

Quantum effects of gravity and their simulation using IBM quantum Computer

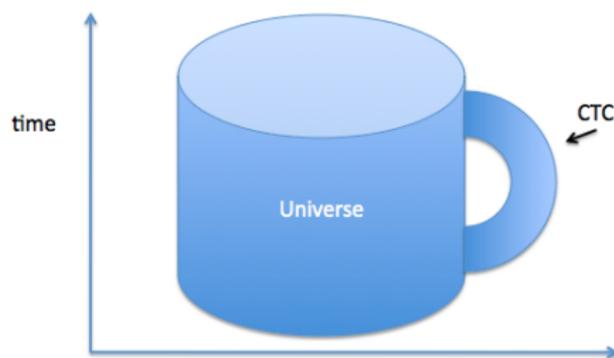
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Closed Timelike Curves

Einstein's field equations allow the existence of closed timelike curves (CTC's), in certain exotic spacetime geometries
So what are CTCs?



TIME TRAVEL!

CTCs, if followed, allow a time traveler (human being or elementary particle) to interact with his/her former self.

But.. this got issues!

grandfather-like paradox: Our time traveller, accidentally or on purpose, kills her grandfather as young man before he as had any children. So, she does not exist; so, she cannot go to the past and kill her grandfather,” (issue of the self-consistency of dynamics)

unproven theorem paradox: Our time traveller learns an elegant proof of a theorem in a conference and goes back in time and submits and presents the proof at the same conference, where she learnt the proof in the first place. (issue of indeterminacy)

Physicists to the rescue!

Deutsch suggested imposing a self-consistency condition, in context of Hilbert Space, postulating self-consistency conditions for the states that enter and exit the closed-timelike curve,
The Deutschian model of CTCs (D-CTCs) impose a boundary condition, in which the density operator of the CTC system that interacts with a chronology respecting (CR) system is the same, both before and after it enters the wormhole.

Formally,

$$\rho_{CTC} = \Phi(\rho_{CTC}) = \text{Tr}_{CR}(U(\rho_{CR} \otimes \rho_{CTC})U^\dagger)$$

where ρ_{CR} is the density matrix for chronology-respecting system, ρ_{CTC} is the initial density matrix of the qubit traveling along the closed timelike curve, and U is the interaction unitary.

Mathematically, this can be seen as nature finding a fixed point solution of the map, Φ , that depends on the chronology respecting system.

Other formulations are physically equivalent, transition probability CTCs (T-CTCs), postselected CTCs (P-CTCs)

CTC and Quantum Information

A different line of research has sought to understand the implications of CTCs, supposing they existed, for quantum mechanics, computation and information and now has a significant body of results in the quantum information literature.

CTC-assisted models of computation can,

- ▶ Solve PSPACE problems in P
- ▶ Distinguish between non-orthogonal states
- ▶ Clone Quantum States (with arbitrary accuracy)
- ▶ ...
- ▶ **Nature of entanglement?**

What we already know about entanglement

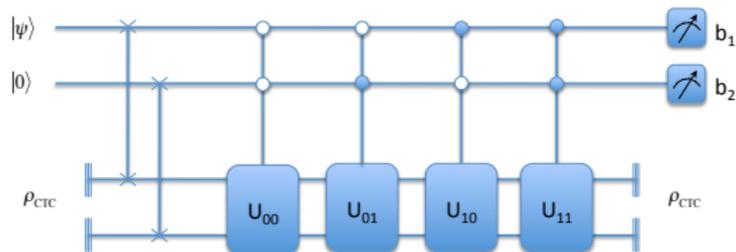
Cannot discriminate between Bell States using LOCC (Ghosh, Kar, Roy, Sen, Sen, PRL 2002)

Discriminate between any set bipartite entangled states?

