

Tests of Lorentz and CPT Invariance in Space *

Matthew Mewes

*Physics Department, Indiana University,
Bloomington, IN 47405, U.S.A.*

Abstract

I give a brief overview of recent work concerning possible signals of Lorentz violation in sensitive clock-based experiments in space. The systems under consideration include atomic clocks and electromagnetic resonators of the type planned for flight on the International Space Station.

1 Introduction

In this contribution to the proceedings of the 2003 NASA/JPL Workshop on Fundamental Physics in Space, I review recent work aimed at understanding possible tests of Lorentz and CPT symmetries in experiments mounted on space platforms such as the International Space Station (ISS) [1].

A realistic description of nature at the Planck scale remains a major goal of theoretical physics. A direct experimental search for Planck-scale effects does not seem feasible using current technology. However, it has been shown that Planck-scale theories may lead to small violations in fundamental symmetries such as Lorentz and CPT covariance in the low-energy effective theory [2]. Such violations might arise out of the nonlocal properties of string theory. Lorentz and CPT symmetries have also been studied in the context of noncommuting geometries [3] and supersymmetry [4].

Lorentz transformations are in general comprised of rotations and boosts. CPT is the combination of the discrete transformations charge conjugation C, space inversion P and time reversal T. There is a general result known as the CPT theorem which states that a Lorentz-covariant theory is also covariant under the combined transformation CPT [5].

In recent years, a number of sensitive experiments have tested Lorentz and CPT to unprecedented levels [6]. The increased activity in the field has been motivated in part by the development of a general Lorentz- and CPT-violating Standard-Model

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Extension (SME) [7]. The SME has provided a theoretical framework for many tests of Lorentz and CPT covariance including experiments involving atomic systems [8, 9, 10, 11, 12, 13, 14], photons [15, 16, 17, 18, 19], hadrons [20, 21], muons [22], and electrons [23, 24].

One particularly sensitive class of experiments involves extremely precise clocks and resonators. A number of experiments of this type are under development to test relativity principles on the ISS. These include the atomic-clock based experiments ACES [25], PARCS [26], RACE [27] and a resonant-cavity experiment, SUMO [28]. Some of the best constraints on Lorentz and CPT violation have been achieved in Earth-based atomic-clock experiments [8, 9, 10, 11, 12]. Recently, similar techniques have been used in Earth-based experiments involving superconducting microwave cavities [15] and cryogenically cooled optical cavities [16] that probed previously untested regions of coefficient space. The basic principle behind all these experiments is to search for variations in frequencies of resonant systems as the Earth rotates. The space-based versions will look for variations as the satellite orbits the Earth.

Here, I review recent theoretical studies concerning the effects of Lorentz and CPT violation on atomic clocks [13, 14] and resonant cavities [19] aboard orbiting platforms such as the ISS. A brief discussion of the SME and the QED limit can be found in Section 2. A general discussion of the types of signals one expects from Lorentz violation are described in Section 3. Some results in atomic clocks and in resonant cavities are given Sections 3.1 and 3.2. Some advantages of space-based experiments are described in Section 4.

2 Lorentz-Violating QED

The purpose of the SME is the characterization of all possible types of Lorentz violation in a single local relativistic quantum field theory. Under mild assumptions, one finds that the form of the theory is restricted to the usual Standard-Model Lagrangian supplemented by terms that consist of Standard-Model field combinations multiplied by small constant coefficients [7]. Each term must form a scalar under Lorentz transformations of the observer so that coordinate invariance is satisfied. Often one restricts attention to renormalizable terms. However, the nonrenormalizable sector is known to be important at very high energies [29].

