Title: A New Perspective on Time Reversal Motivated by Quantum Gravity

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Collection: Quantizing Time

Date: June 15, 2021 - 9:00 AM

URL: http://pirsa.org/21060094

Abstract: Time Reversal T is usually discussed in the traditional framework of quantum mechanics in which T is represented by an anti-unitary operator. But quantum gravity may well need generalization of standard quantum mechanics which may not preserve even its linear structure, let alone the unitarity of dynamics and anti-unitarity of T. Then the currently used arguments to conclude that T violation is a fundamental aspect of Nature will break down. Fortunately, it turns out that one can analyze the T-violation experiments in a much more general setting, of which classical and quantum mechanics are special cases. The setting does not require a Hilbert space, or linearity of either dynamics or symmetry operations such as T. Nonetheless, somewhat surprisingly, one would still be to use the current experiments to conclude that there is T violation at a fundamental level under rather minimal assumptions on the structure of the final quantum gravity theory.

A new perspective on T-violation motivated by quantum gravity

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'Quantizing Time' Workshop, PI, June 15th 2021

Introduction/Motivation

- Choice of Topic : Time Reversal T

Mainstream issues on the nature of time in Quantum Gravity (Relational time à la Leibnitz, Causality, emergent time especially in the early universe, time as an OVM, Quantum clocks, emerging of time from a timeless framework, ...) covered in other talks. So I will focus on another aspect with a particle physics focus rather than GR, Quantum information, ...

- Focus : Fundamental laws of Nature.

unrelated to the traditional 'arrow of time' that emerges from statistical mechanics considerations.
Ex: Gas in a box in classical physics. Newton's laws governing EOM of molecules are T invariant. Arrow of time $\longleftrightarrow$ many more microstates compatible with the final macrostate than the initial.

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- Experimental progress over some 55 years tells us that a Fundamental force/interaction breaks T invariance. This is a genuinely quantum feature associated with time.

But, observations ------▷ conclusion

Heavy use of the detailed Minkowski QFT framework.

↓

These key elements will not survive when gravity is included. But we don't know the full QG framework!

What is the most general theoretical framework that will still allow us to draw a conclusion on breaking of T invaraince in Nature, using current experiments?

Turns out that there is much excess baggage in the current analysis. A 'minimalistic' framework suffices. Provides general pointers for QG as well.

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1. Violation of T invariance

Expts, Theoretical reasoning currently used.

2. General Mechanics

A minimalistic framework motivated by QG considerations that suffices to conclude T-violation from current expts within generalized QM.

3. Discussion

Illustrations of how principal structures of this general Mechanics could arise in the sector of QG suitable for particle physics questions

Motivated by discussions with philosophers of science John Erman (Pittsburgh), Thomas Pashy (Chicago), & particularly Bryan Roberts (LSE).

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1. Violation of T-invariance

A. Indirect Evidence: K_L^0 Decay

Observations:

K_L^0 (Meson) → decay $\pi^+, \pi^- \pi^0$ Prominent

→ Also, $\underbrace{\pi^+ \pi^-}_{\text{Cronin \& Fitch (1964)}}$ Branching Ratio $\sim 10^{-3}$

Big surprise! ⇒ T violation

Even after the discovery of P violation, T was assumed to be exact symmetry of fundamental laws of Nature.

How does this profound conclusion follow?
Need a theoretical framework, which of course, is built on assumptions of Minkowskian QFT in standard discussions.

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Two steps

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Two steps

Assumptions in the first step :

① kinematics: As in QM, Hilbert space & operators

② symmetries C, P, CP represented by unitary operators

③ Interactions that bind quarks into kaons : CP invariant

(& T) strangeness eigenstates : $K^0 = d\bar{s}$; $\bar{K}^0 = \bar{d}s$

$CP|K^0\rangle = |\bar{K}^0\rangle$; $CP|\bar{K}^0\rangle = |K^0\rangle$

CP eigenstates $|K_L^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ $\underline{ev = -1}$
(basis in the H eigenspace)

④ Scattering operator S commutes with CP.
(i.e interaction responsible for decay is CP invariant)

Now, : $CP|\pi^+\pi^-\rangle = |\pi^+\pi^-\rangle$ $CP|\pi^+\pi^-\pi^0\rangle = -|\pi^+\pi^-\pi^0\rangle$

$\Rightarrow \langle\pi^+\pi^-|SK_L^0\rangle = \langle CP\,\pi^+\pi^-|CP\,S\,K_L^0\rangle = -\langle\pi^+\pi^-|S\,K_L^0\rangle$

$\Rightarrow$ Transition $K_0^L \to \pi^+\pi^-$ forbidden!