Cannot create entanglement using LOCC

Entanglement is monogamous

Bob recovers the state $|\psi\rangle$, after CC from Alice and attempts to distinguish the states $\{\alpha|0\rangle \pm \beta|1\rangle, \alpha|1\rangle \pm \beta|0\rangle\}$



$$U_{00} = \begin{bmatrix} \alpha & \beta \\ -\beta & \alpha \end{bmatrix} \otimes \mathbb{I},$$

$$U_{01} = (X \otimes X) \circ \left(\begin{bmatrix} \beta & \alpha \\ \alpha & -\beta \end{bmatrix} \otimes \mathbb{I} \right),$$

$$U_{10} = (X \otimes \mathbb{I}) \circ \left(\begin{bmatrix} \beta & \alpha \\ -\alpha & \beta \end{bmatrix} \otimes \mathbb{I} \right),$$

$$U_{11} = \begin{bmatrix} \alpha & \beta \\ \beta & -\alpha \end{bmatrix} \otimes X$$

Measurements Outcomes, b_1, b_2	State Identified by Bob	Conclusive Bell State
0,0	$\alpha 0\rangle + \beta 1\rangle$	$ \Phi^+\rangle$
0,1	$\alpha 0\rangle - \beta 1\rangle$	$ \Phi^-\rangle$
1,0	$\alpha 1\rangle + \beta 0\rangle$	$ \Psi^+\rangle$
1,1	$\alpha 1\rangle - \beta 0\rangle$	$ \Psi^-\rangle$

The same idea can be extended to discriminate between any set bipartite entangled states,

$$\left\{ \sum_{j=0}^d \lambda_j^{(i)} \left| a_j^{(i)} \right\rangle \left| b_j^{(i)} \right\rangle \right\}_{i=1}^n$$

using LOCC as well, which is again known to be impossible conventionally.

Detour: Smolin States

*“A four-party quantum state which cannot be written in a separable form and from which **no pure entanglement can be distilled by LOCC** among the parties, and yet when any two of the parties come together in the same laboratory they can perform a measurement which enables the other two parties to create a pure maximally entangled state between them without coming together.”*

A four-party unlockable bound-entangled state,

$$\rho = \frac{1}{4}(|\Phi^+\rangle\langle\Phi^+|^{AB} \otimes |\Phi^+\rangle\langle\Phi^+|^{CD} + |\Phi^-\rangle\langle\Phi^-|^{AB} \otimes |\Phi^-\rangle\langle\Phi^-|^{CD} + |\Psi^+\rangle\langle\Psi^+|^{AB} \otimes |\Psi^+\rangle\langle\Psi^+|^{CD} + |\Psi^-\rangle\langle\Psi^-|^{AB} \otimes |\Psi^-\rangle\langle\Psi^-|^{CD})$$

Open time-like curves

The same results hold true for Open time-like curves as well. Open time-like curves (Pienaar et al, Phys. Rev. Lett. 110, 060501 (2013)) modelled the effects of such physical systems, where there was no interaction in the CTC, i.e. the Unitaries are Identity operators. Here, with entanglement between the qubits travelling along a timelike curve and an external chronology-respecting system, the self consistency conditions become,

$$\rho_{OTC \otimes CR} = Tr_{CR}(\rho_{OTC \otimes CR}) \otimes Tr_{OTC}(\rho_{OTC \otimes CR}) = \rho_{OTC} \otimes \rho_{CR}$$

where $\rho_{OTC \otimes CR}$ is a bipartite system, and one of the systems is sent through the OTC.

- ▶ Alice prepares the state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, s.t., $0 \leq \alpha \neq \beta \leq 1$ and $|2\alpha\beta - (\alpha^2 - \beta^2)| > 0$. Then they follow the same strategy as before and Alice teleports the state to Bob.
- ▶ Bob now has the state $|\psi'\rangle \in \{\alpha|0\rangle \pm \beta|1\rangle, \beta|0\rangle \pm \alpha|1\rangle\}$ and needs to determine the exact state to conclude the Bell state.
- ▶ To do this, Bob uses the circuit depicted in Fig 2. The unitary $U_{b_1 b_2}$ is chosen based on Alice's Bell measurement outcomes $b_1 b_2$. The unitaries are defined as

$$\begin{aligned}
 U_{00} &= \begin{bmatrix} \alpha & \beta \\ -\beta & \alpha \end{bmatrix}, & U_{01} &= X \circ \begin{bmatrix} \beta & \alpha \\ \alpha & -\beta \end{bmatrix} \\
 U_{10} &= X \circ \begin{bmatrix} \beta & \alpha \\ -\alpha & \beta \end{bmatrix}, & U_{11} &= \begin{bmatrix} \alpha & \beta \\ \beta & -\alpha \end{bmatrix}
 \end{aligned}$$