The QED limit of the SME serves as a toy-model example of this general framework. It also has physical significance since many systems are accurately represented by this limit. The renormalizable sector of the QED extension is given by the Lagrangian

$$\begin{aligned} \mathcal{L} = & \frac{1}{2}i\bar{\psi}\Gamma^\nu \overleftrightarrow{D}_\nu \psi - \bar{\psi}M\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \\ & - \frac{1}{4}(k_F)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu} + \frac{1}{2}(k_{AF})^\kappa \epsilon_{\kappa\lambda\mu\nu}A^\lambda F^{\mu\nu}, \end{aligned} \quad (1)$$

where D_μ is the usual covariant derivative and

$$\Gamma^\nu = \gamma^\nu + c^{\mu\nu}\gamma_\mu + d^{\mu\nu}\gamma_5\gamma_\mu + e^\nu + if^\nu\gamma_5 + \frac{1}{2}g^{\lambda\mu\nu}\sigma_{\lambda\mu}, \quad (2)$$

$$M = m + a_\mu\gamma^\mu + b_\mu\gamma_5\gamma^\mu + \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu}. \quad (3)$$

The small coefficients $c^{\mu\nu}$, $d^{\mu\nu}$, $H_{\mu\nu}$ and $(k_F)_{\kappa\lambda\mu\nu}$ introduce Lorentz violation and are CPT even. Meanwhile, e^ν , f^ν , $g^{\lambda\mu\nu}$, a_μ , b_μ and $(k_{AF})^\kappa$ are Lorentz violating and CPT odd. Note that taking these coefficients to zero yields the usual QED.

The experiments considered in this work search for frequency shifts due to the above coefficients. For atomic clocks, the frequency is typically determined by Zeeman transitions. The presence of Lorentz and CPT violation results in small shifts in these transitions that depend on the coefficients in the modified QED associated with each of the particle species: protons, neutrons and electrons. These coefficients are denoted a_μ^w , b_μ^w , $c_{\mu\nu}^w$, $d_{\mu\nu}^w$, e_ν^w , f_ν^w , $g_{\lambda\mu\nu}^w$, $H_{\mu\nu}^w$, where the $w = p, n, e$ labels the species [12].

In practice, only certain combinations of coefficients appear. These are commonly denoted by tilde coefficients \tilde{b}_3^w , \tilde{c}_q^w , \tilde{d}_3^w , \tilde{g}_d^w , \tilde{g}_q^w , where I have assumed that the quantization axis is along the 3 direction. As an example of the relationship between the tilde coefficients and those in Eq. (3) consider b_3^e . It is related to the coefficients in the QED for electrons by the expression $\tilde{b}_3^e = b_3^e - m_e d_{30}^e + m_e g_{120}^e - H_{12}^e$. The subscript 3 refers to the quantization axis in the laboratory which in this example was chosen to be in the 3 direction. The subscripts d and q refer to the dipole and quadrupole nature of those terms.

A similar tilde decomposition is useful in the photon sector. The presence of Lorentz violation leads to similar shifts in the resonant frequencies of cavities. When calculating these shifts it is useful to work with the usual electric and magnetic fields. In terms \vec{E} and \vec{B} , the $(k_F)_{\kappa\lambda\mu\nu}$ term in the lagrangian (1) may be written

$$\begin{aligned} -\frac{1}{4}(k_F)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu} &= \frac{1}{2}\tilde{\kappa}_{\text{tr}}(\vec{E}^2 + \vec{B}^2) + \frac{1}{2}\vec{E} \cdot (\tilde{\kappa}_{e+} + \tilde{\kappa}_{e-}) \cdot \vec{E} \\ &\quad - \frac{1}{2}\vec{B} \cdot (\tilde{\kappa}_{e+} - \tilde{\kappa}_{e-}) \cdot \vec{B} + \vec{E} \cdot (\tilde{\kappa}_{o+} + \tilde{\kappa}_{o-}) \cdot \vec{B}. \end{aligned} \quad (4)$$

The subscripts e , o and tr refer to their $O(3)$ properties. The coefficients $\tilde{\kappa}_{\text{tr}}$, $\tilde{\kappa}_{e+}$ and $\tilde{\kappa}_{e-}$ are parity even while $\tilde{\kappa}_{o+}$ and $\tilde{\kappa}_{o-}$ are parity odd. The single coefficient $\tilde{\kappa}_{\text{tr}}$ is rotationally invariant while the others are 3×3 traceless matrices that violate rotational symmetry.

