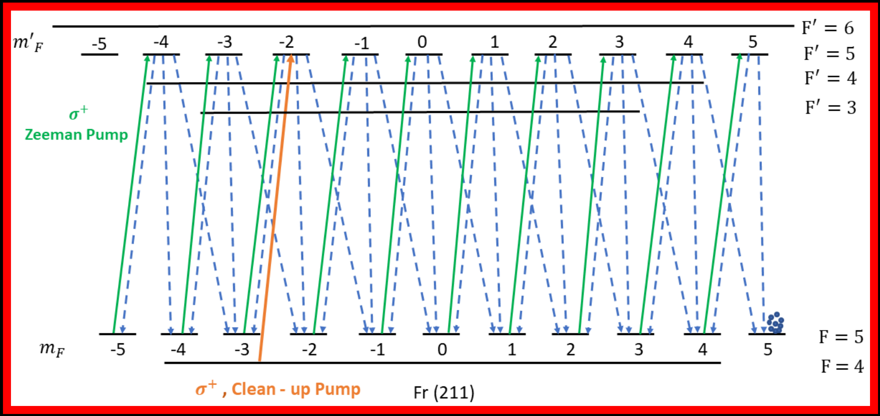
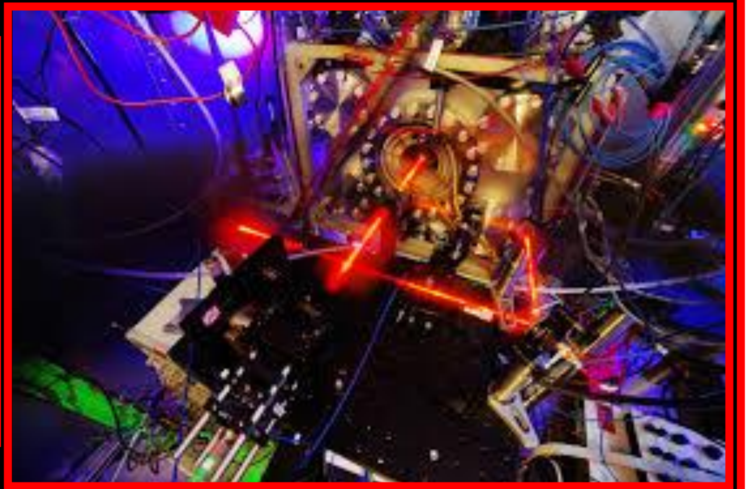
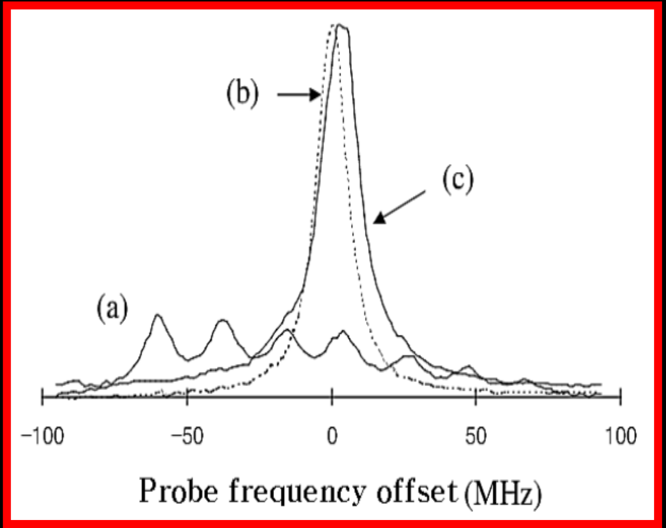
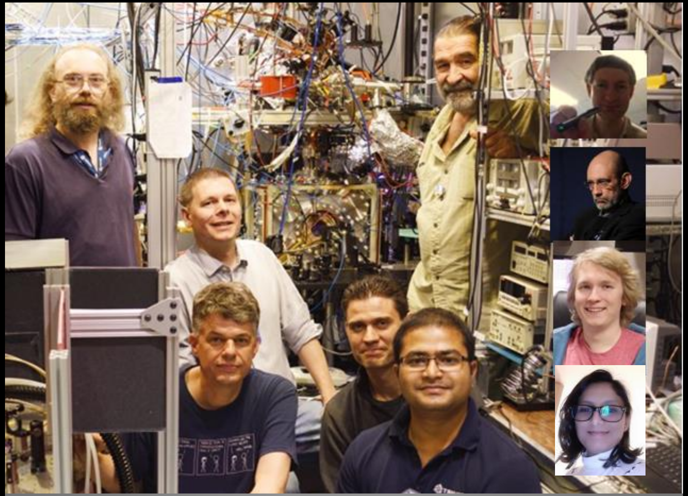
Optical pumping of francium atoms for the measurement of the 7S-8S scalar to vector transition polarizability ratio.









