Quantum asymmetry between space and time: Phenomenological emergence of Lorentz invariance

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Outline

- Introduction/motivation
  - Quantum Time formalism
- The problem/question
  - Galilean relativity of T violation
  - Effective T violation
  - Example of interaction
- Emergence of Lorentz invariance
  - Effect of T violation on Time
  - Effect of T violation on Length
- Conclusion

Introduction/motivation

Asymmetry between space and time

- Special Relativity ⇒ space and time treated *on the same footing*
- Time evolution and conservation laws treat time and space *differently*
  - Momentum operator, $\hat{p}$ is the generator of translations in both positive and negative spatial directions
  - $\hat{H}$ violates the discrete C, P and T symmetry properties, while, $\hat{p}$ does not

Introduction/motivation

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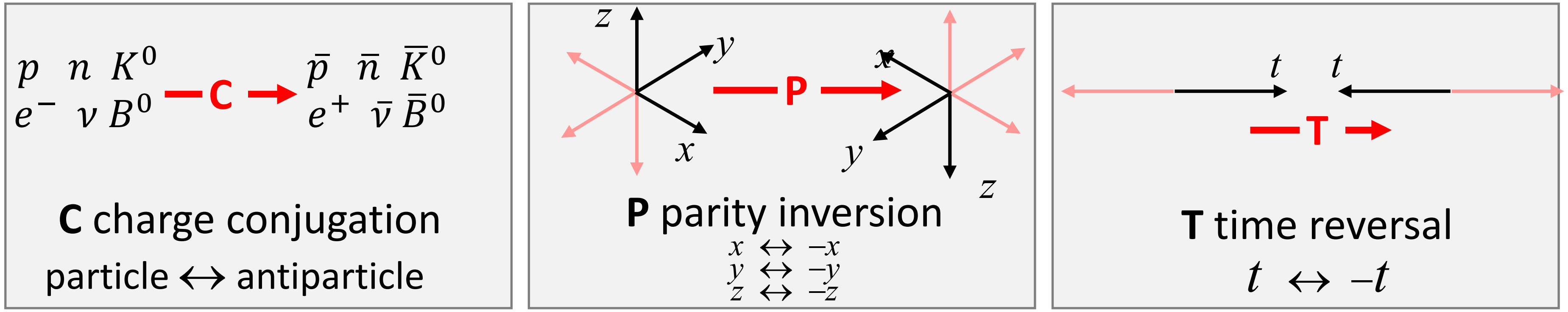
Quantum Time Theory (QTT)

- Attributes asymmetry between the spatial and temporal dimensions to the violation of time reversal symmetry, known as **T violation**
- Represents the quantum state as a sum over virtual paths in time

A quick recap – CPT Theorem

- **Discrete symmetries**



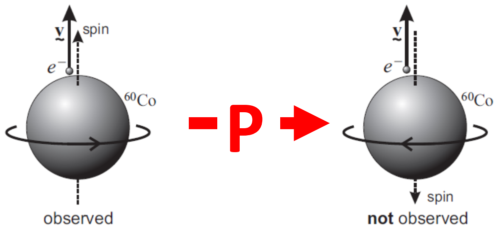
$$\hat{C}\hat{P}\hat{T} = \hat{I}$$

- Lorentz invariance implies invariance under $\hat{C}\hat{P}\hat{T}$ transformation

A quick recap – Violation of CPT

- **History**
  - **P violation:** Lee & Yang, 1956, Brookhaven Nat. Lab., NY

    Phys. Rev. **104**, 254 (1956)
    Phys. Rev. **105**, 1413 (1957)



Wu's experiment, 1957
Columbia Uni. & Nat. Bur. of Stds.

