Towards atomic parity violation in Francium

WNPPC 2021

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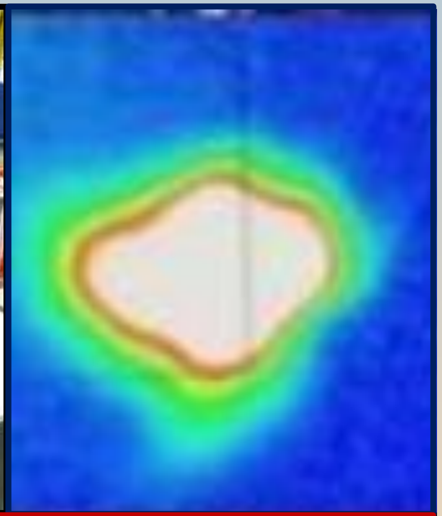

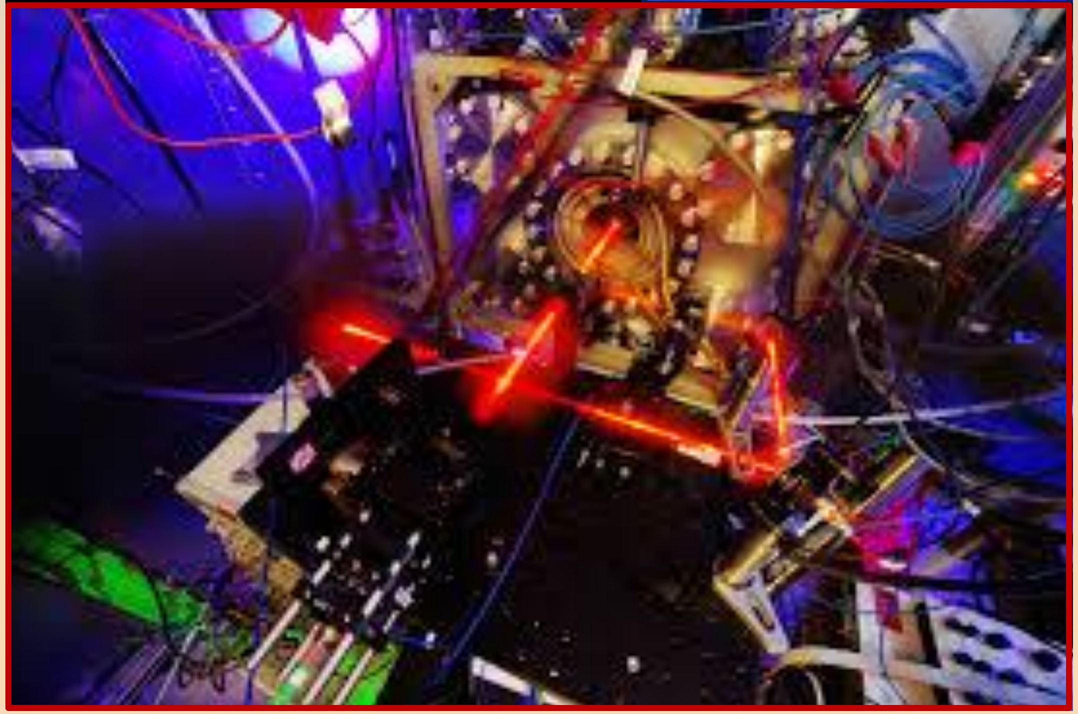

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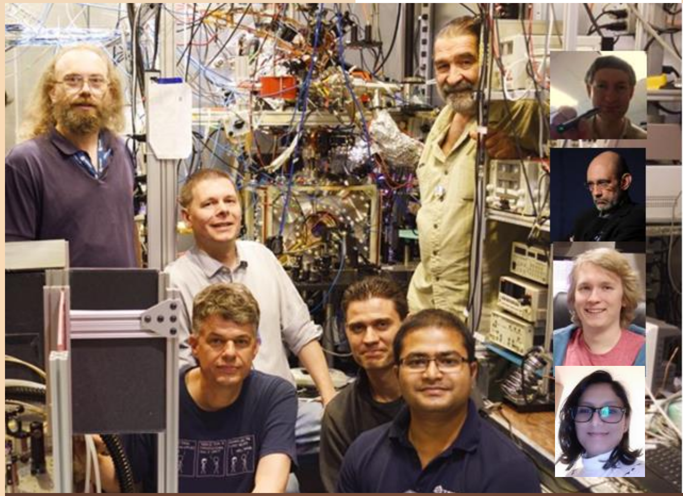

→ Matt Pearson, Seth Aubin, Gerald Gwinner, Eduardo Gomez, Mukut Kalita, Alexandre Gorelov, John Behr, Luis Orozco, Tim Hucko, Anima Sharma.

