Lorentz-symmetry violation and neutrino physics

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Outline:

A. Motivations

→ Possible origins of LV

B. Low-E effects; EFT

→ SME test framework for ν's

C. Phenomenology

→ qualitatively new effects for ν's

A. Why test Spacetime Symmetries?

Motivation (i): philosophical necessity

physics is an experimental science

$\rightarrow$ solid experimental confirmation of foundations of physics is crucial

Motivation (ii): discovery potential

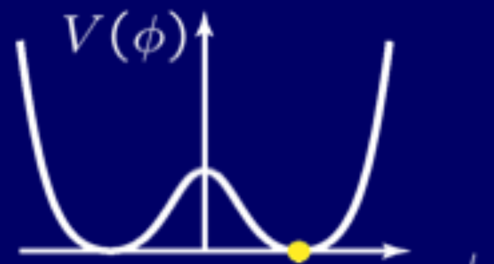
various approaches to physics beyond the Standard Model (e.g., "quantum gravity") can accommodate tiny violations of Relativity

Possible origins for Lorentz/CPT violation

(1) Spontaneous Lorentz breaking in string theory

conventional case:
gauge symmet.

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

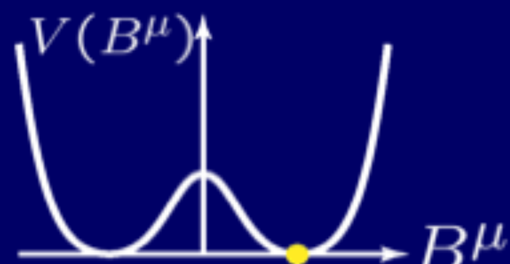


$\langle \phi \rangle \neq 0$

$$\mathcal{L} \supset \underbrace{\lambda \langle \phi \rangle}_{m\,=\,\text{const.}} \overline{\psi} \psi$$

string theory:
Lorentz
symmetry

$\mathcal{L} \supset \lambda B^{\mu} \overline{\psi} \gamma_5 \gamma_\mu \psi$



$\langle B^{\mu} \rangle \neq 0$

$$\mathcal{L} \supset \underbrace{\lambda \langle B^{\mu} \rangle}_{b^{\mu}\,=\,\text{const.}} \overline{\psi} \gamma_5 \gamma_\mu \psi$$

Kostelecký, Perry, Potting, Samuel '89; '90; '91; '95; '00

(2) Cosmol. varying scalars (e.g., fine-structure parameter)

intuitive argument:

gradient of the scalar selects pref. direction

mathematical argument:

$\xi = \xi(x)$ ... varying coupling
ϕ, Φ ... dynamical fields

$$\mathcal{L} \supset \xi \, \partial^\mu \phi \, \partial_\mu \Phi$$

Integration by parts:

$$\mathcal{L}' \supset -(\partial^\mu \xi) \, \phi \, \partial_\mu \Phi$$

slow variation of ξ:
$K^\mu \equiv (\partial^\mu \xi) \simeq$ const.

$$\mathcal{L}' \supset -K^\mu \, \phi \, \partial_\mu \Phi$$

Kostelecký, R.L., Perry '03; Arkani-Hamed et al. '03

Other mechanisms for Lorentz violation

Noncommutative field theory

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

Seiberg-Witten: $\widehat{x}^\mu \rightarrow$ usual Minkowski coordinates x^μ

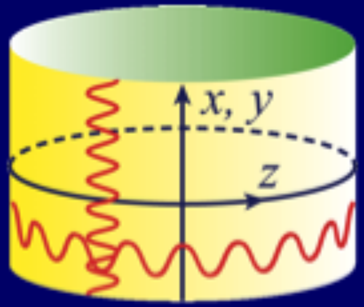
$\rightarrow$ SME terms emerge: $\mathcal{L}_{\text{photon}} \supset \frac{1}{8}\, q\, \theta^{\alpha\beta} F_{\alpha\beta} F^{\mu\nu} F_{\mu\nu}$

e.g. Mocioiu *et al.* '00; Carroll *et al.* '01

Topology (in usual $4d$ spacetime: 1 large compact dim.)

Vacuum fluctuations along this dim.
have periodic boundary conditions
$\rightarrow$ preferred direction in vacuum

$\rightarrow$ calculation: $k^\mu A^\nu \widetilde{F}_{\mu\nu} \subset \mathcal{L}_{\text{SME}}$



Klinkhamer '00

...

B. Effective field theory test framework

Why test framework?

- prediction of experimental effects
- analysis and comparison of tests
- theoretical insight

How to obtain test framework?

Purpose: broad experimental searches independent of details of underlying physics

→ construct gen. model compatible with key phys. principles

Ingredients for test framework?

