Searches for Lorentz and CPT Violation with Confined Particles

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An overview of recent progress on searches for Lorentz- and CPT-violating signals with confined particles and antiparticles in Penning traps is presented. In the context of the Standard-Model Extension (SME), leading-order shifts in the cyclotron and anomaly frequencies of a confined particle and antiparticle due to Lorentz and CPT violation are provided. The two frequencies are then related to comparisons of charge-to-mass ratios and magnetic moments between particles and antiparticles. Applying reported results from Penning-trap experiments leads to new limits on various coefficients for Lorentz violation.

1. Introduction

Penning traps have in recent years provided a powerful tool to precisely measure and compare fundamental properties between particles and antiparticles. For example, the comparison of charge-to-mass ratios between protons and antiprotons has recently reached a precision of 16 ppt by the BASE collaboration at CERN.1 The same group has also measured the magnetic moments of protons and antiprotons to a precision of 0.3 ppb and 1.5 ppb, respectively.2,3 The impressive high sensitivities achieved by Penning-trap experiments offer an excellent opportunity to test fundamental symmetries of Einstein’s General Relativity and the Standard Model of particle physics, such as Lorentz and CPT symmetry. In recent years, it has been shown that tiny violations of Lorentz and CPT symmetry can appear in a more fundamental theory of quantum gravity, such as strings.4 The comprehensive framework to study all possible Lorentz violation is the Standard-Model Extension (SME),5 constructed by adding all possible Lorentz-violating terms to the action of General Relativity and the Standard Model. Each Lorentz-violating term in the SME is formed by contracting a Lorentz-violating operator with a corresponding coefficient.
that controls the size of Lorentz violation. The subset of the SME that restricts to operators of mass dimensions $d \leq 4$ is called the minimal SME, while the nonminimal SME focuses on operators of mass dimensions $d > 4$, which can be viewed as higher-order corrections to the minimal SME. In a general effective field theory, any CPT violation comes with violation in Lorentz symmetry, so the SME also characterizes all possible CPT violation. Over the past few decades, high-precision experiments across a large range of subfields of physics, including Penning traps, have been performed to provide striking limits on coefficients for Lorentz violation in different SME sectors.

2. Theory

In a Lorentz-invariant case, for a single charged Dirac fermion of species $w$, charge $q$, and mass $m_w$ confined in a Penning trap with a magnetic field strength $B$, its charge-to-mass ratio and $g$ factor (which is directly related to the magnetic moment) are related to two frequencies, the cyclotron frequency $\omega_c$ and the Larmor spin precession frequency $\omega_L$, given by

$$\frac{|q|}{m_w} = \frac{\omega_c}{B}, \quad \frac{g}{2} = \frac{\omega_L}{\omega_c} = 1 + \frac{\omega_a}{\omega_c},$$

(1)

where the difference $\omega_a = \omega_L - \omega_c$ is the anomaly frequency. In the presence of Lorentz and CPT violation, the energy levels of the fermion could be modified due to contributions from Lorentz-violating operators. As a result, both the cyclotron frequency $\omega_c$ and anomaly frequency $\omega_a$ could be shifted. In a reference frame with its positive $z$ axis chosen to be aligned with the direction of the magnetic field used in the trap, the leading-order contributions to $\omega_a$ and $\omega_c$ from Lorentz and CPT violation are given by

$$\delta\omega_c^w = \left( \frac{1}{m^2_w} \tilde{b}^{33}_{w} - \frac{1}{m_w} (\tilde{c}^{00}_w + \tilde{c}^{11}_w + \tilde{c}^{22}_w) - (\tilde{b}^{113}_{w} + \tilde{b}^{223}_{w}) \right) \frac{|q|}{B},$$

$$\delta\omega_a^w = 2\tilde{b}^{33}_{w} - 2\tilde{b}^{33}_{F,w} B,$$

(2)

where the tilde coefficients are different combinations of the fundamental coefficients for Lorentz violation, defined in Refs. 9 and 10. The corresponding results of frequency shifts for an antifermion $\bar{w}$ can be obtained by reversing the signs of all the CPT-odd coefficients for Lorentz violation in the definitions of the tilde quantities.

We note that obtaining the frequency shift results in the Sun-centered frame, the standard canonical frame where the coefficients for Lorentz violation are assumed to be constant, requires a transformation matrix involving
3. Applications

In a Penning-trap experiment, the comparison of the charge-to-mass ratios between a particle and an antiparticle is related to the difference in the shifts of their cyclotron frequencies by

$$\frac{|q|/m \omega_w}{|q|/m \omega_w} = 1 \leftrightarrow \frac{\omega_w}{\omega_w} - 1 = \frac{\delta \omega_w}{\omega_w}. \quad (3)$$

From the above result, the tilde coefficients for Lorentz violation that are relevant to the comparison are $\tilde{b}_{3w}$, $\tilde{b}_{3w}^{*}$, $\tilde{b}_{3w}^{F,w}$, and $\tilde{b}_{3w}^{F,w}$. For the proton and antiproton charge-to-mass ratio comparison, the BASE collaboration achieved a precision of 69 ppt in 2015. Therefore, an improvement of a factor of 4 for the constraints on the coefficients listed in Table 1 and Table 2 in Ref. 13 is expected. While for the electron-positron charge-to-mass ratio comparison, a group at the University of Washington reached a precision of 130 ppb. Following a similar analysis as in the proton sector, the reported precision leads to various limits on the coefficients for Lorentz violation in the electron sector, listed in Table 3 in Ref. 13.

The particle-antiparticle $g$ factor comparisons are related to the shifts in both the cyclotron and anomaly frequencies, given by

$$\frac{1}{2}(g_w - g_w) \leftrightarrow \frac{\omega_w}{\omega_w} = \frac{\delta \omega_w}{\omega_w}$$

This shows that the corresponding tilde coefficients for Lorentz violation are $\tilde{b}_{3w}$, $\tilde{b}_{3w}^{*}$, $\tilde{b}_{3w}^{F,w}$, and $\tilde{b}_{3w}^{F,w}$. In the proton sector, the current best measurement of the magnetic moment for the proton and antiproton were both obtained by the BASE collaboration, with a sensitivity of 0.3 ppb and 1.5 ppb, respectively. Combining the two reported results and applying the relevant transformation matrices, another set of tilde coefficients for Lorentz violation was constrained, included in Table 4 in Ref. 13. In the electron sector, the comparison of the anomaly frequencies between electrons and positrons was carried out at the University of Washington, with

in general the sidereal frequency of the Earth, the local sidereal time, the colatitude of the laboratory, and a suitable set of Euler angles.$^{9,11}$
The results of the limits on the tilde coefficients for Lorentz violation from this experiment were presented in Table 5 in Ref. 13. Also, a sidereal-variation analysis of the electron anomaly frequencies was also carried out at Harvard University. This gives constraints on additional coefficients for Lorentz violation that cannot be accessed by a direct anomaly frequency comparison. The related results were also listed in Table 5 in Ref. 13.

In summary, Penning-trap experiments provide highly precise measurements of fundamental properties of confined particles to test Lorentz and CPT symmetry and offer excellent coverage of the coefficients for Lorentz violation. They continue to provide strong motivations to search for possible Lorentz- and CPT-violating signals.

Acknowledgments

This work was supported in part by the W.M. Keck Science Department at Claremont McKenna, Pitzer, and Scripps Colleges.

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