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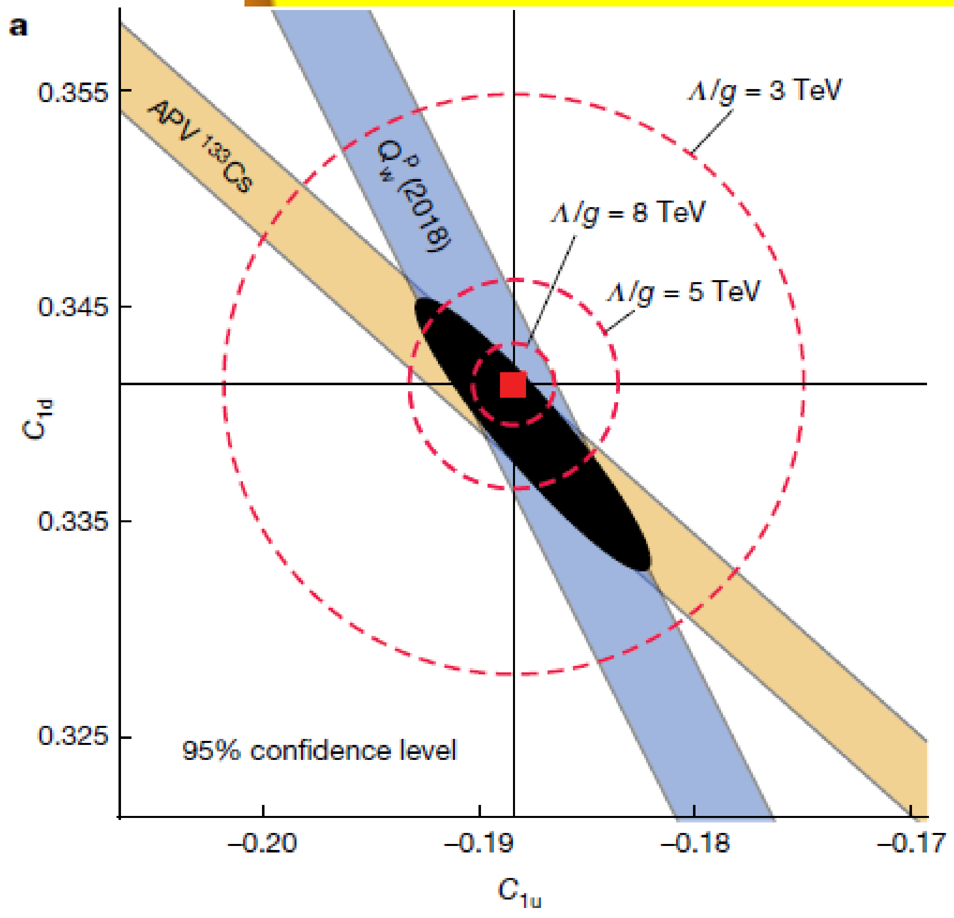
Towards low energy precision tests

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

- ❖ Test of fundamental symmetries
  - ➡ Atomic-spectroscopy based investigation
- ❖ Test the Standard Model (SM)
  - ➡ Investigating the electroweak interaction
- ❖ Precise and direct effort to test the Standard Model
  - ➡ Atomic Parity Violation (APV) in Weak Interaction



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

Atomic Parity Violation

- Z^0 boson exchange b/w atomic electron and quarks in nucleus → PV atomic Hamiltonian H_{PV}
  → H_{PV} mixes atomic S and P states → atomic orbitals lose definite parity

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

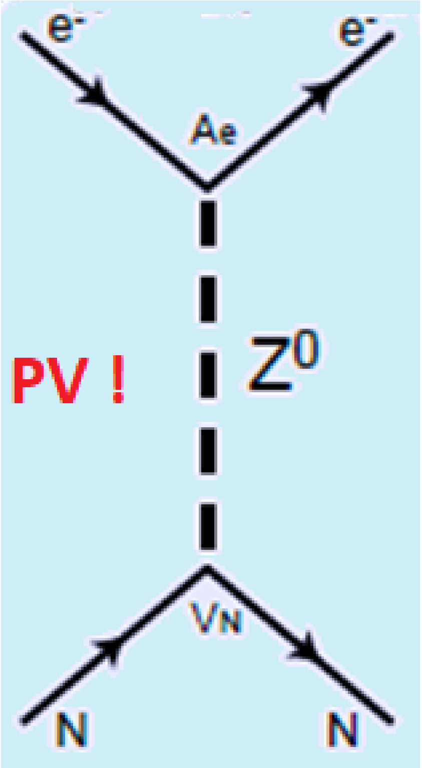
- **APV signature:** drive S → S E1 transition amplitude $\boldsymbol{A_{PV}}$

