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Tests of Lorentz and CPT invariance with neutrinos and photons

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Abstract. Lorentz symmetry is a cornerstone of modern physics. As the spacetime symmetry of special relativity, Lorentz invariance is a basic component of the standard model of particle physics and general relativity, which to date constitute our most successful descriptions of nature. Deviations from exact symmetry would radically change our view of the universe and current experiments allow us to test the validity of this assumption. The propagation of neutrinos and photons can be used to search for deviations from exact Lorentz and CPT invariance.

1. Introduction
The nonconservation of parity (P) violation in weak interactions motivates the search for new physics by using different experimental setups that can be sensitive to the potential breakdown of other combinations of discrete symmetries. In fact, our matter-dominated Universe suggests that minute differences matter and antimatter properties can have profound consequences. Today we search for deviations from the invariance under parity and charge conjugation (CP) in different sectors of the Standard Model (SM) because the size of the CP-violating effects observed in the quark sector cannot fully account for the matter-antimatter imbalance. A more drastic possibility is the potential violation of CPT invariance, this is the combination of parity, charge conjugation, and time-reversal (T). In a realistic quantum field theory, in which unitarity and microcausality are preserved, CPT violation implies the violation of Lorentz symmetry [1].

During the last decade, experimental searches and phenomenological consideration for spacetime anisotropies have been considered [2, 3, 4, 5]. A systematic classification of the most general ways to incorporate Lorentz-violating operators in the SM action is an effective field theory called Standard-Model Extension (SME) [6, 7]. In this general framework, Lorentz-violating terms are introduced at the action level by contracting operators of conventional fields in the SM with controlling coefficients to preserve coordinate invariance. A subset of Lorentz-violating operators also break CPT. This framework can also be written in a curved spacetime and incorporate Lorentz violation in gravity [8]. Since the SME allows the identification of the relevant observable effects in different experiments, the search for possible deviations from exact Lorentz invariance has become a worldwide experimental program [9].

The interferometric nature of neutrino oscillations makes this phenomenon an attractive method to search for novel effects. Similarly, the long distance and the high energy of astrophysical neutrinos and photons makes these two particles cosmic messengers of astrophysical phenomena as well as probes of fundamental physics.
In what follows, the key signatures of deviations of Lorentz and CPT invariance will be studied within the context of the SME; nevertheless, different approaches for CPT-violating physics can be implemented with and without Lorentz invariance \[10, 11, 12, 13, 14, 15, 16, 17\].

2. Lorentz-violating neutrinos

Active neutrinos in the SME are characterized by a $6 \times 6$ effective Hamiltonian, in which a $3 \times 3$ diagonal block $h_{aa}$ describes three left-handed neutrinos, whereas the other $3 \times 3$ diagonal block $h_{bb}$ describes three right-handed antineutrinos. The remaining $3 \times 3$ off-diagonal block $h_{ab}$ corresponds to mixing between neutrinos and antineutrinos arising due to Lorentz violation. The indices $a, b = e, \mu, \tau$ and $\bar{a}, \bar{b} = \bar{e}, \bar{\mu}, \bar{\tau}$ denote the flavors of active neutrinos and antineutrinos, respectively. The neutrino block can be explicitly written in the form \[18\]

$$h_{ab} = |p| \delta_{ab} + \frac{m^2_{ab}}{2|p|} + (aL)_{ab}^\alpha \tilde{p}_\alpha - (cL)_{ab}^{\alpha \beta} \tilde{p}_\alpha \tilde{p}_\beta |p|,$$

where at leading order the neutrino momentum is given by the energy $|p| \approx E$ \[19\]. The first two terms correspond to a Lorentz-invariant description, in which the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix \[20, 21\] is used to parametrize the flavor mixing and mass-squared differences $m^2_{ab}$ lead to conventional neutrino oscillations. The third element in the Hamiltonian \[1\] is an energy-independent term in which the complex matrix $(aL)_{ab}^\alpha$ controls CPT-odd Lorentz violation, while the last term grows linearly with the neutrino energy and describes CPT-even Lorentz violation through the complex matrix $(cL)_{ab}^{\alpha \beta}$. The components of these $3 \times 3$ matrices are called coefficients for Lorentz violation. The four-vector depends on the neutrino direction of propagation $\tilde{p}$ as $\tilde{p}^\alpha = (1; \tilde{p})$. Operators of arbitrary dimension can also be incorporated in the theory, which would lead to higher powers of the neutrino energy in the Hamiltonian \[22, 23\].