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

CAP 2022

Presenter: Anima Sharma.

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Motivation for atomic parity violation (APV) measurement

APV

- Precise and direct test of Standard Model.
  - APV in weak interaction.
  - Measure weak nuclear charge.
  - PV electron quark coupling C_{1u} and C_{1d}.

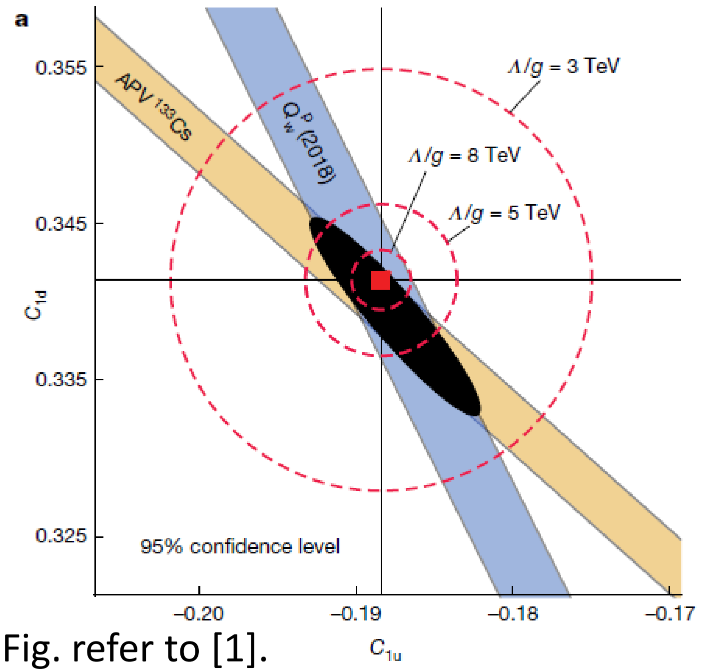

Fig. refer to [1].

- Explore fundamental symmetries.
  - *Symmetry dictates interaction.*[2]
  - Use atomic-spectroscopy based techniques.

- Low energy test of electroweak theory.
  - Symmetry-violating contributions beyond SM.
  - Complementary to high-energy physics results.

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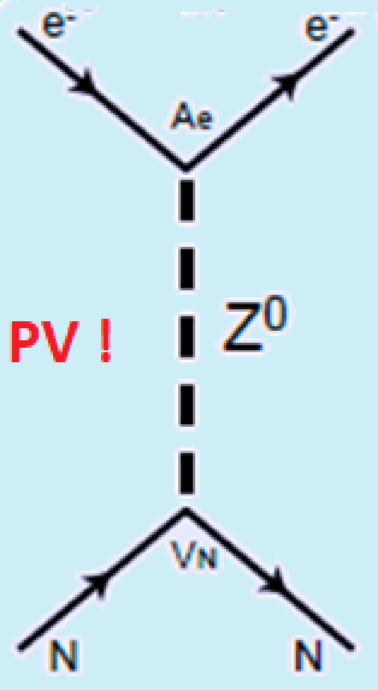
[1]. Q_{weak} Collaboration, Nature 557, 207–211 (2018).

[2]. Quote by C. N. Yang.

Atomic parity violation (APV)

- APV arises -

atomic electrons $\xLeftrightarrow[\text{PV exchange}]{Z^0 \text{ boson}}$ quarks inside the nucleus.



Weak interaction.

H_{PV} mixes |S> and |P> states → atomic orbitals have mixed parity.

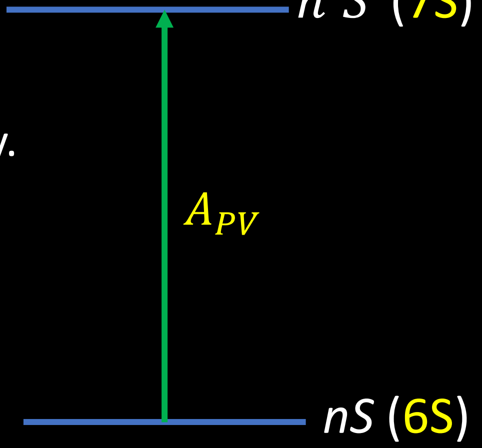
$$\boxed{|S>_{real} = |S>_{pure} + \delta_{PV}|P>_{pure.}}$$

To get observable signal:

Apply external static electric field, E → mixes |S> and |P> states.

gives large parity-conserving tunable signal.

