Towards measuring atomic parity violation effects in francium

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Atomic parity violation (aka APNC, PNC)

- Atomic physics experiment, we use laser cooling and trapping techniques and study electronic transitions dominated by electromagnetism.
- Small contribution to electronic transitions by Z boson exchange leading to parity violation effects.

Nuclear spin independent:
Weak neutral interaction between electrons and nucleons (mostly neutron)

Nuclear spin dependent:
Main contribution from anapole moment of heavy nuclei.
Atomic parity violation (aka APNC, PNC)

- Test SM at low energies
- Search for extra bosons

\[ Q_{\text{weak}}(\text{Cs}) \]

\[ \sin^2 \theta_W(Q_{\text{WS}}) \]

\[ 10^{-4} \quad 10^{-2} \quad 10^0 \quad 10^2 \quad 10 \]

\[ 0.229 \quad 0.231 \quad 0.233 \quad 0.235 \quad 0.237 \quad 0.239 \quad 0.241 \quad 0.243 \]

\[ Q_{\text{weak}}(\text{ep}) \]

\[ \text{PVDIS} \ (e^2\text{H}) \]

\[ \text{NuTeV} \ (\nu\text{-nucleus}) \]

\[ \text{E158} \ (ee) \]

\[ \text{Tevatron} \]

\[ \text{LEP1} \]

\[ \text{SLC} \]

\[ \text{LHC} \]

\[ Q_{\text{weak}} \]

\[ \Lambda/g = 3 \text{ TeV} \]

\[ \Lambda/g = 8 \text{ TeV} \]

\[ \Lambda/g = 5 \text{ TeV} \]

\[ 95\% \text{ confidence level} \]

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

\[ M. \ S. \ Safranova \ et \ al. \ Rev. \ Mod. \ Phys. \ 90, 025008 \]

\[ G. \ Toh \ et \ al. \ arXiv:1905.02768v2 \]
Atomic parity violation (aka APNC, PNC)

- Test SM at low energies
- Search for extra bosons

Isotopic variation of APV

- Atomic parity violation (APV)
- Isotopic variation
- Bounds on $z'$ boson mediated interactions


Measuring APV in ns → (n+1)s transition in heavy alkali atoms

- Electric dipole forbidden.
- Small transition probability due to APV effects (≈ $10^{-20}$ of allowed in Fr).

$$R \propto |A_{\text{stark}} + A_{\text{APV}}|^2 \approx (A_{\text{stark}})^2 \pm 2 \text{Re}(A_{\text{stark}} A_{\text{APV}}^*)$$

Interference term changes sign upon parity reversal

Average of 1 and 2: nuclear spin independent APNC
Difference of 1 and 2: Anapole

→ Modulation of decay fluorescence
**From measurement to extracting $Q_w$**

Modulation of decay fluorescence measurement $\rightarrow$ $A_{APV}/A_{stark}$

$A_{stark}$ calibrated by separate measurements

$$A_{APV} = k_{PV} Q_w$$

Atomic structure factor from theory $\Rightarrow$ Weak charge

Good experiment and good theory $\Rightarrow$ good test
APV experiments:

Best measurement so far (Boulder) 0.35% (exp.) measurement. Science 275 (1997) 1759

Purdue Elliot et al. (in preparation).

Planned exp. using ions (Groningen, U. of Washington, UCSB)

APNC 18x larger

Th. can be done ≈ Cs

Range of isotopes available

Efforts to push Cs, Fr theory to 0.1%. (PRA 98, 032504 (2018))

Yb (exp. 0.5% level) Nat. Phys. 15, 120–123 (2019)
The francium trapping facility

Fr has no stable isotope → experiment at TRIUMF
500 MeV proton beam, UC\(_x\) target.
The francium trapping facility

• Ions up to $2 \times 10^9$/s delivered

Other Fr traps:
• INFN Legnaro (Italy).
• Tohoku University (Japan).

• Glass cell with non stick coating (J. A. Fedchak et al. NIM Phys. R A 391 (1997) 405-416)

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

✓ Two lasers.
✓ Quadrupole B field.
• $\approx 1$ million atoms trapped
The francium trapping facility

- Up to 50% transfer
- 20 s lifetime

• 5, 6 days of beamtime/year
  ➢ Tune with Rb

M. Tandecki et. al. JINST 8, P12006 (2013)
Completed measurements at the francium trapping facility

- D1 isotope shifts in a string of light Fr isotopes.


