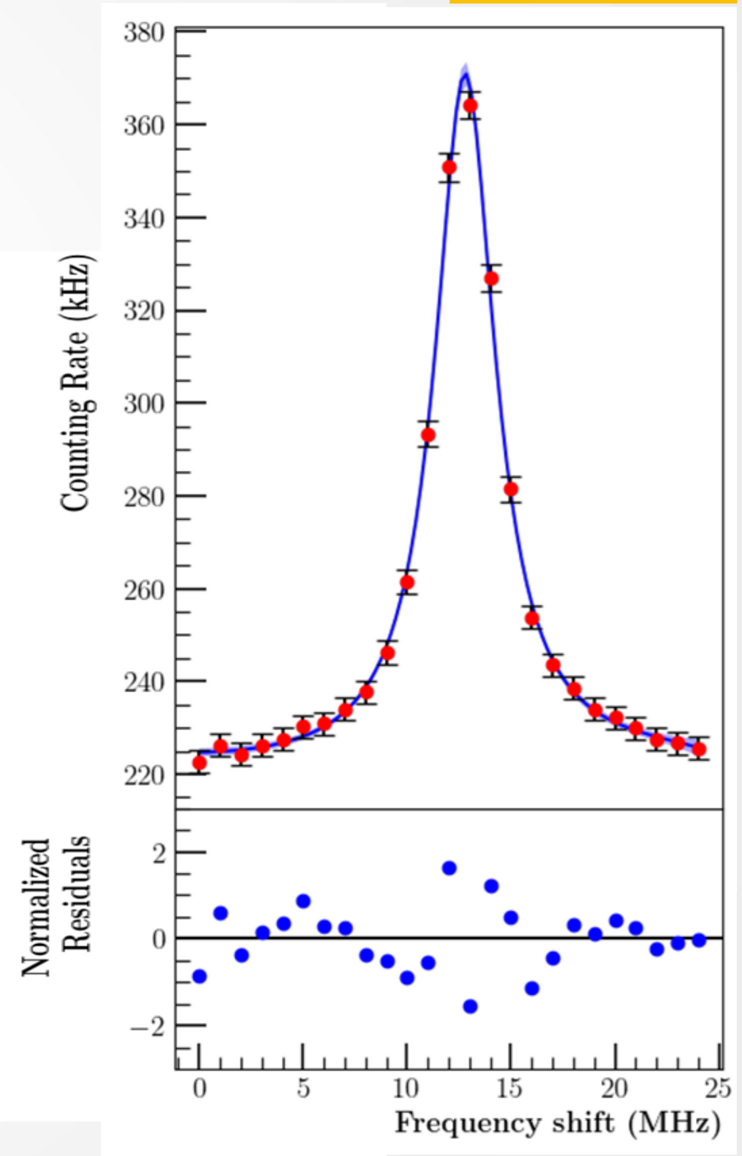
Upper burst signal observed with multi-channel scalar.

