Tests of Lorentz symmetry

Ralf Lehnert

Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México
A. Postal 70-543, 04510 México D.F., Mexico

DOI: http://dx.doi.org/10.3204/DESY-PROC-2009-05/lehnert_ralf

A number of approaches to fundamental physics can lead to the violation of Lorentz and CPT symmetry. This talk discusses the low-energy phenomenology associated with such effects and reviews various sample experiments within this context.

Introduction.—The Standard Model (SM) and General Relativity (GR) provide and excellent phenomenological description of nature. However, from a theoretical viewpoint these two theories leave unanswered a variety of key conceptual questions. It is therefore believed that the SM and GR merge into a single unified theory at high energies that resolves these issues. One possibility for experimental research in this field is to increase the energy in experiments and hope to excite new degrees of freedom, which can give insight into such a unified theory.

A complementary experimental approach is characterized by tests at comparatively low or moderate energies, but with ultra-high precision. Various efforts along these lines, such as searches for axions, axion-like particles, weakly interacting massive particles, and weakly interacting sub-eV particles, have already been discussed at this meeting. This presentation is focused on another class of precision experiments, namely tests of Lorentz and CPT symmetry.

The special theory of relativity and its underlying Lorentz symmetry have been established over a century ago. Since that time, Lorentz symmetry has been subjected to numerous tests, but no credible experimental evidence for departures from Lorentz symmetry has been found. In fact, special relativity has matured into one of the most important cornerstones of physics. It provides not only the basis for present-day physics, but it is also the starting point for most theoretical approaches to new physics beyond the SM and GR.

In recent years, however, it has been realized that various of these approaches to new physics (although built on Lorentz invariance) can accommodate mild, minuscule deviations from this symmetry in the ground state [1]. Examples of candidate underlying models with the possibility of Lorentz violation are strings, loop quantum gravity, cosmologically varying scalars, non-commutative geometry, and multiverses [2]. A further motivation for Lorentz and CPT tests is provided by the fundamental character of these symmetries: they should be backed by experimental evidence of steadily increasing quality.

At energy regimes below the Planck scale, such departures from Lorentz and CPT symmetry can be described in great generality by the Standard-Model Extension (SME) [3]. The SME is an effective field theory that contains both the usual SM and GR. The remaining terms in the SME Lagrangian control the extent of Lorentz and CPT breakdown; they are constructed to involve all operators for Lorentz and CPT violation that are scalars under coordinate changes. This broad scope guarantees widest applicability: it eliminates the association to a particular underlying theory and ensures that practically all present and near-future experiments can be analyzed with regards to their potential to measure Lorentz and CPT symmetry. Numerous investigations have been performed within the SME [4], which confirm its sound theoretical basis. The SME has become the standard framework for the identification and analysis of a wide variety of experimental studies [1, 5]. For instance, the SME predicts modifications in one-particle dispersion relations [6], which in turn could lead to vacuum Cherenkov radiation [7]. The absence of this effect at LEP leads to tight constraints on Lorentz violation in QED [8]. For other limits in electrodynamics, see, e.g., Refs. [9, 10].

The SME test framework.—A test framework that allows for departures from Lorentz and CPT symmetry is useful for the identification and analysis of suitable experiments. Establishing such a test model requires some preliminary thoughts. One issue is the multitude of approaches to underlying physics that can lead to Lorentz and CPT violation: there is presently no single realistic candidate fundamental theory whose low-energy limit can serve as the test framework. A related difficulty is the fact that for some theories beyond the SM and GR the low-energy limit is unknown or not unique. As a consequence, the test framework will be constructed by hand with the objective of relative independence of the details of the underlying physics.

The first step is to determine how Lorentz and CPT breakdown can be implemented into the test framework. One possibility that has proved to be the most general and useful is the inclusion of preferred directions modeled by background vectors and tensors while leaving the Lorentzian structure of spacetime unaffected. This idea is compatible with the fact that most candidate underlying models take Lorentz symmetry as a key basic ingredient. Once the model's dynamics is taken as Lorentz symmetric, symmetry breaking can essentially only arise along the lines of a Lorentz-violating ground state. Moreover, this implementation of deviations from Lorentz and CPT symmetry can maintain coordinate independence, a principle more fundamental than Lorentz symmetry. An immediate consequence is that different inertial coordinate systems are still connected via the usual Lorentz transformations. Violations of the symmetry become apparent only through the physical transformations: boosts and rotations of the experimental set-up; the background vectors and tensors are outside of experimental control and remain fixed under such physical transformations.

