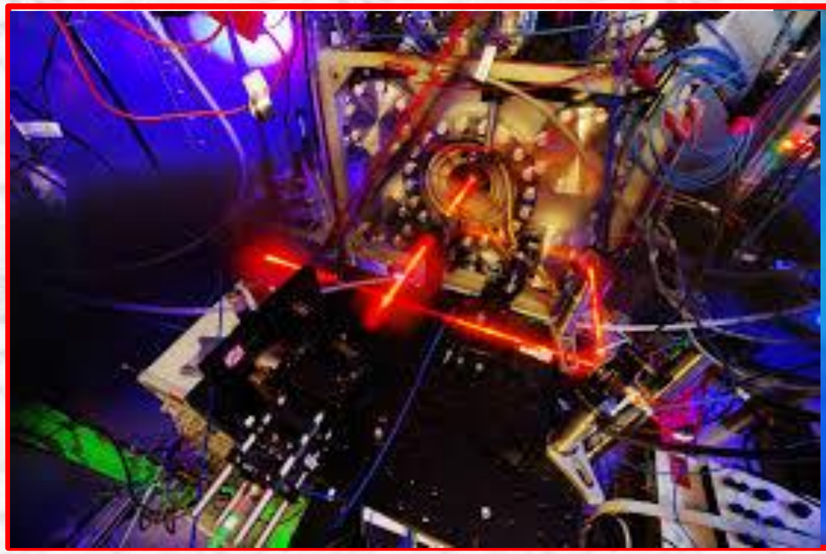
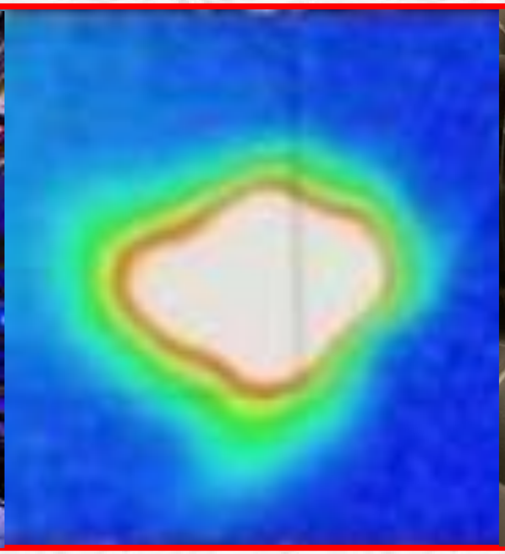
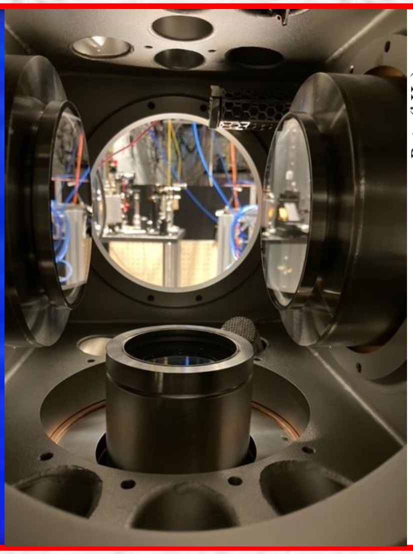
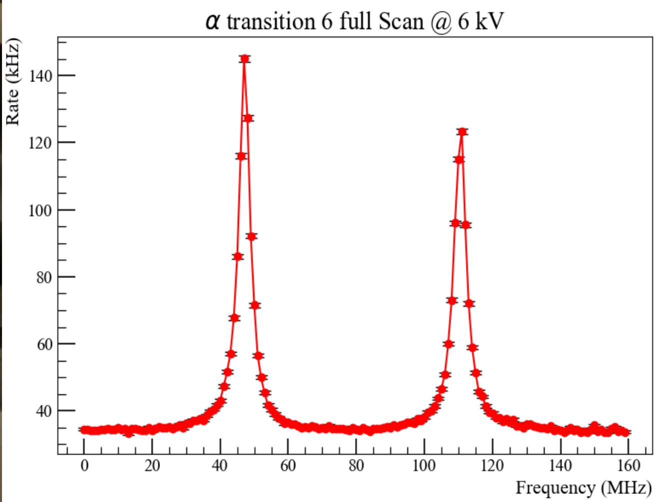
One step closer to Atomic Parity Violation (APV) in Francium: First Observation of highly forbidden magnetic dipole (M1) 7S → 8S transition in Francium

WNPPC 2022

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Feb 17, 2022.

