Concepts in Lorentz and CPT Violation

V. Alan Kostelecký

Physics Department, Indiana University
Bloomington, IN 47405, USA

This contribution to the CPT’22 meeting provides a brief review of some concepts in Lorentz and CPT violation.

1. Introduction

In recent years, substantial advances have been made in the theory and phenomenology of Lorentz and CPT violation, driven by the intriguing possibility that experimental searches for the associated effects could uncover tiny observable signals from an underlying unified theory such as strings. This contribution to the CPT’22 proceedings summarizes a few concepts in the subject, focusing on the approach that uses effective field theory to construct a general realistic framework describing physical effects.

2. Foundations

A key property of Minkowski spacetime is its invariance under Lorentz transformations. The Lorentz transformations include spatial rotations and velocity boosts, which together can be viewed as generalized rotations in spacetime. Theories manifesting isotropy under these spacetime rotations have Lorentz invariance (LI), so a theory with Lorentz violation (LV) incorporates one or more spacetime anisotropies. Experiments testing LI seek to identify possible spacetime anisotropies by comparing physical quantities at different spacetime orientations. For example, symmetry under spatial rotations can be explored by comparing at different spatial orientations the ticking rates of two clocks or the lengths of two standard rulers.

Our most successful fundamental theories describing nongravitational aspects of Nature are constructed on Minkowski spacetime. However, the Universe contains gravitational interactions, which cannot be screened and hence are ubiquitous. Minkowski spacetime is therefore believed to be unphysical in detail, with our Universe instead involving Riemann spacetime.
or perhaps a generalization. A generic Riemann spacetime lacks global LI. Instead, the relevant spacetime symmetries are local Lorentz invariance (LLI) and diffeomorphism invariance (DI). A theory with LLI is isotropic under local spacetime rotations about every point, while one with DI is unchanged by local translations. Experiments can test these symmetries by comparing properties of objects at different orientations and locations in the neighborhood of a spacetime point.

Most experiments and observations involve only weak gravitational fields and so take place in asymptotically flat spacetime, a limit of Riemann spacetime that reduces to Minkowski spacetime for zero gravity. In asymptotically flat spacetime, the standard notion of LI turns out to be a combination of LLI and DI. Experiments searching for LV are therefore in reality sensitive to a combination of local Lorentz violation (LLV) and diffeomorphism violation (DV). The corresponding observables manifest a mixture of local spacetime anisotropy and spacetime-position dependence.

3. Theory

Since no compelling evidence for LV exists to date, a broad-based and model-independent methodology is desirable in the search for possible effects. Any violations are expected to be small corrections to the known physics of General Relativity (GR) and the Standard Model (SM), so it is natural to study LV using the approach of effective field theory. Typically, integrating over high-energy degrees of freedom in a theory generates a specific effective field theory applicable at low energies. In the context of searches for LV, however, the approach can instead be used to study simultaneously a large class of underlying theories and determine possible observable effects in a model-independent way.

The realistic coordinate-independent theory incorporating general LV that is based on GR coupled to the SM is known as the Standard-Model Extension (SME). In a realistic effective field theory, CPT violation comes with LV both in Minkowski spacetime and in asymptotically flat spacetime, so the SME also describes CPT violation in a model-independent way. The Lagrange density \( \mathcal{L} \) of the theory includes LV operators of any mass dimension \( d \), with the minimal theory defined as the subset of operators of renormalizable dimension \( d \leq 4 \). Each term in \( \mathcal{L} \) is constructed as an observer-scalar contraction of a LV operator \( O(x) \) with a coupling coefficient \( k(x) \) or its derivatives. The coefficients are expected to be suppressed either by powers of a high-energy scale such as the Planck energy or via...
a mechanism such as countershading. The explicit forms of all minimal terms and many nonminimal terms are known.

