PROBING THE PLANCK SCALE IN LOW-ENERGY ATOMIC PHYSICS

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Experiments in atomic physics have exceptional sensitivity to small shifts in energy in an atom, ion, or bound particle. They are particularly well suited to search for unique low-energy signatures of new physics, including effects that could originate from the Planck scale. A number of recent experiments have used CPT and Lorentz violation as a candidate signal of new physics originating from the Planck scale. A discussion of these experiments and their theoretical implications is presented.

1 Introduction

It is known that our current understanding of particle interactions as described by the standard model must break down at the Planck scale. This is because the standard model ignores the effects of gravity, which necessarily come into play at the Planck scale $M_{\text{Pl}} = \sqrt{\hbar c/G} \simeq 10^{19} \text{GeV}$. Much of the current work in theoretical high-energy physics is devoted to finding a new fundamental theory that describes physical interactions at the Planck scale. Promising insights are being found in the context of string theory, D-branes, and theories of quantum gravity. Many of these theories include effects that violate assumptions of the standard model, including higher dimensions of spacetime, unusual geometries, nonpointlike interactions, and new forms of symmetry breaking.

A common misconception is that since the Planck scale is so much higher than current accelerator energies, physics at the Planck scale is inaccessible in experiments. However, this view is shortsighted because it fails to take into account that experiments can be performed at exceptionally low energy and are therefore potentially sensitive to effects from the Planck scale that are heavily suppressed at ordinary energies. For example, experiments in atomic physics are routinely sensitive to small frequency shifts at the level of 1 mHz or less. If this is due to an energy shift expressed in GeV, it corresponds to a sensitivity of approximately $4 \times 10^{-27} \text{GeV}$. Such a sensitivity is well within the range of energy one might associate with suppression factors originating from the Planck scale. For example, the fraction $m_p/M_{\text{Pl}}$ multiplying the proton mass yields an energy of approximately $10^{-19} \text{GeV}$, while for the electron the fraction $m_e/M_{\text{Pl}}$ times the electron mass is about $2.5 \times 10^{-26} \text{GeV}$.

Atomic physics has a rich history of testing for low-energy signals of effects originating from high energy. Examples include high-precision tests of
quantum electrodynamics as well as current efforts to measure atomic parity
violation and electric dipole moments in atoms. The latter effects are expected
to occur in the context of the standard model and are associated with suppres-
sion factors originating from the electroweak scale. In order for a low-energy
signal originating from the Planck scale to be detectable in an atomic exper-
iment and not be drowned out by a less suppressed (permissible) signal, it
would necessarily have to involve corrections that cannot be mimicked in the
context of the standard model.

A promising set of candidate signals that could provide unambiguous evi-
dence of new physics originating from the Planck scale is CPT and Lorentz
violation. These violations are forbidden in the standard model. However, it
has been shown in the context of string theory that violations of these sym-
metries can occur. Based on these ideas, a number of recent experiments in
atomic physics have searched for CPT and Lorentz violation as a signal of new
physics originating from the Planck scale. Many have obtained bounds that
are well within the range associated with suppressions from the Planck scale.

In the following sections, I will review the theoretical ideas that motivate
these searches for CPT and Lorentz violation. I will then briefly discuss a
number of the atomic experiments that have been performed in the last two
to three years. Additional details can be found as well in many of the other
articles in this volume.

2 CPT and Lorentz Symmetry

In the context of the standard model, Lorentz symmetry and CPT are exact
fundamental symmetries of nature. In addition, these symmetries are linked
by the CPT theorem, which states that all local relativistic field theories of
point particles are symmetric under CPT. A prediction of the CPT theorem
is that particles and antiparticles should have exactly equal lifetimes, masses,
and magnetic moments.

It has, however, been known for well over a decade that string theory can
lead to violations of CPT and Lorentz symmetry. This is because strings are
nonpointlike and have nonlocal interactions. They can therefore evade the
CPT theorem. There are also mechanisms in string theory that can induce
spontaneous breaking of CPT and Lorentz symmetry. This is due to certain
types of interactions in string theory among Lorentz-tensor fields that can
destabilize the naive vacuum and generate nonzero vacuum expectation val-
ues for Lorentz tensors. The vacuum expectation values fill the true vacuum
and cause spontaneous Lorentz breaking. This mechanism also induces spon-
taneous CPT violation whenever the tensor-field expectation values involve
an odd number of spacetime indices. It has also been shown that geometries with noncommutative coordinates can arise naturally in string theory and that Lorentz violation is intrinsic to noncommutative field theories.

