

Snowmass2021 - Letter of Interest

Neutrinos as Probes for Lorentz and CPT Symmetry

NF Topical Groups: (check all that apply ☐/■)

- (NF1) Neutrino oscillations
- ☐ (NF2) Sterile neutrinos
- (NF3) Beyond the Standard Model
- (NF4) Neutrinos from natural sources
- (NF5) Neutrino properties
- ☐ (NF6) Neutrino cross sections
- ☐ (NF7) Applications
- (TF11) Theory of neutrino physics
- (NF9) Artificial neutrino sources
- ☐ (NF10) Neutrino detectors
- ☐ (Other) *[Please specify frontier/topical group(s)]*

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Abstract:

The coming decade is poised to witness an abundance of measurements with the potential of substantial improvements of our understanding of neutrino physics. Many of these measurements can be harnessed for unprecedented studies of both Lorentz and CPT invariance, two closely intertwined cornerstones of established physics. These symmetries may nevertheless be violated in many theoretical approaches to underlying physics including ones involving departures from the ordinary classical spacetime structure. Within effective field theory, Lorentz and CPT breakdown is predicted to affect neutrino propagation, the kinematics of particle reactions involving neutrinos, and flavor oscillations including transformations between neutrinos and antineutrinos. This letter provides brief descriptions of these effects and efforts to detect them showcasing the bright future for such endeavors.

Motivation. Unmeasured neutrino parameters, as well as tension between various neutrino experiments, hold abundant potential for new discoveries in neutrino physics within the coming decade. Ongoing and future experimental efforts in this context include the unique opportunity to test Lorentz and CPT symmetry in the neutrino sector. These intimately related invariance principles^{1;2} form a pillar of present-day physics. Nevertheless, it is a widely held belief that an underlying framework providing a consistent description of both quantum and gravitational physics will require departures from currently established theoretical foundations, at least to some extent. In particular, a number of approaches in this context, such as string theory,^{3;4} harbor the potential for a breakdown of both Lorentz and CPT invariance. Such effects would entail measurable signals at presently accessible energy scales opening an exciting avenue for probing BSM physics, possibly arising at the Planck scale.

Framework. Paralleling most approaches to underlying physics, effective field theory (EFT) represents the standard tool kit for theoretical predictions of Lorentz- and CPT-violating effects in neutrino physics and beyond. This idea was initiated in the late nineties with the inception of the Standard-Model Extension (SME),^{5–7} an EFT for Lorentz and CPT breaking at the level of the Standard Model and General Relativity. In the intervening two decades, the SME has matured into the standard framework for such symmetry studies and has served as the basis for hundreds of Lorentz and CPT tests across numerous physical systems at all accessible energy scales.⁸ The SME predicts effects in neutrino oscillations, neutrino propagation, beta-decay endpoint physics, and (neutrinoless) double beta decay. Numerous past measurements have constrained neutrino SME coefficients, but large swaths of parameter space remain uncharted indicating ample prospects for new explorations. What follows is a brief outline of these prospects.

Neutrino oscillations. Due to their interferometric nature, neutrino-oscillation measurements offer ultrahigh sensitivities to BSM physics including Lorentz and CPT violation. SME predictions in this context include novel mixing features of neutrino and antineutrino flavor states.^{7;9–12} In particular, Lorentz- and CPT-violating signatures involve unconventional energy dependencies of the oscillation phase, energy-dependent mixing angles in vacuum, direction-dependent oscillation probabilities due to the loss of rotational invariance, time-dependent oscillation probabilities in Earth-based experiments arising from laboratory motion, and mixing between neutrinos and antineutrinos. Past searches for these signatures have been conducted by the SNO,¹³ Daya Bay,¹⁴ Super-Kamiokande,¹⁵ MiniBooNE,¹⁶ MINOS,¹⁷ Double Chooz,¹⁸ LSND,¹⁹ T2K,²⁰ and IceCube²¹ collaborations placing some of the tightest limits on Lorentz and CPT breakdown in nature.

