Abstract

An important open question in fundamental physics concerns the nature of spacetime at distance scales associated with the Planck length. The widespread belief that probing such distances necessitates Planck-energy particles has impeded phenomenological and experimental research in this context. However, it has been realized that various theoretical approaches to underlying physics can accommodate Planck-scale violations of spacetime symmetries. This talk surveys the motivations for spacetime-symmetry research, the SME test framework, and experimental efforts in this field.

Keywords: quantum-gravity phenomenology, Lorentz violation, CPT violation, low-energy precision tests

1. Introduction

Spacetime plays a fundamental role in science: it not only provides the arena in which physical processes take place, but it also exhibits its own dynamics. Like many other basic physical entities, spacetime is, at least partially, characterized by its underlying symmetries. The continuous ones of these symmetries comprise four spacetime translations and six Lorentz transformations (three rotations and three boosts), which are intertwined in the Poincaré group. Because of its fundamental importance, various aspects of Poincaré invariance have been tested in the past century with no credible experimental evidence for deviations from this symmetry. It is fair to say that Poincaré invariance (and in particular Lorentz symmetry) has acquired a venerable status in physics.

Nevertheless, the last decade has witnessed a renewed interest in spacetime-symmetry physics for various reasons. First, the quantum structure of spacetime is likely to be no longer a smooth four-dimensional manifold. This suggests that Planck-suppressed deviations from the usual four-dimensional classical Poincaré symmetry could be a promising quantum-gravity signature. Indeed, many leading theoretical approaches to unify quantum physics and gravity, such as string theory [1], spacetime foam [2], non-commutative field theories [3], and cosmological supergravity models [4], can accommodate minute departures from relativity theory. Second, varying couplings (which break translation symmetry) driven by scalar fields are natural in many theoretical models beyond established physics [5]. Moreover, there have been recent experimental claims of a spacetime-dependent fine-structure parameter α [6].

To identify and analyze suitable experiments that can provide ultra-sensitive tests of Lorentz invariance, an effective field theory called the Standard-Model Extension (SME) has been developed [7]. The SME essentially contains the entire body of established physics in the form of the Lagrangians for the usual Standard Model and general relativity. This fact guarantees that practically all physical systems can be investigated with regards to their potential to test...
Lorentz symmetry. The description of Lorentz violation is achieved with additional lagrangian terms that are formed by covariant contraction of conventional fields with background vectors or tensors assumed to arise from underlying physics. These nondynamical vectors or tensors represent the SME coefficients controlling the nature and size of potential violations of Lorentz symmetry. The set of all such correction terms leads to the full SME [8], whereas the subset of relevant and marginal operators results in the minimal SME (mSME).

Most recent experimental investigations of Lorentz invariance have been performed within the mSME. Specific studies include, for instance, ones with photons [9, 10], neutrinos [11], electrons [12], protons and neutrons [13], mesons [14], muons [15], and gravity [16]. Several of the obtained experimental limits exhibit sensitivities that can be regarded as testing Planck-scale physics. A tabulated overview of tests and their results can be found in Ref. [17]. No solid experimental evidence for deviations from Lorentz symmetry has been found to date, but discovery potential might exist in neutrino physics [18].

The outline of this presentation is as follows. In Sec. 2, various spacetime symmetries are reviewed with particular focus on their interplay. Section 3 presents the basic ideas and the philosophy that underpin the construction of the SME. Three examples for mechanisms that can generate Lorentz-invariance breakdown in Lorentz-symmetric underlying models are contained in Sec. 4. Section 5 describes some experimental Lorentz tests in different physical systems. A brief summary is given in Sec. 6.

2. Spacetime symmetries and relations between them

In conventional nongravitational physics, the four spacetime translations (i.e., three spatial translations and one time translation) form an exact symmetry and therefore lead to the conservation of 4-momentum. One mathematical condition for translation invariance is the absence of explicit spacetime dependencies in the Lagrangian. But it is known that various theoretical approaches to physics beyond the Standard Model can lead to varying couplings. It follows that in such approaches translation symmetry is typically be violated. This idea is presently also attracting attention because of observational claims of a varying $\alpha$, as mentioned in the introduction.