- ❖ Detection rate ~ MHz regime,

New measurement of M1 dipole transition in 2023

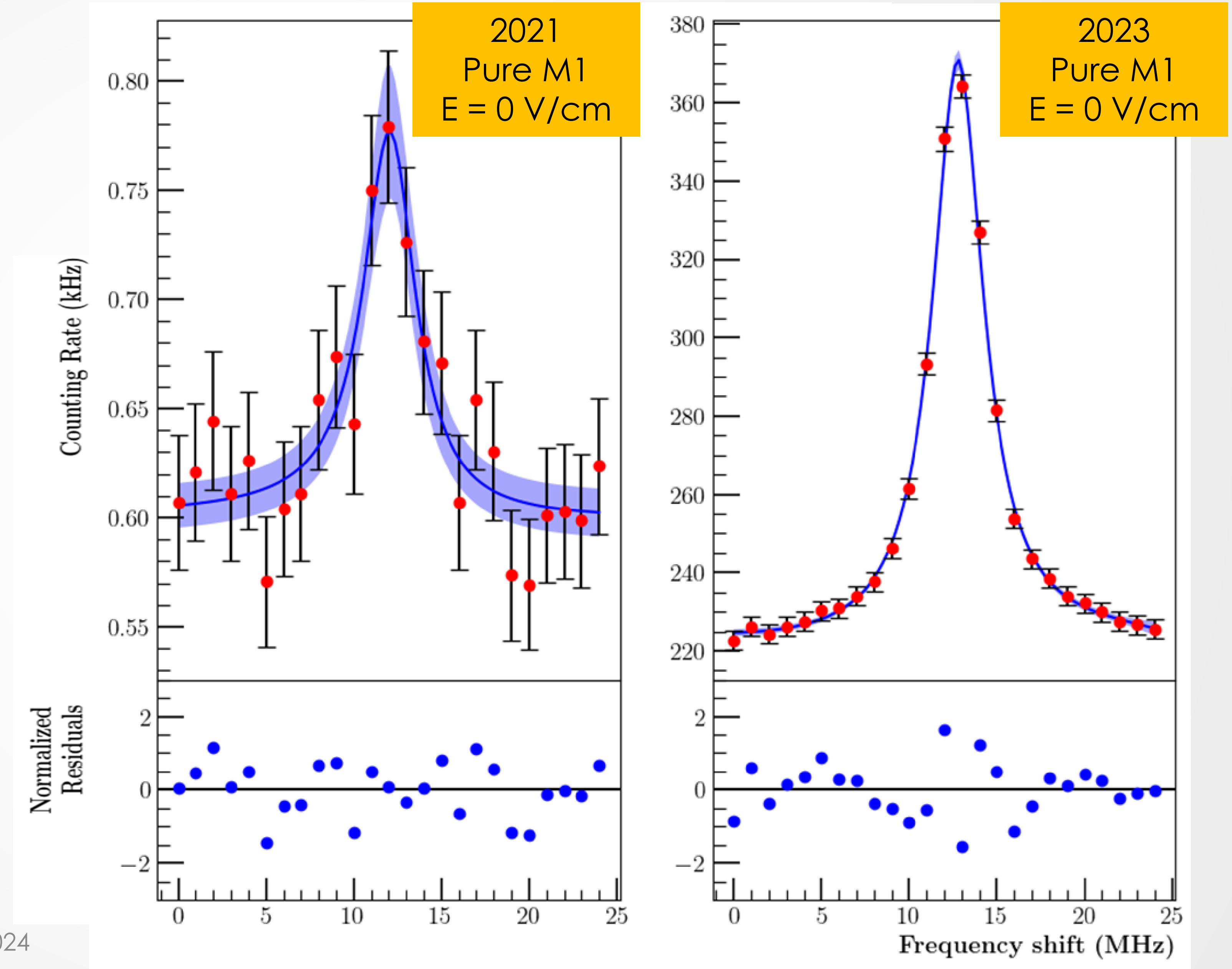
2023
Pure M1
E = 0 V/cm

- In 2023, did on both $\Delta F = \pm 1$,
- Detected with burst technique,
- Got better statistics,
- 2023 data analysis in progress.



New measurement of M1 dipole transition in 2023

- In 2023, did on both $\Delta F = \pm 1$,
- Detected with burst technique,
- Got better statistics,
- 2023 data analysis in progress.