- **Problem**: Cs 6S → 7S experimental rate
  $R_{\mathrm{S}\rightarrow\mathrm{S}} \propto |A_{PV}|^2_{Cs} \approx 10^{-22}$ *Way too small to observe*

- **Solution**: Interfere with much large Parity Conserving 'PC' amplitude! *Tunable*
  External static electric field also mixes S and P → PC "Stark" amplitude $\boldsymbol{A_{ST}}$

- To date **best APV test in** Cesium (Cs) [1]
  $\boldsymbol{A_{PV}}$ measured precisely with fractional uncertainty of 0.35 %

- **Idea**: larger Z, simple alkali structure → Francium (Fr) → Effect 18× larger than in Cs



Weak Interaction

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

Principles of Stark APV experiment

❖ **Transition Rate, R**

$$\mathbf{R} \propto |\, A_{PV} + A_{ST}|^2$$

Observable

$$\approx \underbrace{|A_{PV}|^2}_{\sim 10^{-21}\ (negligible)} + \underbrace{|A_{ST}|^2}_{\sim 10^{-10}} \pm 2\,\mathrm{Re}\,\underbrace{(A_{PV}\ .\ A_{ST})}_{\text{Interference term } (\sim 10^{-15})}$$

❖ Interference term changes sign on parity flip ← E field reversal

❖ Quantity of Interest

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

discuss later

❖ **Experimental approach**

❖ Laser beam excites highly forbidden 7S → 8S transition

❖ Decay sequence is 8S → 7P → 7S

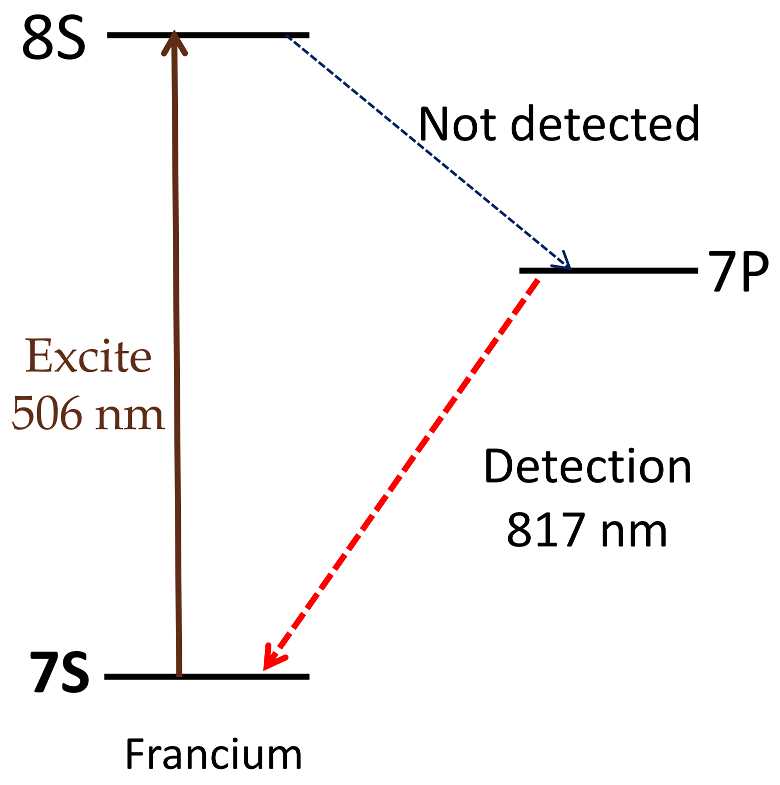
❖ Measure transition rate on 7P → 7S decay

❖ Measure $\frac{A_{PV}}{A_{ST}}$

$$A_{PV} = K_{PV}\ Q_W$$

Atomic structure factor from theory (K_{PV})

Weak Charge (Q_W)



Francium Trapping Facility (FTF) @ 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

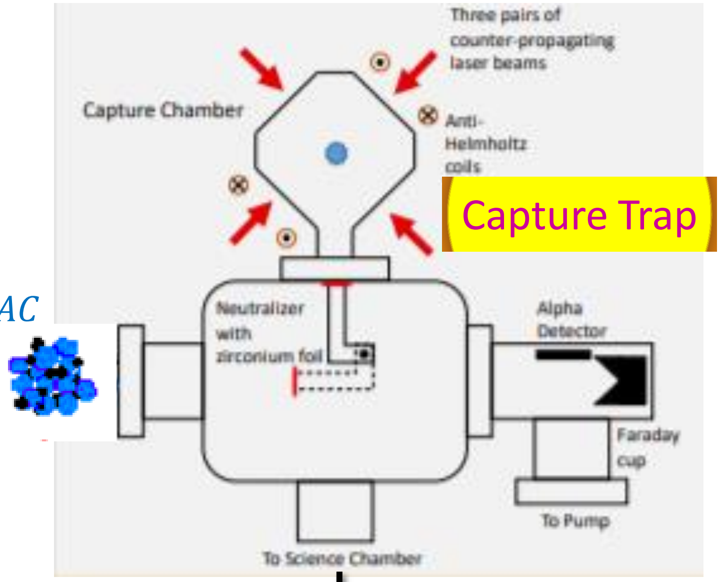
❖ Suspend million of Fr atoms at μK temperature

