FrPNC @ TRIUMF

Atomic Parity Violation in Francium

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FrPNC collaboration

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Funding
Atomic Parity Violation: Basic Processes

- Standard Electromagnetic Interaction (parity conserving)
- $Z^0$ exchange
  - Electron-Nucleon PNC (nuclear spin-independent)
- Intra-nuclear PNC
  - Anapole moment (nuclear spin-dependent)
Atomic Parity Violation: Basic Processes

- **Standard Electromagnetic Interaction** (parity conserving)
- **Z^0 exchange**
  - Electron-Nucleon PNC (nuclear spin-independent)
- **Intra-nuclear PNC**
  - Anapole moment (nuclear spin-dependent)
- **W^±, Z^0 exchange in nucleus**
Motivation 1: Nuclear Spin-Independent PNC

The Hamiltonian for this interaction:
(infinitely heavy nucleon approximation)

\[
H_{PNC, nsi} = \frac{G}{\sqrt{2}} \kappa_1 \gamma_5 \delta(\vec{r})
\]

\[G = \text{Fermi constant} = 10^{-5}/m_p^2\]

Proton: \[\kappa_{1,p} = \frac{1}{2} \left(1 - 4 \sin^2 \theta_W \right) \approx 0.04\]

Neutron: \[\kappa_{1,n} = -0.5\]

[Standard Model values for \(\kappa_{1, (p,n)}\)]
Motivation 1: Nuclear Spin-Independent PNC

For a nucleus with Z protons and N neutrons:

\[
H_{PNC, nsi} = \frac{G}{\sqrt{2}} \frac{Q_{weak}}{2} \gamma_5 \rho(\vec{r})
\]

\(Q_{weak} = \text{weak charge of nucleus} \approx -N\)

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

\(\rho(\vec{r}) = \text{nucleon distribution}\)
Motivation 1:
Testing and Probing the Weak Interaction

Parity Violation = Unique Probe of Weak Interaction

Atomic PNC (APV) experiments test and constrain the Standard Model
Motivation 1:
Testing and Probing the Weak Interaction

Parity Violation = Unique Probe of Weak Interaction

Atomic PNC (APV) experiments test and constrain the Standard Model


[figure by G. Gwinner, adapted from Erler et al. Phys. Rev. D 72, 073003 (2005)]
Atomic PNC

\[ H_{PNC, nsi} = \frac{G}{\sqrt{2}} \frac{Q_{\text{weak}}}{2} \gamma_5 \rho(\vec{r}) = \text{Parity Odd} \]

\[ \Rightarrow \text{Electron wavefunction does not have a definite parity !!!} \]

\[ \begin{align*}
|S\rangle & \rightarrow |S\rangle + \mathcal{E}_{PNC} |P\rangle \\
|P\rangle & \rightarrow |P\rangle + \mathcal{E}_{PNC} |S\rangle
\end{align*} \]

Parity forbidden transitions become possible (slightly) !!!

\[ \mathcal{E}_{PNC, nsi} \propto Z^3 R \sim 10^{-11} \quad (Cs) \]

Francium advantage:

\[ \frac{\mathcal{E}_{PNC, nsi}(Fr)}{\mathcal{E}_{PNC, nsi}(Cs)} \approx 18 \]

relativistic enhancement factor
Motivation 2: Nuclear Spin-Dependent PNC

- **Intra-nuclear PNC**
  - Anapole moment
  - $W^\pm, Z^0$ exchange in nucleus

- **$Z^0$ exchange**
  - Electron-Nucleon PNC (vector) (axial)
  - Hyperfine Interaction + NSI - $Z^0$ exchange (nuclear spin-dependent)
What’s an Anapole Moment?

**Answer:**
Electromagnetic moment produced by a toroidal current.

→ Time-reversal conserving.
→ PNC toroidal current.
→ Localized moment, contact interaction.

\[ W^\pm, Z^0 \text{ exchange in nucleus} \]

[Image of diagrams showing the combination of a dipole current and an anapole current to form a parity violating helico-toroidal current.]

