Lorentz and CPT Tests Involving Antiprotons

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A. Introduction and Motivation

B. The Standard-Model Extension (SME)

C. Antihydrogen Spectroscopy

D. Penning-Trap Tests

E. Summary

Slow $\bar{p}$ Workshop, RIKEN, March 14-16

A. Introduction and Motivation

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 } ⊂ { LORENTZ TESTS }**

Why test Lorentz/CPT symmetry?

Lorentz/CPT symmetry is cornerstone of:

- present-day physics
- many candidate fundamental theories

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→ Lorentz/CPT symmetry must be tested

Why look for Lorentz/CPT violation?

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, varying scalars, …
Problem:	Planck-scale measurements (attainable energies $\ll$ Planck scale)
Idea:	experimentally check relations that - hold exactly in Standard Model - may be violated at fundamental level - can be measured with ultrahigh precision

Lorentz/CPT symmetry satisfy these criteria:

Standard Model (SM):

Lorentz/CPT symm. holds exactly

theories beyond SM:

Lorentz/CPT violation possible

prospect of ultrahigh-precision Lorentz/CPT tests

(e.g., ASACUSA, ATHENA, ATRAP)

Lorentz/CPT tests are useful tool in search for physics beyond SM

Some mechanisms for Lorentz/CPT violation:

String field theory (Kostelecký *et al.* '90)
nontrivial vacuum through spontaneous LV

Spacetime foam (Ellis *et al.* '98)
nontrivial vacuum through virtual black holes

Nontrivial spacetime topology (Klinkhamer '00)
nontrivial vacuum through compact conventional dim.

Loop quantum gravity (Alfaro *et al.* '00)
nontrivial vacuum through choice of spin-network state

Varying scalars (Kostelecký, R.L., Perry '02)
nontrivial vacuum through gradient of scalar

⋮

B. The Standard-Model Extension (SME)

Why low-energy effective theory?

Prediction of observable effects

Example: CPT $\Rightarrow$ particle mass $=$ antiparticle mass

$\not{\text{CPT}} \not\Rightarrow$ particle mass $\neq$ antiparticle mass

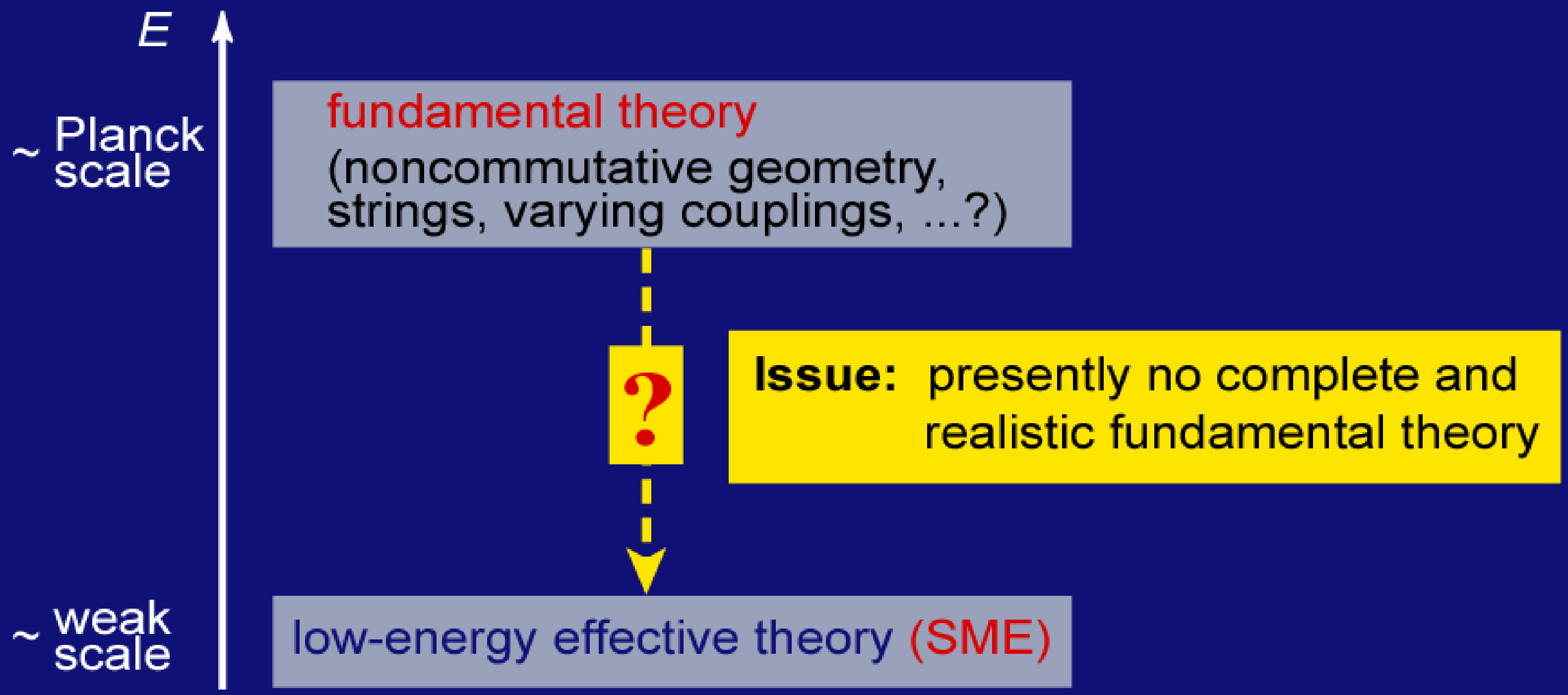
Relation between CPT-/Lorentz-breaking coefficients in different physical systems

