Testing violation of CPT and Lorentz symmetry with a self-compensated $^3$He-K co-magnetometer.

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Abstract Submitted for the DAMOP03 Meeting of The American Physical Society

Testing violation of CPT and Lorentz symmetry with a self-compensated $^3$He-K co-magnetometer. T. W. KORNACK, I. M. SAVUKOV, M. V. ROMALIS, Princeton University We will present the status of an ongoing experiment to test CPT and Lorentz invariance using a $^3$He-K co-magnetometer. A relatively dense $10^{14}$ cm$^{-3}$ K vapor is probed at nearly zero field to obtain a spin-exchange relaxation-free (SERF) magnetometer with a resonant linewidth of 1 Hz. $^3$He is polarized by spin-exchange with K atoms and its magnetization is detected using K by relying on the imaginary part of the spin-exchange cross-section. We have demonstrated self-compensated operation of the co-magnetometer by appropriately adjusting the magnetic fields such that the responses of K and $^3$He to ordinary magnetic fields cancel each other. Light shifts and other systematic effects are also suppressed to first order. A CPT-violating field would interact with the K electron spin and the $^3$He nuclear spin differently and would result in a signal with a period of about 24 hours. We have recently completed a major upgrade of the experiment and implemented a number of feedback systems. First results of long-term data collection will be presented.

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Overview

In this poster

▷ CPT violation and how it can be measured
▷ A sensitive potassium magnetometer.
▷ A self-compensating $^3$He-K co-magnetometer for measurements of CPT violation.
▷ Operational details of the co-magnetometer, how to zero light shifts and residual magnetic fields.
▷ Initial results and long term data.
CPT Violation

- CPT symmetry is exact in the Standard Model, a local field theory.

- CPT symmetry may be violated:
  - in String Theory where particles are not pointlike.
  - in Quantum Gravity.
  - if Lorentz symmetry is otherwise broken.

- CPT violation is a vector interaction:
  \[ L = -b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi = -b_i \sigma_i = -b \cdot S \]

  where \( \sigma_i \) are the Pauli spin matrices.

  - Interacts with spins like a magnetic field:
    \[ L = e \bar{\psi} \gamma^\mu A_\mu \psi = -\frac{ge}{2m} B_i \sigma_i = -\frac{ge}{2m} B \cdot S \]

  - Presumably \( b_i \) interacts with different particles differently from a magnetic field.

  \( \Rightarrow \) A co-magnetometer with two spin species is sensitive to such a field.

  - Signal would appear as a diurnal signal.
A Test of CPT Symmetry

The general form for Lorentz-violating interactions has several terms:

\[ L = -\bar{\Psi}(m + a_\mu \gamma^\mu + b_\mu \gamma_5 \gamma^\mu)\Psi + \frac{i}{2} \bar{\Psi} (\gamma^\nu + c_{\mu\nu} \gamma^\mu + d_{\mu\nu} \gamma_5 \gamma^\mu) d^\nu \Psi \]

Existing experiments provide:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(a_\mu)</th>
<th>(b_\mu^n)</th>
<th>(b_\mu^e)</th>
<th>(c_{\mu\nu})</th>
<th>(d_{\mu\nu}^n)</th>
<th>(d_{\mu\nu}^e)</th>
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<tr>
<td>(K^0-\bar{K}^0)</td>
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<td></td>
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<tr>
<td>electron (g - 2)</td>
<td></td>
<td>(10^{-24})</td>
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<td></td>
<td></td>
<td>(10^{-21})</td>
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<td>(p-\bar{p})</td>
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<td></td>
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<td>(10^{-26})</td>
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<tr>
<td>(199)Hg</td>
<td>(10^{-30})</td>
<td>(10^{-27})</td>
<td></td>
<td>(10^{-28})</td>
<td>(10^{-25})</td>
<td></td>
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<tr>
<td>(3)He—(^{129})Xe Maser</td>
<td>(10^{-31})</td>
<td></td>
<td></td>
<td>(10^{-28})</td>
<td></td>
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<tr>
<td>Polarized Solid</td>
<td></td>
<td>(10^{-28})</td>
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<td>(10^{-28})</td>
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<tr>
<td>(K-3)He (Current)</td>
<td>(10^{-33})</td>
<td>(10^{-30})</td>
<td></td>
<td>(10^{-31})</td>
<td>(10^{-28})</td>
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<tr>
<td>(3)He—(^{21})Ne (Current)</td>
<td>(10^{-33})</td>
<td></td>
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<td>(10^{-31})</td>
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</table>

For our case, \(b_i = \mu_i \delta B\), where \(\mu_i\) is the magnetic moment and \(\delta B\) is the magnetic sensitivity.