Table lists the corresponding Bell States Alice & Bob share. The first column corresponds to Alice's Bell measurements, and the first row lists the possible measurement outcomes for Bob who has an OTC assisted computer. Alice and Bob share the Bell state that is listed in the cell in row and column corresponding to their measurement outcomes. Here $\gamma = (\alpha^2 - \beta^2)^2$ and $\delta = (2\alpha\beta)^2$

Alice's Bell Measurements b_1, b_2	Bob Sees			
	All meas. $ 0\rangle$	All meas. $ 1\rangle$	γN meas. result in $ 0\rangle$ and δN meas. result in $ 1\rangle$	δN meas. result in $ 0\rangle$ and γN meas. result in $ 1\rangle$
0,0	$ \Phi^+\rangle$	$ \Psi^-\rangle$	$ \Phi^-\rangle$	$ \Psi^+\rangle$
0,1	$ \Phi^+\rangle$	$ \Psi^-\rangle$	$ \Phi^-\rangle$	$ \Psi^+\rangle$
1,0	$ \Psi^-\rangle$	$ \Phi^+\rangle$	$ \Psi^+\rangle$	$ \Phi^-\rangle$
1,1	$ \Psi^-\rangle$	$ \Phi^+\rangle$	$ \Psi^+\rangle$	$ \Phi^-\rangle$

- Can discriminate between Bell States using LOCC
- Can discriminate between any set bipartite entangled states
- Can increase entanglement using LOCC

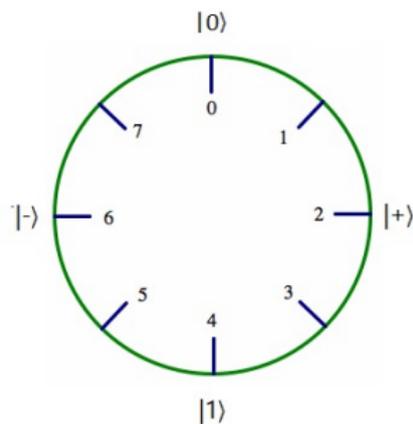
if there exists Deutschian CTCs or Open time-like curves

1. Moulick, S. R. and Panigrahi, P. K. Timelike curves can increase entanglement with LOCC. *Sci. Rep.* **6**, 37958 (2016).
2. Ghosh, S., Adhikary, A., Paul, G. Quantum Signaling to the Past Using P-CTCS. *Quantum Information & Computation*, vol. 18, no. 11 & 12, pp. 965-974 (2018).

Quantum Cost Efficient Scheme for Violating the Holevo Bound and Cloning in the Presence of Deutschian Closed Timelike Curves

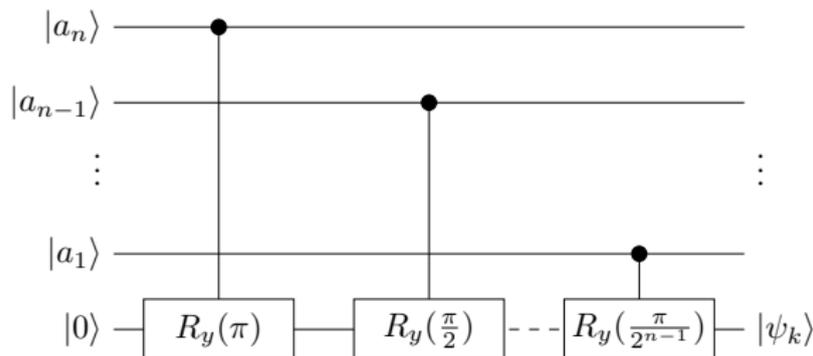
- ▶ We can perfectly distinguish a dictionary of non-orthogonal states in the presence of a D-CTC.
- ▶ Thus, we can transmit any amount of information via a single qubit (violating the Holevo bound).
- ▶ We demonstrate a scheme to do this in an quantum cost efficient way.
- ▶ We also show that this scheme can be modified to clone a qubit, while maintaining efficiency.