Example: CPT-/Lorentz-breaking coefficients of quarks determine conventional, phenomenological CPT-violating parameters of kaon system

Insight into underlying theory

Example: stability / causality constrain underlying physics

How to obtain low-energy effective theory?



Idea: - examine manifestations of Lorentz/CPT violating vacuum
- construct all possible modifications to SM

Advantage: - independent of underlying theory
- describes all low-energy effects of Lorentz violation

Construction of the SME

Definition: $\mathcal{L}_{\text{SME}} = \mathcal{L}_{\text{SM}} + \delta\mathcal{L}$

where $\delta\mathcal{L}$ contains all operators of the form

(tensorial background) covariantly contracted w/ (SM fields)

particle LV — coordinate invariance

Sample terms:

$$b^{\mu}\,\overline{\psi}\,\gamma^5\gamma_{\mu}\psi\,,\ \ (\,b^{\mu}\,\overline{\psi}\,\gamma^5\gamma_{\mu}\psi\,)^2,\ \ c^{\mu\nu}\,\overline{\psi}\,i\gamma_{\mu}D_{\nu}\psi\,,\ \ (k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma},\ \ldots$$

Remarks:

- at low E ($\ll M_{\text{Pl}}$), the background is taken as constant and the renormalizable sector of the SME dominates
- other features (gauge and transl. invariance, ...) can be imposed

} minimal SME

(Colladay, Kostelecký '97; '98)

How to get SME predictions for low-energy fermions?

minimal SME

↓

Lorentz-violating QED

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modified Dirac equation

Remark: for composite fermions (e.g., protons), a few additional coefficients must be considered

↓ ↓

modified Pauli equation for nonrelativistic fermion	modified Pauli equation for nonrelativistic antifermion

These modified Pauli equations are employed for Lorentz/CPT studies with cold protons/antiprotons

Sample consequences of the SME

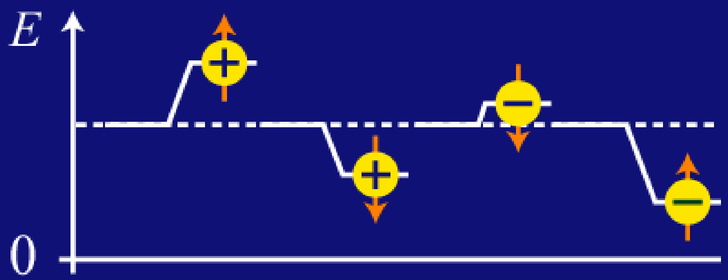
(i) modified, Lorentz-violating dispersion relations