Suppose translation symmetry is indeed broken. It is then natural to ask whether other symmetries, and in particular Lorentz invariance, can be affected. To answer this question, we start by looking at the generator for Lorentz transformations, which is the angular-momentum tensor $J^{\mu\nu}$:

$$J^{\mu\nu} = \int d^3 x \left( \Theta^{\mu} x^\nu - \Theta^{\nu} x^\mu \right).$$

Here, $\Theta^{\mu\nu}$ denotes the energy–momentum tensor, which is associated with spacetime translations. Since translation do not represent a symmetry in the present context, $\Theta^{\mu\nu}$ is now no longer conserved. As a consequence, $J^{\mu\nu}$ will typically become spacetime dependent in models with varying couplings. In particular, the usual spacetime-independent Lorentz-transformation generators cease to exist. It follows that exact Lorentz invariance is not guaranteed. We conclude that (with the exception of special circumstances) translation-symmetry violation leads to Lorentz-invariance breakdown.

Let us continue along this hypothetical avenue and suppose Lorentz symmetry is broken. Together with locality, quantum mechanics, and a few other mild conditions, Lorentz symmetry is a key ingredient for the celebrated CPT theorem discovered by Bell, Lüders, and Pauli over half a century ago. Now, the question arises whether the absence of Lorentz symmetry would affect CPT invariance. Unfortunately, there is no clear-cut answer to this question. For example, in the SME to be discussed in the next section, about half of the relevant and marginal operators for Lorentz breaking also violate CPT symmetry. However, we may also consider a slightly different question and ask which one of the ingredients for the CPT theorem should be dropped, if we want to investigate CPT violation. Clear is that not all of the assumptions for the CPT theorem can survive simultaneously because this would exclude CPT breaking.

The answer to this question is largely dependent on the physics causing CPT breakdown. A general and mild assumption is that the low-energy leading-order effects of new physics are describable by a local effective field theory: such theories represent an immensely flexible framework, and they have been successful in various subfields of physics including solid-state, nuclear, and particle physics. In such a context, it appears unavoidable that the property of exact Lorentz invariance needs to be relaxed. This expectation can be proven rigorously in axiomatic quantum field theory [19, 20]. This result, sometimes called “anti-CPT theorem,” roughly states that in any unitary, local, relativistic
point-particle field theory CPT breakdown comes with Lorentz violation. However, as we have noted above, the converse of this statement (i.e., Lorentz breaking implies the loss of CPT symmetry) is false in general. It is thus apparent that under the above general and plausible assumption, CPT tests also probe Lorentz invariance. We note that other types of CPT breaking resulting from apparently non-unitary quantum mechanics have also been discussed in the literature [21].

3. Building the SME

To study the low-energy effects of Lorentz and CPT violation, both theoretically and phenomenologically, a comprehensive test framework is needed. Early test models for special relativity were seeking to parametrize deviations from the Lorentz transformations. Examples of models of this type are Robertson’s framework [22], its Mansouri–Sexl extension [23], and the $c^2$ model [24]. More recently, also other, quantum-gravity motivated approaches, such as phenomenologically constructed modified one-particle dispersion relations, have been considered. These models have in common that they focus solely on kinematical deviations from Lorentz symmetry. This often provides the advantage of conceptual simplicity when applied to experimental situations. On the other hand, their behavior under the CPT transformation is typically unclear. Moreover, the absence of dynamics implies that only a limited range of tests can be identified and analyzed. The SME, already mentioned in the introduction, has been developed to avoid these issues. This section describes the cornerstones on which the SME test framework has been constructed.

We begin by reasoning in support of a test model that describes dynamical in addition to kinematical physics properties. It is true that a certain set of kinematical laws may be compatible with various dynamical models suggesting a larger degree of generality. Nevertheless, the dynamics of realistic models is restricted by the condition that established physics must emerge under certain conditions. In addition, it appears difficult if not impossible to create a framework for deviations from Lorentz symmetry that contains the usual Standard Model while at the same time possessing dynamics that is substantially different from that of the SME to be discussed below. Finally, most potential signals for Lorentz and CPT violation involve some kind of dynamics, or are incomplete without additional dynamical checks, as mentioned above. For these reasons, it seems advantageous to have at one’s disposal a fully dynamical test framework for Lorentz and CPT violation.

