Atomic magnetometers have a long history in tests of Standard Model since they provide sensitive constraints on new spin interactions. I will review recent progress in magnetometry using electron and nuclear spins, describe some of the limits set on new physics and discuss ideas for future experiments.
Tests of Lorentz symmetry

- Lorentz symmetry is at the foundation of two very successful but mutually incompatible theories:
  - General Relativity
  - Quantum Field Theory
- One approach for resolving this problem is to modify Lorentz symmetry
Experimentalist’s Motivation

- Is the space truly isotropic?

$\Delta E$

Spin Up $\uparrow$ Spin Down $\downarrow$

⇒ Remove magnetic field, other known spin interactions
⇒ Remove the Earth

Is there still an “Up” and a “Down”? 

First experimentally addressed by Hughes, Drever (1960)

V.W. Hughes et al., PRL 4, 342 (1960)
R. W. P. Drever, Phil. Mag 5, 409 (1960); 6, 683(1961)
Is the space really isotropic?

- Cosmic Microwave Background Radiation Map

⇒ The universe appears warmer on one side!
- Well, we are actually moving relative to CMB rest frame

$v = 369 \text{ km/sec} \sim 10^{-3} \text{ c}$

⇒ Space and time vector components mix by Lorentz transformation
⇒ A test of spatial isotropy becomes a true test of Lorentz invariance
(i.e. equivalence of space and time)
Local Lorentz Invariance

- Is the speed of light (photons) rotationally invariant in our moving frame?
  - First established by Michelson-Morley experiment as a foundation of Special Relativity

- Is the speed of "light" as it enters into particle Lorentz transformation rotationally invariant in the moving frame?
  - Best constrained by Hughes-Drever experiments due to finite kinetic energy of nucleons

:\[ \delta = \frac{1}{c^2} \cdot 1 \]

YEAR OF EXPERIMENT
From Clifford M. Will,
Local Lorentz Invariance

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- Is the speed of "light" as it enters into particle Lorentz transformation rotationally invariant in the moving frame? 
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\[ \delta = \frac{1}{c^2} \cdot \delta \]

YEAR OF EXPERIMENT
From Clifford M. Will.
Parametrization of Lorentz violation

\[
\mathcal{L} = -\bar{\Psi}(m + a_\mu\gamma^\mu + b_\mu\gamma_5\gamma^\mu)\Psi + \frac{i}{2} \bar{\Psi}(\gamma^\tau + c_{1\tau\nu}\gamma^\nu + d_{1\tau\nu}\gamma_5\gamma^\nu)\gamma_\tau\gamma^\nu\bar{\Psi} \quad a,b - \text{CPT-odd}
\]
\[
c,d - \text{CPT-even}
\]

- \( a_\mu, b_\mu, c_\tau, d_\tau \) are vector fields in space with non-zero expectation value
- Vector and tensor analogues to the scalar Higgs vacuum expectation value

- Maximum attainable particle velocity:
  \[
  v_{\text{MKT}} = c(1 - c_\theta \hat{v}_j - c_\rho \hat{v}_j \hat{v}_k)
  \]
  \( \Rightarrow \) Implications for ultra-high energy cosmic rays, Cherenkov radiation, etc
  \( \Rightarrow \) Many laboratory limits (optical cavities, cold atoms, etc)

- Something special needs to happen when particle momentum reaches Planck scale
  \( \Rightarrow \) Doubly-special relativity
  \( \Rightarrow \) Horava-Lifshitz gravity
  \( \Rightarrow \) Your favorite recent theory
Parametrization of Lorentz violation

\[ \mathcal{L} = - \bar{\psi} \left( m + a_\mu \gamma^\mu + b_\mu \gamma_5 \gamma^\mu \right) \psi + \frac{i}{2} \bar{\psi} \left( \gamma_\nu + c_{\mu\nu} \gamma^\mu + d_{\mu\nu} \gamma_5 \gamma^\mu \right) \sigma^\nu \psi \]

\(a,b\) - CPT-odd
\(c,d\) - CPT-even

\(a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}\) are vector fields in space with non-zero expectation value

Vector and tensor analogues to the scalar Higgs vacuum expectation value

- Maximum attainable particle velocity
  \[ v_{\text{MAX}} = c \left( 1 - c_{00} - c_{0j} \hat{v}_j - c_{jk} \hat{v}_j \hat{v}_k \right) \]