A useful theoretical tool for studying CPT and Lorentz violation is the standard-model extension. It provides a consistent theoretical framework that includes the standard model (and SU(3)×SU(2)×U(1) gauge invariance) and which allows for small violations of Lorentz and CPT symmetry. It has been shown that any realistic noncommutative field theory is equivalent to a subset of the standard-model extension. To consider experiments in atomic physics it suffices to restrict the standard-model extension to its QED sector and to include only terms that are power-counting renormalizable. The resulting QED extension has energy-momentum conservation, the usual spin-statistics connection, and observer Lorentz covariance. The renormalizability of the QED extension has recently been shown to hold to one-loop. The theory has also been used to study scattering cross sections of electrons and positrons in the presence of CPT and Lorentz violation.

The modified Dirac equation in the QED extension describing a four-component spinor field \( \psi \) of mass \( m \) and charge \( q = -|e| \) in an electric potential \( A^\mu \) is

\[
(i\Gamma^\mu D_\mu - M)\psi = 0 ,
\]

where

\[
\Gamma_\nu = \gamma_\nu + c_{\mu\nu}\gamma^\mu + d_{\mu\nu}\gamma_5\gamma^\mu .
\]

and

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

Here, natural units with \( \hbar = c = 1 \) are used, and \( iD_\mu \equiv i\partial_\mu - qA_\mu \). The two terms involving the effective coupling constants \( a_\mu \) and \( b_\mu \) violate CPT, while the three terms involving \( H_{\mu\nu}, c_{\mu\nu}, \) and \( d_{\mu\nu} \) preserve CPT. All five terms break Lorentz symmetry.

The recent atomic experiments that test CPT and Lorentz symmetry express the bounds they obtain in terms of the parameters \( a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}, \) and \( H_{\mu\nu} \). This provides a straightforward way of making comparisons across different types of experiments and avoids problems that can arise when different physical quantities (g factors, charge-to-mass ratios, masses, frequencies, etc.) are used in different experiments. It is important to keep in mind as well that each different particle sector in the QED extension has a set of Lorentz-violating parameters that are independent. The parameters of the different sectors are distinguished using superscript labels. A thorough investigation of possible CPT and Lorentz violation must look at as many different particle sectors as possible. The atomic experiments discussed here have obtained
bounds on the parameters for the electron, muon, proton, and neutron. In addition to these, there are other experiments that provide bounds on some of the remaining particle sectors, e.g., neutral mesons and photons.

3 Atomic Experiments

Before examining the different atomic experiments that have been performed in recent years, it is useful to discuss some of the more general results that have emerged from these investigations. First, it has become apparent that the sharp distinction between what are considered Lorentz tests and CPT tests has been greatly diminished. Experiments traditionally viewed as Lorentz tests are also sensitive to CPT and vice versa. In particular, it has been shown that it is possible to test CPT in experiments with particles alone, which has opened up a whole new arena of CPT tests. A second general feature of these experiments is the observation that their sensitivity to CPT and Lorentz violation stems primarily from their ability to detect very small anomalous energy shifts. While many of the experiments were originally designed to measure specific quantities, such as differences in g factors or charge-to-mass ratios of particles and antiparticles, it is now seen that they are most effective as CPT and Lorentz tests when all of the energy levels in the system are investigated for possible anomalous shifts. Indeed, several new signatures of CPT and Lorentz violation have been investigated in recent years that were previously overlooked. Examples of this are given in the following sections. It has also become common practice to use the relative size of these anomalous energy shift as figures of merit. These quantities can in turn be computed in terms of the parameters in the standard-model extension, and bounds can be expressed in terms of either. Finally, one last common feature these experiments share is that they all have sensitivity to the Planck scale.

