The CPT theorem has been tested to very high precision in a variety of experiments involving particles and antiparticles confined within Penning traps. These tests include comparisons of anomalous magnetic moments and charge-to-mass ratios of electrons and positrons, protons and antiprotons, and hydrogen ions and antiprotons. We present a theoretical analysis of possible signals for CPT and Lorentz violation in these systems. We use the framework of Colladay and Kostelecký, which consists of a general extension of the $SU(3) \times SU(2) \times U(1)$ standard model including possible CPT and Lorentz violations arising from spontaneous symmetry breaking at a fundamental level, such as in string theory. We work in the context of an extension of quantum electrodynamics to examine CPT and Lorentz tests in Penning traps. Our analysis permits a detailed study of the effectiveness of experimental tests of CPT and Lorentz symmetry performed in Penning traps. We describe possible signals that might appear in principle, and estimate bounds on CPT and Lorentz violation attainable in present and future experiments.

1 Introduction

The CPT theorem and Lorentz symmetry have both been tested to very high accuracy in a variety of physical systems. Papers presented at this meeting have described experiments in astrophysical, nuclear, particle, and atomic systems, all of which provide very stringent bounds on possible CPT or Lorentz breaking. To date, the best bound on CPT has been obtained in particle-physics experiments involving neutral kaons. Since different particle sectors are largely independent, it is important to consider possible CPT and Lorentz breaking in all particle sectors, including mesons, leptons, baryons, and gauge bosons. While kaon experiments clearly provide the best test of CPT in the meson sector, it is interesting to note that the sharpest tests of CPT breaking in both the lepton and baryon systems have not been obtained in high-energy particle experiments. Instead, low-energy experiments on single isolated particles in Penning traps have yielded the best bounds on CPT in the lepton and baryon sectors. These experiments involve comparisons of electrons and positrons, protons and antiprotons, and hydrogen ions and antiprotons.

One consequence of CPT invariance is that particles and antiparticles have equal charge-to-mass ratios and gyromagnetic ratios. Experiments in Penning traps are ideally suited for making very precise comparisons of these quantities. A Penning trap captures a single charged particle in the cavity between
two cap electrodes and a ring electrode. The electrodes are charged and create a quadrupole electric field. A static magnetic field is created using external current coils. A charged particle in the trap is bound due to the combination of the static electric and magnetic fields. By nesting two Penning traps, particles and antiparticles can be probed and quickly switched in the same magnetic field, but with the electric field reversed. The dominant structure of the energy levels for spin-$\frac{1}{2}$ particles at low temperature is that of relativistic Landau levels, with two ladders of energies for the two spin states. Transition frequencies between these levels can be measured with very high precision.

Typically, two types of frequency comparisons of particles and antiparticles are possible in Penning traps. They involve making accurate measurements of the cyclotron frequency $\omega_c$ (for transitions between Landua levels with no spin flip) and the anomaly frequency $\omega_a$ (for transitions between Landau levels accompanied by a spin flip) of single isolated particles confined in the trap. The first type of experiment is an anomalous magnetic moment or $g - 2$ experiment. These compare the ratio $2\omega_a/\omega_c$ for particles and antiparticles. In the context of conventional quantum electrodynamics, this ratio equals $g - 2$ for the particle or antiparticle. The second type of experiment compares values of $\omega_c \sim q/m$, where $q > 0$ is the magnitude of the charge and $m$ is the mass. These therefore involve comparisons of the charge-to-mass ratios for the particle and antiparticle.

Both $g - 2$ and charge-to-mass ratio experiments have been performed with electrons and positrons. With protons and antiprotons, however, only charge-to-mass ratio comparisons have been performed. Because the magnetic moments of protons and antiprotons are much weaker than those of electrons and positrons, $g - 2$ experiments with protons and antiprotons require much lower temperatures and greater sensitivity for detecting spin-flip transitions. Although these $g - 2$ experiments with protons and antiprotons have not been performed to date some suggestions for making these experiments feasible in the future exist in the literature.

