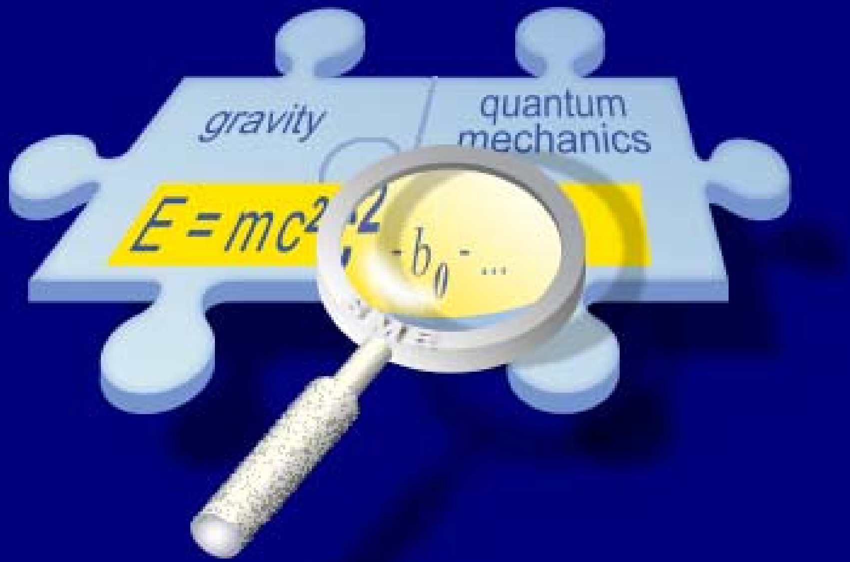
Discrete08

CPT and Lorentz violation as signatures for Planck-scale physics



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Prologue: Connection between Lorentz and CPT symmetry

Local, point-particle quantum field theories:

CPT theorem (Pauli, Lüders, Bell, '54):
"Lorentz symmetry implies CPT invariance"

Lorentz transf.
- rotations
- boosts

CPT transf.
- charge conjugation C
- parity inversion P
- time reversal T

Anti-CPT theorem (Greenberg, PRL '02):
"CPT violation implies Lorentz breaking"

→ **CPT tests are also Lorentz tests**
→ **will discuss CPT and Lorentz violation together**

can further relax assumptions (e.g., drop unitarity, see talk by N. Mavromatos)

Outline:

A. Motivation

B. SME test framework

C. Phenomenology and tests

A. Motivations for spacetime-symmetry tests

(i) philosophical necessity

spacetime symmetries are cornerstone of:

- present-day physics
- many candidate fundamental theories

→ spacetime symmetries must be tested

(ii) possibility of testing Planck-scale physics

Nongravitational physics is well described by Standard Model (SM),

but: - phenomenological (many parameters)
- several distinct interactions
- excludes gravity

Solution:	look for more fundamental theory

Candidates:	string (M) theory, loop gravity, supergravity, …

Problem:	Planck-scale measurements (attainable energies $\ll$ Planck scale)

common approach: scan predictions of a given theory for sub-Planck effects accessible with near-future technology, e.g.,
- novel particles (SuSy)
- large extra dimensions & microscopic black holes
- gravitational-wave background …

Alternative approach: What *can* be measured with Planck precision? *Is* there a corresponding quantum-gravity effect?

Symmetries:

- allow exact theoretical prediction
- are typically amenable to ultrahigh-precision (null) tests

Tests of spacetime symmetries could probe Planck-scale physics

Quantum gravity: likely to affect spacetime structure

- More than 4 dimensions?
- Non-commuting coordinates?
- Discreteness?
- “Foamy” structure? …

Sample mechanisms for Lorentz violation:

String field theory (Kostelecký *et al* ’89; ’90; ’91; ’95; '00)
nontrivial vacuum through spontaneous Lorentz breakdown

Spacetime foam (Ellis *et al* ‘98)
nontrivial vacuum though virtual black holes

Nontrivial spacetime topology (Klinkhamer ‘00)
nontrivial vacuum though compact conventional dim.

