University of Virginia Colloquium

ATOMIC CALCULATIONS FOR TESTS OF FUNDAMENTAL PHYSICS

MARIANNA SAFRONOVA

November 11, 2011
• **Atomic physics tests of fundamental physics**
  • Parity violation
  • Search for permanent electric-dipole moment (EDM)
  • Variation of fundamental constants and atomic clocks

• **Atomic parity violation**
  • Theory: How to calculate APV amplitude?
  • Analysis of Cs experiment and implications for search for physics beyond the Standard Model
  • Nuclear spin-dependent APV effects and weak hadronic interactions
**TRANSFORMATIONS AND SYMMETRIES**

<table>
<thead>
<tr>
<th>Transformation</th>
<th>Conservation Law</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation</td>
<td>Momentum conservation</td>
</tr>
<tr>
<td>Translation in time</td>
<td>Energy conservation</td>
</tr>
<tr>
<td>Rotation</td>
<td>Conservation of angular momentum</td>
</tr>
<tr>
<td>[C] Charge conjugation</td>
<td>C-invariance</td>
</tr>
<tr>
<td>[P] Spatial inversion</td>
<td>Parity conservation (P-invariance)</td>
</tr>
<tr>
<td>[T] Time reversal</td>
<td>T-invariance</td>
</tr>
<tr>
<td>[CP]</td>
<td></td>
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<td>[CPT]</td>
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<td></td>
</tr>
<tr>
<td>[CPT]</td>
<td></td>
</tr>
</tbody>
</table>
Parity-transformed world:

Turn the mirror image upside down.

The parity-transformed world is not identical with the real world.

Parity is not conserved.
### Properties of the Interactions

<table>
<thead>
<tr>
<th>Property</th>
<th>Interaction</th>
<th>Gravitational</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass – Energy</td>
<td>All</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
<td>See Residual Strong Interaction Note</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td></td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td>Quarks, Gluons</td>
<td>Hadrons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td></td>
<td></td>
<td></td>
<td>Gluons</td>
<td>Mesons</td>
</tr>
<tr>
<td>Strength relative to electromag for two u quarks at:</td>
<td>$10^{-18}$ m</td>
<td>$10^{-41}$, $10^{-41}$, $10^{-36}$</td>
<td>$0.8$, $10^{-4}$, $10^{-7}$</td>
<td>1, 1, 1</td>
<td>25, 60</td>
<td>Not applicable to quarks</td>
</tr>
<tr>
<td>for two protons in nucleus</td>
<td>$3 \times 10^{-17}$ m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

Viewed as the exchange of mesons.
Instead of searching for new processes or particles directly, determine the weak charge $Q_W$ from atomic parity violation studies and compare the result with the Standard Model prediction.

http://public.web.cern.ch/, Cs experiment, University of Colorado
Quantifying the strength of the electroweak coupling between atomic electrons and quarks of the nucleus.

Weak Charge $Q_W$
Two sides of the atomic parity violation

NUCLEAR
SPIN-INDEPENDENT
PNC:
SEARCHES FOR NEW
PHYSICS
BEYOND THE
STANDARD MODEL

NUCLEAR
SPIN-DEPENDENT
PNC:
STUDY OF PNC
IN THE NUCLEUS

Weak Charge $Q_W$

Nuclear anapole moment
TRANSFORMATIONS AND SYMMETRIES

Translation → Momentum conservation
Translation in time → Energy conservation
Rotation → Conservation of angular momentum

[C] Charge conjugation → C-invariance
[P] Spatial inversion → Parity conservation (P-invariance)
[T] Time reversal → T-invariance
[CP]
[CPT]
Time-reversal invariance must be violated for an elementary particle or atom to possess a permanent EDM.

\[ \mathbf{d} \rightarrow -\mathbf{d} \]

\[ \mathbf{t} \rightarrow -\mathbf{t} \]

\[ \mathbf{S} \rightarrow -\mathbf{S} \]

\[ \mathbf{d} = \frac{\mathbf{S}}{S} \]

\[ d = 0 \]
Many theories beyond the Standard Model predict EDM within or just beyond the present experimental capabilities.
EDM effects are enhanced in some heavy atoms and molecules.