Example:

general fermion dispersion relation (DR)

$$(p^2 - m^2)^2 + \text{CPT-/Lorentz-breaking corrections} = 0$$

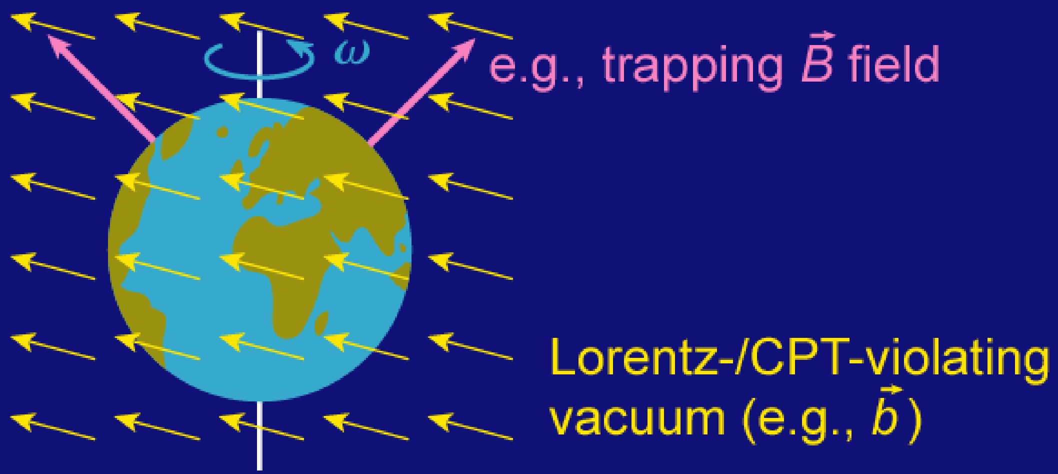
in general,
4-fold degeneracy of
$E\,(\vec{p} = \text{const.})$ is lifted



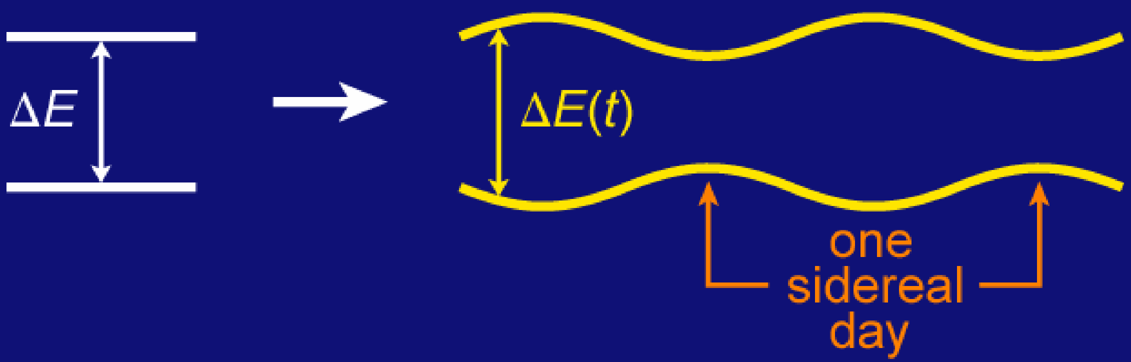
Remark:

can lead to difference in spectra for H and $\overline{\text{H}}$ (see Part C)

(ii) diurnal variations of observables



observables ~ $\vec{b} \cdot \vec{B}$ (e.g., transition frequencies) are time dependent:



Some experiments analysed within the minimal SME

Studies of neutral-meson systems

Kostelecký *et al.* '95; '96; '98; '00
OPAL Collaboration, Ackerstaff *et al.* '97
DELPHI Collaboration, Feindt *et al.* '97
KTeV Collaboration, Hsiung *et al.* '99

