Developments in Lorentz and CPT Violation

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This talk at the CPT’19 meeting outlines a few recent developments in Lorentz and CPT violation, with particular attention to results obtained by researchers at the Indiana University Center for Spacetime Symmetries.

1. Introduction

Motivated by the prospect of minuscule observable effects arising from Planck-scale physics, searches for Lorentz and CPT violation have made impressive advances in recent years. The scope of ongoing efforts presented at the CPT’19 meeting indicates that this rapid pace of development will continue unabated, with experiments achieving sensitivities to Lorentz violation that are orders of magnitude beyond present capabilities and providing unprecedented probes of the CPT theorem. Substantial theoretical advances in the subject are also being made, and the prospects are excellent for completing a comprehensive description of possible effects on all forces and particles and for achieving a broad understanding of the underlying mathematical structure in the near future. In this talk, I summarize some basics of the subject and outline a few recent results obtained at the Indiana University Center for Spacetime Symmetries (IUCSS).

2. Basics

No compelling experimental evidence for Lorentz or CPT violation has been reported to date, so any effects are expected to involve only tiny deviations from the physics of General Relativity (GR) and the Standard Model (SM). In studying the subject, it is therefore desirable to work within a theoretical description of Lorentz and CPT violation that is both model-independent and includes all possibilities consistent with the structure of GR and the SM. The natural context for a description of this type is effective field theory. The realistic and coordinate-independent effective field theory
for Lorentz and CPT violation is known as the Standard-Model Extension (SME).\textsuperscript{3,4} It can be obtained by incorporating all coordinate-independent and Lorentz-violating terms in the action for GR coupled to the SM. These terms also describe general realistic CPT violation,\textsuperscript{3,5} and they are compatible with either spontaneous or explicit Lorentz violation in an underlying unified theory such as strings.\textsuperscript{6}

The SME action incorporates Lorentz-violating operators of any mass dimension $d$, with the minimal SME defined to include the subset of operators of renormalizable dimension $d \leq 4$. A given SME term is formed as the observer-scalar contraction of a Lorentz-violating operator with a coefficient for Lorentz violation that acts as a background coupling to control observable effects. The propagation and interactions of each species are modified and can vary with momentum, spin, and flavor. All minimal-SME terms\textsuperscript{3,4} and many nonminimal terms\textsuperscript{7–9} have been explicitly constructed. The resulting experimental signals are expected to be suppressed either directly or through a mechanism such as countershading via naturally small couplings.\textsuperscript{10} Impressive constraints on SME coefficients from many experiments have been obtained.\textsuperscript{1} The generality of the SME framework insures these constraints apply to any specific Lorentz-violating model that is consistent with realistic effective field theory.

The geometry of Lorentz violation is an interesting issue for exploration. If the Lorentz violation is spontaneous, then the geometry can remain Riemann or Riemann-Cartan\textsuperscript{4} and the phenomenology incorporates Nambu-Goldstone modes.\textsuperscript{11} However, if the Lorentz violation is explicit, then the geometry cannot typically be Riemann and is conjectured to be Finsler instead.\textsuperscript{4} Support for this idea has grown in recent years,\textsuperscript{12,13} but a complete demonstration is lacking at present.

3. Developments from the IUCSS

In the past three years, developments from the IUCSS have primarily involved the quark, gauge, and gravity sectors. In the quark sector, direct constraints on minimal-SME coefficients can be extracted using neutral-meson oscillations,\textsuperscript{14} and numerous experiments on $K$, $D$, $B_d$, and $B_s$ mixing have achieved high sensitivities to CPT-odd effects on the $u$, $d$, $s$, $c$, and $b$ quarks.\textsuperscript{15} Recent work reveals that nonminimal quark coefficients at $d = 5$ provide numerous independent measures of CPT violation,\textsuperscript{16} many of which are experimentally unconstrained to date. The $t$ quark decays too rapidly to hadronize, but $t$-$\bar{t}$ pair production and single-$t$ production
are sensitive to $t$-sector coefficients and are the subject of ongoing experimental analyses. High-energy studies of deep inelastic scattering and Drell-Yan processes also offer access to quark-sector coefficients, and corresponding data analyses are being pursued. Another active line of reasoning adapts chiral perturbation theory to relate quark coefficients to hadron coefficients, yielding further tests of Lorentz and CPT symmetry.

In the gauge sector, the long-standing challenge of constructing all non-abelian Lorentz-violating operators at arbitrary $d$ has recently been solved. The methodology yields all matter-gauge couplings, so the full Lorentz- and CPT-violating actions for quantum electrodynamics, quantum chromodynamics, and related theories are now available for exploration. Constraints on photon-sector coefficients continue to improve. Signals of Lorentz violation arising in clock-comparison experiments at arbitrary $d$ have recently been studied, revealing complementary sensitivities from fountain clocks, comagnetometers, ion traps, lattice clocks, entangled states, and antimatter. These various advances suggest excellent prospects for future searches for Lorentz and CPT violation in the gauge and matter sectors.

In the gravity sector, all operators modifying the propagation of the metric perturbation $h_{\mu\nu}$, including ones preserving or violating Lorentz and gauge invariance, have been classified and constructed. Many of the corresponding coefficients are unexplored but could be measured via gravitation-wave and astrophysical observations. A general methodology exists for analyzing Lorentz-violation searches in experiments on short-range gravity, and constraints on certain coefficients with $d$ up to eight have now been obtained. Work in progress further extends gravity-sector tests to matter-gravity couplings at arbitrary $d$. Results from the SME can also be applied to constrain hypothesized Lorentz-invariant effects whenever these lead to nonzero background values for vector or tensor objects. This idea recently yielded the first experimental constraints on all components of nonmetricity. At the foundational level, further confirmation of the correspondence between the SME and Finsler geometry has been established via the construction of all Finsler geometries for spin-independent Lorentz-violating effects. The scope and breadth of all these results augurs well for future advances in the gravity sector on both theoretical and experimental fronts.

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