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



R_{Cs} (6S → 7S) ∝ $|A_{PV}|^2_{Cs}$

$\approx 10^{-22}$.

Very small to observe experimentally!

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* δ_{PV} signifies the amount of P state mixing into S state, δ_E signifies the electric ('Stark') mixing term.

* A_{PV} - PV E1 transition amplitude, A_{ST} - PC 'Stark' E1 transition amplitude.

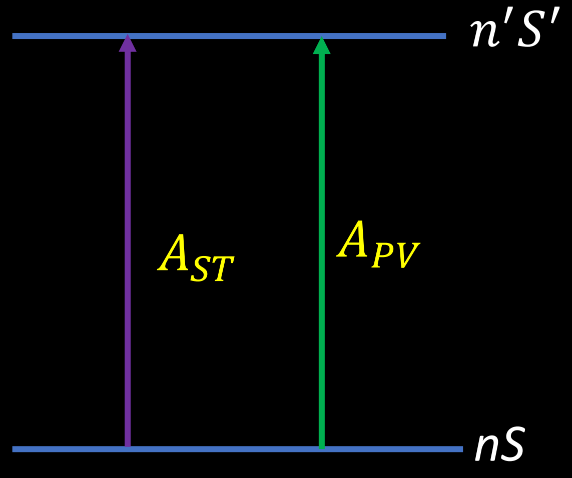
Signal of interest

- **Transition Rate, R**

$$R_{nS\to n'S'} \propto |A_{PV} + A_{ST}|^2,$$

Oscillator strengths

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



$nS \to n'S'$

- Interference term (observable) changes sign on parity flip ($E \to -E, B \to -B$).
  - Quantity of Interest:

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

- Scaling of APV effect:

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

Francium: larger Z, simple alkali structure } APV effect 18× larger than in Cs (**best APV test in** Cesium (Cs) [3]).

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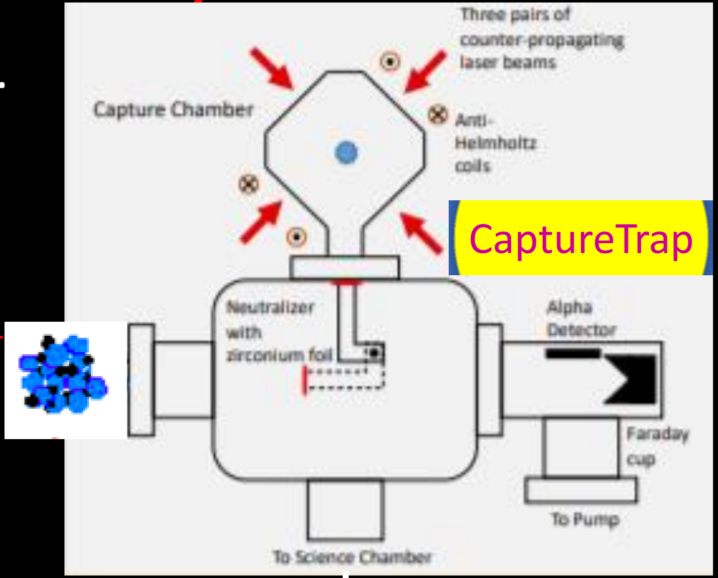
* *[3] Wood et al., Can. J. Phys. 77, 7 (1999).*

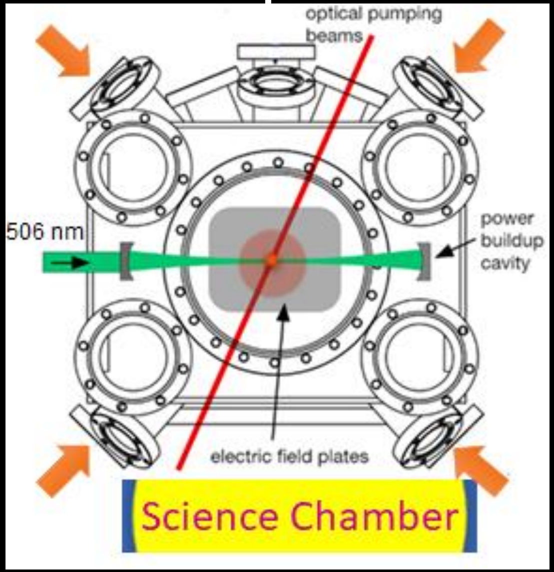
* A_{PV} measured in Cs with fractional uncertainty of 0.35 %.