New measurement of M1 dipole transition in 2023

- In 2023, did on both $\Delta F = \pm 1$,
- Detected with burst technique,
- Got better statistics,
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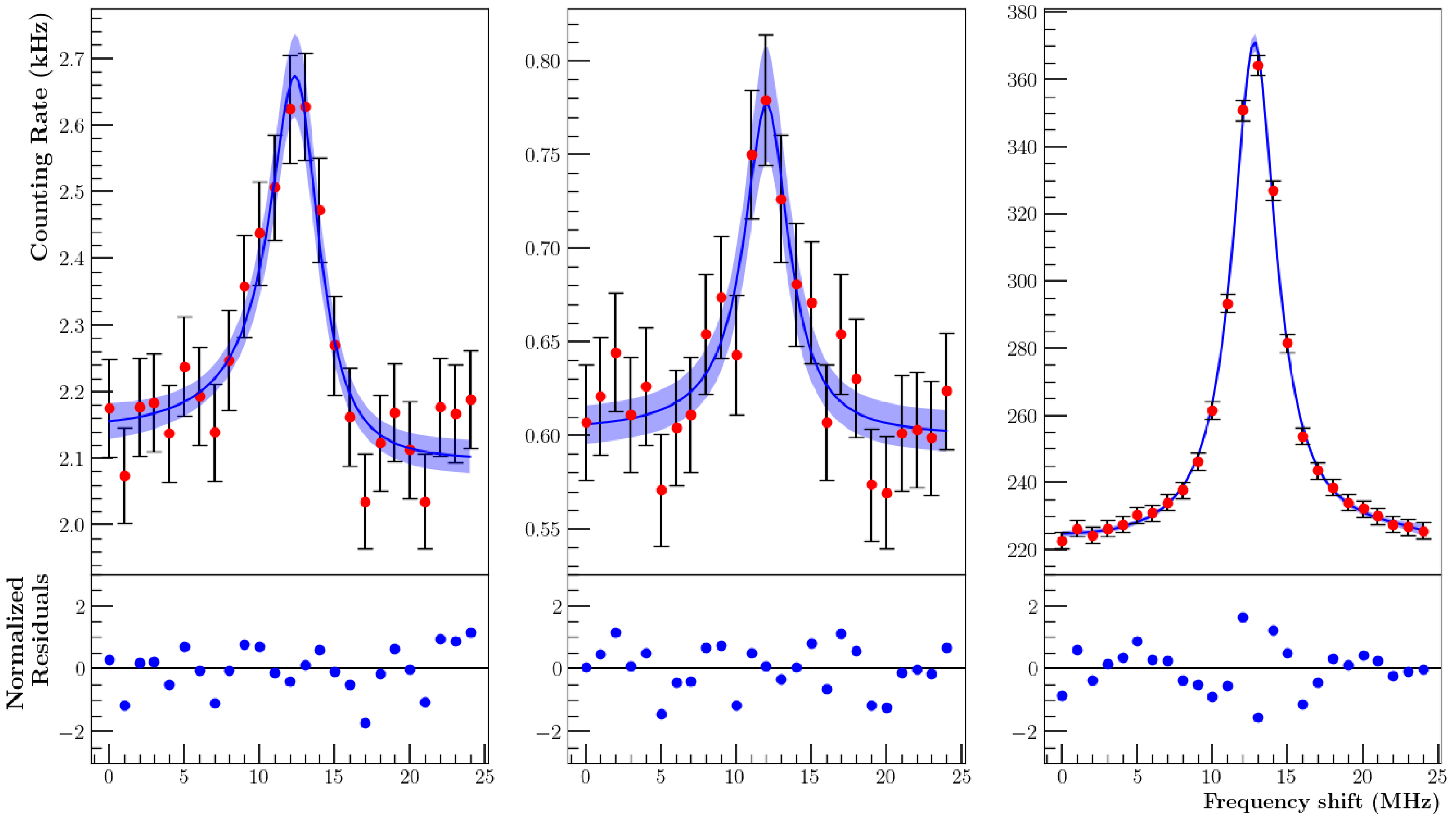
2018	2021	2023
β + M1	Pure M1	Pure M1
E = 6200 V/cm	E = 0 V/cm	E = 0 V/cm