(Note: Don't need to assume S is unitary or even linear!)

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conclusion: Assumption that interaction that binds quarks into $|K_L^0\rangle$ and/or cause the decay is CP invariant is incorrect!

What does this have to do with T invariance?

If we assume in addition that standard assumptions of QFT hold: (Locality, spin-statistics, $\mathbb{P}$ group is unitarily implemented, vacuum $\mathbb{P}$ invariant)

Then CPT is an exact symmetry of S: $[CPT, S] = 0$

$\Downarrow$

$[CP, S] \neq 0 \Rightarrow [T, S] \neq 0$ (since T is invertible)

Note: we do NOT need to know the Hamiltonian! very general.

Thus: $K_L^0 \rightarrow \pi^+\pi^- \Rightarrow$ T violation in a fundamental law provided Nature is described by a local relativistic QFT.

But this framework is too restrictive to include gravity.

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1B: Direct evidence for T violation

1998 CPLEAR K^0-$\bar{K}^0$
2012 BaBar B^0-$\bar{B}^0$

Do not pass through CPT (K0 - $\bar{K}$0 oscillations)

CPLEAR observations : $K^0 \to \bar{K}^0$ Transition occurs with a different probability than $\bar{K}^0 \to K^0$ Transition

Property $T|K^0\rangle = |K^0\rangle$ $T|\bar{K}^0\rangle = |\bar{K}^0\rangle$

Key difference at the kinematical level from C, P & CP symmetries:

(2) T is represented by an anti-unitary operator

$(T(\alpha_1|\psi_1\rangle + \alpha_2|\psi_2\rangle) = \alpha_1^*|\psi_1\rangle + \alpha_2^*|\psi_2\rangle$; $\langle T\phi|T\psi\rangle = \langle\phi,\psi\rangle^*$)

(3) T is a dynamical symmetry : $TS = S^{-1}T$

(Recall $T e^{-iHt} T^{-1} = e^{+iHt}$, or $TU_t T^{-1} = U_{-t}$)

(4) S is a unitary operator

(Didn't need this assumption for CP violation.)

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1B: Direct evidence for T violation

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$(T(\alpha_1|\psi_1\rangle + \alpha_2|\psi_2\rangle) = \alpha_1^*|\psi_1\rangle + \alpha_2^*|\psi_2\rangle$; $\langle T\phi|T\psi\rangle = \langle\phi,\psi\rangle^*)$

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summary of key assumptions: $\begin{cases} \langle \chi | \psi \rangle = \langle T\chi | T\psi \rangle^* = \langle T\psi | T\chi \rangle \\ TS = S^{-1}T; \quad S^{-1} = S^\dagger \end{cases}$

For any states $|\psi\rangle$ & $|\phi\rangle$:

$$\langle \phi | S\psi \rangle \underset{\text{Anti unitarity of } T}{=} \langle TS\psi | T\phi \rangle \underset{T \text{ is a dynamical symmetry}}{=} \langle S^{-1}T\psi | T\phi \rangle$$

$$\underset{\text{unitarity of } S}{=} \langle S^\dagger T\psi | T\phi \rangle = \langle T\psi | S\, T\phi \rangle$$

$\Rightarrow$ Transition prob $\psi \longrightarrow \phi$ = Transition Prob $T\phi \rightarrow T\psi$

$|\psi\rangle = |K^0\rangle$; $|\phi\rangle = |\bar{K}^0\rangle$ $\qquad$ $|T\phi\rangle = |\bar{K}^0\rangle$; $|T\psi\rangle = |K^0\rangle$

So, under our assumptions (in particular: "T is dynamical symmetry") we conclude: Trans Prob $K^0 \rightarrow \bar{K}^0$ = Trans Prob $\bar{K}^0 \rightarrow K^0$

But violated in Nature. $\Rightarrow$ T violation

Did not assume relativistic QFT or $\square$ invariance or locality

This argument for T violation is strong & appealing.

