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Workshop on the original of P, CP and T Violation

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Testing Lorentz & CPT Symmetry.

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Testing Lorentz & CPT Symmetry

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Workshop on the Origins of P, CP, and T Violation
Trieste, July 2008

Outline:

I. Violations of Lorentz and CPT Symmetry?

II. Standard-Model Extension (SME)

III. Minimal SME in Minkowski spacetime

IV. Experimental Signals

V. Lorentz & CPT Tests in QED

VI. Conclusions

Indiana Lorentz Group:

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I. Violations of Lorentz and CPT Symmetry?

Nature appears to be invariant under:

- Lorentz Symmetry
  - Rotations
  - Boosts
- CPT Symmetry
  - Charge Conjugation
  - Parity Reflection
  - Time Reversal

Numerous experiments confirm Lorentz & CPT symmetry:

- Spectroscopic Lorentz tests (Hughes-Drever Expts)
  - ⇒ very precise frequency measurements
  - ⇒ sharp bounds on spatial anisotropies
- CPT tests in high-energy physics
  - ⇒ matter/antimatter experiments

Theorems in QFT connect Lorentz & CPT symmetry:

CPT Theorem (Pauli, Lüders, Bell, 1950s)

- Local relativistic field theories of point particles cannot break CPT symmetry
- Predicts equal masses, lifetimes, g factors, etc. for particles and antiparticles

Lorentz Symmetry is also important in gravity theory

Riemann spacetime $\Rightarrow$ geometry of general relativity

metric = $g_{\mu\nu}$ curvature = $R^{\kappa}{}_{\lambda\mu\nu}$

Lorentz symmetry becomes a local symmetry

- at each point local frames exist where $g_{\mu\nu} \to \eta_{\mu\nu}$
- can Lorentz transform between local frames

Experiment & theory both support Lorentz & CPT invariance

Why look for Lorentz & CPT violation?

$\Rightarrow$ because they are fundamental symmetries

$\Rightarrow$ their breaking would be a signature of new physics

Ideas for Lorentz violation include:

- Spontaneous Lorentz violation
- String theory
- Loop quantum gravity
- Spacetime foam
- Breakdown of quantum mechanics
- Spacetime varying couplings
- Noncommutative geometry
- and more . . .

$\Rightarrow$ quantum theories of gravity may not preserve Lorentz sym.

Example - String theory: (Kostelecky & Samuel, PRD '89)

Mechanisms in SFT can lead to tensor vevs $\langle T \rangle \neq 0$

Low-energy theory gains terms of the form

$$\mathcal{L} \sim \frac{\lambda}{M^k} \langle T \rangle \, \Gamma \, \bar{\psi} (i\partial)^k \chi$$

$\Rightarrow$ can lead to spontaneous Lorentz violation

Example - Noncommutative field theory: (Mocioiu et al, PLB '00)
(Carroll et al, PRL '01)

$$[x^\mu, x^\nu] = i\theta^{\mu\nu}$$

QED is modified: $\mathcal{L} \sim \frac{1}{4} iq \, \theta^{\alpha\beta} \, F_{\alpha\beta} \, \bar{\psi} \, \gamma^\mu \, D_\mu \, \psi$

$\Rightarrow$ appearance of Lorentz-breaking fields

$\Rightarrow$ give corrections to low-energy physics

It is the consideration of these types of terms that leads to the idea of the Standard-Model Extension

II. Standard-Model Extension (SME)

Basic Premise: No matter what the fundamental theory is at the Planck scale, physics at sub-Planck levels is well described by effective quantum field theory.

Construct the most general effective theory that:

(1) is observer coordinate independent

-- Lagrangian terms are observer Lorentz scalars

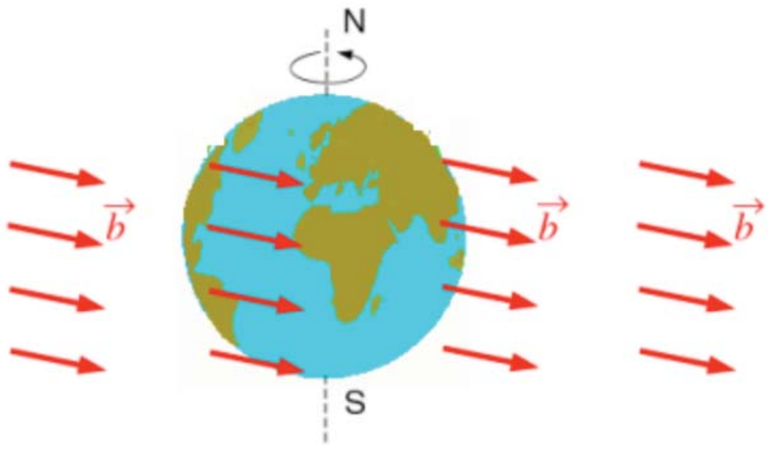
(2) contains known low-energy physics

-- Standard Model & gravity are included.