Theory is needed to calculate enhancement factors and search for new systems for EDM detection.

Recent new limit on the EDM of $^{199}$Hg

$|d(^{199}\text{Hg})| < 3.1 \times 10^{-29} \text{ e cm}$

Phys. Rev. Lett. 102, 101601 (2009)
(1) **Astrophysical constraints** on variation of $\alpha$:
Study of quasar absorption spectra: $4\sigma$ variation!!!

**Atomic calculations**: need to know isotope shifts
Changes in isotopic abundances mimic shift of $\alpha$

(2) **Laboratory atomic clock experiments**: compare rates of different clocks over long period of time to study time variation of fundamental constants

Need: dependence of transition frequency on $\alpha$ and ultra precise clocks!
The ability to develop more precise optical frequency standards will open ways to improve global positioning system (GPS) measurements and tracking of deep-space probes, perform more accurate measurements of the physical constants and tests of fundamental physics such as searches for gravitational waves, etc.
(1) Prediction of atomic properties required for new clock proposals

New clock proposals require both estimation of the atomic properties for details of the proposals (transition rates, lifetimes, branching ratios, magic wavelength, scattering rates, etc.) and evaluation of the systematic shifts (Zeeman shift, electric quadruple shift, blackbody radiation shift, ac Stark shifts due to various lasers fields, etc.).

(2) Determination of the quantities contributing to the uncertainty budget of the existing schemes.

In the case of the well-developed proposals, one of the main current uncertainty issues is the blackbody radiation shift.
ATOMIC PARITY VIOLATION
Two sides of the atomic parity violation

NUCLEAR SPIN-INDEPENDENT PNC: SEARCHES FOR NEW PHYSICS BEYOND THE STANDARD MODEL

nu
Weak Charge $Q_w$

NUCLEAR SPIN-DEPENDENT PNC: STUDY OF PNC IN THE NUCLEUS

Nuclear anapole moment

Diagram:
- Electron (e) and quark (q) interactions
- Weak charge $Q_w$ indication
- Nuclear anapole moment symbol $\alpha$
### EXPERIMENTAL PNC STUDIES

![Image of the periodic table of elements]

**For a description of the data, visit physics.nist.gov/data**

NIST SP 966 (September 2003)
Cesium: atom with single (valence) electron outside a closed core.

Need heavy atom for atomic PNC

$l=0$ to $l=0$ electric dipole transition is forbidden by parity selection rules
Both 6s and 7s states acquire an opposite-parity \((np_{1/2})\) admixture.

\[ Z_0 \text{ exchange: Laporte’s rule is violated!} \]
Atomic Parity Violation

Non-zero transition amplitude
PNC amplitude $E_{PNC}$

Both 6s and 7s states acquire an opposite-parity ($np_{1/2}$) admixture

$Z_0$ exchange: Laporte’s rule is violated!

Note: it is really tiny effect !!! $E_{PNC} \sim 10^{-11}$ atomic units
E1 amplitude for 6s – 6p transition is 4.5 atomic units
The most precise measurement of PNC amplitude (cesium)


Stark interference scheme to measure ratio of the PNC amplitude and the Stark-induced amplitude $\beta$

$$\frac{\text{Im}(E_{\text{PNC}})}{\beta} = \begin{cases} 
-1.6349(80) \text{ mV/cm} & 1 \\
-1.5576(77) \text{ mV/cm} & 2 
\end{cases}$$
Analysis of Cs PNC experiment