The theoretical underpinning used to conclude that there is T violation in fundamental interactions is remarkably general. But it did assume: Linear Hilbert space structure of QM, unitarity of dynamics (S) and the subtle anti-unitary representation of T

All of these features may not survive in quantum gravity. I will mention concrete ideas for generalizations later. But simplest examples are Birula's & Weinberg's nonlinear quantum evolution.

Already in part 2B, we saw that assumptions needed to go from observations to the startling conclusion that fundamental laws are not T invariant can be streamlined.

Can we streamline & generalize further to make the assumptions weaker so that one can still draw conclusions from current observations, with quantum gravity perspective in mind? The answer is in the affirmative.

Minimal Framework

Minimal Framework

1. There is a set $\mathcal{X}$ of states σ of the system
   (Ex: $|\psi\rangle$ or ρ in Quantum Mechanics, both normalized)

2. $\mathcal{X}$ is equipped with an overlap map $\Theta : \mathcal{X} \times \mathcal{X} \to [0,1]$ that measures the overlap between 2 states st
   $$\Theta(\sigma, \sigma') = \Theta(\sigma', \sigma)$$
   (Ex: $\Theta(\rho, \rho') = \mathrm{Tr}\, \rho\rho'$ or $\Theta(\psi, \phi) = |\langle\psi|\phi\rangle|^2$

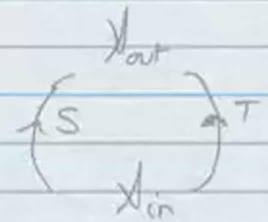
3. There is a 1-1 dynamical map $S : \mathcal{X}_i \to \mathcal{X}_f$; ($\mathcal{X}_i$ & $\mathcal{X}_f$ are copies of $\mathcal{X}$) st $\Theta_i(\sigma_i', \sigma_i) = \Theta_f(S\sigma_i', S\sigma_i)$
   $$\text{Prob } \sigma_i \xrightarrow{\text{evolves to}} \sigma_f' \equiv P(\sigma_f', \sigma_i) := \Theta_f(\sigma_f', S\sigma_i).$$

4. Symmetries : $R : \mathcal{X}_i \xrightarrow[\text{1-1}]{\text{onto}} \mathcal{X}_i$ st $\Theta_i(R\sigma_i, R\sigma_i') = \Theta_i(\sigma_i, \sigma_i')$
   same for $\mathcal{X}_f$
   C, P, CP, Translations, ...

   $$T : \mathcal{X}_i \xrightarrow[\text{1-1}]{\text{onto}} \mathcal{X}_f \qquad \Theta_f(T\sigma_i, T\sigma_i') = \Theta_i(\sigma_i, \sigma_i')$$
   (flip / complex conjugation unnecessary)

Def : T is a dynamical symmetry iff $S^{-1}T = T^{-1}S$

Considerations of 1A on CP violation go through in general mechanics straightforwardly.
I will consider the more interesting case 1.B on T violation



Result: If T is a dynamical symmetry. Then

$$P(\sigma_f', \sigma_i) = P(T\sigma_i, T^{-1}\sigma_f')$$

Notation: $\mathcal{A}\sigma_i = \sigma_f \qquad \mathcal{A}\sigma_i' = \sigma_f'$

$$\Theta_i(\sigma_i, \sigma_i') \underset{\text{property of } S}{=} \Theta_f(S\sigma_i, S\sigma_i') \underset{\text{symmetry of } \Theta_f}{=} \Theta_f(S\sigma_i', S\sigma_i) \underset{\text{Defn of } \sigma_f'}{=} \Theta_f(\sigma_f', S\sigma_i)$$

property of T $\wr\wr$

$$\Theta_f(T\sigma_i, T\sigma_i') \underset{\text{Defn of } \sigma_f'}{=} \Theta_f(T\sigma_i, TS^{-1}\sigma_f') \underset{T \text{ dynamical symmetry}}{=} \Theta_f(T\sigma_i, ST^{-1}\sigma_f')$$

$$\Rightarrow \underbrace{\Theta_f(\sigma_f', S\sigma_i)}_{\text{Prob } \sigma_i \to \sigma_f'} = \underbrace{\Theta_f(T\sigma_i\ ST^{-1}\sigma_f')}_{\text{Prob } T^{-1}\sigma_f' \to T\sigma_i}$$