Combining these two constraints gives the SME, which allows for general Lorentz and CPT violation

(Kostelecky & Potting, PRD '95)
(Colladay & Kostelecky, PRD '97, '98))
(Kostelecky, PRD '04)

Introduce general background fields (SME coeffs.)



How do they transform under Lorentz transfs?

In a Lorentz-invariant theory, transforming coords. & fields are inverses of each other (passive vs. active)

⇒ But with Lorentz violation, must distinguish these

background fields ⇒ transform under observer transfs.

→ change of observer

⇒ do not transform under particle transfs.

→ change of particle fields

Example - fermion in Minkowski spacetime

$$\mathcal{L} = a_\mu \bar{\psi}\gamma^\mu\psi + b_\mu \bar{\psi}\gamma_5\gamma^\mu\psi + \cdots$$

$\mathcal{L}$ → scalar under observer transfs.

$a_\mu, b_\mu, \ldots$ → fixed under particle LTs

⇒ Lagrangian not invariant under particle LTs

SME coeffs. $a_\mu, b_\mu, \ldots$

⇒ explicitly break Lorentz symmetry

⇒ act as fixed background fields in any observer frame

Note: with spontaneous Lorentz violation, the SME coefficients could arise as vevs

In general, the SME has the form:

$$\mathcal{L} = \mathcal{L}_{\text{gravity}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{LV} + \cdots$$

Includes:

- renormalizable and nonrenormalizable terms
- gauge invariant and gauge noninvariant terms
- extensions of QFT → NCQFT
- terms arising from string theory
- terms from spontaneous Lorentz breaking

Can also define a minimal SME:

⇒ restricts to renormalizable terms

⇒ requires SU(3)xSU(2)xU(1) gauge invariance

Can consider flat spacetime or curved spacetime

Use the minimal SME as a first step looking for the leading-order signatures of Lorentz violation

Theoretical Remarks/Issues:

(1) Renormalizable sector of SME (dimensions 3,4)
is expected generically to dominate at low energies
but there can be exceptions, e.g., NCQFT

(2) Dimension-5 operators have recently been classified
(Bolokhov & Pospelov, PRD '08)

(3) Renormalizable sector by itself is valid in any laboratory frame at low energies, but is insufficient at high scales to ensure causality/stability (Kostelecky & Lehnert, PRD '01)

Expect Planck-suppressed terms (operators of dim ≥ 5)
to become important as Planck scale approached

(4) Lorentz/CPT violation may be unphysical in some cases

e.g., QED with term $-a_\mu \overline{\psi} \gamma^\mu \psi$

a field redefinition removes it from the lagrangian

Perspective on Lorentz Violation Phenomenology

FUNDAMENTAL THEORY
(Lorentz covariant?)

Strings, quantum gravity,
higher dims., other…

Lorentz violation
(spontaneous breaking)

SME or its limits:
QED extension, etc.

EFFECTIVE THEORY
low-energy, Lorentz-violating

EXPERIMENT

K, D, B oscillations
Neutrino oscillations
Photon properties
Muon properties
Baryogenesis
Astrophysical tests
Satellite tests

Classic GR tests
Laser ranging
Binary Pulsars
Gyroscope expts
Gravity Probe B

Hydrogen/antihydrogen studies
Anomalous magnetic moments
Clock-comparison experiments
Tests with spin-polarized solids
Torsion pendulum tests
etc.

III. Minimal SME in Minkowski spacetime

The minimal SME restricts the theory to terms involving the SM and gravitational fields and all additional terms that are:

- dim $\leq$ 4 (power-counting renormalizable)
- gauge invariant

For simplicity, here, we restrict to Minkowski spacetime

$\Rightarrow$ ignoring gravitational effects in this talk

Can also form special subsets of the Minimal SME

$\Rightarrow$ QED extension (lagrangian)
$\Rightarrow$ Dirac eq. extension (relativistic QM)
$\Rightarrow$ Hamiltonian (Foldy-Wouthuysen)

Useful for low-energy perturbative calculations

Minimal SME (in Minkowski spacetime)

(Colladay & Kostelecky,PRD '97,'98)

