Fundamental Symmetries in Laser Trapped Francium

Opportunities with a High-Availability Actinide Target at TRIUMF

Gerald Gwinner,
University of Manitoba

November 11, 2008

INT, Seattle
ISAC + actinide target: great place to study fundamental symmetries in heavy atoms

Atoms/nuclei provide access to fun. sym., should be viewed as complementary to high energy approaches

<table>
<thead>
<tr>
<th></th>
<th>Atom</th>
<th>Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged current weak</td>
<td>new powerful techniques (atom traps)</td>
<td>rich selection of spin, isospin, half-life</td>
</tr>
<tr>
<td>interactions, β-decay</td>
<td></td>
<td></td>
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<tr>
<td>Neutral current weak</td>
<td>tremendous accuracy of atomic methods (lasers, microwaves)</td>
<td>huge enhancement of effects (high Z, deformation) over elementary particles</td>
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<tr>
<td>interactions</td>
<td>neutral (strong external fields)</td>
<td>rich selection of spin, isospin, Z, N, deformation</td>
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<tr>
<td>APNC anapoles</td>
<td>traps, cooling</td>
<td></td>
</tr>
<tr>
<td>Permanent electric</td>
<td>accuracy</td>
<td>selection of spin, Z, N</td>
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<tr>
<td>dipole moments</td>
<td></td>
<td></td>
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<tr>
<td>Lorentz-symmetry &amp; CPT violation</td>
<td>accuracy</td>
<td></td>
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</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

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

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:

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

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

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

The "nuclear weak charge" contains the weak interaction physics

\[ < n' L' | H_{\text{PNC}}^{n_{\text{si}}} | n L > \]
\[ = \frac{G}{\sqrt{2}} \frac{Q_W}{2} < n' L' | \delta(r) \vec{\sigma} \cdot \vec{p} | n L > \]
\[ \propto < n' L' | \frac{d}{dr} | n L > |_{r=0} \]

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

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

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

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

Bouchiat, 1974

Thursday, November 13, 2008
The Boulder Cs Experiment (Wood, 1996)

\[ |7s⟩ = |7s + e_p⟩ 7S_{1/2} \]

\[ |6s⟩ = |6s + e_p⟩ 6S_{1/2} \]

After not weak purely mV/cm.

\[ \text{Im}(E1_{PNC}) \beta = -1.5576(77) \text{ mV/cm} \]
\[ = -1.6349(80) \text{ mV/cm} \]

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

Scale dependence in $\overline{\text{MS}}$ scheme including higher orders

$\sin^2 \theta_W$

- current
- future
- SM

- $Q_w(p)$
- eD-DIS
- $Q_w(e)$
- $\nu$-DIS
- APV
- $A_{FB}$
- Z-pole

0.6 % (0.38 % exp, 0.5 % theor.)

future expts. placed arbitrarily on vertical scale
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>$S=-0.13 \pm 0.1 (-0.08)$</td>
</tr>
<tr>
<td>$Z_x$-boson in SO(10) model</td>
<td>$M(Z_x)$</td>
<td>$&gt;550$ GeV</td>
<td>$&gt;900$ GeV</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>

Why is APNC so sensitive?

APNC can also constrain other scenarios, e.g. couplings to new light particles (e.g. Bouchiat & Fayet 05)
Young et al., PRL 2007: Dramatic recent progress from PV electron scattering for \((C_{1u} - C_{1d})\)

APNC uniquely provides the orthogonal constraint \((C_{1u} + C_{1d})\)
Why Cs? Not particularly heavy...

It's the heaviest, stable 'simple atom'

\[ \langle i | H_{PNC,1} | j \rangle = \frac{G_F}{2\sqrt{2}} C_{ij}(Z) N \times \left[ -N q_n + Z(1 - 4 \sin^2 \theta_W) q_p \right] \]

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

\[ q_n = \int \rho_n(r) f(r) d^3r, \]
\[ q_p = \int \rho_p(r) f(r) d^3r. \]

from Pollock et al. 1992
Proposal: 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 radius better than for Cs expt.