For $K^0, \bar{K}^0$ Prob $K^0 \to \bar{K}^0$ = Prob $T^{-1}\bar{K}^0 \to TK^0$ = Prob $\bar{K}^0 \to K^0$

Hence observations $\Rightarrow$ T is not a dynamical symmetry

- The minimalistic framework suffices to conclude from observations that whatever the fundamental laws are that govern the K^0-$\bar{K}^0$ (and B^0-$\bar{B}^0$) system (laws that bind the quarks to form these mesons and that govern their decays) they violate Time Reversal invariance provided the underlying framework has our minimal ingredients

$$\mathcal{X}, \quad (\cdot|\cdot) : \text{overlap fn}, \quad T, \quad S$$

satisfying elementary, physically motivated requirements.

- standard Quantum mechanics provides them but with a lot of excess baggage; Hilbert space (not just $\mathcal{X}$), scalar product (not just $(\cdot|\cdot)$), Anti unitary operator T (not just a 1-1, onto map on $\mathcal{X}$ preserving $(\cdot|\cdot)$), and unitary S (not just 1-1, onto map preserving $(\cdot|\cdot)$).

- Putative QG theory could realize the minimal ingredients via a generalization of the std QM framework. e.g. by recasting the Asymptotic Quantization scheme in a generalized QM framework I now describe.

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Example of Generalized QM

Motivation: Special Relativity $\longrightarrow$ General Relativity

Linear (or affine) structure — Non-linear (Manifold) structure

(??) Hilbert space of QM $\longrightarrow$ Non-linear/Manifold

(??) Linear/Antilinear operators $\longrightarrow$ special Diffeos

concrete illustration to indicate the direction

1st step: Geometric Reformulation of QM (~ Mink Reformulation of special relativity)

(AA + Troy Schilling)

KINEMATICS

Linearity @ forefront — Non-linear geometric structures

- Hilbert space $\longrightarrow$ space of rays = Kähler manifold ($\mathcal{X}$)
- $|\langle\Psi|\Phi\rangle|^2$ $\longrightarrow$ f(Geodesic distance between points) (Θ)
- Symmetries $\longrightarrow$ Diffeos preserving Kähler structure (C, P, T, as well as c^o symmetries)
- SA operators (commutators) $\longrightarrow$ Fns whose Hamiltonian VFs are Killing VFs (PBs on ∞-dim Kähler manifold $\mathcal{X}$)

... kinematic structures of "general mechanics" are

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Linearity @ forefront | Non-linear geometric structures

KINEMATICS

Hilbert space $\longrightarrow$ space of rays = Kähler manifold ($\mathcal{M}$)

$|\langle\psi|\phi\rangle|^2$ $\longrightarrow$ f(Geodesic distance between points) (Θ)

symmetries $\longrightarrow$ Diffeos preserving Kähler structure (C, P, T, as well as C^0 symmetries)

SA operators (commutators) $\longrightarrow$ Fns whose Hamiltonian VFs are killing VFs (PBs on co-dim Kähler manifold $\mathcal{M}$)

Note: kinematic structures of "general mechanics" are concretely realized using geometry. All necessary relations between $\mathcal{M}$, Θ, C, P, CPT, T .... satisfied w/o using linearity.

Dynamics

$i\hbar\,\partial_t|\psi\rangle = H|\psi\rangle$ $\longrightarrow$ Hamiltonian flow on $\mathcal{M}$ (generated by the function corresponding to H)

symmetries eg C, P, T, .. (Rotations) $\longrightarrow$ Discrete (& cont.) diffeos on $\mathcal{M}$ preserving Kähler structure and the Hamiltonian flow.