Fermion sector

$$\mathcal{L}^{\rm CPT-even}_{\rm lepton} = \tfrac{1}{2}i(c_L)_{\mu\nu AB}\overline{L}_A\gamma^\mu \overleftrightarrow{D^\nu} L_B + \tfrac{1}{2}i(c_R)_{\mu\nu AB}\overline{R}_A\gamma^\mu \overleftrightarrow{D^\nu} R_B$$

$$\mathcal{L}^{\rm CPT-odd}_{\rm lepton} = -(a_L)_{\mu AB}\overline{L}_A\gamma^\mu L_B - (a_R)_{\mu AB}\overline{R}_A\gamma^\mu R_B$$

$$\mathcal{L}^{\rm CPT-even}_{\rm quark} = \tfrac{1}{2}i(c_Q)_{\mu\nu AB}\overline{Q}_A\gamma^\mu \overleftrightarrow{D^\nu} Q_B + \tfrac{1}{2}i(c_U)_{\mu\nu AB}\overline{U}_A\gamma^\mu \overleftrightarrow{D^\nu} U_B + \tfrac{1}{2}i(c_D)_{\mu\nu AB}\overline{D}_A\gamma^\mu \overleftrightarrow{D^\nu} D_B$$

$$\mathcal{L}^{\rm CPT-odd}_{\rm quark} = -(a_Q)_{\mu AB}\overline{Q}_A\gamma^\mu Q_B - (a_U)_{\mu AB}\overline{U}_A\gamma^\mu U_B - (a_D)_{\mu AB}\overline{D}_A\gamma^\mu D_B$$

$$\mathcal{L}^{\rm CPT-even}_{\rm Yukawa} = -\tfrac{1}{2}\left[(H_L)_{\mu\nu AB}\overline{L}_A\phi\sigma^{\mu\nu}R_B + (H_U)_{\mu\nu AB}\overline{Q}_A\phi^c\sigma^{\mu\nu}U_B + (H_D)_{\mu\nu AB}\overline{Q}_A\phi\sigma^{\mu\nu}D_B\right] + \text{h.c.}$$

Boson sector

$$\mathcal{L}^{\rm CPT-even}_{\rm Higgs} = \tfrac{1}{2}(k_{\phi\phi})^{\mu\nu}(D_\mu\phi)^\dagger D_\nu\phi + \text{h.c.} - \tfrac{1}{2}(k_{\phi B})^{\mu\nu}\phi^\dagger\phi B_{\mu\nu} - \tfrac{1}{2}(k_{\phi W})^{\mu\nu}\phi^\dagger W_{\mu\nu}\phi$$

$$\mathcal{L}^{\rm CPT-odd}_{\rm Higgs} = i(k_\phi)^\mu\phi^\dagger D_\mu\phi + \text{h.c.}$$

$$\mathcal{L}^{\rm CPT-even}_{\rm gauge} = -\tfrac{1}{2}(k_G)_{\kappa\lambda\mu\nu}\mathrm{Tr}(G^{\kappa\lambda}G^{\mu\nu}) - \tfrac{1}{2}(k_W)_{\kappa\lambda\mu\nu}\mathrm{Tr}(W^{\kappa\lambda}W^{\mu\nu}) - \tfrac{1}{4}(k_B)_{\kappa\lambda\mu\nu}B^{\kappa\lambda}B^{\mu\nu}$$

$$\begin{aligned}\mathcal{L}^{\rm CPT-odd}_{\rm gauge} = {} & (k_3)_\kappa\epsilon^{\kappa\lambda\mu\nu}\mathrm{Tr}(G_\lambda G_{\mu\nu} + \tfrac{2}{3}ig_3G_\lambda G_\mu G_\nu) + (k_2)_\kappa\epsilon^{\kappa\lambda\mu\nu}\mathrm{Tr}(W_\lambda W_{\mu\nu} + \tfrac{2}{3}igW_\lambda W_\mu W_\nu) \\ & + (k_1)_\kappa\epsilon^{\kappa\lambda\mu\nu}B_\lambda B_{\mu\nu} + (k_0)_\kappa B^\kappa\end{aligned}$$

QED Extension (in Minkowski spacetime)

Fermions:

- $a_\mu \bar{\psi} \gamma^\mu \psi$ (CPT odd)
- $b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi$ (CPT odd)
- $H_{\mu\nu} \bar{\psi} \sigma^{\mu\nu} \psi$
- $c_{\mu\nu} \bar{\psi} \gamma^\mu D^\nu \psi$
- $d_{\mu\nu} \bar{\psi} \gamma_5 \gamma^\mu D^\nu \psi$

Photons:

- $(k_{AF})^\kappa \epsilon_{\kappa\lambda\mu\nu} A^\lambda F^{\mu\nu}$ (CPT odd)
- $(k_F)_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu}$

$\Rightarrow$ independent set of coeffs. for each particle species

$\Rightarrow$ can also add terms (dim $\leq$ 4) for QED that do not come from the fermion representations in the SME

SME coefficients for protons & neutrons are composite coeffs. comprised from underlying quark/gluon coeffs.

IV. Experimental Signals

Any Lorentz violation in nature must be small

⇒ SME parameters suppressed by a large mass scale

$$M_{\text{weak}}/M_{\text{Planck}} \simeq 3 \times 10^{-17}$$

$$m_e/M_{\text{Planck}} \simeq 5 \times 10^{-23}$$

How can expts attain sensitivity to Planck-scale effects?

