Self-compensated $^3$He-K magnetometer for CPT tests

T. Kornack, I. Kominis, M. Romalis
Princeton University

J. Allred, R. Lyman
University of Washington

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Overview

- **High sensitivity potassium magnetometer**
  - Direct sensitivity measurements
  - Gradient measurements and relative sensitivity

- **Test of CPT Symmetry**
  - The $^3$He-K co-magnetometer
  - Behavior of the co-magnetometer
  - Self-compensating operation

- **Coherent interaction of electron and nuclear spin ensembles**
Magnetometers and Spin-Exchange Relaxation

- State-of-the-art magnetometers:
  - use K or Rb at a low density $\sim 10^9 \text{ cm}^{-3}$ in a large cell, 10 - 15 cm.
  - obtain a linewidth of $\sim 1 \text{ Hz}$.
  - 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!

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

⇒ Measured linewidth $1/T_2 = 1.1 \text{ Hz}$ dominated by spin-destruction collisions and wall relaxation

⇒ Unaffected by spin exchange $1/T_{SE} = 20 \text{ kHz}$
The Potassium Magnetometer

External fields are zeroed out with coils.

Pump laser polarizes potassium.

Probe laser detects the tilt of the K polarization in a $\hat{y}$ magnetic field.

Faraday rotation of the probe beam used for detection.
Potassium Magnetometer Sensitivity

- Applied 700 fT\textsubscript{rms} modulation at 10, 20, 30 and 40 Hz:
  - Measured $\delta B = 10 \text{ fT}/\sqrt{\text{Hz}}$
    - More sensitive than High $T_c$ SQUIDs: $\delta B = 30 \text{ fT}/\sqrt{\text{Hz}}$
    - Less sensitive than Low $T_c$ SQUIDs: $\delta B = 1 \text{ fT}/\sqrt{\text{Hz}}$

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

- Shot noise limit is much lower:
  \[ \delta B = \frac{1}{\gamma\sqrt{nT_2Vt}} = 0.002 \text{ fT}/\sqrt{\text{Hz}} \]

- How can we get down to the shot noise limit?
  * Differential measurement.
  * Superconducting shields.
Magnetic Gradient Imaging

▷ How can we suppress the Johnson current noise and improve sensitivity?

▷ Using:
  1. Higher buffer gas pressure
     → Reduces diffusion and wall relaxation
  2. Higher K density
     Higher polarization pumping rate
     → Increases bandwidth
  3. Differential measurement
     → Suppresses noise

▷ Predicted sensitivity:
\[ \delta B \sim 0.1 \text{ fT}/\sqrt{\text{Hz}} \]

▷ A single probe beam samples many points in the cell:

▷ Sensitive to heart and brain electrical activity.

▷ In imaging applications, a single cell can replace an array of SQUIDs.
A Test of CPT Symmetry

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

- CPT symmetry may be violated:
  - in String Theory or Quantum Gravity
  - if Lorentz symmetry is otherwise broken

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

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

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

  \[ \Rightarrow \text{ A co-magnetometer with two spin species is sensitive to such a field.} \]

  - Signal would appear as a diurnal signal.

- Expected sensitivity: \( b^e_i = 10^{-30} \text{ GeV}, b^n_i = 10^{-33} \text{ GeV} \)
  (Using present sensitivity \( \delta B = 10 \text{ fT}/\sqrt{\text{Hz}} \))

  - 100 times more sensitive than existing limits.
  - Potentially much better!
The $^3$He-K Co-Magnetometer

- Use a $^3$He buffer gas in our K magnetometer:

  $I_{^3\text{He}}$ 
  $M_{^3\text{He}}, \mu_{^3\text{He}}$ 
  $M_K, \mu_K$ 
  $B_z$

  - $^3$He is polarized by spin-exchange with polarized K.

  - Introduce an axial field $B_z$:
    - to cancel the magnetization field of the $^3$He, $B_z = -\frac{8\pi}{3} \kappa_0 M_{^3\text{He}}$, so that the K magnetometer operates near zero field.
    - to reduce $T_1$ relaxation of $^3$He polarization due to field gradients.
Co-Magnetometer Self-Compensated Operation

- Introduce a perturbative field (here, $B_x$):
  
  (a) $^3$He cancels the external field $B_z$
  (b) $^3$He compensates for $B_x$

- The $^3$He spins adiabatically track the field and the aggregate $^3$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 $^3$He and K spins differently.
Co-Magnetometer Perturbation Response

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

⇒ No steady-state variation in K signal due to perturbation; fully compensated

▷ Apply sine wave perturbation field $B_y$, analyze transient response:

⇒ Fully compensated for $f \to 0$. 
Coupled Spin Ensembles

- Apply a step field perturbation and tune $B_z$ for compensation:

![Graph showing K Signal (arb.) vs. Time (s)]

- Why does $T_2 \to 0$ in fully compensated mode?
  - The field seen by $K$ is $B_z^K = B_z + M_z$, which is close to zero.
  - $^3$He and $K$ spin systems are coupled when the field seen by the electron is so low that their precession frequencies resonate; $\omega_K/\omega_{^3\text{He}} \to 1$.
  - When the $^3$He and $K$ spin systems resonate, the transverse motion of $^3$He spin is dissipated by the much faster relaxation of $K$.

- The red line is given by Bloch equations with a coupling term proportional to the product of the $^3$He and $K$ magnetizations.

- All data fit to a single set of parameters.
Modeling Coupled Spin Ensembles

- Summarizing the previous data, we plot frequency response:

- The data clearly indicate a resonance where the K and $^3$He precession frequencies converge.
Summary

We have demonstrated:

- a K sensitive magnetometer
  - unaffected by spin-exchange
- a $^3$He-K co-magnetometer
  - effectively compensates for magnetic fields
  - reduces noise at low frequency

We will perform a test of CPT symmetry using this facility.