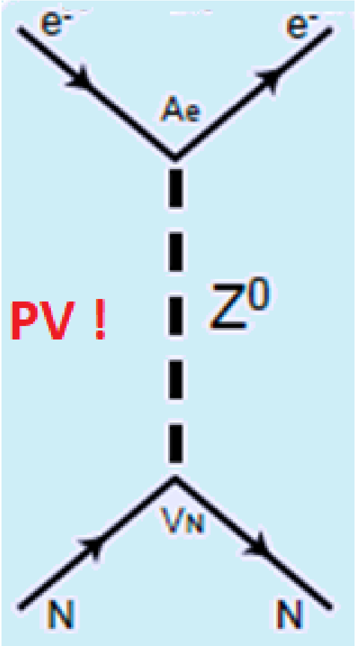
Mission of our project

- **Interest:** Study 7S → 8S transition in Francium (Fr). Forbidden because of states with same parity.

- **Trickish savior:** Z^0 boson exchange b/w atomic electron and quarks in nucleus → Parity violation (PV) atomic Hamiltonian H_{PV} → mixes atomic S and P states → atomic orbitals lose definite parity.

$$< n'\, S' \mid H_{PV} \mid \mathrm{nS} > \;\propto\; Z^3.$$

Atomic Parity Violation (APV)



Weak Interaction

- **Difficulty:** 7S → 8S transition rate ($R_{7S\,\rightarrow\,8S} \approx 10^{-20}$) carries **APV signature.** Too small to observe.

- **Solution:** Add large parity conserving signal.
  External static electric field also mixes S and P → PC "Stark" amplitude. Tunable strength.

- **Why Fr?**
  Heavy atom with larger Z,
  simple alkali structure.
  → Francium (Fr) → Effect 18× larger than in Cesium

  To date best APV test [1]

[1] Wood et al., Can. J. Phys. 77, 7 (1999).

Transition rate of 7S → 8S transition

- **Transition Rate**, $R_{7S \rightarrow 8S}$

  Sum of three distinct contributions:

$$R_{7S\rightarrow 8S} \propto \Big| \underbrace{E1_{ST}}_{\text{Stark-induced transition PC amplitude } f\sim 10^{-10}} + \underbrace{M1}_{\text{Magnetic dipole PC amplitude } f\sim 10^{-13}} + \underbrace{E1_{PV}}_{\text{Parity violating amplitude } f\sim 10^{-21}} \Big|^2$$

(unobservable)

Progress Status: Past Present

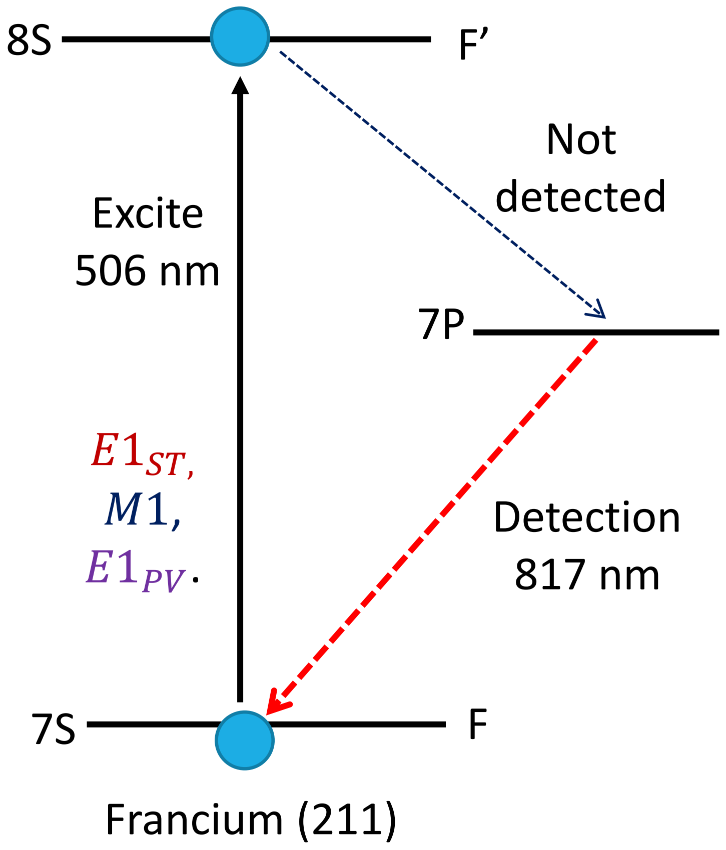
* f is oscillator strength of the corresponding transition.

- **Signal of Interest:** Interference term of PC and PV amplitudes.

- **Experimental approach**
- Laser beam excites highly forbidden 7S → 8S transition
- Decay sequence is 8S → 7P → 7S
- Measure transition rate on 7P → 7S decay
- Measure $\frac{E1_{PV}}{E1_{ST}}$. $E1_{PV} = K_{PV}\, Q_W$

Atomic structure factor from theory (K_{PV})

Weak charge (Q_W): Our ultimate goal to test the Standard Model.



