OBSERVATION OF MAGNETIC DIPOLE M1 TRANSITION IN FRANCIUM

A KEY STEP TO MEASURE ATOMIC PARITY VIOLATION

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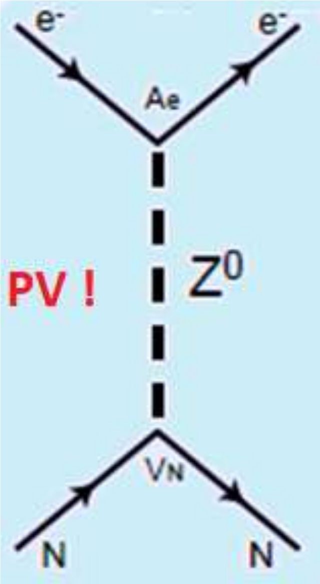
ATOMIC PARITY VIOLATION (APV)

- APV : Exchange of Z_0 boson between atomic electrons and quarks inside the nucleus.
- PV interaction in atom : H_{PV} mixes the opposite parity atomic states.



Weak Interaction

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

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

- Drives : $|S> \rightarrow |S>$ electric dipole E1 transition.

→(*this makes forbidden transition slightly possible.*)

- Transition rate, $R_{S\rightarrow S}$

$$R_{7S\rightarrow 8S} \propto |A_{PV}|^2 \approx (\delta_{PV})^2\, R_{allowed\ EM} \approx 10^{-21}.$$

→(*Very very small signal to observe.*)

Francium benefit:

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

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

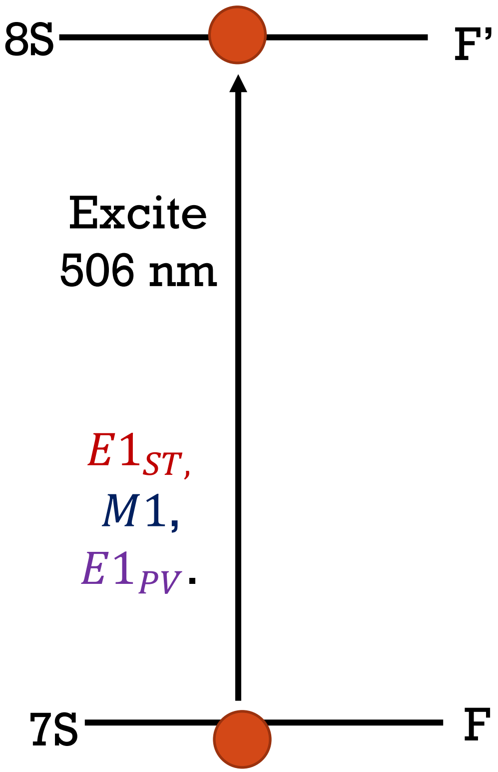
- Intelligent approach : Add large PC signal, apply external dc electric field, 'Stark' amplitude.

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

P state mixed into S state

Stark mixing term, tunable

Transition rate of 7S → 8S transition



Francium (211)

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

  Sum of three distinct contributions:

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

Stark-induced transition PC amplitude $f{\sim}10^{-10}$	Magnetic dipole PC amplitude $f{\sim}10^{-13}$	Parity violating amplitude $f{\sim}10^{-21}$ (unobservable)

Progress Status: Past → Present

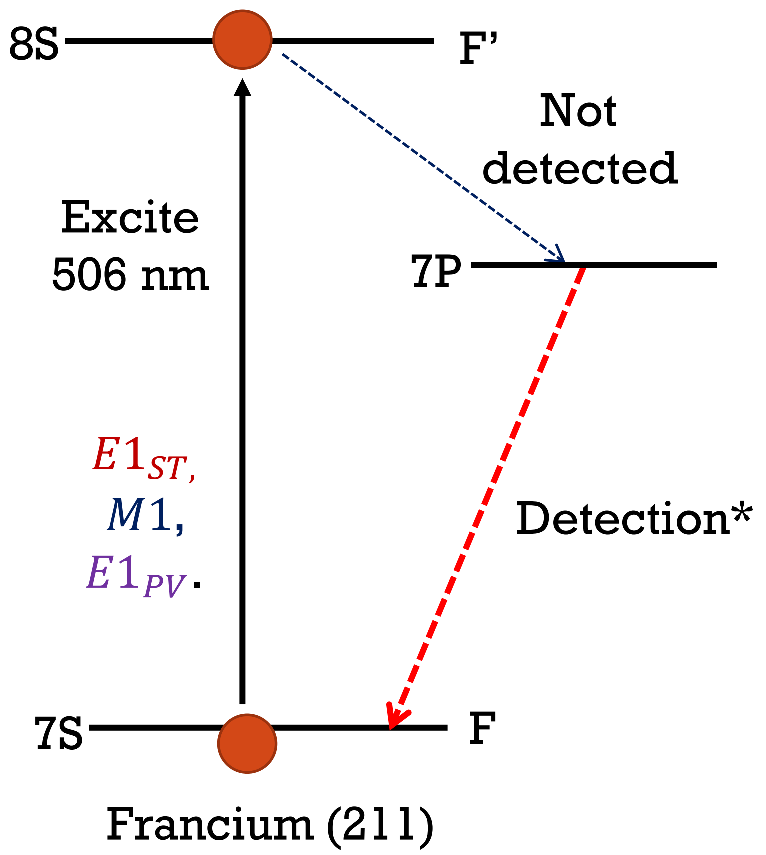
* f is oscillator strength of the corresponding transition.

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

  Interference term $\propto |E1_{ST}| \,.\, |E1_{PV}|$

  → Change sign on parity flip.