**NUCLEAR SPIN–INDEPENDENT PNC**

$$\text{Average of 1} \& 2$$

$$\frac{\text{Im}(E_{PNC}^{si})}{\beta} = -1.5935(56) \text{ mV/cm}$$

**Weak Charge $Q_W$**

**NUCLEAR SPIN–DEPENDENT PNC**

$$\text{Difference of 1} \& 2$$

$$\Delta \left[ \text{Im}(E_{PNC}^{sd}) / \beta \right]_{34-43} = -0.077(11) \text{ mV/cm}$$

**Nuclear anapole moment**
Analysis of Cs PNC experiment

**NUCLEAR SPIN-INDEPENDENT PNC**

Average of 1 & 2

\[
\frac{\text{Im}(E_{\text{PNC}}^{\text{si}})}{\beta} = -1.5935(56) \text{ mV/cm}
\]

Weak Charge $Q_w$
How to extract weak charge $Q_w$ from Cs experiment?

Electron-quark parity violating interaction (exchange of virtual $Z_0$ boson)

$$H_W = \frac{G_F}{\sqrt{2}} \left( -e\gamma_\mu \gamma_5 e \right) \left\{ C_{1u} \bar{u}\gamma^\mu u + C_{1d} \bar{d}\gamma^\mu d \right\} + ...$$

Electronic sector:

$$H^{(1)}_{\text{PNC}} = \frac{G_F}{2\sqrt{2}} Q_w \gamma_5 \rho(r)$$

Extraction of weak the charge:

Theoretical calculation of PNC amplitude

\[ E_{\text{PNC}} = E_{\text{PNC}}^{\text{theory}} Q_{\text{inferred}} \]

Measured value
1. Main part – Coulomb interactions

\[ E_{PNC}^{\text{theory}} = \sum_{n=2}^{\infty} \langle 7s | d | np_{1/2} \rangle \langle np_{1/2} | H_{PNC} | 6s \rangle + \sum_{n=2}^{\infty} \langle 7s | H_{PNC} | np_{1/2} \rangle \langle np_{1/2} | d | 6s \rangle \]

- \( E_{6s} - E_{np_{1/2}} \)
- \( E_{7s} - E_{np_{1/2}} \)

Sum is separated to main part, \( n = 6 - 9 \) and the tail

2. Other small corrections:

Breit, QED, Neutron skin, e – e weak interaction
REDUCING THEORY UNCERTAINTY: 
WHY IS IT SO DIFFICULT?

\[ |\Psi_v\rangle = \Omega |\Psi_v^{(0)}\rangle \]

Exact wave function

Many-body operator, describes excitations from lowest-order

Cs: 55 electrons

55-fold excitations to get exact wave function

Even for 100 function basis set  \[ 100^{55} \]

Approximate methods: perturbation theory does not converge well, Need to use all-order methods (coupled-cluster method and correlation potential method)
\[ \left| \Psi_v \right\rangle = \Omega \left| \Psi_v^{(0)} \right\rangle = \exp(S) \left| \Psi_v^{(0)} \right\rangle \quad \text{DHF wave function} \]

\[ \exp(S_1 + S_2) \quad \text{CCSD single-double coupled-cluster} \]

\[ S_1 + S_2 \quad \text{LCCSD coupled-cluster} \]

Coupled-cluster method (CCSD)
Lowest order

Core

\[ |\Psi_v^{(0)}\rangle \]

Core

valence electron

any excited orbital

Single-particle excitations

\[ \sum_{ma} \rho_{ma} a_m^\dagger a_a |\Psi_v^{(0)}\rangle \]

\[ \sum_{m\neq v} \rho_{mv} a_m^\dagger a_v |\Psi_v^{(0)}\rangle \]

Double-particle excitations

\[ \frac{1}{2} \sum_{mnab} \rho_{mnab} a_m^\dagger a_n^\dagger a_b a_a |\Psi_v^{(0)}\rangle \]

\[ \sum_{mna} \rho_{mnva} a_m^\dagger a_n^\dagger a_a a_v |\Psi_v^{(0)}\rangle \]
Actual implementation: problem 1

There are some many equations!

