FUNDAMENTAL SYMMETRIES, ATOMIC CLOCKS AND QUANTUM COMPUTERS

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Applications of Atomic Calculations

- Study of fundamental symmetries with atoms
  - Parity violation: tests the of Standard Model
  - Parity violation: study of weak hadronic interactions
  - Search for permanent elector electric-dipole moment
  - Search for variation of fundamental constants

- Atomic clocks

- Quantum computers
  - Development of high-precision atomic methodologies

- Web site: www.physics.udel.edu/~msafrono
**Transformations and Symmetries**

<table>
<thead>
<tr>
<th>Transformation</th>
<th>Symmetry</th>
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<tr>
<td>Translation</td>
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<td></td>
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</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>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td></td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td></td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td></td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrally charged</td>
<td></td>
</tr>
<tr>
<td>Particles mediating:</td>
<td></td>
<td>Graviton (not yet observed)</td>
<td>$W^+$, $W^-$, $Z^0$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>Strength relative to electromag for two u quarks at:</td>
<td></td>
<td>$10^{-41}$</td>
<td>0.8</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$3 \times 10^{-17}$</td>
<td>$10^{-4}$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10^{-36}$</td>
<td>$10^{-7}$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>for two protons in nucleus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Gravitational**: Mass – Energy
- **Weak (Electroweak)**: Flavor, Quarks, Leptons, Electrically charged $W^+$, $W^-$, $Z^0$
- **Electromagnetic**: Color Charge, Quarks, Gluons, Hadrons, Electrally charged $\gamma$
- **Strong**: Color Charge, See Residual Strong Interaction Note, Quarks, Gluons, Hadrons, $25$, 60, Not applicable to hadrons, Mesons, 20
**Weak Charge $Q_W$**

$$Q_W = -N + Z(1 - 4\sin^2 \theta_W)$$

$Q_W$ quantifies the strength of the electroweak coupling between atomic electrons and quarks of the nucleus.

Non-zero transition amplitude $E_{PNC}$
The most precise measurement of PNC amplitude (in cesium)

0.3% accuracy


\[
\frac{\text{Im}(E_{\text{PNC}})}{\beta} = \begin{cases} 
-1.6349(80) \text{ mV/cm} & 1 \\
-1.5576(77) \text{ mV/cm} & 2 
\end{cases}
\]

NEED ATOMIC THEORY TO GET \( Q_W \) FROM THE EXPERIMENT
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

Dirac-Hartree-Fock wave function (lowest order)

Cs: 55 electrons \rightarrow 55-fold excitations to get exact wave function

Even for 100 function basis set \rightarrow 100^{55}

Approximate methods: perturbation theory does not converge well, Need to use all-order methods (coupled-cluster method and correlation potential method)
Atomic physics tests of the standard model, Cs nucleus

Standard Model \[ Q_W = -73.16(3) \]

1999 analysis of Cs experiment showed 2.5\(\sigma\) deviation from the Standard Model

Most current result:

Atomic physics [1] \[ Q_W = -73.16(29)_{\text{exp}}(20)_{\text{th}} \]

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

Figure is from Bentz et al. Phys. Lett. B693, 462 (2010).
Probing new physics: extra Z bosons

$Z'_x$ in SO(10) GUT, Marciano & Rosner

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

Direct search at Tevatron collider [2]

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

Parity violation in atoms: Part 2
Study of Weak Hadronic Interactions

Parity-violating nuclear moment

\[ H_{\text{PNC}}^{(a)} = \frac{G_F}{\sqrt{2}} \kappa_a \alpha \cdot I \rho_v(r) \]

Valence nucleon density

Anapole moment

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 $^{133}$Cs anapole moment.

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

$$k = 0.107(16)* \ [ 1\% \ \text{theory accuracy} ]$$

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

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Time-reversal invariance must be violated for an elementary particle or atom to possess a permanent EDM.

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

\[ d = 0 \]
Many theories beyond the Standard Model predict EDM within or just beyond the present experimental capabilities.
Atomic calculations and search for EDM

EDM effects are enhanced in some heavy atoms and molecules.