- Long travel times (photons)
- Small phase oscillations (mesons, neutrinos)
- Extreme low energy (atoms, trapped particles, etc.)

Many particle sectors can be analyzed using the SME

·photons	·protons	·neutrons	·gravity
·electrons	·muons	·mesons	·Higgs
·neutrinos	·atoms	·molecules	·SUSY

⇒conduct systematic investigations for different particle species e.g., in the neutrino sector:

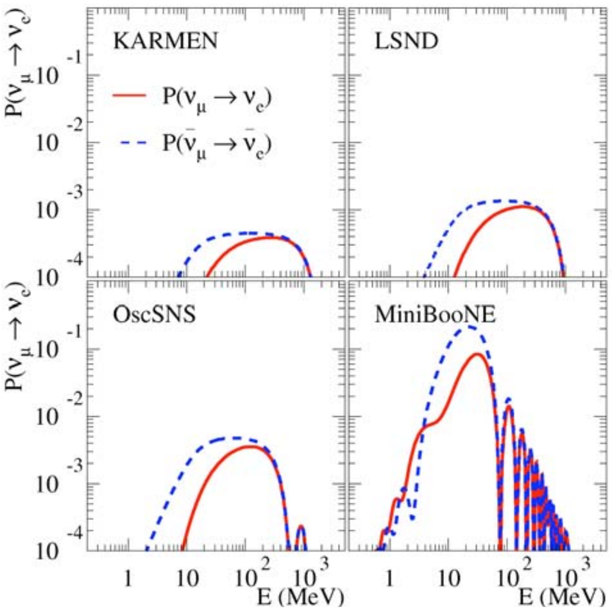
General analysis for free oscillating neutrinos with Dirac & Majorana couplings has been performed. (Kostelecky & Mewes, PRD '04)

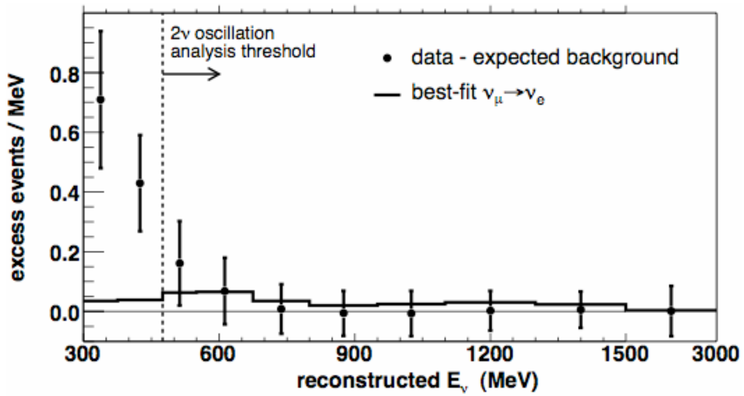
- simple 2-coeff. model without ν mass (bicycle model) come close to reproducing experimental neutrino data

  ⇒ detailed fits don't quite work (Barger, Mafatia, & Whisnant, PLB '07)

Tandem model (Katori,Kostelecky,Tayloe PRD'06)

- 3-coeff. model (1 mass + 2 isotropic LV coeffs) (1 CPT odd)
- double ("tandem") Lorentz-violating seesaw
- unconventional energy dependences, no direction dependence
- predicts low-energy signal in MiniBooNE (2006)





(MiniBooNE PLB'07)

e.g., in the meson sector:

Relevant mesons: P = K, D, B_d, B_s and antiparticles

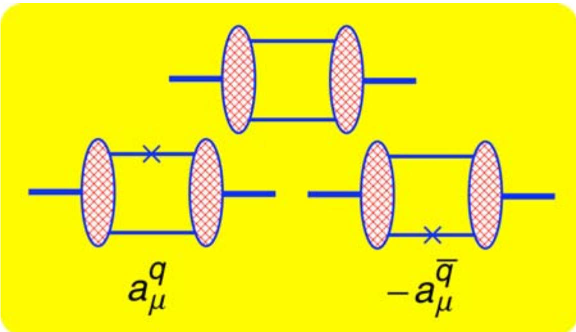
Effective 2x2 hamiltonian gives time evolution of P system

Eigenvalues give physical masses, decay rates

$$\Lambda \equiv \frac{1}{2}\Delta\lambda \begin{pmatrix} U+\xi & VW^{-1} \\ VW & U-\xi \end{pmatrix} \qquad \begin{aligned} U &\equiv \lambda/\Delta\lambda \\ V &\equiv \sqrt{1-\xi^2} \end{aligned}$$

CPT violation: ξ_P

zero in standard model, calculable in SME



$$\boxed{\xi_P \propto \beta_\mu \Delta a^\mu}$$

4-velocity

(Kostelecky, PRL'98,PRD'00,PRD'01)