Loop quantum gravity (Alfaro *et al* ‘00)
nontrivial vacuum though choice of spin-network state

Noncommutative geometry (Carroll *et al* ‘01)
nontrivial vacuum through fixed $\theta^{\mu\nu} \sim [x^\mu, x^\nu]$

⋮

B. The SME test framework

(1) new transformations

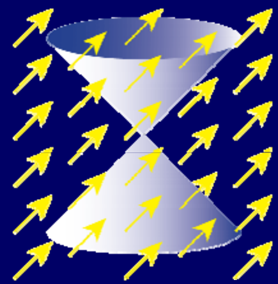
- vacuum remains "empty"
- no Minkowski structure
- deformed lightcone

- relativ. simple, kinematical, and phenomenological

E.g.: Robertson's framework, its Mansouri-Sexl extension, DSR, ...

(2) "background" fields

- ext. "fields" in vacuum
- conv. Minkowski structure
- conv. lightcone



- microscopic, dynamical, can be motivated (Sec. A)

SME: contains some of the kinematical approaches; will focus on this description

Construction of the SME

$$\mathcal{L}_{\mathrm{SME}} = \underbrace{\mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{EH}}}_{\text{present physics}}$$

- k^{μ}, $s^{\mu\nu}$, ... coefficients for Lorentz violation
- minimal SME $\rightarrow$ fermion 44, photon 23, ...
- amenable to ultrahigh-precision tests (Sec C)
- generated by underlying physics (Sec A)

Remark:

in gravitational context, various novel effects are possible (see R. Potting's talk)

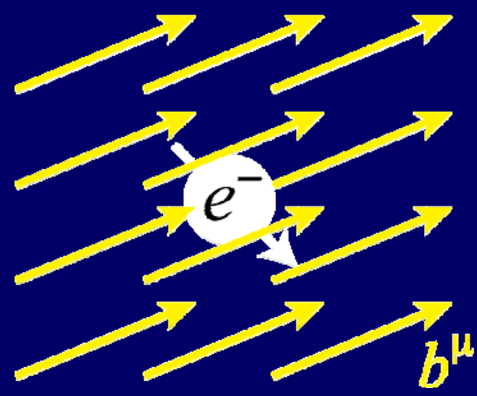
C. Phenomenology and tests

What needs to be measured?
Example:

- direction in vacuum
- assumed to be caused by underlying physics
- on observational grounds: extremely small
- want to bound it or measure its size and direction

$$\delta\mathcal{L}_{\text{fermion}} \supset \overline{\psi}\, b^\mu \gamma_5 \gamma_\mu \psi$$

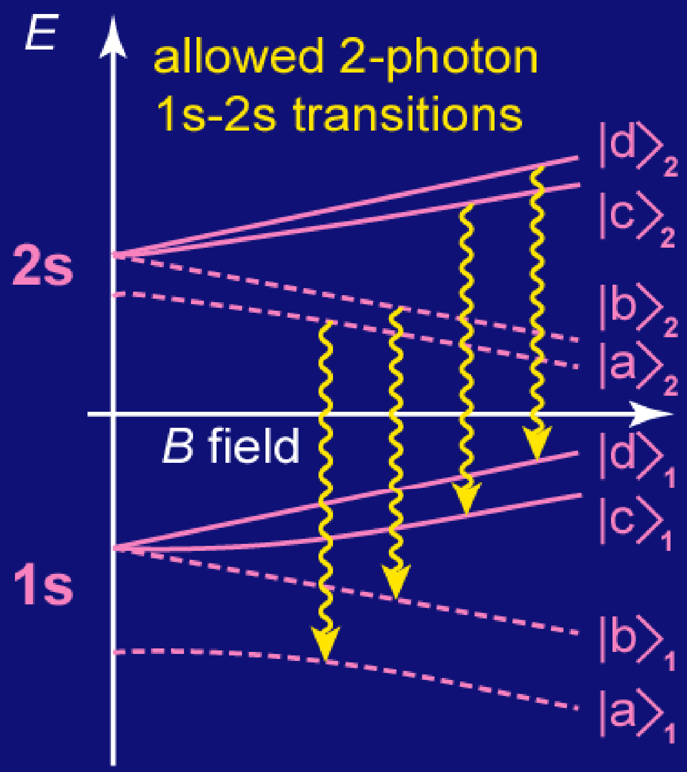
wave function of a fermion (e.g., electron) and usual Dirac gamma matrices (details of coupling)