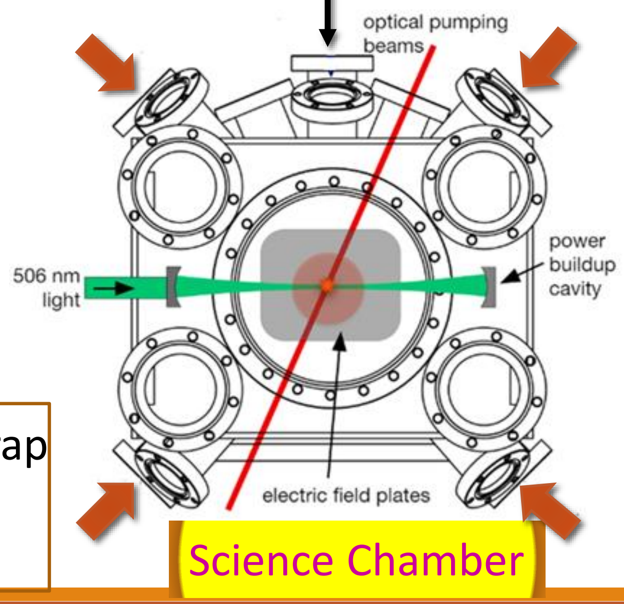
❖ Trap atoms on $7S_{1/2}$ (F = 5) → $7P_{3/2}$ (F' = 6) transition

❖ Precise control of electric and magnetic fields

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

Fr^{+} *from ISAC*





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

Measurements done so far by Fr group

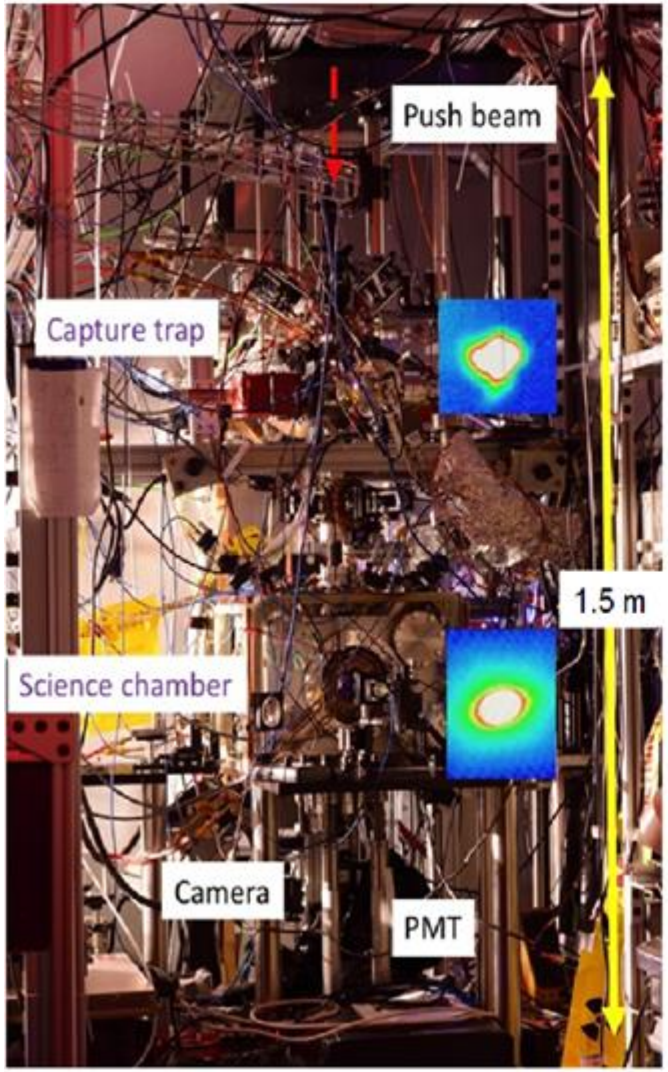
- Measurement of the 7S - $7P_{1/2}$ (D1) isotope shift in $^{206-213,221}Fr$
  R. Collister et al. Phys. Rev. A 90 052502 (2014)

- Measurement of the $7P_{1/2}$ hyperfine splitting in a chain of Fr isotopes
  Zhang et. al. Phys. Rev. Lett. 115 042501 (2015)

