INTRODUCTION

At a fundamental level, nature appears invariant under Lorentz transformations. This symmetry, which includes rotations and boosts, is incorporated into the standard model of particle physics. Like other local relativistic field theories of point particles, the standard model is also invariant under the CPT transformation, which is formed from the combination of charge conjugation $C$, parity reflection $P$, and time reversal $T$. Numerous experimental tests of Lorentz and CPT symmetry have been performed [1, 2]. The exceptional sensitivity of these tests and the cornerstone role of Lorentz and CPT symmetry in established theory make studies of possible Lorentz and CPT violation of interest in the context of physics beyond the standard model [3].

Talks at previous conferences in this series (Orbis Scientiae 1997-I [4], 1997-II [5], and 1998) have presented the idea that Lorentz and CPT symmetry might be spontaneously broken in nature by effects emerging from a fundamental theory beyond the standard model, such as string theory [6]. They also have outlined the low-energy description of the resulting effects and have described a candidate consistent standard-model extension incorporating Lorentz and CPT violation [7]. In this talk, I summarize some of the recent experimental constraints on the standard-model extension that have been obtained since the previous conference. New constraints on Lorentz and CPT violation are also being announced for the first time at this meeting, as reported in other contributions to the proceedings [7, 8].

Since the natural dimensionless suppression factor for observable Lorentz or CPT violation is the ratio $r \sim 10^{-17}$ of the low-energy scale to the Planck
scale, relatively few experimental tests are capable of detecting any associated effect. Among those with the necessary sensitivity and placing interesting constraints on parameters in the standard-model extension are studies of neutral-meson oscillations [3, 10, 11, 12, 13, 14], comparative tests of QED in Penning traps [15, 16, 17, 18, 19], spectroscopy of hydrogen and antihydrogen [20, 21, 22], measurements of muon properties [22], clock-comparison experiments [23, 24, 8], observations of the behavior of a spin-polarized torsion pendulum [25, 7], measurements of cosmological birefringence [26, 6, 27, 28], and observations of the baryon asymmetry [29]. Effects on cosmic rays have also been investigated in a restricted version of the standard-model extension [30, 31]. In this contribution to the proceedings, I limit considerations to recent results directly relevant to the standard-model extension and obtained in kaon oscillations and in clock-comparison experiments.

**EXPERIMENTS WITH NEUTRAL KAONS**

Neutral-meson oscillations provide a sensitive tool for studies of Lorentz and CPT symmetry. In the kaon system, experiments already constrain the CPT figure of merit $r_K \equiv |m_K - m_{\overline{K}}|/m_K$ to better than a part in $10^{18}$ [3, 4, 32], with improvements expected in the near future [33].

The standard analysis [34, 35] of possible CPT violation in the kaon system is purely phenomenological, introducing a complex parameter $\delta_K$ in the standard relationships between the physical meson states and the strong-interaction eigenstates. However, in the context of the standard-model extension with Lorentz and CPT violation, the parameter $\delta_K$ is calculable rather than purely phenomenological. Thus, a meson with velocity $\vec{\beta}$ in the laboratory frame and associated boost factor $\gamma$ displays CPT-violating effects given by [13]

$$\delta_K \approx i \sin \hat{\phi} e^{i\hat{\phi}} \gamma (\Delta a_0 - \vec{\beta} \cdot \Delta \vec{a})/\Delta m.$$  \hspace{1cm} (1)

In this expression, $\hat{\phi} \equiv \tan^{-1}(2\Delta m/\Delta \gamma)$, where $\Delta m$ and $\Delta \gamma$ are the mass and rate differences between the physical eigenstates, and the four components of the quantity $\Delta a_\mu$ control certain specific Lorentz- and CPT-violating couplings in the standard-model extension.

Equation (1) exhibits several unexpected features, including dependence on momentum magnitude and orientation. These imply various observable consequences including, for example, time variations of the measured value of $\delta_K$ with the Earth’s sidereal (not solar) rotation frequency $\Omega \approx 2\pi/(23 \text{ h 56 min})$ [13]. To display explicitly the time dependence of $\delta_K$ arising from the rotation of the Earth, one can introduce a convenient nonrotating frame. Denote the nonrotating-frame basis as $(\hat{X}, \hat{Y}, \hat{Z})$. The natural choice for $\hat{Z}$ is the rotation axis of the Earth, and celestial equatorial coordinates can be used to fix the $\hat{X}$ and $\hat{Y}$ axes [24].