**Limits on the electron EDM**

**TI atom:** $|d_e| < 1.6 \times 10^{-27} \, e \, cm$


**YbF molecule:** $|d_e| < 1.05 \times 10^{-27} \, e \, cm$

Hudson et al., Nature 473, 493 (2011)

Both results crucially depend on the calculated values of the effective electric field on the valence electron. In the case of TI this effective field is proportional to the applied field $E_0$, $E = K E_0$ and $d^{(205\text{TI})}=K d_e$, $K = -585$
Summary: TI EDM enhancement factor


\[ \mathcal{K} = -585 \text{ (30-60)} \]

V. A. Dzuba and V. V. Flambaum, PRA 80, 062509 (2009)

\[ \mathcal{K} = -582 \text{ (20)} \]

H. S. Nataraj, B. K. Sahoo, B. P. Das, and D. Mukherjee, PRL 106, 200403 (2011)

\[ \mathcal{K} = -466 \text{ (10)} \]


\[ \mathcal{K} = -573 \text{ (20)} - \text{several calculations carried out} \]
Atomic calculations and variation of fundamental constants

(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!
ATOMIC CLOCKS
Microwave Transitions

Optical Transitions

Neutral atoms in optical lattices
Single ion
Th: nuclear clock?

Cs: $4 \times 10^{-16}$


Al$^+$: $8.6 \times 10^{-18}$

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.
Atomic clocks: Black-body radiation (BBR) shift

REALLY HARD TO MEASURE OR GET RID OF!

BBR shift gives large contribution into uncertainty budget for some of the atomic clock schemes.

Accurate calculations (or measurements) are needed to achieve ultimate precision goals at room temperature.
Transition frequency should be corrected to account for the effect of the black body radiation at $T=300$K.
Summary of the fractional uncertainties $\Delta v/v_0$ due to BBR shift and the fractional error in the absolute transition frequency induced by the BBR shift uncertainty at $T = 300$ K in various frequency standards

<table>
<thead>
<tr>
<th>Atom</th>
<th>Clock transition</th>
<th>$\Delta v/v_0$</th>
<th>Uncertainty</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rb</td>
<td>$5s (F=2 - F=1)$</td>
<td>$-1.25 \times 10^{-14}$</td>
<td>$4 \times 10^{-17}$</td>
<td>Safronova et al. 2010</td>
</tr>
<tr>
<td>Cs</td>
<td>$6s (F=4 - F=3)$</td>
<td>$-1.7 \times 10^{-14}$</td>
<td>$3 \times 10^{-17}$</td>
<td>Simon et al. 1998</td>
</tr>
<tr>
<td>Ca$^+$</td>
<td>$4s - 3d_{5/2}$</td>
<td>$9.2 \times 10^{-16}$</td>
<td>$1 \times 10^{-17}$</td>
<td>Safronova et al. 2011</td>
</tr>
<tr>
<td>Sr$^+$</td>
<td>$5s - 4d_{5/2}$</td>
<td>$5.6 \times 10^{-16}$</td>
<td>$2 \times 10^{-17}$</td>
<td>Jiang et al. 2009</td>
</tr>
<tr>
<td>Yb$^+$</td>
<td>$6s - 5d_{2D_{3/2}}$</td>
<td>$-5.3 \times 10^{-16}$</td>
<td>$1 \times 10^{-16}$</td>
<td>Tamm et al. 2007</td>
</tr>
<tr>
<td>Yb$^+$</td>
<td>$6s - 4f_{13} 6s^2 2F_{7/2}$</td>
<td>$-5.7 \times 10^{-17}$</td>
<td>$1 \times 10^{-17}$</td>
<td>Hosaka et al. 2009</td>
</tr>
<tr>
<td>Mg</td>
<td>$3s^2 , ^1S_0 - 3s3p , ^3P_0$</td>
<td>$-3.9 \times 10^{-16}$</td>
<td>$1 \times 10^{-17}$</td>
<td>Porsev et al. 2006</td>
</tr>
<tr>
<td>B$^+$</td>
<td>$2s^2 , ^1S_0 - 2s2p , ^3P_0$</td>
<td>$1.42 \times 10^{-17}$</td>
<td>$1 \times 10^{-18}$</td>
<td>Safronova et al. 2011</td>
</tr>
<tr>
<td>Al$^+$</td>
<td>$3s^2 , ^1S_0 - 3s3p , ^3P_0$</td>
<td>$-3.8 \times 10^{-18}$</td>
<td>$4 \times 10^{-19}$</td>
<td>Safronova et al. 2011</td>
</tr>
<tr>
<td>In$^+$</td>
<td>$5s^2 , ^1S_0 - 5s5p , ^3P_0$</td>
<td>$-1.36 \times 10^{-17}$</td>
<td>$1 \times 10^{-18}$</td>
<td>Safronova et al. 2011</td>
</tr>
<tr>
<td>Tl$^+$</td>
<td>$6s^2 , ^1S_0 - 6s6p , ^3P_0$</td>
<td>$-1.06 \times 10^{-17}$</td>
<td>$1 \times 10^{-18}$</td>
<td>Zuhrianda et al. 2012</td>
</tr>
<tr>
<td>Sr</td>
<td>$5s^2 , ^1S_0 - 5s5p , ^3P_0$</td>
<td>$-5.5 \times 10^{-15}$</td>
<td>$7 \times 10^{-17}$</td>
<td>Porsev et al. 2006</td>
</tr>
<tr>
<td>Yb</td>
<td>$6s^2 , ^1S_0 - 6s6p , ^3P_0$</td>
<td>$-2.6 \times 10^{-15}$</td>
<td>$3 \times 10^{-16}$</td>
<td>Porsev et al. 2006</td>
</tr>
<tr>
<td>Hg</td>
<td>$6s^2 , ^1S_0 - 6s6p , ^3P_0$</td>
<td>$-1.6 \times 10^{-16}$</td>
<td></td>
<td>Hachisu et al. 2008</td>
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QUANTUM COMPUTERS
Why quantum information?

