Implications of a Matter-Antimatter Mass Asymmetry in Penning Trap Experiments

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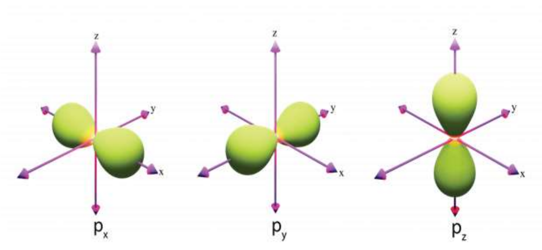
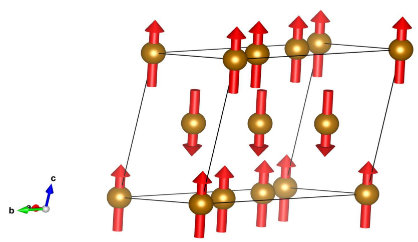
Cheng et al., Physics Letters B, 2023

Symmetry in physics

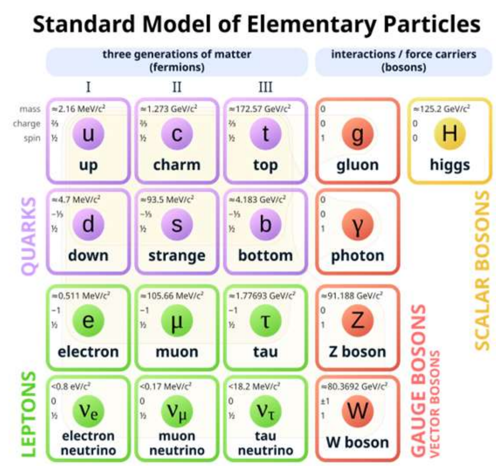
- Symmetry plays a crucial role in our understanding of physical systems



Atomic orbitals



Ordered states of matter



Quantum fields and elementary particles

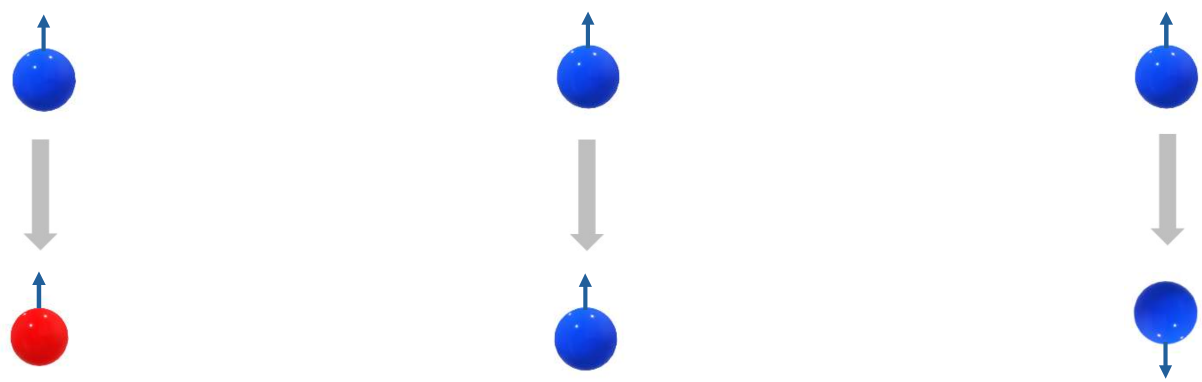
Symmetries can be explicitly or spontaneously broken

CPT symmetry in quantum field theory

- Theorem: All Lorentz-invariant, local QFTs are invariant under the simultaneous action of CPT: charge conjugation (C), parity (P), and time-reversal (T)

$\mathcal{C} : q \to -q$ $\qquad$ $\mathcal{P} : (t, \mathbf{r}) \to (t, -\mathbf{r})$ $\qquad$ $\mathcal{T} : (t, \mathbf{r}) \to (-t, \mathbf{r})$

Action on a spinful charged particle:

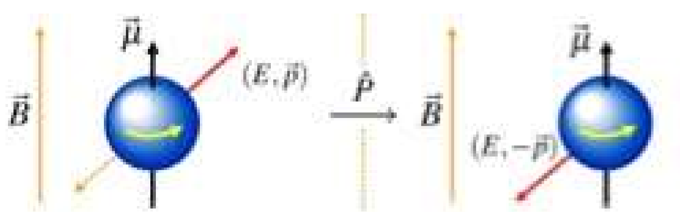


Parity violation in the weak sector

- The **strong** and **E&M** sectors of the Standard Model are P-invariant
- But not the **weak** sector:
  - P-violation: Beta decay of cobalt-60 nuclei in an applied magnetic field

Wu et al., Physical Review (1957)

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$



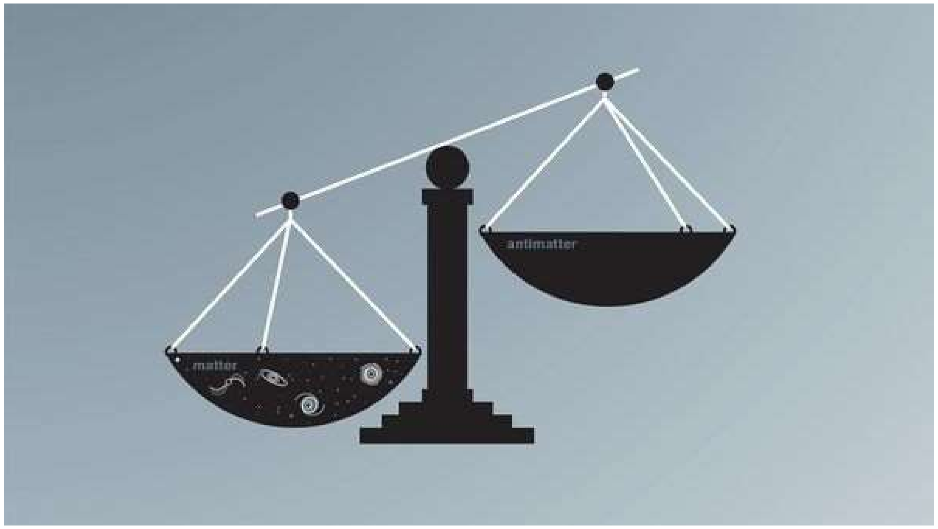
Mirrored (orientation-reversed) process is inequivalent!

  - CP-violation: Inferred by analyzing decay of neutral kaons into pions

Christenson, et al., PRL (1964)

Motivation for Violation of CPT

- Violation of CPT symmetry in theories of quantum gravity[1].
- Violation of CPT could also explain the matter-antimatter asymmetry in the universe[1].



From the LEGEND Collaboration: https://legend-exp.org/science/neutrinoless-bb-decay/the-matter-antimatter-asymetry

1. Ting Cheng, Manfred Lindner, Manibrata Sen, Implications of a matter-antimatter mass asymmetry in Penning-trap experiments, Physics Letters B, Volume 844, 2023, 138068, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2023.138068.

CA0

Tests of CPT Symmetry

- The difference between the mass of a particle and its anti-particle serves as a test of CPT symmetry[1].
- The three tests of CPT symmetry mentioned in our paper are Penning trap experiments, neutrino oscillation experiments, kaon oscillation experiments[1].
- These experiments measure different parameters to access the mass difference.

$$|m - \bar{m}| > 0 \rightarrow CPT\ Violated!$$

m = mass of particle
$\bar{m}$ = mass of anti-particle

1. Ting Cheng, Manfred Lindner, Manibrata Sen, Implications of a matter-antimatter mass asymmetry in Penning-trap experiments, Physics Letters B, Volume 844, 2023, 138068, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2023.138068.