For the general case of a kaon with three-velocity $\vec{\beta}$ in the laboratory
frame, an expression for the parameter $\delta_K$ in the nonrotating frame can be found. However, for simplicity in what follows I restrict attention to the special case of experiments involving highly collimated uncorrelated kaons with nontrivial momentum spectrum and large mean boost, such as the E773 and KTeV experiments \[3, 36\] where the average boost factor $\bar{\gamma}$ is of order 100. General theoretical expressions and a discussion of issues relevant to other classes of experiment can be found in Ref. \[13\].

In experiments with boosted collimated kaons, the $\hat{z}$ axis for the laboratory frame can be chosen along the kaon three-velocity, $\vec{\beta} = (0, 0, \beta)$. The general expression for $\delta_K$ in the nonrotating frame then reduces to

$$\delta_K(p, t) = \frac{i \sin \hat{\phi} e^{i\phi}}{\Delta m} \gamma[\Delta a_0 + \beta \Delta a_Z \cos \chi + \beta \sin \chi(\Delta a_Y \sin \Omega t + \Delta a_X \cos \Omega t)],$$

(2)

where $\cos \chi = \hat{z} \cdot \hat{Z}$. Note that this equation shows that each component of $\Delta a_\mu$ in the nonrotating frame is associated with momentum dependence through the boost factor $\gamma$, but only the coefficients of $\Delta a_X$ and $\Delta a_Y$ vary with sidereal time.

Experiments are performed over extended time periods, so a conventional analysis for CPT bounds disregarding the momentum and time dependence is sensitive to a time and momentum average over the data momentum spectrum given by

$$|\delta_K| = \frac{\sin \hat{\phi}}{\Delta m} \gamma(\Delta a_0 + \bar{\beta} \Delta a_Z \cos \chi),$$

(3)

where $\bar{\beta}$ and $\bar{\gamma}$ are averages of $\beta$ and $\gamma$. This expression allows the derivation of a bound on a combination of the quantities $\Delta a_0$ and $\Delta a_Z$ \[13\]:

$$|\Delta a_0 + 0.6 \Delta a_Z| \lesssim 10^{-20} \text{ GeV}.$$  

(4)

In practice, the experimental constraints on $\delta_K$ are obtained via measurements on other observables such as the mass difference $\Delta m$, the $K_S$ lifetime $\tau_S = 1/\gamma_S$, and the ratios $\eta_{+-}, \eta_{00}$ of amplitudes for $2\pi$ decays. Analysis shows that only the phases $\phi_{+-}$ and $\phi_{00}$ of the latter vary with momentum and sidereal time at leading order \[13\]. For example, the phase $\phi_{+-}$ is given by

$$\phi_{+-} \approx \hat{\phi} + \frac{\sin \hat{\phi}}{\eta_{+-}|\Delta m|} \gamma[\Delta a_0 + \beta \Delta a_Z \cos \chi + \beta \sin \chi(\Delta a_Y \sin \Omega t + \Delta a_X \cos \Omega t)].$$

(5)

This expression shows that distinct bounds on the components of $\Delta a_\mu$ can in principle be obtained in experiments with boosted collimated kaons if the momentum spectrum is sufficiently resolved.

The KTeV collaboration has recently placed a constraint $A_{+-} \lesssim 0.5^\circ$ on the amplitude $A_{+-}$ of time variations of the phase $\phi_{+-}$ with sidereal
periodicity \[14\]. This gives the limit
\[
\sqrt{\left(\Delta a_X\right)^2 + \left(\Delta a_Y\right)^2} \lesssim 10^{-20} \text{ GeV} , \tag{6}
\]
which represents the first bound obtained on the parameters \(\Delta a_X\) and \(\Delta a_Y\).

It should be noted that experiments with neutral mesons are presently the only ones known to be capable of detecting effects associated with the Lorentz- and CPT-violating parameter \(\Delta a_\mu\ \[13\]. Note also that the two bounds \((1)\) and \((3)\) discussed here are independent constraints on possible CPT violation. Relative to the kaon mass, both bounds compare favorably with the ratio of the kaon mass to the Planck scale.

**CLOCK-COMPARISON EXPERIMENTS**

Among the most sensitive tests of Lorentz and CPT symmetry are the clock-comparison experiments \[23\]. These provide limits on possible spatial anisotropies and hence on violations of rotation symmetry by bounding the relative frequency change between two hyperfine or Zeeman transitions as the Earth rotates. Data from these experiments can be interpreted in the context of the standard-model extension \[24\]. In this section, I provide a brief outline of the primary results of this study.

