Astrophysical Limits on Lorentz Violation
For All Charged Species

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Abstract

If Lorentz violation exists, it will affect the thresholds for pair creation processes. Lorentz-violating operators that change the maximum velocities of charged particles may increase or decrease the extinction rate of \(\gamma\)-rays moving through space. If the emissions from high-energy astrophysical sources do not show any signs of anomalous absorption, this allows us to place bounds on the Lorentz-violating \(c\) coefficients for multiple species of charged particles. The bounds for a species of mass \(m_X\) based on observing photons at an energy \(E_\gamma\) can be \(\mathcal{O}(m_X^2/E_\gamma^2)\), which corresponds to limits at the \(10^{-15}(m_X^2/m_e^2)\) level for the most energetic photons.

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There is growing interest in the possibility that Lorentz symmetry may not be exact in nature. Many candidate theories of quantum gravity predict Lorentz violation in some regimes. For example, Lorentz violation may arise spontaneously in string theory [1, 2] or elsewhere [3]. There could also be Lorentz-violating physics in loop quantum gravity [4, 5] and non-commutative spacetime [6, 7] theories, Lorentz violation through spacetime-varying couplings [8], or anomalous breaking of Lorentz and CPT symmetries [9] in certain spacetimes.

If Lorentz violation were uncovered experimentally, it would be a discovery of tremendous importance, telling us a great deal about the structure of new physics. To date, there is no significant evidence for Lorentz violation, although there have been many high-precision searches. The experimental tests have included studies of matter-antimatter asymmetries for trapped charged particles [10, 11, 12] and bound state systems [13, 14], determinations of muon properties [15, 16], analyses of the behavior of spin-polarized matter [17, 18], frequency standard comparisons [19, 20, 21, 22], Michelson-Morley experiments with cryogenic resonators [23, 24, 25], Doppler effect measurements [26, 27], measurements of neutral mesons [28, 29, 30, 31, 32, 33], polarization measurements on the light from distant galaxies [34, 35, 36], high-energy astrophysical tests [37, 38, 39, 40] and others. In this paper, we shall look at some further astrophysical bounds, based on observations of high-energy \( \gamma \)-rays; what is especially interesting about these bounds is that some of them apply to all charged particle species—including those of the second and third fermion generations and the charged intermediate vector bosons.

Possible violations of Lorentz invariance are described theoretically by the standard model extension (SME). The SME contains local Lorentz-violating operators built from known standard model fields (including gravity) and constant background tensors [41, 42, 43]. Constraints on various Lorentz-violating effects can be translated into bounds on the renormalizable coefficients of the SME.

We shall consider a form of Lorentz violation that can exist for any type of particle. This type of Lorentz violation is very simple, and it also happens that if the Lorentz-violating coefficients are Plank scale suppressed, their effects will become important just at the very highest observable energy scales. The Lagrange density for free fermions with this form of Lorentz violation is

\[ \mathcal{L}_\psi = \bar{\psi} [i(\gamma^\mu + c^{\nu\mu} \gamma_\nu) \partial_\mu - m_\psi] \psi. \]  

(1)

The coefficients \( c^{\nu\mu} \) form a traceless tensor, and at leading order, only the symmetric part of the tensor is physical. For spinless charged particles, the equivalent form of Lorentz violation is

\[ \mathcal{L}_\phi = (\partial^\mu \phi^*)(\partial_\mu \phi) + k^{\mu\nu}_\phi (\partial_\nu \phi^*)(\partial_\mu \phi) - m_\phi^2 |\phi|^2, \]  

(2)

and for a gauge field

\[ \mathcal{L}_A = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} (k_F)^\alpha_{\nu\alpha\mu} (F^{\rho\mu} F^\rho_{\nu} + F^{\nu\rho} F^\rho_{\nu}). \]  

(3)
For a non-Abelian gauge field, there is an implied sum over the gauge components of the field strength. The dispersion relations for the scalar, spinor, and vector fields are the same if $c_{\nu\mu} = \frac{1}{2} (k_\phi)_{\nu\mu} = \frac{1}{2} (k_F)^{\alpha}_{\nu\alpha\mu}$, to leading order in the Lorentz violation. By making slightly more elaborate modifications of the Lagrangians, the energy-momentum relations for the various particles may be made to coincide to all orders. However, since any physical Lorentz violation must be miniscule, we shall neglect all higher-order corrections.