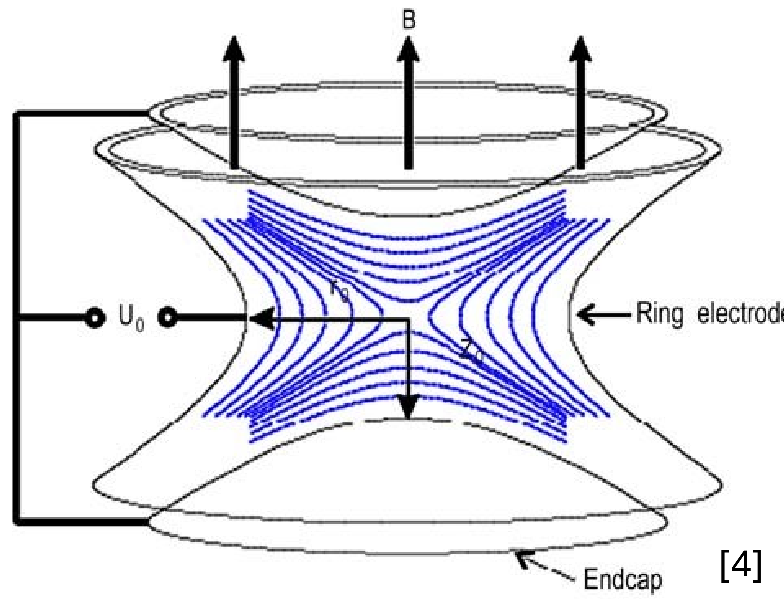
Slide 6

CA0 Move this right after the CPT intro? This seems like it would lead into the Penning Trap, Kaon Oscillation, and Neutrino slides

Clarke, Andrew, 2024-12-06T20:12:41.730

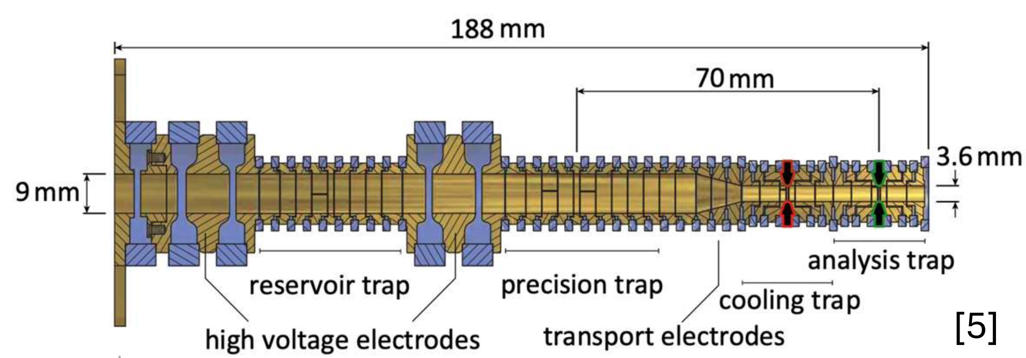
Methodology introduction

- Penning traps confine charged particles using static electric and magnetic fields
  - Axial magnetic field -> radial trapping
  - Quadrupole electric field -> axial trapping



[4]

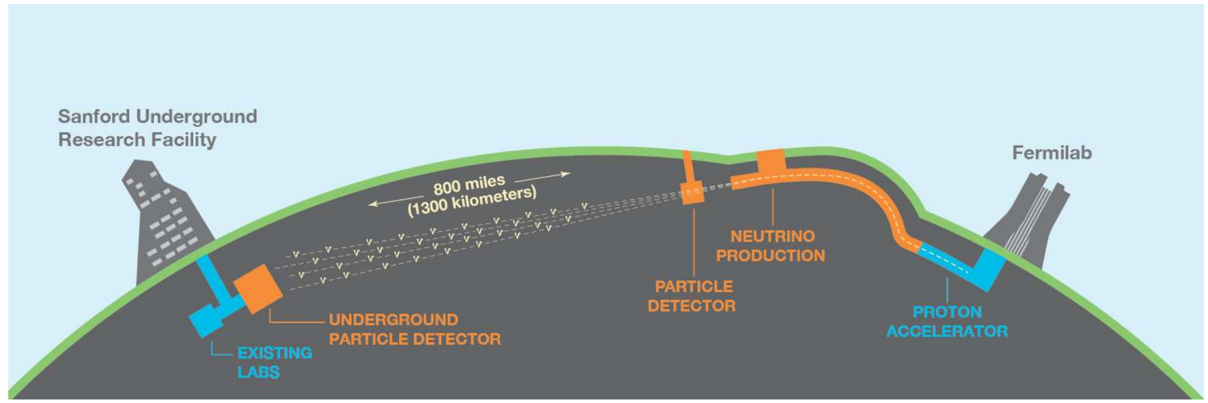
- BASE experiment
  - Investigations of the fundamental properties of the antiproton
  - Charge-to-mass ratio
  - Multi-trap system