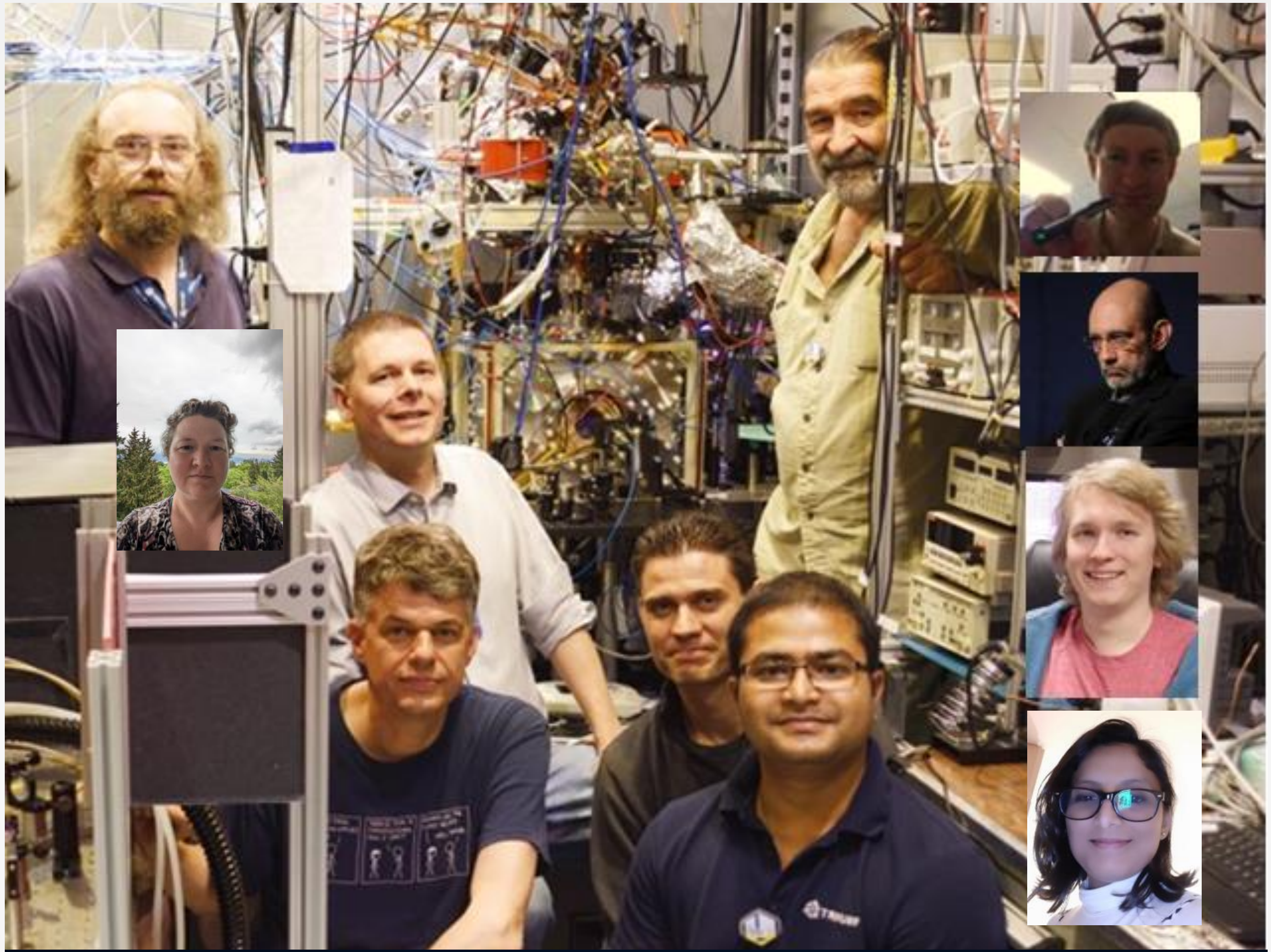
Summary

- Measured M1 – a very faint, 13 orders weaker transition than an allowed transition.
- → by implementing PBC and Burst technique.
- Increased the sensitivity of our system by several folds.
- Highly motivated for precision APV measurements (f ≈ 16.5).
- Complete the 2023 M1 analysis.
  - Determine $\mathrm{M1_{hf}}$ precisely → establish the value of $\boldsymbol{\beta}$ → characterizes $E1_{PV}$ signal.