There are natural reasons to expect that these forms of Lorentz violation should be the most important at high energies. The dimensionless $c$ and $k_\phi$ coefficients modify the kinetic parts of the spinor and scalar Lagrangians, and kinetic modifications, because they depend on the momentum, grow in importance at high energies. This growth is enhanced by the fact that the $c$, $k_\phi$, and $(k_F)^{\alpha}_{\nu\alpha\mu}$ coefficients have the correct discrete symmetries to mix with the Lorentz-invariant kinetic terms; other spin-dependent kinetic modifications are possible in the spinor and gauge sectors, but without the mixing, these do not grow as quickly. The effects of $c$ and $k_\phi$ become important at the momentum scales $\sim m_\psi/\sqrt{|c|}$ and $\sim m_\phi/\sqrt{|k_\phi|}$, respectively. Other Lorentz violating kinetic terms, such as $L_d = -id^{\mu\nu}\bar{\psi}\gamma_\nu\gamma_5\partial_\mu\psi$ become important only at the scale $\sim m_\psi/|d|$. In the pure gauge sector, where there is no mass term, a similar argument does not hold. However, we shall be interested here in constraining the $k_F$ coefficients for the charged $W^\pm$ bosons, which gain mass through the Higgs mechanism. For massive gauge bosons, the $(k_F)^{\alpha}_{\nu\alpha\mu}$ are again the most important terms at high energies.

Henceforth, we shall use the fermionic notation $c$ for all particles. A subscript on $c$ will denote the charged particle species to which it refers. Hence $c_e$ is the $c$ coefficient for electrons, $c_K$ is $\frac{1}{2}$ times the $k_\phi$ for $K^\pm$, and $c_W$ is $\frac{1}{2} (k_F)^{\alpha}_{\nu\alpha\mu}$ for $W^\pm$ bosons.

With a coordinate transformation, we may eliminate the Lorentz violation from any one sector. We shall choose to make the electromagnetic sector conventional, so that the photon dispersion relation $E = |\vec{k}|$ is unmodified. The bounds we shall place on the Lorentz-violating coefficients then arise from a possible mismatch between the dispersion relations for photons and charged particles.

As was pointed out in [37], the thresholds for the processes $\gamma \rightarrow X^+ + X^-$ and $\gamma + \gamma \rightarrow X^+ + X^-$ may depend on Lorentz violation. Without Lorentz violation, the first process—photon decay into a particle-antiparticle pair—is forbidden by energy-momentum conservation unless the decay products are massless. The analysis in [37] was restricted to electrons and assumed that rotation symmetry was exact; Lorentz invariance was broken by a single parameter $\delta$, describing the difference between the maximum electron speed and the speed of light. We shall generalize that analysis here.

In [37], the maximum electron speed was $1 + \delta$, so that the electron dispersion relation was simply $E = \sqrt{m^2 + (1 + 2\delta) |\vec{p}|^2}$ to leading order in $\delta$. In the presence of a Lorentz-violating $c$ term, the maximum velocity is generally direction dependent; it is equal to $1 - c_{jk}\hat{e}_j\hat{e}_k - c_{0j}\hat{e}_j - c_{00}$ in the $\hat{e}$-direction, where $c_{(0j)} = c_{0j} + c_{j0}$. This suggests that the model with $c$ may be effectively equivalent to the model in [37], but with a direction-
dependent
\[ \delta(\hat{e}) = -c_{jk}\hat{e}_j\hat{e}_k - c_{(0j)}\hat{e}_j - c_{00}. \] (4)

In fact, for ultrarelativistic particles, this suggestion is correct. The single-particle energy in the presence of \( c \) is

\[ E = (1 - c_{00}) \left( \sqrt{m^2 + p_j p_j - 2c_{j0}p_j - c_{(0j)}p_j} \right). \] (5)

Moving the \( c_{(0j)}p_j \) and \( c_{00} \) terms into the square root gives

\[ E = \sqrt{m^2 + p_j p_j - 2c_{jk}p_jp_k - 2c_{(0j)}p_j\sqrt{m^2 + p_j p_j} - 2c_{00}(m^2 + p_j p_j)} \] (6)

\[ E = \sqrt{m^2 + p_j p_j \left[ 1 - 2c_{jk}\hat{p}_j\hat{p}_k - 2c_{(0j)}\hat{p}_j \right]} \sqrt{1 + \frac{m^2}{p_j p_j} - 2c_{00} \left(1 + \frac{m^2}{p_j p_j} \right)}. \] (7)

When \( E \gg m \), this looks just like the direction-dependent \( \delta(\hat{e}) \). At nonrelativistic energies, the \( c_{(0j)} \) and \( c_{00} \) terms make it look quite different, but this is not unexpected, since in the nonrelativistic regime the measurable effects of \( c_{(0j)} \) and \( c_{00} \) are generally suppressed relative to those of \( c_{jk} \) by powers of the velocity. However, since we are interested in particles at the highest energies, the \( \delta(\hat{e}) \) description is sufficient for our purposes.