  \(\Rightarrow\) Implications for ultra-high energy cosmic rays, Cherenkov radiation, etc
  \(\Rightarrow\) Many laboratory limits (optical cavities, cold atoms, etc)

- Something special needs to happen when particle momentum reaches Planck scale
  \(\Rightarrow\) Doubly-special relativity
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  \(\Rightarrow\) Your favorite recent theory
Search for CPT-even Lorentz violation with nuclear spin

- Need nuclei with orbital angular momentum and total spin $\sim 1/2$
- Quadrupole energy shift due to angular momentum of the valence nucleon:
  \[ E_0 \simeq (c_{11} + c_{22} - 2c_{33}) \left( p_x^2 + p_y^2 - 2p_z^2 \right) \]
  \[ I.L \]
  \[ p_x^2 + p_y^2 - 2p_z^2 > 0 \]
  \[ P_n \]
- Previously has been searched for in two experiments using $^{201}$Hg and $^{21}$Ne with sensitivity of about 0.5 μHz

\[ \Delta E(t) = E_0 + E_{TX} \cos 2\Omega t + E_{XY} \sin 2\Omega t \]

\[ c_{\mu
u} = \begin{pmatrix}
  c_{TT} & c_{TX} & c_{TY} & c_{TZ} \\
  c_{XT} & c_{XX} & c_{XY} & c_{XZ} \\
  c_{YT} & c_{YX} & c_{YY} & c_{YZ} \\
  c_{ZT} & c_{ZX} & c_{ZY} & c_{ZZ}
\end{pmatrix} \]

\[ \{ 1^{st} \text{ Harmonic}, 2^{nd} \text{ Harmonic} \}

\[ \text{Suppressed by } \gamma_{\text{Earth}} \]
Search for CPT-even Lorentz violation with nuclear spin

- Need nuclei with orbital angular momentum and total spin $\geq 1/2$
- Quadrupole energy shift due to angular momentum of the valence nucleon:

$$E_0 \sim (c_{11} + c_{22} - 2c_{33}) (p_x^2 + p_y^2 - 2p_z^2)$$

$$I.L$$

$$p_x^2 + p_y^2 - 2p_z^2 > 0$$

- Previously has been searched for in two experiments, using $^{201}$Hg and $^{21}$Ne with sensitivity of about 0.5 nHz

Sidereal Variation

$$\Delta E(t) = E_0 - E_{1X}(\cos \Omega t) + E_{1Y}(\sin \Omega t)$$

Semi-sidereal Variation

$$\Delta E(t) = E_0 - E_{2X}(\cos 2\Omega t) + E_{2Y}(\sin 2\Omega t)$$

$$c_{\mu \nu} = \begin{pmatrix} c_{TT} & c_{TX} & c_{TY} & c_{TZ} \\ c_{XT} & c_{XX} & c_{XY} & c_{XZ} \\ c_{YT} & c_{XY} & c_{YY} & c_{YZ} \\ c_{ZT} & c_{ZX} & c_{ZY} & c_{ZZ} \end{pmatrix}$$

- 2nd Harmonic
- 1st Harmonic
- Suppressed by Earth
Search for CPT-even Lorentz violation with nuclear spin

- Need nuclei with orbital angular momentum and total spin \( \frac{1}{2} \)
- Quadrupole energy shift due to angular momentum of the valence nucleon:
  \[
  E_0 \sim (c_{11} + c_{22} - 2c_{33}) \left( p_x^2 + p_y^2 - 2p_z^2 \right) + I.L
  \]
  \[
  p_x^2 + p_y^2 - 2p_z^2 > 0
  \]
  \[
  P_n
  \]
- Previously has been searched for in two experiments, using \(^{209}\)Hg and \(^{21}\)Ne with sensitivity of about 0.5 nHz

\[
\Delta E(t) = E_0 + E_{1X} \cos \Omega t + E_{1Y} \sin \Omega t = E_{2X} \cos 2\Omega t + E_{2Y} \sin 2\Omega t
\]

\[
C_{\mu\nu} = \begin{pmatrix}
C_{TT} & C_{TX} & C_{TY} & C_{TZ} \\
C_{XT} & C_{XX} & C_{XY} & C_{XZ} \\
C_{YT} & C_{YX} & C_{YY} & C_{YZ} \\
C_{ZT} & C_{ZX} & C_{ZY} & C_{ZZ}
\end{pmatrix}
\]