Experimental approach



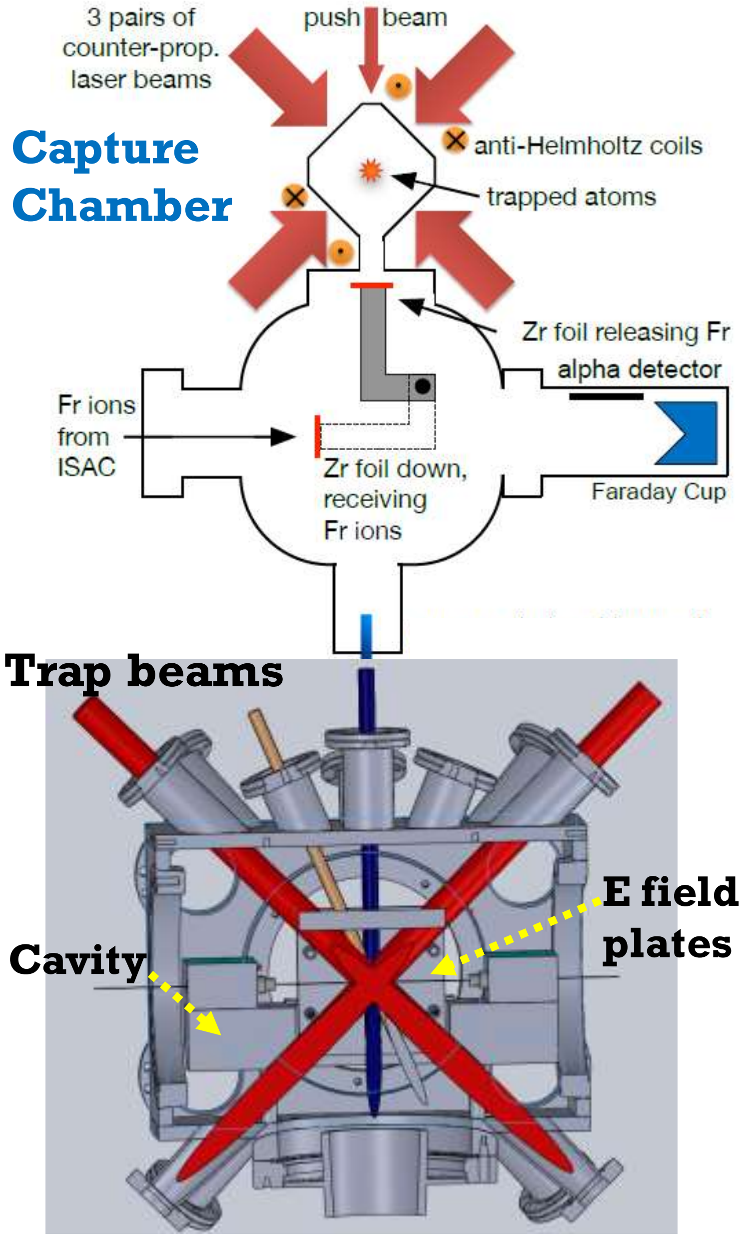
* More on detection later in the talk.

- Laser beam excites highly forbidden $7S \rightarrow 8S$ transition
- Decay sequence is $8S \rightarrow 7P \rightarrow 7S$
- Measure transition rate on $7P \rightarrow 7S$ decay
- Measure $\frac{E1_{PV}}{E1_{ST}}$.

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

Atomic structure factor from theory (K_{PV}),
Weak Charge, Q_W: The goal is to test the Standard Model.

Francium Trapping Facility at TRIUMF



Science Chamber*

*Sectional view of science chamber

- Need for traps: Fr has no stable isotope → need radioactive beam facility → not enough Fr production for atomic beam.
- Re-use atoms in a trap in magneto-optical trap (MOT).
  Trap atoms on $7S_{1/2}$ (F = 5) → $7P_{3/2}$ (F' = 6) cycling transition.
- MOT: 10^5 trapped Fr atoms → for tens of seconds → @ μK temperature → ultra-high vacuum (10^{-10} mbar).
- 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

Motivation to measure M1

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

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

- Transition polarizabilities

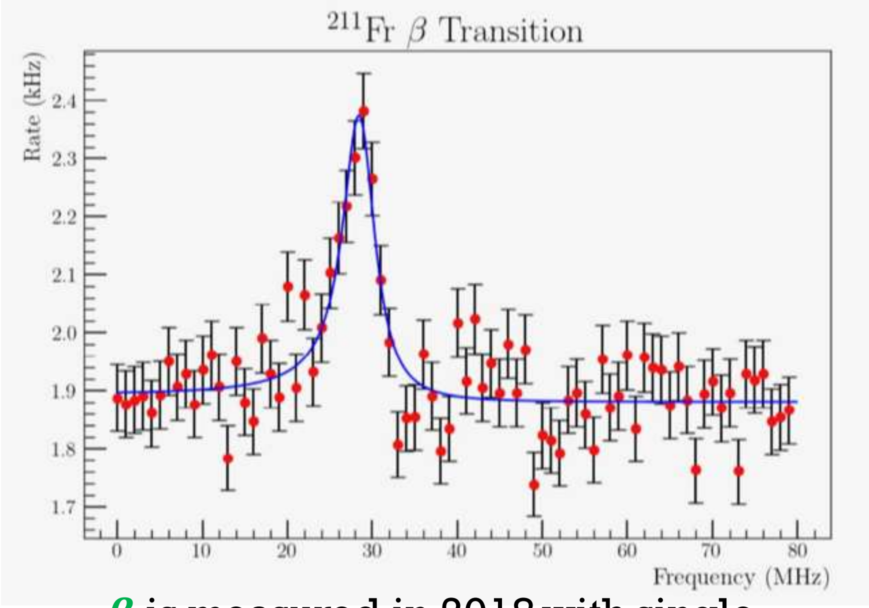
Scalar, α	Vector, β	m – level dependent term
$\Delta F = 0, \varepsilon \,||E$	$\Delta F = \pm 1, \varepsilon \perp E$	

APV signature

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

measure — extract — know

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



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

- β needs to be known accurately → extract $E1_{PV}$,
- Can characterize transition by determining α and β.