Dictionary of non-orthogonal states



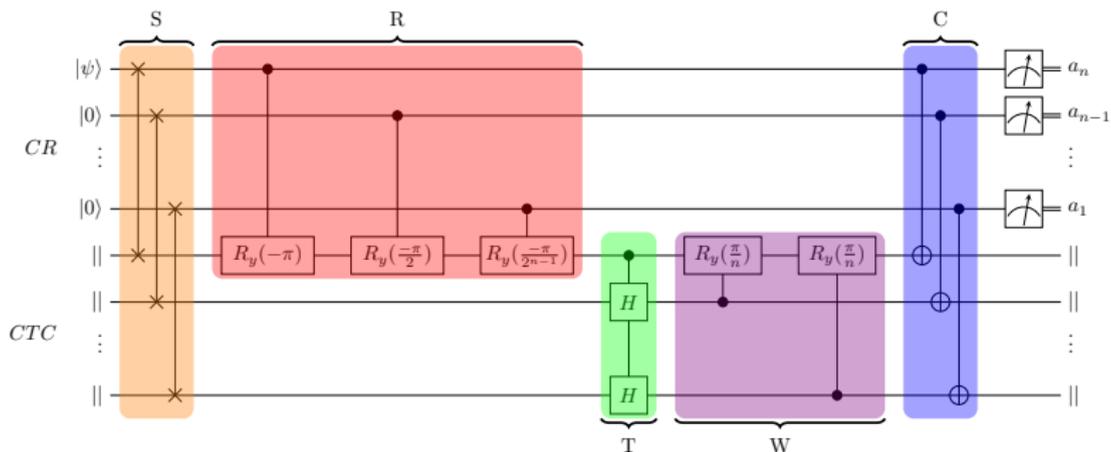
- ▶ Alice wants to send information to Bob. Alice prepares one of these single qubit states.
- ▶ These states are evenly spaced and lie on the XZ plane of the Bloch sphere.
- ▶ Here, for example, Alice can choose from 8 different states (3-bits of information).

Encoding of an n -bit register in a single qubit



- ▶ Alice can employ this circuit to prepare her qubit.
- ▶ To encode $k = (a_n \dots a_1)$, the total rotation performed on $|0\rangle$ is $R_y(\frac{2\pi k}{2^n})$.
- ▶ $|\psi_k\rangle$ is the states in our dictionary, which corresponds to the value k . She sends this to Bob.

Retrieving the n -bit register from the encoded qubit

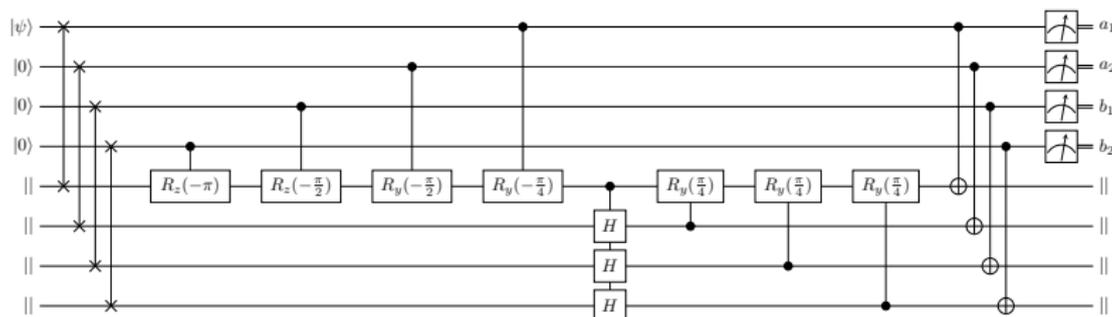


- ▶ Bob employs this circuit to retrieve k .
- ▶ S swaps the CR and CTC registers.
- ▶ R is the circuit in the previous slide, although the rotation is performed in the opposite direction.

