Investigating Lorentz and CPT symmetry with antihydrogen

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Outline

- Lorentz & CPT violation
  - the standard-model extension
  - signal properties
- Hydrogen and Antihydrogen
  - 1S to 2S
  - Hyperfine Zeeman
- Results in other systems
  - Neutral mesons, Atomic systems, Electrodynamics

Lorentz and CPT symmetry

Nature appears symmetric under the transformations

Lorentz
- Rotations
- Boosts

CPT
- Charge conjugation
- Parity reversal
- Time reversal

CPT Theorem

Pauli, Lüders, Bell (1954)

Premise: local, point-particle, field theory, Lorentz invariant

Conclusion: CPT symmetric

Recently:

Greenberg hep-ph/0201258 (2002)

Premise: local quantum field theory

Conclusion: CPT violation implies Lorentz violation

Approaches to testing CPT

	Phenomenological	Theoretical Framework
PROS	•Practical approach	•Consistency with standard model •Experimental breadth •Predicts signal types
CONS	•Unclear theoretical basis •Experiment dependent •Limited predictive ability	•Challenging to find

Standard-model extension: a consistent, microscopic, general theoretical framework allowing Lorentz and CPT violation

Kostelecký, Potting, PRD **51** 3923 (1995)
Colladay, Kostelecký, PRD **55** 6760 (1997); PRD **58** 116002 (1998)

Standard-Model Extension: Idea

Fundamental Theory — String Theory?

↓

Spontaneous symmetry breaking?

↓

Standard model + minuscule extension terms

↓

QED, Dirac equation, ... + minuscule extension terms

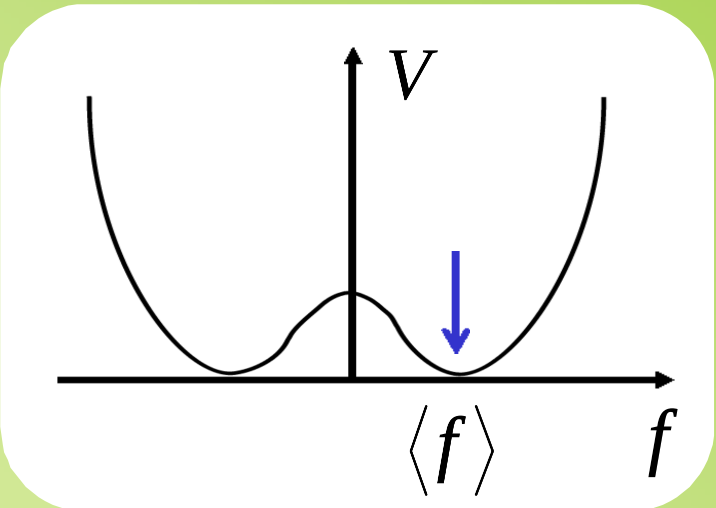
All break Lorentz symmetry;
some also break CPT

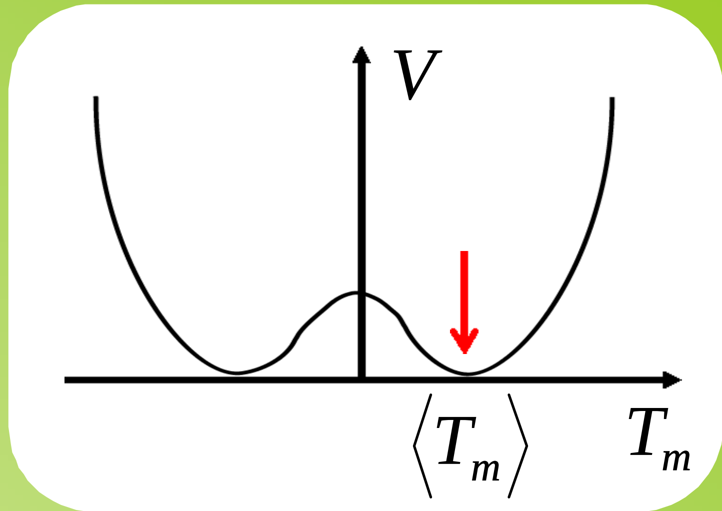
Kostelecký, Potting, PRD **51** 3923 (1995)
Colladay, Kostelecký, PRD **55** 6760 (1997); PRD **58** 116002 (1998)