The above decomposition is motivated by constraints on birefringence of light originating from very distant galaxies. Nonzero coefficients $\tilde{\kappa}_{e+}$ and $\tilde{\kappa}_{o-}$ cause birefringence in light as it traverses empty space resulting in a well defined energy dependence in its polarization. Spectropolarimetric observations of light emitted from distant radio galaxies places a limit on this effect and leads to constraints on the order of $\sim 10^{-32}$ on $\tilde{\kappa}_{e+}$ and $\tilde{\kappa}_{o-}$ [19].

3 Signatures of Lorentz Violation

In the event of appreciable Lorentz violation, we would expect experiments to depend on their orientation since rotations are a subgroup of Lorentz transformations. The Lorentz group also contains boosts which implies we would expect velocity dependence as well. A common approach in tests of Lorentz covariance is to search for these types of dependences by looking for variations in some observable as the Earth rotates and orbits the Sun. The rotation of the Earth causes changes in the orientation of the apparatus, while the orbital motion results in changes in velocity. Note that boost effects resulting from the change in velocity are typically suppressed by a factor of $\beta_{\oplus} \sim 10^{-4}$, the velocity of the Earth around the Sun.

To understand how the orientation and velocity dependence is quantified, we must define at least two frames of reference. The first is the laboratory frame with coordinates $(0, 1, 2, 3)$.¹ The clock or cavity is at rest in this frame which simplifies calculations. In these experiments the Lorentz violation typically leads to frequency shifts that are linear in the tilde coefficients discussed in the previous section. However, these tilde coefficients are not necessarily constant since they are associated with the $(0, 1, 2, 3)$ frame which is not inertial.

To express the frequency shifts in terms of constant coefficients we must choose an inertial frame of reference. The conventional choice is a standard Sun-centered celestial equatorial frame with coordinates (T, X, Y, Z) . This frame may be considered inertial for all practical purposes and provides a common set of coefficients which all experiments can refer to. We can relate the coefficients in the $(0, 1, 2, 3)$ frame to those in the (T, X, Y, Z) frame by a Lorentz transformation which is time-dependent since the laboratory frame is in constant motion. For Earth-based experiments this typically introduces a periodic variation at the Earth's rotation rate $\omega_{\oplus} \simeq 2\pi/(23 \text{ h}, 56 \text{ min.})$ and at $2\omega_{\oplus}$, providing a signal for Lorentz violation. Similar variations at the orbital frequency $\omega_s \simeq 92 \text{ min.}$ and $2\omega_s$ occur in experiments aboard the ISS.

3.1 Atomic Clocks in Space

As an example, here I briefly discuss how atomic-clock experiments on the ISS could be used to search for Lorentz violation. For details I refer the reader to the recent analyses found in Refs. [13, 14].

A typical clock-comparison experiment consists of two co-located clocks using different atomic species or operating on different transitions. Each species and transition responds differently to Lorentz violation. If we compare the signals from the two clocks we may be able to detect a relative shift in their frequencies. For simplicity, one clock could operate on a transition that is known to be insensitive to Lorentz violation [12].

¹A standard set of frames for Earth-based and satellite-based experiments is defined in Ref. [19].

Consider a clock at rest in the ISS frame with its quantization axis along the 3 direction. In general, the frequency shift depends on the combinations $\tilde{b}_3^w, \tilde{c}_q^w, \tilde{d}_3^w, \tilde{g}_d^w, \tilde{g}_q^w$. The instantaneous values of these coefficients determine the frequency of the clock at any point in the orbit. Expressing these coefficients in terms of Sun-frame coefficients reveals time dependence not present in the absence of Lorentz violation. It is this time dependence that provides a discernible signal for violations in Lorentz and CPT covariance.