Need very accurate (large) basis sets for parity violation.

\[ \rho_{mnab} \]

Cs: \( a,b = 1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}5s^25p^6 \)

\( m,n : \text{finite basis set} = (35 \times 13) \times (35 \times 13) \)

Total actually \( 15412 \times 35 \times 35 \sim 19 000 000 \) equations

to be solved iteratively!

Our implementation of the coupled-cluster is different from quantum chemistry – new sets of codes were developed.
These are really complicated equations !!!

- “Quadruple” term:

\[ \sum_{r,s} g_{mnrs} \rho_{rsab} \]

Indices \( mnrs \) can be ANY orbitals

Basis set: \( n_{\max} = 35, l_{\max} = 6 \)

\[ 17 \times 17 \times (35 \times 13)^4 = 5 \times 10^{12}! \]

- Program has to be exceptionally efficient!
1. Add more terms to the all order wave-function

   Non-linear terms  Triple excitations

   \[ \frac{1}{2}(S_1^2 + 2S_1S_2 + S_2^2) \]

   \[ + \frac{1}{6}(S_1^3 + 3S_1^2S_2) + \frac{1}{24}S_1^4 \]

2. Restore complete 4th order for matrix elements
Non-linear terms

\[ H \frac{1}{2} S_2^2 \left| \Psi_v^{(0)} \right> \rightarrow a_i^+ a_j^+ a_l a_k : a_m^+ a_n^+ a_r^+ a_s^+ a_d a_c a_b a_a a_v^+ : |0_v> \]
$\frac{1}{2} S_2^2$

Contract operators by Wick’s theorem

$H \frac{1}{2} S_2^2 | \Psi^{(0)}_v \rangle \rightarrow: a_i^+ a_j^+ a_l a_k : a_m^+ a_n^+ a_r^+ a_s^+ a_d a_c a_b a_a a_v^+ : | 0_c \rangle$

800 TERMS!
The derivation gets **really complicated** if you add triples and non-linear terms!

Solution: **develop analytical codes** that do all the work for you!

**Input:** ASCII input of terms of the type

\[
\sum_{mnrab} \sum_{ijkl} g_{ijkl} \rho_{mnrvab} : a_i^\dagger a_j^\dagger a_l a_k : : a_m^\dagger a_n^\dagger a_r a_b a_a a_v : \left| \Psi_v^{(0)} \right> \]

**Output:** final simplified formula in LATEX to be used in the all-order equation
Triple excitations

\[ \sum_{mnrb} \rho_{mnrvab} a_{m}^{\dagger} a_{n}^{\dagger} a_{r}^{\dagger} a_{a} a_{b} a_{v} |\Psi_{v}^{(0)}\rangle \]

**Problem 1:** too many excitation coefficients \( \rho_{mnrvab} \)

**Problem 2:** increased complexity of equations
Triple excitations

**Problem:** too many excitation coefficients $\rho_{mnrvab}$.

Doubles:

$\rho_{mnab}$

Cs: $a,b = 1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}5s^25p^6$

$m,n : \text{finite basis set} = (35 \times 13) \times (35 \times 13)$

Smallest required basis set:

Need total about 300 MB (+extra 150MB file)

Extra index $r$ gives at least a factor $(35 \times 13) : \text{over } 130\text{GB}$!

The complexity of the equations also increases.
Problem with all-order extensions: TOO MANY TERMS

Solution: automated code generation!

Codes that write formulas

Codes that write codes

Input: list of formulas to be programmed
Output: final code (need to be put into a main shell)

Features: simple input, essentially just type in a formula!
### RESULTS FOR ALKALI-METAL ATOMS: E1 MATRIX ELEMENTS (A.U.)