Lorentz violation through spontaneous symmetry breaki

$\mathcal{L} \supset \lambda \phi \bar{\psi} \psi$

$\mathcal{L} \supset i T_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi$





$$\mathcal{L} \supset \underbrace{\lambda \langle \phi \rangle}_{m} \bar{\psi} \psi$$

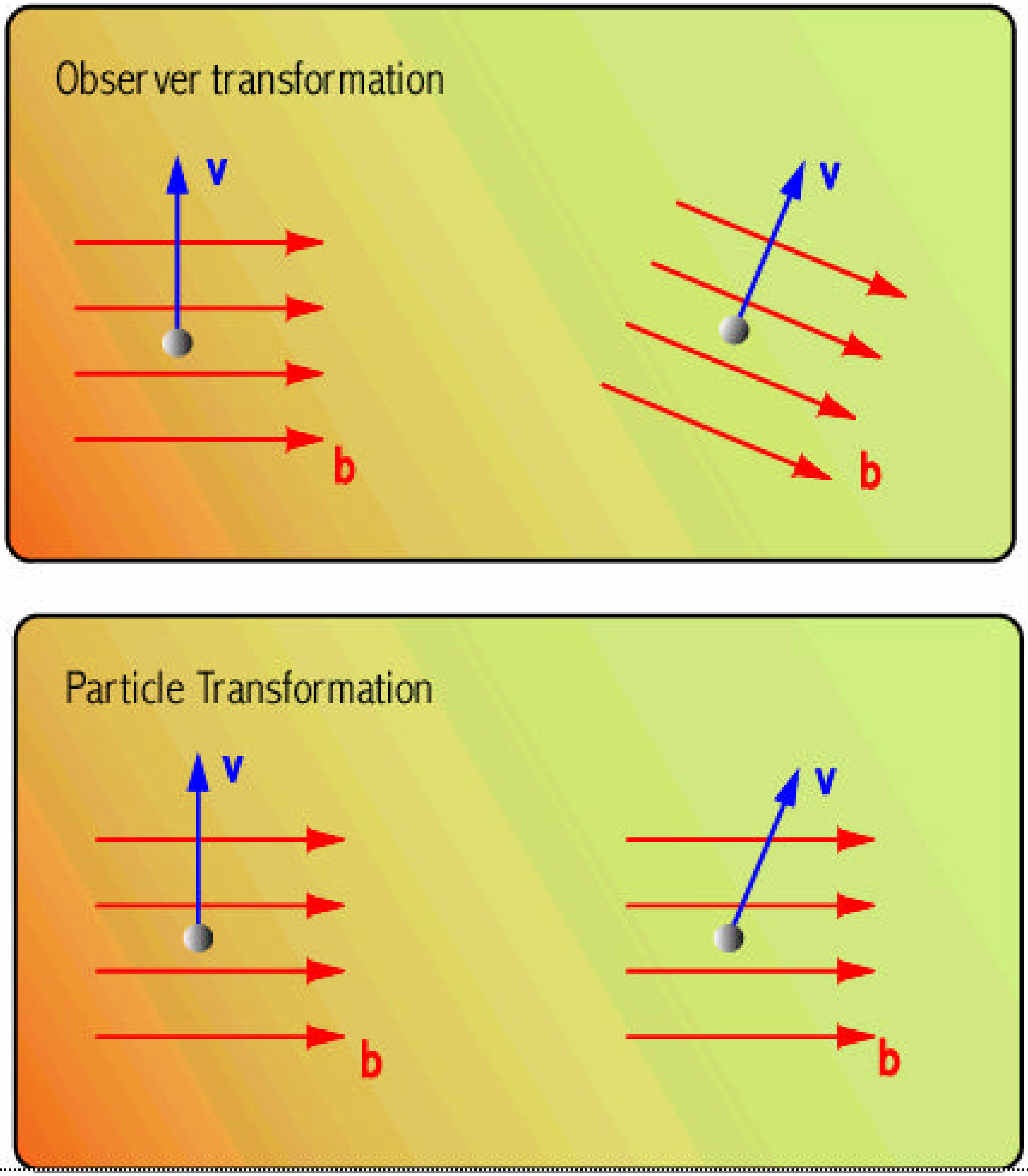
$$\mathcal{L} \supset \underbrace{\xi \langle T_\mu \rangle}_{b_\mu} \bar{\psi} \gamma_5 \gamma^\mu \psi$$

conventional

unconventional

Kostelecký, Samuel, PRD **39** 683 (1989); PRD **40** 1886 (1989)