\( \{ \) 2nd Harmonic
\( \{ \) 1st Harmonic
- Suppressed by \( \nu_{\text{Earth}} \)
K-\(^3\)He Co-magnetometer

1. Optically pump potassium atoms at high density (10\(^{13}\)-10\(^{14}\) cm\(^3\))
2. \(^3\)He nuclear spins are polarized by spin-exchange collisions with K vapor
3. Polarized \(^3\)He creates a magnetic field felt by K atoms
   \[ B_K = \frac{8\pi}{3} K_0 M_{He} \]
4. Apply external magnetic field \(B_2\) to cancel field \(B_K\)
   \(\Rightarrow\) \(K\) magnetometer operates near zero magnetic field
5. At zero field and high alkali density \(K-K\) spin-exchange relaxation is suppressed
6. Obtain high sensitivity of \(K\) to magnetic fields in spin-exchange relaxation free (SERF) regime

*Turn most-sensitive atomic magnetometer into a co-magnetometer*

References:

- T.W. Kornack and MVR, PRL 89, 235002 (2002)
K-\(^{3}\)He Co-magnetometer

1. Optically pump potassium atoms at high density (10\(^{13}\)-10\(^{14}\)/cm\(^3\))

2. \(^{3}\)He nuclear spins are polarized by spin-exchange collisions with K vapor

3. Polarized \(^{3}\)He creates a magnetic field felt by K atoms
   \[ B_K = \frac{8\pi}{3} \kappa_0 M_{\text{He}} \]

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   *Turn most-sensitive atomic magnetometer into a co-magnetometer*

---

J. C. Allred, R. N. Lyman, T. W. Kornack, and MVR, PRL 89, 130801 (2002)
T. W. Kornack and MVR, PRL 89, 253002 (2002)
T. W. Kornack, R. K. Ghosh and MVR, PRL 95, 230801 (2005)
Magnetic field self-compensation

(a) $^3$He cancels the external field $B_z$

(b) $^3$He compensates for $B_z$

K feels no field

K feels no change

He
Response to transient signals

- Fast transient response
  - $^3$He has $T_2$ of 1000s of seconds
  - Transient signals decay in 0.3 seconds
  - Due to spin-damping coupling to K atoms

- Integral of the signal is proportional to spin rotation angle for arbitrary pulse shape
Response to transient signals

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- Integral of the signal is proportional to spin rotation angle for arbitrary pulse shape
Magnetic field sensitivity

- Sensitivity of \(\sim 1\) fT/Hz^{1/2} for both electron and nuclear interactions
  \(\Rightarrow\) Frequency uncertainty of 20 pHz/month^{1/2} for \(^3\)He
  20 nHz/month^{1/2} for electrons
- Reverse co-magnetometer orientation every 20 sec to operate in the region of best sensitivity
Co-magnetometer on rotating platform

- Rotate – stop – measure – rotate
  - Fast transient response crucial
- Record signal as a function of magnetometer orientation
CPT-odd data summary

- Take data 6 month apart to separate diurnal from sidereal effects
- Reverse spin and magnetic field directions
- Errors increased by $\sqrt{2}$ to compensate for additional scatter (mostly in summer data)
- Introduce extra modulation to remove background drifts in the winter data
- Data consistent across all systematic checks
Recent compilation of CPT limits

Many new limits in last 10 years

<table>
<thead>
<tr>
<th>Coefficient</th>
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<th>Electron</th>
</tr>
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<tbody>
<tr>
<td>$\tilde{b}_X$</td>
<td>$10^{-27}$ GeV</td>
<td>$10^{-31}$ GeV</td>
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</tr>
<tr>
<td>$\tilde{b}_Y$</td>
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<td>–</td>
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<td>$\tilde{b}_T$</td>
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<td>$10^{-27}$ GeV</td>
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<td>$\tilde{b}_J$ ($J = X, Y, Z$)</td>
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<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\tilde{c}_-$</td>
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<tr>
<td>$\tilde{d}_Z$</td>
<td>–</td>
<td>–</td>
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V.A. Kostelecky and N. Russell

arXiv:0801.0287 v3
CPT-odd data summary

- Take data 6 month apart to separate diurnal from sidereal effects
- Reverse spin and magnetic field directions
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<td>$d_1$</td>
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</tr>
<tr>
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</tr>
<tr>
<td>$a_{\ell}$</td>
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<td>$10^{-15}$ GeV</td>
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</tr>
<tr>
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Many new limits in last 10 years

Natural size for CPT violation?

$$b \sim \frac{m^2}{M_{pl}}$$

$m$ - fermion mass or SUSY breaking scale?