In the ultra-high-energy processes \( \gamma \to X^+ + X^- \) and \( \gamma + \gamma \to X^+ + X^- \), an initial energetic \( \gamma \)-ray and the daughter particles are all essentially collinear; this is required by energy-momentum conservation. Observations of a given astrophysical source can therefore only probe the quantity \( \delta(\hat{e}) \), where \( \hat{e} \) is the source-to-Earth direction. However, every charged species \( X \) has its own set of Lorentz-violating coefficients \( c_X \) and therefore its own \( \delta_X(\hat{e}) \). Data from a single source may be used to place bounds on all the different \( \delta_X(\hat{e}) \) parameters simultaneously.

Thresholds for new effects involving the particle species \( X \) typically occur at roughly the energy scale \( m_X/\sqrt{\delta(\hat{e})} \), where \( m_X \) is the mass parameter for the species. So the experimental sensitivity to \( \delta_X \) and \( c_X \) for an experiment collecting data at an energy \( E \) is typically of order \( m_X^2/E^2 \). For any other Lorentz-violating modifications of the kinetic part of the Lagrangian, the sensitivity would be of order \( m_X/E \) at best.

In [39][40], we placed bounds on \( c_\tau \) by considering the radiation processes \( e^- + \gamma \to e^- + \gamma \), and the bounds were at precisely the \( m^2_\tau/E^2 \) level. However, that analysis cannot be generalized to other charged species, because we relied on the presence of radiation-emitting electrons in the source. There are not, for example, large numbers of radiating \( \tau \) leptons in supernova remnants; consequently, the analysis in [39][40] does not lead to any bounds on \( c_\tau \). If we look instead at the disappearance of high-energy photons traveling through space, through a process such as \( \gamma \to X^+ + X^- \), it makes no qualitative difference whether \( X = e \) or \( X = \tau \). If we place a bound on \( c_e \) by looking at this process, we also get a bound on \( c_\tau \)—one that is weaker by precisely a factor of \( m^2_\tau/m^2_e \approx 1.2 \times 10^7. \)
Table 1: Energies of observed $\gamma$-rays from various astrophysical sources. References are given for each value of the energy.

| Emission source | $\hat{e}_X$ | $\hat{e}_Y$ | $\hat{e}_Z$ | $E_\gamma/m_e$ |
|-----------------|-------------|-------------|-------------|----------------|
| Crab nebula     | -0.10       | -0.92       | -0.37       | $1.6 \times 10^8$ [45] |
| G 0.9+0.1       | 0.05        | 0.88        | 0.47        | $10^7$ [46] |
| G 12.82-0.02    | -0.06       | 0.95        | 0.29        | $5 \times 10^7$ [47] |
| G 18.0-0.7      | -0.11       | 0.97        | 0.24        | $7 \times 10^7$ [48, 49] |
| G 347.3-0.5     | 0.16        | 0.75        | 0.64        | $2 \times 10^7$ [50] |
| MSH 15-52       | 0.34        | 0.38        | 0.86        | $8 \times 10^7$ [51] |
| Mkn 421         | 0.76        | -0.19       | -0.62       | $3 \times 10^7$ [52, 53] |
| Mkn 501         | 0.22        | 0.74        | -0.64       | $4 \times 10^7$ [54] |
| SNR 1006 AD     | 0.52        | 0.53        | 0.67        | $7 \times 10^6$ [55] |
| Vela SNR        | 0.44        | -0.55       | 0.71        | $1.3 \times 10^8$ [56] |

For the $\tau$ specifically, there have been no published bounds on Lorentz violations. The $\tau$ bounds we shall derive here are significantly worse than the electron bounds, but they are still interesting. However, better bounds on a wider variety of Lorentz-violating coefficients might be possible with a careful reanalysis of $\tau$ production data from collider experiments.

Single-photon pair creation, $\gamma \rightarrow X^+ + X^-$, is forbidden unless the dispersion relation for $X$ satisfies $E < |\vec{p}|$. The threshold at which this process becomes allowed is easily seen to be $E_\gamma = m_X \sqrt{-2/\delta_X(\hat{e})}$; the threshold only exists for photons moving in the direction $\hat{e}$ if $\delta_X(\hat{e}) < 0$. Electromagnetic decays occur extremely rapidly compared with astrophysical time scales, so any observation of a $\gamma$-ray of energy $E_\gamma$ coming from the direction $-\hat{e}$ constrains $\delta_X(\hat{e}) > -2m_X^2/E_\gamma^2$ for every charged species $X$.