To compare the sensitivities of CPT tests in Penning traps with those in the meson system, we list some of the relevant figures of merit. The conventional figure of merit in the neutral kaon system is given by

$$r_K \equiv \frac{|m_K - m_{\bar{K}}|}{m_K} \lesssim 2 \times 10^{-18},$$

whereas for $g - 2$ experiments with electrons and positrons, electron-positron charge-to-mass ratio experiments, and charge-to-mass ratio experiments with protons and antiprotons, respectively, the conventional figures of merit are
Recently, an experiment comparing the cyclotron frequencies of hydrogen ions \( H^- \) and antiprotons has been performed in a Penning trap. This experiment has the advantage that both particles in the trap have the same electric charge, thereby reducing systematic errors associated with reversing the sign of the electric field. An improved charge-to-mass ratio comparison for protons and antiprotons has been obtained from these results, which is given by

\[
r_m^p \equiv \frac{|(q_p/m_p) - (q_{\bar{p}}/m_{\bar{p}})|}{|q/m|_{\text{avg}}} \lesssim 1.5 \times 10^{-9}.
\]

Measurements of frequencies in Penning traps typically have parts-per-billion (ppb) accuracies, which are four or five orders of magnitude better than the measurements made in kaon experiments. This raises some interesting questions concerning the sensitivity of these experiments to different possible types of CPT breaking. One goal of this work is to understand the Penning-trap experiments better and to address the question of why they do not provide sharper tests of CPT. To accomplish this, we must work in the context of a theoretical framework that permits CPT breaking. Such a framework has been developed by Colladay and Kostelecký.

In the following sections, the parts of the framework providing an extension of quantum electrodynamics are described, and the results of our theoretical analysis of CPT and Lorentz tests in Penning traps are presented. In particular, we analyze the \( g - 2 \) experiments on electrons and positrons, charge-to-mass ratio experiments on protons and antiprotons, and comparisons of cyclotron frequencies for \( H^- \) and antiprotons. Since the framework we use includes both a CPT-violating sector and a CPT-preserving sector (both of which violate Lorentz symmetry) in addition to investigating the sensitivity of Penning-trap experiments to CPT, we also examine how these experiments test CPT-preserving Lorentz symmetry.
2 Theoretical Framework

The theoretical framework of Colladay and Kostelecký is an extension of the $SU(3) \times SU(2) \times U(1)$ standard model. It originates from the idea of spontaneous CPT and Lorentz breaking in a more fundamental theory. This type of CPT violation is a possibility in string theory because the usual axioms of the CPT theorem do not apply to extended objects like strings. In a theory with spontaneous symmetry breaking, the dynamics of the action remains CPT invariant, which means the framework can preserve desirable features of quantum field theory such as gauge invariance, power-counting renormalizability, and microcausality. CPT and Lorentz violation occurs only in the solutions of the equations of motion. This mechanism is similar to the spontaneous breaking of the electroweak theory in the standard model.

In our analysis of Penning-trap experiments, we use a restriction of the full particle-physics framework to quantum electrodynamics. The effects of possible CPT and Lorentz violation in this context lead to a modification of the Dirac equation. The modified form (in units with $\hbar = c = 1$) is given by

$$(i\gamma^\mu D_\mu - m - a_\mu \gamma^\mu - b_\mu \gamma^5 \gamma^\mu - \frac{1}{2} H_{\mu\nu} \sigma^{\mu\nu} + ic_{\mu\nu} \gamma^\mu D^\nu + id_{\mu\nu} \gamma^5 \gamma^\mu D^\nu)\psi = 0.$$  \hspace{1cm} (6)$$

Here, $\psi$ is a four-component spinor, $A_\mu$ is the electromagnetic field, $iD_\mu \equiv i\partial_\mu - qA_\mu$ is the covariant derivative, and $a_\mu$, $b_\mu$, $H_{\mu\nu}$, $c_{\mu\nu}$, $d_{\mu\nu}$ are the parameters describing possible violations of CPT and Lorentz symmetry. The terms involving $a_\mu$, $b_\mu$ break CPT and those involving $H_{\mu\nu}$, $c_{\mu\nu}$, $d_{\mu\nu}$ preserve CPT, while all five terms break Lorentz symmetry.