The standard-model extension allows for flavor-dependent effects. Since distinct species of atoms and ions have different compositions in terms of elementary particles, the corresponding signals in clock-comparison experiments can crucially depend on the chosen species. The complexity of most atoms and ions makes it impractical to perform a complete \textit{ab initio} calculation of energy-level shifts arising from Lorentz-violating terms in the standard-model extension. Fortunately, since any Lorentz-violating effects must be minuscule, it suffices to determine leading-order effects in a perturbative calculation. The leading perturbative contribution to Lorentz-violating energy-level shifts consists of a sum of shifts originating from each elementary particle in the atom, generated through the expectation value of the nonrelativistic Lorentz-violating hamiltonian in the multiparticle unperturbed atomic state.

The appropriate single-particle nonrelativistic hamiltonian is known \[37\], and its perturbation component \(\delta h\) for Lorentz violation has the form
\[
\delta h = \left(a_0 - mc_{00} - me_0\right) + \left(-b_j + m\xi_jg_{k0} + \frac{1}{2}\xi_jg_{k0}H_{kl}\right)\sigma^j + \ldots
\]
\[\tag{7}\]
Here, \(m\) is the single-particle mass, each Lorentz index is split into a timelike component 0 and spacelike cartesian components \(j = 1, 2, 3\), \(\xi_j\) is the totally antisymmetric rotation tensor, and the Pauli matrices are denoted by \(\sigma^j\). The other quantities are parameters for Lorentz and CPT violation arising in the standard-model extension. A complete expression for \(\delta h\) is given in Refs. \[24, 37\].
The multiparticle Lorentz-violating perturbative Hamiltonian describing an atom $W$ is formed as the sum of the perturbative Hamiltonians for each of the $N_w$ particles of type $w$ comprising $W$:

$$h' = \sum_w \sum_{N=1}^{N_w} \delta h_{w,N}.$$  \hspace{1cm} (8)

Here, $w$ is $p$ for the proton, $n$ for the neutron, and $e$ for the electron. The perturbative Hamiltonian $\delta h_{w,N}$ for the $N$th particle of type $w$ has the form given in Eq. (7), except that the dependence of the parameters for Lorentz violation is shown by a superscript $w$.

The perturbative Lorentz-violating energy shift of the state $|F, m_F\rangle$ of $W$ is derived as the expectation value $\langle F, m_F | h' | F, m_F \rangle$ of the perturbative Hamiltonian (8) in the appropriate unperturbed quantum state. After some calculation, one finds \cite{24}

$$\langle F, m_F | h' | F, m_F \rangle = \tilde{m}_F E_d^W + \tilde{m}_F E_q^W.$$  \hspace{1cm} (9)

Here, $\tilde{m}_F$ and $\tilde{m}_F$ are ratios of Clebsch-Gordan coefficients \cite{24}. The dipole and quadrupole energy shifts $E_d^W$ and $E_q^W$ are explicitly given in Ref. \cite{24}, and they involve components of the parameters for Lorentz violation defined in the laboratory frame.

Since the laboratory frame rotates with the Earth, the laboratory-frame components change cyclically with the Earth’s sidereal rotation frequency $\Omega$. It is therefore more convenient to work in a nonrotating frame. Denote the nonrotating-frame basis by $(\hat{X}, \hat{Y}, \hat{Z})$ as in the previous section, and let the laboratory-frame basis be $(\hat{x}, \hat{y}, \hat{z})$. The $\hat{z}$ axis here is taken as the quantization axis of $W$ for the given experiment, and the angle $\chi \in (0, \pi)$ given by $\cos \chi = \hat{z} \cdot \hat{Z}$ is assumed nonzero.

To express the results in a relatively compact form, it is convenient to introduce nonrotating-frame combinations of Lorentz-violating parameters, denoted $\tilde{b}_J$, $\tilde{c}_Q$, $\tilde{c}_{Q,J}$, $\tilde{c}_{-}$, $\tilde{c}_{XY}$, $\tilde{d}_J$, $\tilde{g}_{D,J}$, $\tilde{g}_Q$, $\tilde{g}_{Q,J}$, $\tilde{g}_{-}$, $\tilde{g}_{XY}$. Their definitions in terms of quantities in the nonrelativistic Hamiltonian $h$ can be found in Ref. \cite{24}. As one example,

$$\tilde{b}_J^w := b_J^w - mJ_0 + \frac{1}{2} m \epsilon_{J0}^w \tilde{g}_{K0}^{w} - \frac{1}{2} \epsilon_{JK} H_k^w,$$  \hspace{1cm} (10)

which involves a combination of CPT-odd and CPT-even couplings in the standard-model extension. Here, spatial indices in the nonrotating frame are denoted by $J = X,Y,Z$, the time index is denoted 0, and $\epsilon_{JKL}$ is the nonrotating-frame antisymmetric tensor.