Table 1 lists the observed $\gamma$-ray energies for a number of high-energy sources, parameterized in terms of $E_\gamma/m_e$. The typical $E_\gamma/m_e$ values range from $\sim 10^7$–$10^8$, corresponding to $\gamma$-ray energies of $\sim 5$–$50$ TeV. The source-to-Earth direction $\hat{e}$ for each source is given in terms of the right ascension $\alpha$ and declination $\delta$ as $\hat{e}_X = -\cos \delta \cos \alpha$, $\hat{e}_Y = -\cos \delta \sin \alpha$, and $\hat{e}_Z = -\sin \delta$, in the standard sun-centered celestial equatorial coordinate system used in the parameterization of Lorentz violations. (The $X$ in these coordinates should not be confused with the species label $X$.)

There is no shortage of sources on which these bounds can be based. Unfortunately though, all the limits coming from the data in table 1 are one-sided. It is not possible, based on these bounds alone, to constrain all the $c$ coefficients to lie within a bounded region of parameter space. However, the bounds do give some idea what scale of Lorentz violation might reasonably allowed for different species. The scales of the bounds appropriate to different species are listed in table 2.

For electrons, the lightest charged particles, the bounds are the strongest, at roughly
Table 2: Characteristic sizes of the bounds on $c_X$ for a number of interesting species.

| $X$ | $m_e/m_X$ | bounds on $c_X$ |
|-----|-----------|-----------------|
| $e$ | 1         | $10^{-15}$      |
| $\mu$ | $4.8 \times 10^{-3}$ | $10^{-11}$ |
| $\pi$ | $3.7 \times 10^{-3}$ | $10^{-10}$ |
| $K$ | $1.0 \times 10^{-3}$ | $10^{-9}$ |
| $p$ | $5.4 \times 10^{-4}$ | $10^{-9}$ |
| $\tau$ | $2.9 \times 10^{-4}$ | $10^{-8}$ |
| $D$ | $2.7 \times 10^{-4}$ | $10^{-8}$ |
| $B$ | $9.7 \times 10^{-5}$ | $10^{-7}$ |
| $W$ | $6.4 \times 10^{-6}$ | $10^{-5}$ |

the $10^{-15}$ level, comparable to the more comprehensive astrophysical bounds in \cite{39, 40} and to the laboratory bounds in \cite{57}. For muons, the bounds are at roughly the $10^{-11}$ level; such bounds are still interesting, although the best muon bounds, on different combinations of coefficients, are quite a bit better. The bounds for the tau are at approximately $10^{-8}$, and these are the first published bounds for this species.

Bounds for hadrons are obviously also available. There are already much better bounds on the proton $c$ coefficients from clock comparison experiments, but the corresponding coefficients for the light mesons are not so well bounded. There are no published bounds specifically for the charged pions; however, proton and neutron data constrain the Lorentz-violating coefficients for the quark and gluon constituents fairly strongly, so the $\sim 10^{-10}$ bounds derived here are not at all unexpected. For the charged kaons, which contain strange quarks, the situation is somewhat different. Although there are very strong bounds on the CPT-violating $a$ coefficients for strange and other heavier quarks coming from neutral meson experiments, the CPT-even $c$ coefficients are relatively unconstrained. This makes the derived bound on $c_K$, at the $10^{-9}$ level, relatively interesting, and similarly for the successively weaker bounds for the heavier mesons.

Finally, there are also bounds placed on the Lorentz violation in the $SU(2)_L$ gauge sector. Because of the large mass of the $W$, the resulting bounds on $c_W$ are only at the $10^{-5}$ level. Although bounds on Higgs and electroweak Lorentz violation have been considered before \cite{58}, these are the first robust bounds that do not assume that Lorentz violation exists in only a single sector.

Bounds complementary to the preceding one-sided bounds could come from analyses of the process $\gamma + \gamma \to X^+ + X^-$, when one photon is an ultra-high-energy $\gamma$-ray and the other comes from a low-energy background source. This process contributes significantly to the absorption of energetic photons, and once again, $c$-type Lorentz violation can affect the threshold. Lorentz violation has previously been discussed as a possible resolution to apparent anomalies in the absorption spectra of blazars \cite{59, 60}. If the characteristic size
of the Lorentz-violating coefficients $c_X$ is $m_e/M_P$, where $M_P$ is the Planck mass, then the scale at which the Lorentz-violating effects become important is quite similar to the highest energy scales seen in astrophysical objects, roughly in the range of 100–1000 TeV; this apparent coincidence in scales can make explanations in terms of Lorentz violation numerically quite appealing.