Francium trapping facility & Experimental approach

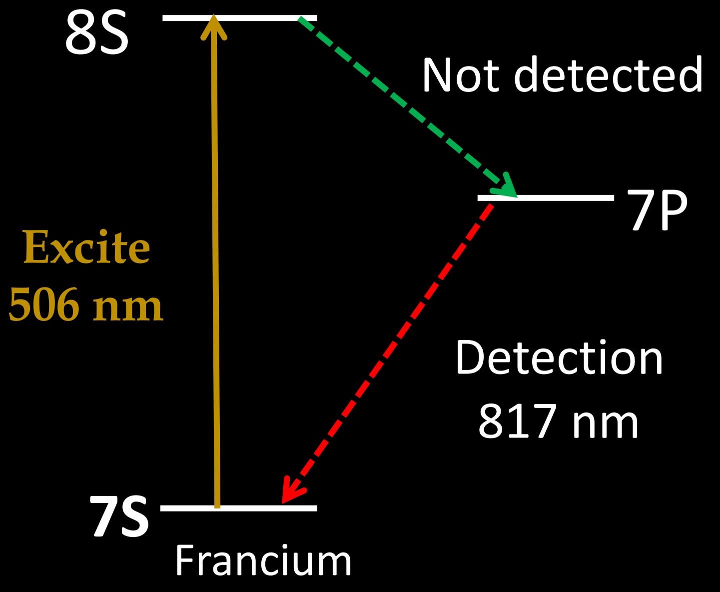
- Trap atoms in magneto-optical trap.
  - 10^6- 10^7 trapped Fr atoms,
  - For tens of seconds,
  - At μK temperature.
  - Ultra-high vacuum,
  - Precise control over E and B fields.
  - 5-6 days of beamtime of Fr/year.
  - Use Rubidium to test apparatus/new techniques.

$\sim 1E8\ Fr^+$
from $ISAC$





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



- 506 nm laser beam excites
  - highly forbidden 7S → 8S transition.
  - Decay sequence is 8S → 7P → 7S.
  - Measure R on 7P → 7S decay.
  - Measure $\frac{A_{PV}}{A_{ST}}$.

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

* where (K_{PV}) is an atomic structure factor from theory, (Q_W) is weak $charge$ of Fr.

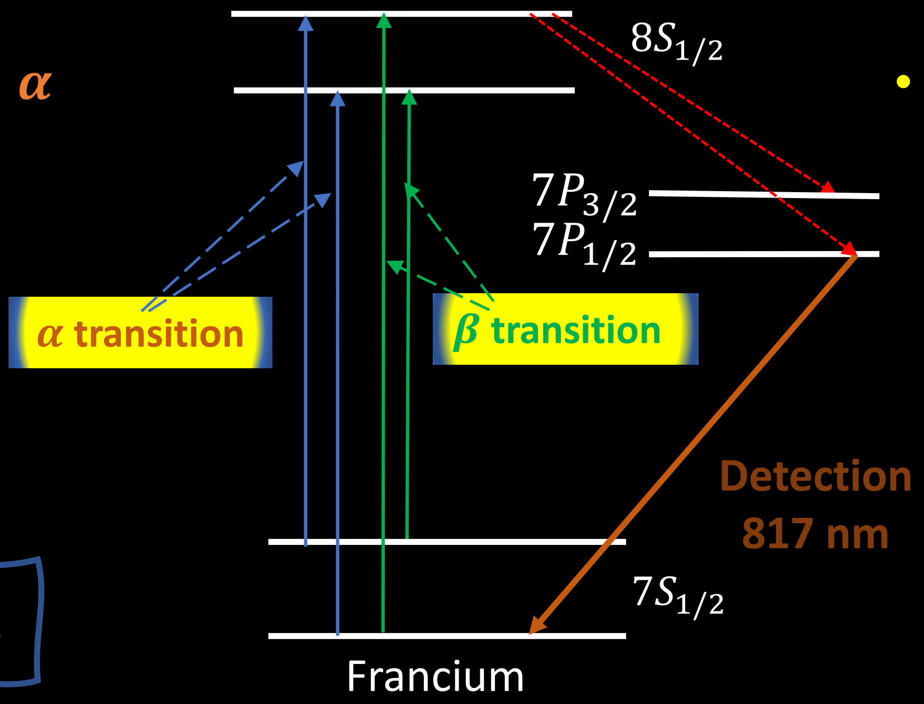
Details of the Stark-amplitude, A_{ST}

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

'm' dependent term

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

- **Scalar transition polarizabilities α**
  - $\Delta F = 0\,,\ \ \Delta m_F = 0,$
  - E || ϵ,
  - Zero contribution to the interference term.



