Towards measuring the ratio of scalar to vector transition polarizabilities in the 7S → 8S transition in francium.

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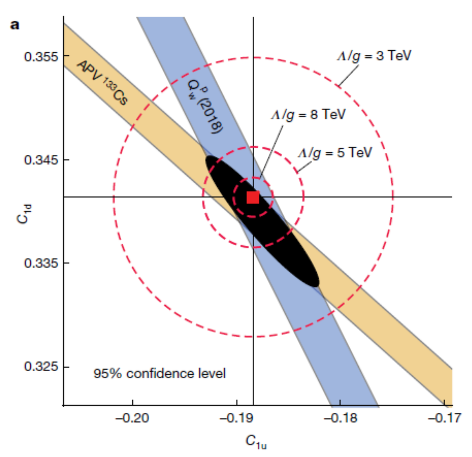
a) Goal of our experiment

- Test fundamental symmetries with atomic-spectroscopy based investigation of electroweak interaction.
- Atomic Parity Violation (**APV**) in weak interaction is a precise and direct effort to test the Standard Model (SM).

The predictions for weak quark coupling constants, C_{1u} and C_{1d}, by APV expt. are pretty much in agreement with SM predictions shown by red square.

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



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

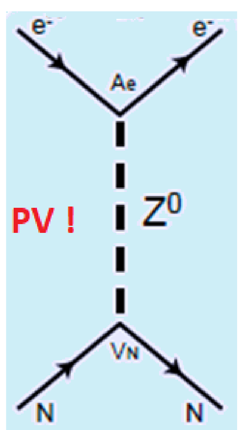
b) What is APV ?

- **APV** arises with Z^0 boson exchange between atomic electron and quarks in nucleus → PV atomic Hamiltonian H_{PV}.
- H_{PV} mixes atomic S and P states → atomic orbitals lose definite parity.

$$< n' \, S' \mid H_{PV} \mid nS > \propto Z^2 N$$

- **APV signature:** drive optical S → S E1 transition amplitude A_{PV} .
- **Problem**: experimental rate for 6S → 7S in Cs $R_{S\to S} \propto |A_{PV}|^2_{Cs} \approx 10^{-22}$

which is very small to observe experimentally.



Weak Interaction

- **Solution**: Interfere A_{PV} with much larger Parity Conserving 'PC' amplitude!

External static electric field also mixes S and P states → PC "Stark" amplitude A_{ST} ← which is tunable.

- To date **best APV test in** Cesium (Cs) [2] A_{PV} is measured in Cs precisely with fractional uncertainty of 0.35 % .
- **Idea**: Francium (Fr) is a good candidate with larger Z and simple alkali structure where APV effect is predicted to be 18× larger than in Cs.

c) Principles of Stark APV experiment

- Transition Rate, **R**

$$\mathbf{R} \propto |\, A_{PV} \;+\; A_{ST}|^2 \quad \text{Signal of interest}$$

$$\approx |A_{PV}|^2 + |A_{ST}|^2 \pm 2\,\mathrm{Re}\,(A_{PV} \,.\, A_{ST})$$

$\sim 10^{-21}$ (negligible) $\sim 10^{-10}$ Interference term ($\sim 10^{-15}$)

- Interference term changes sign on parity flip
- Quantity of Interest

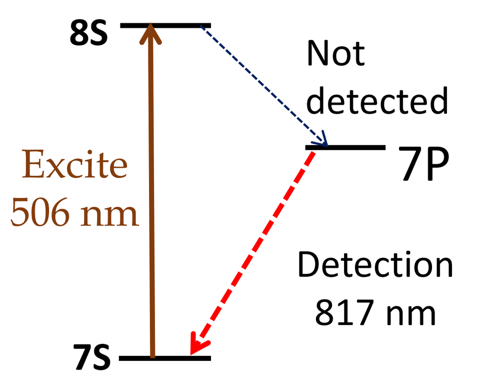
Can be done by E field reversal

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

← Important to know.

d) Experimental approach

- Laser beam excites highly forbidden 7S → 8S transition.
- Decay sequence is 8S → 7P → 7S.
- Measure transition rate on 7P → 7S decay.



Francium

- Measure $\frac{A_{PV}}{A_{ST}}$

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

K_{PV}: Atomic structure factor from theory (K_{PV})