Experimental tests of CPT symmetry

(i) Antihydrogen spectroscopy

The 1s-2s transition



only the c, d states are trapped

$|d\rangle_n = |\tfrac{1}{2},\tfrac{1}{2}\rangle$ **Note:** no spin mixing

$|c\rangle_n = \sin\theta_n\,|{-\tfrac{1}{2}},\tfrac{1}{2}\rangle + \cos\theta_n\,|\tfrac{1}{2},{-\tfrac{1}{2}}\rangle$

with $\tan 2\theta_n \simeq \dfrac{51\text{mT}}{n^3 B}$

Note: θ_n, and thus spin mixing, depends on level n and field B

How are $d \to d$ and $c \to c$ transitions affected by Lorentz/CPT violation?

The $d_2 \rightarrow d_1$ transition with Lorentz/CPT violation

Leading-order energy shifts (Bluhm, Kostelecký, Russell, PRL '99)

Hydrogen (electron and proton angular momenta J and I):

$$\Delta E_{LV} = \Delta E_{e+p} + \Delta E_{e} \frac{m_J}{|m_J|} + \Delta E_{p} \frac{m_I}{|m_I|}$$

level-independent combinations
of Lorentz-/CPT-violating SME coefficients

Note: both d_1 and d_2 have $m_J = 1/2$ and $m_I = 1/2$
$\longrightarrow$ shift is level independent

Result: no leading-order Lorentz/CPT violation in $d_2 \rightarrow d_1$ transition

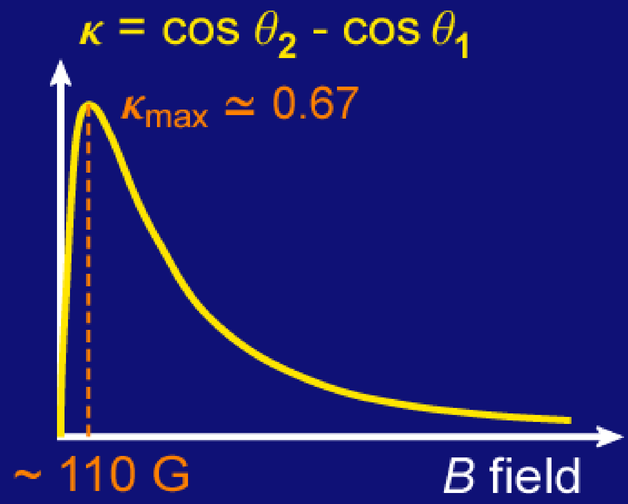
The $c_2 \rightarrow c_1$ transition with Lorentz/CPT violation

Difference between H and $\bar{\text{H}}$ transition frequencies
(Bluhm, Kostelecký, Russell, PRL '99):