Most analyses have assumed constant ξ_P

SME analysis shows that CPT violation

- can differ among meson species
- is governed by 4 independent coefficients Δa_μ for each
- varies with momentum magnitude/direction, sidereal time

Status of sensitivity to Δa_μ :
(in GeV)

Coefficient	K system
$\tilde{a}$ / GeV	$\lesssim 10^{-20}$
$a_\perp$ / GeV	$\lesssim 10^{-21}$

KTeV Expt

Coeff.	K system	D system	B_d system	B_s system
Δa_0	$\lesssim 10^{-17}$	$\lesssim 10^{-15}$	$\lesssim 10^{-14}$	?
Δa_x	$\lesssim 10^{-17}$	$\lesssim 10^{-15}$	$\lesssim 10^{-14}$	?
Δa_y	$\lesssim 10^{-17}$	$\lesssim 10^{-15}$	$\lesssim 10^{-14}$	?
Δa_z	$\lesssim 10^{-17}$	$\lesssim 10^{-15}$	$\lesssim 10^{-14}$	?
Expts.	KLOE	FOCUS	BaBar	

Existing/future K, D, B_d data could yield new sensitivities

V. Lorentz & CPT Tests in QED

Remainder of talk will focus on QED tests in flat spacetime.

Minimal QED extension Lagrangian: $\mathcal{L}_{\rm QED} = \mathcal{L}_0 + \mathcal{L}_{\rm int}$

$$\mathcal{L}_{\rm int} = -a_\mu \bar{\psi}\gamma^\mu\psi - b_\mu\bar{\psi}\gamma_5\gamma^\mu\psi - \tfrac{1}{2}H_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$$
$$+ic_{\mu\nu}\bar{\psi}\gamma^\mu D^\nu\psi + id_{\mu\nu}\bar{\psi}\gamma_5\gamma^\mu D^\nu\psi$$
$$-\tfrac{1}{4}(k_F)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu} + \tfrac{1}{2}(k_{AF})^\kappa\epsilon_{\kappa\lambda\mu\nu}A^\lambda F^{\mu\nu}$$

$$a_\mu,\ b_\mu,\ k_{AF} \Rightarrow \text{break CPT}$$
$$H_{\mu\nu},\ c_{\mu\nu},\ d_{\mu\nu},\ k_F \Rightarrow \text{preserve CPT}$$

Look for leading-order effects due to Lorentz & CPT violation in:

- photon expts.
- atomic expts

Photon Sector (Kostelecky & Mewes, PRL '01, PRD '02)

CPT-odd term: Expts. suggest $k_{AF} \approx 0$ (will ignore)

(Carroll, Field, & Jackiw, PRD '90)

CPT-even term: Leads to modified Maxwell Lagrangian

The k_F term can be decomposed as

$$\mathcal{L} = \frac{1}{2}[(1+\tilde{\kappa}_{\rm tr})\vec{E}^2-(1-\tilde{\kappa}_{\rm tr})\vec{B}^2]+\frac{1}{2}\vec{E}\cdot(\tilde{\kappa}_{e+}+\tilde{\kappa}_{e-})\cdot\vec{E}$$
$$-\frac{1}{2}\vec{B}\cdot(\tilde{\kappa}_{e+}-\tilde{\kappa}_{e-})\cdot\vec{B}+\vec{E}\cdot(\tilde{\kappa}_{o+}+\tilde{\kappa}_{o-})\cdot\vec{B}$$

$$\tilde{\kappa}_{e+},\ \tilde{\kappa}_{e-},\ \tilde{\kappa}_{o+},\ \tilde{\kappa}_{o-},\ \tilde{\kappa}_{\rm tr} \Rightarrow 19 \text{ ind. coeffs.}$$

The 19 SME parameters in the CPT-even sector have been explored in several astrophysical and laboratory experiments

Birefringence of light:

- light polarizations have different speeds
- polarization angles have wavelength dep.

Spectropolarimetry of distant galaxies bounds 10 coeffs:

$$\tilde{\kappa}_{e+},\ \tilde{\kappa}_{o-} \lesssim 10^{-32}$$

Optical & microwave cavities:

- Modern versions of Michelson-Morley,
- Kennedy-Thorndike, & Ives-Stilwell

Give bounds on the remaining coeffs:

$$\tilde{\kappa}_{e-} \lesssim 10^{-15} \qquad \tilde{\kappa}_{o+} \lesssim 10^{-12} \qquad \tilde{\kappa}_{\mathrm{tr}} \lesssim 10^{-7}$$

(Wolf, Tobar et al, PRL, '03, PRD '05)
(Mueller, Peters et al., PRL '05)
(Mueller, Peters, Tobar, Wolf, et al, PRL, '07)

(Schiller et al., PRA '05)
(Lipa et al., PRL, '03)
(Reinhardt et al., Nature Physics '07)

Atomic Systems

High-precision atomic experiments have Planck-scale sensitivity!

