Towards Parity Violation Measurements in Laser Trapped Francium Isotopes

G. Gwinner — University of Manitoba
ISAC + actinide target: great place to study fundamental symmetries in heavy atoms

Atoms/nuclei provide access to fundamental symmetries, should be viewed as complementary to high energy approaches

<table>
<thead>
<tr>
<th>Charged current weak interactions, β-decay</th>
<th>Atom</th>
<th>Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>new powerful techniques (atom traps)</td>
<td></td>
<td>rich selection of spin, isospin, half-life</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutral current weak interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>APNC anapoles</td>
</tr>
<tr>
<td>tremendous accuracy of atomic methods (lasers, microwaves)</td>
</tr>
<tr>
<td>neutral (strong external fields)</td>
</tr>
<tr>
<td>huge enhancement of effects (high Z, deformation) over elementary particles</td>
</tr>
<tr>
<td>rich selection of spin, isospin, Z, N, deformation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Permanent electric dipole moments</th>
</tr>
</thead>
<tbody>
<tr>
<td>traps, cooling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lorentz-symmetry &amp; CPT violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>accuracy</td>
</tr>
<tr>
<td>selection of spin, Z, N</td>
</tr>
</tbody>
</table>

Some of most promising new candidates are heavy, radioactive systems (Rn, Fr)
Radioactive beam facilities are crucial

Demanding, long experiments → strong motivation for dedicated beam delivery
Atomic Parity Violation

Z-boson exchange between atomic electrons and the quarks in the nucleus

nucl. spin independent interaction: coherent over all nucleons

$H_{PNC}$ mixes electronic $s$ & $p$ states

$\langle n's' | H_{PNC} | np \rangle \propto Z^3$

Drive $s \rightarrow s$ E1 transition!

Cs: 6s $\rightarrow$ 7s osc. strength $f \approx 10^{-22}$

use interference:

$f \propto |A_{PC} + A_{PNC}|^2$

$\approx A_{PC}^2 + A_{PC}A_{PNC} \cos \varphi$
The nuclear-spin independent APNC Hamiltonian for a pointlike nucleus:

\[ H_{PNC}^{nsi} = \frac{G}{\sqrt{2}} \frac{Q_W}{2} \gamma_5 \delta(r). \]

\[ Q_W = 2(\kappa_{1p}Z + \kappa_{1n}N) \]

\[ \kappa_{1p} = \frac{1}{2}(1 - 4 \sin^2 \theta_W), \quad \kappa_{1n} = -\frac{1}{2} \]

The "nuclear weak charge" contains the weak interaction physics.

\[ < n' L' | H_{PNC}^{nsi} | nL > = \frac{G}{\sqrt{2}} \frac{Q_w}{2} < n' L' | \delta(r) \hat{\sigma} \cdot \hat{p} | nL > \]

\[ \propto < n' L' | \frac{d}{dr} | nL > |_{r=0} \]

\[ R_{nL} \approx r^L Z^{L+1/2} \]

\[ \Rightarrow \text{at } r = 0 \text{ only } R_{ns}, \frac{d}{dr} R_{np} \text{ are finite} \]

\[ H_{PNC} \text{ mixes } s \text{ and } p \text{ states} \]

\[ < ns | H_{PNC}^{nsi} | n' p > \propto Z^3 \]

Bouchiat, 1974
Weak Mixing Angle: Running of $\sin^2 \theta_W$
APNC uniquely provides the orthogonal constraint \((C_{1u} + C_{1d})\)

Only APV and Qweak together can extract \(Q_w\) neutron

Implications on 'new physics' from the Boulder Cs experiment (adapted from D. Budker, WEIN 98)

<table>
<thead>
<tr>
<th>New Physics</th>
<th>Parameter</th>
<th>Constraint from atomic PNC</th>
<th>Direct constraints from HEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oblique radiative corrections</td>
<td>$S+0.006T$</td>
<td>$S = -0.56(60)$ *</td>
<td>$S=-0.13\pm0.1\ (-0.08)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$T=-0.13\pm0.11\ (+0.09)$</td>
</tr>
<tr>
<td>$Z_x$-boson in SO(10) model</td>
<td>$M (Z_x)$</td>
<td>$&gt; 1.4$ TeV *</td>
<td>$&gt; 820$ GeV LHC $&gt; 2$ ($\rightarrow 5$) TeV</td>
</tr>
<tr>
<td>Leptoquarks</td>
<td>$M_S$</td>
<td>$&gt;0.7$ TeV</td>
<td>$&gt; 256$ GeV. $&gt;1200$ GeV indir.</td>
</tr>
</tbody>
</table>

Why are low-energy experiments such as APV relatively sensitive to new physics at higher energy scales?
APNC can also constrain other scenarios, e.g. couplings to new light particles (e.g. Bouchiat & Fayet 05)

Parity violation from dark bosons [Davoudiasl PRD 89, 095006 (2014)]
The Boulder Cs Experiment (Wood, 1996)

\[ |7s\rangle = |7s + \epsilon p\rangle 7S_{1/2} \]
\[ |E_1^{\text{Stark}} + E_1^{\text{PNC}}|^2 \]

\[ |6s\rangle = |6s + \epsilon p\rangle 6S_{1/2} \]

\[ \frac{\text{Im}(E_1^{\text{PNC}})}{\beta} = -1.5576(77) \text{ mV/cm} \]
\[ -1.6349(80) \text{ mV/cm} \]

6S \( F = 3 \rightarrow 7S \ F' = 4 \)

6S \( F = 4 \rightarrow 7S \ F' = 3 \)
Why Cs? Not particularly heavy...

It's the heaviest, stable 'simple atom'

Precise experiments in TI (and Bi, Pb) have been limited by their more complicated atomic structure!