Construction of the SME. To appreciate the generality of the SME, we briefly describe the philosophy and main ideas behind its construction [7, 8]. The starting point for establishing the SME is the entire body of known physics in the form of the conventional Standard-Model and Einstein–Hilbert Lagrangians $L_{SM}$ and $L_{EH}$, respectively. To implement Lorentz and CPT violation, the most general set of lagrangian correction terms $\delta L_{LV}$ (compatible with otherwise desirable features) is then included:

$$L_{SME} = L_{SM} + L_{EH} + \delta L_{LV}.$$  \hspace{1cm} (2)

In the above equation, the SME Lagrangian is denoted by $L_{SME}$. The terms $\delta L_{LV}$ describing the nature and extent of Lorentz and CPT breakdown can in principle be of any mass dimensionality. They are built by covariant contraction of Standard-Model and gravitational fields with Lorentz-breaking tensorial coefficients yielding scalars, which ensures coordinate independence. The nondynamical tensorial coefficients represent a nontrivial vacuum with background vectors or tensors, which violate Lorentz symmetry and in some cases also CPT invariance. These background vectors and tensors are assumed to be generated by more fundamental physics, such as quantum-gravity models. It then becomes apparent that the entire set of possible contributions to $\delta L_{LV}$ yields the most general effective field theory of leading-order Lorentz violation at the level of an observer Lorentz-invariant unitary Lagrangian.

Examples of terms contained in the flat-spacetime limit of the SME are the following:

$$\delta L_{LV} \supset b^\mu \bar{\psi} \gamma_\mu \gamma_5 \psi, \quad (r^\mu \bar{\psi} \gamma_5 \gamma_\mu \psi)^2, \quad (kF)^{\alpha \beta \gamma} \bar{F}_{\alpha\beta} F_{\gamma\delta} + \frac{1}{4} \epsilon_{\alpha\beta\gamma\delta} (kF)^{\gamma} A^\alpha F^\beta \delta \delta.$$ \hspace{1cm} (3)

In these expressions, $\psi$, $F$, and $A$ denote a conventional spinor field and a conventional gauge field strength, and a conventional gauge potential respectively. The quantities $b^\mu$, $r^\mu$, and $(kF)^{\alpha \beta \gamma}$ are SME coefficients controlling the size and type of Lorentz violation. They are taken as caused by underlying physics, perhaps by some quantum-gravity model. An experiment would seek to measure or constrain these coefficients. The mSME mentioned in
the introduction is restricted by further physical requirements, such as translational invariance, and power-counting renormalizability. For instance, the mSME does not contain the $\rho^\mu$ term shown in the above expression \( \text{[1]} \).

We note in passing that in a curved-manifold context involving gravitational physics, this idea is most easily implemented utilizing the vierbein formalism. A key result in this context is that explicit Lorentz violation typically results in an incompatibility between the Bianchi identities and the covariant conservation laws for the energy–momentum and spin-density tensors. However, a spontaneous breakdown of Lorentz invariance avoids this issue, so that some type of dynamical symmetry violation is favored for generating SME coefficients. Examples of such mechanisms are given in the next section. Two consequences for the present discussion are that when gravity cannot be neglected, SME coefficients would need to exhibit a certain spacetime dependence as dictated by compatibility, and new degrees of freedom may occur.

The SME is flexible enough to incorporate additional potential features of new physics, such as non-pointlike elementary excitations or a fundamental discreteness of spacetime at the Planck scale. It is therefore improbable that the above effective-field-theory approach is insufficient at currently attainable energies. One may even argue that presently established physics (i.e., the Standard Model and general relativity) is also regarded as a low-energy effective description of underlying physics. It would then seem surprising if potential Lorentz-violating effects from such underlying physics could not also be described within effective field theory. We finally remark that the requirement for a low-energy description outside the framework of effective field theory is difficult to imagine for new physics with novel Lorentz-invariant features, such as further particle species or scalar fields, new symmetries, or additional spacetime dimensions. Notice in particular that Lorentz-symmetric modifications can therefore easily be included into the SME, if it becomes necessary \( \text{[23]} \).

