Thesis Proposal

A test of CPT symmetry using a high sensitivity potassium magnetometer

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I propose to conduct a test of CPT symmetry at least 100 times more sensitive than existing limits using a new, high-sensitivity atomic magnetometer. A lower limit on CPT violation provides strong constraints on the design of new physical theories. CPT symmetry is critically dependent on Lorentz symmetry, a fundamental statement of the geometry of spacetime. Such a robust property of nature must be violated at some level, however, if non-local field theories including Quantum Gravity and String Theory are accurate. The non-local behavior of these theories must violate Lorentz symmetry on some level. This experiment is designed to probe Lorentz and CPT symmetry to new levels in search of an asymmetry. A new limit on CPT violation set by this experiment must be taken into account in revisions of modern unified theories.

Kostelecky and Lane (1999) have provided a general theoretical framework for approaching CPT symmetry violation. In the non-relativistic limit, CPT violating effects are likely to appear as magnetic-like vector fields when they couple to the spins of electrons and nuclei:

$$L = -b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi = -b_i \sigma_i \tag{1}$$

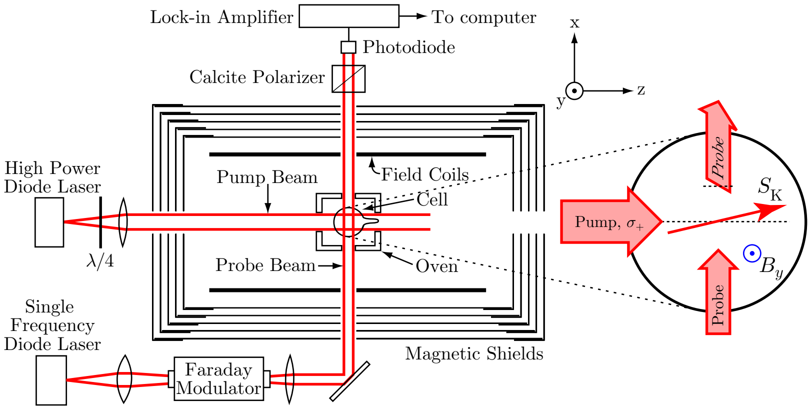


Figure 1: Schematic of the experiment. See text for a description of the operation. Pump and probe lasers access the cell through holes in a five-layer magnetic shield that suppresses external fields by a factor of 10^6. Magnetic fields and their first order gradients can be applied using coils on the inside of the shield.

where L is the Lagrangian, ψ is a wavefunction that we take to be a spin system represented by the Pauli spin matricies σ_i, and b_μ represents the degree of CPT violation coupling to the wavefunction of this form. The form of the Lagrangian for CPT violating fields is identical to that of a magnetic field, $L = -B_i \sigma_i$. Whereas a normal magnetic field couples to the magnetic moments of nuclear and electron spins σ_i^e and σ_i^n, the CPT violating field couples to different spin species by different amounts. As such, the coupling to electron and nuclear spins is written using the following notation:

$$L = -b_i^n \sigma_i^n, \quad L = -b_i^e \sigma_i^e, \quad b_i^n \neq b_i^e \tag{2}$$

To distinguish a CPT violating field from a normal magnetic field, one must make a differential measurement, $b_i^n - b_i^e$, using two distinct spin species. For the present experiment, a differential co-magnetometer will be implemented using K (potassium) electrons and the ^{3}He nuclei.

The atomic magnetometer operates by measuring the precession of polarized K electrons, as depicted in Figure 1. A vapor of atomic K is generated by heating a droplet of metallic K in a glass cell. A broadband, circularly-polarized pump laser spin-polarizes the K vapor. As the K electron spins precess in the presence of a transverse magnetic field, the spin angle is measured using a probe laser that is tuned off the K resonance. The off-resonant interaction with the K vapor rotates the polarization of the probe beam in proportion to the projection of the K spins along the probe beam. The angle of the probe beam polarization can be measured using a second polarizer and lock-in techniques.

Current state-of-the-art atomic magnetometers are fundamentally limited by spin-exchange collisions. During the collision of two polarized electrons, the electrons can transition to different hyperfine states. Since electrons in different hyperfine states precess in opposite directions, the spins quickly decohere. Existing magnetometers simply attempt to reduce the number of collisions by using low densities and large cells (Budker et al., 1998; Alexsandrov et al., 1995). We have recently demonstrated, however, that the sensitivity required for this precise measurement of magnetic field can be obtained by using techniques to suppress spin-exchange relaxation (Allred et al., 2002) that were developed by Happer and Tang (1977).

The operation and sensitivity of our magnetometer is presented in Allred et al. (2002). The fundamental sensitivity, δB, of an atomic magnetometer is limited by the shot-noise of a probe laser in which each photon interacts with an atom in the cell:

$$\delta B = \frac{1}{\gamma\sqrt{nT_2Vt}} \tag{3}$$

where γ is the gyromagnetic ratio for the K electron, n is the density of gas, V is the volume of the cell, T_2 is the transverse spin decoherence time and t is the integration time. Spin relaxation time T_2 is not dominated by spin-exchange relaxation; rather, it is dominated by the much slower K-K spin destruction rate (Kadlecek et al., 1998). We have directly measured T_2 by synchronously pumping the precessing K electrons to be $T_2 \simeq 1.1$ Hz. For our one inch diameter cell containing a density $n \sim 10^{14}$ cm^{-3} of K vapor, the shot-noise limit is $\delta B = 0.002$ fT/$\sqrt{\text{Hz}}$, which is two orders of magnitude more sensitive than the most sensitive superconducting quantum interference devices (SQUIDs).