  - **CP violation:** Cronin & Fitch, 1964, Princeton Uni. NJ

    Phys. Rev. Lett. **13,** 138 (1964)

K^0 decay

$$K_L^0 \rightarrow \pi^+\pi^-$$

$$K_L^0 = (K_-^0 + \epsilon K_+^0) \neq \pi^+\pi^-$$

K_-^0: CP=−1, ϵK_+^0: CP=+1; $\pi^+\pi^-$: CP=+1

  - **T violation:** BABAR, SLAC 2012, Stanford Uni., CA

    Phys. Rev. Lett. **109**, 211801 (2012)

B^0 decay

$$\bar{B}^0 \rightarrow B_- \;\neq\; B_- \rightarrow \bar{B}^0 \quad (\text{—T}\rightarrow)$$

QTT formalism

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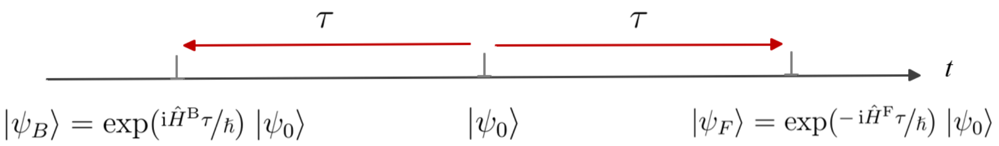
J.A. Vaccaro, *Proc. R. Soc. A* **472**, 2185 (2016)

QTT formalism

- Attributes asymmetry between the spatial and temporal dimensions to the violation of time reversal symmetry, known as **T violation**
- Represents the quantum state as a sum over virtual paths in time
- **Two versions of the Hamiltonian** related by Wigner's time reversal operation $\hat{T}$

The generator of translations

- towards "forward": $\widehat{H}^F = \widehat{H}$
- towards "backward": $\widehat{H}^B = \hat{T}\widehat{H}\hat{T}^{-1}$
  - T-symmetry holds $\longrightarrow$ $\hat{T}\widehat{H}\hat{T}^{-1} = \widehat{H}$ $\longrightarrow$ $\widehat{H}^F = \widehat{H}^B$
  - Violation of T-symmetry $\longrightarrow$ $\hat{T}\widehat{H}\hat{T}^{-1} \neq \widehat{H}$ $\longrightarrow$ $\widehat{H}^F \neq \widehat{H}^B$



J.A. Vaccaro, *Proc. R. Soc. A* **472**, 2185 (2016)

QTT formalism

- Localised sources of T-violation
  - neutral mesons
  - neutrinos
- Spatially uniform T violating scalar field
- Spatial Variation of T violation

QTT formalism

- Localised sources of T-violation
  - neutral mesons
  - neutrinos
- Spatially uniform T violating scalar field
- Spatial Variation of T violation → Quantum time dilation / Quantum length contraction

⇒ associated with spatially varying T violation, **not relative speed**

The problem/question

*Could a **T-violation source that varies with relative velocity** give rise to velocity-dependent versions that **mirror the original time dilation and length contraction effects** in special relativity?*

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The problem/question

Lorentz Invariance:

- So far, **treated as one of the fundamental symmetries** *of relativity*
- However, **may not be an exact symmetry** over all energy ranges
- Question: does Lorentz invariance have **a phenomenological origin**?

We want to find out the role Lorentz symmetry plays in quantum time formalism

Galilean relativity of T violation

- All the system are affected by **a uniform source of T violation** that exists **throughout the universe**
- This source is assumed to be a **non-relativistic** complex scalar field
- **Non-relativistic expressions** for the energy and momentum operators
- Two objects moving relative to each other within a **Galilean space-time framework**, experience **different T violation effects**
- The objects **do not include any localised T violating subsystems**

Effective T violation

- T violation will inevitably **involve an interaction between fields**
- The corresponding Hamiltonians:

$$\hat{H}_n^{\mathrm{F}} = \int \mathrm{d}^3\mathbf{p}\, \omega^F_{\mathbf{p},n}\, (a^\dagger_{\mathbf{p}} + f^*_{\mathbf{p}})(a_{\mathbf{p}} + f_{\mathbf{p}})$$

$$\hat{H}_n^{\mathrm{B}} = \hat{T}\hat{H}_n^{\mathrm{F}}\hat{T}^{-1} = \int \mathrm{d}^3\mathbf{p}\, \omega^B_{\mathbf{p},n}\, (a^\dagger_{\mathbf{p}} + f_{\mathbf{p}})(a_{\mathbf{p}} + f^*_{\mathbf{p}})$$

- $f_{\mathbf{p}}$ ⇒ Interaction term
- Frequencies in different frames ⇒

$$\omega^F_{\mathbf{p},n} \equiv \omega_{\mathbf{p},0} + \mathbf{p}\cdot\mathbf{v}_n$$

$$\omega^B_{\mathbf{p},n} \equiv \omega_{\mathbf{p},0} - \mathbf{p}\cdot\mathbf{v}_n$$