**Benefits of the SME.** The SME permits the identification, analysis, and direct comparison of practically all currently feasible experiments that can search for deviations from Lorentz and CPT invariance. In certain limiting cases of the SME, one can recover classical kinematics test models of special relativity (such as the aforementioned framework by Robertson, its Mansouri–Sexl extension to arbitrary clock synchronizations, or the \( c^2 \) model) \( \text{[8, 26]} \). An additional advantage of the SME is the flexibility of including further desirable features besides coordinate independence. For instance, it is possible to impose spacetime-translation invariance (at least in the flat-spacetime limit), SU(3)$\times$SU(2)$\times$U(1) gauge invariance, power-counting renormalizability, unitarity, and locality. These additional features put further constraints on the parameter space for Lorentz and CPT violation. Another possibility is to make simplifying choices, such as a residual rotational invariance in certain classes of inertial coordinate systems. For example, the latter hypothesis together with additional simplifications of the SME has been considered in some investigations \( \text{[27]} \).

**Consistency of the SME.** Thus far, we have reviewed just the general idea for building the SME framework. One may also inquire about its theoretical consistency. To date, there have been a number of more formal and theoretical investigations within the SME. They have addressed subjects such as radiative corrections \( \text{[28]} \), renormalizability \( \text{[29]} \), supersymmetry \( \text{[23]} \), causality \( \text{[30]} \), kinematics \( \text{[31]} \), symmetry studies \( \text{[32]} \), higher-derivative terms \( \text{[33]} \), gravity \( \text{[34]} \), and mathematical studies \( \text{[35]} \). None of these investigations has found inconsistencies or other difficulties that would render the SME unsuitable for describing Lorentz and CPT violation.

**4. Generating Lorentz breakdown.**

Thus far, we have examined how the breakdown of one spacetime symmetry can also lead to the violation of another spacetime invariance, and we have constructed by hand a low-energy effective description for such effects. Another key question concerns actual mechanisms within theoretical approaches to physics beyond the Standard Model that can lead to symmetry breaking in the first place. In the present section, we set out to address this question by providing some intuition regarding possible sources for Lorentz violation in candidate fundamental models. A number of possible mechanisms have already been mentioned in the introduction. Here, we will discuss three of them—spontaneous Lorentz breakdown, Lorentz violation through varying couplings, and non-commutative field theory—in some more detail.

**Spontaneous Lorentz and CPT violation.** The mechanism of spontaneous symmetry breakdown is well established in various subfields of physics. For example, it can occur in the physics of elastic media and in condensed-matter physics. This mechanism is also part of the Standard Model of particle physics. From a theoretical point of view,
this mechanism is quite appealing because of the following. In many circumstances, the internal consistency of a QFT requires the presence of a symmetry. However, the symmetry is not observed in nature. Spontaneous symmetry violation resolves such situations: The dynamical underpinnings of the model remain symmetric, which ensures consistency. On the other hand, the ground-state solution (which essentially corresponds to the observed physical system) fails to exhibit the full symmetry of the model.

The key ingredient for spontaneous symmetry breakdown is an interaction that destabilizes the naive vacuum and triggers a vacuum expectation value. This can, for instance, be achieved with a potential-energy term in the Lagrangian. As an example consider a Higgs-type field \( \varphi \) whose expression for the potential-energy density is given by \( V(\varphi) = g(\varphi^2 - \lambda^2)^2 \). Here, \( \lambda \) and \( g \) are constants. We note in passing that a possible spacetime dependence \( \varphi = \varphi(x) \) would result in additional, positive-valued contributions to the energy density, which permits us to focus solely on a constant \( \varphi \). The basic idea now is that the vacuum is usually taken as the state with the lowest energy. The lowest-energy configuration requires \( \varphi \) to be nonzero: \( \varphi = \pm \lambda \). As a consequence, the physical vacuum for a system involving a Higgs-type field \( \varphi \) is not empty; it contains, in fact, the condensate of the spacetime-constant scalar field \( \varphi_{\text{vac}} \equiv \langle \varphi \rangle = \pm \lambda \neq 0 \), where \( \langle \varphi \rangle \) denotes the vacuum expectation value (VEV) of \( \varphi \). It is important to notice that \( \langle \varphi \rangle \) is a Lorentz scalar, and thus it does not select a preferred direction in spacetime leaving Lorentz symmetry intact.