[A. Weis, U. Fribourg (2003)]
Motivation 2:
Nuclear Anapole Moment

For heavy atoms, the anapole moment term dominates.

\[ H_{PNC,nsd} = \frac{G}{\sqrt{2}} \frac{K}{I(I+1)} \kappa_{anapole(p,n)} \vec{I} \cdot \vec{\alpha} \rho(\vec{r}) \]
Motivation 2:
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\[ H_{PNC,nsd} = \frac{G}{\sqrt{2}} \frac{K}{I(I+1)} \kappa_{anapole(p,n)} \vec{I} \cdot \vec{\alpha} \rho(\vec{r}) \]

\[ \kappa_{anapole(p,n)} = \frac{9}{10} g_{p,n} \frac{\alpha \mu_{p,n}}{m_p \tilde{r}_0} (Z + N)^{2/3} \]

\[ K = (I + 1/2)(-1)^{I+1/2+I} \]
\[ I = \text{nuclear spin} \]
\[ l = \text{valence nucleon orbital angular momentum} \]
\[ \alpha = 1/137 \]
\[ \mu = \text{nucleon magnetic moment} \]
\[ \tilde{r}_0 = 1.2 \text{ fm} = \text{nucleon radius} \]
Motivation 2: Nuclear Anapole Moment

For **heavy** atoms, the anapole moment term dominates.

\[
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\kappa_{\text{anapole}(p,n)} = \frac{9}{10} g_{p,n} \frac{\alpha \mu_{p,n}}{m_p \tilde{r}_0} (Z + N)^{2/3}
\]

\[
g_p \sim 4 \text{ and } 0.2 < g_n < 1 \text{ characterize the nucleon-nucleus weak potential.}
\]

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\]

\[
I = \text{nuclear spin}
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l = \text{valence nucleon orbital angular momentum}
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\mu = \text{nucleon magnetic moment}
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\[
\tilde{r}_0 = 1.2 \text{ fm = nucleon radius}
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Motivation 2: Isovector & Isoscalar Nucleon Couplings

Cs anapole (Boulder) and low-energy nuclear PNC measurements produce conflicting constraints on weak meson-nucleon couplings. (Desplanques, Donoghue, and Holstein model)

Need to understand nuclear structure better.

Measure anapole in a string of Fr isotopes

Motivation 2:
Isovector & Isoscalar Nucleon Couplings

Cs anapole (Boulder) and low-energy nuclear PNC measurements produce conflicting constraints on weak meson-nucleon couplings.

(Desplanques, Donoghue, and Holstein model)

Francium isotopes provide orthogonal constraints !!!

Francium advantage:

\[
\frac{\varepsilon_{\text{PNC, anapole}}(\text{Fr})}{\varepsilon_{\text{PNC, anapole}}(\text{Cs})} \approx 11
\]

FrPNC program: Atomic PNC Experiments in Francium

- Fr is the heaviest of the simple (alkali atoms).
  - Electronic structure is well understood.
  - Particle/nuclear physics can be reliably extracted.

- Fr has large (relatively) PNC mixing.
  - $\varepsilon_{\text{PNC}} \sim 10^{-10}$ is still really really small … we’re going to need a lot of Fr.

- Fr does not exist sufficiently in nature.