Current and planned international efforts including at existing and future US-led neutrino-physics facilities foreshadow further breakthroughs in this field. For example, DUNE’s exquisite design capabilities for the detection of beam, atmospheric, and supernova neutrinos bode well for improving various existing Lorentz and CPT tests by up to about three orders of magnitude, and delivering at least 45 first-ever constraints on a^μ - and $c^{\mu\nu}$ -type SME coefficients alone.²² Likewise, the anticipated influx of new data from SBN programs²³ can be expected to generate continued interest and activities in short-baseline SME measurements.⁹ Further significant potential for novel and improved Lorentz and CPT tests exist with high-energy neutrinos in IceCube,²⁴ a regime in which SME oscillation effects are expected to dominate. NO ν A,²⁵ a currently operating long-baseline experiment that is specifically designed for precision comparisons of neutrino oscillations to antineutrino oscillations, is also in an unparalleled position for testing CPT and Majorana-like Lorentz violation in the neutrino sector.

Neutrino propagation. Modifications to one-particle dispersion relations represent another consequence of Lorentz and CPT violation. As a result, neutrino velocity may exhibit dispersion and anisotropies.²⁶ Beam experiments that can measure neutrino time of flight,²⁷ such as DUNE,²² MiniBooNE, NO ν A,²⁵ and SBN programs²³ are ideally positioned to search for these effects. In the era of astrophysical neutrinos, the sole observation of high-energy events in neutrino telescopes can also serve as a sensitive probe for uncon-

ventional neutrino-propagation behavior, including neutrino dispersion, time-of-flight effects, and particle-reaction kinematics.²⁸ At low energies, the observation of supernova neutrinos offers a sensitive probe of effects like neutrino dispersion due to enhancements resulting from long propagation distances. IceCube, the premier US-led neutrino telescope, has already demonstrated extreme sensitivity to Lorentz violation in neutrino oscillations.²¹ IceCube and its descendants²⁴ offer unique opportunities to probe Lorentz and CPT invariance over the extremely long baselines and very high energies afforded by astrophysical neutrinos. Further supported by an abundance of related and proposed ultrahigh-energy-neutrino observation efforts,^{29–34} the pace of activities in this field is certain to accelerate.

Beta decay. Although neutrino oscillations and high-energy astrophysical neutrinos offer remarkable sensitivities to effects of operators of mass dimension $d \geq 4$ in EFT, other Lorentz- and CPT-violating operators, called *countershaded*, are unobservable in these experiments: they leave unaffected flavor-oscillation and velocity features of neutrinos. However, they do, for example, affect the phase space available for neutrinos in the final state of nuclear reactions.^{35;36} The high precision achievable in modern beta-decay endpoint measurements seeking to determine the absolute neutrino mass scale are also ideally suited to search for such countershaded SME operators. Such particle-decay measurements have the only known experimental sensitivity to such effects, which may have escaped detection by other methods and could therefore be comparatively large. Recently published endpoint measurements by KATRIN’s first four-week science run³⁷ are poised to improve existing limits inferred from the earlier Troitsk and Mainz endpoint experiments,^{35;38} and KATRIN’s time-resolved data allows access to previously unbounded countershaded Lorentz and CPT violation.^{35;38} These developments point towards intensified activity in this field in the coming years.

Double beta decay. Countershaded SME effects can also be studied taking advantage of the striking low-background sensitivity of double beta decay experiments.³⁵ Paralleling the single beta decay signals described above, Lorentz- and CPT-violating phase-space corrections may lead to distinct distortions of a specific portion of the two-neutrino double beta decay spectrum. Moreover, the responsible operator also breaks CPT symmetry while maintaining T invariance thereby providing a new source of CP violation in the neutrino sector. Finally, the mixing between neutrinos and antineutrinos due to Lorentz violation can also trigger neutrinoless double beta decay in the absence of a Majorana mass term. These features make neutrinoless double beta decay experiments sensitive probes of Lorentz invariance and CPT symmetry,³⁵ a result recently exploited by the CUPID,³⁹ NEMO-3,⁴⁰ Aurora,⁴¹ EXO-200,⁴² and GERDA⁴³ collaborations. The high precision and low background of existing and future double beta decay experiments can utilize spectral analyzes already exploited, but also study unexplored direction-dependent effects that can be accessed via unique tracking capabilities of detectors such as SuperNEMO.⁴⁴

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