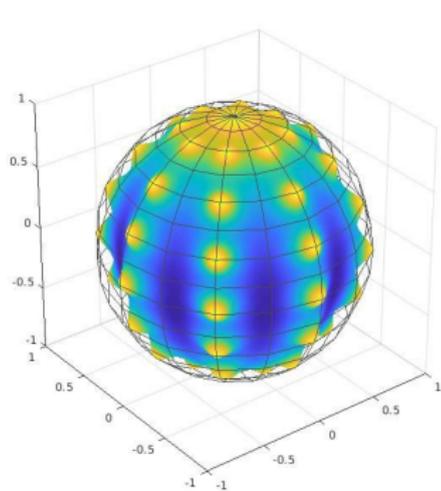
Retrieving the n -bit register from the encoded qubit

- ▶ If the CTC system is initialized to $|k\rangle$, R yields $|0\rangle$. T and W have no influence and C copies k to the CTC. The self-consistency condition is satisfied.
- ▶ if the CTC system is not initialized to $|k\rangle$, R does not rotate $|\Psi_k\rangle$ to $|0\rangle$.
- ▶ Then, T and W transforms the CTC system in a superposition of all the computational basis states. The action of C still yields a complete superposition.
- ▶ the output of the CTC has a non-zero projection onto $|k\rangle$. This ensures that there are no other solutions to the self-consistency condition.
- ▶ Thus, the CTC system always is initialized as $|k\rangle$. Bob can simply measure the qubits to retrieve k .

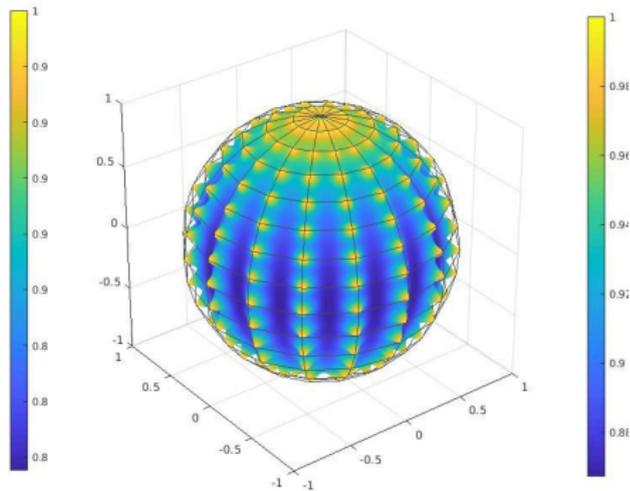
CTC-assisted circuit to clone a single qubit state



- ▶ We can extend our dictionary of distinguishable states by rotation along both the Y and Z axis.
- ▶ Rotation along Z: Azimuthal angle; Rotation along Y: Polar angle
- ▶ Here, (a_1, a_2) gives the polar angle and (b_1, b_2) gives azimuthal angle.



(a)



(b)

- ▶ Cloning is imperfect. We can evaluate the fidelity of cloning for the other states and plot this on a Bloch sphere.
- ▶ (a) corresponds to 3 qubits for both azimuthal and polar angles. (b) corresponds to 4 qubits each.

Quantum Signaling to the Past Using P-CTCS

Quantum Signaling to the Past Using P-CTCS*

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Closed Timelike Curves (CTCs) are intriguing relativistic objects that allow for time travel to the past and can be used as computational resources. In Deutschian Closed Timelike Curves (D-CTCs), due to the monogamy of entanglement, non-local correlations between entangled states are destroyed. In contrast, for Postselected Closed Timelike Curves (P-CTCs), a second variant of CTCs, the non-local correlations are preserved. P-CTCs can be harnessed for the signaling of non-orthogonal states to the past without a disruption of causality. In this paper, we take up signaling to the past and show a method of sending four non-orthogonal states to the past using P-CTCs. After constructing our signaling protocol, we study the causality violations that our protocol results in and put forward two consistency relations to prevent them.