The coefficients for Lorentz violation $(aL)_{ab}^\alpha$ and $(cL)_{ab}^{\alpha \beta}$ behave like fixed background fields that produce measurable effects when the experiment is boosted or rotated. In order to systematically compare different experiments searching for Lorentz-violation, a common inertial frame must be chosen. Experimental results are conventionally reported in the Sun-centered equatorial frame \[9\]. In this frame, a neutrino beam rotates with sidereal frequency $\omega_\oplus \simeq 2\pi/(23 \, \text{h} \, 56 \, \text{min})$ with respect to the background fields for experiments with detector and source on the surface of the Earth. This time dependence can be used to parametrize the relevant observable in terms of harmonics of the sidereal angle $\omega_\oplus T_\oplus$. In addition to searching for generic effects of Lorentz violation in neutrinos, some studies have considered the possibility of using the Hamiltonian \[1\] to describe all the neutrino-oscillation data as an alternative to the conventional mass-driven oscillations. These global models based on the SME have interesting features that could accommodate all the established data as well as some anomalous results reported by different experiments \[24, 25, 26, 27, 28, 29\].

As simple classification of the different experimental signatures of the many SME coefficients, neutrino experiments can be classified into two types: flavor mixing and oscillation-free effects. As the name suggests, mixing effects arise from off-diagonal elements in flavor space and leading to neutrino oscillations. Oscillation-free effects, on the other hand, correspond to modifications that affect the behavior of the three neutrino flavors in the same form, leaving oscillations unaffected because they arise from factors proportional to the identity matrix in flavor space. These oscillation-free effects can be observed in kinematical measurements such as neutrino velocity and weak decays.

3. Neutrino oscillations

Flavor mixing makes neutrinos natural interferometers that can be used as sensitive tools to study the coefficients in the Hamiltonian \[1\]. Perturbative methods can be implemented for the
determination of the relevant oscillation probabilities, depending on the details of the experiment of interest.

Experiments with long baselines have a far detector located where the first oscillation maximum is expected according to the conventional massive-neutrino description. Given the propagation distance from the source to the detector, in these experiments the oscillation signal due to neutrino masses is large and Lorentz-violating effects can be incorporated as a small perturbation to the mass-driven oscillations. Using conventional time-dependent perturbation theory, we can write the oscillation probabilities as a power series [30]

\[
P_{\nu_b \to \nu_a} = P_{\nu_b \to \nu_a}^{(0)} + P_{\nu_b \to \nu_a}^{(1)} + P_{\nu_b \to \nu_a}^{(2)} + \cdots, \tag{2}
\]

where the conventional oscillation probability from the massive-neutrino model is corresponds to the leading-order term \(P_{\nu_b \to \nu_a}^{(0)}\), whereas the next term, \(P_{\nu_b \to \nu_a}^{(1)}\), arises from the interference between the mass-driven oscillations and Lorentz violation. Each term in the series (2) can be calculated order by order. In the Sun-centered frame mentioned earlier, the orientation of the neutrino beam varies with sidereal phase \(\omega_\odot T\), with respect to the fixed background fields \((a_L)_{ab}\) and \((c_L)_{ab}\), which also introduces direction-dependent effects. The sub-leading term in the series (2), for example, can be written as an expansion on harmonics of the sidereal phase in the form

\[
\frac{P_{\nu_b \to \nu_a}^{(1)}}{2L} = (P_{\nu_b \to \nu_a}^{(1)})_{ab} + (P_{\nu_b \to \nu_a}^{(1)})_{ab} \sin \omega_\odot T + (P_{\nu_b \to \nu_a}^{(1)})_{ab} \cos \omega_\odot T \\
+ (P_{\nu_b \to \nu_a}^{(2)})_{ab} \sin 2\omega_\odot T + (P_{\nu_b \to \nu_a}^{(2)})_{ab} \cos 2\omega_\odot T. \tag{3}
\]

The amplitude of each term in this expansion has units of energy and depends on the coefficients for Lorentz violation as well as properties of the experiment such as the orientation of the neutrino beam, the location of the detector, and the neutrino energy [30, 31]. Corresponding expressions for antineutrino oscillations can be obtained directly by replacing \((a_L)_{ab} \to -(a_L)_{ab}^*\) and \((c_L)_{ab} \to (c_L)_{ab}^*\).