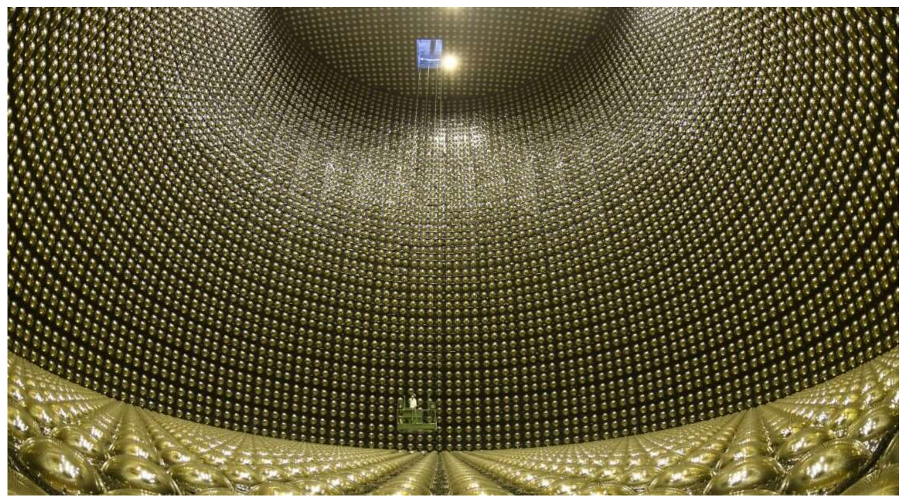
[5]

Neutrino Oscillations as a Test of CPT

- Mixing ratio related to squared mass difference of flavors[3].
- Difference between the mass squared difference for neutrinos and anti-neutrinos used as test of CPT[3].
- Experiments include DUNE, and T2K.



Above: The DUNE experiment: https://www.dunescience.org/



Left: The Super-Kamiokande detector used by the T2K experiment: https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/outline/

$$|\Delta m_{\nu}^{2} - \Delta m_{\bar{\nu}}^{2}|$$

CPT violation parameter measured using neutrino oscillation experiments

3. G. Barenboim, C.A. Ternes, M. Tórtola, Neutrinos, DUNE and the world best bound on CPT invariance, Physics Letters B, Volume 780, 2018, Pages 631-637, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2018.03.060.

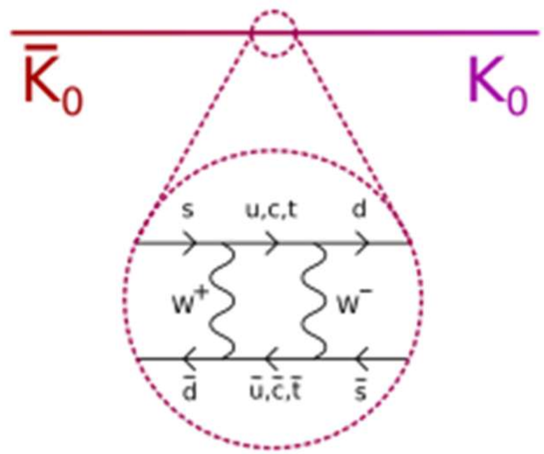
Kaon Oscillations as Evidence for CPT Violation

- Oscillation of neutral Kaons between $\overline{K_0}$ and K_0 states[1]
- Matrix elements of mixing related to the squared mass difference of $\overline{K_0}$ and K_0 states.
- Have not been observed
- No recent experiments dedicated to the search

$$\left|K_1^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right)$$

$$\left|K_2^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right)$$

Above: Neutral Kaon eigenstates: https://en.wikipedia.org/wiki/Neutral_particle_oscillation#Neutral_kaon_oscillation_and_decay



Left: Feynman Diagram of Kaon Oscillation: https://en.wikipedia.org/wiki/Neutral_particle_oscillation#Neutral_kaon_oscillation_and_decay

1. Ting Cheng, Manfred Lindner, Manibrata Sen, Implications of a matter-antimatter mass asymmetry in Penning-trap experiments, Physics Letters B, Volume 844, 2023, 138068, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2023.138068.