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[Diagram of atomic configuration and experimental setup with labels: magnetic field coils, Fr ion beam from ISAC, laser push beam, trapped Fr atoms, dryfilm coated cell (capture MOT), 'precision' MOT, dipole trap, UC at ISAC Dec. 2010 2 nA]
Atomic PNC in Fr (NSI)

Excitation to continuum (ionization)

Fr atoms (trapped)

$\varepsilon_{PNC} \propto \vec{B}_{DC} \cdot (\vec{k} \times \vec{E}_{Stark})$

Amplification by Stark Interference

Transition Rate = $|A_{Stark} \pm A_{PNC}|^2$

= $|A_{Stark}|^2 \pm 2 \text{Re}(A_{Stark} A_{PNC}^*) + |A_{PNC}|^2$

Statistical Sensitivity:
- $10^6$ trapped atoms, 1.0% APNC: 2.3 hours
- $10^7$ trapped atoms, 0.1% APNC: 23 hours

M1 is strongly suppressed.
New Method: Anapole can be measured by driving a parity forbidden E1 transition between two hyperfine states with $\Delta F=\pm 1$, $\Delta m_F=\pm 1$.

\textit{\pi/2 pulse preparation:} the atoms are prepared in a 50/50 superposition of the initial and final states (equivalent to interference amplification) before application of the microwave driving E-field.
Anapole Moment in Fr

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\[ 7S_{1/2} \]

\[ |F', m_F'\rangle \]

\[ |F, m_F\rangle \]
**Anapole Moment in Fr**

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**π/2 pulse preparation:** the atoms are prepared in a 50/50 superposition of the initial and final states (equivalent to interference amplification) before application of the microwave driving E-field.

$$\langle F', m_F' | F, m_F \rangle$$

Signal-to-noise $\sim 20\sqrt{Hz^{-1}}$ for $E_{\text{microwave}} \sim 0.5 \text{ kV/cm}$ and $10^6$ atoms.

$[E.\ Gomez\ et\ al.,\ Phys.\ Rev.\ A\ 75,\ 033418\ (2007)]$
Simulating Fr Anapole with Rb

180 ms coherence time in blue-detuned dipole trap

($\pi/2$ pulse with Rb)

Simulating the PNC Interference

Transition Rate = $\left| \frac{1}{2} \pm A_{PNC} \right|^2$

$\approx \frac{1}{4} \pm |A_{PNC}| \cos \theta_{phase}$

$A_{PNC}$ simulated with $10^{-4}$ M1 transition

[Data by D. Sheng (Orozco Group, U. of Maryland)]
**FrPNC: Current Status**

**Present:** Construction of an on-line, shielded laser laboratory at TRIUMF with 100 db RF suppression.

**Fall 2011:** *(14 shifts in December)*
Installation of high efficiency MOT (from U. of Maryland).

**2012:** Physics starts !!!
Hyperfine anomaly (Pearson), 7S-8S M1 (Gwinner), Anapole (Orozco), optical PNC (Gwinner), …
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Funding
Outline

**Theory**

A. Motivation 1: Spin-independent PNC
   → Testing the electroweak standard model.

B. Motivation 2: Spin-dependent PNC
   → Nuclear anapole moment.
   → Weak meson-nucleon couplings problem.

**Experiment**

1. The FrPNC program
   → Methods.
   → Expected sensitivities.

2. Current Status
Motivation 2: Nuclear Spin-Dependent PNC

\[ H_{PNC, nsd} = \frac{G}{\sqrt{2}} \frac{K}{I(I+1)} \bar{I} \cdot \bar{\alpha} \left( \kappa_{anapole(p,n)} - \frac{K-1/2}{K} \kappa_{2(p,n)} + \frac{I+1}{K} \kappa_{QW} \right) \rho(\vec{r}) \]
What’s an Anapole Moment?

Answer:
Electromagnetic moment produced by a toroidal current.

- Time-reversal conserving.
- PNC toroidal current.
- Localized moment, contact interaction.

\[ H_{\text{anapole}} = e \vec{\alpha} \cdot \vec{a} \delta(r) \]

\[ \vec{a} = -\pi \int d^3r \ r^2 \vec{J}(\vec{r}) \]

\[ = \frac{1}{e} \frac{G}{\sqrt{2}} \frac{K}{j(j+1)} \kappa_{\text{anapole}(p,n)} \vec{j}_{p,n} \]

[figure from V. V. Flambaum, Atomic Physics 16: ICAP 16., edited by W. E. Baylis and G. W. F. Drake (AIP, 1998)]

nucleon angular momentum
FrPNC program:
Atomic PNC Experiments in Francium

- Fr is the heaviest of the simple (alkali atoms).
  - Electronic structure is well understood.
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- Fr has large (relatively) PNC mixing.
  - $\varepsilon_{\text{PNC}} \sim 10^{-10}$ is still really really small ... we’re going to need a lot of Fr.

