Antimatter, the SME, and gravity

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Abstract A general field-theoretic framework for the analysis of CPT and Lorentz violation is provided by the Standard-Model Extension (SME). This work discusses a number SME-based proposals for tests of CPT and Lorentz symmetry, including antihydrogen spectroscopy and antimatter gravity tests.

Keywords Antimatter · Lorentz violation · Gravity

1 Introduction

The Standard Model of particle physics along with General Relativity provide an excellent description of known physics. As a foundational principle of each of our best theories, Lorentz symmetry, along with the associated CPT symmetry [1], should be well tested experimentally. It is also likely that the Standard Model and General Relativity are limits of a more fundamental theory that provides consistent predictions all the way to the Planck scale. A technically feasible means of searching for potential suppressed signals from a complete theory at the Planck scale is provided by tests of CPT and Lorentz symmetry [2]. A comprehensive test framework for searching for such potential signals across all areas of known physics is provided by the SME [3, 4].
2 Theory

The basic theory relevant for the discussion to follow is the QED extension limit of the gravitationally coupled SME [4]. Schematically, the action for the theory can be written

\[ S = S_\psi + S_A + S_{\text{gravity}}. \]  

(1)

The first term here is the gravitationally coupled fermion sector, the second is the photon sector, and the final term is the pure-gravity sector. Each of the above terms consists of known physics, followed in general by all Lorentz-violating terms. Here we consider what is known as the minimal SME, which is the restriction to operators of dimension 3 and 4.

The minimal fermion-sector action can be written

\[ S_\psi = \int d^4x \left( \frac{1}{2} i e e^\mu_a \bar{\psi} \Gamma^a D_\mu \psi - e \bar{\psi} M \psi \right), \]  

(2)

where

\[ \Gamma^a = \gamma^a - c_{\mu\nu} e^{\nu a} e^\mu_b \gamma^b - d_{\mu\nu} e^{\nu a} e^\mu_b \gamma^5 \gamma^b - e_{\mu} e^{\mu a} \gamma^a - f_{\mu} e^{\mu a} \gamma^5 \gamma^a + \frac{1}{2} g_{\lambda\mu\nu} e^{\nu a} e^\mu_b \epsilon^{bce}, \]  

(3)

\[ M = m + a_\mu e^\mu_a \gamma^a + b_\mu e^\mu_a \gamma_5 \gamma^a + \frac{1}{2} H_{\mu\nu} e^\mu_a e^\nu_b \sigma^{ab}, \]  

(4)

and \( a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}, e_\mu, f_\mu, g_{\lambda\mu\nu}, H_{\mu\nu} \) are coefficient fields for Lorentz violation. Couplings to gravity occur here via the vierbein \( e^\mu_a \) and contributions to the covariant derivative. The form of the Minkowski-spacetime fermion-sector action can be recovered by taking the limit \( e^\mu_a \to \delta^\mu_a \).

The action \( S_A \) provides the photon sector. It contains Maxwell electrodynamics followed in the minimal case by Lorentz-violating terms of dimension 3 and 4, though operators of arbitrary dimension have now been classified, and numerous new experimental proposals associated with them have been made [5]. Though generically of considerable interest, the explicit form of \( S_A \) is omitted here since it is not directly relevant for the discussion to follow.

The minimal contributions to the pure-gravity sector take the form

\[ S = \frac{1}{2\kappa} \int d^4x \left( R - u R + s^{\mu\nu} R^T_{\mu\nu} + t^{\lambda\mu\nu} C_{\kappa\lambda\mu\nu} \right), \]  

(5)

where \( R^T_{\mu\nu} \) is the traceless Ricci tensor, and \( C_{\kappa\lambda\mu\nu} \) is the Weyl tensor. The standard Einstein-Hilbert action is provided by the first term. The coefficient field \( s^{\mu\nu} \) in the third term is responsible for the relevant Lorentz-violating signals in the post-Newtonian analysis [6]. The fourth term provides no contributions in the post-Newtonian analysis, while the second term is not Lorentz violating.

The Minkowski-spacetime limit of action (1) forms the basis of the discussion of nongravitational tests in Section 3. Here the pure-gravity sector action (5) is irrelevant and gravitational couplings in the fermion-sector action (2) can be neglected. Relevant theoretical techniques for the analysis of a variety of experiments...