This situation changes when the scalar field \( \varphi \) is replaced by a vector or tensor field. For simplicity, let us consider a 3-vector field \( \vec{R} \) as an example \([34]\). The relativistic generalization to 4-vectors or 4-tensors is relatively simple. Neither the \( \vec{R} \) field nor its relativistic generalizations are present in the Standard Model, and there is currently no experimental evidence for such types of field. Nevertheless, additional vector fields like \( \vec{R} \) are contained in numerous candidate fundamental theories. Paralleling the previous Higgs-type case, we posit the following the expression for the energy density of \( \vec{R} = \text{const.} \):

\[
V(\vec{R}) = (\vec{R}^2 - \lambda^2)^2.
\]

We see that the lowest possible energy associated with the vacuum state is zero. As in the previous \( \varphi \)-field example, this lowest energy requires \( \vec{R} \) to be nonzero: \( \vec{R}_{\text{vac}} \equiv \langle \vec{R} \rangle = \lambda \), where \( \lambda \) is any constant vector satisfying \( \vec{R}^2 = \lambda^2 \).

Again, the vacuum does not stay empty; it actually contains the VEV of the vector field, \( \langle \vec{R} \rangle \). It follows that the true vacuum in the above model possesses an intrinsic direction given by \( \langle \vec{R} \rangle \). The point is that such an intrinsic direction violates rotation symmetry and therefore Lorentz invariance. We remark that interactions generating energy densities like those in Eq. (4) are absent in conventional renormalizable gauge theories, but they may occur in the context of string field theory, for example.

**Spacetime-dependent scalars.** A spacetime-dependent scalar, such as a cosmologically varying coupling typically leads to the breakdown of spacetime-translation invariance \([4]\), regardless of the mechanism causing this dependence. Since a fundamentally varying scalar violates translation invariance, it will typically also break Lorentz symmetry, as was explained in Sec. 2. Here, we will focus on an explicit example for this effect.

Consider a physical system with a varying coupling denoted by \( \xi(x) \) and two scalar fields \( \phi \) and \( \Phi \). Suppose further that the Lagrangian \( L \) contains a kinetic-type interaction of the form \( \xi(x) \partial^\mu \phi \partial_\mu \Phi \). Under mild assumptions, one may integrate by parts the action associated with this Lagrangian (for example with respect to the first partial derivative in the above term) without any change in the equations of motion. An equivalent Lagrangian \( L' \) is then given by

\[
L' \supset -K^\mu \phi \partial_\mu \Phi.
\]

Here, \( K^\mu(x) \equiv \partial^\mu \xi(x) \) is an external nondynamical 4-vector. It is apparent that this 4-vector selects a preferred direction in spacetime, which violates Lorentz invariance. We note that for variations of \( \xi(x) \) on cosmological scales, \( K^\mu \) is approximately spacetime constant locally (e.g., on solar-system scales) to an excellent approximation.

Intuitively, the violation of Lorentz invariance as a result of a varying scalar can be visualized as follows. The 4-gradient of the varying scalar must clearly be nonzero—at least in some spacetime region. Otherwise, the scalar would be constant. This 4-gradient then picks out a preferred direction in this region, as is illustrated in Fig. 1. Consider, for instance, a particle that exhibits certain interactions with the varying scalar. Its propagation properties might be affected differently in the directions parallel and perpendicular to the gradient. But directions that are physically inequivalent must lead to rotation-symmetry breaking. Because rotations are contained in the Lorentz group, Lorentz symmetry must be broken.

**Non-commutative field theory.** An approach to quantum gravity that has been gaining popularity for some time now is non-commutative field theory. Roughly speaking, the basic idea is to achieve some description of a quantum
vacuum with varying scalar

\[ K^\mu(x) \equiv \partial^\mu \xi(x) \]

Figure 1: Lorentz-invariance violation via varying scalars. The background shading of gray represents the magnitude of the scalar: the darker regions correspond to larger values of the scalar. The black arrows represent the gradient \( K^\mu(x) \equiv \partial^\mu \xi(x) \) of the scalar, which determines a preferred direction in spacetime. It follows that Lorentz invariance is violated.