<table>
<thead>
<tr>
<th></th>
<th>Na</th>
<th>K</th>
<th>Rb</th>
<th>Cs</th>
<th>Fr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3p_{1/2}-3s</td>
<td>4p_{1/2}-4s</td>
<td>5p_{1/2}-5s</td>
<td>6p_{1/2}-6s</td>
<td>7p_{1/2}-7s</td>
</tr>
<tr>
<td>All-order</td>
<td>3.531</td>
<td>4.098</td>
<td>4.221</td>
<td>4.478</td>
<td>4.256</td>
</tr>
<tr>
<td>Experiment</td>
<td>3.5246(23)</td>
<td>4.102(5)</td>
<td>4.231(3)</td>
<td>4.489(6)</td>
<td>4.277(8)</td>
</tr>
<tr>
<td>Difference</td>
<td>0.18%</td>
<td>0.1%</td>
<td>0.24%</td>
<td>0.24%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>


- **Cs**: R.J. Rafac et al., Phys. Rev. A 60, 3648 (1999),

Monovalent systems: very brief summary of what we calculated with all-order method

Properties

- Energies
- Transition matrix elements (E1, E2, E3, M1)
- Static and dynamic polarizabilities & applications
  - Dipole (scalar and tensor)
  - Quadrupole, Octupole
  - Light shifts
  - Black-body radiation shifts
  - Magic wavelengths
- Hyperfine constants
- C₃ and C₆ coefficients
- Parity-nonconserving amplitudes (derived weak charge and anapole moment)
- Isotope shifts (field shift and one-body part of specific mass shift)
- Atomic quadrupole moments
- Nuclear magnetic moment (Fr), from hyperfine data

Systems

Li, Na, Mg II, Al III, Si IV, P V, S VI, K, Ca II, In, In-like ions, Ga, Ga-like ions, Rb, Cs, Ba II, Tl, Fr, Th IV, U V, other Fr-like ions, Ra II

http://www.physics.udel.edu/~msafrono
1989 – 2003: Summary of the PNC calculations

-0.902, -0.908 (-0.905 average) Blundell et al. (1992)
-0.908 Dzuba et al. (1989)

-0.909 Safronova & Johnson (1999)
-0.905 Kozlov et al. (2001)
-0.908 Dzuba et al. (2002) **0.5% uncertainty**

Units: \( i|e|a_B(-Q_W/N) \times 10^{11} \)

-0.6% Breit correction
-0.2(1)% neutron skin correction
+0.4% vacuum polarization
-0.8% radiative corrections

(Several works for all corrections)
Determination of $Q_W : 1997 - 2003$

**Wood et al. (1997)** $\text{Im}(E_{\text{PNC}})/\beta$
-72.11(29)$_{\text{expt}}^{(89)}$$_{\text{theor}}$ $1\sigma$
-72.06(29)$_{\text{expt}}^{(34)}$$_{\text{theor}}$ $2.5\sigma$