Francium Trapping Facility @ Triumf

- **Why ISAC?**

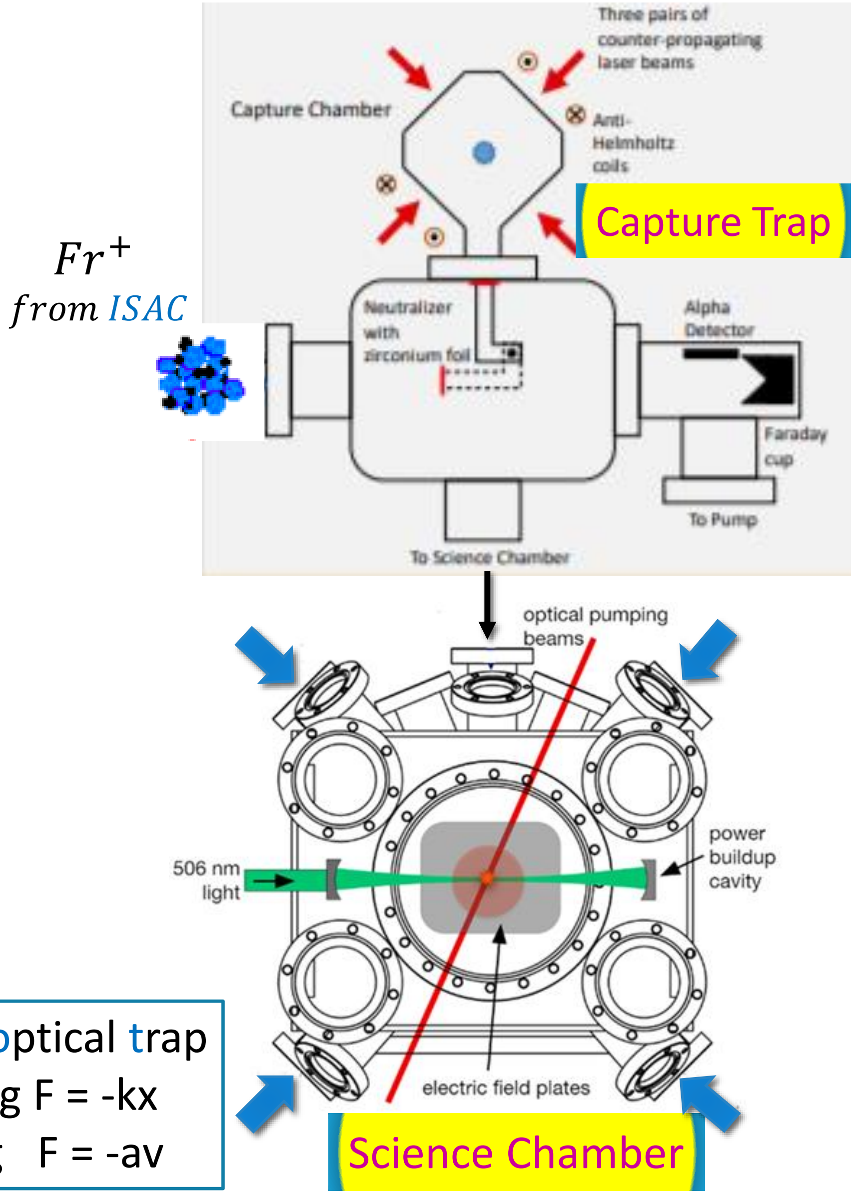
  Fr has no stable isotope → need radioactive beam facility

- **Why Trap?**

  → not enough Fr production for atomic beam
  → Re-use atoms in a trap

- Suspend million of Fr atoms at μK temperature
- Trap atoms on $7S_{1/2}$ (F = 5) → $7P_{3/2}$ (F' = 6) transition
- Precise control of electric and magnetic fields

- Test procedure with Rubidium (Rb)
  (except APV → too small)