3.1 Penning-Trap Experiments

The original experiments with Penning traps were designed to make high-precision comparisons of the g factors and charge-to-mass ratios of particles and antiparticles confined within the trap. These quantities were obtained through measurements of the anomaly frequency $\omega_a$ and the cyclotron frequency $\omega_c$. For example, $g - 2 = 2\omega_a/\omega_c$. The frequencies were measured to $\sim 10^{-9}$ for the electron thereby determining $g$ to $\sim 10^{-12}$. In computing these ratios it was not necessary to keep track of the times when $\omega_a$ and $\omega_c$ were measured. It has since been found, however, that there are additional signals
of possible CPT and Lorentz violation in this system, which has led to two new tests being performed.

The first was a reanalysis performed by Dehmelt’s group of existing data for electrons and positrons in a Penning trap. The idea was to look for an instantaneous difference in the anomaly frequencies of electrons and positrons, which can be nonzero when CPT and Lorentz symmetry are broken. (In contrast the instantaneous cyclotron frequencies remain equal at leading order in the CPT and Lorentz-violation corrections). Dehmelt’s original measurements of $g − 2$ did not involve looking for possible instantaneous variations in $ω_a$. Instead, the ratio $ω_a/ω_c$ was computed using averaged values. The new analysis is particularly relevant because it can be shown that the CPT-violating corrections to the anomaly frequency $ω_a$ can occur even though the g factor remains unchanged. The new bound found by Dehmelt’s group based on a possible instantaneous difference in the electron and positron anomaly frequencies can be expressed in terms of the parameter $b_3^e$, which is the component of $b_μ^e$ along the quantization axis in the laboratory frame. The bound they obtained is $|b_3^e| \lesssim 3 \times 10^{-25}$ GeV.

A second new signal for CPT and Lorentz violation in the electron sector has been obtained using only data for the electron. Here, the idea is that the CPT and Lorentz-violating interactions depend on the orientation of the quantization axis in the laboratory frame, which changes as the Earth turns on its axis. As a result, both the cyclotron and anomaly frequencies have small corrections which cause them to exhibit sidereal time variations. Such a signal can be measured using electrons alone, eliminating the need for comparison with positrons. The bounds in this case must be given with respect to a nonrotating coordinate system such as celestial equatorial coordinates. The interactions involve a combination of laboratory-frame components that couple to the spin of the electron. This combination is denoted as $\tilde{b}_J \equiv b_5^e − md_3^e − H_1^2$. When expressed in terms of components $X$, $Y$, $Z$ in the nonrotating frame, the bound obtained by Mittleman et al. is $|\tilde{b}_J| \lesssim 5 \times 10^{-25}$ GeV for $J = X, Y$.

3.2 Clock-Comparison Experiments

The classic Hughes-Drever experiments are atomic clock-comparison tests of Lorentz invariance. These experiments look for relative changes between two “clock” frequencies as the Earth rotates. The “clock” frequencies are typically atomic hyperfine or Zeeman transitions. At the time of the last CPT Meeting in 1998, the best bounds at leading-order for the proton, neutron and electron all came from the experiment of Berglund et al.. These were, respectively, $\tilde{b}_J^p \simeq 10^{-27}$ GeV, $\tilde{b}_J^n \simeq 10^{-30}$ GeV, and $\tilde{b}_J^e \simeq 10^{-27}$ GeV for $J = X, Y$. 

Note that these limits involve bounds on CPT violation in addition to Lorentz violation.

In the three years since the last meeting, several new clock-comparison tests have been performed or are in the planning stages. For example, Bear et al. have used a two-species noble-gas maser to test for CPT and Lorentz violation in the neutron sector. They obtained a new bound $|\tilde{b}_n| < 10^{-31}\text{GeV}$ for $J = X,Y$. This is currently the best bound for the neutron sector. As spectacular as these bounds are, however, it should be pointed out that certain assumptions about the nuclear configurations must be made in obtaining them. For this reason, these bounds should be viewed as good to within about an order of magnitude. To obtain cleaner bounds it is necessary to consider simpler atoms or to perform more sophisticated nuclear modeling.