**Bennett & Wieman (1999)**
Measurement of $\beta$

**Derevianko (2000, 2002)**
Calculation of Breit correction

**Dzuba et al. (2000)**
Calculation of Breit correction

**Kozlov et al. (2001)**
Calculation of $E_{\text{PNC}}$, Breit correction

**Johnson et al. (2001)**
Calculation of vacuum pol. corr.

**Milstein & Sushkov (2002)**
Calculation of vacuum pol. corr.

**Vasilyev et al. (2002)**
Measurement of 6s-7p trans., $\beta$

**Dzuba et al. (2002)** $E_{\text{PNC}}$

**Flambaum & Kuchiev (2002)**

**Milstein et al. (2003)**
self-energy & vertex corr.

**Dzuba et al. (2002)**

**Flambaum & Kuchiev (2002)**

**Milstein et al. (2003)**

**Kozlov et al. (2001)**
Calculation of vacuum pol. corr.

**Johnson et al. (2001)**
Calculation of vacuum pol. corr.

**Milstein & Sushkov (2002)**
Calculation of vacuum pol. corr.

**Vasilyev et al. (2002)**
Measurement of 6s-7p trans., $\beta$
## Summary of the PNC amplitude calculations

<table>
<thead>
<tr>
<th>Coulomb interaction</th>
<th>Porsev et al., PRL 102, 181601 (2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main part, n = 6 - 9</td>
<td>0.8823(18)</td>
</tr>
<tr>
<td>Tail</td>
<td>0.0175(18)</td>
</tr>
<tr>
<td>Total</td>
<td>0.8998(25)</td>
</tr>
</tbody>
</table>

### Corrections

<table>
<thead>
<tr>
<th></th>
<th>Derevianko, PRL 85, 1618 (2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breit</td>
<td>-0.0054(5)</td>
</tr>
<tr>
<td>QED</td>
<td>-0.0024(3)</td>
</tr>
<tr>
<td>Neutron skin</td>
<td>-0.0017(5)</td>
</tr>
<tr>
<td>e-e weak interactions</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

| Final                  | 0.8906(26)                               |
|                        | Porsev et al., PRL 102, 181601 (2009)   |

Units: $i |e| a_B (-Q_W / N) \times 10^{11}$
Cs PNC: Comparison with the standard model

Standard Model [1]:

\[ Q_{W}^{SM} = -73.16(3) \]

Most current result for Cs PNC Expt/Theory:

Atomic physics [2]:

\[ Q_{W}^{\text{inferred}} = -73.16(29)_{\text{expt}}^{(20)}_{\text{theory}} \]

No deviation from the Standard Model

IMPLICATIONS FOR PARTICLE PHYSICS
Confirms fundamental “running” (energy dependence) of the electroweak force over energy span 10 MeV → 100 GeV

New physics can be phenomenologically described by weak isospin - conserving $S$ and isospin - breaking $T$ parameters \[1\].

\[
\Delta Q = Q_{W}^{\text{inferred}} - Q_{W}^{\text{SM}} = -0.800S - 0.007T
\]

Present result \[2\]: \[S\] < 0.45

Parameter $S$ is important for indirect constraint on the mass of Higgs particle \[1\].

\[1\] J.L. Rosner, PRD 65, 073026 (2002)
Atomic parity violation is uniquely sensitive to $Z'$

$Z'_\chi$ in SO(10) GUT, Marciano & Rosner

$$\Delta Q = Q_{W}^{\text{inferred}} - Q_{W}^{\text{SM}} \approx \left( \frac{0.736 \text{ TeV} / c^2}{M_{Z'_x}} \right)^2$$
Probing new physics: extra Z bosons

$Z'_\chi$ in SO(10) GUT, Marciano & Rosner

$$\Delta Q = Q^\text{inferred}_W - Q^\text{SM}_W \approx \left( \frac{0.736 \, \text{TeV} / c^2}{M_{Z'_\chi}} \right)^2$$

Cs result [1] implies $M_{Z'_\chi} > 1.3\,\text{TeV} / c^2$

Direct search at Tevatron collider [2]

$M_{Z'_\chi} > 0.82\,\text{TeV} / c^2$

Parity violation in atoms

NUCLEAR SPIN-DEPENDENT PNC: STUDY OF PNC IN THE NUCLEUS

The other part of the story

Nuclear anapole moment
Spin-dependent parity violation: Nuclear anapole moment

Parity-violating nuclear moment

Valence nucleon density

Nuclear anapole moment is parity-odd, time-reversal-even E1 moment of the electromagnetic current operator.
Constraints on nuclear weak coupling constants

The constraints obtained from the Cs experiment were found to be **inconsistent** with constraints from other nuclear PNC measurements, which favor a smaller value of the $^{133}\text{Cs}$ anapole moment.

Possible atomic calculation solution?