4. Backgrounds

Any given coefficient $k(x)$ in $\mathcal{L}$ can be viewed as a prescribed background in spacetime, which may arise as a vacuum expectation value of a field. All indices carried by $k(x)$ are contracted with those of the corresponding operator $\mathcal{O}(x)$, so $k(x)$ is covariant under observer local Lorentz transformations and general coordinate transformations. However, $k(x)$ is unaffected by particle local Lorentz transformations and diffeomorphisms, which act only on dynamical fields. Covariant and contravariant local indices on $k(x)$ are physically equivalent because the local metric $\eta$ is Minkowski and non-dynamical. In contrast, covariant and contravariant spacetime indices can generate physically distinct effects because the spacetime metric $g$ is dynamical. Disregarding derivatives of $k(x)$, a generic term in $\mathcal{L}$ thus takes the form $\mathcal{L} \supset k^{\mu_1 \ldots \nu_1 \ldots a_1}(x)\mathcal{O}_{\mu_2 \ldots \nu_2 \ldots a_2}(x)$, where spacetime indices are Greek and local indices are Latin. The term is LLV when $k(x)$ carries a local index and is DV when $k(x)$ carries a spacetime index or varies with $x$.

It is physically useful to distinguish two types of backgrounds $k(x)$, denoted as $\langle k \rangle$ and $k$. Spontaneous backgrounds $\langle k \rangle$ arise dynamically from solving equations of motion, so they satisfy the Euler-Lagrange equations and are thus on shell. Their dynamical origin means that small fluctuations around $\langle k \rangle$ can occur, so additional modes appear in the effective theory including Nambu-Goldstone and massive modes. Explicit backgrounds are externally prescribed and hence nondynamical. They are unconstrained by Euler-Lagrange equations and thus can be off shell, and no dynamical fluctuations occur. The spontaneous or explicit nature of the LLV and DV can be used to classify terms in $\mathcal{L}$ and determine their physical implications. The geometry of gravity is affected differently in the two scenarios. For spontaneous violation, it can remain Riemann or Riemann-Cartan. For explicit violation, in contrast, the geometry is conjectured instead to be Finsler leading to unique gravitational effects.

5. Applications

By virtue of its generality and model independence, the SME can be expected to contain the large-distance limit of any realistic theory with LV. The background coefficients affect the behavior of experimentally known
force and matter fields and hence can be used to predict possible observable signals of Lorentz and CPT violation. The physical definition of a given particle species can be affected, and both its free propagation and interactions can be modified in a flavor-dependent way. The effects can depend on the magnitude and orientation of momenta and spins and can differ between particles and antiparticles. For spontaneous LV, the dynamical fluctuations around $\langle k \rangle$ can also modify the physics and can even play the role of the photon or graviton. In any scenario, the coefficients are the targets for experimental searches. Since a coefficient changes under observer frame transformations, the inertial frame used to present results must be specified. In practice no laboratory is inertial, and the Earth’s rotation and revolution imply that LV measurements typically exhibit time variations. Instead, the canonical choice to report experimental results is the Sun-centered frame. Many experiments have achieved impressive sensitivities to coefficients expressed in this frame.

The SME framework also has applications in broader contexts. One concerns searches for new LI physics beyond GR and the SM. By virtue of its inclusion of all effective background couplings, the framework can describe physical effects from any new field producing a background over a spacetime region of experimental relevance, and hence it can be used to deduce bounds on new LI physics from existing constraints on LV. This technique has led, for example, to tight constraints on torsion and nonmetricity, and similar ideas have been adopted for spacetime-varying couplings and ghost-free massive gravity. Another application in a different context involves the description of emergent LI in certain condensed-matter systems. For example, properties of Dirac and Weyl semimetals are calculable in the SME framework. Future explorations in these and other contexts offer excellent prospects for conceptual and practical advances.

Acknowledgments

This work was supported in part by US DoE grant DE-SC0010120 and by the Indiana University Center for Spacetime Symmetries.