Tests involving photons and radiative effects

Carroll, Field, Jackiw '90
Colladay, Kostelecký '98
Jackiw, Kostelecký '99
Kostelecký, Mewes '01; '02
Kostelecký, R.L., Perry '02
Müller *et al.* '03
Lipa *et al.* '03

Penning-Trap experiments (see Part D)

Bluhm, Kostelecký, Russell '97; '98
Gabrielse *et al.* '99
Mittelman *et al.* '99
Dehmelt *et al.* '99

Hydrogen and Antihydrogen spectroscopy (see Part C)

Bluhm, Kostelecký, Russell '99
Phillips *et al.* '01

Studies of muons

Bluhm, Kostelecký, Lane '99
Hughes *et al.* '00

Clock-comparison tests

Kostelecký, Lane '99
Hunter *et al.* '99
Stoner '99
Bear et al. '00

Studies of baryogenesis

Bertolami *et al.* '97

Studies of neutrinos

Coleman, Glashow '99
Barger, Pakvasa, Weiler, Whisnant '00
Kostelecký, Mewes '03; '04

Kinematical studies of cosmic rays

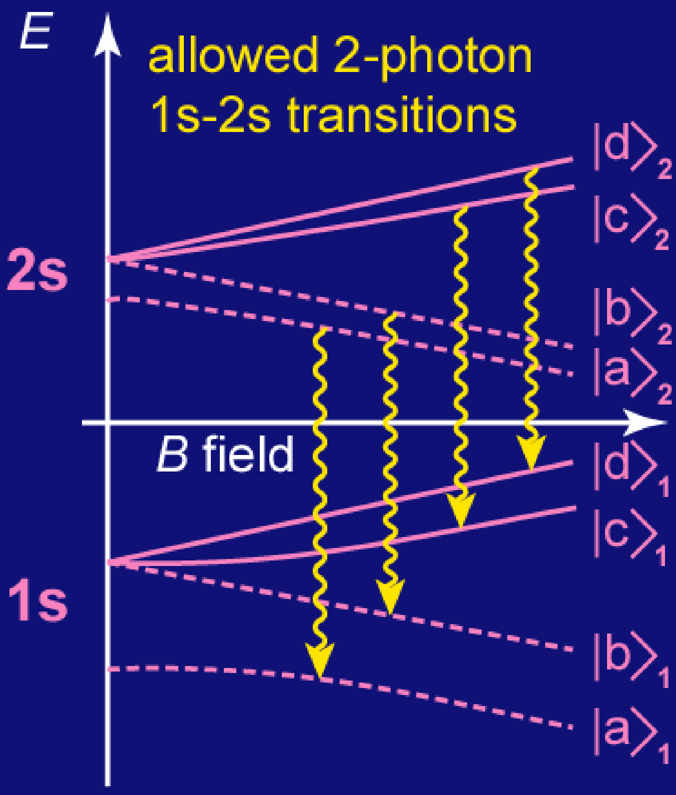
Coleman, Glashow '99
Bertolami, Carvalho '00
R.L. '03
Jankiewicz, Buniy, Kephart, Weiler '04

Tests on the ISS

Kostelecký *et al.* '02; '03
ACES
PARCS
RACE
SUMO
(OPTIS?)