- Measurement of the $7P_{3/2}$ photo – ionization cross section
  R. Collister et al. Can J. Phys (2017)

- Two photon 7S – 8S spectroscopy: Isotope shift measurements and comparison to ab initio theory
  M.R. Kalita et al. Phys. Rev. A 97, 042507 (2018)

- DC stark shift signal in Fr (2018)
  Milestone: Observation of the β transition



Capture trap and Science Chamber in Fr lab

Important step: Understand the Stark amplitude

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

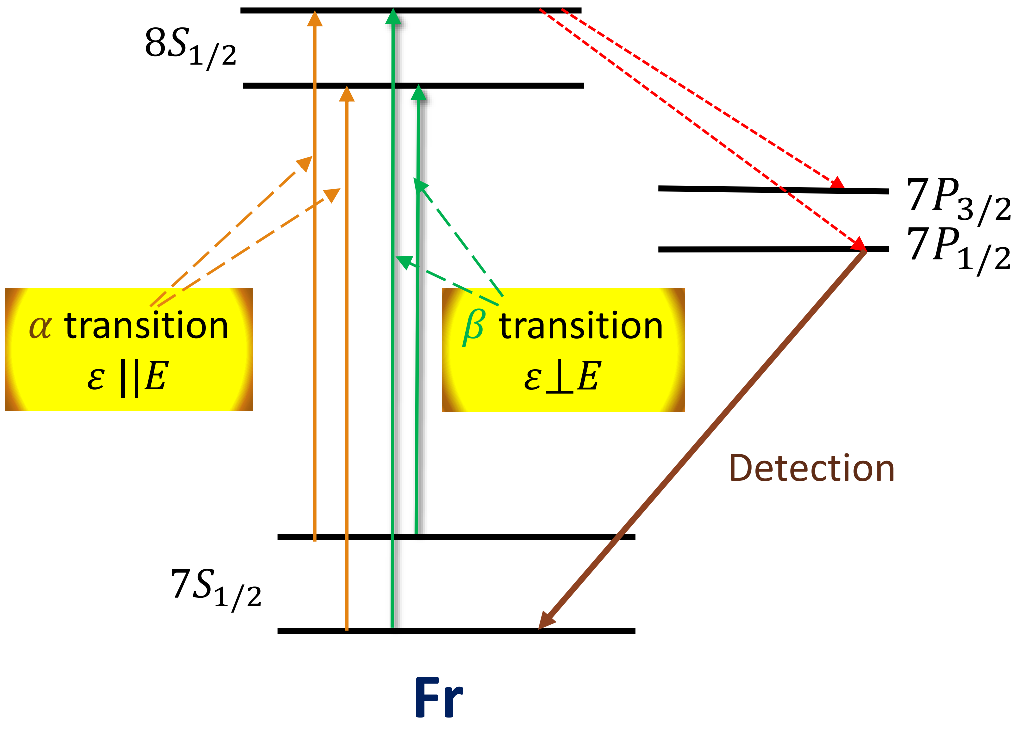
'm' dependent term

$$A_{ST}(\mathrm{F}', m_{F'}, \mathrm{F}, m_F) = \alpha\, E.\epsilon\, \delta_{F'F}\delta_{m_{F'}m_F} + \mathrm{i}\, \underbrace{\beta\, (E \times \epsilon) \cdot < \mathrm{F}', m_{F'} |\sigma| \mathrm{F}, m_F >}_{\text{Interfere with } A_{PV}}$$

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

- Transition Polarizabilities
  - → Scalar, α, $\Delta F = 0$, $\Delta m_F = 0$
  - → Vector, β, $\Delta F = \pm 1$, $\Delta m_F = \pm 1, 0$