Answers: (i) go to TRIUMF’s actinide target to get loads of Fr
(ii) the upcoming PREX experiment at Jefferson Lab will measure the neutron radius of $^{208}\text{Pb}$
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!
A Fr APNC experiment at TRIUMF

- Actinide target will make ISAC the best 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

- APNC work can start even with low current on ISAC target!
- 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 $^{208}\text{Pb}$ with PREX would put a 0.2 % uncertainty on $Q_w$ in $^{212}\text{Fr}$ (Sil 2005)
- Atomic theory similar to Cs (0.4 - 0.5 % uncertainty), so progress in this direction required to go beyond Wood et al. (but can be expected)
- Isotopic ratio will need next gen. neutron radius experiment (also mostly sensitive to NP in proton) (Sil 2005)
- Can expect that all aspects improve over time
What I like particularly about APNC measurements:

To reach sensitivity to New Physics, APNC:

- [atomic] triggered the best atomic structure calculations in heavy atoms, truly advanced the state-of-the-art, and keeps doing so

- [nuclear] requires, and motivates the most accurate neutron skin determination (very interesting by itself)

- [laser technology...] pushes experimental techniques in atomic physics
  - Cs beam: 800 kW/cm² narrowband light, extreme control of external fields
  - next generation trap-based expts.: frequency control of RF fields and light, new, efficient atom trapping schemes, densest samples of short-lived radioactive atoms, state-of-the-art position control for atoms

- [particle] result
Nuclear spin dependent APNC

NSD Z-exchange

PV hadronic interactions ⇒ PV anapole moment of the nucleus

hyperfine correction to the weak neutral current

\[ H_{\text{PNC}} = \frac{G_F}{\sqrt{2}} \left( -\frac{Q_w}{2} \gamma_5 + \left( \frac{K}{I+1} \kappa_\alpha + \kappa_2 + \kappa Q_w \right) \frac{1}{I} \sigma_n \gamma_0 \gamma \right) \rho(\mathbf{r}) \]

\[ |\kappa_2| \approx O(1 - 4 \sin^2 \theta_W) \]

\[ K = (-)^{I+1/2-\ell} (I + 1/2) \]

\[ g_p \approx 5 \quad g_n \approx -1 \]

Khriplovich and Flambaum (1980)

\[ \kappa_\alpha \approx 1.15 \times 10^{-3} A_2/3 \mu_n g_n \]
Nuclear spin dependent APNC

For $A \geq 20$ the anapole dominates the NSD part (at least for unpaired protons)

$$a = - \pi \int j(r) r^2 d^3 r = \frac{1}{e} \frac{G}{\sqrt{2}} \frac{KI}{I(I+1)} \kappa_a$$

PV hadronic interactions $\Rightarrow$ PV anapole moment of the nucleus

$$\kappa_a \propto A^{2/3}$$

Flambaum & Khriplovich 1980

A. Weis, U. of Fribourg,
Limits on weak nucleon coupling from various experiments

Constraints of couplings from measuring two francium isotopes (note: the Cs band is somewhat different from the Haxton-Wieman plot due to different choices for the $g_i$).

But: Anapoles in nuclei are interesting by themselves, and data is VERY sparse. They tell us about the weak nucleon-nucleon interaction in nuclear matter.
Review: the Boulder Cs experiment

\[ |7s\rangle = |7s + \epsilon p\rangle \ 7S_{1/2} \]

\[ A_{\text{Stark}} + A_{M1} + A_{\text{PNC}} |^2 \]

Dye Laser (540 nm)

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

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

6S \ F = 3 \rightarrow 7S \ F' = 4 \text{ anapole is extracted from difference}

6S \ F = 4 \rightarrow 7S \ F' = 3
Interference scheme for hyperfine transitions

Drive $E_{1PNC}$ between electr. ground state hyperfine levels
$\Rightarrow$ NSI PNC effect absent, pure NSD APNC