spacetime by promoting coordinates to operators: \( x^\mu \rightarrow \hat{x}^\mu \). As a result, the \( \hat{x}^\mu \) no longer commute; they obey the relation

\[ [\hat{x}^\mu, \hat{x}^\nu] = i\theta^\mu\nu. \tag{6} \]

Here, \( \theta^\mu\nu \) is a spacetime constant tensor. As such, \( \theta^\mu\nu \) selects preferred directions in spacetime violating Lorentz symmetry. To see explicitly this violation, the theory must be interpreted properly. It turns out that in some circumstances a model on a non-commutative spacetime can be mapped to a quantum field theory on conventional Minkowski space. This procedure generates lagrangian terms like \( \theta^\alpha\beta F^\alpha_\mu F^\beta_\nu \), which are present in the SME [3]. It thus becomes apparent that non-commutative field theories provide a third mechanism that can lead to Lorentz breakdown describable within the SME.

5. Testing Lorentz violation

Because operators of all mass dimensionalities are allowed in the full SME, an infinite number of Lorentz- and CPT-breaking coefficients arise. However, in an effective quantum field theory one might generically expect the relevant and marginal operators to dominate in the low-energy limit. As mentioned in the introduction, the restriction to this subset of SME operators is referred to as the mSME. This section contains a brief overview of a representative sample of experimental efforts that are primarily concerned with mSME coefficients.

**Kinematical tests with particle collisions.** A widely known effect of Lorentz breakdown is the modification of one-particle dispersion relations. Such modified dispersion relations would generate corrections in the energy–momentum conservation equations in particle collisions. We remark in passing that the flat-spacetime mSME coefficients are taken as spacetime constant, so translational symmetry, and thus energy–momentum conservation, still hold. The Lorentz-violating corrections to the collision kinematics could, for example, cause the following effects: reaction thresholds may be shifted, reactions kinematically forbidden in Lorentz-symmetric physics may now occur, and certain conventional reactions may no longer be allowed kinematically.

Consider, for instance, the spontaneous emission of a photon from a free charge. In ordinary physics, the conservation of energy and momentum does not permit this process to occur. Nevertheless, certain types of Lorentz and CPT violation can cause the speed of light to be slower relative to the speed of, say, electrons. In analogy to conventional Cherenkov radiation (when light propagates slower inside a macroscopic medium with refractive index \( n > 1 \)), free electrons can now emit Cherenkov photons in a Lorentz- and CPT-breaking vacuum [27, 10]. This so-called “vacuum Cherenkov effect” may or may not exhibit a threshold depending on the type of mSME coefficient. In what follows, we consider mSME coefficients that lead to a threshold for vacuum Cherenkov radiation. In this case, one can extract an observational limit on the size of these mSME coefficients, as we will describe next. Electrons propagating faster than the modified speed of light would slow down and fall below threshold through energy loss due to the emission of

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1Contrary to our earlier remarks in Sec. 3, the Lorentz violation is explicit at this level. However, non-commutativity with the effective description 6 can also be generated dynamically in underlying physics.
vacuum Cherenkov radiation. We can then conclude that if highly energetic stable electrons exist in nature, they cannot be above threshold. This information gives a lower bound for the threshold, which in turn yields a limit on Lorentz violation. Using, in this context, data from LEP electrons with energies up to 104.5 GeV determines the constraint $k_\text{th} - \frac{1}{c^{\text{th}}_0} \lesssim 1.2 \times 10^{-11}$ [37]. Here, $k_\text{th}$ and $c^{\text{th}}_0$ parametrize the isotropic, polarization-independent, mass-dimension four SME operators for the photon and the electron, respectively.

We next consider the decay of photons in vacuum. This is another particle reaction process not allowed kinematically by energy–momentum conservation in conventional physics. However, certain combinations of mSME coefficients can cause light to travel faster than the maximal attainable speed of electrons. In analogy to the vacuum-Cherenkov case discussed above, in which high-energy electrons become unstable, we expect now that high-energy photons can become unstable against decay into an electron–positron pair. With the modified dispersion relations emerging from the mSME, one can indeed confirm that this expectation is met. As in the case of the vacuum Cherenkov effect, photon decay in a Lorentz-breaking vacuum often occurs above a threshold, and it can then be used to determine an observational constraint on this particular type of Lorentz violation. The reasoning is as follows. Suppose high-energy stable photons are observed. They must then essentially be below the threshold for photon decay. This implies that the threshold energy must lie above the energy of these stable photons. This bound on the threshold energy can be converted into a constraint on the size of the corresponding type of Lorentz breakdown. Stable photons with energies up to 300 GeV were observed at the Tevatron. In this case, our reasoning yields the limit $-5.8 \times 10^{-12} \lesssim k_\text{th} - \frac{1}{c^{\text{th}}_0}$ [37].