- Fr does not exist sufficiently in nature.

ISAC facility @ TRIUMF
500 MeV protons (2 $\mu$A) on UC (30 g/cm$^2$).
Demonstrated production: $10^7$-$10^8$ Fr/s
M1 suppression

M1 hyperfine transition mimics $E_{1PNC}$ and must be suppressed by $10^9$ !!!

a) Suppress $B_{microwave}$:

Fabri-Perot cavity: Place atoms at B node, E anti-node.

$\rightarrow$ Suppression: $5 \times 10^{-3}$.

b) Selection rule:

$B_{microwave} // B_{DC}$ can only drive $\Delta m_F = 0$ transitions.

$\rightarrow$ Suppression: $10^{-3}$.

b) Dynamical averaging:

When atoms slosh around the B node, the M1 is further averaged away.
Neutron nuclear skin radius
<table>
<thead>
<tr>
<th>Observable Constraint</th>
<th>Set value</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{Ry} A_{E1}$</td>
<td>Microwave amplitude 476 V/cm</td>
<td>0.03</td>
</tr>
<tr>
<td>$A_{Ry} A_{Ry}$</td>
<td>Raman amplitude 121 rad</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$(\hbar \delta)^2$</td>
<td>Microwave frequency 45 GHz</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td></td>
<td>Dipole trap Stark shift 6.3 Hz</td>
<td>0.07</td>
</tr>
<tr>
<td>DC Magnetic field</td>
<td>1500 Gauss</td>
<td>$4.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$A_{Rx} A_{Rx}$</td>
<td>Raman polarization 0 rad</td>
<td>$10^{-3}$ rad</td>
</tr>
<tr>
<td>$A_{Ry} A_{Mi y}$</td>
<td>Mirror separation 13 cm</td>
<td>$7.7 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>Antenna power 57 mW</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Antenna phase 0 rad</td>
<td>0.01 rad</td>
</tr>
<tr>
<td>$A_{Ry} A_{Mo x}$</td>
<td>Mirror birrefringence 0 rad</td>
<td>$1 \times 10^{-4}$ rad</td>
</tr>
<tr>
<td></td>
<td>Trap displacement 0 m</td>
<td>$3 \times 10^{-11}$ m</td>
</tr>
</tbody>
</table>

**TABLE III.** Fractional stability required for a 3% measurement. The observable associated with each constraint is also included.
Motivation 1: Sensitivity to Std. Model extensions

Atomic PNC experiments are sensitive to certain high-energy extensions of the Standard Model.

<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>$S + 0.006 T$</td>
<td>$S = -0.56(60)$</td>
<td>$S = -0.13 \pm 0.1\ (-0.08)$</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, ILC: $&gt; 5$ 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>
<tr>
<td>Composite Fermions</td>
<td>$L$</td>
<td>$&gt; 14$ TeV</td>
<td>$&gt; 6$ TeV</td>
</tr>
</tbody>
</table>

[figure from G. Gwinner and adapted from D. Budker, WEIN 98.]
Outline

Justification 1: Low-energy parity violation → sensitivity to extra neutral bosons.

Justification 2: Anapole moment → resolve nucleon-meson weak couplings discrepancy (Cs133 anapole vs. F18/19 gamma)

Why francium?

Brief of History of francium experiments.

Z0 experiment
   → expected sensitivity.

Anapole experiment
   → expected sensitivity.

Challenges of an accelerator environment … shielding necessary!!!

Current status: group members, funding, shielded laboratory.