Local Lorentz Invariance

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Outline

- Local Lorentz Invariance
- Standard Model Extension
- Experiments
- Clock-Comparison Experiment
- Current Limits
- Summary
Local Lorentz Invariance

- Rotations (3) and Boosts (3)
- Lorentz Covariant quantities
  - Scalars
    - Space-time interval $s^2 = (ct)^2 - r^2$, rest mass $(mc^2)^2 = E^2 - (pc)^2$, proper time $\tau$
  - Four-vectors
    - Four-velocity, Four-momentum $p_i = (E, p)$
  - Four-tensors
    - Electromagnetic Field tensor $F_{\alpha\beta}$
  - Spinors
    - Majorana and Dirac spinors $\omega = \left[ \begin{array}{c} \phi \\ \sigma \frac{p}{E + m} \phi \end{array} \right]$
- Addition of Gravity (Special Relativity) requires only local Lorentz covariance
- CPT Violation implies Lorentz violation
Particle vs. Observer Transformation

- Observer transformation invariance means laws of physics do not depend on orientation.
- Particle transformation is when the particle is moving with respect to a fixed reference frame.
- If there is a Lorentz violation, physical laws could be different for a moving observer vs. a stationary one.
Standard Model Extension

- Proposed and developed by Alan Kostelecky
- Generalization of RMS theory-
  - CMB as vacuum expectation value
- Observer transformations are still valid
- Particle boosts or transformations relative to vacuum expectation values can give apparent violations
- Similar to a particle moving through a crystal
  - Symmetries are broken, not due to a problem with the theory, but due to background fields
- SME contains all properties of the Standard Model and GR, except it allows the breaking of Lorentz and CPT symmetries
- Adds all possible coordinate-invariant operators formed by Standard Model and gravitational fields combining with couplings having Lorentz indices.
- Makes no predictions of magnitude or the “best test”
- All possible couplings = lots of experiments needed
- Sidereal time variation – 360° rotation of Earth
Atomic Clocks in Space

Bluhm, Kostelecky, Lane, Russell PRL 2002

Bluhm, Kostelecky, Lane, Russell PRL 2002
Doesn’t this look familiar?
Current Experiments

- Clock-Comparison Experiments
  - $^{199}\text{Hg}$ and $^{133}\text{Cs}$
  - $^{129}\text{Xe}$ and $^3\text{He}$ **
  - Hydrogen Masers
  - Atomic Clock on ISS in 2005
- QED tests in Penning Traps
  - Electron-Positron g-2 measurement, and Proton-Antiproton g-2
- Oscillation Experiments
  - Neutral-B   BaBar
  - Neutral-D   FOCUS
  - Neutrino    LSND
  - Kaon        KTeV
- Spin-polarized torsion pendulum
- Muonium spectroscopy
- Vacuum-birefringence
- Limits set from astronomy
Clock Comparison Experiment

- Walsworth Group at Harvard
- $^{129}\text{Xe}$ and $^3\text{He}$ co-located masers
- 1.7 kHz $^{129}\text{Xe}$, 4.9 kHz $^3\text{He}$
- Extremely Stable - 100 nHz hr
- Nuclear spin-1/2 Zeeman transitions
- Single $^{1}\text{S}_{1/2}$ valence neutron
- Magnitude and sign of Lorentz violating shift is the same for both masers
  \[ \delta \nu_j = \delta \nu_j^{Lorentz} \mid 1 - \frac{\gamma_{\text{He}}}{\gamma_{\text{Xe}}} \mid \approx 1.75 \delta \nu_j^{Lorentz} \]
- Referenced to master Hydrogen maser
  - Hyperfine; insensitive to Zeeman effect in first order

\[
L = \frac{1}{2} \hbar \gamma \overline{\bar{\psi}} \gamma \psi - \bar{\psi} M \psi
\]

\[
\Gamma_{\gamma} = \frac{e^2}{\hbar} \nabla + \frac{1}{2} \gamma_{\text{He}} \gamma_{\text{Xe}} + \frac{1}{2} \gamma_{\text{He}} \gamma_{\text{Xe}} + \frac{1}{2} \gamma_{\text{He}} \gamma_{\text{Xe}}
\]

Reference: Kostelecky, CPT and Lorentz symmetry, World Scientific, Singapore 1999

\[ L = -b_{\mu} \bar{\psi} \gamma_5 \gamma^\mu \psi \]

For spin 1/2 particles...

\[ \langle F, m_F | h | F, m_F \rangle = \frac{m_F}{E_{\text{dipole}}} \]

H maser

Nuclear Zeeman maser (spin 1/2)

For spin 1/2 particles...