Magneto optical trap
Trapping F = -kx
Cooling F = -av

Stark-induced amplitude: primary contributor

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

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

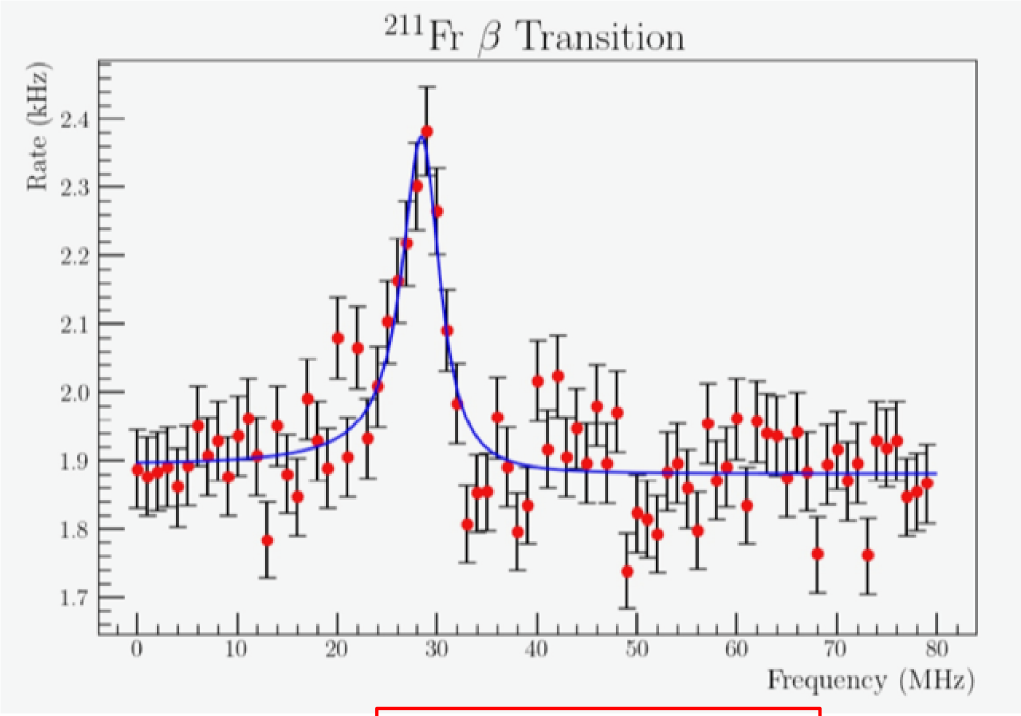
where σ is the Pauli spin operator,
E is the static electric field,
ϵ is the laser polarization.

- Transition Polarizabilities
  - → Scalar, α, $\Delta F = 0$ Started with α signal, $\varepsilon \,||\, E$
  - → Vector, β, $\Delta F = \pm 1$ Saw β signal in 2018. $\varepsilon \perp E$

- β is 25 × smaller than α [2].

- **Motivation for M1:**
  - → β needs to be known accurately → extract $E1_{PV}$,
  - → β can be calibrated via measurement of M1.

- **Shifted our focus now to M1**



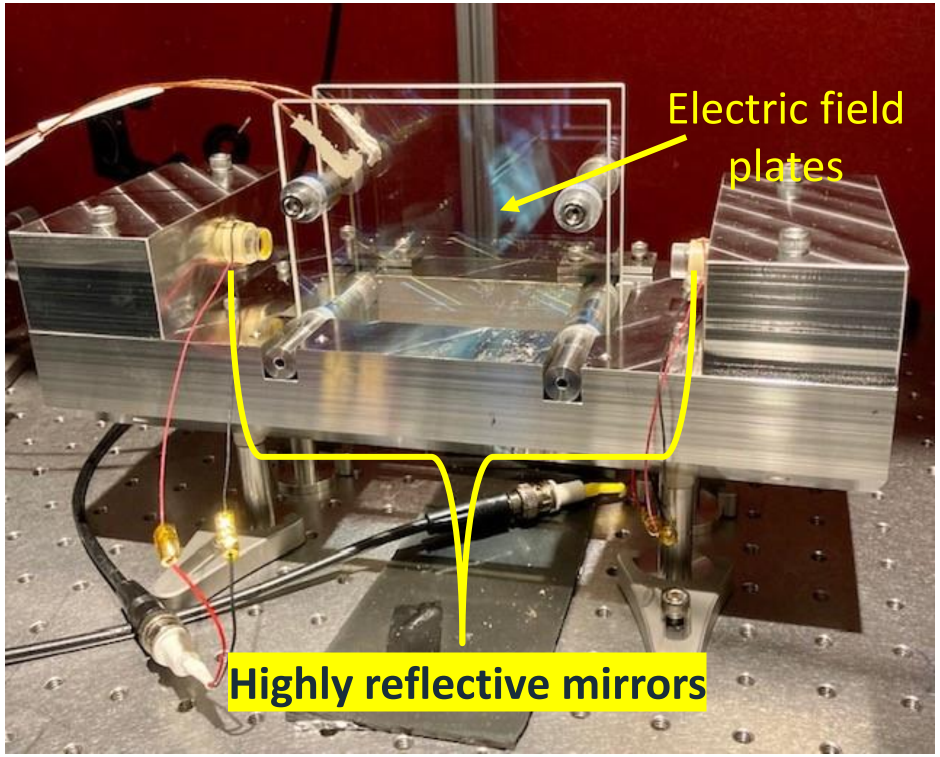
APV signature

$$\underbrace{\frac{\Delta R}{R}}_{\text{measure}} \propto \frac{\overbrace{Im(E1_{PV})}^{\text{extract}}}{\underbrace{\beta E}_{\text{know}}}$$

[2] *M. S. Safronova, W. R. Johnson, and A. Derevianko, Phys. Rev. A, 60, pp. 4476–4487, 1999.*

Power Build Up Cavity (PBC): Key to observe M1 transition

- **PBC:** A spherical mirror resonator where the laser beam bounces back and forth between two highly reflective mirrors.
- UHV compatible power build up cavity.
- Increase in laser power in interaction region by ~ 4000.
- Use Pound-Drever-Hall (PDH) technique → lock the cavity → TEM_{00} mode.
- Cavity length fixed → error signal feedback with piezos.
- Accomodates the electric field plates, MOT beams.
- Stay locked with our vibration sensitive environment.