C. 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→d and c→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):

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

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

Note: both d_1 and d_2 have $m_J = 1/2$ and $m_I = 1/2$

⟶ shift is level independent

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

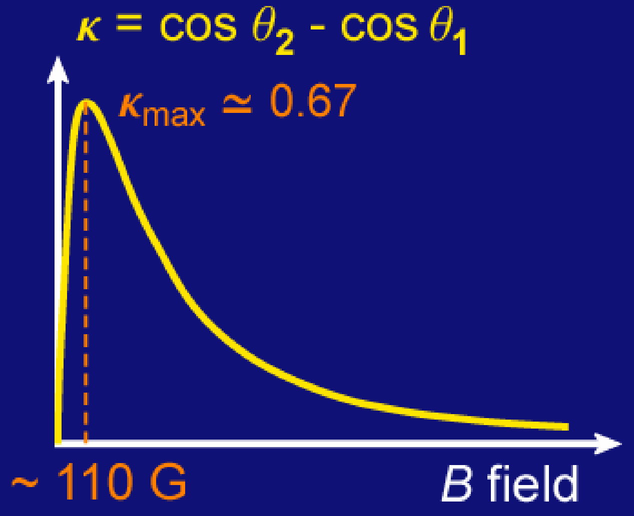
The $c_2 \rightarrow c_1$ transition with Lorentz/CPT violation

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

level-dependent spin mixing
⟶ unsupported signal

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

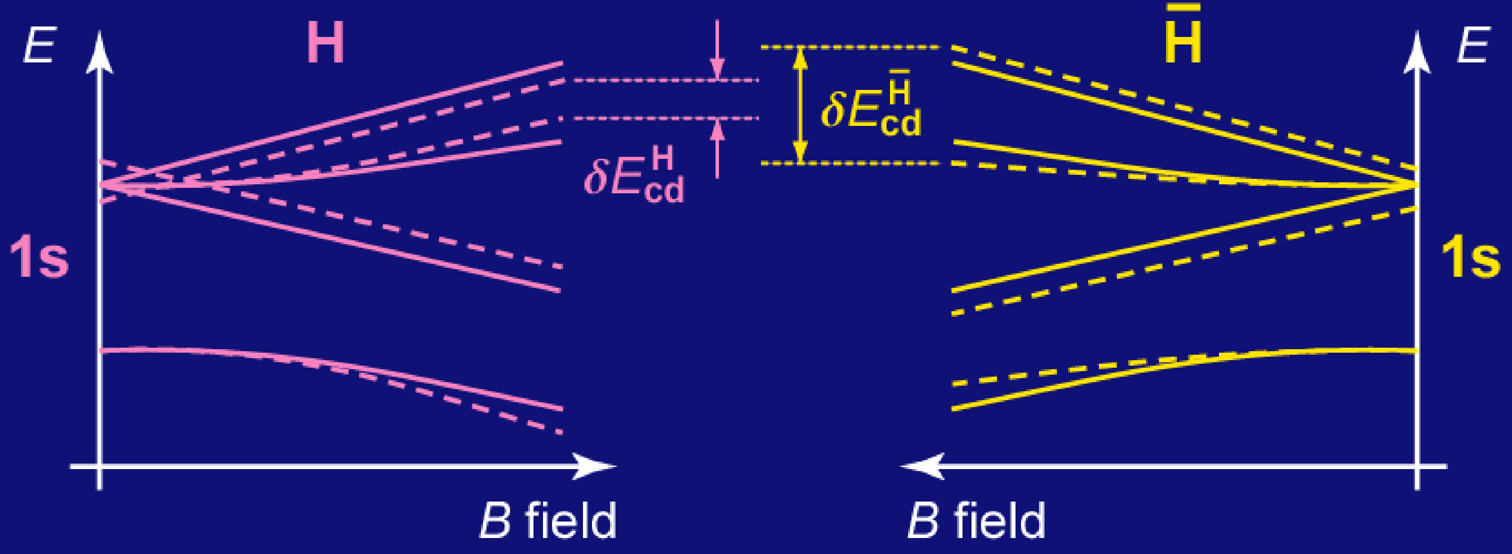
combination
of Lorentz-/CPT-violating
SME coefficients



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; Hayano's talk tomorrow):