- **Vector transition polarizabilities β**
  - $\Delta F = \pm 1{,}0,\ \ \Delta m_F = \pm 1{,}0,$
  - E ⊥ ϵ,
  - Contributes to the interference term → transitions between different m-levels.

- Predicted value [4] $\frac{\alpha}{\beta} \approx 5.05.$

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

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

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

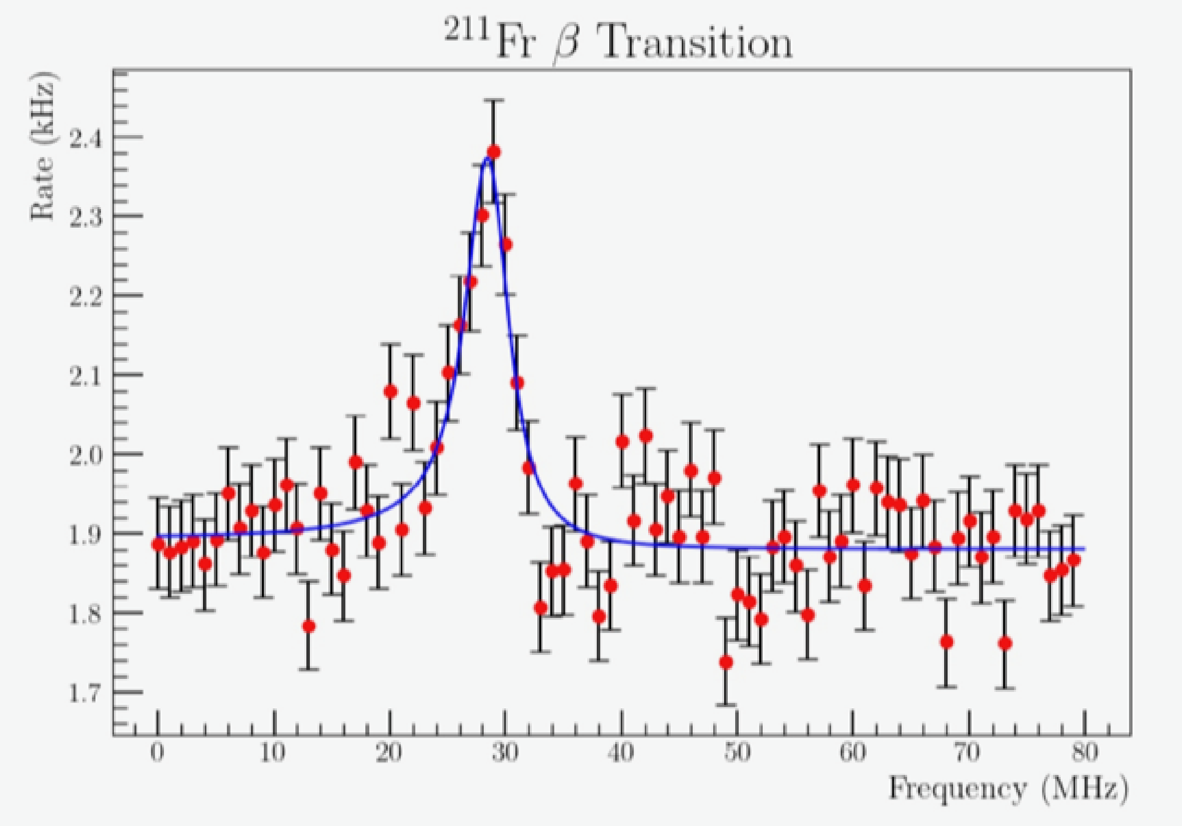
APV signature

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

- To extract $E1_{PV}$, ‘β’ needs to be known accurately.
- $\beta \rightarrow$ hard to measure.
- $\frac{\alpha}{\beta}$ measurable → 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 $| F, m_F >$.

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.