Lorentz Transformations



Standard-model extension properties

Conventional	Unconventional
Gauge structure Power-counting renormalizability Energy and momentum conservation Quantization Microcausality Spin-statistics Observer Lorentz covariance	Particle Lorentz non-covariance CPT violation

Kostelecký, Potting, PRD **51** 3923 (1995)
Colladay, Kostelecký, PRD **55** 6760 (1997); PRD **58** 116002 (1998)

Special cases of standard-model extension include:

Realistic noncommutative field theories

-- noncommutative coordinates: $[x^\mu, x^\nu] = i\theta^{\mu\nu}$

-- q plays role of prescribed background tensor in QFT

Carrol et al, PRL **87** 141601 (2001)

Isotropic high-energy limit:

-- preferred frame,

-- one parameter for each species: Coleman, Glashow PRD **59** 116008 (1999

Others...

Perturbed Hamiltonian

Four-component spinor
for electron, positron,
or (anti)proton

CPT violating

$$\left(i\gamma^{\mu} D_{\mu} - m - a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_5\gamma^{\mu} - \tfrac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^{\mu}D^{\nu} + id_{\mu\nu}\gamma_5\gamma^{\mu}D^{\nu}\right)\psi = 0$$

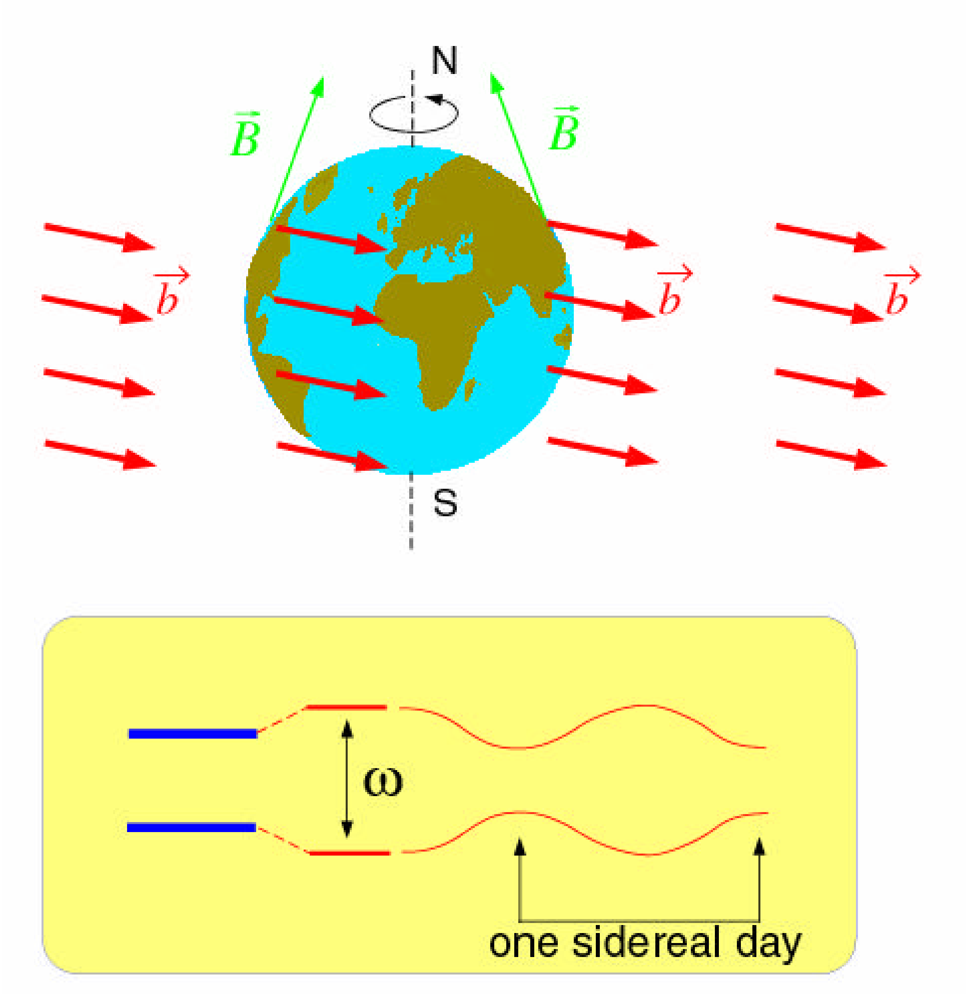
Regular Dirac
equation

- Minuscule Lorentz-violating terms
- Different parameters for each particle sector
- Field redefinition needed for Hamiltonian

Bluhm, Kostelecký, Russell PRL **82** 2254 (1999), for example

Sidereal variations

Kostelecký, PRL **80** 1818 (1998)

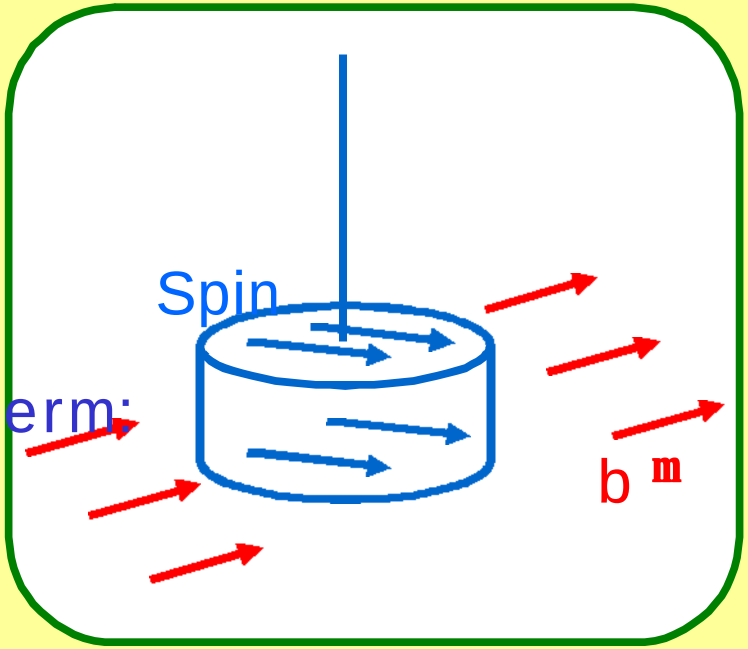


Example: Spin-polarized Matter

Torsion-balance apparatus
Spin-polarized test mass

Probe standard-model extension term:

$$V = \vec{b} \cdot \vec{s}$$



Analysis applies sidereal effects

Result:

$$\tilde{b}_J^e \lesssim 10^{-29}\ \text{GeV}$$

Bluhm, Kostelecký,
PRL **84** 1381 (2000)

Heckel, EotWash group,
CPT '01 Proceedings

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Hydrogen and Antihydrogen

ATRAP – first talk this session, Gabrielse

ATHENA – second talk this session, Doser

cold antihydrogen:

-- theoretical analysis possible for simple system

-- clean bounds should be possible

-- atomic clocks: no antiatoms, analysis complex, need models

Antiprotonic atoms

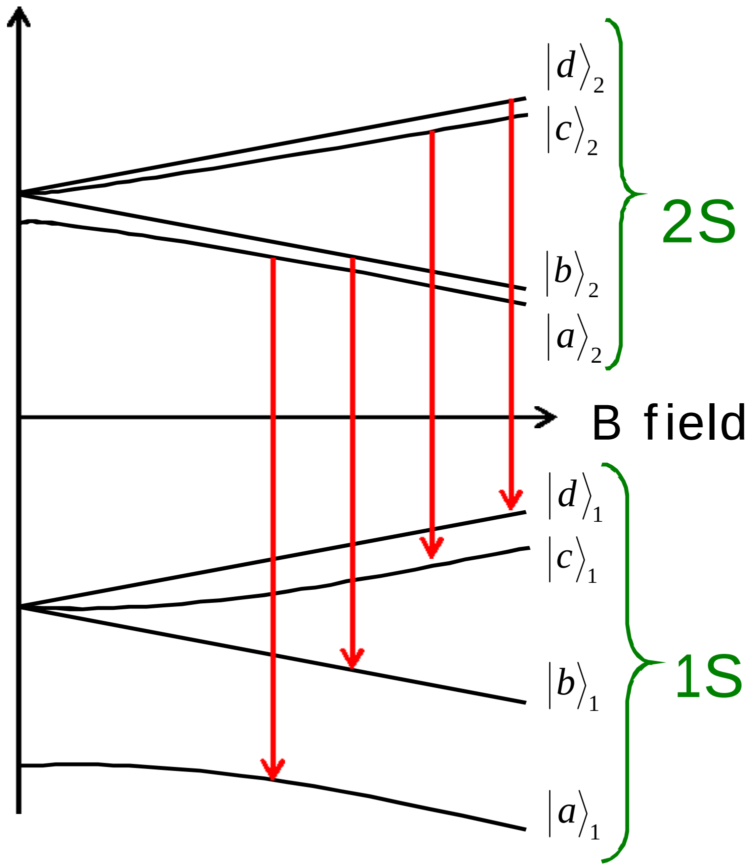
ASACUSA – third talk this session, Widmann

Antiprotonic He, for example:

-- potential for tests involving antiproton/proton comparison

1S-2S transition in trapped antihydrogen and hydrogen

Allowed 1S-2S transitions



Only the c and d states are trapped

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

$$\tan 2\theta_n \approx \frac{(51\ \mathrm{mT})}{n^3 B}$$

What are the effects on the c → c and d → d transitions?

Shifts in energy levels

Hydrogen with electron and proton angular momenta J and I :

$$\Delta E^H(m_J, m_I) \approx (a_0^e + a_0^p - c_{00}^e m_e - c_{00}^p m_p)$$
$$+(-b_3^e + d_{30}^e m_e + H_{12}^e) m_J/|m_J|$$
$$+(-b_3^p + d_{30}^p m_p + H_{12}^p) m_I/|m_I|$$

Antihydrogen: reverse signs of a, d and H parameters

No zero-order effect in d→d transition,
since n=1 and n=2 states have identical spin:

$$\left| m_J = +1/2, m_I = +1/2 \right\rangle$$

Bluhm, Kostelecký, Russell,
PRL **82** 2254 (1999)

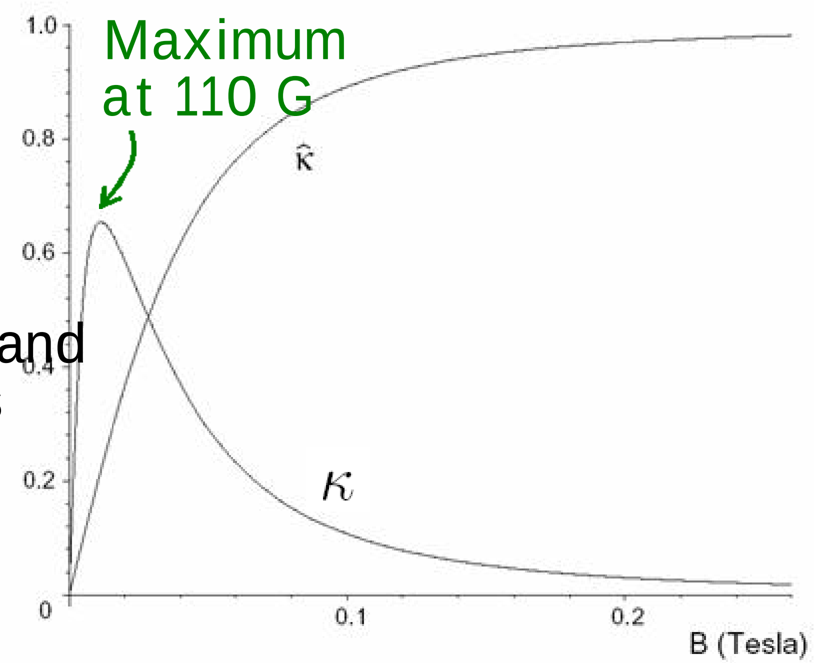
Signal in |c>→|c> transition

Spin mixing is different in 1S and 2S →unsuppressed signal

For c→c in hydrogen:

$$\delta\nu_c^H \approx -\kappa(b_3^e - b_3^p - d_{30}^e m_e + d_{30}^p m_p - H_{12}^e + H_{12}^p)/2\pi$$