Things that need attention in future.

- Have a better understanding of background and number of atoms → normalize the data.
- Good control on turning OFF the trap and other lasers.
- Atoms in MOT are unpolarized → *Polarize the atoms in MOT.* ← Next project!

Thank you!



→ Matt Pearson, Andrea Teigelhoefer, Seth Aubin, Gerald Gwinner, Eduardo Gomez, Mukut Kalita, Alexandre Gorelov, John Behr, Luis Orozco, Tim Hucko, Anima Sharma, (Iris Halolivic, Tasanul Morshed, Liang Xie :– not shown in picture).

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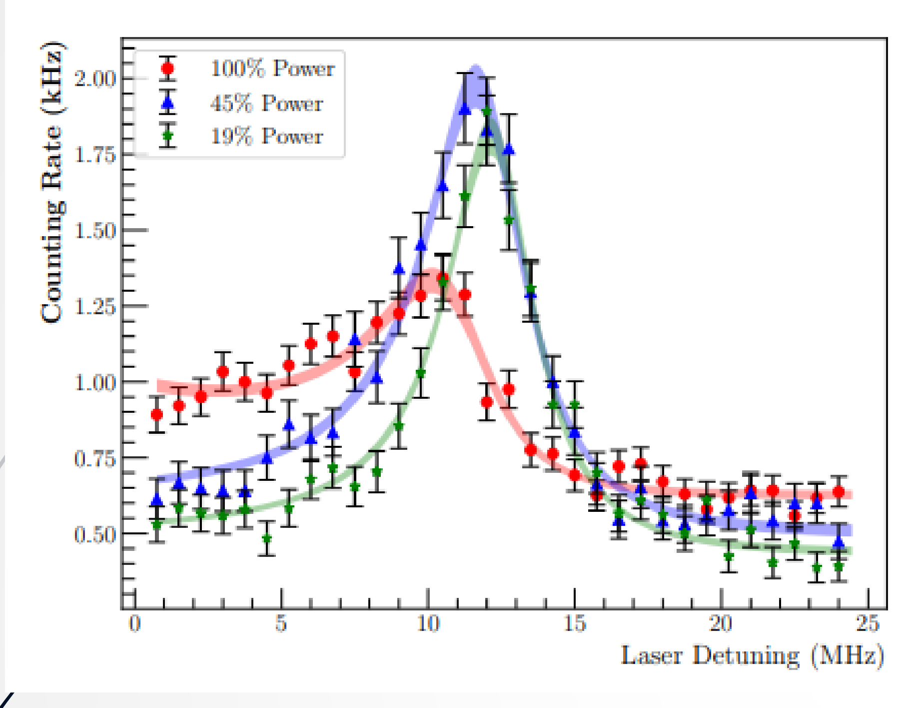
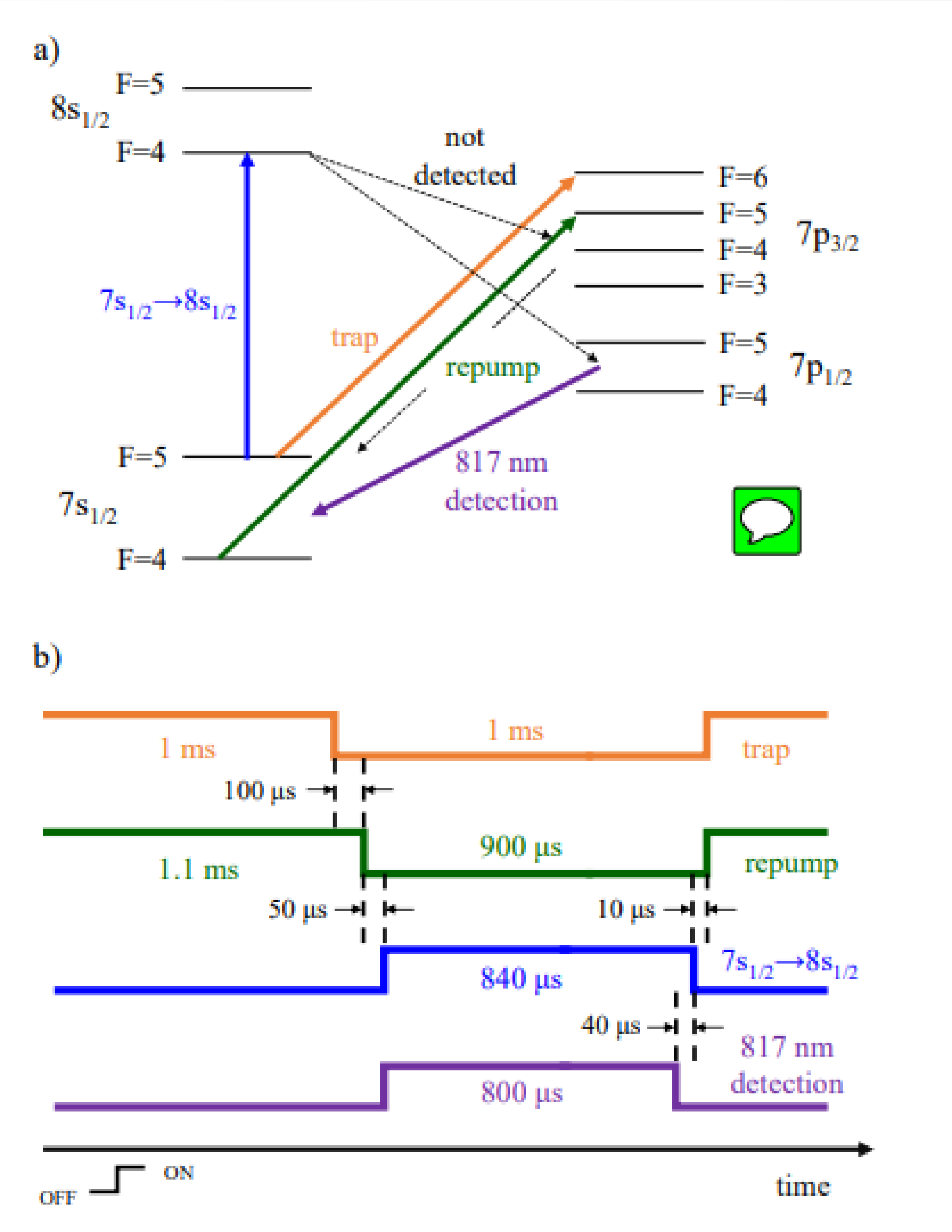
Chartered 1693