Since no CPT or Lorentz breaking has been observed in experiments to date, the quantities $a_\mu$, $b_\mu$, $H_{\mu\nu}$, $c_{\mu\nu}$, $d_{\mu\nu}$ must all be small. We can estimate the suppression scale for these quantities by taking the scale governing the fundamental theory as the Planck mass $m_{Pl}$ and the low-energy scale as the electroweak mass scale $m_{ew}$. The natural suppression scale for Planck-scale effects in the standard model would then be of order $m_{ew}/m_{Pl} \approx 3 \times 10^{-17}$. If instead, we consider the electron mass scale as the low-energy scale, we obtain $m_e/m_{Pl} \approx 5 \times 10^{-23}$. Since a more fundamental theory (which would determine these parameters more precisely) remains unknown, these ratios give only an approximate indication of the suppression scale.

We use this theoretical framework to analyze comparative tests of CPT and Lorentz symmetry on particles and antiparticles in Penning traps. Some technical issues include the following. First, the time-derivative couplings in Eq. 6 alter the standard procedure for obtaining a hermitian quantum-mechanical hamiltonian operator. To overcome this, we perform a field redefinition at the
lagrangian level that eliminates the additional time derivatives. Second, to obtain a hamiltonian for the antiparticle, we use charge conjugation to find the Dirac equation describing the antiparticle. Perturbative calculations can then be carried out for both the particle and antiparticle, and the leading-order effects of CPT and Lorentz breaking can be obtained.

3 Electron-Positron Experiments

Experiments testing CPT in the electron-positron system compare cyclotron frequencies $\omega_c$ and anomaly frequencies $\omega_a$ of particles and antiparticles in a Penning trap. A result of the CPT theorem is that electrons and positrons of opposite spin in a Penning trap with the same magnetic fields but opposite electric fields should have equal energies. The experimental relations $g - 2 = 2\omega_a/\omega_c$ and $\omega_c = qB/m$ provide connections to the quantities $g$ and $q/m$ that appear in the figures of merit $r^c_g$ and $r^c_{q/m}$. Calculations are performed using Eq. 107 to obtain possible shifts in the energy levels due to either CPT-breaking or CPT-preserving Lorentz violation. The effectiveness of Penning-trap experiments on electrons and positrons as tests of both CPT-breaking and CPT-preserving Lorentz violation can then be analyzed. From the calculated energy shifts we determine how the frequencies $\omega_c$ and $\omega_a$ are affected and whether the conventional figures of merit are appropriate.

The dominant contributions to the energy of an electron or positron in a Penning trap come from interactions with the constant magnetic field of the trap. Interactions with the quadrupole electric field generate smaller effects. In a perturbative treatment, the dominant CPT- and Lorentz-breaking effects can therefore be obtained by working with the relativistic Landau levels as unperturbed states. Conventional perturbations, such as the usual corrections to the anomalous magnetic moment, do not break CPT or Lorentz symmetry and are the same for electrons and positrons. Any violations of CPT or Lorentz symmetry result in either differences between electrons and positrons or in unconventional effects such as diurnal variations in measured frequencies.

Our calculations show that the leading-order corrections to the energies $E^e_{n,s}$ for the electron and $E^{e^+}_{n,s}$ for the positron due to the effects of CPT and Lorentz violation are

$$
\delta E^e_{n,\pm 1} \approx a^e_0 \pm b^e_1 - c^e_{00}m_e \pm d^e_{30}m_e \pm H^e_{12}
- \frac{1}{2}(c^e_{00} + c^e_{11} + c^e_{22})(2n + 1 \pm 1)\omega_c .
$$

(7)

$$
\delta E^{e^+}_{n,\pm 1} \approx -a^{e^+}_0 \pm b^{e^+}_1 - c^{e^+}_{00}m_e \pm d^{e^+}_{30}m_e \pm H^{e^+}_{12}
- \frac{1}{2}(c^{e^+}_{00} + c^{e^+}_{11} + c^{e^+}_{22})(2n + 1 \mp 1)\omega_c .
$$

(8)
From these we find the modified transition frequencies including the leading-order effects of CPT and Lorentz breaking. These are given by

\[ \omega_e^\pm \approx \omega_c^\pm \approx (1 - c_{00} - c_{11} - c_{22}) \omega_c, \]  
(9)

\[ \omega_a^\pm \approx \omega_a \pm 2b_3^e + 2d_{30}^e m_e + 2H_{12}^c. \]  
(10)

Here, \( \omega_c \) and \( \omega_a \) represent the unperturbed electron or positron frequencies, while \( \omega_e^\pm \) and \( \omega_a^\pm \) denote the frequencies including corrections. Superscripts have been added to the parameters \( b_\mu \), etc. to denote that they describe the electron-positron system.