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descriptions given relative to a third, arbitrarily chosen, inertial reference frame

- $f_{\mathbf{p}}$ ⇒ Interaction term
- Frequencies in different frames ⇒

$$\omega_{\mathbf{p},n}^{F} \equiv \omega_{\mathbf{p},0} + \mathbf{p}\cdot\mathbf{v}_n$$

$$\omega_{\mathbf{p},n}^{B} \equiv \omega_{\mathbf{p},0} - \mathbf{p}\cdot\mathbf{v}_n$$

⇒

$$\omega_{\mathbf{p},2}^{F} \equiv \omega_{\mathbf{p},1} + \mathbf{p}\cdot\Delta\mathbf{v}$$

$$\omega_{\mathbf{p},2}^{B} \equiv \omega_{\mathbf{p},1} - \mathbf{p}\cdot\Delta\mathbf{v}$$

$$\Delta\mathbf{v} \equiv \mathbf{v}_2 - \mathbf{v}_1$$

Effective T violation

- The effective T violation in respective frames

$$\lambda_n = \langle\psi|[\hat{H}_n^{\mathrm{F}}, \hat{H}_n^{\mathrm{B}}]|\psi\rangle$$

$$t_{\mathrm{cl,n}} = t_0\sqrt{\frac{\lambda_0}{\lambda_n}}$$

$t_{\mathrm{cl,n}}$ ⇒ clock time in respective frames
λ ⇒ effective T violation in respective frames

Example of interaction

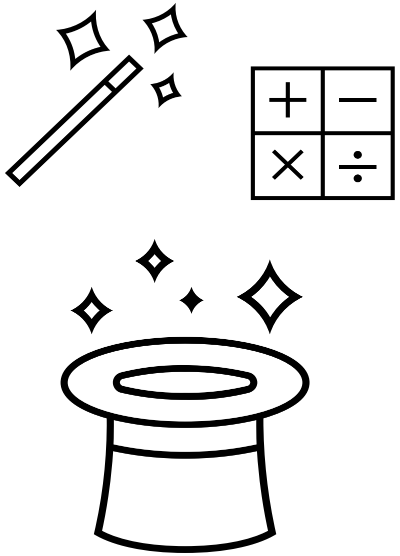
- We assume –
  - a complex scalar field has acquired a large nonzero vacuum expectation value through spontaneous symmetry breaking
  - $f_{\mathbf{p}}$ is from the interaction with symmetry breaking field

$$f_{\mathbf{p}} = f(\mathbf{p}) = \beta \frac{4\pi}{p^3} \left(\sin(pX) - pX \cos(pX) \right)$$

$\beta \Rightarrow$ complex T violation parameter comes from the interaction with the field with broken symmetry

Example of interaction

After some pages of mathematics ….



Example of interaction

$$\lambda_n = \langle\psi|[\hat{H}_n^{\mathrm{F}}, \hat{H}_n^{\mathrm{B}}]|\psi\rangle = 4\pi u^2 \left(1 - \frac{v_n^2}{3u^2}\right) \int \mathrm{d}p\, p^2 ({f_{\mathbf{p}}^{*}}^2 - {f_{\mathbf{p}}}^2)$$

- Reminder, clock time: $t_{\mathrm{cl,n}} = t_0 \sqrt{\frac{\lambda_0}{\lambda_n}}$

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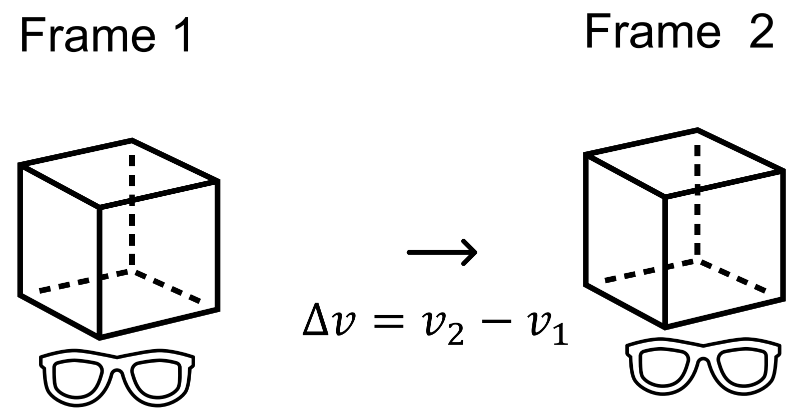
Emergence of Lorentz invariance