- Predicted value [2]
  - → $\frac{\alpha}{\beta} \approx 5.05$



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

Motivation for the $\frac{\alpha}{\beta}$ measurement

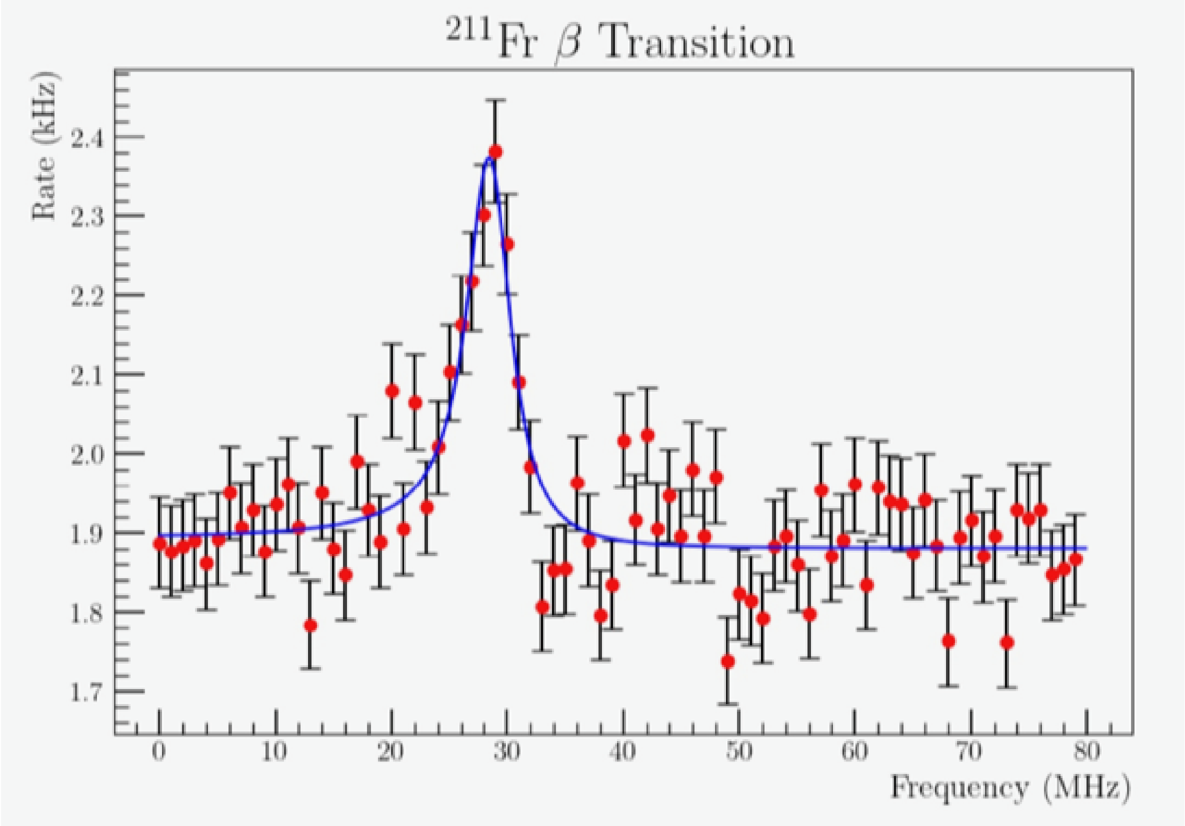
- To extract the $E1_{PV}$, 'β' needs to be known accurately.
- $\beta \rightarrow$ hard to measure.
- $\frac{\alpha}{\beta}$ measurable $\rightarrow$ test theory prediction for β.
- $\frac{\alpha}{\beta}$ experimental quantity is a good test for atomic PV theory calculations.
- β amplitude is m - dependent, α amplitude is not.
- Atoms in MOT have unpredictable m – level distribution.
- Need to optically pump atoms in specific $|F, m_F\ >$

APV signature

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

First Observation of the 7S → 8S β Stark induced transition

- About $10^9 - 10^{10}$ times weaker than typical atomic transitions
- Have also observed α transition ($\times$ 25 larger)
- → Re- measure with optically pumped atoms