1 mHz frequency resolution $\Rightarrow$ 4×10^{-27} GeV energy sensitivity

Use Lorentz & CPT violation as a signal for Planck-scale physics

A number of recent atomic expts with Planck-scale sensitivity have searched for CPT/Lorentz violation:

- $\Rightarrow$ Penning-trap experiments
- $\Rightarrow$ Clock-comparison experiments
- $\Rightarrow$ Hydrogen/antihydrogen experiments
- $\Rightarrow$ Muon experiments
- $\Rightarrow$ Spin-polarized matter

They have been analyzed in terms of the SME

General features of the expts:

(1) Lorentz & CPT violation cause energy shifts that

- ⇒ differ for particles & antiparticles
- ⇒ exhibit sidereal time variations

(2) Can calculate bounds on coeffs. b_μ, $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$ . . .

- ⇒ permits comparisons across experiments

(3) Particle sectors are independent

- ⇒ must test each different particle sector

(4) Lorentz vs. CPT Tests

- ⇒ Lorentz tests are sensitive to CPT violating coeffs.
- ⇒ CPT tests are sensitive to Lorentz violation

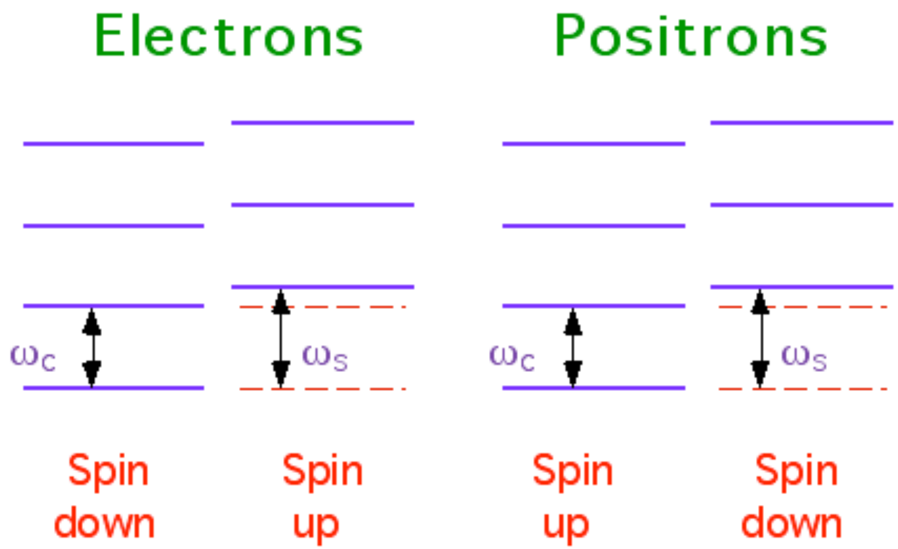
But the signals & sensitivities are different

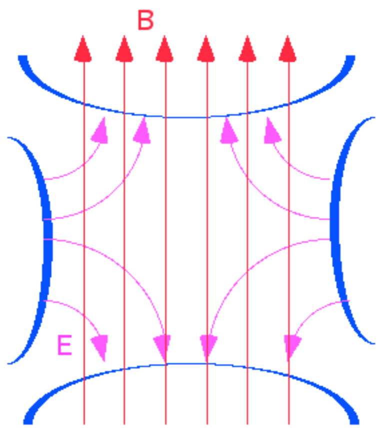
⇒ involve different combinations of SME coeffs.

Let's look at some examples . . .

Tests in Atomic Systems

(1) Penning trap experiments (RB, Kostelecky & Russell, PRL '97, PRD '98)



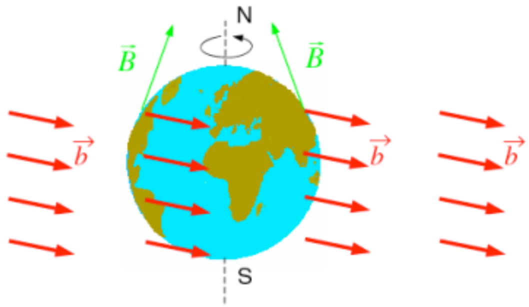


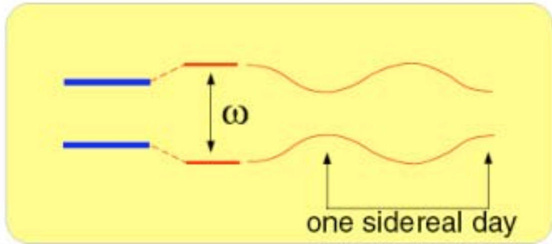
Expts measure ω_a and ω_c to ~ppb

Can consider 2 types of experiments:

- ⇒ look for sidereal time variations in ω_a and ω_c
- ⇒ look for a difference in ω_a for e+ and e-

Sidereal time variations (Mittleman, Dehmelt *et al.*, '99)





Bounds involve a combination of parameters:

$$\tilde{b}_j^e \equiv b_j^e - m d_{j0}^e - \tfrac{1}{2}\varepsilon_{jkl} H_{kl}^e$$

with respect to a nonrotating basis

$$|\tilde{b}_J^e| \lesssim 5 \times 10^{-25}\ \mathrm{GeV}\ \ (J = X, Y)$$

Expt comparing e^+ & e^- (Dehmelt *et al.*, PRL '99)

⇒ looks for an instantaneous difference in anomaly freqs

Bound on CPT violating coefficient:

$$|b_3^e| \lesssim 3 \times 10^{-25}\,\mathrm{GeV}$$

(2) Clock-comparison experiments (Kostelecky,& Lane, PRD '99)

⇒ classic Hughes-Drever experiments

⇒ high-precision tests of Lorentz invariance

Hughes *et al.*, PRL 1960
Drever, Phil. Mag. 1961
Prestage *et al.*, PRL 1985
Lamoreaux *et al.*, PRL 1986
Chupp *et al.*, PRL 1989
Berglund *et al.*, PRL 1995
Bear *et al.*, PRL 2000
Wolf *et al.*, PRL 2006

⇒ expts search for relative changes between two "clock" frequencies as Earth rotates

⇒ "clock" freqs are atomic hf or Zeeman trans.

Results of clock-comparison experiments:

Partial list of experimental bounds:

⇒ 10^{-nn} in GeV units

⇒ J = X, Y in nonrotating frame

	Tilde coeff.	Prestage et al.	Lamoreax et al.	Chupp et al.	Berglund et al.	Bear et al.	Wolf et al.
p	b_J	*	*	-	10^{-27}	*	-
p	d_J	*	*	-	10^{-25}	*	-
p	c_{QJ}	*	-	-	-	-	10^{-22}
p	c_-	*	*	*	-	-	10^{-25}
p	c_{XY}	*	*	*	-	-	-
n	b_J	10^{-27}	10^{-29}	-	10^{-30}	10^{-31}	-
n	d_J	10^{-25}	10^{-26}	-	10^{-28}	10^{-29}	-
n	c_{QJ}	10^{-25}	-	-	-	-	-
n	c_-	10^{-25}	10^{-27}	10^{-27}	-	-	-
n	c_{XY}	10^{-25}	10^{-27}	10^{-27}	-	-	-
e	b_J	-	-	-	10^{-27}	-	-
e	d_J	-	-	-	10^{-22}	-	-
e	c_{QJ}	-	-	-	-	-	-
e	c_-	-	-	-	-	-	-
e	c_{XY}	-	-	-	-	-	-

Tilde coeffs.

$$\begin{aligned}
\tilde{b}_J &:= b_J - m d_{J0} - \tfrac{1}{2}\epsilon_{JKL}H_{KL} \\
\tilde{d}_J &:= m(d_{0J} + d_{J0}) \\
&\quad -\tfrac{1}{2}(m d_{J0} + \tfrac{1}{2}\varepsilon_{JKL}H_{KL}) \\
\tilde{c}_{Q,J} &:= m(c_{JZ} + c_{ZJ}) \\
\tilde{c}_{-} &:= m(c_{XX} - c_{YY}) \\
\tilde{c}_{XY} &:= m(c_{XY} + c_{YX})
\end{aligned}$$

Sensitivity is to X,Y directions in nonrotating frame

⇒ insensitive to direction along Earth's axis (J = Z)

⇒ velocity of Earth, lab, etc. ignored

⇒ no bounds on timelike components (J = T)

For J = Z, T sensitivity, perform boosted-frame analyses

- annual time variations in co-located masers

$$|\tilde{b}^n_T| \lesssim 10^{-27}\,\mathrm{GeV}$$ (Cane *et al.*, PRL '04)

- Doppler-shifted expts.

$$|c^p_{JJ}| \lesssim 10^{-11} \quad |c^p_{TJ}| \lesssim 10^{-8}$$ (Gwinner *et al.*, PRL '04)
(Lane, PRD '05)