The full expressions relating the coefficients in each frame are rather lengthy. However, to first order in small velocities, they take the form [14]:

$$\begin{aligned} \tilde{b}_3, \tilde{d}_3, \tilde{g}_d &= \cos \omega_s T_s[\sim] + \sin \omega_s T_s[\sim] \\ &\quad + \beta_s \cos 2\omega_s T_s[\sim] + \beta_s \sin 2\omega_s T_s[\sim] + \beta_s[\sim], \end{aligned} \quad (5)$$

$$\begin{aligned} \tilde{c}_q, \tilde{g}_q &= \beta_s \cos \omega_s T_s[\sim] + \beta_s \sin \omega_s T_s[\sim] \\ &\quad + \cos 2\omega_s T_s[\sim] + \sin 2\omega_s T_s[\sim] + [\sim], \end{aligned} \quad (6)$$

where each $[\sim]$ indicates a different linear combination of the Sun-frame tilde coefficients $\tilde{b}_T, \tilde{b}_X, \tilde{b}_Y, \tilde{b}_Z, \tilde{g}_T, \dots$. The quantities $\omega_s \simeq 2\pi/92$ min. and $\beta_s \simeq 10^{-5}$ are the frequency and velocity of the ISS orbit and T_s is the time with an appropriately chosen zero. Note that the $2\omega_s$ variations in the vector and dipole coefficients and the ω_s variations in the quadrupole terms are suppressed by β_s .

3.2 Resonant Cavities in Space

Also slated to fly aboard the ISS is the SUMO experiment [28]. This experiment utilizes superconducting microwave oscillators. The frequencies of resonant cavities are also shifted by Lorentz violation. However, they are sensitive to the photon sector of the QED extension. A detailed analysis of the effects of the $\tilde{\kappa}$ coefficients on the resonant frequencies of cavities can be found in Ref. [19]. The results relevant to SUMO are summarized below.

The cavities used in SUMO are cylindrical with circular cross section and operate in the fundamental TM_{010} mode. Working in a frame where the symmetry axis coincides with 3 axis, a perturbative calculation finds that the frequency shift is linear in the coefficient combinations $(3\tilde{\kappa}_{e+} + \tilde{\kappa}_{e-})^{33}$ and $\tilde{\kappa}_{\text{tr}}$. The frequency shift is easily generalized to a cavity that is at rest in the laboratory but arbitrarily oriented with its symmetry axis denote by a unit vector \hat{N} . The result is the fractional-frequency shift

$$\frac{\delta\nu}{\nu} = -\frac{1}{4}\hat{N}^j\hat{N}^k(3\tilde{\kappa}_{e+} + \tilde{\kappa}_{e-})^{jk} - \tilde{\kappa}_{\text{tr}}, \quad (7)$$

where the indices sum over laboratory-frame coordinates, $j, k = 1, 2, 3$. This expression is valid in any laboratory frame at rest with respect to the cavity.

In order to fully understand the effects of Lorentz violation on a cavity in orbit, we must transform the coefficients to the Sun-centered frame. To first order in the

boost velocity, the answer can be written

$$\frac{\delta\nu}{\nu} = -\frac{1}{4}\hat{N}^j\hat{N}^k R^{jJ} R^{kK} (\tilde{\kappa}_{e'})^{JK} - \frac{1}{2}(\delta^{jk} + \hat{N}^j\hat{N}^k) R^{jJ} R^{kK} \epsilon^{JPQ} \beta^Q (\tilde{\kappa}_{o'})^{KP} - \tilde{\kappa}_{\text{tr}}, \quad (8)$$

where for convenience we define

$$(\tilde{\kappa}_{e'})^{JK} = 3(\tilde{\kappa}_{e+})^{JK} + (\tilde{\kappa}_{e-})^{JK}, \quad (\tilde{\kappa}_{o'})^{JK} = 3(\tilde{\kappa}_{o-})^{JK} + (\tilde{\kappa}_{o+})^{JK}. \quad (9)$$

The uppercase indices represent the Sun-centered coordinates, $J, K = X, Y, Z$. The matrix R is the rotation between the two frames and β is the velocity of the laboratory in the Sun frame. Inserting the explicit time-dependent expressions R and β leads to periodic variations similar to the atomic-clock case.

