Progress towards testing CPT and Lorentz symmetry using a self-compensating K-\(^3\)He co-magnetometer

Thomas Kornack, Thomas Jackson, Michael Romalis
Princeton University

DAMOP
27 May 2004
Thursday morning oral session [G4.006]

Work supported by
NASA, NIST, NSF & The Packard Foundation
A Test of CPT Symmetry

- CPT violation occurs:
  - if Lorentz Symmetry is broken
  - in String Theory, Quantum Gravity

- Non-relativistic interactions that violate CPT (Kostelecký):

\[ L = -\bar{\Psi}(m + a_\mu \gamma^\mu + b_\mu \gamma^5 \gamma^\mu)\Psi + \frac{i}{2} \bar{\Psi}(\gamma_\nu + c_{\mu\nu} \gamma^\mu + d_{\mu\nu} \gamma^5 \gamma^\mu) d^\nu \Psi \]

- Experimental limits in $\text{GeV}$ on these parameters:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$a_\mu$</th>
<th>$b_\mu^n$</th>
<th>$b_\mu^e$</th>
<th>$c_{\mu\nu}^n$</th>
<th>$d_{\mu\nu}^n$</th>
<th>$d_{\mu\nu}^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0 - K^0$</td>
<td>$10^{-20}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron $g - 2$</td>
<td></td>
<td></td>
<td>$10^{-24}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p - \bar{p}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cs-$^{199}$Hg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^3$He-$^{129}$Xe Maser</td>
<td>$10^{-30}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarized Solid</td>
<td>$10^{-31}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^3$He-$^{21}$Ne (Projected)</td>
<td>$10^{-33}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-$^3$He (Projected)</td>
<td>$10^{-33}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This experiment
CPT Violation: Spin Coupling

- We can build a sensitive magnetometer using atomic spins
- CPT Violating terms that couple to spin:
  \[ L = -b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi = -b_i \sigma_i = -b \cdot S \]

\[ \Rightarrow \] Different coupling of \( b \) to electron spin and nuclear spin
  - Use a co-magnetometer with K electron and \(^3\)He nuclear spins
- Search for sidereal signal:

\[ L = -b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi = -b_i \sigma_i = -b \cdot S \]
No Spin-exchange Relaxation!

- **Traditional atomic magnetometers:**
  - Different hyperfine states precess in different directions
  - Spin exchange collisions cause transverse spin relaxation

- **At high alkali density and low field:**
  - Rate of collisions is much faster than rate of precession
  - All spins sample both hyperfine states via rapid collisions and precess coherently
  - Sensitivity limit \(~ 2 \text{ aT/Hz}^{1/2}\)
  - 1 Hz linewidth ⇒
  - 20 kHz spin-exchange rate

\[
\omega_F = \pm I \pm \frac{1}{2} = \pm g\mu_B B \frac{h}{2I + 1}
\]

\[
\omega_1 = \frac{3(2I + 1)}{3 + 4I(I + 1)} \omega = \frac{2}{3} \omega_F = I \pm \frac{1}{2}
\]

DAMOP 2004 CPT Violation Experiment, Romalis Lab, Princeton University
Magnetic Sensitivity Record

Achieved sensitivity: 0.5 fT/Hz$^{1/2}$

Use this magnetometer to image brain activity:
A. Baranga’s Friday PM Poster [P1.085]

- Magnetic shield noise: 7 fT/Hz$^{1/2}$
- Best SQUID
- Gradient Sensitivity: 0.5 fT/Hz$^{1/2}$ over 3 mm

- Fundamental sensitivity: 2 aT/Hz$^{1/2}$

DAMOP 2004
CPT Violation Experiment, Romalis Lab, Princeton University
The $^3$He-K Co-magnetometer

- Helium-3 joins Potassium in the cell:

  $\Rightarrow$ Helium-3 cancels the effects of external magnetic fields on K:

  (a) $^3$He cancels the external field $B_z$
  (b) $^3$He compensates for $B_x$

- This co-magnetometer is insensitive to regular magnetic fields but sensitive to all other CPT-violating fields

DAMOP 2004 6 CPT Violation Experiment, Romalis Lab, Princeton University
Insensitivity to regular fields

- The co-magnetometer is insensitive to applied magnetic fields:

Co-magnetometer Frequency Response
External Field Cancellation
Compensated  Slightly Uncompensated

Co-magnetometer Noise Suppression
K magnetometer  K-3He co-magnetometer

Gradient Suppression

3He-K hybrid resonance
Gyrosopic effect due to optical table mechanical resonances
Magnetic Johnson Noise
Experimental Setup

[Diagram of an experimental setup showing various components such as high power diode laser, spectrometer, wavelength feedback, photodiode, intensity feedback, position detector, analyzing polarizer, magnetic shields, oven, field coils, and probe beams.]
Zeroing Ambient Fields

- A solution to the coupled Bloch equations for K and $^3$He:

$$S = \frac{K_z b^K_y - b^{He}_y + L_y + B_c \left( \frac{B_y}{B_z} + \frac{L_x}{R} \right)}{1 + \left( \frac{B_c + L_z}{R} \right)^2} + \frac{B_x B_c (B_c + L_z)}{B_z R} + \frac{L_x L_z}{R}$$

- Operate with magnetic fields ($B_i$) and lightshifts ($L_i$) close to zero
  - The signal is sensitive to changes only in second order
- An appropriate choice of magnetic field and lightshift modulation allows zeroing of the same:

![Graphs](image-url)
Recent Performance

- Can subtract probe beam movement from signal to reduce drift:

- Sidereal Fit: $(5.0 \pm 0.3)$ fT $\Leftrightarrow$ Dominated by thermal fluctuations
  - Existing limit: 1 fT (Walsworth’s He-Xe maser)

- Diurnal signal from room temperature can be eliminated by:
  1. Reversing co-magnetometer polarization
  2. Waiting 6 months during which diurnal signals lags sidereal signals by 180°
Review

- We have a co-magnetometer that is sensitive to CPT Violating fields and insensitive to regular magnetic fields.
- Long term stability has improved to about 5 fT in one day.
- We will be working on controlling temperature fluctuations to further reduce systematic effects.