(L. Orozco, Maryland)

| $7p$ ⟩
| $\rightarrow$ Raman transition $E1$
| $7sF'$ ⟩

$\rightarrow$ NSI PNC effect absent, pure NSD APNC

$\rightarrow$ NSI PNC effect absent, pure NSD APNC

microwave cavity

Gomez et al. PRA 2007
The big challenge: the M1 amplitude

- M1 transition is allowed (unlike in optical APNC Stark experiments)
  - $|A_{E1}/A_{M1}| \sim 10^{-9}$!
- Need some tricks to reduce the M1 amplitude
  - (1) Place atoms at the node of the magnetic field, reduction of $5 \times 10^{-3}$
    - any travelling wave component must be suppressed, bi-directional feeding of cavity
microwave resonant for $|\Delta m|=1$ E1 transitions

- E1 polarized along the x axis
- M1 polarized along z axis, M1: $\Delta m=0$
- M1 tuned out of resonance, suppression of $10^{-3}$

- dynamical suppression via atom movement in the trap
Signal to Noise

\[ \frac{S}{\mathcal{N}_P} = 2 \frac{A_{E1} t_R}{\hbar} \sqrt{N} \]

\[ \mathcal{N}_P = \sqrt{N|c_e|^2(1 - |c_e|^2)} \]

t_R = 1 \text{ sec}, 300 \text{ atoms}, 10^4 \text{ meas. cycles: 3 \% measurement}

10^6 \text{ atoms: S/N of 20 in 1 second}
**Canadian SAP plan: high priority for francium**

- Hyperfine anomalies: study of nuclear properties, tune up Fr apparatus (E 1010 approved)
- Anapole measurement (E 1065 approved)
- 7s-8s Stark/M1: precursor to optical APNC (in preparation)
- Optical APNC (future EEC proposal)
- e-EDM: letter of intent by H. Gould (LBNL)
Weak Nucleon-Nucleon Interactions by Parity Nonconservation Measurements in Francium (E 1065)

by the FrPNC collaboration (in fairly arbitrary order):
G. Gwinner (Manitoba)
E. Gomez (Univ. Autonoma San Luis Potosi, Mexico)
G.D. Sprouse (Stony Brook)
J.A. Behr, K.P. Jackson, M.R. Pearson (TRIUMF)
L.A. Orozco, A. Perez Galvan, D. Norris, D. Sheng (Univ. of Maryland)
V. Flambaum (Univ. of New South Wales)
S. Aubin (College of William and Mary)

PReX →

Winnipeg (“where all atoms are ultracold”)
Fractional stability required for a 3% measurement. The observable associated with each constraint is also included.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Constraint</th>
<th>Set value</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{Ry}A_{E1}$</td>
<td>Microwave amplitude</td>
<td>476 V/cm</td>
<td>0.03</td>
</tr>
<tr>
<td>$A_{Ry}A_{Ry}$</td>
<td>Raman amplitude</td>
<td>121 rad/s</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$(\hbar \delta)^2$</td>
<td>Microwave frequency</td>
<td>45 GHz</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td></td>
<td>Dipole trap Stark shift</td>
<td>6.3 Hz</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>dc magnetic field</td>
<td>1500 G</td>
<td>$4.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$A_{Rx}A_{Rx}$</td>
<td>Raman polarization</td>
<td>0 rad</td>
<td>$10^{-3}$ rad</td>
</tr>
<tr>
<td>$A_{Ry}A_{Miy}$</td>
<td>Mirror separation</td>
<td>13 cm</td>
<td>$7.7 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>Antenna power</td>
<td>57 mW</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Antenna phase</td>
<td>0 rad</td>
<td>0.01 rad</td>
</tr>
<tr>
<td>$A_{Ry}A_{Mox}$</td>
<td>Mirror birefringence</td>
<td>0 rad</td>
<td>$1 \times 10^{-4}$ rad</td>
</tr>
<tr>
<td></td>
<td>Trap displacement</td>
<td>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.
Atomic parity nonconservation, neutron radii, and effective field theories of nuclei

Tapas Sil, M. Centelles, and X. Viñas
Departament d'Estructura i Constituïents de la Matèria, Facultat de Física, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain

J. Piekarewicz
Department of Physics, Florida State University, Tallahassee, Florida 32306

In the case of the isotopic ratio \( R_1 \), it has been claimed that a significant test of the standard model requires a determination of \( R_1 \) to better than 0.1\%. This precision would be required for \( R_1 \) to supersede the \(^{133}\text{Cs}\) experiment as the most stringent test for new physics within the APNC program. Unfortunately, our results indicate that the projected 1\% accuracy in the measurement of the neutron radius of \(^{208}\text{Pb}\) at the Jefferson Laboratory appears unlikely to translate into the required 0.1\% (or lower) uncertainty in \( R_1 \). Instead, we have established an uncertainty in \( R_1 \) that is two to three times larger (of the order of 0.25\%–0.35\%). Although the Jefferson Laboratory experiment is unlikely to achieve the desired accuracy, it is plausible that second-generation experiments may reach this goal.

radioactive atoms, we have computed the weak nuclear charge of the two longest lived francium isotopes: \(^{212}\text{Fr}\) (20 min) and \(^{223}\text{Fr}\) (21.8 min). Our assumed uncertainty in the neutron radii of \(^{212}\text{Fr}\) and \(^{223}\text{Fr}\) translated into a theoretical uncertainty in the value of their weak nuclear charges of 0.2\% and 0.3\%, respectively.

\[
R_1 \approx \frac{Q^{SM}_W(N', Z) - Q^{SM}_W(N, Z)}{Q^{SM}_W(N', Z) + Q^{SM}_W(N, Z)} \times \left[ 1 + \frac{N'}{\Delta N} [q_n(N', Z) - q_n(N, Z)] \right],
\]

\[
t = r_n - r_p \quad \text{neutron skin}
\]
Dispelling the curse of the neutron skin in atomic parity violation

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1Department of Physics and Astronomy, and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA
2Department of Physics, University of Nevada, Reno, Nevada 89557
3School of Physics, University of New South Wales, Sydney 2052, Australia

(Dated: April 28, 2008)

FIG. 1: The neutron skin $\Delta R_{np}$ for nuclei above $^{100}$Sn are shown in the bottom panel (all $Z$, even $N$ values). The nuclei for a given isotope are connected by lines. The filled circles are those for the nuclei of interest for atomic parity violation.
\[ R = \frac{E_{PNC}}{E'_{PNC}} = \frac{Q_W}{Q'_W} \left( \frac{R_p}{R'_p} \right)^{2\gamma-2} \]

\[ Q_W = -N\,q_n + Z\,q_p \left( 1 - 4\sin^2\theta_W \right) + \Delta Q_{\text{new}} \]

\[ q_n = 1 + f_n \left( \frac{R_n}{R_p} \right) \]

\[ R \approx \frac{N}{N'} \left( \frac{R_p}{R'_p} \right)^{2\gamma-2} \times \left( 1 + \left[ f_n \left( \frac{R_n}{R_p} \right) - f_n \left( \frac{R'_n}{R'_p} \right) \right] \right) \]

\[ \Delta R_{n.s.} = (R - R_0) / R_0 = f_n \left( \frac{R_n}{R_p} \right) - f_n \left( \frac{R'_n}{R'_p} \right) \]
FIG. 2: Neutron skin vs. “new physics”. The neutron-skin-induced uncertainties for isotopic chains are compared with the constraints from parity-violating electron scattering.

\[
\Delta Q_{\text{new}} \equiv Z \ h_p + N \ h_n
\]

\[
\mathcal{F} = \frac{h_p}{h_0} = \left( \frac{R}{R_0} - 1 \right) \frac{N \ N'}{Z \Delta N}
\]

\[
\delta \mathcal{F} = \frac{N \ N'}{Z \Delta N} \left\{ \frac{\delta R_{\text{exp}}}{R_0} + \delta(f_n - f_n') \right\}.
\]

At this point we focus on the error in the difference

\[
\delta(f_n - f_n') \approx \frac{3}{14} (\alpha Z)^2 \delta \left[ \frac{R_n'}{R_p'} - \frac{R_n}{R_p} \right].
\]