Snowmass2021 - Letter of Interest

Probes of Lorentz and CPT Symmetry with Particles and Radiation of Astrophysical Origin

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
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Abstract: Minuscule departures from Lorentz and CPT symmetry can be accommodated in various theoretical approaches to physics beyond the Standard Model and General Relativity. At attainable energies, the effective field theory description of these departures predicts symmetry-breaking signatures that include changes to the free propagation of known particles and fields—such as modified dispersion relations and polarization effects—which may either grow in importance with energy or accumulate in proportion with the path lengths traveled. The ultrahigh energies afforded by some cosmic rays and the extreme propagation distances involved in many astrophysical observations translate into a correspondingly powerful reach for Lorentz and CPT tests based on astronomical observations. With numerous observational efforts involving gravitational waves, cosmic rays, as well as astrophysical photons and neutrinos continuing to collect data in the coming decade, the cosmic frontier exhibits excellent prospects for probing regions of the parameter space for Lorentz and CPT violations that are otherwise inaccessible with conventional laboratory methods.

Introduction. Many approaches to physics beyond the Standard Model and General Relativity predict new physics associated with some large mass scale M. Phenomenological progress may then be achieved, e.g., in physical systems with characteristic energy E approaching M or in systems in which the novel phenomena are amplified. Observations of cosmological sources offer these two features due to the ultrahigh energies of certain cosmic rays and the accumulation of minute effects over astrophysical propagation distances. Thus, measurements involving such systems represent key tools for fundamental physics research.

Lorentz- and CPT-invariance studies assume particular relevance in this context: deviations from these symmetries indicate fundamentally new physics. Conversely, such deviations may be expected in approaches to new physics involving departures from the usual notions of classical spacetime structure, such as string theory.[1;2] Lorentz violation is typically reflected in modifications to the energy-momentum relations for quanta, which may affect particle reaction kinematics or lead to unconventional dispersion behavior. The visibility of the resulting effects may grow directly with particle momentum, or they may be characterized by unconventional thresholds, with reactions only occurring above certain frame-dependent energies. These reactions can therefore affect the composition, energy spectrum, and arrival times of cosmic rays, such that higher-energy observations yield increased sensitivities to Lorentz violation. The Standard-Model Extension (SME),[3;4] an effective-field-theory framework that has spawned hundreds of Lorentz and CPT tests,[5] also predicts further experimental signatures, such as ones involving polarization observables. These effects typically grow with the propagation distance L, so they can be used to place bounds proportional to $1/L$.

Gravitational waves and interactions. The growing catalogue of gravitational-wave observations provides many novel ways to test Lorentz invariance, including speed-of-gravity and waveform measurements. The observation of the binary neutron star merger in 2017 using both photons and gravitational waves was a leap forward in speed-of-gravity measurements generating a ten-order-of-magnitude improvement in sensitivity to the associated Lorentz-violating effects.[6] While impressively sensitive, it remains one measurement. Recent efforts using the propagation of gravitational waves across the Earth led to complementary breadth in these searches.[7;8] Additional observations in the coming years will lead to further improvements in both the depth and breadth of such measurements. The LIGO and Virgo Scientific Collaborations have sought dispersion of gravitational waves due to Lorentz violation in detected events.[9] These efforts will be extended much further as more events are observed and sensitivities to Lorentz violation are attained in the context of the gravitational SME.[10;11] One exciting possibility highlighted by the field-theoretic approach is that of birefringence of gravitational waves, which will be sought in this context. Another class of tests is based on the prediction that SME corrections produce observable signals in the gravitational interaction of cosmological objects. A promising idea in this context concerns pulsar-timing studies: first results are already available.[12] With upcoming observatories, such as FAST[13] and SKA,[14] as well as the demand for strong-field SME modeling, such efforts are poised for a prominent role in the future of this field.[15]

Measurements of threshold effects with quanta of astrophysical origin. Lorentz-violating changes in the energy-momentum relations for ultrahigh-energy quanta can be tested by looking at evidence from energetic cosmic rays. With the modified dispersion relations, particles that are stable at rest may be unstable above some threshold velocity, and particles that are unstable at rest may display thresholds above which they do not decay. The presence or absence of certain ultrarelativistic species among primary cosmic rays can therefore indicate whether those particles' dispersion relations behave conventionally up to the energies at which they are observed.[16–18] Moreover, for particles such as TeV photons (produced primarily by inverse Compton scattering in which highly energetic electrons upscatter low-energy photons) the experimental observations of the secondary particles can also tell us about the energy-momentum relations of the primary particles (the electrons in the inverse Compton case) that produced them.[19;20] Additionally, thanks to relativistic beaming effects, these experiments also tend to provide bounds on relatively clean combinations of the Lorentz-violating SME coefficients; all the energetic quanta involved in an observable ultrarelativistic particle-production interaction must have been moving essentially collinearly, in the direction toward the