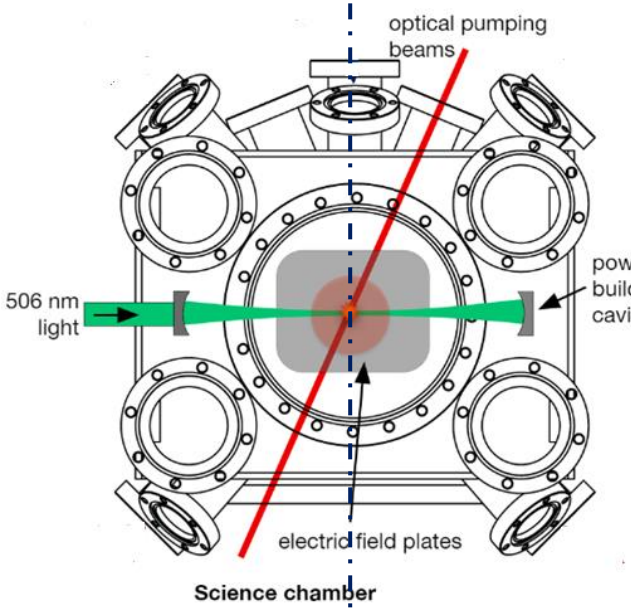


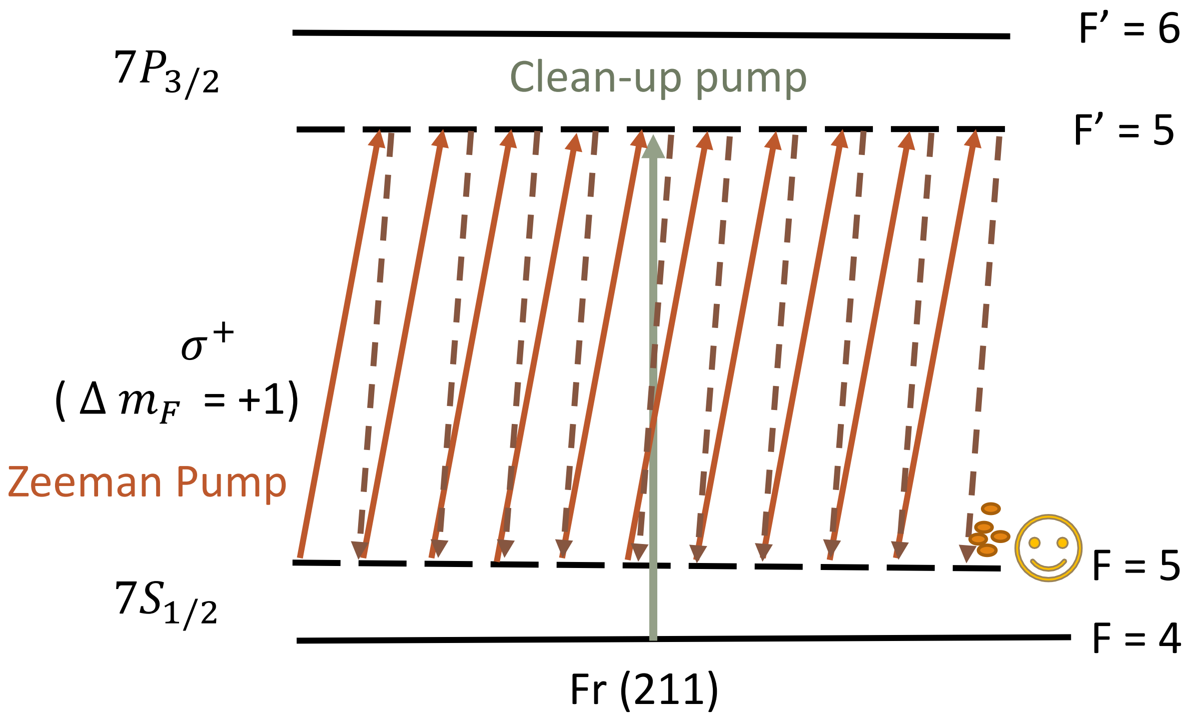
First signal of β Stark induced transition

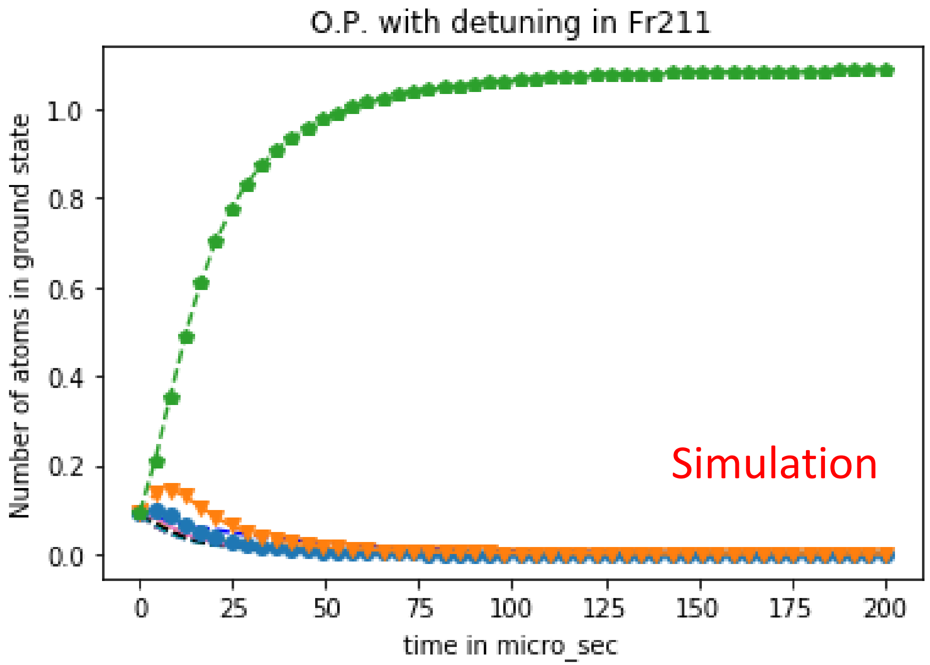
Optical Pumping (O.P.)

- Two processes to get population in a single F, m_F ground state
  - a) Transfer of angular momentum to atoms in MOT
  - b) Deplete the atoms from unwanted hyperfine level

- The creation of atomic ground state polarization is 'Optical Pumping'.
- Apply magnetic field to define 'quantization axis'.