We remark that the above bounds assume that the rates for both vacuum Cherenkov radiation and photon decay are sufficiently fast. The purely kinematical reasoning we have presented above is by itself inadequate for conservative experimental constraints. This goes hand in hand with the discussion in Sec. 3 arguing that a dynamical framework is desirable, and the full mSME (not only the predicted modified dispersion relations) are required. Appropriate studies within the mSME indeed show that the rates for vacuum Cherenkov radiation and photon decay would be efficient enough to validate the above arguments [38, 39, 37].

**Spectropolarimetry of cosmological sources.** There is one vectorial coefficient in the mSME’s photon sector that breaks both Lorentz and CPT symmetry. The corresponding operator is of mass dimension three, and its structure is that of a Chern–Simons interaction. It is parametrized by a background 4-vector usually denoted $(k_{AF})^\mu$. Among the physical effects caused by the $(k_{AF})^\mu$ operator is birefringence of electromagnetic waves [40], vacuum Cherenkov radiations [10], as well as certain frequency shifts in cavities [41]. These effects absent in known physics are amenable to experimental inquiries. Birefringence studies of electromagnetic radiation from cosmological sources are particularly well suited to search for this term: the extremely long propagation distance directly converts into ultrahigh sensitivity to this type of Lorentz and CPT violation. Spectropolarimetric investigations of astrophysical data have established an upper bound on $(k_{AF})^\mu$ at the level of $10^{-42} \ldots 10^{-43}$ GeV [38, 40].

**Spectroscopy of cold antihydrogen.** Comparative spectroscopy of hydrogen (H) and antihydrogen (H) is an excellent test of Lorentz and CPT breakdown. There are various transitions that can be studied. One of these is the unmixed 1S–2S transition, which appears to be an attractive candidate: the projected experimental sensitivity for this line is expected to be approximately at the level of $10^{-18}$. This sensitivity is promising in light of the anticipated Planck-scale suppression of quantum-gravity effects. However, an mSME study at first order in Lorentz and CPT violation predicts the same shifts for free H and H in the initial and final levels with respect to the usual energy states. From this perspective, the 1S–2S transition is actually less useful for the determination of unsuppressed Lorentz- and CPT-violating effects. Within the mSME, the leading non-trivial correction to this transition is generated by relativistic effects, and it enters with two further powers of the fine-structure parameter $\alpha$. The predicted modifications in the transition energy, already expected to be minuscule at zeroth order in $\alpha$, come therefore with a further suppression factor of more than ten thousand [42].

Another spectral line that can be utilized for Lorentz and CPT tests is the spin-mixed 1S–2S transition. When H or H is confined in an electromagnetic trap, such as a Ioffe–Pritchard trap, the 1S and the 2S levels are each split as a consequence of the usual Zeeman effect. An mSME calculation for this case then shows that the 1S–2S transition between the spin-mixed levels is indeed affected by Lorentz and CPT breakdown at leading order. A drawback from a practical viewpoint is the dependence of this transition on the magnetic field inside the trap, so that the experimental sensitivity is limited by the size of the inhomogeneity of the trapping field $B$. The development of novel experimental techniques might circumvent this problem, and a frequency resolutions close to the natural linewidth might then be achievable [43].
A third transition that is attractive for Lorentz- and CPT-violation studies is the hyperfine Zeeman transition within the $1S$ state itself. Even in the limit of a vanishing $\vec{B}$ field, mSME calculations show that there are first-order level shifts in two of the transitions between the Zeeman-split states. We note that this result may also be beneficial from an experimental point of view because a variety of other transitions of this type, like the conventional H-maser line, can be well resolved in the laboratory.