Substituting the above into the expression for the energy-level shift gives

$$\langle F, m_F | h' | F, m_F \rangle = E_0 + E_{1X} \cos \Omega t + E_{1Y} \sin \Omega t + E_{2X} \cos 2\Omega t + E_{2Y} \sin 2\Omega t.$$  \hspace{1cm} (11)
The energy $E_0$ is constant in time and is therefore irrelevant for clock-comparison experiments. The four other energies are given explicitly in terms of the Lorentz-violating parameters and other quantities in Ref. [24]. In clock-comparison experiments, the result is typically a bound on the amplitude of the time variation of a transition frequency, determined here as the difference between two energy-level shifts of the form $\langle F, m_F | h' | F, m_F \rangle$.

In the remainder of this section, I consider the clock-comparison experiments performed by Prestage et al., Lamoreaux et al., Chupp et al., and Berglund et al. [23]. Each of the bounds from each of these experiments fits one of the following forms:

$$\sum_w u_0^w (\beta_w \tilde{b}_w^X + \delta_w \tilde{a}_w^X + \kappa_w \tilde{g}_D^X, \chi) + u_1^w (\gamma_w \tilde{c}_Q^X, X) + \lambda_w \tilde{g}_{Q,Y}^X)$$

$$\sum_w u_0^w (\beta_w \tilde{b}_w^X + \delta_w \tilde{a}_w^X + \kappa_w \tilde{g}_D^X, \chi) + u_1^w (\gamma_w \tilde{c}_Q^X, X) + \lambda_w \tilde{g}_{Q,Y}^X)$$

$$\sum_w u_0^w (\beta_w \tilde{b}_w^X + \delta_w \tilde{a}_w^X + \kappa_w \tilde{g}_D^X, \chi) + u_1^w (\gamma_w \tilde{c}_Q^X, X) + \lambda_w \tilde{g}_{Q,Y}^X)$$

$$\sum_w u_0^w (\beta_w \tilde{b}_w^X + \delta_w \tilde{a}_w^X + \kappa_w \tilde{g}_D^X, \chi) + u_1^w (\gamma_w \tilde{c}_Q^X, X) + \lambda_w \tilde{g}_{Q,Y}^X)$$

$$\sum_w u_0^w (\beta_w \tilde{b}_w^X + \delta_w \tilde{a}_w^X + \kappa_w \tilde{g}_D^X, \chi) + u_1^w (\gamma_w \tilde{c}_Q^X, X) + \lambda_w \tilde{g}_{Q,Y}^X)$$

$$\sum_w u_0^w (\beta_w \tilde{b}_w^X + \delta_w \tilde{a}_w^X + \kappa_w \tilde{g}_D^X, \chi) + u_1^w (\gamma_w \tilde{c}_Q^X, X) + \lambda_w \tilde{g}_{Q,Y}^X)$$

In these expressions, the coefficients $u_0, u_1, u_2,$ and $v$ contain the dependences on quantities such as $m_F, \tilde{m}_F, \chi,$ and gyromagnetic ratios. The quantities $\beta, \delta, \kappa, \gamma, \lambda$ with superscripts and subscripts are special matrix elements described in Ref. [24]. The parameter $v = g_A/g_B$ is the ratio of gyromagnetic ratios for the atomic species $A$ and $B$ involved in the particular experiment. The associated bounds on the amplitudes of frequency shifts are denoted $\varepsilon_{1,X}, \varepsilon_{1,Y}, \varepsilon_{2,-}, \varepsilon_{2,Y},$ corresponding to sidereal or semi-sidereal variations as $\cos \Omega t, \sin \Omega t, \cos 2\Omega t, \sin 2\Omega t,$ respectively. All the quantities in the above experiment are tabulated in Ref. [24] for each of the experiments in question.

It turns out that the experimental results all constrain distinct linear combinations of parameters for Lorentz violation. A useful tool for studying specific sensitivities is the nuclear Schmidt model [38]. In this context, the Prestage et al., Lamoreaux et al., and Chupp et al. experiments are sensitive to neutron parameters for Lorentz violation, while the Berglund et al. experiment is sensitive to electron, proton, and neutron parameters. In fact, only a subset of the allowed parameter space is constrained [24] by all these experiments. However, the bounds obtained are impressive and represent sensitivity to Planck-scale physics.