This experiment 100 times more sensitive to \(b_\mu\) than existing limits, using present sensitivity \(\delta B = 10 \text{ fT}/\sqrt{\text{Hz}}\).
Magnetometers and Spin-Exchange Relaxation

- State-of-the-art magnetometers:
  - use K or Rb
  - operate at a low density $\sim 10^9$ cm$^{-3}$ in a large cell, 10 - 15 cm.
  - obtain a linewidth of $\sim 1$ Hz.
  - are shot-noise limited at $\sim 0.3$ fT/$\sqrt{\text{Hz}}$.
  - are fundamentally limited by spin-exchange relaxation.

[D. Budker (Berkeley); E. Aleksandrov (St. Petersburg)]

⇒ Spin-exchange relaxation is eliminated in low field and high pressure!

⇒ Measured linewidth $1/T_2 = 1.1$ Hz

⇒ Using K at high density $\sim 10^{14}$ cm$^{-3}$ in a small, 2.5 cm cell.

⇒ $T_2$ dominated by spin-destruction collisions and wall relaxation.

⇒ Unaffected by spin exchange $1/T_{SE} = 20$ kHz

⇒ High sensitivity ideal for test of CPT violation.
The Potassium Magnetometer Cell

- Potassium is vaporized in a 2.5 cm cell at 190 C.
- Pump laser polarizes potassium.
- A $B_y$ magnetic field tilts K polarization.
- Faraday rotation of the probe beam detects orientation of K electronic spin.
- We use a small, 2.5 cm cell.
The Potassium Magnetometer Schematic

- Hot Air Flow
- Cooling Jacket
- Oven Cell
- Probe Beam
- Magnetic Shields
- Pump Beam
- Grating
- Feedback
- 2 Segment Photodiode
- Photodiode
- Wavelength Feedback
- Lock-in Amplifier
- (Analyzing) Polarizer
- Magnetic Shields
- Hot Air Flow
- Cooling Jacket
- Oven
- Cell
- Field Coils
- Pump Beam
- Faraday Modulator
- Field Coils
- Lock-in Amplifier
- Polarizer
- Photodiode
- Intensity Feedback
- High Power Diode Laser
- Variable Waveplate Attenuator
- 2 Segment Photodiode
- Grating Feedback
- Single Frequency Diode Laser
- Fabry-Perot Wavelength Feedback
- Photodiode
- Intensity Feedback
- High Power Diode Laser
- Faraday Modulator
- Polarizer
Potassium Magnetometer Sensitivity

- Measurement limited by Johnson noise currents flowing in the shields:
  \[ I = \sqrt{\frac{4kT \Delta f}{R}} \rightarrow \delta B \approx 7 \pm 2 \text{ fT/\sqrt{Hz}} \]

- Differential measurement: \( \delta B \approx 500 \text{ aT/\sqrt{Hz}} \)

- Shot noise limit is much lower:
  \[ \delta B = \frac{1}{\gamma \sqrt{nT_2 V_t}} = 2 \text{ aT/\sqrt{Hz}} \]
The $^3\text{He}$-$\text{K}$ Co-Magnetometer

Now we seek to make this magnetometer insensitive to normal magnetic fields $B_i$ while retaining sensitivity to anomalous, CPT-Violating fields $b_i$.

▷ Use a $^3\text{He}$ buffer gas in our K magnetometer:

$^3\text{He}$ is polarized by spin-exchange with polarized K.

▷ Introduce an axial field $B_z$ to cancel the magnetization field of the $^3\text{He}$, $B_z = -\frac{8\pi}{3} \kappa_0 M_{^3\text{He}}$ so that the K magnetometer still operates near zero field.
Co-Magnetometer Self-Compensated Operation

▷ Introduce a perturbative field (here, $B_x$):

(a) $^3\text{He}$ cancels the external field $B_z$

(b) $^3\text{He}$ compensates for $B_x$

The $^3\text{He}$ spins adiabatically track the field and the aggregate $^3\text{He}$ magnetization maintains field cancellation.

⇒ $K$ atoms are insensitive to $B$ field perturbations!

