This proceedings contribution summarizes recent investigations of Lorentz violation in matter-gravity couplings.

1. Introduction

In spite of the many high-sensitivity investigations of Lorentz violation performed in the context of the fermion sector of the minimal Standard-Model Extension (SME) in Minkowski spacetime, only about half of the coefficients for Lorentz violation in that sector have been investigated experimentally. Reference establishes a methodology for obtaining sensitivities to some of these open parameters by considering gravitational couplings in the fermions sector of the SME, extending pure gravity work. Of particular interest are the coefficients for baryons and charged leptons, which are unobservable in principle in Minkowski spacetime, but could be relatively large due to gravitational countershading.

The first half of Ref. develops the necessary theoretical results for the analysis of Lorentz violation in matter-gravity couplings. Those results are summarized in Sec. below, while Sec. summarizes the experimental predictions provided in the second half of that work.

2. Theory

The theoretical portion of Ref. addresses a number of useful conceptual points prior to developing the necessary results for experimental analysis. This includes a discussion of the circumstances under which relevant types of Lorentz violation are observable in principle. It turns out that the coefficient, which can be removed from the single fermion theory in Minkowski
spacetime via a spinor redefinition cannot typically be removed in the presence of gravity. This makes it an interesting case for study in the remainder of Ref. 3. A coordinate choice that can be used to fix the sector of the theory that defines isotropy is also discussed and ultimately used to take the photon sector to have $\eta_{\mu\nu}$ as the background metric.

Another issue is the development of general perturbative techniques to treat the fluctuations in the coefficient fields in the context of matter-gravity couplings. Two notions of perturbative order are introduced. One, denoted $O(m, n)$, tracks the orders in Lorentz violation and in gravity, where the first entry represents the order in the coefficients for Lorentz violation and the second represents the order in the metric fluctuation $h_{\mu\nu}$. The secondary notion of perturbative order, denoted PNO($p$), tracks the post-newtonian order. The goal of Ref. 3 is to investigate dominant Lorentz-violating implications in matter-gravity couplings, which are at $O(1,1)$.

Reference 3 provides the necessary results to analyze experiments at a variety of levels while working toward the classical nonrelativistic equations of motion, which are most relevant for many of the experiments to be considered. Development of the quantum theory of the gravity-matter system provides the first step. Starting from the field-theoretic action, the relativistic quantum mechanics in the presence of gravitational fluctuations and Lorentz violation is established after investigating methods of identifying an appropriate hamiltonian in the presence of an effective inverse vierbein $E_\mu^0$. The explicit form of the relativistic hamiltonian involving all coefficients for Lorentz violation in the minimal QED extension is provided. Attention is subsequently specialized to the study of spin-independent Lorentz-violating effects, which are governed by the coefficient fields $(a_{\text{eff}})_\mu$, $c_{\mu\nu}$ and the metric fluctuation $h_{\mu\nu}$. Analysis then proceeds to the nonrelativistic quantum hamiltonian via the standard Foldy-Wouthuysen procedure.

While the quantum mechanics above is useful for analysis of quantum experiments, most measurements of gravity-matter couplings are performed at the classical level. Thus the classical theory associated with the quantum-mechanical dynamics involving nonzero $(a_{\text{eff}})_\mu$, $c_{\mu\nu}$, and $h_{\mu\nu}$ is provided at leading order in Lorentz violation both for the case of the fundamental particles appearing in QED and for bodies involving many such particles. These results enable the derivation of the modified Einstein equation and the equation for the trajectory of a classical test particle. Solving for the trajectory requires knowledge of the coefficient and metric fluctuations. A systematic methodology for calculating this information is provided, and general expressions for the coefficient and metric fluctuations...
to $O(1,1)$ in terms of various gravitational potentials and the background coefficient values $(\tau_{\text{eff}})_\mu$ and $\tau_{\mu\nu}$ are obtained. Bumblebee models are considered as an illustration of the general results.

3. Experiments

A major class of experiments that can achieve sensitivity to coefficients $(\tau_{\text{eff}})_\mu$ and $\tau_{\mu\nu}$ involve laboratory tests with ordinary neutral matter. Tests of this type are analyzed via the PNO(3) lagrangian describing the dynamics of a test body moving near the surface of the Earth in the presence of Lorentz violation. The analysis reveals that the gravitational force acquires tiny corrections both along and perpendicular to the usual free-fall trajectory near the surface of the Earth, and the effective inertial mass of a test body becomes a direction-dependent quantity. Numerous laboratory experiments sensitive to these effects are considered. The tests can be classified as either gravimeter or Weak Equivalence Principle (WEP) experiments and as either force-comparison or free-fall experiments for a total of 4 classes.

Free-fall gravimeter tests monitor the acceleration of freely falling objects and search for the characteristic time dependence associated with Lorentz violation. Falling corner cubes and matter interferometry provide examples of such experiments and are discussed in Ref. 3. Force-comparison gravimeter tests using equipment such as superconducting gravimeters are also studied. Note that the distinction, force comparison versus free fall, is important due to the potential Lorentz-violating misalignment of force and acceleration. Making direct use of the flavor dependence associated with Lorentz-violating effects implies signals in WEP tests. A variety of free-fall WEP tests are considered including those using falling corner cubes, atom interferometers, tossed masses, balloon drops, drop towers, and sounding rockets along with force-comparison WEP tests with a torsion pendulum. For all of the tests considered, the possible signals for Lorentz violation are decomposed according to their time dependence, and estimates of the attainable sensitivities are obtained.

Satellite-based WEP tests which offer interesting prospects for improved sensitivities to Lorentz violation, are also discussed in detail. The signal is decomposed by frequency and estimated sensitivities are obtained.

The experimental implications of Lorentz violation in the gravitational couplings of charged particles, antimatter, and second- and third-generation particles are also studied. These tests are experimentally challenging, but can yield sensitivities to Lorentz and CPT violation that are otherwise difficult or impossible to achieve. Possibilities including charged-particle in-
terferometry, ballistic tests with charged particles, gravitational experiments with antihydrogen and signals in muonium free fall are discussed. Simple toy models are used to illustrate some features of antihydrogen tests.

Solar-system tests of gravity including lunar and satellite laser ranging tests and measurements of the precession of the perihelion of orbiting bodies are also considered. The established advance of the perihelion for Mercury and for the Earth is used to obtain constraints on combinations of $(\pi_{\text{eff}})_{\mu}, \pi_{\mu\nu}$, and $\pi_{\mu\nu}$, which provides the best current sensitivity to $(\pi_{\text{eff}})_{J}$.

A final class of tests involves the interaction of photons with gravity. Signals arising in measurements of the time delay, gravitational Doppler shift, and gravitational redshift, are considered along with comparisons of the behaviors of photons and massive bodies. Implications for a variety of existing and proposed experiments and space missions are considered.

Existing and expected sensitivities from the experiments and observations summarized above are collected in Tables XIV and XV of Ref. 3. These sensitivities reveal excellent prospects for using matter-gravity couplings to seek Lorentz violation. The opportunities for measuring the countershaded coefficients $(\pi_{\text{eff}})_{\mu}$ are particularly interesting in light of the fact that these coefficients typically cannot be detected in nongravitational searches. Thus the tests proposed in Ref. 3 offer promising new opportunities to search for signals of new physics, potentially of Planck-scale origin.

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