- clock-comparison expts in space (RB,Kostelecky,& Lane, PRL '03)

e.g., ACES mission on the ISS

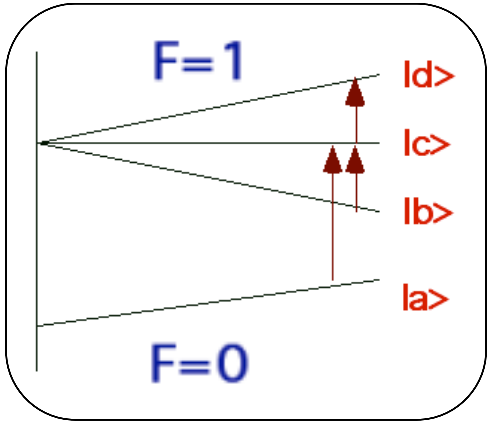
Bounds depend on nuclear modeling (Schmidt model)

⇒ sharper bounds require more sophisticated nuclear models or simpler atoms

(3) Hydrogen/Antihydrogen expts

(RB, Kostelecky & Russell, PRL '99)

Clock Comparison using H Masers



- ⇒ measure ground-state Zeeman hf trans.
- ⇒ look for sidereal time variations
- ⇒ use double-resonance technique

Obtain electron and proton bounds

$$|\tilde{b}^e_J + \tilde{b}^p_J| \lesssim 2 \times 10^{-27}\,\mathrm{GeV}, \quad J = X, Y$$

(Phillips *et al.*, PRD '01)

Hydrogen/Antihydrogen experiments at CERN

⇒ compare spectral lines in trapped H & $\overline{\mathrm{H}}$

1S-2S Transitions $\quad \text{linewidth} \simeq 10^{-15}$

Compare hyperfine Zeeman transitions for sharp CPT tests

CPT bounds $b^p_3 \lesssim 10^{-27}\,\mathrm{GeV}$ feasible at ~1 mHz level

(4) Muon experiments (RB & Kostelecky, PRL '00)

Muonium spectroscopy:

$\Rightarrow$ Zeeman hyperfine frequencies depend on orientation & exhibit sidereal time variations as Earth rotates

- $\Rightarrow$ measure hf Zeeman transitions in 1.7 T field
- $\Rightarrow$ sidereal variations $\leq$ 20 Hz (10 ppb)

$$|\tilde{b}_J^\mu| \leq 2 \times 10^{-23}\,\mathrm{GeV}, \quad J = X, Y$$ (Hughes et al., PRL '01)

BNL muon g-2 expt:

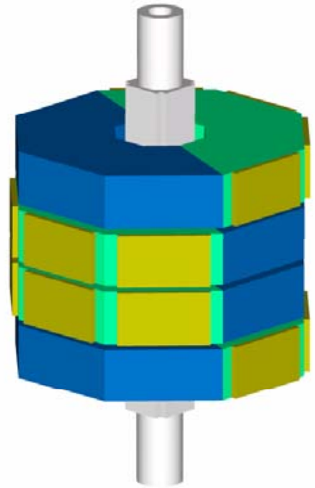
- $\Rightarrow$ relativistic μ+ and μ- in 1.45 T magnetic field
- $\Rightarrow$ compare μ+ and μ- anomaly frequencies
- $\Rightarrow$ search for sidereal time variations as Earth rotates

$$|b_Z^\mu| \lesssim 10^{-23}\,\mathrm{GeV}, \quad |\check{b}_J^\mu| \lesssim 10^{-24}\,\mathrm{GeV}, \quad J = X, Y$$

(Muon g-2 collaboration, PRL '08)

(5) Spin-polarized torsion pendulum (RB & Kostelecky, PRL '00)

Eöt-Wash expt at the Univ. of Washington



- stacked toroidal magnets with B ≈ 0
- S ≈ 8 x 10^{22} aligned spins
- rotates around suspension axis with ang. freq. ω

$$\vec{S} = S(\cos\omega t\,\hat{x} + \sin\omega t\,\hat{y})$$

⇒ Signal of Lorentz violation is variation of the torque τ(t) with two time variations:

- period of rotating turntable ω
- period of rotating Earth Ω

⇒ rotating turntable gives sensitivity to X, Y, Z

$$|\tilde{b}_J^e| \lesssim 2 \times 10^{-31}\,\mathrm{GeV}, \quad J = X, Y$$

$$|\tilde{b}_Z^e| \lesssim 10^{-30}\,\mathrm{GeV}$$

(Heckel, Adelberger, et al., PRL '06)

VI. Conclusions

⇒ Can use Lorentz & CPT violation as a candidate signal of new physics from the Planck scale

⇒ The Standard-Model Extension provides a common theoretical framework to analyze experiments

SME subsectors (Minimal SME, QED extension, etc.) can be used as a framework for theoretical investigations of Lorentz & CPT violation in a variety of experiments

⇒ atomic	⇒ nuclear
⇒ particle	⇒ astrophysical
⇒ gravitational	⇒ macroscopic

⇒ Impressive new CPT & Lorentz bounds have been obtained in QED experiments in recent years

(For data tables, see Kostelecky & Russell, arXiv:0801.0287)

New tests will continue to improve these results