Hadron Mass Decomposition

Gluon Field Energy ↓ QCD Anomaly ↓

$$H_{QCD} = \cancel{H_E} + \cancel{H_g} + H_m + \cancel{H_a}$$

↑ Bare Quark Mass

Hadron mass differences allows us to put bounds on quark-antiquark mass differences

Limits on CPT Violation Parameter

MAMA	Proton	Kaon	Neutrino
$\lvert \sum_j \delta_j \rvert$ (MeV)	$\mathcal{O}(10^{-10} - 10^{-9})$	$\mathcal{O}(10^{-16})$	$\mathcal{O}(10^{-9})$
δ (MeV)	$\mathcal{O}(10^{-10} - 10^{-9})$	trivial	$\mathcal{O}(10^{-9})$
$r - 1$	$\mathcal{O}(10^{-11} - 10^{-10})$	$\mathcal{O}(10^{-18})$	$\mathcal{O}(10^{-1})$
α	$\mathcal{O}(10^{-12})$	$\mathcal{O}(10^{-19})$	$\mathcal{O}(10^{-2})$

Cheng et al., Physics Letters B, 2023

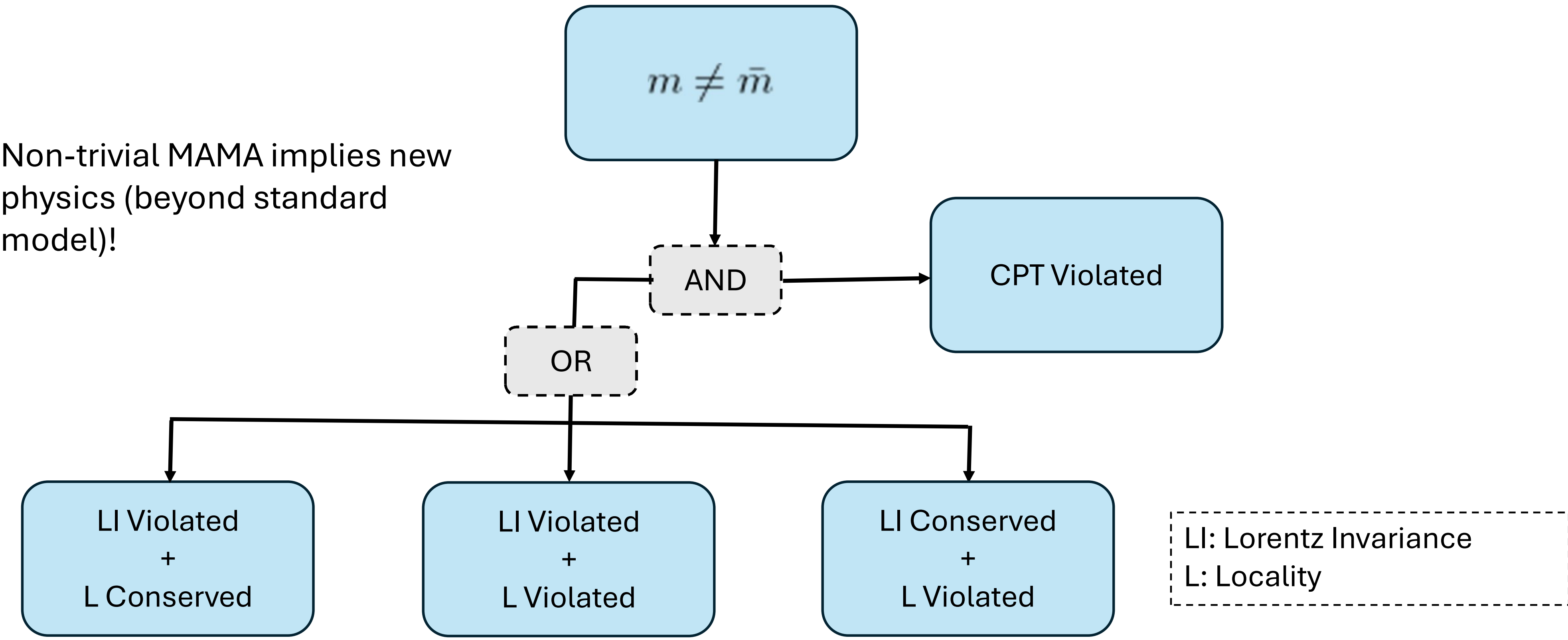
$$\alpha \equiv \left| \frac{m_{\bar{x}} - m_x}{m_{\bar{x}} + m_x} \right|$$

A non-zero α would indicate CPT violation

Kaon oscillation experiments provide the strictest bound on a possible CPT violation

Consequences of CPT Violation

Non-trivial MAMA implies new physics (beyond standard model)!

