Indiana University

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Physics of Fundamental Symmetries and Interactions

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IUCSS

Indiana University Center for Spacetime Symmetries

Tests of Lorentz symmetry in neutron decay

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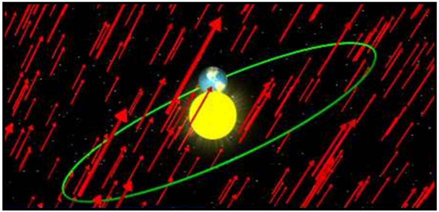
based on arXiv:1305.4636
in collaboration with V.A. Kostelecký and R. Lehnert

Standard-Model Extension (SME)

Colladay & Kostelecký, PRD **55**, 6760 (1997)
Colladay & Kostelecký, PRD **58**, 116002 (1998)
Kostelecký, PRD **69**, 105009 (2004)

SME $=$ **Standard Model coupled to General Relativity** $+$ **all possible terms that break Lorentz symmetry**



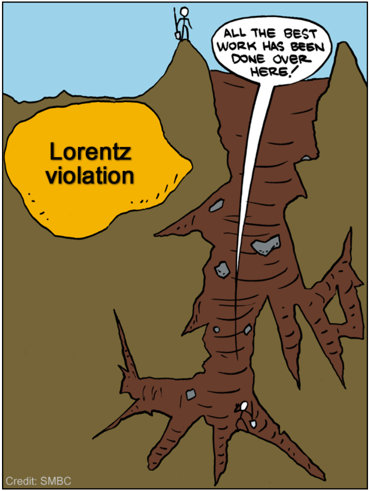
example (from the fermion sector):

$$\mathcal{L}_{\text{LV}} \supset a_\mu \left(\overline{\psi} \gamma^\mu \psi \right)$$

- Standard fields
- Controlling coefficients
- Observer scalars
- CPT violation included (no $m \neq \bar{m}$ terms)

- General framework for studying possible breaking of Lorentz symmetry
- It tells us what effect to look for in a given experiment

Searches for Lorentz-violating neutrinos



Systematic searches based on the SME

study	source	method	Ref.
LSND	accelerator	oscillations	PRD 2005
MINOS	accelerator	oscillations	PRL 2008
MINOS	accelerator	oscillations	PRL 2010
IceCube	atmospheric	oscillations	PRD 2010
MINOS	accelerator	oscillations	PRD 2012
Double Chooz	reactor	oscillations	PRD 2012
Kostelecký *et al.*	accelerator	time of flight	PRD 2012
"	SN1987A	time of flight	"
"	atmospheric	Čerenkov	"
MiniBooNE	accelerator	oscillations	PLB 2013
Mufson *et al.*	accelerator	oscillations	AP 2013
JSD *et al.*	reactor	oscillations	1307.5789
Super-K	atmospheric	oscillations	1308.2210
JSD *et al.*	atmospheric	Čerenkov	1308.6344
"	astrophysical	Čerenkov	"

Data tables for Lorentz and CPT violation
2013 edition arXiv:0801.0287v6

some *oscillation-free operators* can only be studied in weak decays!

Neutrinos in the minimal SME

Kostelecký & Mewes, PRD 69, 016005 (2004)
Kostelecký & Mewes, PRD 85, 096005 (2012)

$$\mathcal{L}_\nu = \tfrac{i}{2}\,\overline{\psi}\gamma^\alpha\partial_\alpha\psi + \tfrac{1}{2}\,(\boldsymbol{c}_L)_{\alpha\beta}\left(\overline{\psi}\gamma^\alpha\partial^\beta\psi\right) + \tfrac{1}{2}\,(\boldsymbol{a}_L)_\alpha\left(\overline{\psi}\gamma^\alpha\psi\right) + \text{h.c.}$$

CPT even: $(\boldsymbol{c}_L)^{\alpha\beta} = (\boldsymbol{c}_{\text{of}})^{\alpha\beta} + (\boldsymbol{c}_{\text{osc}})^{\alpha\beta}$

CPT odd: $(\boldsymbol{a}_L)^{\alpha} = (\boldsymbol{a}_{\text{of}})^{\alpha} + (\boldsymbol{a}_{\text{osc}})^{\alpha}$

decomposition into oscillation-free & oscillatory terms

Experimental observable

coefficient	oscillations	time of flight	weak decays	energy regime
$(\boldsymbol{c}_{\text{of}})^{\alpha\beta}$	×	✓	✓	high E
$(\boldsymbol{c}_{\text{osc}})^{\alpha\beta}$	✓	✓	✓	high E
$(\boldsymbol{a}_{\text{of}})^{\alpha}$	×	×	✓	E **independent**
$(\boldsymbol{a}_{\text{osc}})^{\alpha}$	✓	×	✓	E independent