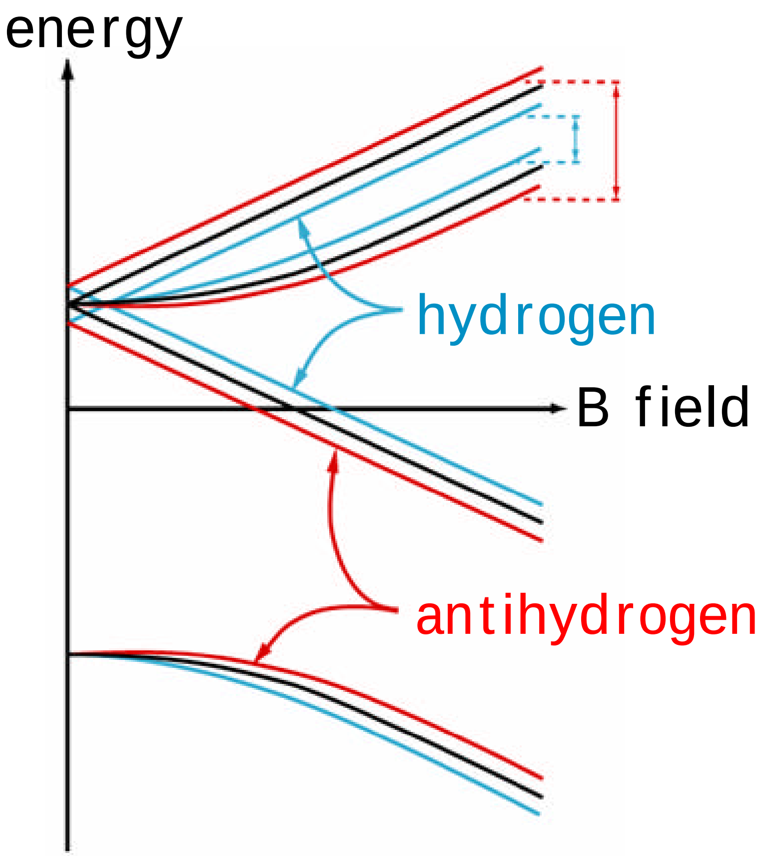
$$\kappa \equiv \cos 2\theta_2 - \cos 2\theta_1$$



For c→c in antihydrogen:
reverse signs of b parameters and
instantaneous comparison gives

$$\nu_c^H - \nu_c^{\overline{H}} \approx -\kappa(b_3^e - b_3^p)/\pi$$

Hyperfine Zeeman transitions



Bluhm, Kostelecký, Russell,
PRL **82** 2254 (1999)

Shifts are in opposite directions

$$\delta\nu^{H}_{c\to d} \approx (-b^p_3 + d^p_{30}m_p + H^p_{12})/\pi$$
$$\delta\nu^{\overline{H}}_{c\to d} \approx (b^p_3 + d^p_{30}m_p + H^p_{12})/\pi$$

Instantaneous comparison:

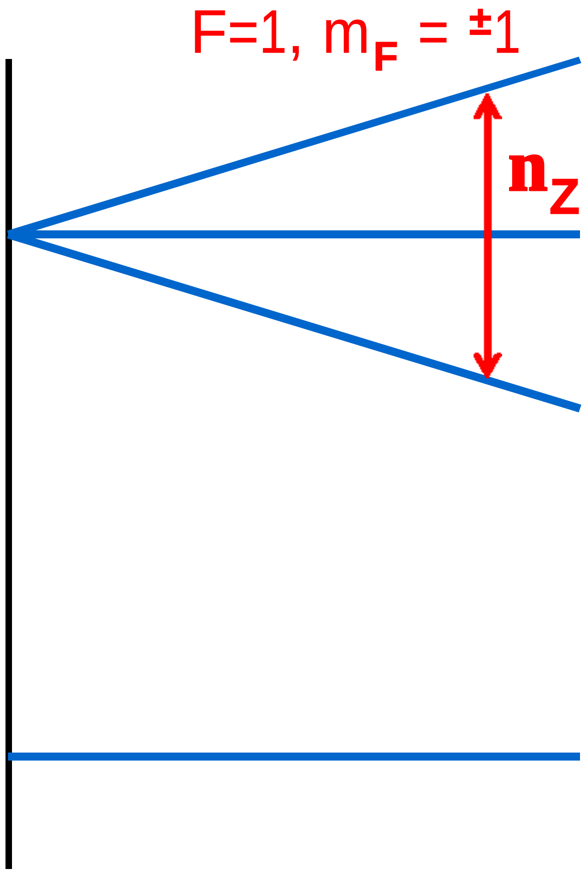
$$\nu^{H}_{c\to d} - \nu^{\overline{H}}_{c\to d} \approx -2b^p_3/\pi$$