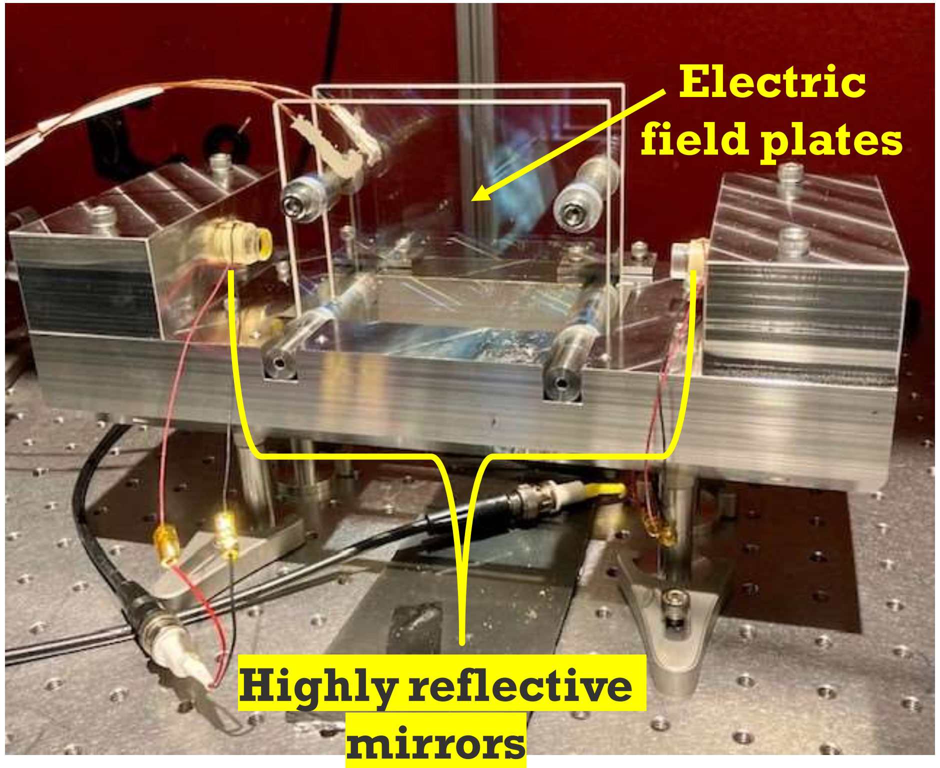
- β can be calibrated via measurement of M1.
  → β and M1 have same m-level dependence,

- β is 25 × smaller than α [1].
- $\frac{\beta E}{M1} \sim 100$.

[1] *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

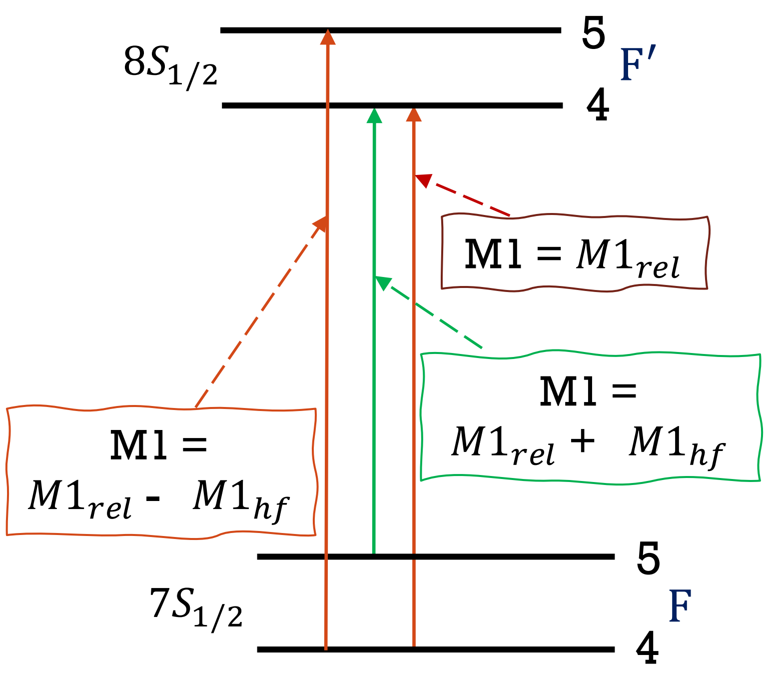
- **PBC:** A spherical mirror resonator where the laser beam bounces back and forth between two highly reflective mirrors.



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

- UHV compatible power build up cavity.
- Increase the laser power in interaction region by ~ 4000 fold.
- Use Pound-Drever-Hall (PDH) technique → lock the cavity → TEM_{00} mode.
- Cavity length fixed → error signal feedback with piezo.
- Accomodates electric field plates, MOT beams.
- Stay locked in our vibration sensitive environment.

Understand the magnetic dipole amplitude, M1



Fr

Known hyperfine splitting

$$M1_{hf} = \frac{\sqrt{\Delta\omega_{7s}\Delta\omega_{8s}}}{\omega_{7s-8s}}\mu_B$$

Known 7s-8s transition energy

- $M1\,(F', m' \rightarrow F, m) = < 8S_{F',m'}|\vec{\mu}_M.\vec{B}|7S_{F,m} >$
  where $\vec{\mu_M} = \vec{\mu_B}\,(g_L L + g_S S + g_I I\,)$, $\vec{\mu_B}$ is Bohr magneton.