**Experiments in Penning traps.** The mSME predicts not only that atomic energy levels can be shifted by the presence of Lorentz and CPT violation, but also, for example, the levels of protons and antiprotons inside a Penning trap. A perturbative calculation shows that only a single mSME coefficient (a CPT-violating $b^\mu$-type background vector, which is coupled to the chiral current of a fermion) affects the transition-frequency shifts in the proton case differently from those in the antiproton case at leading order. To be more specific, the anomaly frequencies are shifted in opposite directions for protons and their antiparticles. This effect can be utilized to extract a clean experimental constraint on the proton’s $b^\mu$ coefficient $[13]$. 

**Neutral-meson interferometry.** A well established and widely known CPT-invariance test compares the K-meson’s mass to that of the corresponding antimeson: even tiny mass differences would give measurable effects in Kaon-interferometry experiments. In spite of the fact that the mSME contains only a single mass operator for a given quark–antiquark species, particle and antiparticle are nevertheless affected differently by the Lorentz- and CPT-violating background in the mSME. This generates different dispersion relations for a meson and its antimeson, so that mesons and antimesons can exhibit distinct energies at equal 3-momenta. It is this energy split that would ultimately be responsible for interferometric signals, and it is therefore potentially observable in meson oscillations $[14]$. We note that not only the K-meson but also other neutral mesons can be studied. Notice in particular that in addition to CPT violation, Lorentz breaking is involved as well, so that boost- and rotation-dependent effects can be searched for.

**Low-energy precision tests with neutrons.** Another particle that offers excellent possibilities for ultra-high-sensitivity measurements is the neutron. Experimental difficulties that would arise from its instability can be avoided by performing measurements with bound neutrons. Such measurements have placed limits down to $10^{-33}$ GeV on certain Lorentz- and CPT-violating neutron coefficients of the mSME $[13]$. A drawback of tests with bound neutrons is that the primary source for theoretical errors is due to nuclear modeling. Experiments with free neutrons are therefore of interest as well. The first such experiment consisted of Larmor-frequency measurements with ultracold neutrons by the nEDM collaboration. This test has placed the bound of $10^{-29}$ GeV on Lorentz- and CPT-violation of the neutron $[13]$. Although of less sensitivity, this experimental constraint provides a supplementary and much cleaner measurements.

6. Summary

At the present time, no convincing experimental evidence for Lorentz or CPT breakdown exists. Nevertheless, various approaches to more fundamental physics (e.g., quantum-gravity models) contain mechanisms for generating feeble violations of Lorentz, CPT, and translational invariance. In this talk, a brief survey of the motivations, theoretical ideas, and experimental efforts in the field of spacetime-symmetry tests has been presented.

We have explained that a quantum description of the dynamics of spacetime is likely to require new spacetime concepts: the smooth-manifold picture may have to be abandoned at Planck-size distance scales. Among the many possible observational signals for such a quantum spacetime, symmetry considerations are particularly promising for two reasons. First, symmetries are perhaps the only feature of a putative quantum nature of spacetime amenable to Planck-precision tests at the present time. Second, theoretical models can accommodate departures from spacetime symmetries, which we have exemplified by spontaneous symmetry breakdown in string field theory, varying scalars, and non-commutative geometry.

At energies that can currently be reached in experiments, general Lorentz- and CPT-violating effects can be described by an effective field theory known as the SME. This framework incorporates practically all of established physics (i.e., the Standard Model and general relativity), so that the Lorentz- and CPT-violating properties of essentially all physical systems can be studied, at least in principle. The SME coefficients for Lorentz and CPT breakdown are given by externally prescribed non-dynamical background vectors and tensors that are presumed to be caused by underlying physics.

Spacetime symmetries provide the basis for a wide variety of physical effects. For this reason, Lorentz and CPT tests can be performed in a broad range of physical systems. This fact, together with the availability of the modern
SME test framework and encouraging motivations for Lorentz and CPT violations has resulted in the recent rise in experimental interest in the field. We have reviewed a representative sample of experimental efforts along these lines including dispersion-relation analyses, spectropolarimetry of cosmological sources, and low-energy ultrahigh-precision laboratory studies.

A number of important open questions remain in this subject. They are of foundational, of phenomenological, and of observational nature; they provide ample ground for future research in the field of spacetime-symmetry physics.

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