3.3 Hydrogen-Antihydrogen Experiments

The simplest atom one can consider is hydrogen. Two experiments are being planned at CERN which will make high-precision spectroscopic measurements of the 1S-2S transitions in hydrogen and antihydrogen. These are forbidden transitions with a relative linewidth of approximately $10^{-15}$. The idea is ultimately to measure the line center of this transition to a part in $10^{3}$ yielding a frequency comparison between hydrogen and antihydrogen at a level of $10^{-18}$. An analysis of the 1S-2S transition in the context of the standard-model extension reveals that the magnetic field plays an important role in the sensitivity of the transition to Lorentz and CPT breaking. For example, in free hydrogen in the absence of a magnetic field, the 1S and 2S levels shift by the same amount at leading order. As a result of this, there are no leading-order corrections to the 1S-2S transition frequency in free H or \(\bar{H}\). However, in a magnetic trap there are fields that mix the spin states in the four hyperfine levels. Since the Lorentz-violating couplings are spin-dependent, there will be leading-order sensitivity to Lorentz and CPT violation in comparisons of 1S-2S transitions in trapped hydrogen and antihydrogen. However, these transitions are also field-dependent, which makes the experimental challenges all the greater.

As an alternative to 1S-2S measurements, a recent experiment of Phillips et al. has considered measurements of the ground-state Zeeman hyperfine transitions in hydrogen alone. It has been shown that these transitions in a hydrogen maser are sensitive to leading-order Lorentz-violating effects. Measurements of these transitions have now been made using a double-resonance technique. They give rise to new bounds for the electron and proton. The bound for the proton alone is $|\tilde{b}_p| < 10^{-27}\text{GeV}$. Due to the simplicity of hydrogen, this is an extremely clean bound, and it is currently the most stringent
test of Lorentz and CPT symmetry for the proton.

3.4 Spin-Polarized Matter

A recent experiment at the University of Washington used a spin-polarized torsion pendulum\textsuperscript{14} to achieve very high sensitivity to Lorentz violation in the electron sector. Its sensitivity comes from the combined effect of a large number of aligned electron spins. The experiment uses stacked toroidal magnets with a net electron spin $S \approx 8 \times 10^{22}$, but which have a negligible magnetic field. The apparatus is suspended on a turntable and a time-varying harmonic signal is sought. An analysis of this system shows that in addition to a signal with the period of the rotating turntable, the effects of Lorentz and CPT violation would induce additional time variations with a sidereal period caused by Earth’s rotation. The University of Washington group has analyzed their data and have obtained a bound on the electron parameters equal to $|\tilde{b}_J| \lesssim 10^{-29}$ GeV for $J = X,Y$ and $|\tilde{b}_Z| \lesssim 10^{-28}$ GeV.\textsuperscript{14} These are now the best Lorentz and CPT bounds for the electron.

3.5 Muon Experiments

Experiments with muons involve second-generation leptons and provide tests of CPT and Lorentz symmetry that are independent of the tests involving electrons. There are several different types of experiments with muons that are currently being conducted, including muonium experiments\textsuperscript{15} and $g-2$ experiments with muons at Brookhaven.\textsuperscript{16} In muonium, experiments measuring the frequencies of ground-state Zeeman hyperfine transitions in a strong magnetic field have the greatest sensitivity to Lorentz and CPT violation. A recent analysis has searched for sidereal time variations in these transitions. A bound at the level of $|\tilde{b}_J^{(\mu)}| \leq 5 \times 10^{-22}$ GeV has been obtained\textsuperscript{26} in relativistic $g-2$ experiments using positive muons with “magic” boost parameter $\delta = 29.3$. Bounds on Lorentz-violation parameters are possible at a level of $10^{-25}$ GeV. These experiments are currently underway at Brookhaven and their results should be forthcoming in the near future.\textsuperscript{27}

4 Conclusions

In summary, the three years since the first CPT meeting have been a busy time for the atomic experimentallists conducting tests of CPT and Lorentz symmetry. Five new sets of bounds have emerged for the electron, proton, neutron, and muon. The leading-order bounds from these tests are summarized in Table 1. All of these bounds are within the range of sensitivity associated
with suppression factors arising from the Planck scale. However, as sharp as these bounds are, there continues to be room for improvement. Several of the other talks at this meeting describe efforts to improve these bounds by several orders of magnitude. In addition, it should be possible to obtain bounds on many of the parameters that do not appear in Table 1, including in particular $Z$ components and timelike components of the Lorentz-violation parameters. One promising approach is to conduct clock-comparison tests in a space satellite.[9] For these reasons, the next few years are likely to be as busy as the previous three. Atomic experiments will continue to provide increasingly sharp new tests of CPT and Lorentz symmetry in matter.

Acknowledgments

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