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

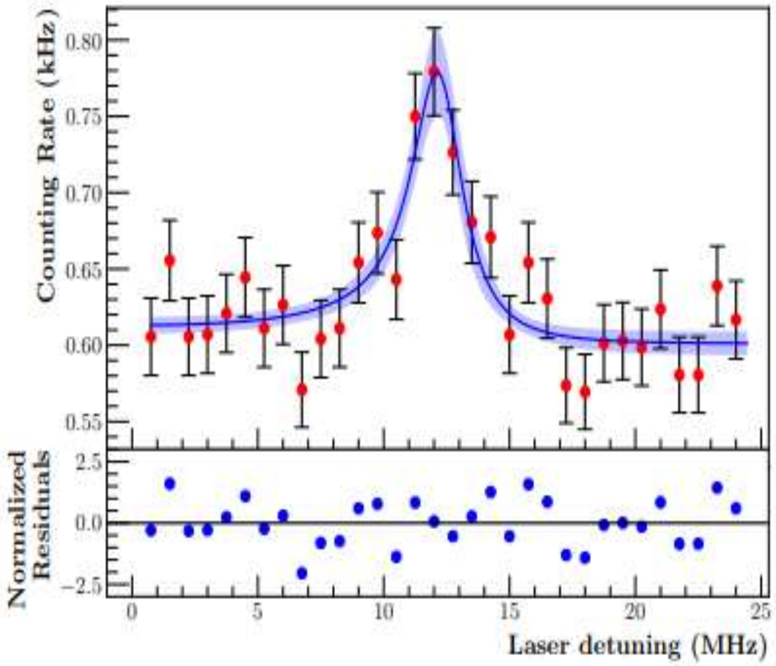
- $M1\,(F, m \rightarrow F', m') = M1'\,(\hat{k} \times \hat{\varepsilon}).< F', m'|\vec{\sigma}|\, F, m >,$
- **To measure:** $M1' \propto M1_{rel} + (F - F')\, M1_{hf}.$

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

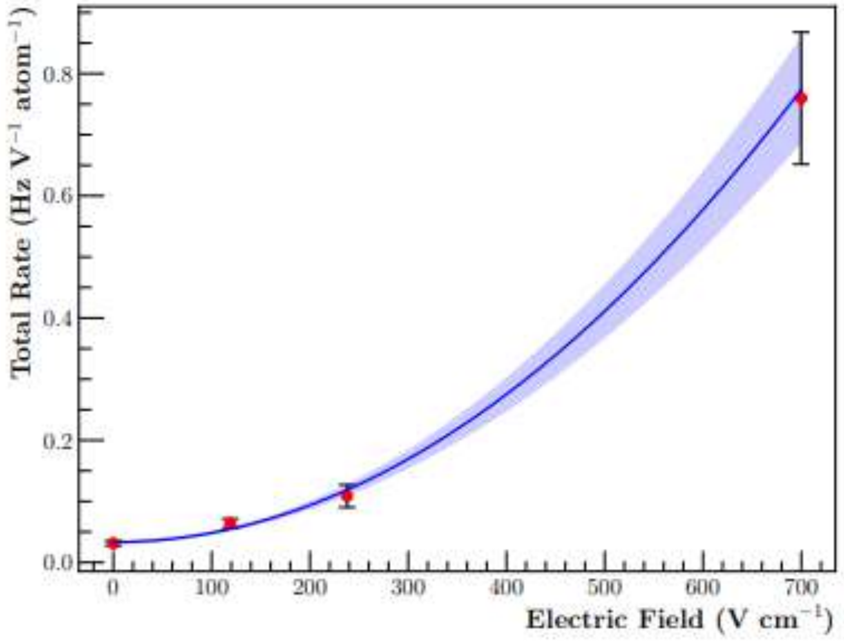
- Measure $\frac{\mathbf{M1}}{\boldsymbol{\beta}}$ on $\Delta F = \pm 1$ and know $M1_{hf}$
  → to calibrate $\boldsymbol{\beta}$ and $M1_{rel}$.

Observation of M1 transition in Sept. 2021

- First observation of 'free transition' → unassisted by 'Stark mixing' → **M1 transition** ($f \sim 10^{-13}$), $R_{7S\rightarrow 8S} \propto |\beta E + M1|^2$.
- Made possible by PBC, 4000 folds sensitivity improvement since 2018.
- What we did? Measured only on $\Delta F = -1$ due to limited beamtime → measure ratio $M1/\beta$ via transition rates at various E fields.
- Combine calculations of β and $M1_{hf}$ to experimentally determine $M1_{rel}$.



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



Normalized transition rates vs electric field.

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

- Result with combination of E field and PBC is below:

Measurements	Experiment [2]	Theory
$\frac{M1}{\beta} = \frac{M1_{rel} + M1_{hf}}{\beta}$	148 ± 12 V/cm.	-
$M1_{rel}$	$(135 \pm 11) \times 10^{-5}\ \mu_B$	Tran MBPT3 [3] Fr NBr $8s-7s$ 139.9 Br $8s-7s$ 137.4 $\times 10^{-5}\ \mu_B$

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

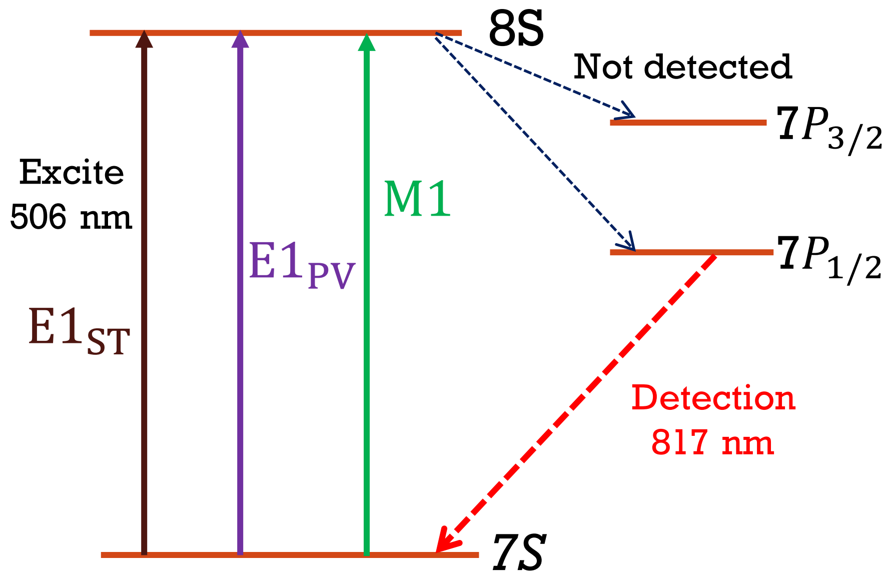
- Possible solution: Decrease E field or 506 nm laser power.
- Next step: Measure M1 transition on $\Delta F = +1$ transition in upcoming beamtime (Aug. 2023).