▷ The magnetometer does not compensate for (CPT violating) $b_i$ fields because $b_i$ interacts with $^3\text{He}$ and $K$ spins differently.
Co-Magnetometer Perturbation Response

▷ Apply square wave perturbation field $B_y$, focus on DC response:

- $B_z = 0.536 \text{ mG}$, Slightly Uncompensated
- $B_z = 0.529 \text{ mG}$, Compensated

⇒ No *steady-state* variation in K signal due to perturbation; fully compensated
Apply sine wave perturbation field $B_y$, analyze transient response:

$\Rightarrow$ With $B_z$ tuned to the compensation point (solid line), the magnetometer response is zero in steady state ($f \to 0$).

$\Rightarrow$ When tuned away the compensation point (solid line), the magnetometer response shows separate K and $^3$He resonances.
Coupled Spin Ensembles

\[
\frac{\partial M^e}{\partial t} = \frac{\gamma e}{S(\beta)} (B + \lambda M^n) \times M^e + \frac{M^e_0 \hat{z} - M^e}{T_e S(\beta)}
\]

\[
\frac{\partial M^n}{\partial t} = \gamma_n (B + \lambda M^e) \times M^n + \frac{M^n_0 \hat{z} - M^n}{\{T_{2n}, T_{2n}, T_{1n}\}}.
\]

\[B_z = -0.750 \text{ mG}\]
\[B_z = -1.038 \text{ mG}\]
\[B_z = -1.107 \text{ mG}\]
\[B_z = -1.151 \text{ mG}\]
\[B_z = -1.378 \text{ mG}\]

We well understand the dynamics of the K and $^3$He coupled spin ensembles.

\[
K \text{ Magnetization } M^e_x (\text{arb. units})
\]

\[
\text{Time } t \text{ (s)}
\]

\[
T (s)
\]

\[
M^e_x (arb. units)
\]
The compensated magnetometer suppresses some of the magnetic field noise.

The compensated magnetometer suppresses some of the magnetic field noise.
Modeling the CPT Violation Signal

Include in the Bloch equations magnetic-like fields $b^e$ and $b^n$ that couple only to the electron or nuclear spin.

The response of the magnetometer to slow variations is given by

$$M^e_x = \frac{M^e_z (\lambda M^n_z b^n_y + (B_z + \lambda M^e_z) b^e_y) \gamma_e T_e / B_z}{1 + [(B_z + \lambda M^n_z + \lambda M^e_z) \gamma_e T_e]^2}.$$  

With $B_z$ tuned to the compensation point ($B_z + \lambda M^n_z + \lambda M^e_z = 0$), the magnetometer response simplifies to:

$$M^e_x = M^e_z \gamma_e T_e (b^n_y - b^e_y)$$

Note that the magnetometer remains insensitive to magnetic fields $B_y = b^n_y = b^e_y$ while retaining sensitivity to anomalous fields $b^n_y \neq b^e_y$. 
Simulating the CPT Violation Signal

- We can directly simulate the effect of the anomalous fields by introducing off-resonant light to produce a light shift.

- The light shift only appears as a magnetic field to the K; the $^3$He does not respond.
Zeroing the magnetometer

▷ A steady state solution to the bloch equations:

\[
S = \frac{K_z}{R} \frac{L_y}{1 + \left(\frac{B_c + L_z}{R}\right)^2} + \left(\frac{B_y}{B_z} + \frac{L_x}{R}\right) R_L y + \left(\frac{B_x B_c (B_c + L_z)}{B_z R} + \frac{L_x L_z}{R}\right)
\]

▷ Choosing suitable modulation of \(\delta B_x\), \(\delta B_y\), and \(\delta B_z\), it is possible to zero out magnetic fields and light shifts.

▷ A numerical zeroing routine finds the zero point of these curves, corresponding to zeroing the local magnetic field around the magnetometer.

▷ Other modulations zero the light shift and, in the future, the beam alignment.
Zeroing the light shifts

▷ The symmetry of the transient is proportional to the light shift along the pump beam.

▷ We numerically zero the integrated transient; when the transient is fully symmetric, it’s integral is zero.
Long Term Operation

⇒ Watch for signal as earth rotates.
Many undesirable correlations remain in the magnetometer signal.
Our signal is dominated by long timescale drifts.
Summary and Future Plans

- We have demonstrated a magnetometer that is sensitive to $\sim 10 \text{ fT}/\sqrt{\text{Hz}}$

- The $^3$He-K co-magnetometer compensates for applied fields and suppresses some noise.

⇒ Need to reduce long term drifts; they are our dominant source of noise.