With 1mHz resolution,

$$\left|b^p_3\right| \le 10^{-27}\,\mathrm{GeV}$$

Cleaner than any competing experiment

Hydrogen maser experiment



$$\left|\tilde{b}_3^p + \tilde{b}_3^e\right| \leq 2\pi\delta\nu_Z$$

$\delta\nu_Z$ < 370 nHz

Using electron bound,

$$\tilde{b}_J^p \leq 2 \times 10^{-27} \text{ GeV}$$

➔ Best proton bound

Phillips et al, PRD **63** 111101 R (2001)

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Neutral Mesons

Relevant mesons: *K, D,* B_d, B_s and antiparticles

Time evolution via 2×2 effective hamiltionian $\Lambda : i\partial_t \Psi = \Lambda\Psi$

CPT symmetry $\Leftrightarrow x = 0$ where $x \approx \Lambda_{11} - \Lambda_{22}$

Standard-model extension: $$x \approx b^m \Delta a_m$$

Decay probabilities have

velocity â dependence

sidereal dependence

Assumption of constant î is incompatible with QFT

Kostelecký, PRL **80** 1818 (1998);
PRD **61** 016002 (1999);
PRD **64** 076001 (2001)

Neutral Mesons: status of bounds on Δa_μ

Coefficient	K system	D system	B_d system	B_s system
$\tilde{a}$ / GeV	$\lesssim 10^{-20}$	$\lesssim 10^{-15}$	?	?
$a_\perp$ / GeV	$\lesssim 10^{-21}$	$\lesssim 10^{-15}$	?	?
Experiments	E773 reanalysis, KTeV	E831 (FOCUS) preliminary		

CPT '01 Proceedings:
Nguyen, KTeV Collab

CPT '01 Proceedings:
Gardner, FOCUS Collab

Existing/future B_d data could yield bounds (BaBar, BELLE, BTeV...)

Clock-comparison bounds

$^9Be^+$ and H maser
^{201}Hg and ^{199}Hg
^{21}Ne and ^3He
^{199}Hg and ^{133}Cs
^3He and ^{129}Xe

Sidereal, GeV

Kostelecký, Lane
PRD **60** 116010 (1999)

	tilde coefficient	Prestage *et al.*	Lamoreaux *et al.*	Chupp *et al.*	Berglund *et al.*	Bear *et al.*
p	b_J	*	*	–	−27	*
p	d_J	*	*	–	−25	*
p	$g_{D,J}$	*	*	–	−25	*
p	$c_{Q,J}$	*	–	–	–	–
p	$g_{Q,J}$	*	–	–	–	–
p	c_-	*	*	*	–	–
p	g_-	*	*	*	–	–
p	c_{XY}	*	*	*	–	–
p	g_{XY}	*	*	*	–	–
n	b_J	−27	−29	–	−30	−31
n	d_J	−25	−26	–	−28	−29
n	$g_{D,J}$	−25	−27	–	−28	−29
n	$c_{Q,J}$	−25	–	–	–	–
n	$g_{Q,J}$	*	–	–	–	–
n	c_-	−25	−27	−27	–	–
n	g_-	*	*	*	–	–
n	c_{XY}	−25	−27	−27	–	–
n	g_{XY}	*	*	*	–	–
e	b_J	–	–	–	−27	–
e	d_J	–	–	–	−22	–
e	$g_{D,J}$	–	–	–	−22	–
e	$c_{Q,J}$	–	–	–	–	–
e	$g_{Q,J}$	–	–	–	–	–
e	c_-	–	–	–	–	–
e	g_-	–	–	–	–	–
e	c_{XY}	–	–	–	–	–
e	g_{XY}	–	–	–	–	–