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

Improvement in detection system

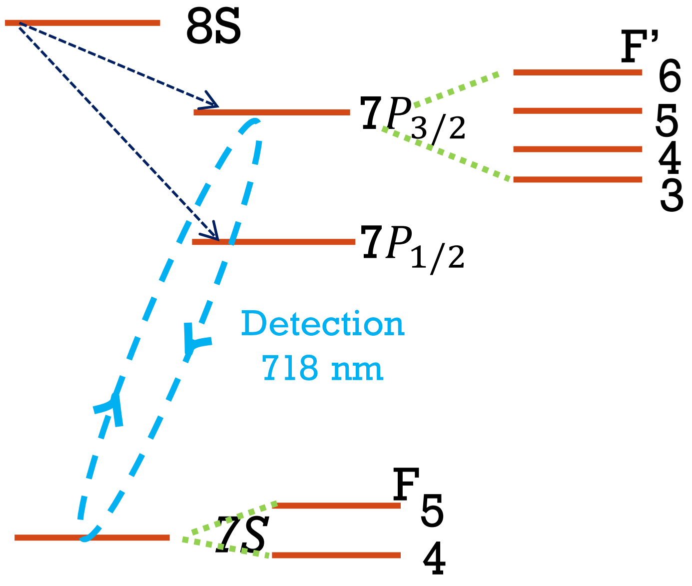
Effective detection efficiency = Solid angle * Filter transmission * Polarizing beam splitter * Detector's detection efficiency

- Detection @ 817 nm: Detection efficiency ≈ 1/4000.
- Detection @ 718 nm: Allows cycling transition → get a burst of photons,
  → estimated cycling of ~ 16000 photons in ~ 1.3 ms for Fr 211,
  → every atom can be cycled enough to get fully detected.



$7S \rightarrow 8S$

Fr 211



$7S \rightarrow 8S$

Fr 211

- **Large signals: PMT (H7422-50)**
  → photon counting mode,
  → can't handle large signals.
- **SiPM (C14456-3050GD):**
  Better quantum efficiency,
  → can be linear ≈ 10 MHz.

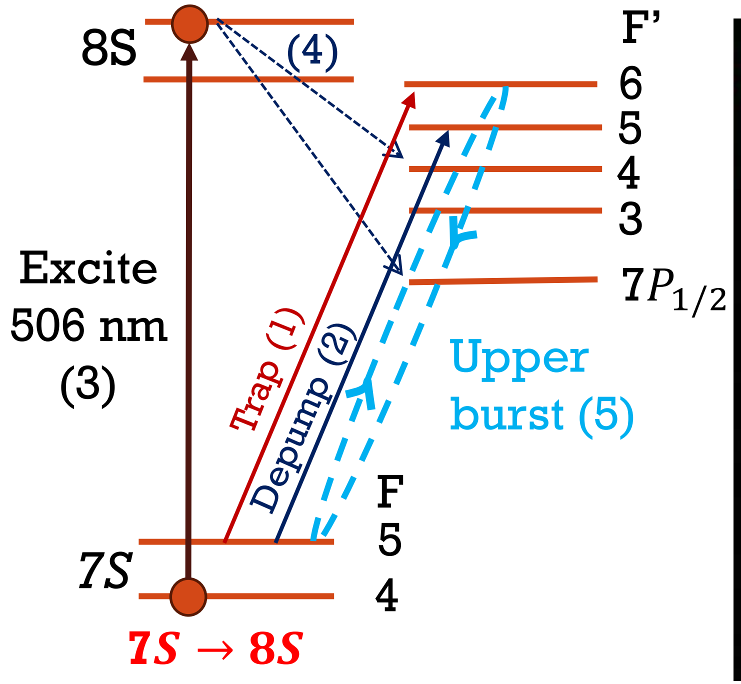
Burst of photons for detection

Upper burst

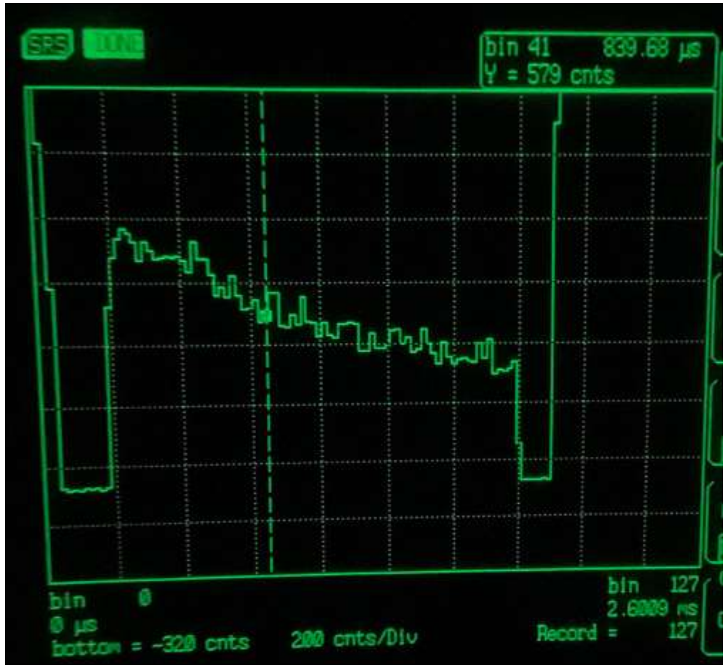
(1) Trap on cycling transition,
(2) Clean F = 5 state → Depump atoms,
(3) Excite (506 nm) → 8S,
(4) Decay 8S to 7S via 7P,
(5) Cycling transition (upper burst).