Coefficient $(\boldsymbol{a}_{\text{of}})^{\alpha}$ controls **Lorentz violation** and **CPT violation**

→ four independent components $(\boldsymbol{a}_{\text{of}})_{00}, (\boldsymbol{a}_{\text{of}})_{10}, \text{Re}(\boldsymbol{a}_{\text{of}})_{11}, \text{Im}(\boldsymbol{a}_{\text{of}})_{11}$

Neutron decay in the minimal SME

JSD, Kostelecký & Lehnert, arXiv:1305.4636

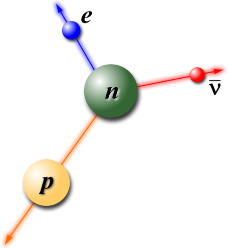
Theoretical considerations:

- Lorentz violation in the neutrino sector*
- antineutrino spinors get modified
- modified antineutrino phase space

Lorentz violation in W boson

S.E. Müller, H.Interact. 210, 33 (2012)
J.P. Noordmans, PRC 87, 055502 (2013)
E.A. Dijck et al., arXiv:1303.6419
J.P. Noordmans, arXiv:1308.5570
B. Altschul, arXiv:1308.2602

$$d\Gamma \propto E\omega\left\{1 + a\frac{\boldsymbol{p}\cdot\widetilde{\boldsymbol{q}}}{E\omega} + A\,\frac{\hat{\boldsymbol{n}}\cdot\boldsymbol{p}}{E} + B\,\frac{\hat{\boldsymbol{n}}\cdot\widetilde{\boldsymbol{q}}}{\omega} + D\,\frac{\hat{\boldsymbol{n}}\cdot(\boldsymbol{p}\times\widetilde{\boldsymbol{q}})}{E\omega}\right\} \times\frac{d^3p}{2E}\frac{d^3\widetilde{q}}{2\omega}\,\delta(E+\omega-E_0)$$



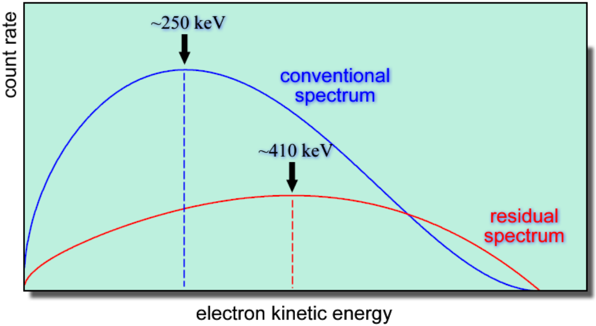
Observable effects

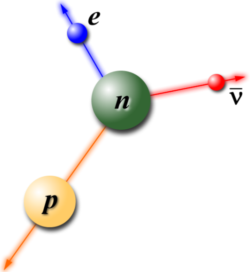
- spectrum distortion
- modified experimental electron-neutrino asymmetry a_{exp}
- modified experimental neutrino asymmetry B_{exp}

Neutron decay in the minimal SME

JSD, Kostelecký & Lehnert, arXiv:1305.4636

1. spectrum distortion



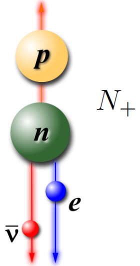


- generated by isotropic Lorentz violation: $(a_{\text{of}})_{00}$
- requires searching for deviations from conventional spectrum
- effect is maximal at a well-defined energy
- $(a_{\text{of}})_{00}$ also controls a **new source of CP violation**

Neutron decay in the minimal SME

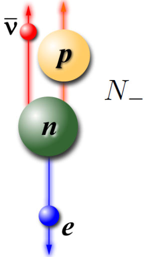
JSD, Kostelecký & Lehnert, arXiv:1305.4636

2. experimental electron-neutrino asymmetry a_{exp}



$$a_{\text{exp}} = \frac{N_+ - N_-}{N_+ + N_-}$$

$$= a\beta + (a_{\text{exp},\mathcal{C}}) + (a_{\text{exp},s}) \sin \omega_\oplus T_\oplus + (a_{\text{exp},c}) \cos \omega_\oplus T_\oplus$$