A number of different experiments are possible. For example, a cavity could be compared to an atomic clock. The clock could be used as reference by choosing a transition that is insensitive to Lorentz violation. This setup would only be sensitive to violations in the photon sector. In contrast, operating the clock on a transition sensitive to Lorentz violation would provide sensitivity to combinations of photon and fermion coefficients.

It is also possible to construct cavities that are insensitive to given tilde coefficients. For example, geometries exist that support modes that are insensitive to $\tilde{\kappa}_{e-}$. With the constraints from birefringence, this leaves only the β suppressed variations due to $\tilde{\kappa}_{o+}$. Therefore, cavities might serve as reference frequencies for atomic clocks.

Traditionally, two cavities oriented at right angles are used in tests of relativity. This method could also be implemented in space-based experiments. In two-cavity experiments, the quantity of interest is normally the beat frequency obtained by combining their signals. On the ISS, this will take the form

$$\frac{\nu_{\text{beat}}}{\nu} \equiv \frac{\delta\nu_1}{\nu} - \frac{\delta\nu_2}{\nu} = \mathcal{A}_s \sin \omega_s T_s + \mathcal{A}_c \cos \omega_s T_s + \mathcal{B}_s \sin 2\omega_s T_s + \mathcal{B}_c \cos 2\omega_s T_s + \mathcal{C}, \quad (10)$$

where the amplitudes \mathcal{A}_s , \mathcal{A}_c , \mathcal{B}_s , and \mathcal{B}_c are linear combinations of the tilde coefficients. These are typically rather cumbersome [19] but depend on the orientation of the cavity pair in the laboratory and on the orientation of the orbital plane with respect to the Sun-centered frame.

It can be shown that orienting a cavity with \hat{N} in the orbital plane maximizes the sensitivity to the second harmonics, at leading order in β and that orienting a cavity so that \hat{N} is 45° out of the plane maximizes sensitivity to the first harmonics. Therefore, a sensible configuration might have one cavity in the orbital plane and one 45° out of it.

4 Advantages of Space-Based Experiments

There are several advantages to space-based experiments over their ground-based counterparts. A major advantage stems from the relatively short orbital period of the

Coefficient	Birefringence	Microwave	Optical
$(\tilde{\kappa}_{e+})^{JK}$	-32	*	*
$(\tilde{\kappa}_{o-})^{JK}$	-32	*	*
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	n/a	-13	-15
$(\tilde{\kappa}_{e-})^{ZZ}$	n/a	-	-
$(\tilde{\kappa}_{e-})^{XY}, (\tilde{\kappa}_{e-})^{XZ}, (\tilde{\kappa}_{e-})^{YZ}$	n/a	-13	-15
$(\tilde{\kappa}_{o+})^{XY}, (\tilde{\kappa}_{o+})^{XZ}, (\tilde{\kappa}_{o+})^{YZ}$	n/a	-9	-11
$\tilde{\kappa}_{\text{tr}}$	n/a	-	-

Table 1: Existing bounds for cosmological birefringence [19], microwave cavities [15] and optical cavities [16]. A star indicates that constraints probably exist. However, to date, no analysis has included these coefficients.

ISS. In Earth-based experiments, the relevant period is one sidereal day. Comparing this to the 92 min. period of the ISS orbit implies that an experiment on the ISS could acquire a comparable dataset in approximately one-sixteenth the time.

Another advantage arises from the properties of the ISS orbital plane. For fixed Earth-based experiments, there are combinations of coefficients such as \tilde{b}_Z and $(\tilde{\kappa}_{e-})^{ZZ}$ that do not contribute to sidereal variations and are therefore unobservable.² This is due to the constancy of the Earth's rotational axis which is fixed and points in the \hat{Z} direction. The analogous direction in the case of the ISS is given by its orbital axis. However, this axis precesses about the \hat{Z} axis at an angle of approximately 52° , implying that there is no analogous set of inaccessible coefficients.

