Fundamental Symmetries in Laser Trapped Francium

Unique Opportunities with a High- Availability Actinide Target at TRIUMF

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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>Charged current weak interactions, $\beta$-decay (JB)</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>
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Neutral current weak interactions

<table>
<thead>
<tr>
<th>APNC anapoles</th>
<th>tremendous accuracy of atomic methods (lasers, microwaves) neutral (strong external fields)</th>
<th>huge enhancement of effects (high Z, deformation) over elementary particles</th>
</tr>
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<tbody>
<tr>
<td>Permanent electric dipole moments (TC)</td>
<td>traps, cooling</td>
<td>rich selection of spin, isospin, Z, N, deformation</td>
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</tbody>
</table>

Lorentz-symmetry & CPT violation (GG)

| accuracy | selection of spin, Z, N |

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

Demanding, long experiments $\rightarrow$ 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:

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

\[ \approx A_{PC}^2 + A_{PC}A_{PNC}\cos\varphi \]
Nuclear spin dependent APNC

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

\[ |\kappa_2| \approx \mathcal{O}(1 - 4 \sin^2 \theta_w) \quad K = (-)^{I+1/2-\ell}(I + 1/2) \]

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

Khriplovich and Flambaum (1980)

\[ \kappa_a \approx 1.15 \times 10^{-3} A^{2/3} \mu_n g_n \]
Nuclear spin dependent APNC

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

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

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 $g_i$).

Nuclear structure in heavy nuclei probably not well enough understood at this point to make reduction to meson couplings (anyway, EFT is the real deal now...)

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

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

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

Dye Laser (540 nm)

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

\[ \text{Im}(E_{1PNC}) \frac{1}{\beta} = -1.5576(77) \text{ mV/cm} \]
\[ -1.6349(80) \text{ mV/cm} \]

6S \( F = 3 \rightarrow 7S \ F' = 4 \) 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
⇒ NSI PNC effect absent, pure NSD APNC

(L. Orozco, Maryland)

$|7p\rangle$  

Raman transition $E1$ $E1$

$|7sF\rangle$  

$|7sF\rangle$  

$|7sF\rangle$  

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 atoms, } 10^4 \text{ meas. cycles: 3 % measurement}

10^6 \text{ atoms: S/N of 20 in 1 second}
The Boulder Cs Experiment (Wood, 1996)

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

\[ |E1_{\text{Stark}} + E1_{\text{PNC}}|^2 \]

Dye Laser (540 nm)

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

\[ \frac{\text{Im}(E1_{\text{PNC}})}{\beta} = -1.5576(77) \text{ mV/cm} \quad 6S F = 3 \rightarrow 7S F' = 4 \]

\[ -1.6349(80) \text{ mV/cm} \quad 6S F = 4 \rightarrow 7S F' = 3 \]
Weak Mixing Angle

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

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

future expts. placed arbitrarily on vertical scale

$Q_w(p)$
$e\overline{D}$-DIS
$Q_w(e)$
$ν$-DIS
$A_{FB}$
Z-pole

$\sin^2 \theta_W$ vs. $Q [\text{GeV}]$
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 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>
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</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...

- heaviest, stable, ‘simple’ atom
- lack of atomic structure knowledge in Bi, Tl, Pb

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/cm\(^2\) 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-th-art position control for atoms
- [particle] result
Electron EDM in heavy alkalis with an atomic fountain (H. Gould, Berkeley)

- fountain: motional B-field much smaller, cancellation atom by atom
- proof of principle in Cs (Amini 2007), \( d < 10^{-22} \) e cm
- believe that 'real' Cs expt can improve current limit 100 x
- e-EDM 10x enhanced in Fr rel. to Cs
- estimate: need \( 10^{14} \) interrogated atoms (just like 0.1 % APNC, hence similar time scale)
- 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 (Univ. of Maryland)
V. Flambaum (Univ. of New South Wales)
S. Aubin (College of William and Mary)

good mix of in-house & external scientists
experts: radioactive beams/nuclear physics
fundamental symmetry measurements
quantum optics
Fractional stability required for a 3% measurement. The observable associated with each constraint is also included.

| Observable       | Constraint                | Set value     | Stability
|------------------|---------------------------|---------------|------------
| $A_{Ry}A_{E1}$   | Microwave amplitude       | 476 V/cm      | 0.03       |
| $A_{Ry}A_{Ry}$   | Raman amplitude           | 121 rad/s     | $2.5 \times 10^{-4}$ |
| $(\hbar \delta)^2$ | Microwave frequency       | 45 GHz        | $10^{-11}$ |
|                  | Dipole trap Stark shift   | 6.3 Hz        | 0.07       |
|                  | dc magnetic field         | 1500 G        | $4.7 \times 10^{-5}$ |
| $A_{Rx}A_{Rx}$   | Raman polarization        | 0 rad         | $10^{-3}$  rad |
| $A_{Ry}A_{Miy}$  | Mirror separation         | 13 cm         | $7.7 \times 10^{-7}$ |
|                  | Antenna power             | 57 mW         | 0.02       |
|                  | Antenna phase             | 0 rad         | 0.01 rad |
| $A_{Ry}A_{Mox}$  | Mirror birefringence      | 0 rad         | $1 \times 10^{-4}$  rad |
|                  | Trap displacement         | 0 m           | $3 \times 10^{-11}$ m |