Spin Entanglement Witness for Quantum Gravity

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Understanding gravity in the framework of quantum mechanics is one of the great challenges in modern physics. However, the lack of empirical evidence has led to a debate on whether gravity is a quantum entity. Despite varied proposed probes for quantum gravity, it is fair to say that there are no feasible ideas yet to test its quantum coherent behavior directly in a laboratory experiment. Here, we introduce an idea for such a test based on the principle that two objects cannot be entangled without a quantum mediator. We show that despite the weakness of gravity, the phase evolution induced by the gravitational interaction of two micron size test masses in adjacent matter-wave interferometers can detectably entangle them even when they are placed far apart enough to keep Casimir-Polder forces at bay. We provide a prescription for witnessing this entanglement, which certifies gravity as a quantum coherent mediator, through simple spin correlation measurements.

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Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

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All existing quantum-gravity proposals are extremely hard to test in practice. Quantum effects in the gravitational field are exceptionally small, unlike those in the electromagnetic field. The fundamental reason is that the gravitational coupling constant is about 43 orders of magnitude smaller than the fine structure constant, which governs light-matter interactions. For example, detecting gravitons—the hypothetical quanta of the gravitational field predicted by certain quantum-gravity proposals—is deemed to be practically impossible. Here we adopt a radically different, quantum-information-theoretic approach to testing quantum gravity. We propose witnessing quantumlike features in the gravitational field, by probing it with two masses each in a superposition of two locations. First, we prove that any system (e.g., a field) mediating entanglement between two quantum systems must be quantum. This argument is general and does not rely on any specific dynamics. Then, we propose an experiment to detect the entanglement generated between two masses via gravitational interaction. By our argument, the degree of entanglement between the masses is a witness of the field quantization. This experiment does not require any quantum control over gravity. It is also closer to realization than detecting gravitons or detecting quantum gravitational vacuum fluctuations.

DOI: 10.1103/PhysRevLett.119.240402

Quantum circuit for simulating the scheme.

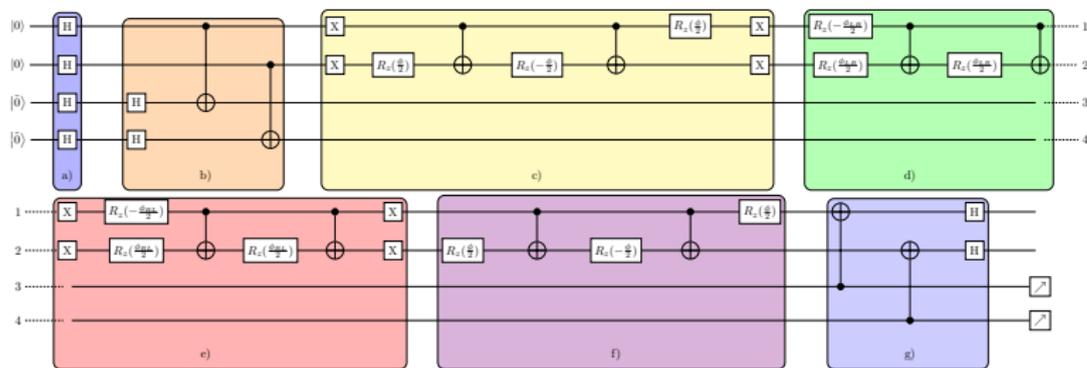


Figure: $|0\rangle$ and $|\tilde{0}\rangle$ denote the mass quantum states and the spin quantum states respectively. **Step a:** we create superposition of both mass and spin quantum states using Hadamard gates. **Step b:** we entangle the mass qubit with the corresponding spin qubit of either of the test masses. **Step c, d, e, f:** we introduce the gravitational phase to the system via ‘LOCC’. **Step g:** we disentangle mass and the spin qubits and then measure the spin qubits in two complementary bases to calculate entanglement witness \mathcal{W} .