The sensitivity of our magnetometer is measured directly by applying a known field to the magnetometer. These data, shown in Figure 2a, imply a sensitivity of 10 fT/$\sqrt{\text{Hz}}$. This sensitivity is much larger than the shot-noise limit because the sensitivity is limited by magnetic noise due to thermal Johnson currents flowing in the shields. Calculations of the magnetic noise generated by the shields agree with this measurement. The magnetic noise

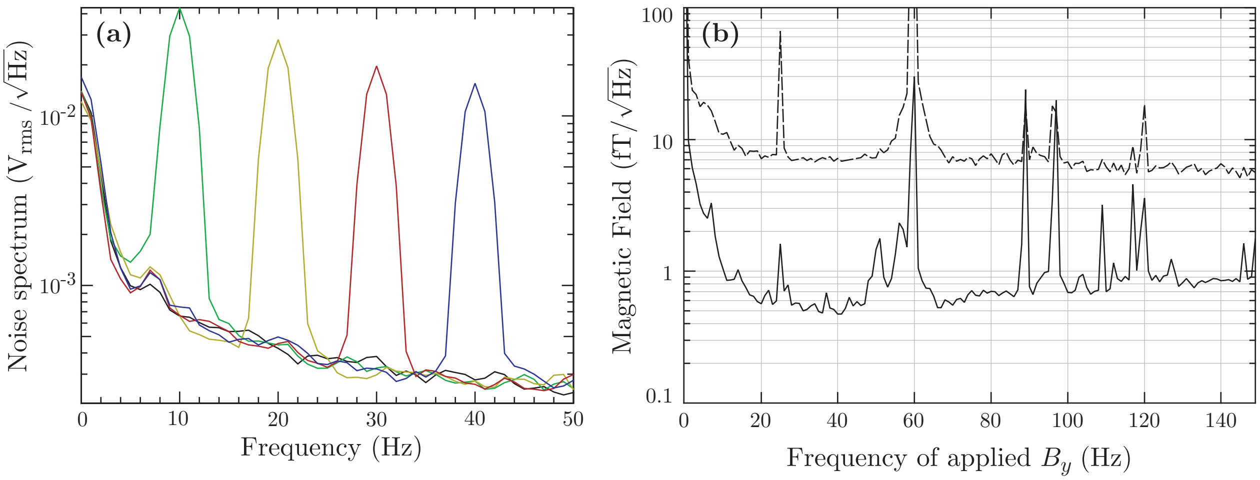
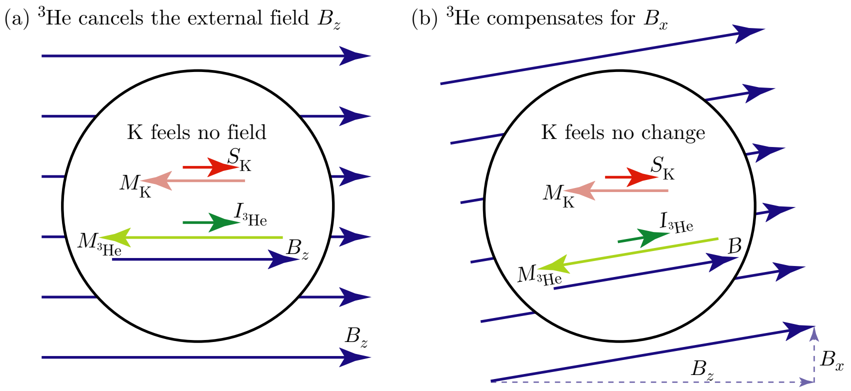


Figure 2: Direct measurements of the sensitivity of the magnetometer: (a) 700 fT fields at 10, 20, 30 and 40 Hz were applied to the magnetometer. We can infer a magnetometer sensitivity of 10 fT/$\sqrt{\text{Hz}}$ from the ratio of the applied signal to the the noise level. (b) Magnetic field sensitivity frequency response from a single channel (dashed line) and from the difference of two adjacent channels (solid line). The differential measurement suppresses the magnetic noise and allows the measurement of applied gradient fields down to 0.54 fT/$\sqrt{\text{Hz}}$.


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

(b) ^{3}He compensates for B_x

Figure 3: Operation of K-^{3}He magnetometer. A small applied transverse field B_x is compensated by the passive reaction of the polarized ^{3}He gas, thereby shielding the K vapor from applied magnetic fields.

can be suppressed by subtracting the field measured at two adjacent points. Applying a gradient field provides a signal which can be used to infer sensitivity. The noise-suppressed sensitivity of the magnetometer is plotted in Figure 2b. The measured sensitivity over the range 20-40 Hz is 0.54 fT/$\sqrt{\text{Hz}}$ which is, to the best of our knowledge, unsurpassed by any other measurement technique.