The relatively complicated form of the results (12) can be simplified under certain assumptions. If one supposes both no appreciable cancellation of effects between the species $A$ and $B$ and no cancellations among different terms in the sums appearing in Eq. (12), then the numerical value of each
bound can be applied to each term in the sum, producing individual constraints on the parameters for Lorentz violation appearing in Eq. (12). To obtain specific values, one can work within the context of the Schmidt model and make some crude dimensional estimates of the unknown matrix elements. The results of this procedure are tabulated in Ref. [24]. For example, one finds that the Lorentz- and CPT-violating parameters $\tilde{b}_w^J$ are most tightly constrained by the experiment of Berglund et al., which gives $|\tilde{b}_w^J| \lesssim 10^{-20}$ GeV, $|\tilde{\beta}_w^J| \lesssim 10^{-27}$ GeV, $|\tilde{\beta}_w^J| \lesssim 10^{-27}$ GeV. The experiments in Ref. [23] also bound other parameters, as described in Ref. [24].

Experiments producing both calculable and clean bounds would evidently be of particular theoretical interest. One possibility for improving both calculability and cleanliness is to use species $W$ for which the Lorentz-violating energy shifts depend predominantly on a single valence particle $w$. For example, in the case where $w$ is an electron, substances of nuclear spin zero could be used. For the case where $w$ is a nucleon, a list of nuclei theoretically expected to yield relatively calculable and clean bounds is provided in Ref. [24].

**NEW RESULTS REPORTED AT THIS CONFERENCE**

In other presentations to this conference [7, 8], new experimental results are reported that provide relatively calculable and clean bounds on certain Lorentz-violating parameters in the standard-model extension. In this final section, I provide a brief summary placing these results in the context of the preceding discussion.

*Neutron parameters.* An interesting limit on neutron parameters for Lorentz violation is attainable using a dual nuclear Zeeman $^3\text{He}-^{129}\text{Xe}$ maser [39] because the $I = \frac{1}{2}$ nucleus $^{129}\text{Xe}$ is sensitive to dipole energy shifts from neutron parameters. Within the Schmidt model, the description of the $^3\text{He}$ and $^{129}\text{Xe}$ systems are related, which leads to a relatively clean bound [24]. At this conference, Walsworth discusses [8] an experiment producing a bound of $80 \text{nHz}$ on sidereal variations of the free-running $^3\text{He}$ frequency using $^{129}\text{Xe}$ as a reference. In the context of the Schmidt model and the assumptions described in the previous section, this can be interpreted as a bound on equatorial components of $|\tilde{b}_n^J|$ of approximately $10^{-31}$ GeV [8].

*Electron parameters.* High-sensitivity tests of Lorentz symmetry in the electron sector can be performed by searching for Lorentz-violating spin couplings with macroscopic materials having a net spin polarization generated by the effects of many electrons [25]. The most sensitive apparatus of this type at present is the spin-polarized torsion pendulum used with the Eötvös II instrument at the University of Washington [40, 41, 7], which involves stacked layers of toroidal magnets producing a large net electron spin but negligible magnetic moment. At this conference, Heckel describes [7] an analysis of
data taken with this apparatus that places a strong constraint on the components $|\tilde{b}_J^e|$, at the level of about $10^{-29}$ GeV for the equatorial components and about $10^{-28}$ GeV for the component along $\hat{Z}$.

**Proton parameters.** Since hydrogen is theoretically well understood, it is a good candidate for a substance producing a calculable bound in a clock-comparison experiment. In fact, the reference transition in the Prestage et al. experiment was a hydrogen maser. In the context of the standard-model extension, analyses of experiments with hydrogen and antihydrogen have been performed \[16, 20, 21\]. The standard H-maser line involves atomic states with $m_F = 0$ and is insensitive to Lorentz violation, but the other ground-state hyperfine lines involve states with $m_F = \pm 1$ and therefore are sensitive to Lorentz violation. The sidereal variations of these lines are determined at leading order by the combinations $\tilde{b}_J^e \pm \tilde{b}_J^p$. At this conference, Walsworth describes \[8\] an experiment with hydrogen masers that places a bound of 0.7 mHz on the magnitude of sidereal variations in these frequencies. Combined with the above constraints on $\tilde{b}_J^e$ in the electron sector announced by Heckel \[7\], this can be interpreted as a bound on the equatorial components of $|\tilde{b}_J^p|$ of approximately $4 \times 10^{-27}$ GeV \[8\].

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