From these relations we find the electron-positron differences for the cyclotron and anomaly frequencies to be

\[ \Delta \omega_e^c \equiv \omega_e^- - \omega_c^+ \approx 0, \]  
(11)

\[ \Delta \omega_a^c \equiv \omega_a^- - \omega_a^+ \approx -4b_3^e. \]  
(12)

In the context of this framework, comparisons of cyclotron frequencies to leading order do not provide a signal for CPT or Lorentz breaking, since the corrections to \( \omega_c \) for electrons and positrons are equal. On the other hand, comparisons of \( \omega_a \) provide unambiguous tests of CPT.

We also find that there are no leading-order corrections due to CPT or Lorentz violation to the \( g \) factors for either electrons or positrons. This leads to some unexpected results concerning the figure of merit \( r_g \) in Eq. 2. With \( g_{e^-} \) and \( g_{e^+} \) equal to leading order, we find that \( r_g \) vanishes, which would seem to indicate the absence of CPT breaking. However, this conclusion would be incorrect because the framework we are working in contains explicit CPT violation. In addition, calculations in the context of our framework show that with \( \vec{b} \neq 0 \) the experimental ratio \( 2\omega_a/\omega_c \) depends on the magnetic field and is undefined in the limit of a vanishing \( B \) field. Because of this, the usual relation \( g - 2 = 2\omega_a/\omega_c \) does not hold in the presence of CPT violation. For these reasons, we conclude that in the context of our framework the figure of merit \( r_g \) in Eq. 2 is inappropriate, and an alternative is suggested next.

Since it is a prediction of the CPT theorem that electron and positron states of opposite spin in the same magnetic field have equal energies, we propose as a model-independent figure of merit

\[ r_{wa}^e \equiv \frac{|E_{n,s}^- - E_{n,-s}^+|}{E_{n,s}^e}. \]  
(13)

Here, \( E_{n,s}^e \) are the Landau-level energies, with \( n \) denoting the Landau level, and \( s = \pm 1 \) the spin. In the context of our framework, we find \( r_{wa}^e \approx \frac{|2b_3^e|}{m_e} \).
which can be bounded by experiments. Assuming ppb frequency resolutions, we estimate as a bound,

$$r_{\omega a} \lesssim 10^{-21}.$$  \hspace{1cm} (14)

The figure of merit $r_{\omega a}$ is compatible with the corresponding figure of merit $r_K$ which describes the neutral-kaon system. This is because both figures of merit involve energy ratios, which makes comparisons across experiments more meaningful. In contrast, the figures of merit $r_{\omega}^e$ and $r_K$ involve ratios of different physical quantities. Moreover, our estimated bound for $r_{\omega a}^e$ is more in line with the high precision that is experimentally accessible in frequency measurements in a Penning trap and appears to improve on the bound given in terms of $r_K$.

It is important to stress, however, that performing CPT tests in the meson sector remains essential because CPT violation in this sector is controlled by distinct CPT-violating parameters that appear only in the quark sector.

Alternative signatures of CPT and Lorentz violation can be considered as well. These include possible diurnal variations in the anomaly and cyclotron frequencies. We estimate bounds for these quantities based on ppb accuracies in $\omega_a$ and $\omega_c$. They are

$$r_{\omega_a,\text{diurnal}}^e \approx \frac{2|b_3 + d_{30} m_e + H_{12}e|}{m_e} \lesssim 10^{-21},$$ \hspace{1cm} (15)

$$r_{\omega_c,\text{diurnal}}^e \approx \frac{|c_{11}^e + c_{22}^e| \omega_c}{m_e} \lesssim 10^{-18}. \hspace{1cm} (16)$$

Tests for these effects would provide bounds on some of the components of the CPT-preserving but Lorentz-violating parameters $c_{\mu\nu}^e$, $d_{\mu\nu}^e$, and $H_{\mu\nu}^e$.