\[ \langle F, m_F | h | F, m_F \rangle = \frac{m_F}{E_{\text{dipole}}} \]

Experimental Schematic

- $^{129}$Xe used as magnetometer, phase locked to 1.7 kHz reference signal
- Signal fed back to 1.5 G solenoid
- B fields would shift frequencies proportional to magnetic moments
- Population inversion from Rb spin flip collision
- Systematic effects eliminated/recorded
  - Temperature of vacuum
  - East-West room B-field
  - Magnetization of Rb
    - Stable for days by servo loop
  - Power of Rb repumper laser
    - Controls population inversion rate
  - Noble-gas polarization frequency shifts were primary source of noise
Clock Comparison Experiment Continued

Rotation...

Earth's rotation frequency \( \omega_n = \frac{2 \pi}{23 \text{ h } 36 \text{ min}} = 2 \pi \times 10^{-5} \text{ Hz} \)

Laboratory co-latitude \( \chi = 47.6^\circ \)

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \chi \cos \omega t & \cos \chi \sin \omega t & 0 \\
0 & \sin \omega t \cos \chi & \sin \omega t \sin \chi & \sin \omega t \\
0 & \sin \omega t \sin \chi & -\sin \omega t \cos \chi & \cos \omega t
\end{pmatrix}
\]

Boost...

Earth's angular revolution velocity \( \Omega_n = \frac{2 \pi}{165.4} = 2 \times 10^{-4} \text{ Hz} \)

Earth's revolution velocity \( \beta_n = \frac{v}{c} = 10^{-4} \)

Laboratory rotational velocity \( \beta_x = \frac{\omega_x \sin \chi}{c} = 1.1 \times 10^{-5} \)

Earth's axis inclination \( \eta = 23.4^\circ \)

\[
\frac{2 \omega \omega_{\text{frame}}}{2 - \omega \omega_{\text{frame}}} = \frac{\gamma \omega B(t) + 2 \beta^\text{0}}{-\gamma \omega B(t) + 2 \beta^\text{0}} = \frac{2 b_1^\text{0} \beta_1}{-2 (b_X^\text{0} + b_1^\beta \sin \Omega^\text{0} t) \sin \omega t + 2 (b_Y^\text{0} - b_1^\beta \cos \eta \cos \Omega^\text{0} t) \cos \omega t}
\]

Co-Magnetometry...

\( \delta \eta = \frac{v \eta_{\text{frame}}}{v_{\text{lab}}} = k \)

\( \delta \eta = \left[ -b_1^\beta \beta_1 \sin \Omega^\text{0} t \sin \omega t + b_1^\beta \beta_2 \cos \eta \cos \Omega^\text{0} t \cos \omega t \right] \)

\( \delta \eta_{\text{exp}} = \delta \eta_{\text{lab}}(t) \sin \omega t + \delta \eta_{\text{lab}}(t) \cos \omega t \)
Data Analysis

- Minimal fit model

\[ \delta \varphi_{He} = \varphi_0 + 2\pi v_0 t + 2\pi \Omega_s^{-1} [\delta v_X \sin(\Omega_s t) - \delta v_Y \cos(\Omega_s t)] \]

- Linear least-squares fit to \( \delta v_X \) and \( \delta v_Y \) to minimize \( \chi^2 \)

- Check with false signal of known frequency and phase to make sure covariance matrix is preserved

- 90 total days of data over 3 runs

\[ R = (\delta v_X^2 + \delta v_Y^2)^{1/2} \]

- \( R = 53 \pm 45 \text{ nHz} \)

- \( (6.4 \pm 5.4) \times 10^{-31} \text{ GeV} \) for SME neutron parameter
Current Limits

- **Proton**
  - $10^{-27}$ GeV  Maser, $^{199}$Hg and $^{133}$Cs clock experiments
  - $10^{-26}$ GeV  Proton-Antiproton (g-2) measurements

- **Neutron**
  - $10^{-31}$ GeV  Walsworth clock experiment

- **Electron**
  - $10^{-27}$ GeV  Maser, $^{199}$Hg and $^{133}$Cs clock experiments
  - $10^{-29}$ GeV  Spin-polarized torsion pendulum
  - $10^{-25}$ GeV  Electron-Positron (g-2) measurements

- **Photon**
  - $10^{-11}$ GeV  Rotating cryogenic-temperature sapphire oscillators

**Also limits on neutral-B, neutral-D, neutrinos and kaons**
Summary

- Lorentz and CPT violations included in some theories attempting to unify GR and Standard Model
- SME makes no predictions of magnitude or sector
- Lots of precision experiments needed

- No ether wind yet
References

- See my paper on the class website for articles on specific experiments