Back up slides



three-level atom. We find that saturation via hyperfine level pumping reduces the transition rate by a factor of $([1 - e^{R/R_{\text{sat}}}]R_{\text{sat}}/R)$, where R is the unsaturated transition rate and R_{sat} is the saturation rate. A similar result



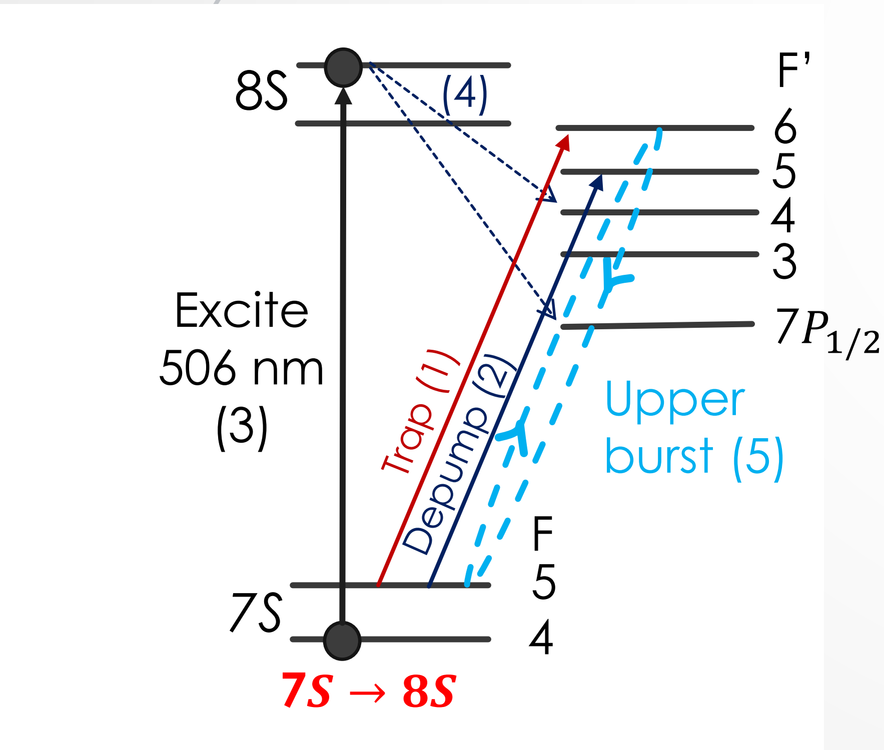
Burst of photons for detection

Upper burst

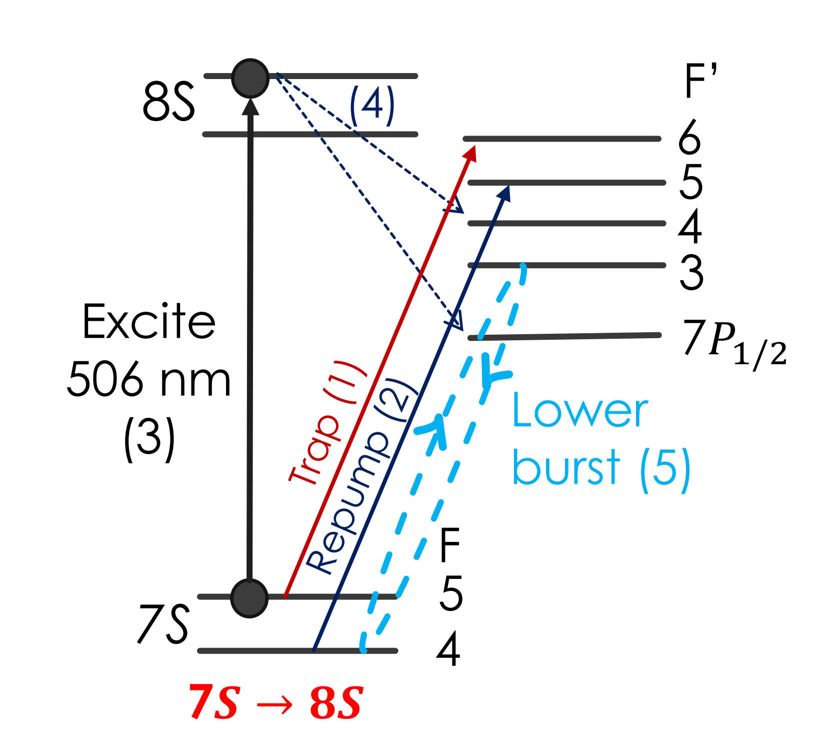
(1) Trap on cycling transition,
(2) Clean F = 5 state → Depump atoms,
(3) Excite (506 nm) → 8S,
(4) Decay 8S to 7S via 7P,
(5) Cycling transition (upper burst).

Lower burst

(1) Trap on cycling transition,
(2) Clean F = 4 state → Repump atoms,
(3) Excite (506 nm) → 8S,
(4) Decay 8S to 7S via 7P,
(5) Cycling transition (lower burst).