- established physics → all feasible tests can be described
- effective field theory (well established & versatile tool)
- Lorentz/CPT violation (preferred directions; prev. Sec)

Actual construction of the effective field theory (SME)

$$\mathcal{L}_{\text{SME}} = \underbrace{\mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EH}}}_{\text{present physics}} + e k_\mu A_\nu \tilde{F}^{\mu\nu} + \frac{e}{2\kappa} s^{\mu\nu} R_{\mu\nu} + \ldots$$

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

Remarks:

- k^μ, $c^{\mu\nu}$, ... coefficients usually taken as spacetime constant
- situations involving gravity require more care
- many theor. SME studies → thus far no inconsistencies

Neutrinos with Lorentz/CPT violation

consider 6-dim. Hilbert space $(|e\rangle, |\mu\rangle, |\tau\rangle, |e\rangle^C, |\mu\rangle^C, |\tau\rangle^C)$:

q.m. ν propagation (incl. oscillations) governed by 6x6 Hamiltonian

$$H = \underbrace{\begin{pmatrix} |\vec{p}| + \frac{m_l m_l^\dagger}{2|\vec{p}|} & 0 \\ 0 & |\vec{p}| + \frac{m_l^\dagger m_l}{2|\vec{p}|} \end{pmatrix}}_{\text{usual LI piece}} + \underbrace{\frac{1}{|\vec{p}|}\begin{pmatrix} \hat{a} - \hat{c} & \hat{H} - \hat{g} \\ \hat{H}^\dagger - \hat{g}^\dagger & -\hat{a}^T - \hat{c}^T \end{pmatrix}}_{\text{LV \& CPTV correction}}$$

Lorentz-/CPT-violating *a*, *c*, *g*, and *H* contain:

(1) preferred directions arising from LV/CPTV background in $\delta\mathcal{L}$

(2) powers $(p^\mu)^{(d\text{-}3)}$ arising from operators of mass-dimension *d*

(3) polarization vectors ε^μ arising from the underlying spin d.o.f.

sample structure: $\hat{H} \supset \sim \epsilon_\mu \epsilon^*_\nu H^{(d)\mu\nu}{}_{\alpha_1 \dots \alpha_{d-3}}\, p^{\alpha_1} \dots p^{\alpha_{d-3}}$

Kostelecký and Mewes, arXiv:1112.6395

Reasoning leading to this result:

define $\Psi_A = (\psi_e, \psi_\mu, \psi_\tau, \psi_e^C, \psi_\mu^C, \psi_\tau^C)^T, \quad A = 1, \ldots, 6$

most general free, local, unitary, transl.-inv. EFT Lagrangian

$$\delta\mathcal{L}_{\rm EFT} = \overline{\Psi}_A(\hat{S}_{AB} + \hat{P}_{AB}\gamma_5 + \hat{V}^\mu_{AB}\gamma_\mu + \hat{A}^\mu_{AB}\gamma_5\gamma_\mu + \hat{T}^{\mu\nu}_{AB}\sigma_{\mu\nu})\Psi_B$$

S, P, V, A, T consist of LV/CPTV backgrounds & arbitrary # of ∂'s

Example: $$\hat{S}_{AB} \equiv \sum_{d=3}^{\infty} S^{(d)\ \alpha_1\alpha_2\ldots\alpha_{d-3}}_{AB}\,\partial_{\alpha_1}\partial_{\alpha_2}\ldots\partial_{\alpha_{d-3}}$$

Remarks:

- still some redundancies and LI pieces (removable)
- need to add h.c. for hermitian Lagrangian

$$\overset{B\ \longrightarrow}{A \downarrow \begin{pmatrix} \text{Dirac} & \text{Majorana} \\ \text{Majorana} & \text{Dirac} \end{pmatrix}}$$

assumptions: - LI masses are type-I seesaw compatible
- treat LV/CPTV as perturbation

LI unitary transformation #1:
- separate spinors into light Ψ_L and heavy Ψ_R fields
- effect: linear mixture of LV/CPTV terms

heavy Ψ_R don't propagate at low E can be projected out
- may now use 2-component Weyl spinors ξ for remaining Ψ_L
- effect: entries of flavor-space H reduce from 4x4 γ $\rightarrow$ 2x2 σ

LI unitary transformation (ultrarel. limit) #2:
- block-diagonalize to disentangle LI Dirac & Majorana m terms
- effects: linear mixture of LV/CPTV terms & p^{-1} dependence

remove C-conjugation redundancy by projecting onto positive E:
- effect 1: $\xi^{+} \sigma^{\mu} \xi$ introduces polarizations ε^{μ}
- effect 2: entries of flavor-space H reduce from 2x2 σ $\rightarrow$ $\mathbb{C}$

→ prev. displayed most general q.m. ν-propagation Hamiltonian in $(|e\rangle, |\mu\rangle, |\tau\rangle, |e\rangle^C, |\mu\rangle^C, |\tau\rangle^C)$ space compatible with EFT:

$$\delta H_{\rm SME}^{\rm propagation} = \frac{1}{|\vec{p}|}\begin{pmatrix} \hat{a} - \hat{c} & \hat{H} - \hat{g} \\ \hat{H}^\dagger - \hat{g}^\dagger & -\hat{a}^T - \hat{c}^T \end{pmatrix}$$

where a, c, g, H are lin. combinations of the LV/CPTV S, P, V^μ, A^μ, $T^{\mu\nu}$ quantities in the EFT Lagrangian

note: ν and anti-ν coefficients cannot be chosen independently

Ex. 1: no room for mass difference between ν and anti-ν in SME

Ex. 2: special choice: diagonalizable, isotropic, $c = 0$
→ $g = 0$, $H = 0$, and a takes special form involving $\overset{\circ}{a}{}_e^{(d)}$

neutrino disp. rel. $\overset{\circ}{E}_{\nu_e} = |\vec{p}| + \frac{m_e}{2|\vec{p}|} + \sum_d |\vec{p}|^{d-3} \overset{\circ}{a}{}_e^{(d)}$

antineutrino disp. rel. $\overset{\circ}{E}_{\overline{\nu}_e} = |\vec{p}| + \frac{m_e}{2|\vec{p}|} - \sum_d |\vec{p}|^{d-3} \overset{\circ}{a}{}_e^{(d)}$