Lower burst

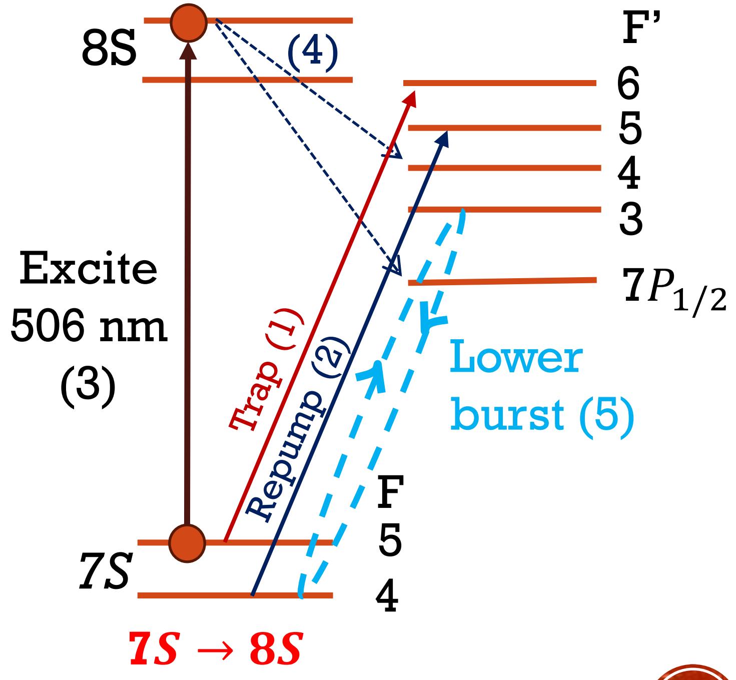
(1) Trap on cycling transition,
(2) Clean F = 4 state → Repump atoms,
(3) Excite (506 nm) → 8S,
(4) Decay 8S to 7S via 7P,
(5) Cycling transition (lower burst).



Fr 211



Upper burst signal in Rb(87), 1/e ~ 532 us
Observed with multi-channel scalar.



Fr 211

Summary

- Observed an extremely weak transition in radioactive Fr.
- Highly motivated in pursuing the APV measurement.
- Will try to reduce the systematic effect of hyperfine pumping and
- Will complete the $\frac{M1}{\beta}$ measurement.
- Determine $M1_{hf}$ precisely
  → establish the value of β
  → characterizes $E1_{PV}$ signal.