Fr 211

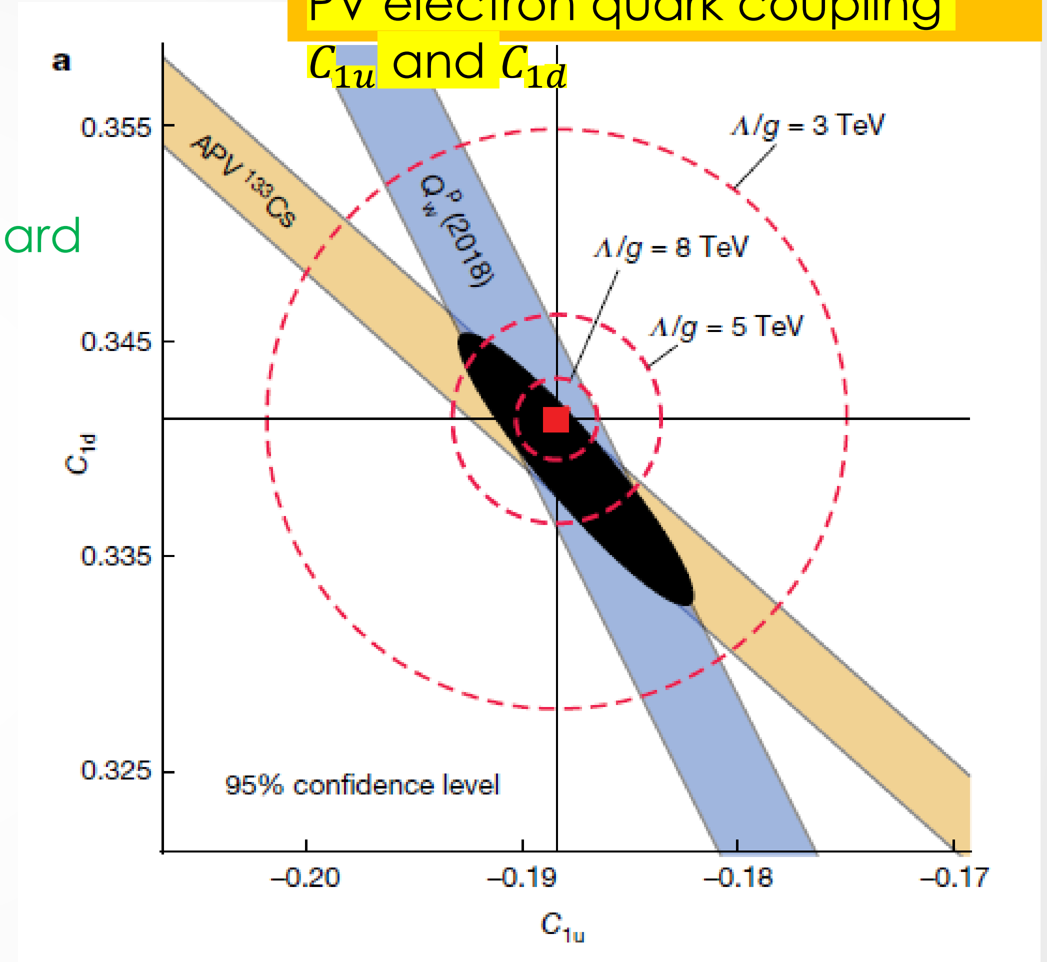


Fr 211

APV critical for testing the SM PV electron quark coupling C_{1u} and C_{1d}

Atomic structure factor from theory (K_{PV})
Weak charge (Q_W): Our ultimate goal to test the Standard Model.

$$E1_{PV} = K_{PV}\, Q_W$$



Q_{weak} Collaboration, Nature 557, 207–211 (20

Francium trapping facility

❖ No stable isotope → Use a radioactive beam facility → cool and trap atoms in magneto optical trapping (MOT) → suspend 10^5 Fr atoms.