One last major advantage is due to β suppressed terms like those that appear in Eqs. (5) and (6). Note that similar β_\oplus and β_s suppressed terms appear in the $[\sim]$ combinations of Eqs. (5) and (6) and in the amplitudes of Eq. (10). These terms are due to the changing velocity of the ISS in the Sun frame and introduce new time dependences and sensitivities to coefficient combinations that do not appear when considering rotational effects alone. Analogous terms do arise in Earth-based experiments. However, the terms that introduce new time dependences are suppressed by the smaller laboratory velocity $\beta_L \lesssim 1.5 \times 10^{-6} \ll \beta_s$.

5 Summary and Discussion

Table 1 lists the approximate base-10 logarithm of existing constraints on Lorentz violation in the photon sector. Ground-based experiments involving microwave [15] and optical [16] cavities have measured all components of $\tilde{\kappa}_{e-}$ and $\tilde{\kappa}_{o+}$ except $(\tilde{\kappa}_{e-})^{ZZ}$. A space-based experiment could immediately access the unconstrained coefficient $(\tilde{\kappa}_{e-})^{ZZ}$. Improved sensitivities are also expected. It has been estimated that SUMO

²Coefficients of this type can be accessed with the use of a turntable as in Ref. [24].

Coefficient	Proton	Neutron	Electron
\tilde{b}_X, \tilde{b}_Y	-27[-27]	[-31]	-27[-29]
\tilde{b}_Z	-27	-	-27[-28]
\tilde{b}_T	-23	-	-23
\tilde{g}_T	-23	-	-23
\tilde{H}_{JT}	-23	-	-23
\tilde{d}_\pm	-23	-	-23
\tilde{d}_Q	-23	-	-23
\tilde{d}_{JK}	-23	-	-23
\tilde{d}_X, \tilde{d}_Y	-25[-25]	[-29]	-22[-22]
\tilde{d}_Z	-25	-	-22
$\tilde{g}_{DX}, \tilde{g}_{DY}$	-25[-25]	[-29]	-22[-22]
\tilde{g}_{DZ}	-25	-	-22
\tilde{g}_{JK}	-21	-	-18
\tilde{g}_c	-23	-	-23
\tilde{c}_{TJ}	-20	-	-
\tilde{c}_-	-25	[-27]	-
\tilde{c}_Q	-25	-	-
\tilde{c}_X, \tilde{c}_Y	-25	[-25]	-
\tilde{c}_Z	-25	[-27]	-
\tilde{c}_{TJ}	-21	-	-
\tilde{g}_-	*[*]	[*]	-
\tilde{g}_Q	*	-	-
$\tilde{g}_{TX}, \tilde{g}_{TY}$	*[*]	[*]	-
\tilde{g}_{TZ}	*[*]	[*]	-

Table 2: Estimated sensitivity to tilde coefficients for ISS experiments with ^{133}Cs and ^{87}Rb clocks taken from Ref. [14]. Existing bounds [8, 9, 10, 11, 24] are shown in brackets. A star indicates possible sensitivity in realistic nuclear model.

may be able to achieve sensitivity at the level of 10^{-17} [15].

The above discussion could also be applied to optical-cavity experiments. Currently, the most precise measurements of $\tilde{\kappa}_{e-}$ and $\tilde{\kappa}_{o+}$ are from an optical-cavity experiment [16] and space-based versions such as those proposed for the OPTIS experiment [30] could also yield interesting results.

Note that the rotationally invariant component $\tilde{\kappa}_{tr}$ is also unconstrained. This is because, at order β , it results in unobservable constant shifts. However, it becomes important at order β^2 and could be accessed at interesting levels in experiments involving larger boosts or better sensitivity.

Table 2 lists the estimates given in Ref. [14] for the sensitivities of ^{133}Cs and ^{87}Rb clocks on the ISS. The brackets indicate measurements from current ground-based experiments. The table illustrates the main advantage of space-based clock-comparison experiments. The additional freedom in the motion of the ISS results in access to a much larger portion of the coefficient space.

Future clock-comparison experiments in space will probe regions of coefficient space difficult to access on Earth. They will do it more quickly and perhaps with better sensitivity than their ground-based counterparts.

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