$T_1 \approx 900$ ppm, $T_2 \approx 50$ ppm,
radii of curvature, $R_1 = R_2 = 100$ cm,
separation between mirrors = 16 cm.

Understanding the magnetic dipole amplitude, $M1$

- $$M1\,(F', m' \rightarrow F, m) = \langle 8S_{F',m'} | \overrightarrow{\mu_M} \cdot \vec{B} | 7S_{F,m} \rangle$$

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

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

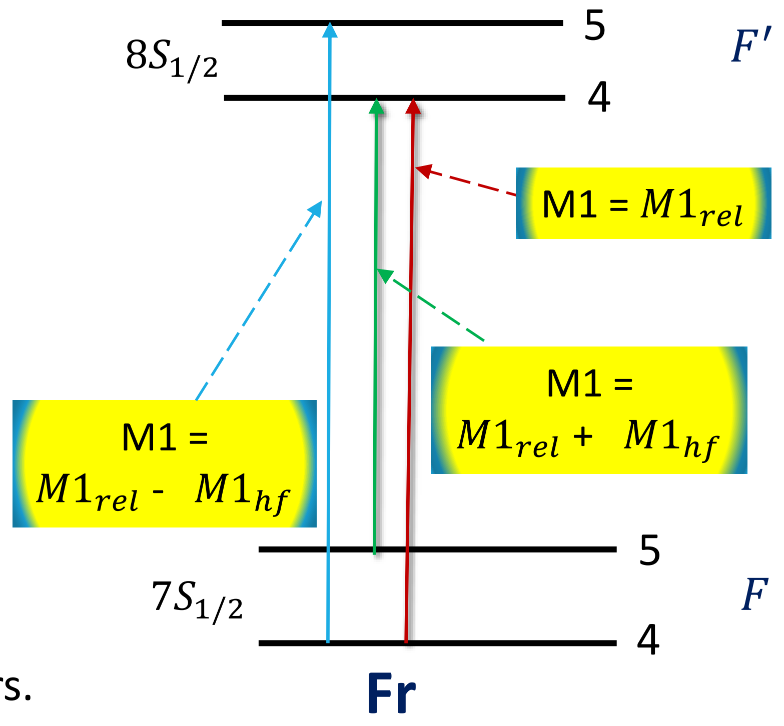
- $$M1\,(F, m \rightarrow F', m') = M1'\,(\hat{k} \times \hat{\varepsilon}).\langle F', m' | \vec{\sigma} | F, m \rangle,$$

- **To measure:**

  $$\boxed{\mathrm{M1} \propto M1_{rel} + (F - F')\, M1_{hf}.}$$

  Where $M1_{rel}$ is the relativistic and spin orbit effect → difficult!
  $M1_{hf}$ is from off-diagonal hyperfine interaction.

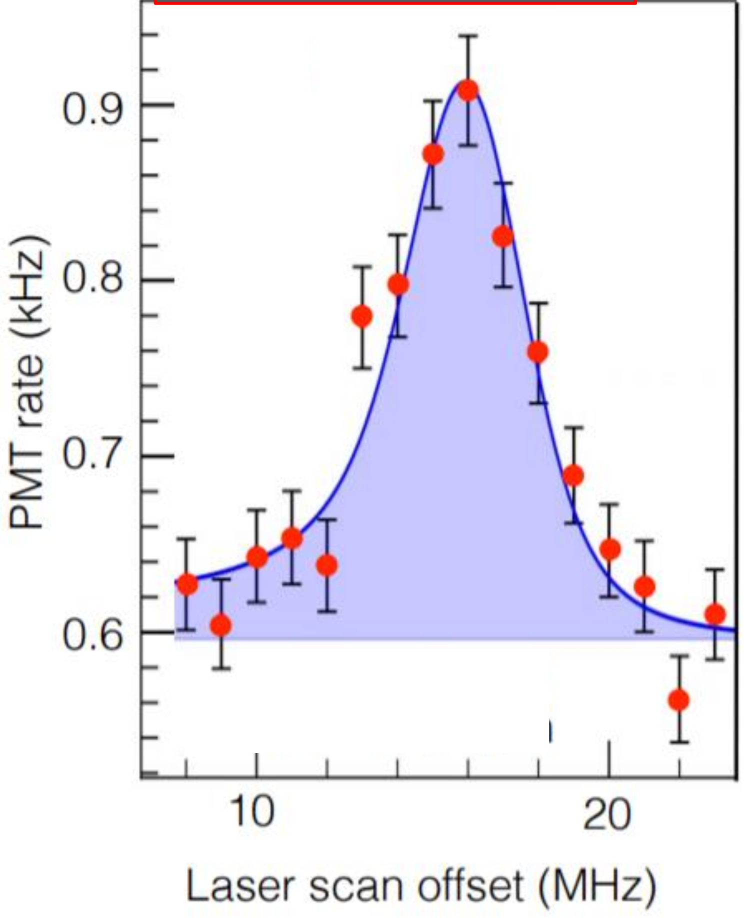
  → Calculable to high precision,
  Only calibrated amplitude in our system compared to all others.