^{129}Xe/^{3}He Maser

Best test for neutron parameters in standard-model extension

$$\tilde{b}^n_\perp \equiv \sqrt{(\tilde{b}^n_X)^2 + (\tilde{b}^n_Y)^2} = (4.0 \pm 3.3) \times 10^{-31}\ \mathrm{GeV}$$

Bear et al, PRL **85** 5038 (2000)

Space-based clock-comparison tests

ACES, PARCS, RACE, SUMO:

Cs, Rb, and H masers planned for International Space Station;

Also Superconducting microwave oscillator experiment

Advantages of satellite platform

Orbit inclination and precession gives access to many more coefficient

- About 50 to 60 coefficients for each experiment

Greater speeds and rotation rates accessible in space

- Boost factor $v = 10^{-4}$ c
- Earth period 24 hours; Space station 92 minutes

Possible technological advantages

Bluhm, Kostelecký, Lane, Russell, PRL **88** 090801 (2002)

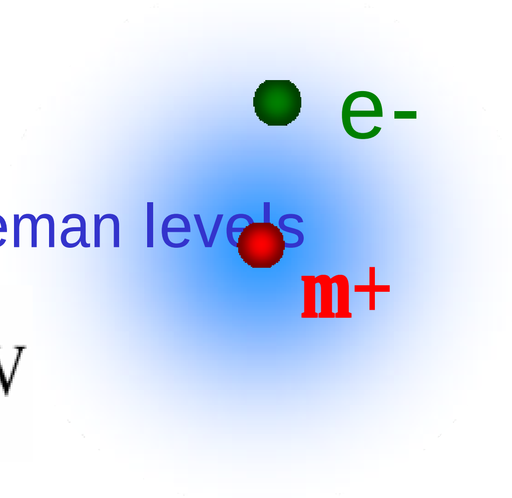
Penning-trap bounds

Results in context of standard-model extension

Type	Particles	Result	Reference
Instantaneous anomaly frequency	Electron, positron	10^{-21}	Dehmelt et al, PRL **83** 4694 (1999)
Instantaneous cyclotron frequency	Hydrogen ion, antiproton	10^{-26}	Gabrielse et al, PRL **82** 3198 (1999)
Sidereal anomaly frequency	Electron	10^{-21}	Mittleman et al, PRL **83** 2116 (1999)

Bluhm, Kostelecký, Russell, PRL **79** 1432 (1997);
PRD **57** 3932 (1998)

Muons



Muonium spectroscopy of hyperfine Zeeman levels

$$\sqrt{(\tilde{b}_X^{\mu})^2 + (\tilde{b}_Y^{\mu})^2} \leq 2 \times 10^{-23}\ \text{GeV}$$

CERN and BNL g-2 Experiments

Anomaly-frequency comparisons

$$b_Z^{\mu} < 10^{-23}\ \text{GeV}$$

Sidereal anomaly-frequency variations (estimated)

$$b_J^{\mu} < 10^{-24}\ \text{GeV}$$

Bluhm, Kostelecký, Lane, PRL **84** 1098 (2000);
Hughes et al, PRL **87** 111804 (2001);
Deile et al, CPT ’01 Proceedings

Electrodvnamics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}(k_F)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu}$$

Standard-model extension predicts birefringence

➔ Sensitive tests using astrophysical sources

Bounds from pulse spreading:

$$|k^a| < 3\text{x}10^{-16}$$

Bounds from differential polarization ro

$$|k^a| < 2\text{x}10^{-32}$$

"Best test of Special Relativity"

Kostelecký, Mewes, PRL **87** 251304 (2001); hep-ph/0205211

Summary

Standard-model extension: a viable theoretical framework that allows Lorentz and CPT violation

Trapped Antihydrogen

- Unsuppressed signal occurs in the 1S-2S transition
- Another occurs in the hyperfine Zeeman transition
- Comparisons of hydrogen and antihydrogen would produce clean bound on an untested parameter combination

Bounds exist in other systems —
neutral mesons, atomic systems, electrodynamics