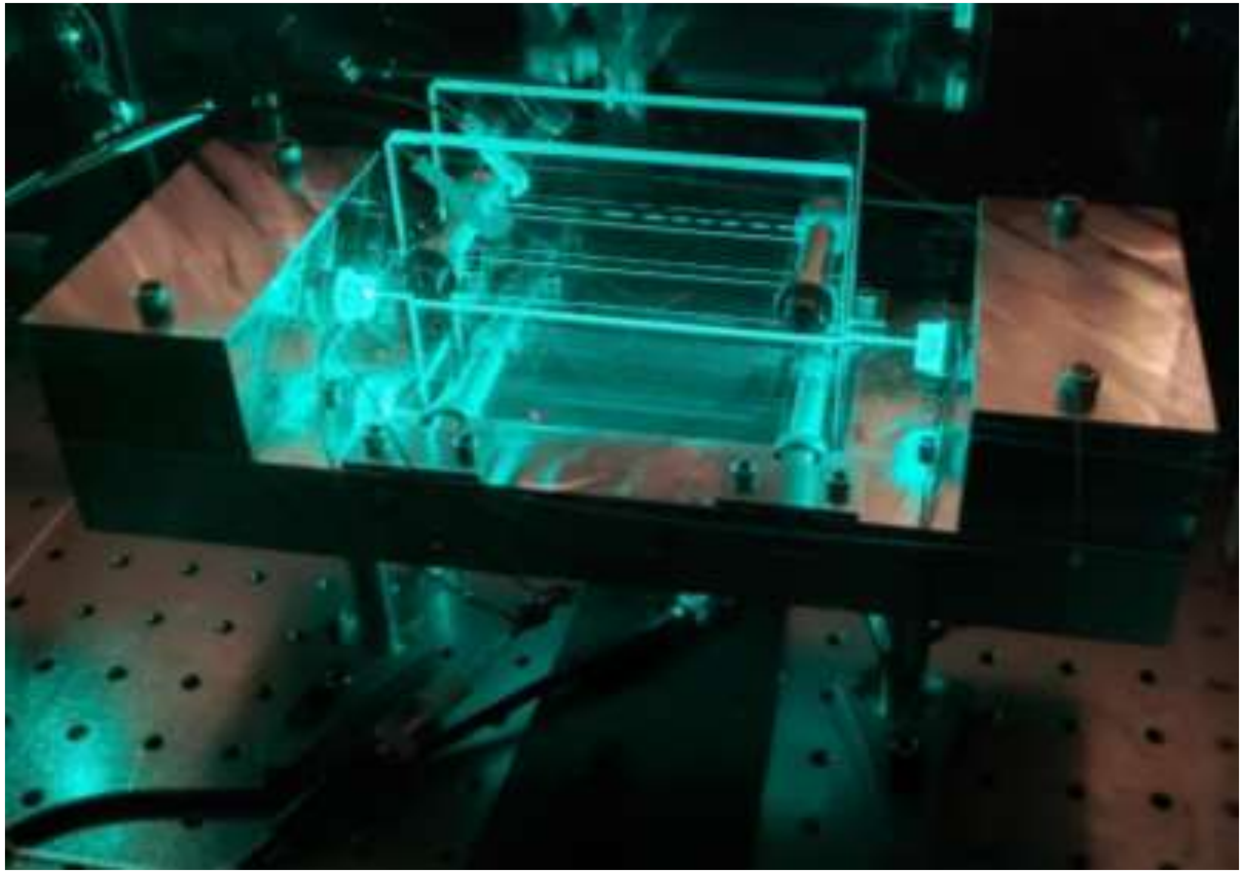
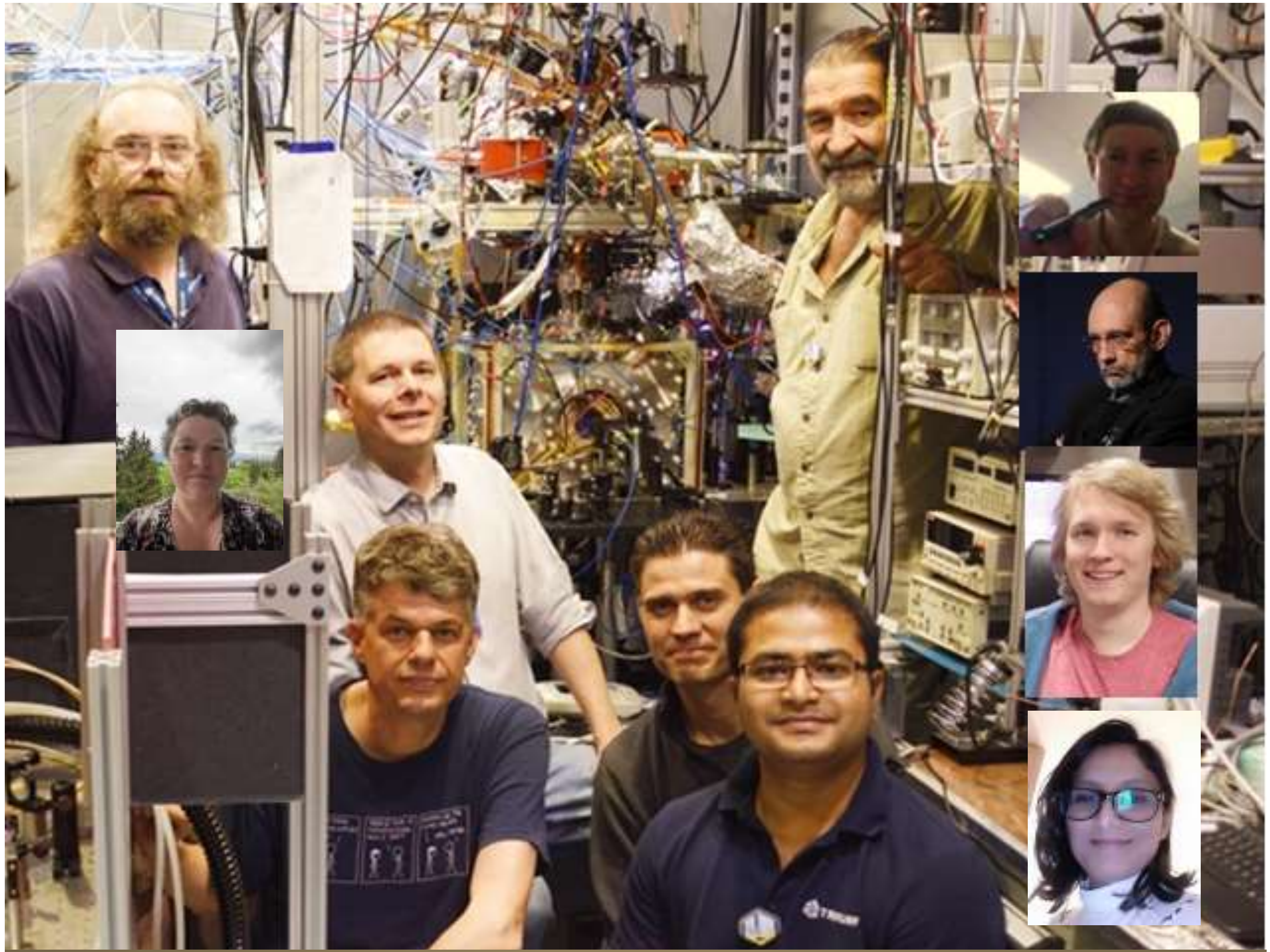


Fig. shows an intense beam of 506 nm light in PBC, and electric field plates.

Thank you!



→ Matt Pearson, Andrea Teigelhoefer, Seth Aubin, Gerald Gwinner, Eduardo Gomez, Mukut Kalita, Alexandre Gorelov, John Behr, Luis Orozco, Tim Hucko, Anima Sharma.

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Back-up slides

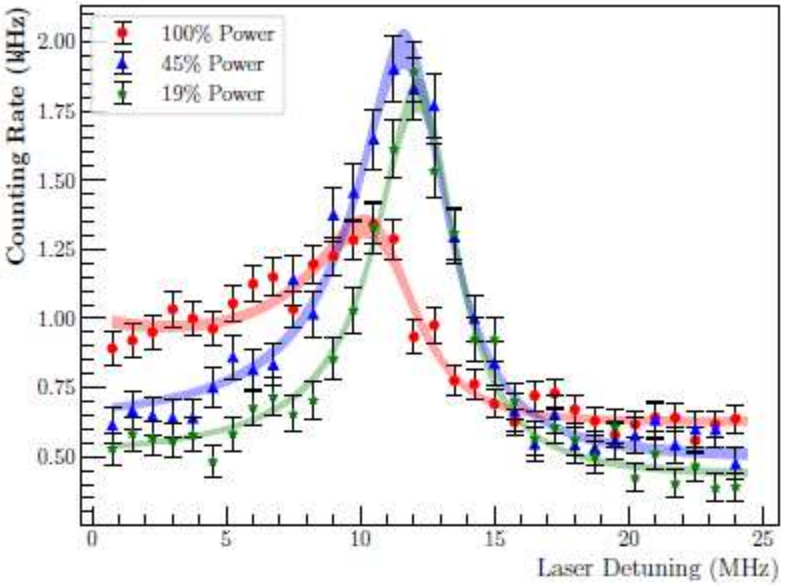


FIG. 4. Demonstration of saturation via hyperfine level pumping. Data points plotted for different input laser powers at an electric field of 700 V/cm. The band represents the fitted function with a 1 σ uncertainty. The difference in peak height can be attributed to the difference in atom number and laser intensity

$$\mathcal{L}_{\rm Exp}(\nu) = a_0 + e^{-\nu/a_2}\frac{a_1}{\pi}\frac{a_4/2}{(\nu-a_3)^2+(a_4/2)^2}.$$

Minimize the χ_2 of the fit function using iminuit by floating the fit parameters: background (a_0), peak height (a_1), trap lifetime (a_2), peak position (a_3), and the linewidth (a_4).