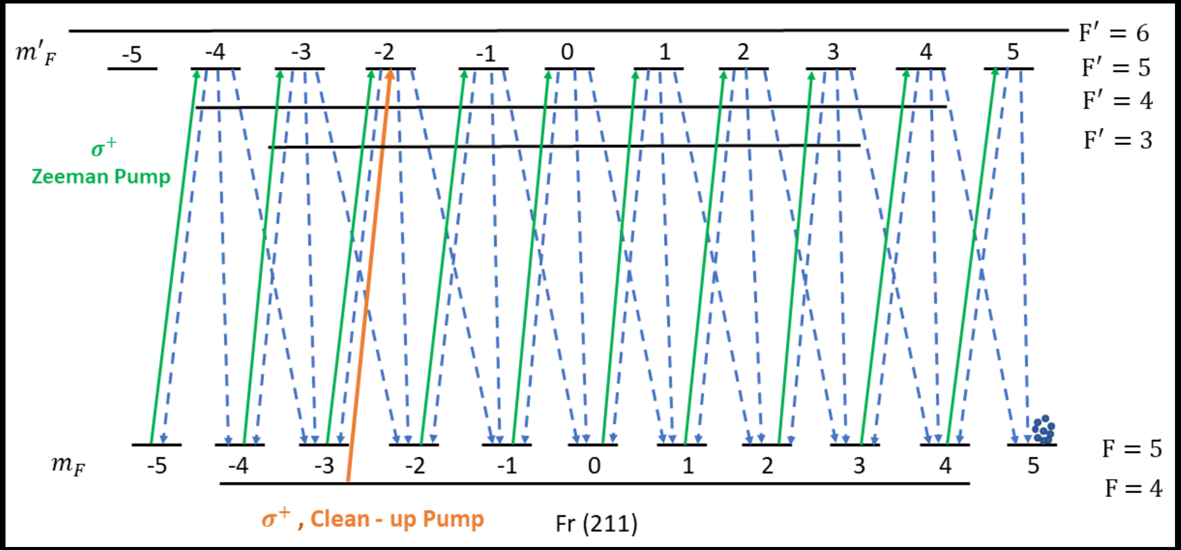
First signal of β Stark induced transition.

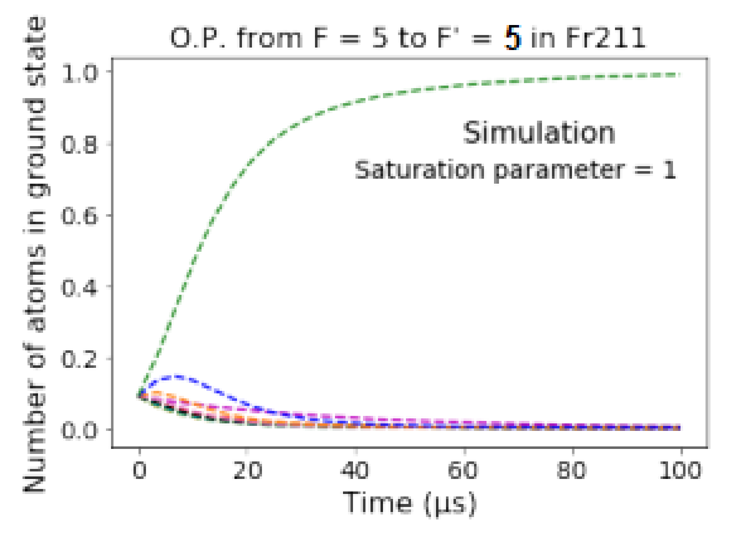
Optical Pumping of francium atoms

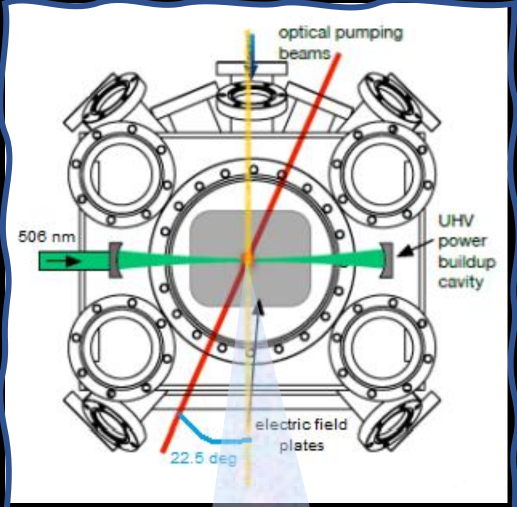
- To create ground state polarization of atomic sample of Fr.