In high-energy experiments with a short baseline, no oscillations are expected according to the conventional massive-neutrino model. In this case, the first two terms in the series (2) vanish and any oscillation signal would be a consequence of Lorentz violation. Direct calculation shows that for appearance experiments the leading-order driving the oscillation probability for neutrinos takes the explicit form [31]

\[
P_{\nu_b \to \nu_a} \propto L^2 \left| (a_L)_{ab} \hat{p}_a - (c_L)_{ab} \hat{p}_a \hat{p}_b E \right|^2, \quad a \neq b, \tag{4}
\]

where \(L\) is the baseline and \(E\) the neutrino energy.

The two limits described above have been implemented to perform several independent searches for Lorentz and CPT violation by Double Chooz [32], IceCube [33], LSND [34], MiniBooNE [35, 36], MINOS [37, 38, 39], and Super-Kamiokande [40]. The complementarity of these searches is due to the study of different oscillation channels, which depend on similar coefficients but with different flavor indices. To date no compelling evidence for Lorentz violation has been found and tight constraints on several SME coefficients have been determined in these experimental searches [9].

There is also a type of oscillation that can occur in the SME context that is absent in the conventional Lorentz-invariant case. As mentioned at the beginning of the previous section, in the presence of Lorentz violation neutrinos and antineutrinos can also mix. The oscillation between left-handed neutrinos and right-handed antineutrinos would be caused by an independent set of SME coefficients. These oscillations always exhibit direction dependence.
and are absent in the first two terms of the series (2). In other words, the SME coefficients that produce neutrino-antineutrino mixing appear quadratically in the oscillation probability. For these oscillations, the probability can be written in the same form as the linear term (3). However, being a second-order effect the sidereal decomposition will include up to fourth harmonics [30]. Experimental searches of these neutrino-antineutrino oscillations have been performed using accelerator [41] and reactor neutrinos [42].

4. Oscillation-free signals

Modifications to the neutrino propagation properties that change the three flavors in the same way produce no effects in oscillations because they would correspond to a uniform shift of the eigenstate energies (oscillations only depend on eigenstate energy differences). These oscillation-free effects can be studied in experiments that can measure the neutrino velocity. In the SME, the neutrino velocity can be written as [22]

$$v_\nu \approx 1 - \frac{|m|^2}{2E^2} + \sum_{djm} (d-3)E^{d-4}e^{im\omega_{0}T_{\odot}} 0N_{jm}(a^{(d)}_{of})_{jm} - (c^{(d)}_{of})_{jm},$$

(5)

where the real mass parameter $|m|^2$ does not participate in oscillations, $E$ the neutrino energy, and we have used a spherical decomposition for the Lorentz-violating part. This spherical decomposition is very handy to describe transformation properties under rotations of the independent coefficients indicated by the sum The index $d$ denotes the mass dimension of the operator in the theory, whereas the angular momentum indices $jm$ label the rotation properties of the oscillation-free coefficients for CPT-odd $(a^{(d)}_{of})_{jm}$ and CPT-even $(c^{(d)}_{of})_{jm}$ for Lorentz violation. The information regarding the orientation of the neutrino beam as well as the location of the laboratory is encoded in the angular factors $0N_{jm}$ and the harmonics of the sidereal phase $\omega_{0}T_{\odot}$ is controlled by the index $m$. For this reason, the neutrino velocity becomes time dependent for $m \neq 0$. Similarly, direction-dependent effects appear for $j \neq 0$ due to the loss of invariance under rotations. The isotropic limit corresponds to the particular case $j = 0$.

It should be noticed that the sum (5) only one of the coefficients appear for a given value of the index $d$. Explicitly, $(a^{(d)}_{of})_{jm} = 0$ for $d$ even and $(c^{(d)}_{of})_{jm} = 0$ for $d$ odd. Here we notice that for odd $d$, CPT violation makes neutrinos and antineutrinos move at different speed (for antineutrinos the coefficient $(a^{(d)}_{of})_{jm}$ has opposite sign). The expression for the neutrino velocity (5) can be directly applied to this type of studies in beam experiments [43, 44, 45, 46, 47, 48, 49].

For operators of dimension $d > 5$ in the theory, the neutrino velocity (5) becomes energy dependent, which can produce novel effects including the dispersion of a neutrino burst due to the the independent speed of neutrinos of different energies. Dispersive effects and time delays due to modifications of the neutrino speed can be tested to high precision using astrophysical sources of neutrinos because the long distances traveled enhance the small effects of the coefficients for Lorentz violation [22, 50].