- sensitivity to anisotropic Lorentz violation
- constant modification: $(\boldsymbol{a}_{\text{of}})_{10}$
- sidereal variation of asymmetry: $\text{Re}(\boldsymbol{a}_{\text{of}})_{11}$, $\text{Im}(\boldsymbol{a}_{\text{of}})_{11}$
- requires time stamps for each event

Earth's sidereal frequency: $\omega_\oplus \simeq 2\pi/(23 \text{ h } 56 \text{ min})$

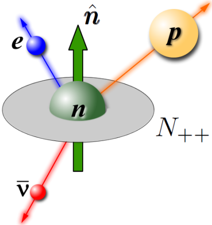
Neutron decay in the minimal SME

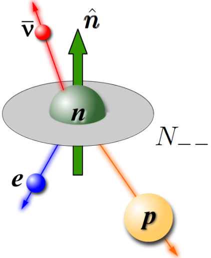
JSD, Kostelecký & Lehnert, arXiv:1305.4636

3. experimental neutrino asymmetry B_{exp}

$$B_{\text{exp}} = \frac{N_{--} - N_{++}}{N_{--} + N_{++}}$$

$$= B_{\text{exp},0} + (B_{\text{exp},\mathcal{C}}) + (B_{\text{exp},s}) \sin \omega_\oplus T_\oplus + (B_{\text{exp},c}) \cos \omega_\oplus T_\oplus$$





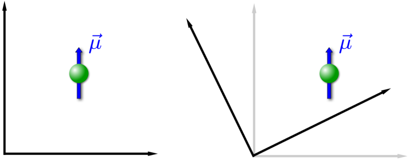
- polarized neutrons
- sensitivity to anisotropic Lorentz violation
- constant modification: $(a_{\text{of}})_{10}$
- sidereal variation of asymmetry: Re$(a_{\text{of}})_{11}$, Im$(a_{\text{of}})_{11}$
- requires time stamps for each event

Summary

- We have determined the **key observable effects** of neutrino Lorentz and CPT violation using neutron decay
- Neutron experiments have access to **unique and unexplored** effects of Lorentz violation in the neutrino sector
- Beta decay is a **complement** to oscillation tests of Lorentz invariance
- Interesting prospects for **theory-experiment collaboration**
- Most of the data for these tests **already exist**

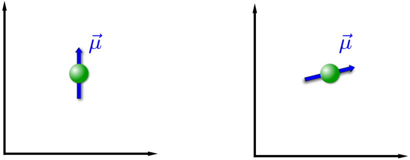
Lorentz transformations

Observer transformation



coordinate invariance

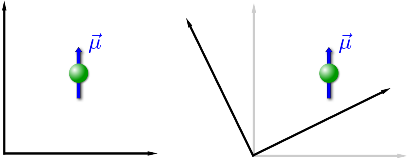
Particle transformation



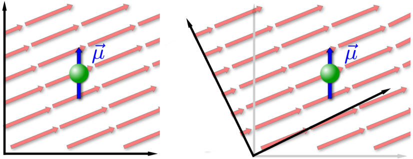
symmetry

Lorentz transformations

Observer transformation

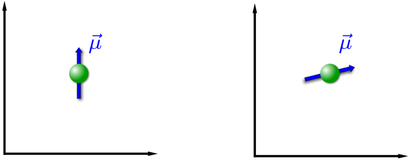


coordinate invariance



coordinate invariance

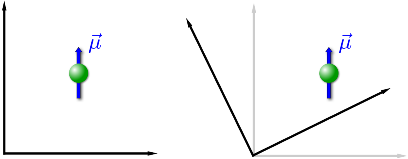
Particle transformation



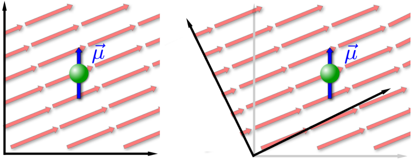
symmetry

Lorentz transformations

Observer transformation

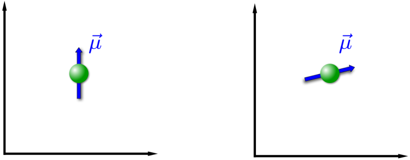


coordinate invariance

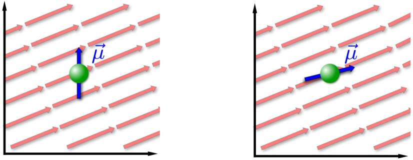


coordinate invariance

Particle transformation



symmetry



broken symmetry

References

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