Effect of T violation on Time

- Two events that are happening at the same position in Frame 1
- Observer at rest in Frame 1 is measuring the time interval, Δt_1
- Observer at rest in Frame 2, measuring the same interval, Δt_2



Emergence of Lorentz invariance

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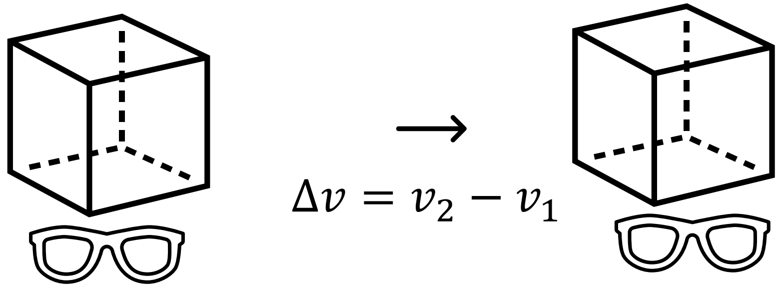
Frame 1 Frame 2



$$\frac{\Delta t_1}{\Delta t_2} = \sqrt{\frac{\lambda_2}{\lambda_1}} = \sqrt{1 - \frac{(\Delta v)^2}{c^2}} = \gamma^{-1}$$

$\Delta t_1 < \Delta t_2 \Rightarrow$ **analogous to proper time** in special relativity

$\lambda_2 > \lambda_1 \Rightarrow$ in agreement with the prediction of QTT
the larger the effective T-violation, slower the clocks

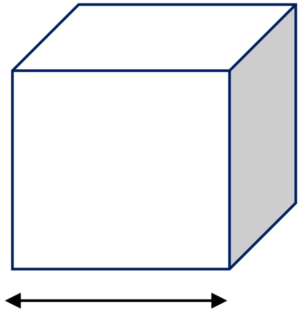
Emergence of Lorentz invariance

Effect of T violation on Length

- A box with length D_1 in its rest frame, Frame 1

- An observer in Frame 2, would measure the length

Frame 1



$D_1 = c\,T_1$

Frame 2

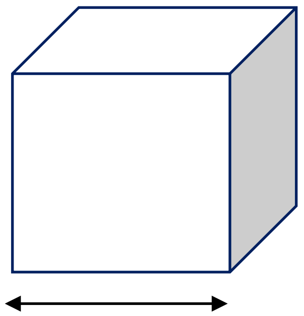
$D_2 = c\,T_2 = \gamma^{-1} c T_1$

Emergence of Lorentz invariance

Effect of T violation on Length

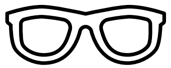
- A box with length D_1 in its rest frame, Frame 1
- An observer in Frame 2, would measure the length

Frame 1



$D_1 = c\,T_1$

Frame 2



$\Delta v \longrightarrow$

$D_2 = c\,T_2 = \gamma^{-1} c T_1$

$$D_2 = \sqrt{1 - \frac{(\Delta v)^2}{c^2}}\, D_1$$

⟶ Equivalent to relativistic length contraction

Emergence of Lorentz invariance

NOTE:

Special relativity:

Speed of light is constant $\longrightarrow$ Time dilation

Quantum time formalism:

Time dilation $\longrightarrow$ speed of light is constant

Conclusion

- A short review of Quantum Time formalism
- In the new formalism, Lorentz invariance **arises from the relative velocity of a spatially-uniform background T violating field**
- **Without introducing special relativity** into the theory –
  - relativistic quantum time dilation
  - relativistic quantum length contraction
- The theory predicts the state of the clock to be affected –
  - Lorentz effect is seen in the dynamical state, not in the coordinates (which are in Galilean spacetime)
  - Likewise, distances are measured with clocks and light pulses and are similarly affected (not the coordinates)
- A proposal for the **phenomenological origin** of Lorentz invariance

Thank you!

Question?

Thursday Poster Session

- Khai Bordon (board 7)
- Ayden Howarth (board 6)

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