$\kappa = 0.117(16)$

Incomplete correlation calculation of spin-dependent PNC amplitude?
More spin-dependent PNC effects

\[ \mathcal{K} = \mathcal{K}_a + \mathcal{K}_2 + \mathcal{K}_{hf} \]

Weak-hyperfine interference term

This term does not reduce to the same interaction but “effective” constant \( \mathcal{K}_{hf} \) can be calculated.

Same Hamiltonian as anapole moment term with \( \mathcal{K}_a \Rightarrow \mathcal{K}_2 \)

New all-order (CCSD) calculation of spin-dependent PNC

First four terms in the sums are replaced by all-order matrix elements

1% accuracy is expected

Electric-dipole matrix elements

PNC matrix elements

\[ E_{\text{PNC}}^{(2a)} = A_1 \sum_{j \neq \nu} \langle 7s | d^j \rangle \langle j | j \rangle \langle j | d^j | 6s \rangle + A_2 \sum_{j \neq w} \langle 7s | H^{(2a)}_{\text{PNC}} | j \rangle \langle j | j \rangle \langle j | H^{(2a)}_{\text{PNC}} | 6s \rangle \]

\[ E_{6s} - E_j \]

\[ E_{7s} - E_j \]
The constraints obtained from the Cs experiment were found to be inconsistent with constraints from other nuclear PNC measurements, which favor a smaller value of the $^{133}$Cs anapole moment.

All-order (LCCSD) calculation of spin-dependent PNC amplitude:

$$k = 0.107(16)^* \ [ \ 1\% \ theory \ accuracy \ ]$$

No significant difference with previous value $k = 0.112(16)$ is found.

**NEED NEW EXPERIMENTS!!!**

Fr, Yb, Ra$^+$

NEED NEW EXPERIMENTAL PNC STUDIES WANTED!
# Periodic Table of the Elements

**Experimental PNC Studies**

<table>
<thead>
<tr>
<th>Group 1 (IA)</th>
<th>Hydrogen (H)</th>
<th>1.00784</th>
<th>12.0004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period 1</td>
<td>Lithium (Li)</td>
<td>6.941</td>
<td>9.01225</td>
</tr>
<tr>
<td></td>
<td>Sodium (Na)</td>
<td>22.9898</td>
<td>24.305</td>
</tr>
</tbody>
</table>

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)
All-order Correlation potential

CI+MBPT
Fr and Ra+: 1-3% at present
0.5% possible with CCSDT (same as Cs)

Yb: 9% at present
Significant improvement should be possible with CI + coupled-cluster, especially if triples are implemented

Dy: ? Previous: no signal within 2 orders of magnitude from prediction. The problems appear to be somewhat understood at this time. Significant improvement possible if CI+MBPT could be implemented.

Tl, Bi, Pb – improvements to 1% should be possible
A: New analysis of atomic PNC experiment is Cs: Nuclear spin-independent part:

(1) Provided most accurate to-date test of the low-energy electroweak sector of the SM.

(2) Confirmed fundamental “running” (energy dependence) of the electroweak force.

(3) Placed constraints are on a variety of new physics scenarios beyond the SM.

B: New analysis of atomic PNC experiment is Cs: Nuclear spin-independent part (anapole moment)

(1) New calculations, accurate to 1% - essentially the same result.

(2) Constraints on nuclear weak coupling constants are still inconsistent with nuclear physics experiments.
COLLABORATORS

Michael Kozlov, PNPI, Russia
Sergei Porsev, PNPI, Russia
(presently research scholar at the University of Delaware)
Charles Clark, NIST
Ulyana Safronova, University of Nevada-Reno
Andrei Derevianko, University of Nevada-Reno
Ephraim Eliav, Tel Aviv University, Israel
Walter Johnson, University of Notre Dame

GRADUATE STUDENTS:

Rupsi Pal*
Dansha Jiang*
Bindiya Arora*
Jenny Tchoukova*
Zhuriadna
Matt Simmons

*Graduated with a Ph.D.