- Benchmarks state of the art atomic theory.

These are all dipole allowed transitions!

*R. Collister, PhD, 2015 (U. of Manitoba)  
J. Zhang, PhD, 2014 (U. of Maryland)*
Completed measurements at the francium trapping facility

- Hyperfine anomaly in light Fr isotopes.
  

- Reconfirms that in terms of nuclear structure 208-213 are “simple” nuclei for APNC/anapole.

These are all dipole allowed transitions!

*R. Collister, PhD, 2015 (U. of Manitoba)  
J. Zhang, PhD, 2014 (U. of Maryland)*
Completed measurements at the francium trapping facility

- Francium $7p_{3/2}$ photoionization
  

- Determines loss of atoms from trap during spectroscopy

These are all dipole allowed transitions!

\textit{R. Collister, PhD, 2015 (U. of Manitoba)}
\textit{J. Zhang, PhD, 2014 (U. of Maryland)}
Observed for the first time 7s-8s transition using two photon spectroscopy in $^{208}\text{Fr}$, $^{209}\text{Fr}$, $^{210}\text{Fr}$, $^{211}\text{Fr}$, $^{213}\text{Fr}$.

Radioactive lifetime ($T_{1/2}$) from 50 s to 192 s.

Isotope shifts.

- Isotope shifts.
  - Completed measurements at the francium trapping facility

\[ \left( \frac{M_A M_{A'}}{M_A - M_{A'}} \right) \delta \theta_{1S,D1} = (N_{D1} + S_{D1}) - (N_{SS} + S_{SS}) \frac{F_{D1}}{F_{SS}} + \frac{F_{D1}}{F_{SS}} \left( \frac{M_A M_{A'}}{M_A - M_{A'}} \right) \delta \theta_{1S,SS} \]

Slope $\propto (\Delta \Psi(0)^2)_{D1} I(\Delta \Psi(0)^2)_{SS}$

- $1.228 \pm 0.019$ (experiment)
- $1.234 \pm 0.010$ (ab. initio theory)

\[ \text{M. Kalita et al. with theory by V. Dzuba, V. Flambaum, M. Safronova Phys. Rev. A 97, 042507 (2018)} \]
Transparent electrodes, ultra precise laser lock for $7s \rightarrow 8s$

- Transparent Electric field plates with ITO coating.
  - Works at $10^{-10}$ Torr, up to 6200 V/cm without sparks for hours at a time.
  - Operate magneto optic trap between the field plates!

- Laser lock for 506 nm based on ULE Fabry Perot cavity.
  - < 200 kHz drift in 6 hr $\rightarrow$ absolute stability at the $10^{-10}$ level!

Masters thesis A.C. Dehart, U of Manitoba, 2018
Basis for PNC: Stark induced 7s → 8s

- Laser locked to ULE Fabry Perot cavity.
- E field using ITO electrodes.

8s

7p_{3/2}

7p_{1/2}

506 nm

7s
Basis for PNC: Stark induced $7s \rightarrow 8s$ observed in September 2018!

- Laser locked to ULE Fabry Perot cavity.
- E field using ITO electrodes.

This is the transition we will use to do our PNC experiment.
- $10^{-9}$ times smaller than allowed transition

Side note: we have also observed the equivalent transitions in $^{87}\text{Rb}$. Poster
Things to do before attempting Stark interference:

1. Stark induced $10^{-10}$ to $10^{-8}$
2. M1 $10^{-11}$
3. PNC $10^{-20}$

• Magnetic dipole transition $M_{hf}$ and $M_{rel}$.
• Measure $M_{hf} / A_{stark}$.
• $M_{hf}$ can be calculated accurately.
• Calibrate $A_{stark}$.
• Use calibrated $A_{stark}$ in $A_{APV} / A_{stark}$.
System upgrade: increase power for 7s → 8s using a cavity in vacuum

- Lock power build up cavity to ULE cavity stabilized laser.