Earth, and this sharply limits the number of Lorentz-violation coefficients that can play a role in determining the reaction kinematics. With coming upgrades to cosmic-ray observatories, such as Auger[21] and TA,[22] and planned γ-ray Cherenkov telescopes including SWGO,[23] CTA,[24] and LHAASO[25] on the horizon, major activities in all these types of experimental Lorentz- and CPT-violation studies are imminent.

Astrophysical photon propagation and polarization studies. In addition the aforementioned threshold investigations involving photons, pure photon propagation and polarization investigations also provide exceptional opportunities for measuring various Lorentz- and CPT-violating observables.[26] In the SME's photon sector, these effects are governed by a series of operators of mass dimension $d \geq 3$. The corresponding signatures typically grow with photon energy, making high-energy astrophysical sources, such as gamma-ray bursts (GRBs), particularly sensitive to many forms of Lorentz breakdown.

Dispersion effects result from operators with $d \neq 4$. The search for vacuum dispersion involves comparing arrival times of photons of different energy emitted by GRBs and other high-energy pulsed sources.[27] Since Lorentz and CPT breaking generally also includes violations of rotational invariance, the resulting vacuum dispersion is typically direction dependent. This implies that multiple sources at different locations on the sky are required to constrain fully the possible violations.

Lorentz and CPT violation can also lift the usual degeneracy between different helicities of light so that the polarization of light evolves as it travels. Astrophysical propagation distances immensely amplify this effect, permitting some of the best relativity tests in any system.[28–30] Depending on the type of Lorentz violation, such effects can be energy independent or grow with energy. In the first case, the CMB, which is the oldest light with known polarization, is an ideal source for these tests. Moreover, its full-sky coverage permits searches for anisotropies in these effects.[29] In the second case, higher-energy sources are preferable, and details of source polarization are inessential: measurements typically search for unexpected energy dependencies in the polarization. Spectropolarimetry data at the highest energies are limited, but there is evidence for polarization in GRBs leading to extremely tight SME limits.[30] The community is also eagerly awaiting the launch of NASA's IXPE,[31] XL-Calibur,[32] and COSI[33] missions. These X-ray, hard X-ray, and gamma-ray observations are uniquely positioned for setting invaluable new bounds.

Astrophysical neutrinos. One prominent example for testing dispersion-relation modifications is based on measurements with neutrino telescopes. Such measurements are capable of detecting key signatures of Lorentz violation, such as anisotropies in the flux of high-energy astrophysical neutrinos.[34] Moreover, the sole observation of high-energy events in neutrino telescopes can serve as a sensitive tool for Lorentz-symmetry studies due to the aforementioned unconventional threshold behavior.[35] At lower energies, the observation of supernova neutrinos provides a promising avenue for probing neutrino dispersion effects due to enhancements in sensitivity resulting from cosmological propagation distances. The US-led IceCube neutrino telescope has already conducted unmatched measurements of SME coefficients involving neutrino oscillations.[36] IceCube and its upgrades[37] are uniquely positioned to take advantage of the high energies and cosmological propagation distances offered by astrophysical neutrinos; these efforts are poised for great strides towards novel types of Lorentz tests and substantial improvements of past SME measurements. Major impetus on such activities also derives from numerous related and proposed observation efforts[38–42] including the US-led POEMMA space-based mission,[43] which further boost the future vitality of this field.

Multimessenger Lorentz and CPT tests. Some Lorentz- and CPT-violating free-propagation effects are known to be undetectable in single-species physics, for example those not associated with dispersion and birefringence signals. Comparisons of observables from different species, such as arrival times from two species emitted from the same event, provide an ideal measurement tool for these types of effects. It has been demonstrated that this can be successfully employed,[6;34] and with an expected surge in multimessenger data in the coming decade, tests for these kinds of Lorentz and CPT violation will unquestionably become a major focus in the field.

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