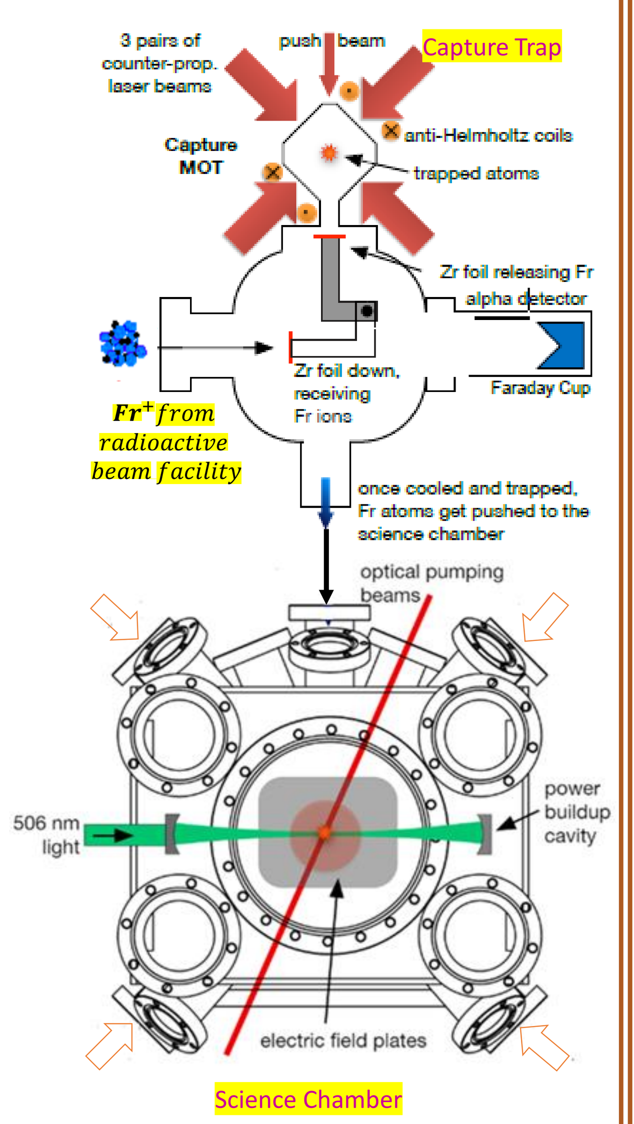
Q_W: Weak Charge (Q_W)

We can estimate Q_W once A_{PV} and K_{PV} are known.

e) Fr trapping facility at TRIUMF

- Fr has no stable isotope, a radioactive beam facility is needed.
- A high production rate of Fr is needed to make an atomic beam.
- Re-use Fr atoms by trapping and cooling them in a magneto - optical trap (MOT).
- We capture millions of Fr atoms at μK temperature.
- Trap atoms on $7S_{1/2}$ (F = 5) → $7P_{3/2}$ (F′ = 6) transition.

Fr⁺ ions delivered from TRIUMF get neutralized on a Zr foil which is heated up to 850⁰C to release neutral Fr atoms into a capture trap cell, a glass-cell coated with a silane-based dry-film. The laser beams trap and cool the atoms in a MOT. Once trapped and cooled, a laser push beam from the top launches the atoms into the science chamber to do spectroscopy in well-controlled magnetic and electric fields. This cycle repeats every 20 s.



f) Understanding the Stark amplitude

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

m dependent term

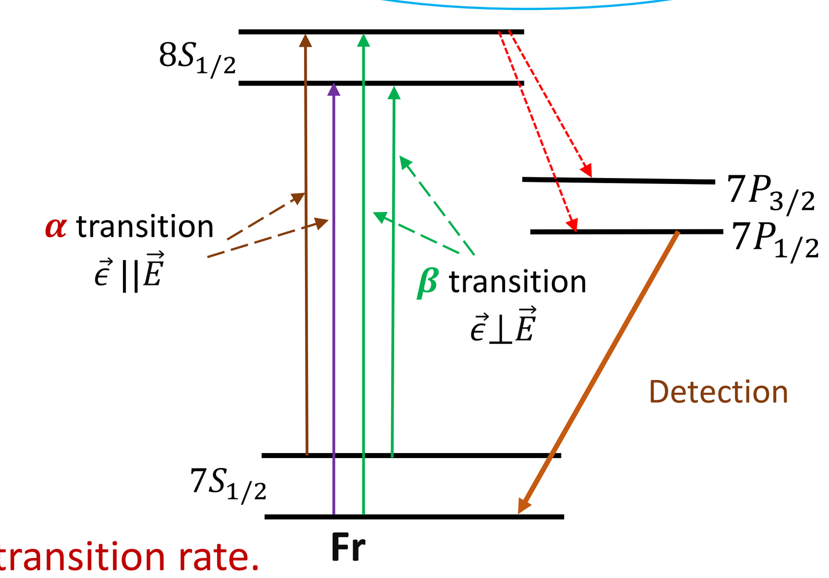
$$A_{ST}(\mathrm{F}', m_{F'}, \mathrm{F}, m_F) = \alpha\, \vec{E}.\vec{\epsilon}\; \delta_{F'F}\delta_{m_{F'}m_F} + \; i\, \beta\, (\vec{E}\times\vec{\epsilon}) \cdot <\mathrm{F}', m_{F'}|\vec{\sigma}\,|\mathrm{F}, m_F>.$$

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

- Transition Polarizabilities

Scalar, α, $\Delta F = 0$, $\Delta m_F = 0$,
Vector, β, $\Delta F = \pm1$, $\Delta m_F = \pm1, 0$.

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



- α doesn't contribute any interference term to transition rate.
- β: Interference term contains information about transition b/w different Zeeman sublevels.