One type of experiment searching for diurnal variations would involve the electron alone or the positron alone in a Penning trap. Diurnal variations in the cyclotron and anomaly frequencies would occur because the spatial components of the parameters in Eq. 10 would change as the Earth rotates. A figure of merit can be defined which is based on the relative size of the diurnal energy variations. First, consider the following quantities for the electron and positron:

$$\Delta e_{\omega_a} = \frac{|E_{0,1}^e - E_{1,-1}^e|}{E_{0,1}^e}, \quad \Delta e_{\omega_a}^+ = \frac{|E_{0,-1}^e - E_{1,1}^e|}{E_{0,1}^e}. \hspace{1cm} (17)$$

Suitable figures of merit $r_{\omega_a,\text{diurnal}}^e$ and $r_{\omega_a,\text{diurnal}}^e$ can then be defined as the amplitude of the diurnal variations in $\Delta e_{\omega_a}^e$ and $\Delta e_{\omega_a}^e$, respectively. In the context of the framework we are using, we compute that

$$r_{\omega_a,\text{diurnal}}^e \approx \frac{2|b_3 + d_{30} m_e + H_{12}e|}{m_e}. \hspace{1cm} (18)$$
Among the experimental issues involved in obtaining a bound on \( r_{e \omega,\text{diurnal}} \) is maintaining stability in the magnetic field. For example, drifts in the magnetic field at a level of about 5 parts in \( 10^9 \) over the duration of the experiment would correspond to a 1 Hz frequency resolution. The data would then need to be plotted and fitted as a function of the orientation of the magnetic field with respect to a celestial coordinate system.

Bounds obtained in an experiment on electrons alone or positrons alone would involve the combination \( \mp b_3^e + d_{30}^e m_e + H_{12}^e \) of parameters in the standard-model extension. The dominant signal would therefore involve corrections to the anomaly and cyclotron frequencies which exhibit periodicities of approximately 24 hours. Subleading order corrections might exhibit 12-hour periodicities. However, these effects would be suppressed relative to the leading-order effects. All three of the quantities \( b_3^e, d_{30}^e, \) and \( H_{12}^e \) break Lorentz symmetry, but only the coupling \( b_3^e \) breaks CPT. If a signal were detected, it would indicate Lorentz breaking but not necessarily CPT violation. A subsequent experiment comparing anomaly frequencies of electrons and positrons which would bound the CPT-breaking parameter \( b_3^e \) in isolation would then need to be performed.

A preliminary analysis of this type of experiment on electrons alone has recently been performed. With a precision of approximately 1 Hz in detecting diurnal variations, an estimated bound on Lorentz breaking is given as

\[
r_{e \omega,\text{diurnal}} < 10^{-20} .
\]

(19)

## 4 Proton-Antiproton Experiments

We also investigate the sensitivity to CPT and Lorentz violations of charge-to-mass-ratio experiments and possible future \( g - 2 \) experiments involving protons and antiprotons in Penning traps. In this analysis, it suffices to work at the level of an effective theory in which the protons and antiprotons are regarded as basic objects described by a Dirac equation. The coefficients \( a_\mu^p, b_\mu^p, H_{\mu\nu}^p, c_{\mu\nu}^p, d_{\mu\nu}^p \) represent effective parameters, which at a more fundamental level depend on underlying quark interactions.

To leading order, we find the proton-antiproton differences for the cyclotron and anomaly frequencies are

\[
\Delta \omega_p^c \equiv \omega_p^c - \omega_{\bar{p}}^c \simeq 0 ,
\]

(20)

\[
\Delta \omega_p^a \equiv \omega_p^a - \omega_{\bar{p}}^a \simeq 4b_3^p .
\]

(21)

Assuming \( \omega_p^a \) and \( \omega_{\bar{p}}^a \) can be measured with ppb accuracies, and defining an
appropriate figure of merit, we estimate for $g - 2$ experiments

$$r_{g_{sa}}^P \equiv \frac{|E_{n,s}^P - E_{n,-s}^P|}{E_{n,s}^P} \lesssim 10^{-24} \ ,$$