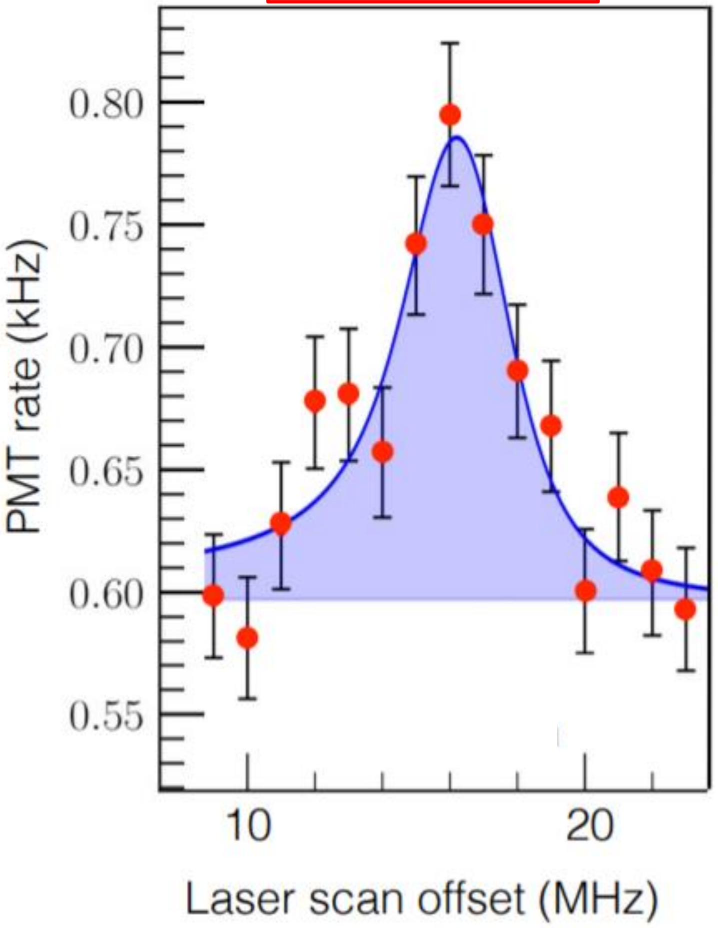
Observation of M1 transition in Sept. 2021

- First observation of ‘free transition’ → unassisted by ‘Stark mixing’ → **M1 transition (f$\sim 10^{-13}$).**
- Made possible by PBC, 4000 folds sensitivity improvement since 2018.
- Can compare relative strength of $\boldsymbol{\beta}$ and M1.

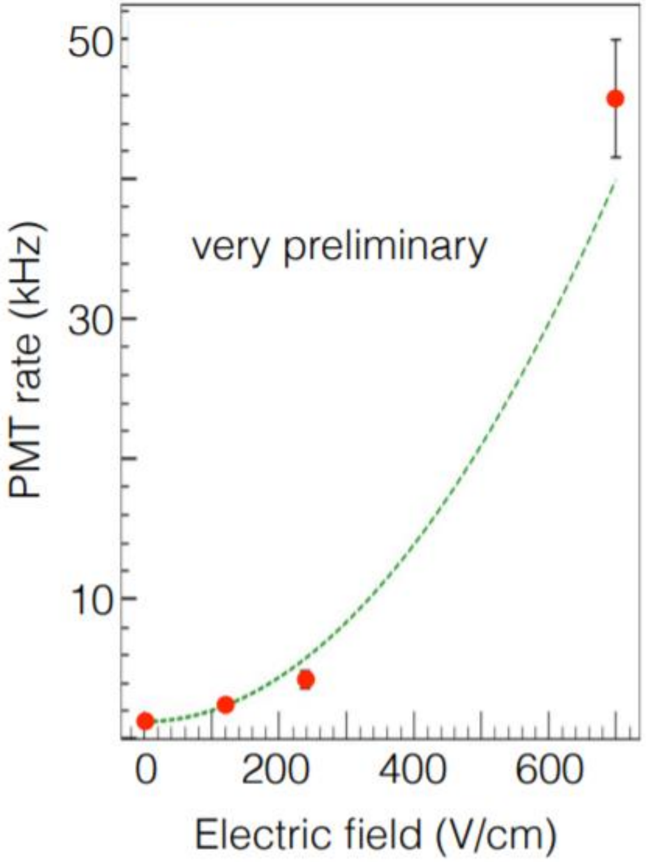
E = 120 V/cm: $\boldsymbol{\beta}$E ≈M1



E = 0: M1 only



$R_{7S\to 8S} \propto |\boldsymbol{\beta}\mathrm{E} + M1|^2$



Towards determination of $\frac{M1}{\beta}$

- Measure $\frac{M1}{\beta}$ on $\Delta F = \pm 1$ and know $M1_{hf}$ → to calibrate β and $M1_{rel}$.
- 2021 beamtime: only $\Delta F = -1$ due to target problems,
- → use predicted values for β and $M1_{hf}$ to measure $M1_{rel}$.