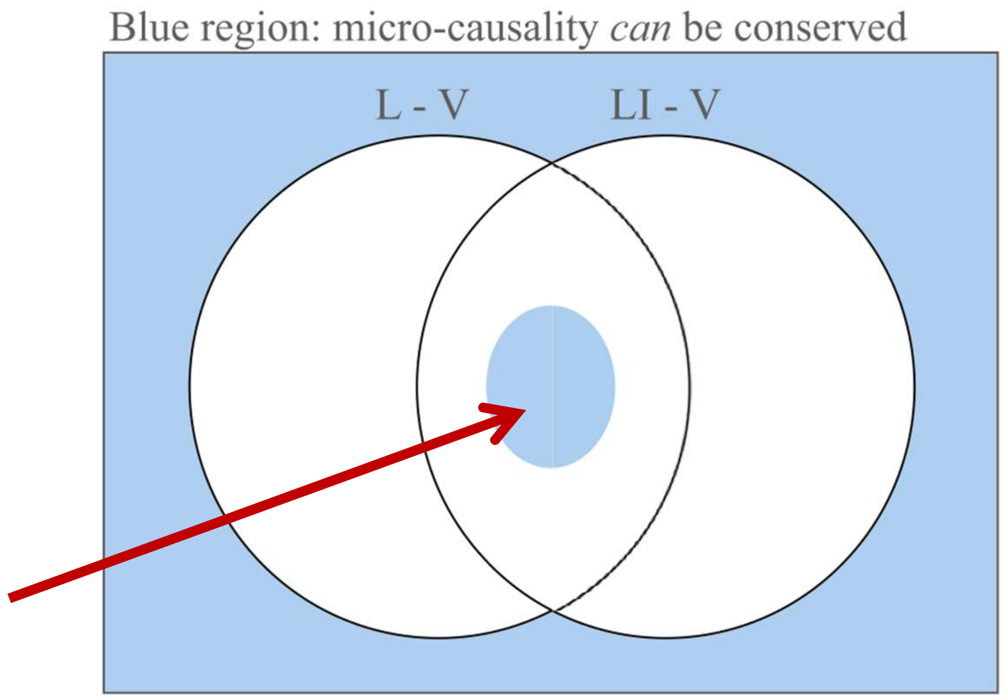


Consequences of CPT Violation

Either **LI** or **L** (or both) is violated. Is this even possible?

We are at the risk of breaking **causality**!

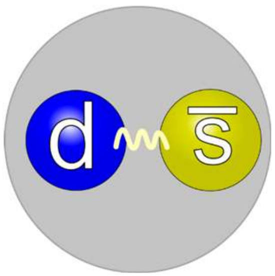
If Lorentz Invariance and Locality are both violated, micro-causality may still be conserved!



LI: Lorentz Invariance
L: Locality
V: Violation

Comparison With Past Results

- Neutrino oscillation experiments generally considered the most sensitive test of CPT symmetry [2], [3].
- Measurable parameter for kaons is mass squared difference not mass difference[3].
- Limits on relevant parameter for neutrinos smaller than that of Kaons[2].
- Kaon not a fundamental particle, so it is argued that a test of the Kaon mass difference is more of a test of QCD than CPT[3].



Left: Depiction of internal structure of K_0. Image from: https://commons.wikimedia.org/wiki/File:Quark_structure_of_the_neutral_kaon.png

Left: Depiction of three flavors of neutrinos. Image from: https://nures.uta.edu/home-2/

2. Hitoshi Murayama, CPT tests: kaon vs. neutrinos, Physics Letters B, Volume 597, Issue 1, 2004, Pages 73-77, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2004.06.106.
3. G. Barenboim, C.A. Ternes, M. Tórtola, Neutrinos, DUNE and the world best bound on CPT invariance, Physics Letters B, Volume 780, 2018, Pages 631-637, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2018.03.060.