Entanglement Witness

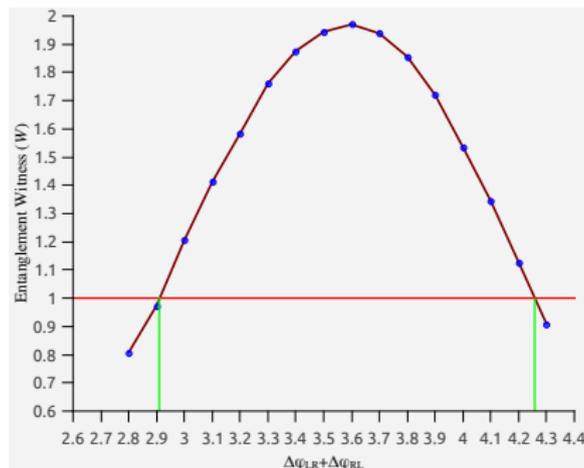


Figure: Entanglement Witness (W) vs $\Delta\phi_{LR} + \Delta\phi_{RL}$ plot. Data points in the upper half of the horizontal red line denotes entangled states. The section of the x-axis in between two vertical green lines are the corresponding $\Delta\phi_{LR} + \Delta\phi_{RL}$ values for which the state is entangled.

Conservation Law for Massive Scale-Invariant Photons in Weyl-Invariant Gravity

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Conservation law for massive scale-invariant photons in Weyl-invariant gravity

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Conservation Law for Massive Scale-Invariant Photons in Weyl-Invariant Gravity

- ▶ It is demonstrated that a Stueckelberg-type gauge theory, coupled to the scalar-tensor theory of gravity, is invariant under both gauge and Weyl transformations.
- ▶ It is found that broken scale invariance leads to simultaneous spontaneous breaking of the gauge symmetry.

Here is the following scalar-tensor lagrangian density;

$$\mathcal{L}_{\text{ST}} = \frac{1}{\kappa} \left[\frac{1}{12} \sqrt{-g} R \varphi^2 + \frac{1}{2} \sqrt{-g} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi \right]. \quad (1)$$

The infinitesimal Weyl symmetry,

$$\delta g^{\mu\nu} = 2\theta g^{\mu\nu}, \delta \varphi = \theta \varphi, \quad (2)$$

changes the Lagrangian by a total derivative, leading to *off-shell* contribution to the conserved current as,

$$X^\mu = \frac{1}{2\kappa} \sqrt{-g} \varphi^2 g^{\mu\nu} \partial_\nu \theta. \quad (3)$$

The use of Euler-Lagrange equations for φ and $g_{\mu\nu}$, re-casts the variation of the Lagrangian as a total derivative, leading to the *on-shell* contribution to the Weyl current,

$$K^\mu = \frac{1}{2\kappa} \sqrt{-g} \varphi^2 g^{\mu\nu} \partial_\nu \theta. \quad (4)$$

As both these contributions are equal, the conventional conserved Nöther Weyl current vanishes: $J^\mu = K^\mu - X^\mu = 0$, deeming the Weyl symmetry as a fake one.

The situation is unchanged upon application of Nöether's second theorem, appropriate for local symmetries, such as the Weyl symmetry here. The present aim is to obtain an extended theory having genuine generalized symmetry, instead of the 'fake' one, thereby obtaining a non-vanishing current. Although the matter of extended Weyl symmetries have been discussed earlier, with additional fields, having general coupling to STG and massive excitations, the issue of the conserved current was not addressed. We have constructed the simplest example of a theory, non-trivially coupled to the STG, yielding an extended, but genuine, Weyl symmetry.

- ▶ R. Jackiw and S.-Y. Pi, Physical Review D 91, 067501 (2015).
- ▶ A. Shukla, K. Abhinav, P. K. Panigrahi, Classical and Quantum Gravity 33, 235008 (2016).
- ▶ A. Shukla, K. Abhinav, P. K. Panigrahi, European Physical Journal C 76(11) (2016).

ThankYou