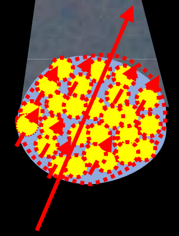
→ Deplete the population from unwanted hyperfine ground state → Clean-up pump.

→ Transfer angular momentum to atoms to put them into an extreme m-level, a dark state → Zeeman pump.

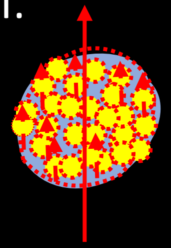








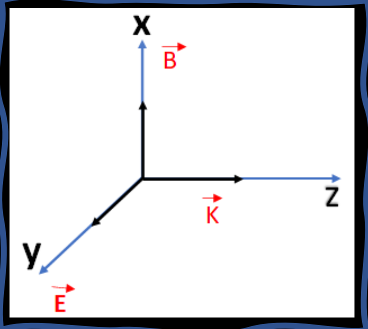
Apply < 5 G to → spin polarize the Fr atoms in MOT.



Rotate quantization axis → B field by 22.5.^{0}

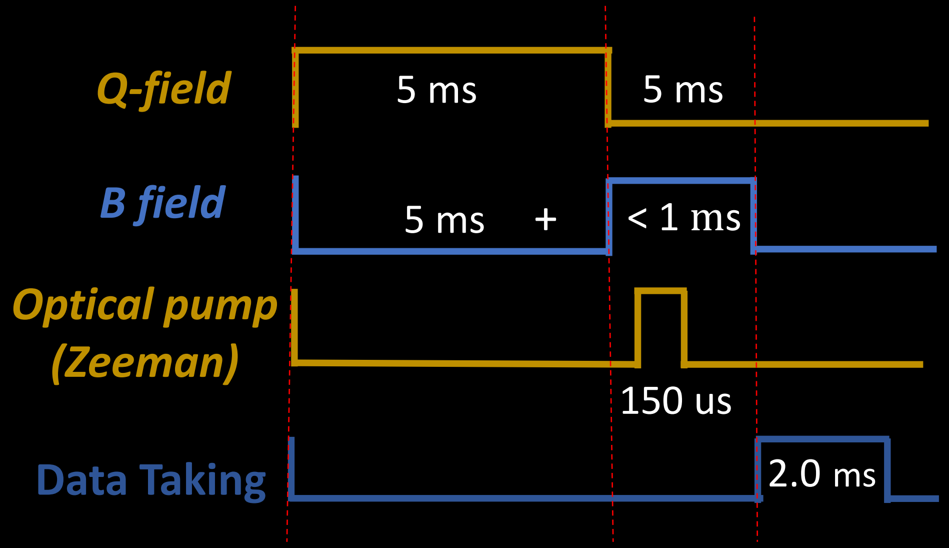
we get

Required configuration of fields →



Progress towards optical pumping

- Magnetic fields plays an important role:
  - To get MOT → position restoring force on atoms in MOT, a quadrupole field.
  - To define quantization axis → spin polarize the atoms, optical pumping.



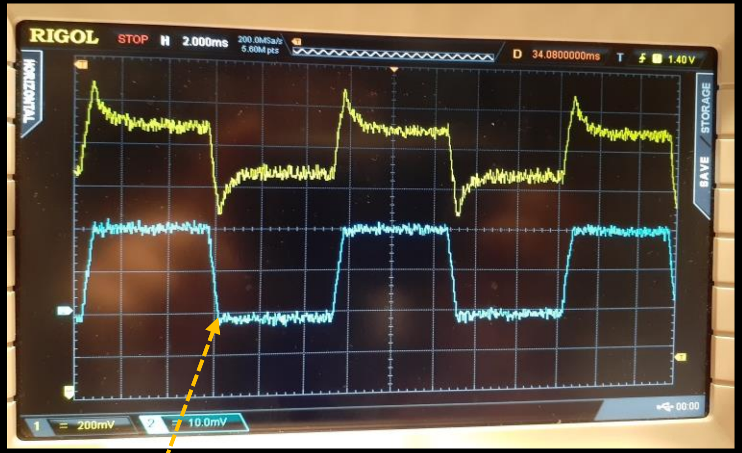
Q-field 5 ms 5 ms

B field 5 ms + < 1 ms

Optical pump (Zeeman) 150 us

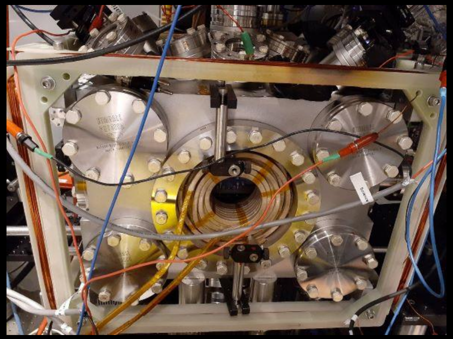
Data Taking 2.0 ms

Overshoot arbitrary waveform.