Preliminary data analysis results [3]	Experiment	Theory
$\frac{M1}{\beta} = \frac{M1_{rel} + M1_{hf}}{\beta}$	144 ± 12 V/cm.	-
$M1_{rel}$	$(131 \pm 11) \times 10^{-5}\ \mu_B$	[4] Tran MBPT3: Fr NBr $8s-7s$ 139.9; Br $8s-7s$ 137.4 $\times 10^{-5}\ \mu_B$

Our preliminary results → first measurement will have better than 10% accuracy on the M1 rate, similar to difference between theory and experiment of the analogous transition in Cs, where the best APV experiment was done.

Changes/implementations ahead

- Improve our detection system, photon counting mode → current mode.
- Determine $M1_{hf}$ precisely → establish the value of β → characterizes $E1_{PV}$ signal.
- Will implement optical pumping → know magnetic (m_F) sublevel dependence of atoms → better understand the signal.

[3]. Results from data analysis by colleague, Tim Hucko.
[4]. Safronova et al. Phys. Rev. A 95, 042507, 2017(table VI).

Summary

- ❑ Observed an extremely weak transition in radioactive Fr.
- ❑ Highly motivated in pursuing the APV measurement.
- ❑ Will improve our detection system.
- ❑ Will complete the $\frac{M1}{\beta}$ measurement.