The springboard for the construction of the SME is the SM Lagrangian $\mathcal{L}_{\rm SM}$ and the Einstein–Hilbert Lagrangian $\mathcal{L}_{\rm EH}$, which essentially contain the entire body of present-day physics. This guarantees that departures from Lorentz and CPT symmetry in all known physical systems can be described. The small Lorentz- and CPT-violating corrections $\delta\mathcal{L}_{\rm LIV}$ are formed by contracting the background vectors and tensors with ordinary SM and gravitational fields to yield scalars under coordinate changes:

$$\mathcal{L}_{\rm SME} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm EH} + \delta\mathcal{L}_{\rm LIV}\ . \qquad (1)$$

Examples of terms present in the Minkowski-spacetime limit of $\delta\mathcal{L}_{\rm LIV}$ are

$$\delta\mathcal{L}_{\rm LIV} \supset b_\mu\, \overline{\psi}\gamma^\mu\gamma_5\psi,\ (r_\mu\, \overline{\psi}\gamma^\mu\gamma_5\psi)^2,\ (k_F)^{\alpha\beta\gamma\delta}F_{\alpha\beta}F_{\gamma\delta},\ (k_{AF})^\alpha A^\beta \tilde{F}_{\alpha\beta},\ \ldots\ . \qquad (2)$$

Here, ψ, A, and F are a conventional spinor field, a conventional gauge potential, and a conventional gauge field strength, respectively. The non-dynamical b_μ, r_μ, $(k_F)^{\alpha\beta\gamma\delta}$, and $(k_{AF})^\alpha$ are minute Lorentz-violating background vectors and tensors assumed to be generated by a candidate fundamental theory. Experimental tests seek to bound or measure these vectors and tensors. We finally mention that the minimal SME (mSME) is restricted by further physical requirements, such as translational invariance, the usual gauge symmetries, and power-counting renormalizability. For example, the mSME does not contain the r_μ term present in the above expression (2).

Lorentz violation via varying scalars.—In the construction of the SME, we have included the external non-dynamical background vectors and tensors that select preferred directions by hand without reference to underlying physics. A natural question to ask is whether such Lorentz-violating preferred directions can really be generated by candidate fundamental theories. We will briefly discuss one example illustrating that this is indeed the case: varying scalars.

Many theoretical approaches to underlying physics predict novel scalar fields. In fact, certain cosmological observations, such as the flatness and the accelerated expansion of the universe, can be explained by invoking new scalars. In such cosmological contexts, scalar fields can acquire nonzero expectation values with time dependencies driven by the evolution of the scale factor. As one example, we may consider $N = 4$ supergravity in four spacetime dimensions, which contains novel axion a and dilation b fields coupled via a function $f(a, b)$ to the electromagnetic field strength. In a simple cosmological model one can determine the evolution of a and b with the comoving time t. One of the couplings to electrodynamics then generates the effective Lagrangian term $f(t)F\tilde{F}$. In a local, experimental setting, such a term would indeed be perceived as a varying coupling—in this case, as a time-dependent θ angle.

A spacetime-dependent scalar, regardless of the mechanism that causes the variation, normally implies the breakdown of spacetime-translation invariance. But also Lorentz symmetry is typically violated in such situations because the gradient of the scalar selects a preferred direction. At the formal level, this fact is intuitively reasonable: the definition of the Lorentz-transformation generators contains the energy–momentum tensor, which is now no longer conserved. Thus, the usual time-independent boost and rotation generators no longer exist. To see this explicitly in our toy supergravity model, we can perform an integration by parts in the action:

$$f(t)F\tilde{F} \to -2\,(\partial^\alpha f)\, A^\beta \tilde{F}_{\alpha\beta}\ . \tag{3}$$

The cosmological background $f(t)$ is essentially outside of experimental control for the purposes of local measurements, so $\partial^\alpha f$ can be taken as non-dynamical. If we identify $-2\,(\partial^\alpha f)$ with $(k_{AF})^\alpha$ in Eq. (2), we explicitly see how this Lorentz- and CPT-violating Chern–Simons-type correction [9] can be generated by underlying physics.

Experimental tests.—Since Lorentz symmetry underpins many areas and concepts in physics, it can be tested in a multitude of physical systems. The tests with the best potential for highest sensitivity can be identified and analyzed with the SME. We briefly discuss three sample tests.

The first example concerns an astrophysical search for the Cherns–Simons-type term (3) mentioned earlier. A theoretical analysis of this term reveals that it causes birefringence. Even the smallest birefringence effects would accumulate for light that has traveled a sufficiently large distance. It is therefore unsurprising that the best experimental constraints on this particular type of Lorentz- and CPT-violation have been obtained from observations of cosmological sources. One predicted effect would be following. Suppose an astrophysical source is emitting flashes of light containing all polarizations. En route to Earth, such a pulse would separate because one of its two components travels faster than the other due to birefringence. A somewhat more sophisticated and sensitive approach is to observe a cosmological object known to emit a spectrum of mostly polarized light and measure the polarization of this light as a function of its wavelength at Earth. For birefringence due to a Chern–Simons-type interaction (3), this function should display a predicted characteristic. Such analyses have indeed been performed, and no such characteristic was found. This implies the bound $(k_{AF})^\alpha < 10^{-43}\,\text{GeV}$ [9, 10].