(22)

whereas in experiments searching for diurnal variations we estimate

$$r_{\omega_{\text{diurnal}}^P} \approx \frac{2| \mp b_0 + d_{30}^p m_p + H_{12}^p |}{m_p} \lesssim 10^{-24} \ ,$$

(23)

$$r_{\omega_{\text{diurnal}}^c} \approx \frac{|c_{11}^c + c_{22}^c | \omega_c}{m_p} \lesssim 10^{-24} \ .$$

(24)

A recent experiment\cite{9} compares antiproton cyclotron frequencies with those of an $H^-$ ion instead of a proton. This comparison provides a sharp test of CPT-preserving Lorentz symmetry. In the context of our framework, the difference between the cyclotron frequencies of the $H^-$ hydrogen ion and the antiproton can be computed and is given by

$$\Delta \omega_{c,\text{th}}^H \approx (c_{00}^e + c_{11}^e + c_{22}^e)(\omega_c - \omega_c^H)$$

$$- \frac{2m_e}{m_p}(c_{00}^e + c_{11}^e + c_{22}^e - c_{00}^p - c_{11}^p - c_{22}^p)\omega_c^H \ .$$

(25)

The estimated bound that follows from this is\cite{3}

$$r_{\omega_{c}^H} \approx |\Delta \omega_{c,\text{th}}^H|/m_p \lesssim 10^{-25} \ .$$

(26)

5 Conclusions

In summary, we find that the use of a general theoretical framework incorporating CPT and Lorentz violation permits a detailed investigation of possible experimental signatures in Penning-trap experiments.

In the electron-positron system, our results indicate that the sharpest tests of CPT in Penning-trap experiments emerge from comparisons of anomaly frequencies in $g - 2$ experiments and that bounds of order $10^{-21}$ are attainable. In the context of our theoretical framework, we find that the conventional figure of merit $r_g^c$ does not provide an appropriate bound on CPT, and we have suggested an alternative. We find that comparisons of cyclotron frequencies are not sensitive to leading-order CPT or Lorentz violation, whereas diurnal variations in $\omega_a$ and $\omega_c$ can provide new signals for Lorentz violation with bounds of order $10^{-21}$ and $10^{-18}$, respectively. Experiments searching for
diurnal variations in electrons alone can provide a bound on Lorentz breaking at a level of approximately $10^{-20}$.

In the proton-antiproton system, our results show that future $g - 2$ experiments on protons and antiprotons could provide stringent test of CPT, with bounds of order $10^{-24}$. Experiments searching for diurnal variations in the proton-antiproton system can also provide bounds on Lorentz and CPT breaking at a level of approximately $10^{-24}$. A recent comparison of $H^-$ and antiproton cyclotron frequencies have provided a new test of CPT-preserving Lorentz invariance at a level of $10^{-25}$.

Table I contains a summary of the estimated bounds attainable in Penning-trap experiments in the three systems considered here.

| System | Expt. | Fig. Merit | Est. Bound |Parms. | Test |
|--------|-------|------------|------------|-------|------|
| $e^- e^+$ | $\Delta \omega_a$ | $r_{\omega_a}^e$ | $10^{-21}$ | $b_j^e$ | CPT |
| & $\omega_a$ diurnal | $r_{\omega_a,\text{diurnal}}^e$ | $10^{-21}$ | $d_{j0}^e, H_{jk}^e$ | Lorentz |
| & $\omega_c$ diurnal | $r_{\omega_c,\text{diurnal}}^e$ | $10^{-18}$ | $c_{jj}^e$ | Lorentz |
| $p \bar{p}$ | $\Delta \omega_a$ | $r_{\omega_a}^p$ | $10^{-24}$ | $b_j^p$ | CPT |
| & $\omega_a$ diurnal | $r_{\omega_a,\text{diurnal}}^p$ | $10^{-24}$ | $d_{j0}^p, H_{jk}^p$ | Lorentz |
| & $\omega_c$ diurnal | $r_{\omega_c,\text{diurnal}}^p$ | $10^{-24}$ | $c_{jj}^p$ | Lorentz |
| $H^- \bar{p}$ | $\Delta \omega_c$ | $r_{\omega_c}^{H^-}$ | $10^{-25}$ | $c_{jj}^{H^-}, c_{jj}^p$ | Lorentz |

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