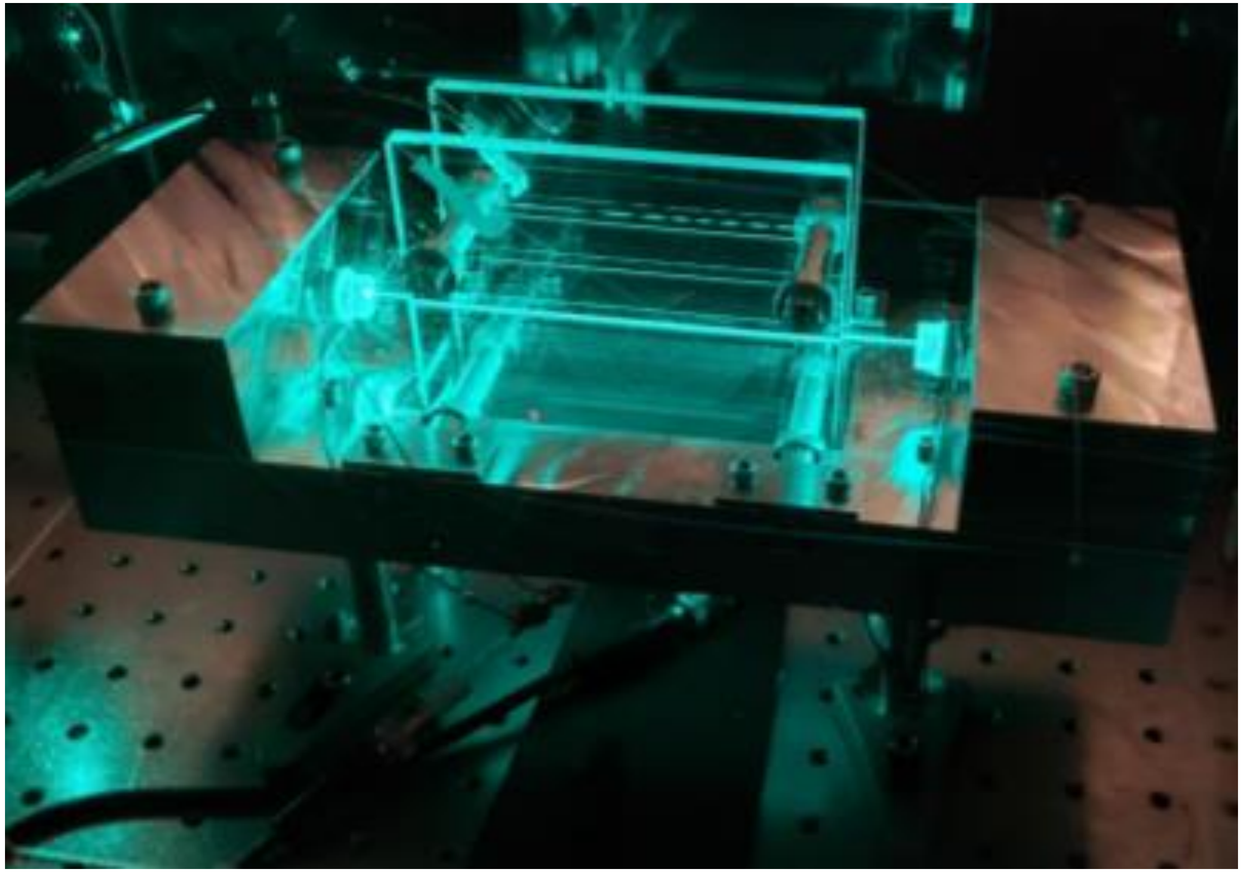
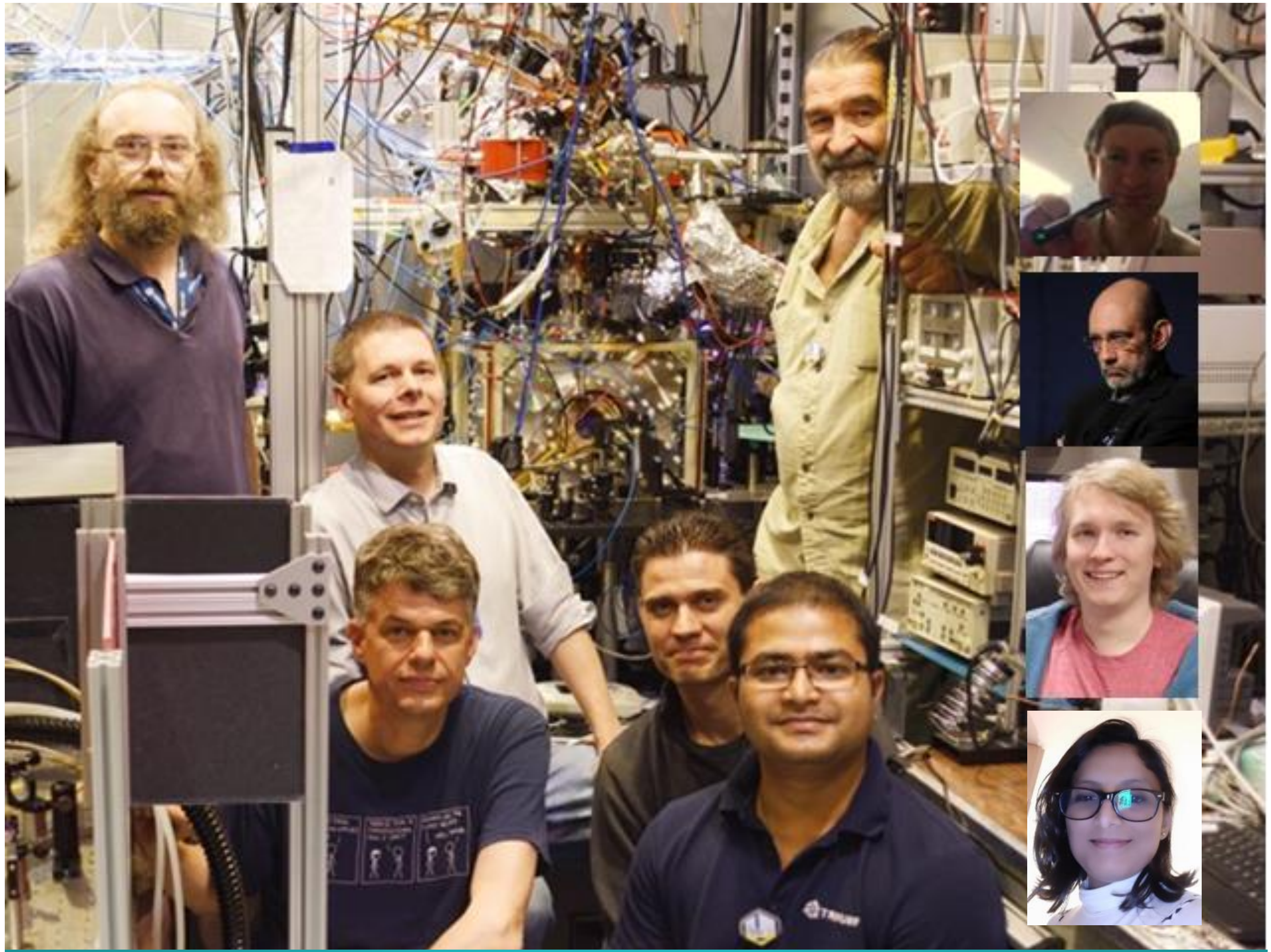


Fig. shows an intense beam of 506 nm light in PBC, and electric field plates[5].

[5]. Image credit to colleague Tim Hucko.

Thank you!



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Funding supported by:
- ❑ NSERC
- ❑ NRC/TRIUMF
- ❑ U o Manitoba
- ❑ U o Maryland

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