![Diagram of system upgrade]

- TiSapphire 1012 nm
- Freq. Doubler 506 nm
- Freq. shifter
- ULE based laser
- Feedback to laser
- Freq. stabilization
- Feedback to PBC
- Science chamber
- PBC in vacuum
- PBC stabilization

- Aim for first generation: factor of 1000 build up
  - Install late summer, 2019
From left to right: Michael Kossin, A.C. DeHart, Matt Pearson, Seth Aubin, Gerald Gwinner, Eduardo Gomez, Mukut Kalita, Alexandre Gorelov, John Behr, Luis Orozco, Tim Hucko, Anima Sharma. Not in the picture: Andrew Senchuk
Conclusion:

- We can routinely trap francium at the Francium Trapping Facility at TRIUMF and transfer them to our measurement region.

- We have observed the 7s-8s transition in several isotopes using two photon spectroscopy.

- Recently, we have observed the single photon Stark induced 7s-8s transition in $^{211}$Fr for the first time. This is the transition we will use to do our PNC experiment.

- We are preparing for measurement of magnetic dipole transition in the 7s-8s in Fall 2019.

- We are aiming to do our first attempt at observing the PNC effect in francium in a year or two.

Thank You
Back up slides after this
Neutron Skins, a correction to atomic PNC

- Weak $e^- - p$ coupling $\approx 1 - 4 \sin^2 \theta_W \approx 0$
  So mostly sensitive to weak $e^- - n$ coupling
  $$\langle s|H_W|p\rangle \sim Z^2 N$$

- Momentum transfer:
  $Q \approx 2.4$ MeV/c Cs, 9 MeV/c Fr $\rightarrow$
  $\lambda \sim 82, 22$ fm $\Rightarrow$ Sensitivity to $\langle r^2_{\text{neutron}} \rangle$

- Brown Derevianko Flambaum PRC 2009,
  Summarizing nuclear phenomenology and experiment:
  For $^{133}$Cs, $0.23 \pm 0.05\%$ correction
  For $^{211}$Fr, $0.41 \pm 0.12\%$ correction

- Sil et al. 2 EFT’s spanning symmetry energy agrees (PRC 2005):

JLAB’s PREXI 2012
Parity-violating $e^- + ^{208}$Pb
Q tuned to neutron skin
Model independent $\rightarrow$
neutron skins larger by $2 \pm 1$
We hope PREXII refines this
The francium experiment

- Accounting for correlations in some systematic uncertainties between the two measurement periods, the combined result is $A_{\text{ep}} = -226.5 \pm 7.3$ (statistical) $\pm 5.8$ (systematic) p.p.b. The total uncertainty achieved (9.3 p.p.b.) sets a new level of precision for parity-violating electron scattering (PVES) from a nucleus to $-\zeta/\beta$ of $(-\zeta/\beta)_e = (Q_e/Q_w)(-\zeta/\beta)_{\text{N=103}} \approx -1.2$ mV cm$^{-1}$. b. Bounds on light $Z'$-mediated PV electron-proton interactions. The black line represents the 1σ limit on the particular coupling, shown for a large range of the boson mass $m_{Z'}$. The coloured region in the plot corresponds to the parameter space excluded by the Yb experiment. The low-mass ($m_{Z'} < 100$ eV) limit for the coupling is $|g_{eZ'}^A g_p^Y| = 1.6 \times 10^{-12}$, and the corresponding large-mass asymptotic limit ($m_{Z'} > 100$ MeV) is $|g_{eZ'}^A g_p^Y|/m_{Z'}^2 = 1.3 \times 10^{-6}$ GeV$^{-2}$. c. Bounds on light $Z'$-mediated PV electron-neutron interactions. This result comes from combining existing limits on the effective electron-nucleon coupling, derived from the Cs PV experiment, with the Yb experimental limits shown in b. The low-mass limit for the interaction is $|g_{eZ'}^A g_n^Y| = 1.2 \times 10^{-12}$, and the corresponding large-mass asymptotic limit is $|g_{eZ'}^A g_n^Y|/m_{Z'}^2 = 9.3 \times 10^{-7}$ GeV$^{-2}$.

Neutralizer:

✓ Zr, work function 4.0 eV, mechanically strong, ionization potential of Fr 4.1 eV.
✓ Up-to 30% release, 800°C, 500,000 cycles.

(A. Gorelov et al. in preparation)