Information is physical!
Any processing of information is always performed by physical means

Bits of information obey laws of classical physics.
Why Quantum Computers?

Computer technology is making devices smaller and smaller... reaching a point where classical physics is no longer a suitable model for the laws of physics.
Fundamental building blocks of classical computers:

**BITS**

STATE:

Definitely

0 or 1

Fundamental building blocks of quantum computers:

Quantum bits

or

**QUBITS**

Basis states: $|0\rangle$ and $|1\rangle$

Superposition:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$
Fundamental building blocks of classical computers:

**BITS**

STATE: Definitely

0 or 1

Fundamental building blocks of quantum computers:

Quantum bits or **QUBITS**

Basis states: $|0\rangle$ and $|1\rangle$

$|\uparrow\rangle + |\downarrow\rangle$
Multiple qubits

- Two bits with states 0 and 1 form four definite states 00, 01, 10, and 11.
- Two qubits: can be in superposition of four computational basis set states.

\[ |\psi\rangle = \alpha |00\rangle + \beta |01\rangle + \gamma |10\rangle + \delta |11\rangle \]

<table>
<thead>
<tr>
<th>Number of Qubits</th>
<th>Amplitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 qubits</td>
<td>4 amplitudes</td>
</tr>
<tr>
<td>3 qubits</td>
<td>8 amplitudes</td>
</tr>
<tr>
<td>10 qubits</td>
<td>1024 amplitudes</td>
</tr>
<tr>
<td>20 qubits</td>
<td>1 048 576 amplitudes</td>
</tr>
<tr>
<td>30 qubits</td>
<td>1 073 741 824 amplitudes</td>
</tr>
<tr>
<td>500 qubits</td>
<td>More amplitudes than our estimate of number of atoms in the Universe!!!</td>
</tr>
</tbody>
</table>

*Hilbert space is a big place!*
- Carlton Caves
Qubit: any suitable two-level quantum system

\[ |\uparrow\rangle + |\downarrow\rangle \]

single trapped atom:

trap

electron in both orbits, simultaneously
(1) Need information for various cooling and trapping schemes (for example, magic wavelength)

Magic wavelength $\lambda_{\text{magic}}$ is the wavelength for which the optical potential $U$ experienced by an atom is independent on its state

$$U \propto \alpha(\lambda)$$
(2) Need information to minimize decoherence during quantum gate operation.

(3) Need to know various atomic properties for quantum information proposals.

**Example:** Quantum gate schemes using dipole blockade via Rydberg excitations

Excitations to Rydberg states are suppressed due to a dipole-dipole interaction or van der Waals interaction

http://www.physics.uconn.edu/~rcote/
Quantum Mechanics

Applications

Atomic Clocks

Parity Violation

Structure within the Atom

Quark
Size $< 10^{-18}$ m

Electron
Size $< 10^{-18}$ m

Neutron and Proton
Size $< 10^{-18}$ m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

NEED

ATOMIC
CALCULATIONS

Quantum information