C. Phenomenology and Tests

Novel qualitative features in neutrino oscillations

eff. Hamiltonian for 3 left-handed ν's in flavor basis (a,b ... e,μ,τ):

p_μ ... ν propagation direction
→ directional dependence

$$(H+\delta H)_{ab} = \frac{1}{2|\vec{p}|}(m_l\, m_l{}^\dagger)_{ab} + (a^\mu)_{ab}\,\overbrace{\hat{p}_\mu} - (c^{\mu\nu})_{ab}\,\overbrace{\hat{p}_\mu\hat{p}_\nu}E + \ldots$$

$$(a^\mu)_{ab} \xrightarrow{\bar{\nu}} -(a^\mu)^*_{ab}$$

→ CPT violation

unconventional
E dependence
→ $U = U(E)$

→ great flexibility for matching observations models based on this general effective Hamiltonian:

- "bicycle model" (Kostelecký *et al.*, 2004)
- "tandem model" (Katori *et al.*, 2006)
- "BMW model" (Barger *et al.*, 2007)
- "puma model" (Díaz *et al.*, 2010)
- "isotropic bicycle model" (Barger *et al.*, 2011) . . .

phenomenology: example "puma model"

	3νSM	"puma model"
established results (with $\theta_{13} = 0$)	needs 5 parameters	needs only 2 parameters
LSND anomaly MiniBooNE low-*E* excess	its 6 parameters are insufficient	needs 6 parameters

most recent exp. results: arXiv:0801.0287v5, January 2012 edition

- 12 pages of tables for $d = 2, 3, 4, 5, 6$, and $d > 6$
- analyses by MINOS, IceCube, MiniBooNE, LSND, …
- sample section of table:

Table XIII. Neutrino sector, $d = 3$

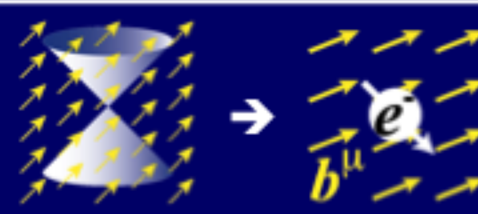
Combination	Result	System	Ref.
$\lvert \mathring{a}^{(3)} \rvert$	$< 1.9 \times 10^{-7}$ GeV	IceCube meson threshold	[13]*
$\lvert \mathrm{Re}(a_L)^X_{\mu\tau} \rvert$	$< 5.9 \times 10^{-23}$ GeV	MINOS	[103]
$\lvert \mathrm{Im}(a_L)^X_{\mu\tau} \rvert$	$< 2.2 \times 10^{-20}$ GeV	"	[103]
$\lvert \mathrm{Re}(a_L)^Y_{\mu\tau} \rvert$	$< 6.1 \times 10^{-23}$ GeV	"	[103]
$\lvert \mathrm{Im}(a_L)^Y_{\mu\tau} \rvert$	$< 2.2 \times 10^{-20}$ GeV	"	[103]
$a_L^X,\ a_L^Y$	$< 1.8 \times 10^{-23}$ GeV	IceCube	[104]
$\lvert (a_L)^X_{\mu\tau} \rvert$	$< 5.9 \times 10^{-23}$ GeV	MINOS FD	[105]
$\lvert (a_L)^Y_{\mu\tau} \rvert$	$< 6.1 \times 10^{-23}$ GeV	"	[105]
$\lvert a_L^X \rvert,\ \lvert a_L^Y \rvert$	$< 3.0 \times 10^{-20}$ GeV	MINOS ND	[106]
$\lvert \mathrm{Re}(a^{(3)}_{\mathrm{eff}})^{e\mu}_{00} \rvert$	$< 1.3 \times 10^{-18}$ GeV	LSND	[13]*
"	$< 1.5 \times 10^{-19}$ GeV	MiniBooNE	[13]*
"	$< 9.2 \times 10^{-20}$ GeV	MiniBooNE $\overline{\nu}$	[13]*

Summary

presently no compelling exp. evidence for Relativity violations, but:

(1) various theoretical approaches to quantum gravity can cause such violations

(2) at low E, such violations are described by SME test framework (eff. field theory + background fields)



(3) for free ν's, all Lorentz-/CPT-violating operators compatible with local, unitary EFT have been classified

(4) Lorentz/CPT violation predicts a wealth of qualitatively novel features; provides ample ground for phenomenological model building