Furthermore, the modified neutrino (and antineutrino) energy and momentum relation exhibited by the Hamiltonian (1) indicates that the oscillation-free coefficients can also be studied by exploring the properties of modified dispersion relations in different processes. One of the remarkable effects of Lorentz violation is the possibility of making kinematically forbidden reactions allowed and vice versa. This means that nonzero SME coefficients can open the phase space of conventionally forbidden processes as well as blocking certain processes that would be otherwise allowed. Consider the leptonic decay of a charged meson $M^+$ of the form $M^+ \rightarrow l^+ + \nu_l$, which becomes forbidden above some threshold energy $E_{th}$ [22, 51, 52, 53, 54, 55, 56, 57, 58]. If the decay products are observed at a given energy $E_0$, then the size of the SME coefficients must lead to a threshold energy such that $E_{th} > E_0$. This threshold condition can be written
directly from energy-momentum conservation relations and the Hamiltonian (1) in the form [22]

\[ \sum_{j m} E_0^{d-2} Y_{jm}(\hat{p}) [ \pm (a_{of}^{(d)})_{jm} - (r_{of}^{(d)})_{jm} ] < \frac{1}{2} (M_M - m_{l\pm})^2, \]

(6)

where \( M_M \) denotes the mass of the parent charged meson, \( m_{l\pm} \) indicates the mass of the charged lepton, and the sign \(+\) (−) refers to neutrinos (antineutrinos). The spherical harmonics \( Y_{jm} \) encode possible direction-dependent effects (for \( j \neq 0 \)). This expression shows that better constraints on the SME coefficients can be obtained by observing energetic neutrinos. The observation of energetic neutrinos in IceCube [59, 60] serves as a very sensitive probe of Lorentz and CPT invariance using this threshold analysis. In particular, the observation of several events can be used to go beyond conventional isotropic studies and to explore direction-dependent effects, which requires a spread of events in the sky [61].

Following a similar approach, forbidden processes can become allowed due to Lorentz and CPT violation. For instance, some coefficients in the neutrino velocity (5) can produce superluminal neutrinos, which could lose energy in the form of Cherenkov radiation [22, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72]. The determination of a characteristic energy-loss distance \( D(E) = -E/(dE/dx) \) due to Cherenkov radiation can be used to write the condition \( L < D(E) \), where \( L \) is the distance traveled by the neutrino [22]. For the electron-positron emission in the process \( \nu \rightarrow \nu + e^- + e^+ \) the rate of energy loss takes the explicit form [22, 61]

\[ -\frac{dE}{dx} = C \int \frac{\kappa^0 \kappa'^2}{(\kappa^2 - M_Z^2)^2} \frac{\partial |\kappa'|}{\partial \kappa_0} \frac{q \cdot k'}{q_0 q_0' k_0'} d^3 p' d\Omega', \]

(7)

where \( \kappa = k + k' \) and \( \kappa' = k - k' \) are auxiliary 4-vectors defined in terms of the momentum of the electron \( (k) \) and the positron \( (k') \), \( C \) is a constant, and \( q/q_0 = (1, \hat{p}) \), \( q'/q_0' = (1, \hat{p}') \) encode the Lorentz-violating effects in the neutrino dispersion relation. This formula can be used to search for Lorentz violation through the observation of high-energy astrophysical neutrinos [61, 73, 74, 75, 76].

There one type of oscillation-free coefficient, however, that cannot be studied in experiments sensitive to modifications of the neutrino velocity (5). Arising from operators of dimension \( d = 3 \), the coefficients \( (a_{of}^{(3)})_{jm} \) leave the neutrino velocity unchanged; however, their experimental signatures would appear weak decays [77]. For single beta decay, the observable signatures of Lorentz and CPT violation appear due to the modified dispersion relation of the antineutrino as well as the altered spinor solutions of the equation of motion [78]. Additionally, a CPT-violating Majorana couplings in the SME can trigger neutrinoless double beta decay even for a negligible Majorana mass [79].

5. Conclusions
Potential violations of Lorentz and CPT invariance have been studied both theoretically and experimentally in a wide range of systems. Neutrinos offer the possibility to perform a great variety of tests of the validity of these spacetime symmetries, from the high precision of low-energy experiments studying weak interactions to the great power of neutrino oscillations thanks to their interferometric nature as well as the high energy of astrophysical neutrinos traveling long distances before reaching our detectors. Lorentz and CPT invariance have survived the several tests performed using the SME as a general framework; nonetheless, there are many other effects that remain unexplored.

Neutrinos have amazed us since they were proposed to save the conservation of energy, today neutrinos offer the opportunity to challenge the cornerstone of modern physics.
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