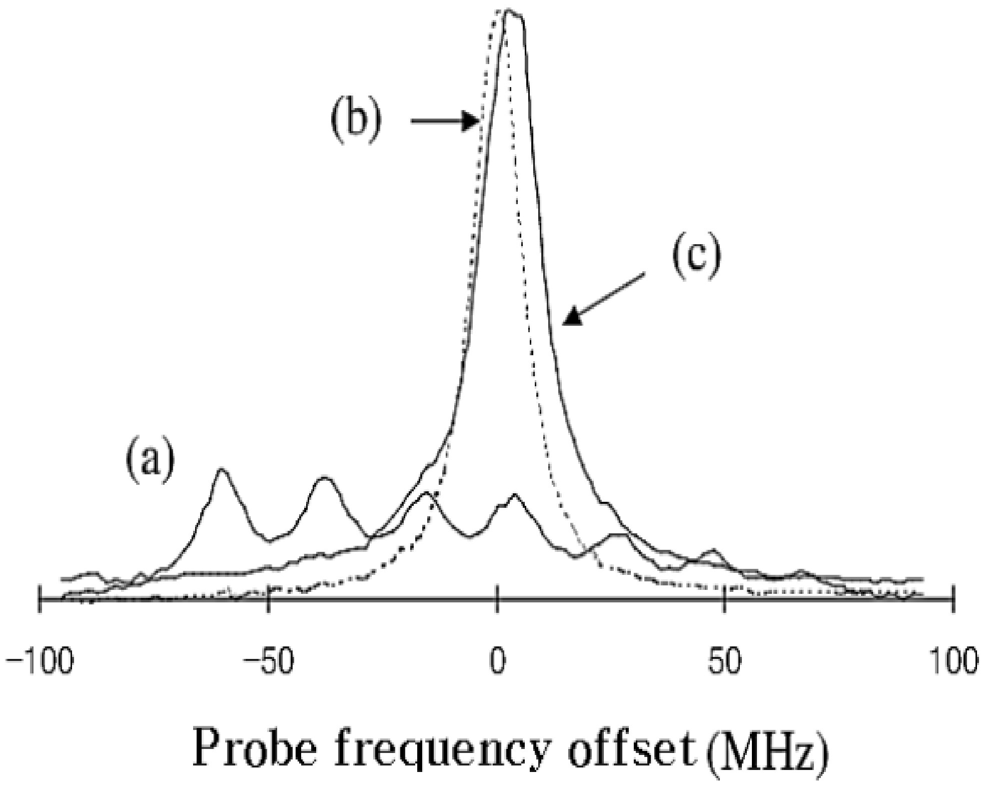
Detection of Optical Pumping

- Need to experimentally verify the quality of O.P.
- Resolve Zeeman sublevels by several linewidths by applying a large magnetic field
- Scan the laser over resolved ‘m’ sublevels and observe the spectra.

Challenges for implementation

- Several magnetic (B) fields have to be switched On/Off at ~ 100 μs scale
- Eddy currents in Chamber walls
- Tight geometrical constraints of O.P. beam implementation in our chamber

- Currently implementing B – field control
- Summer 2021: Test O.P. sometime soon



[2] The distribution of atoms $6S_{1/2}\ (F = 4, m_F)$ as measured by probe frequency scan

(a) Without O.P. with 30 G

(b) w/o O.P. when B = 0 G

(c) With O.P. into m_F = 0 with B = 30 G in Cs

[2] Choi et al., JKPS, Vol. 46, No.2, Feb 2005, pp. 425 ~ 430

Summary

- Towards APV $\rightarrow$ need to spin polarize the atoms.

- Combination of O.P. with cooling and trapping techniques can control internal and external degrees of freedom.

- To extract $E1_{PV}$, 'β' needs to be known precisely.

- $\frac{\alpha}{\beta}$ measurement in Rb and Fr will be a critical step to determine β.

Thank you!

(Back up slide) Theory

- ❖ Parity violating electric dipole transition amplitude, A_{PV}

  $A_{PV}(F', m'_F, F, m_F) = i\, Im\, (E1_{PV})\, \epsilon. < F', m'_F\, |\sigma| F, m_F >$

- ❖ Stark Induced electric dipole transition amplitude, A_{ST}

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

- ❖ Transition Rate, **R**

$$\mathbf{R} = |\, A_{PV} + A_{ST} |^2$$

$$= |A_{PV}|^2 + |A_{ST}|^2 \pm \underbrace{2\, \mathrm{Re}\, (A_{PV} \,.\, A_{ST})}_{\text{Interference term}}$$

- ❖ Interference term changes sign on parity reversal
- ❖ Quantity of Interest

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