Citation Evaluation & Outlook

- Fairly new paper
  - One citation

- Improves bound on CPT Violation from neutrino oscillation

- Field moving away from kaon oscillation in favor of neutrino oscillation experiments

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Neutrino *CPT* violation in the solar sector

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In this paper, we place new bounds on *CPT* violation in the solar neutrino sector analyzing the results from solar experiments and KamLAND. We also discuss the sensitivity of the next-generation experiments DUNE and Hyper-Kamiokande, which will provide accurate measurements of the solar neutrino oscillation parameters. The joint analysis of both experiments will further improve the precision due to cancellations in the systematic uncertainties regarding the solar neutrino flux. In combination with the next-generation reactor experiment JUNO, the bound on *CPT* violation in the solar sector could be improved by 1 order of magnitude in comparison with current constraints. The distinguishability among *CPT*-violating neutrino oscillations and neutrino nonstandard interactions in the solar sector is also addressed.

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1. Ting Cheng, Manfred Lindner, Manibrata Sen, Implications of a matter-antimatter mass asymmetry in Penning-trap experiments, Physics Letters B, Volume 844, 2023, 138068, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2023.138068.

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4. Satyajit, K. T., et al. "Loading detection and number estimation of an electron plasma in a Penning trap." Plasma Science and Technology 11.5 (2009): 521.

5. Smorra, C., Blaum, K., Bojtar, L. *et al.* BASE – The Baryon Antibaryon Symmetry Experiment. *Eur. Phys. J. Spec. Top.* **224**, 3055–3108 (2015). https://doi.org/10.1140/epjst/e2015-02607-4

What is CPT?

- Charge, Parity, and Time symmetry (CPT) is a symmetry of the standard model resulting from it being a Lorentz-Invariant, Local, and Unitary Quantum Field Theory. [1].
- CPT symmetry means that a system is left invariant under the simultaneous action of charge conjugation, parity reversal, and time reversal
- Any signs of CPT symmetry violation would imply Physics beyond the Standard Model

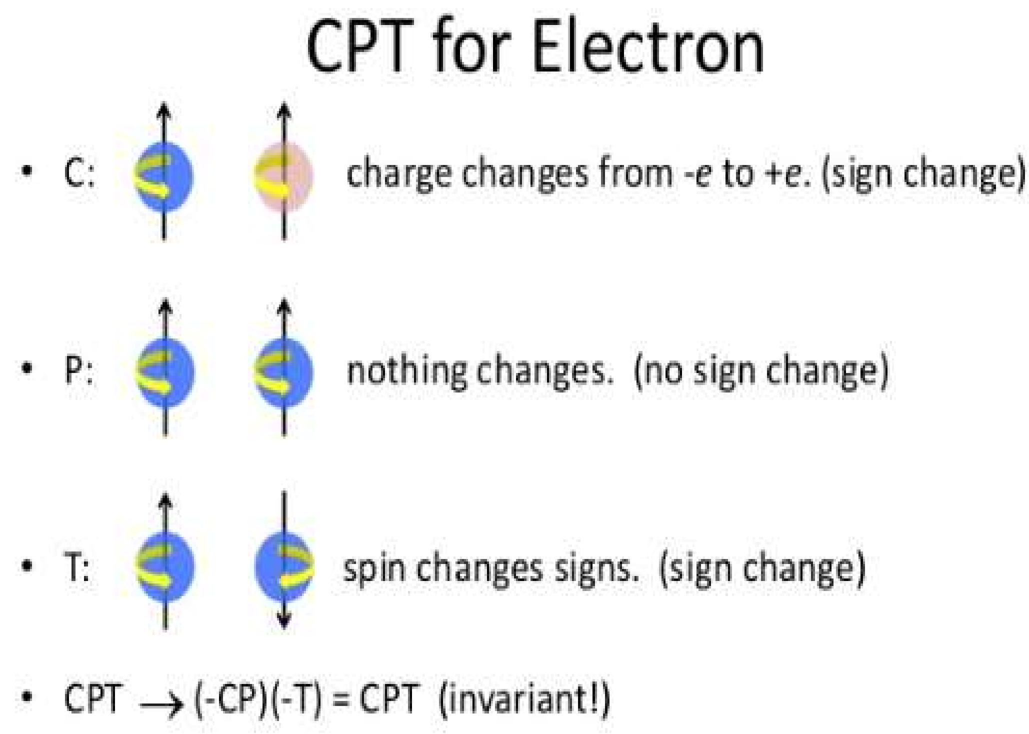

Figure from: https://universe-review.ca/R15-12-QFT04a.htm