Pair creation in the interaction between low- and high-energy photons can only occur if the low-energy photon has an energy of at least $\epsilon_\gamma = m_X^2/E_\gamma + E_\gamma \delta_X(\hat{e})/2$, where $E_\gamma$ is the $\gamma$-ray energy and $\hat{e}$ is again its direction. The previously quoted bounds on negative values of $\delta_X(\hat{e})$ derive from the fact that if $\delta_X(\hat{e})$ is large enough and negative, the threshold $\epsilon_\gamma$ may be pushed to zero, causing a rapid extinction of the highest-energy $\gamma$-rays. On the other hand, a positive $\delta_X(\hat{e})$ will raise the threshold, causing there to be less absorption. Since $\epsilon_\gamma$ increases appreciably only for $\delta_X(\hat{e}) > m_X^2/E_\gamma^2$, if a normal pattern of absorption is observed for photons of energies up to $E_\gamma$, then it may be possible to place further bounds on the various $\delta_X(\hat{e})$ for the relevant direction.

However, determining whether there is anomalous absorption can be tricky, because it requires some knowledge of the source’s emission profile as well as the density of radiation along the path from the source to Earth. Since this density is generally low, large distances and extragalactic sources are best suited for this kind of analysis. There is also an additional complication. If absorption by pair creation of the species $X$ is negligible even without Lorentz violation, it would be impossible to observe any further diminishment of that absorption. For the pair creation of electrons and positrons by $\gamma$-rays with energies in the hundreds of GeV, the threshold $\epsilon_\gamma$ is approximately 1 eV, which is a reasonable energy for quanta of starlight. For pions and muons, the threshold is in the x-ray region, so even for these fairly light species, the corresponding absorption process is unimportant. So only for electrons can we derive interesting bounds by looking for an absence of decreased absorption.

In [37], the example was cited of Markarian 501, for which the absorption appears to remain conventional up to energies of 20 TeV. This then gives a two-sided bound on $\delta_X(\hat{e})$ for one value of $\hat{e}$. The other prototypical $\gamma$-ray blazar, Markarian 421, also exhibits normal absorption up to the maximum observable energy of roughly 15 TeV [52, 61], giving another two-sided bound in the electron sector. The two-sided bounds are

$$\begin{align*}
0.05c_{XX} + 0.55c_{YY} + 0.41c_{ZZ} + 0.16c_{(XY)} - 0.14c_{(XZ)} \\
-0.47c_{(YZ)} + 0.22c_{(0X)} + 0.74c_{(0Y)} - 0.64c_{(0Z)} + c_{00} < 1.3 \times 10^{-15} \\
0.58c_{XX} + 0.04c_{YY} + 0.38c_{ZZ} - 0.14c_{(XY)} - 0.47c_{(XZ)} \\
+0.12c_{(YZ)} + 0.76c_{(0X)} - 0.19c_{(0Y)} - 0.62c_{(0Z)} + c_{00} < 2.5 \times 10^{-15}.
\end{align*}$$

Mkn 421 and Mkn 501 are located at redshifts of roughly $z = 0.03$. However, recent measurements of sources at somewhat higher redshifts have found less absorption than was expected [62]. This anomaly can be explained away, provided that levels of extragalactic
background light are lower than previously thought. That is certainly the most likely explanation, but this data could alternatively be a subtle hint of Lorentz violation.

In order to improve on the absorption-based bounds, we would need better data on the extragalactic absorption of TeV $\gamma$-rays. If we wanted to test whether the absorption data were consistent with Lorentz violation as an explanation, we would first need to understand better the character of the Lorentz-invariant absorption. More data on the extragalactic absorption of high-energy photons is therefore quite important. Moreover, we would also need to know in more detail how $c$ affects the cross section for the $\gamma + \gamma \to e^+ + e^-$ process. However, it happens that one of the few known Lorentz-violating cross sections is that of the inverse process of electron-positron annihilation $e^+ + e^- \to \gamma + \gamma$ in the presence of $c_e$.

Our presently incomplete understanding of these matters makes placing bounds on Lorentz violation based on observations of anything but the best understood sources a tricky proposition. Nevertheless, the process $\gamma + \gamma \to e^+ + e^-$ can be used to set some interesting bounds on some of the Lorentz-violating $c$ coefficients for electrons. Much more general bounds come from $\gamma \to X^+ + X^-$, and what makes these latter bounds especially interesting is that they apply to every species of charged particles. The typical scale of the bounds on the $c_X$ coefficients is $10^{-15}(m_X^2/m_e^2)$, and this allows us to place bounds on some previously unconstrained sectors of the SME.

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