The second sample Lorentz test involves (anti)protons in Penning traps. The basic idea is as follows. The Lorentz-violating preferred background directions act in many respects just like external fields. In conventional physics, such external fields can cause level shifts in bound systems like atoms (e.g., the Zeeman and Stark effects). Calculations within the SME reveal that Lorentz and CPT breakbown would cause similar level shifts for charges in Penning traps, for example. More precisely, the anomaly transitions would acquire opposite corrections for protons and their antiparticles. This fact can be employed to extract clean experimental limits on the b^μ coefficient (see expession (2)) for the proton with a sensitivity of about 10^{-24} GeV [11].

In the experimental investigations discussed above, gravitational effects could be neglected and the flat-spacetime limit of the SME was considered. However, tests involving gravity have recently been one focus of attention [12, 13]. In particular, antimatter, such as antihydrogen, offers the possibility of testing Lorentz and CPT symmetry in the SME's gravity sector. For instance, the acceleration of antihydrogen in the Earth's gravitational field could be investigated [13]. We also note that in gravitational contexts, various SME coefficients that are inaccessible in the flat-spacetime limit now become measurable [13].

Acknowledgments.—The author wishes to thank Jörg Jäckel for the invitation to this stimulating meeting. This work is supported by CONACyT under Grant No. 55310.

References

[1] For recent reviews of various ideas in the subject see, e.g., V.A. Kostelecký, ed., *CPT and Lorentz Symmetry I-IV*, World Scientific, Singapore, 1999-2008; R. Bluhm, Lect. Notes Phys. **702**, 191 (2006) [hep-ph/0506054].

[2] See, e.g., V.A. Kostelecký and S. Samuel, Phys. Rev. D **39**, 683 (1989); V.A. Kostelecký and R. Potting, Nucl. Phys. B **359**, 545 (1991); J. Alfaro, H.A. Morales-Técotl, and L.F. Urrutia, Phys. Rev. Lett. **84**, 2318 (2000); S.M. Carroll *et al.*, Phys. Rev. Lett. **87**, 141601 (2001); V.A. Kostelecký, R. Lehnert, and M.J. Perry, Phys. Rev. D **68**, 123511 (2003); O. Bertolami *et al.*, Phys. Rev. D **69**, 083513 (2004); J.D. Bjorken, Phys. Rev. D **67**, 043508 (2003); N. Arkani-Hamed *et al.*, JHEP **0701**, 036 (2007).

[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); V.A. Kostelecký, Phys. Rev. D **69**, 105009 (2004); V.A. Kostelecký and M. Mewes, Phys. Rev. D **80**, 015020 (2009).

[4] See, e.g., R. Jackiw and V.A. Kostelecký, Phys. Rev. Lett. **82**, 3572 (1999); V.A. Kostelecký *et al.*, Phys. Rev. D **65**, 056006 (2002); B. Altschul and V.A. Kostelecký, Phys. Lett. B **628**, 106 (2005); R. Lehnert, J. Math. Phys. **45**, 3399 (2004); Phys. Rev. D **74**, 125001 (2006); arXiv:0711.4851 [hep-th]; A.J. Hariton and R. Lehnert, Phys. Lett. A **367**, 11 (2007).

[5] V.A. Kostelecký and N. Russell, arXiv:0801.0287 [hep-ph].

[6] R. Lehnert, Phys. Rev. D **68**, 085003 (2003).

[7] R. Lehnert and R. Potting, Phys. Rev. Lett. **93**, 110402 (2004); Phys. Rev. D **70**, 125010 (2004).

[8] M.A. Hohensee *et al.*, Phys. Rev. Lett. **102**, 170402 (2009); Phys. Rev. D **80**, 036010 (2009).

[9] S.M. Carroll, G.B. Field, and R. Jackiw, Phys. Rev. D **41**, 1231 (1990).

[10] V.A. Kostelecký and M. Mewes, Phys. Rev. Lett. **99**, 011601 (2007); M. Mewes, Phys. Rev. D **78**, 096008 (2008).

[11] R. Bluhm, V.A. Kostelecký, and N. Russell, Phys. Rev. D **57**, 3932 (1998).

[12] Q.G. Bailey and V.A. Kostelecký, Phys. Rev. D **74**, 045001 (2006); H. Müller *et al.*, Phys. Rev. Lett. **100**, 031101 (2008); J.B.R. Battat, J.F. Chandler, and C.W. Stubbs, Phys. Rev. Lett. **99**, 241103 (2007); Q.G. Bailey, Phys. Rev. D **80**, 044004 (2009).

[13] V.A. Kostelecký and J. Tasson, Phys. Rev. Lett. **102**, 010402 (2009).