References

1. V.A. Kostelecký and S. Samuel, Phys. Rev. D 39, 683 (1989); V.A. Kostelecký and R. Potting, Nucl. Phys. B 359, 545 (1991); Phys. Rev. D 51, 3923 (1995).
2. See, e.g., S. Weinberg, Proc. Sci. CD 09, 001 (2009).
3. D. Colladay and V.A. Kostelecký, Phys. Rev. D 55, 6760 (1997); Phys. Rev. D 58, 116002 (1998); V.A. Kostelecký and R. Lehnert, Phys. Rev. D 63, 065008 (2001).
4. V.A. Kostelecký, Phys. Rev. D 69, 105009 (2004).
5. V.A. Kostelecký and Z. Li, Phys. Rev. D 103, 024059 (2021).
6. O.W. Greenberg, Phys. Rev. Lett. 89, 231602 (2002).
7. V.A. Kostelecký and J.D. Tasson, Phys. Rev. Lett. 102, 010402 (2009); Phys. Rev. D 83, 016013 (2011).
8. V.A. Kostelecký and M. Mewes, Phys. Rev. D 80, 056005 (2009); Phys. Rev. D 85, 096005 (2012); Phys. Rev. D 88, 096006 (2013); Y. Ding and V.A. Kostelecký, Phys. Rev. D 94, 056008 (2016).
9. V.A. Kostelecký and Z. Li, Phys. Rev. D 99, 056016 (2019).
10. Q.G. Bailey et al., Phys. Rev. D 91, 022006 (2015); V.A. Kostelecký and M. Mewes, Phys. Lett. B 757, 510 (2016); Phys. Lett. B 766, 137 (2017); Phys. Lett. B 779, 136 (2018).
11. R. Bluhm and V.A. Kostelecký, Phys. Rev. D 71, 065008 (2005); R. Bluhm et al., Phys. Rev. D 77, 065020 (2008); V.A. Kostelecký and R. Potting, Gen. Rel. Grav. 37, 1675 (2005); Phys. Rev. D 79, 065018 (2009); M.D. Seifert, Phys. Rev. D 81, 065010 (2010); B. Altschul et al., Phys. Rev. D 81, 065028 (2010).
12. Y. Nambu, Phys. Rev. Lett. 4, 380 (1960); J. Goldstone, Nuov. Cim. 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).
13. R. Bluhm, Phys. Rev. D 91, 065034 (2015); Phys. Rev. D 92, 085015 (2015); R. Bluhm and A. Sehic, Phys. Rev. D 94, 104034 (2016); R. Bluhm, H. Bossi, and Y. Wen, Phys. Rev. D 100, 084022 (2019).
14. M. Schreck, Phys. Lett. B 793, 70 (2019); B.R. Edwards and V.A. Kostelecký, Phys. Lett. B 786, 319 (2018); D. Colladay and P. McDonald, Phys. Rev. D 85, 044042 (2012); V.A. Kostelecký, Phys. Lett. B 701, 137 (2011); V.A. Kostelecký and N. Russell, Phys. Lett. B 693, 2010 (2010).
15. V.A. Kostelecký and Z. Li, Phys. Rev. D 104, 044054 (2021).
16. V.A. Kostelecký, E. Passemar, and N. Sherrill, arXiv:2207.04545.
17. V.A. Kostelecký, Phys. Rev. Lett. 80, 1818 (1998).
18. R. Bluhm et al., Phys. Rev. D 68, 125008 (2003); Phys. Rev. Lett. 88, 090801 (2002); V.A. Kostelecký and M. Mewes, Phys. Rev. D 66, 056005 (2002).
19. V.A. Kostelecký and N. Russell, arXiv:0801.0257v15.
20. R. Lehnert, W.M. Snow, and H. Yan, Phys. Lett. B 730, 353 (2014); V.A. Kostelecký, N. Russell, and J.D. Tasson, Phys. Rev. Lett. 100, 111102 (2008).
21. R. Lehnert, W.M. Snow, Z. Xiao, and R. Xu, Phys. Lett. B 772, 865 (2017); J. Foster et al., Phys. Rev. D 95, 084033 (2017).
22. V.A. Kostelecký, R. Lehnert, and M.J. Perry, Phys. Rev. D 68, 123511 (2003); V.A. Kostelecký and R. Potting, Phys. Rev. D 104, 104046 (2021).
23. V.A. Kostelecký, R. Lehnert, N. McGinnis, M. Schreck, and B. Seradjeh, Phys. Rev. Res. 4, 023106 (2022); A. Gómez, A. Martín-Ruiz, and L. Urrutia, Phys. Lett. B 829, 137043 (2022).