The test of CPT symmetry requires a differential measurement involving not only the K electron but also the nuclear spin of ^{3}He. We introduce 3 atm ^{3}He in the magnetometer cell containing the K vapor. The ^{3}He polarizes through spin-exchange collisions with the polarized K vapor. The polarized ^{3}He gas has a large (few mG) magnetization that points opposite to its nuclear spin. This magnetization would cause spin-exchange relaxation in the K vapor which heretofore has been operating in a near-zero magnetic field. To maintain the zero-field operation of the K magnetometer in the presence of polarized ^{3}He, a magnetic field, B_z, is introduced that exactly compensates for the ^{3}He magnetization field,

$$B_z = -\lambda M_{^3\text{He}} = -\frac{8\pi}{3}\kappa_0 M_{^3\text{He}} \tag{4}$$

where we have used the expression for the field generated by a uniform sphere of magnetized material, κ_0 is the enhancement over the classical field due to the attraction of the K electron towards the ^{3}He nucleus and $M_{^3\text{He}}$ is the magnetization of ^{3}He. When this compensation field is applied, the K electrons experience no magnetic field, as depicted in Figure 3a. The

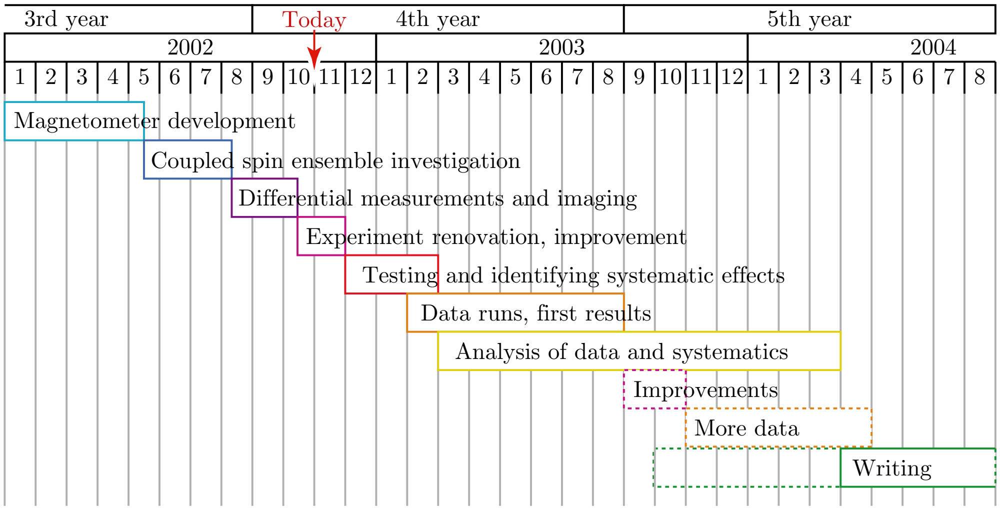


Figure 4: Timeline for completion by the end of my 5th year.

polarized, compensated ^{3}He gas has the important property of passively compensating for small applied magnetic fields. As shown in Figure 3b, the ^{3}He spins adiabatically follow the changing magnetic field and to first order the ^{3}He magnetization, which is antiparallel to the spin, maintains the field cancellation. As a result, the K magnetometer is completely insensitive to applied magnetic fields. CPT violating fields, however, couple to the ^{3}He and K spins differently and the ^{3}He compensation effect would not work. As such, this K-^{3}He system is only sensitive to CPT violating fields.

We have developed a simple theoretical model of the magnetometer implementing Bloch equations with CPT violating, magnetic-like fields, b^e and b^n, that couple only to the electron or nuclear spin. By solving for small transverse oscillations and with B_z tuned to the compensation point ($B_z + \lambda M_z^n + \lambda M_z^e = 0$), the magnetometer response simplifies to:

$$M_x^e = M_z^e \gamma_e T_e (b_y^n - b_y^e) \tag{5}$$

Note that the magnetometer remains insensitive to magnetic fields $B_y = b_y^n = b_y^e$ while retaining sensitivity to anomalous fields $b_y^n \neq b_y^e$.

A timeline for the completing of my thesis work by the end of my 5th year is presented in Figure 4. I am presently making major modifications to the experiment in preparation for taking data early next year. Early on, my work will focus on the fabrication of the experiment and automated control systems for unattended operation. Later, I will focus on identifying, characterizing and minimizing all the systematic effects in our system so that we can be confident in any signals we do see. Finally, I will write analysis packages to reduce the large quantities of data and look for statistically significant signals.

Whether or not we detect CPT violation, this experiment provides useful results for physics. If no CPT violation is detected, then this experiment will establish a new limit on the level of CPT violation in the universe. Such a limit will provide a strong constraint on unified theories of physics. Of course, detection of CPT asymmetry would be tremendously exciting news as it would signal the presence of new physics and provide a benchmark for string theory, quantum gravity and other unified theories.

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