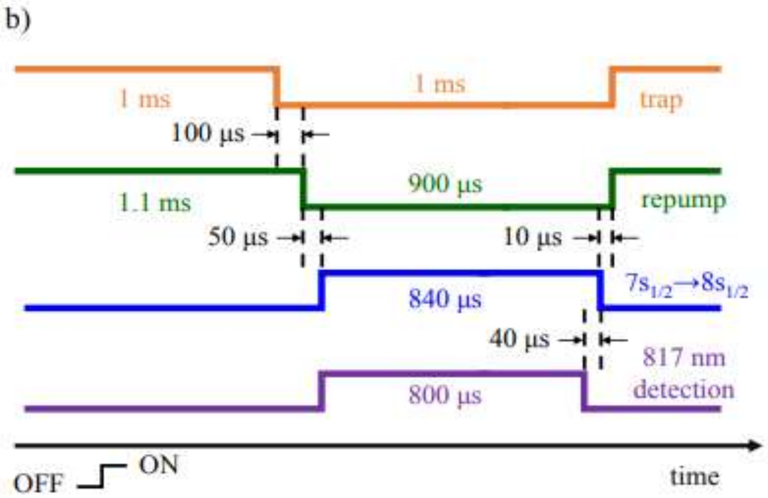


FIG. 1. a) Energy level diagram for ^{211}Fr with relevant transitions. We excite the $7s \rightarrow 8s$ transition with 506 nm light and we detect the 817 nm photons emitted from the decay down to the $7s$ ground state from the $7p_{1/2}$ state. Hyperfine levels not to scale. **b)** Trap-measurement cycle which repeats 39 times at each frequency step of the 1012 nm laser. When the trap (orange) and repump (green) lights are truned off, we excite the the $7s \rightarrow 8s$ (blue) and detect 817 nm photons (purple) at the same time. The entire trap-measurement cycle takes 12.8 s to complete.

$([1-e^{R/R_{\rm sat}}]R_{\rm sat}/R)$, where R is the unsaturated transition rate and $R_{\rm sat}$ is the saturation rate.

- Trap facility: ISAC delivers Fr^+ ions → deposits on Zr foil → heat Zr foil to release neutral Fr → atoms get trapped in capture chamber → push captured atoms to science chamber.

- Explored M1 for last couple of years.

- $\mathrm{M1}_{\mathrm{hf}}$: Calculable to high precision, only calibrated amplitude in our system compared to all others.

- Can compare relative strength of $\boldsymbol{\beta}$ and M1.

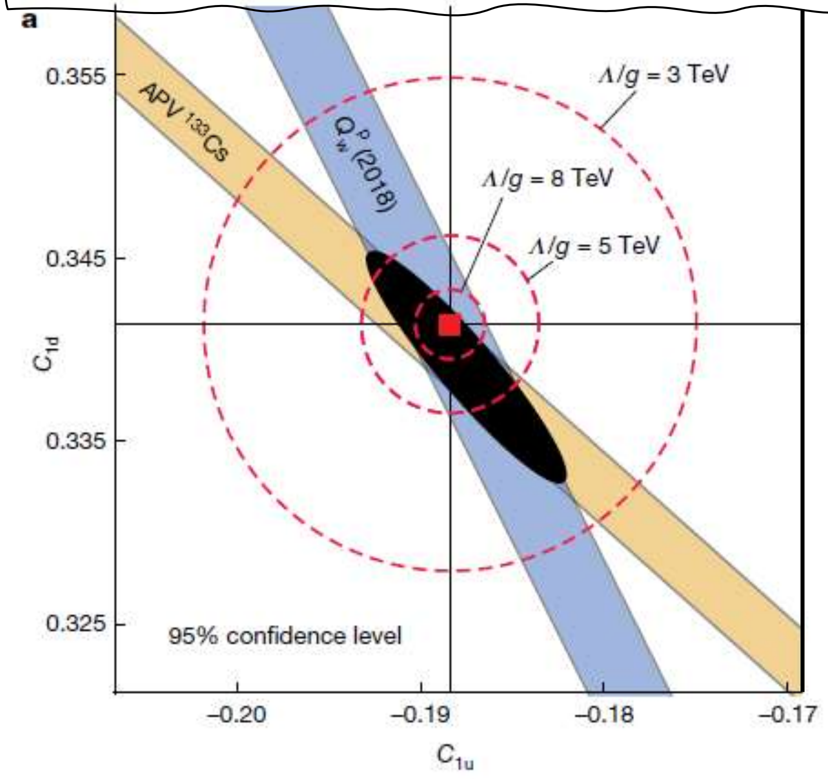
- $\boldsymbol{\beta}$ is understood theoretically much better than $\mathrm{M1}_{\mathrm{rel}}$.

- Having both HF transition rates → ratio of $\mathrm{M1}_{\mathrm{hf}}$ and $\boldsymbol{\beta}$E can be extracted.

This measurement has 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.

LOW ENERGY PRECISION TESTS

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



Q_{weak} Collaboration, Nature 557, 207–211 (2018).

- Test of fundamental symmetries.

Atomic spectroscopy-based techniques.

- APV uncovers the neutral current weak interaction.

Compare parity violating (PV) part on different momentum scale.

- Test the standard model 'SM'.

Determine the coupling constants: C_{1u} and C_{1d},

$$Q_W = 2[(2Z + N)\, C_{1u} + (2N + Z)\, C_{1d}\,]$$

Calculate Weak Charge, Q_W : atomic physics 'window' into SM.