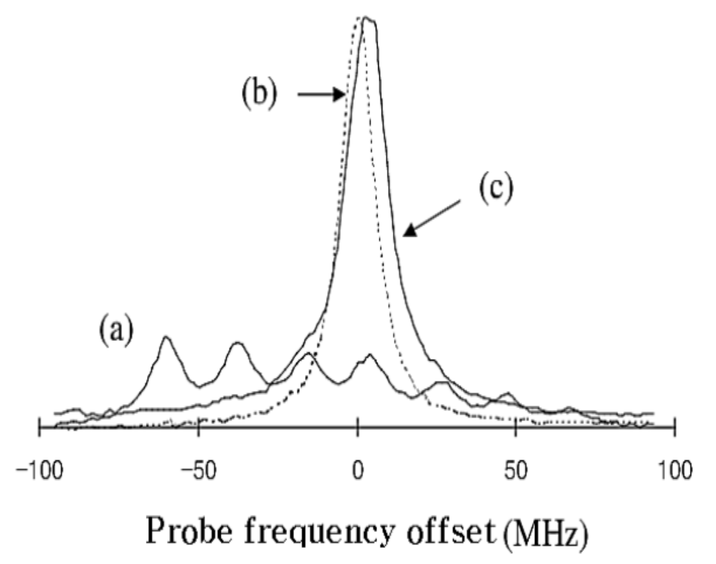
Switching of B field at MOT position in < 1ms.

- Challenges to overcome:
  - Eddy currents from surroundings of Science Chamber. →
  - Tight geometrical constraints to implement optical pumping beam.
  - Maintain the quality of right circularly polarized beam.
  - Improve our detection system, run fluorescence photons → cycling transition.



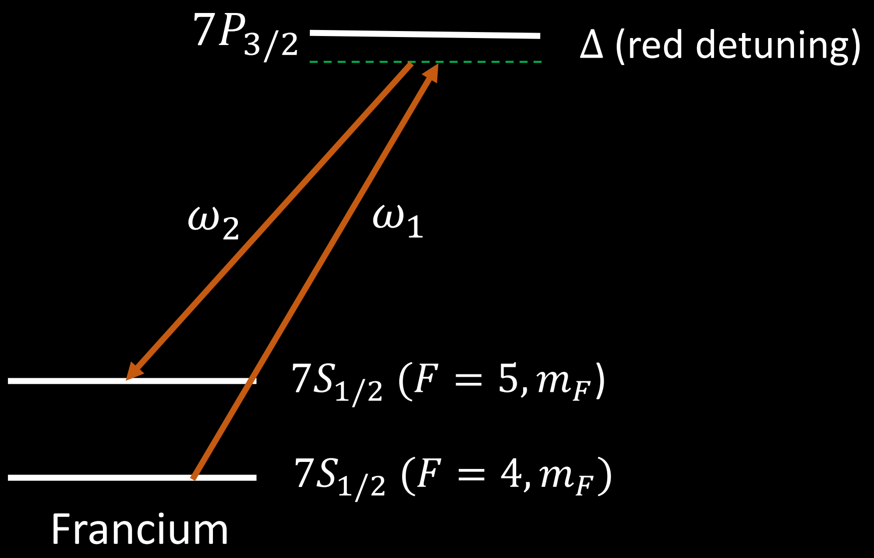
Detection of quality of optical pumping

- Resolve Zeeman sublevels by several linewidths by applying a large magnetic field.
  - Scan the laser over resolved 'm' sublevels and observe the spectra.



[5] Distribution of atoms $6S_{1/2}\ (F = 4, m_F)$: 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.

- Stimulated Raman transitions
  - Λ transition



- Can drive:
  - σ^+ polarization → ΔF = 1, Δm_F = 0.
  - probe the m_F population → same conditions as the $\boldsymbol{\alpha}/\beta$ measurement.
  - New setup: degenerate laser modes (ω_1, ω_2),
    - distinguished polarization of the laser,
    - good phase coherence in ω_1 and ω_2.

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

Highlights of the talk…….

- Towards APV → 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!