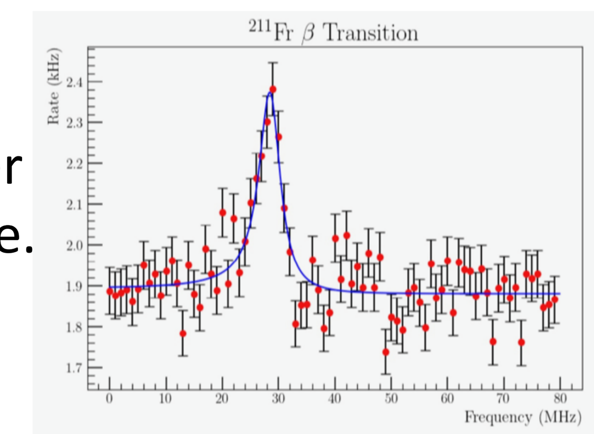
g) Motivation for the α/β measurement

- To extract the $E1_{PV}$, 'β' needs to be known accurately.
- $\frac{\alpha}{\beta}$ measurement is to test theory prediction for β.
- β amplitude is m - dependent, α amplitude is not.
- But atoms in MOT have unpredictable m - level distribution.
- To know m, we need to optically pump atoms in specific $|F, m_F>$.

Optical Pumping (O.P.) is the creation of atomic ground state polarization by shining polarized light on atomic sample.

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

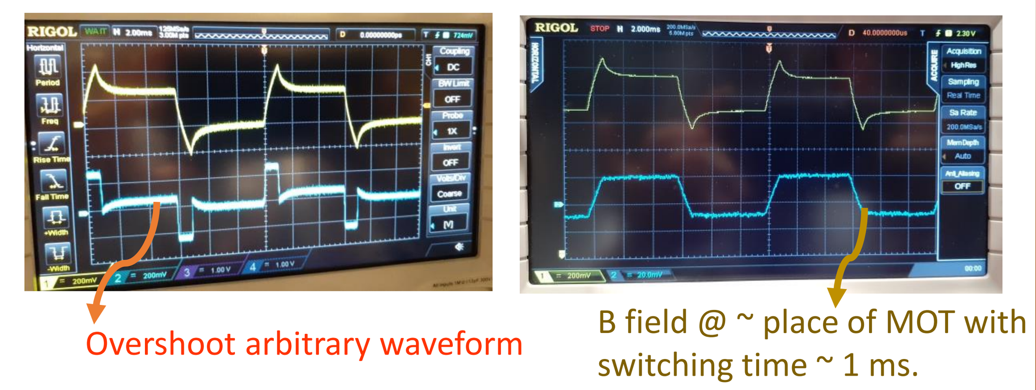
- The β transition is about $10^9 - 10^{10}$ × weaker than typical atomic transitions, hard to measure.
- Have also observed α transition (× 25 larger) than β transition.
- Will re- measure with optically pumped atoms.



First signal of β Stark induced transition

i) Challenges for implementation

- Several magnetic (B) fields need to be switched On/Off at ~ 100 μs scale.
- Deal with eddy currents due to copper gaskets on Science Chamber.
- Designed a simple arbitrary waveform, fed to Matsusada DOS series power supply to deal with the slow switching time of B field coils.
- Will improve the switching time of B field.



Signal shows the response of anti-Helmholtz coil on S.C. which needs to be turned off to do O.P. in MOT (not to disturb the quantization axis for O.P.).

- Tight geometrical constraints of O.P. beam implementation in our chamber.
- Need to maintain polarization quality of right circularly polarized O.P. beam.

j) Detection of polarized Fr atoms

- To check the quality of pumped atoms, we will resolve 'm' levels by applying large B.
- Scan the laser over resolved 'm' levels.
- We expect to see a large peak for optically pumped extreme 'm' sublevel.

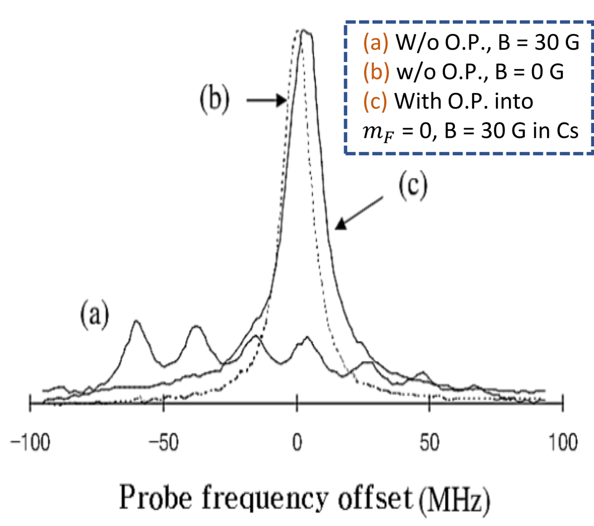


Figure taken from ref. [5].

Acknowledgement: Thanks for the financial support from NSERC, NRC, TRIUMF, U Manitoba, U Maryland.

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Discovery, accelerated