level-dependent spin mixing
$\longrightarrow$ unsuppressed signal

$$\Delta E_H - \Delta E_{\bar{H}} \simeq \kappa \, \Delta E_{e+p}$$

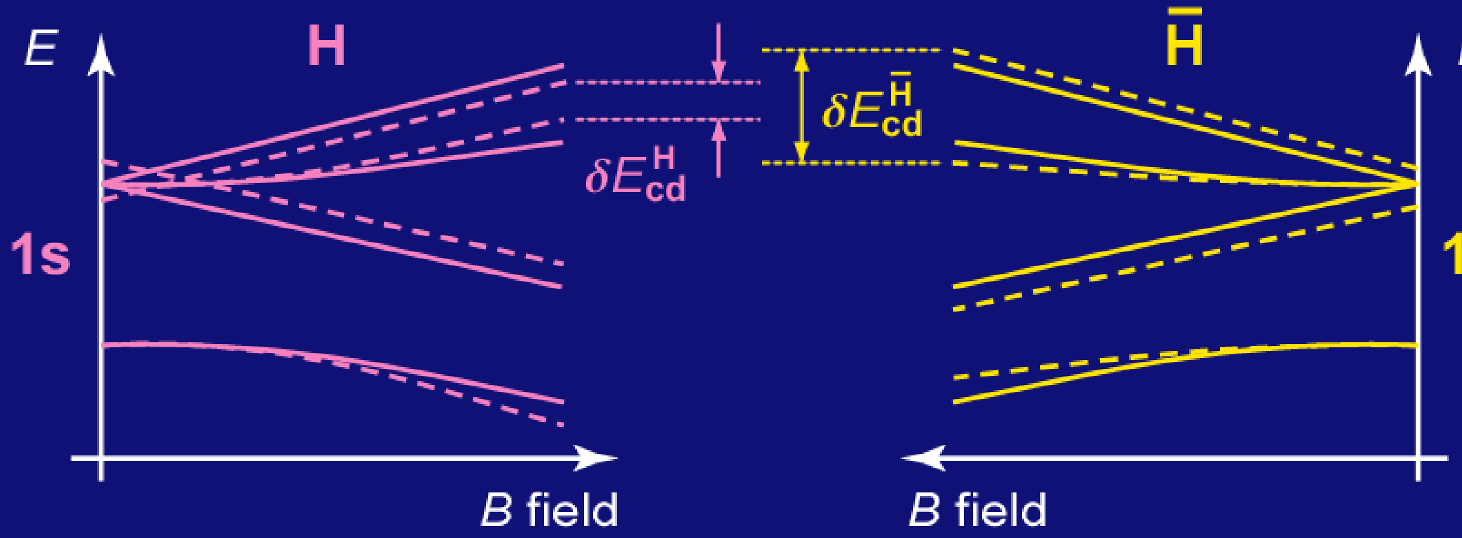
combination
of Lorentz-/CPT-violating
SME coefficients



Result: - leading-order Lorentz/CPT violation in $c_2 \rightarrow c_1$ transition
- experimental issue: effect is B-field dependent

Hyperfine Zeeman transitions within the 1s state

Difference between H and $\bar{\mathrm{H}}$ d1 → c1 transition frequencies
(Bluhm, Kostelecký, Russell, PRL '99):



at field-independent transition point ($B \simeq 0.65$T):

$\delta E^{\mathrm{H}}_{\mathrm{cd}} - \delta E^{\bar{\mathrm{H}}}_{\mathrm{cd}} \simeq$ (CPT-/Lorentz-violating SME coefficient for p)

instantaneous comparison assuming 1m Hz resolution:
10^{-17} eV sensitivity to |CPT-/Lorentz-violating SME coefficient for p|

(see E. Widmann's and B. Juhász' talks)

(ii) Neutral-meson oscillations

Effective description of neutral-meson system:

$$i\partial_t \psi = \Lambda \psi$$

two-component wave function

2x2 effective Hamiltonian

CPT violation iff difference of diagonal pieces of Λ nonzero

$$\Delta\Lambda \equiv \Lambda_{11} - \Lambda_{22} \neq 0$$

Nonzero prediction for $\Delta\Lambda$ within the SME:

$$\Delta\Lambda \simeq \beta^{\mu} \Delta a_{\mu}$$

4-velocity of meson in lab

difference of SME quark coefficients $-a_{\mu}^{q}\bar{q}\gamma^{\mu}q$

$\rightarrow$ requires time and direction binning

Sample sensitivities to Δa-type coefficients

K:	10^{-17}... 10^{-22} GeV	KLOE (see A. Di Domenico's talk), KTeV
D:	10^{-16} GeV	FOCUS
B_d:	10^{-15} GeV	BaBar

Summary

(1) At present, there are no experimental indications that CPT (or Special Relativity) is violated.

(2) Many theoretical approaches to fundamental physics lead to vacuum with a preferred direction (background), and therefore to CPT/Relativity violations.

(3) These effects are described (largely model independent) by a general test framework called the SME.

(4) Testing these ideas requires ultrahigh precision. Experimental studies with antimatter are excellent tools for these purposes.