Existing limits

$$\eta \sim 10^{-14}$$

Even $1 M_{pl}^2$ effects are excluded
$^{21}\text{Ne}-\text{Rb-Cs co-magnetometer}$

- Replace $^3\text{He}$ with $^{21}\text{Ne}$
  - A factor of 10 smaller gyromagnetic ratio of $^{21}\text{Ne}$ gives the co-magnetometer 10 times better energy resolution for anomalous interactions

- Use hybrid optical pumping $\text{Cs} \rightarrow \text{Rb} \rightarrow ^{21}\text{Ne}$
  - Small concentration of Cs is optically-thin, allows uniform pump light illumination
  - Rb is polarized by fast spin-exchange with Cs
  - $^{21}\text{Ne}$ is polarized by spin-exchange with high density Rb vapor
  - Probe laser is tuned near Rb D1 line
  - Allows operation with 10 times higher Rb density, lower $^{21}\text{Ne}$ pressure.
  - Overcomes faster quadrupole spin relaxation of $^{21}\text{Ne}$

Search for CPT-even Lorentz violation with $^{21}$Ne-Rb-K co-magnetometer

- About 2 month of data collection
- Sensitivity is about a factor of 100 higher than previous experiments
- Limited by systematic effects due to Earth rotation

Tensor frequency shift resolution
\[ \sim 1 \text{nHz} \]

Earth rotation signal is $10^4$ times larger, causes drift of signal due to changes in sensitivity and orientation.
Results of Tensor Lorentz-Violation Search

<table>
<thead>
<tr>
<th>$\times 10^{-29}$</th>
<th>East-West</th>
<th>North-South</th>
<th>Comb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{xx}-c_{yy}$</td>
<td>$0.86 \pm 1.1 \pm 0.56$</td>
<td>$3.6 \pm 2.8 \pm 1.6$</td>
<td>$1.2 \pm 1.1$</td>
</tr>
<tr>
<td>$c_{xx}+c_{yy}$</td>
<td>$0.14 \pm 1.1 \pm 0.56$</td>
<td>$0.57 \pm 2.8 \pm 1.6$</td>
<td>$0.19 \pm 1.1$</td>
</tr>
<tr>
<td>$c_{yz}+c_{zy}$</td>
<td>$5.2 \pm 3.9 \pm 2.1$</td>
<td>$-4.2 \pm 15 \pm 18$</td>
<td>$4.8 \pm 4.3$</td>
</tr>
<tr>
<td>$c_{xx}+c_{zx}$</td>
<td>$-4.1 \pm 2.2 \pm 2.4$</td>
<td>$17 \pm 14 \pm 13$</td>
<td>$-3.5 \pm 3.2$</td>
</tr>
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</table>

- Constrain 4 out of 5 spatial tensor components of $c_{\mu\nu}$ at $10^{-29}$ level
- Improve previous limits by 2 to 3 orders of magnitude
- Most stringent constrains on CPT-even Lorentz violation!
- Assume Schmidt nucleon wavefunction – not a good approximation for $^{21}$Ne – better wavefunction calculations in progress with Alex Brown (MSU)
- Assume kinetic energy of valence nucleon $\sim 5$ MeV

Recent compilation of Lorentz limits

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</tr>
<tr>
<td>b_3</td>
<td>$10^{-27}$ GeV</td>
<td>$10^{-25}$ GeV</td>
<td>$10^{-23}$ GeV</td>
</tr>
<tr>
<td>b_4</td>
<td>$10^{-27}$ GeV</td>
<td>$10^{-25}$ GeV</td>
<td>$10^{-23}$ GeV</td>
</tr>
<tr>
<td>b_5 (J = X, Y, Z)</td>
<td>$10^{-27}$ GeV</td>
<td>$10^{-25}$ GeV</td>
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Natural size for CPT-even Lorentz violation?

$c \sim \eta \frac{m^2}{M_{Pl}^2}$  $m$ - SUSY breaking scale??