Use francium (Z=87)

atomic structure (theory) understood at the same level as in Cs

APNC effect 18 x larger!

Problems: (i) no stable isotope
(ii) need to know neutron skin of Fr nucleus
(iii) need to know charge radius of Fr nucleus

Answers: (i) go to TRIUMF’s actinide target to get loads of Fr, and use trap
(ii) the PREX experiment at Jefferson Lab measures the neutron radius of $^{208}\text{Pb}$
(iii) new idea to measure nuclear charge radius of unstable elements
A Fr APNC experiment at TRIUMF

- Actinide target will make ISAC a great place to pursue Fr physics such as NSI APNC
- Data collection time (purely statistical, no duty factor)
  - $10^6$ trapped atoms, 1.0% APNC: 2.3 hours
  - $10^7$ trapped atoms, 0.1% APNC: 23 hours

 GPI: APNC work can start even with low current on ISAC target!
 GPI: But: most of the time needs to be spent on systematics. So realistically we are talking 100 days or more of beam, spread of more than a year!

- 1% neutron radius measurement in $^{208}$Pb with PREX would put a 0.2% uncertainty on $Q_w$ in $^{212}$Fr (Sil 2005)
- Atomic theory similar to Cs (0.25%), so progress in this direction required to go beyond Wood et al.
- Can expect that all aspects improve over time (already happening: new Cs (alkali) APNC calculations, Porsev 2009, Dzuba 2012)
A Francium APNC Experiment at TRIUMF

Boulder Cs: massive atomic beam
\( (10^{13} \text{ s}^{-1} \text{ cm}^{-2}) \)
key figure: \( 10^{10} \) 6s-7s excitations /sec

Fr trap:
excitation rate per atom: 30 s\(^{-1}\)
but asymmetry 18x larger
APNC possible with \( 10^6 \) - \( 10^7 \) atoms!

\[ \text{continuum} \]

We measured \( 7p_{3/2} \) photo-ionization rate
The Francium Trapping Facility at TRIUMF/ISAC
part 1: online capture trap

Fr ions from ISAC

once cooled and trapped, Fr atoms get pushed to the science chamber

Faraday Cup

alpha detector

+ 

Fr ions from ISAC

once cooled and trapped, Fr atoms get pushed to the science chamber

Capture MOT

Y foil releasing Fr

anti-Helmholtz coils
3 pairs of counter-prop. laser beams

push beam

trapped atoms

Y foil down, receiving Fr ions

Faraday Cup

Y foil releasing Fr

alpha detector

3 pairs of counter-prop. laser beams

push beam

trapped atoms

Y foil down, receiving Fr ions

Faraday Cup
The Francium Trapping Facility

- Sep 2012 - Sep 2013: first beam, trapping of many isotopes: $^{206m, 206, 207-213, 221}$Fr
- Beamline and capture laser trap commissioned
- First physics measurements on allowed transitions $\rightarrow$ yielded useful info for future APNC
D1 isotope shifts in a string of light francium isotopes


Benchmarks state-of-the-art atomic theory in Fr by Safranova and others.
Reconfirms that in terms of nuclear structure, 208-213 are “good” nuclei for APNC/ anapoles
Photo-ionization cross-section of the 7p3/2 state in francium

Collister et al., accepted for Can J Phys

\[ \varepsilon = 0.46 \text{ eV} \]

Allows us to predict the maximum 506 nm light intensity in the power buildup cavity.

Good news: This is better than the previously used conservative estimates.
Towards parity violation measurements

1. Getting the atoms into a clean environment

Busy doing actual work:
J. Behr
L. Orozco
Towards parity violation measurements
1. Getting the atoms into a clean environment

Busy doing actual work:
J. Behr
L. Orozco
Towards parity violation measurements

1. Getting the atoms into a clean environment

≈ 50% transfer efficiency!

Busy doing actual work:
J. Behr
L. Orozco

capture trap
science chamber
Fr atoms from capture MOT enter here

science MOT beams

506 nm light

power buildup cavity

optical pumping beams

electric field plates

Science chamber
Current developments

• August 2016
  • Observed for first time 7s - 8s using two-photon spectroscopy
  • Measured DC Stark shift of the 7s - 8s transition

• In development
  • reliable laser sources at 506 nm (Fr) and 496 nm (Rb)
  • ultra-stable (100 kHz) ULE cavity to lock those lasers
  • transparent field plates for internal operation of MOT

• Starting soon
  • UHV-compatible power-buildup cavity to enhance laser power for 7s - 8s spectroscopy
\[ A_{7s \rightarrow 8s} = E1_{\text{stark}} + M1 + E1_{\text{pnc}} \]

- One of the faintest transitions observed in atoms
- \( M1_{\text{rel}} \) hard to calculate (20-30 % discrepancy to expt. in Cs)
- “Most sensitive transition to the accuracy of the relativistic description of an atomic system” (Savukov et al, PRL 1999)
- So far, only measured in Cs, in context of APNC measurements

4 beamtimes with 8 shifts each
FrPNC collaboration

TRIUMF:
  John Behr, Alexandre Gorelov, Mukut Kalita, Matt Pearson, Michael Tandecki

University of Manitoba
  Austin deHart, Gerald Gwinner, Michael Kossin, Andrew Senchuk, Robert Collister, Kyle Shiells

University of Maryland
  Luis Orozco, Jiehang Zhang

University of William and Mary
  Seth Aubin

Autonomous University of San Luis Potosi
  Eduardo Gomez

Funded by:
  Canada:
    NSERC
    TRIUMF via NRC
  USA:
    NSF, DOE

Graduate student
Postdoc/research associate
Former member
The glow of a million francium atoms (not really)