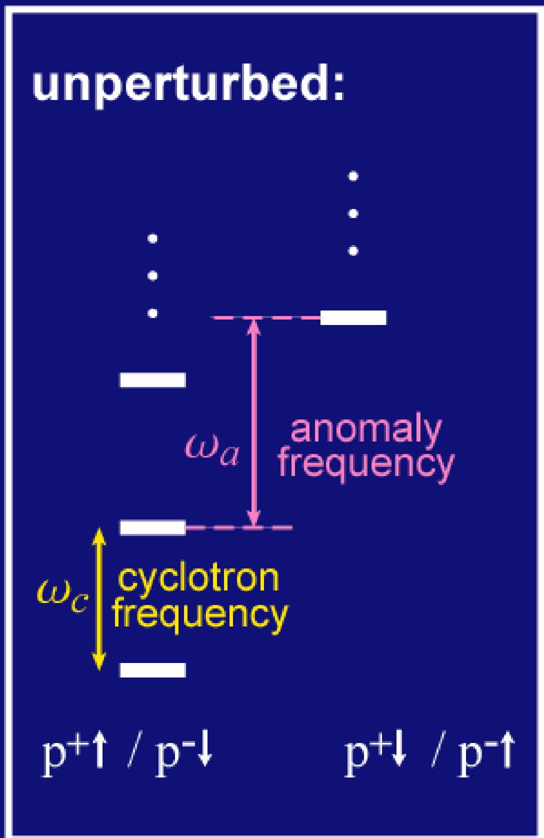
at field-independent transition point ($B \simeq 0.65$T):

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

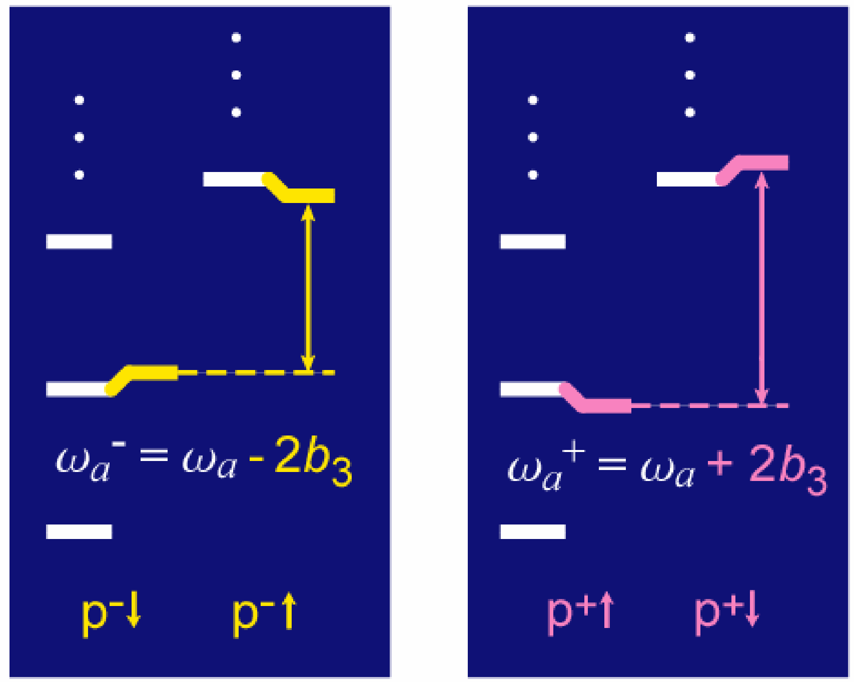
instantaneous comparison assuming 1m Hz resolution:
10^{-17} eV sensitivity to |CPT-/Lorentz-violating SME coefficient for p|

D. Penning-trap tests

Quantum-mechanical Penning-trap levels:



with Lorentz/CPT violation
(only SME b_3 coefficient contributes):



instantaneous comparison assuming 2 Hz resolution:
10^{-15} eV sensitivity to $|2b_3|$

E. Summary

observational tests of Lorentz/CPT symmetry are essential

- this symmetry is key ingredient in established physics
- promising tool in search for Planck-scale effects

test model for Lorentz/CPT violation is the SME

- extends our established basic physics laws to include leading-order Lorentz/CPT violation
- most general effective-field-theory test model
- has been basis for numerous Lorentz/CPT tests

cold antiprotons offer Planck-reach Lorentz/CPT tests

- unsuppressed effects in 1s-2s transition
- others in 1s hyperfine Zeeman transition
- bound parameter combinations inaccessible by other expts