$\eta > 1$ allowed for $m = 1$ TeV

Need to get to $c \sim 10^{-31} - 10^{-32}$

V.A. Kostelecky and N. Russell
arXiv:0801.0287
v4
Astrophysical Limits on Lorentz Violation

Synchrotron radiation in the Crab Nebula
\[ c_e < 6 \times 10^{-20} \]
Brett Altschul

Spectrum of Ultra-high energy cosmic rays at Auger:
\[ c_\pi - c_p < 6 \times 10^{-23} \]
Seully and Stecker
South Pole

- Most systematic errors are due to two preferred directions in the lab: gravity vector and Earth rotation vector.
- If the two vectors are aligned, rotation about that axis will eliminate most systematic errors.
- Amundsen-Scott South Pole Station
  - Within a few hundred meters of geographic South Pole.
South Pole

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- Amundsen-Scott South Pole Station
  ⇒ Within a few hundred meters of geographic South Pole
South Pole Setup

- Reliable operation with minimal human intervention
  - Simple laser setup
  - Whole apparatus in vacuum at 1 Torr
  - Automatic fine-tuning and calibration procedures

Diagram:
- 894 nm DBR pump laser for Cs D1
- M2K Laser tapered amplifier polarizer
- 4/4 WP
- Photodiode PEM 4/4 WP
- Polarizers
- 795 nm DBR probe laser for Rb D1
- μ-metal shields
- Vapor cell
- Ferrite shield
- Vacuum chamber
- Mirrors
Orientations

Dipole and quadrupole Lorentz violating coefficients are constrained by operating with the quantization axis in two orthogonal configurations.

Bző Vertical
1st Harmonic: cₓ, cᵧ, bₓ, bᵧ
2nd Harmonic: none

Bｚ Horizontal
1st Harmonic: bₓ, bᵧ
2nd Harmonic: cₓ, cz
Distance to Pole

- 230 meters from geographic South Pole
- Earth signal on the order of 0.1 ft
- 26,000x smaller than Earth's signal at Princeton

Gyroscope Pick-up of Earth's Rotation
Challenges at the Pole

The building’s tilt is slowly drifting
Requires regular leveling

Aggressive temperature cycling
Temperature gradient across apparatus

Other challenges:
Isolation platform damping failed, probe laser burned out, rotation stage got stuck, etc...
Need spares for everything!
Data from first year

1st harmonic  2nd harmonic

Recently implemented upgrades, in particular, frequent automatic leveling of the apparatus, continuing data taking for second season
Limits on neutron spin-spin forces

- Constraints on pseudo-scalar coupling

\[ L^{\text{Der}} = \frac{g}{2m} \bar{\Psi}(x) \gamma_\mu \gamma_5 \Psi(x) \bar{\Phi}(x) \]
\[ L^{\text{Yuk}} = -ig \bar{\Psi}(x) \gamma_\mu \Psi(x) \Phi(x) \]

Limit on proton nuclear-spin dependent forces (Ramsey)

Recent limit from Walsworth et al., PRL 101, 261801 (2008)

Limit from gravitational experiments for Yukawa coupling only (Adelberger et al.)


Anomalous spin forces between neutrons are:
- \(2 \times 10^{-8}\) of their magnetic interactions
- \(2 \times 10^{-3}\) of their gravitational interactions

First constraints of sub-gravitational strength!
Limits on neutron spin-spin forces

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  \[ L^{\text{Der}} = \frac{g}{2m} \bar{\Psi}(x)i\gamma_{\mu}\gamma_{5}\Psi(x)\Phi(x) \]
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- \(2 \times 10^{-3}\) of their gravitational interactions

First constraints of sub-gravitational strength!
Spin-mass searches with co-magnetometer

- Source mass being constructed
- First test to be more sensitive than astrophysical limits
Next-generation co-magnetometer

- Developing a co-magnetometer using $^3$He and $^{129}$Xe atoms in free precession (scalar) mode
- Rb is used as sensor, but is “turned off” for nuclear spin precession “in the dark”
- Minimize frequency shifts to achieve clock-like stability
- Short-term sensitivity is not very good yet, but is being improved.
- Much better long-term stability
- Allows to search for spin interactions that are difficult to reverse, such as Earth’s gravity

![Diagram of 3He and 129Xe atoms with rotation rate uncertainty graph](image)
Conclusions

- Atomic co-magnetometers set the most stringent limits on both CPT-odd and CPT-even Lorentz violation coefficients
- Set limits on spin-dependent forces at 20 pHz level, the most sensitive energy shift measurements
- Search for spin-mass coupling under way, should exceed astrophysical limits
- High accuracy magnetometers are being developed

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