Quantum Gravity and Quantum Computing

(State of the art)

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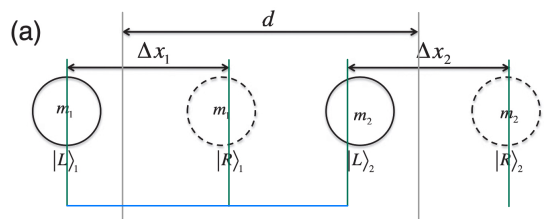
$$|\psi(t=0)\rangle = |\psi_1(t=0)\rangle \otimes |\psi_2(t=0)\rangle$$

$$= \frac{1}{\sqrt{2}}\left(|L\rangle_1 + |R\rangle_1\right) \frac{1}{\sqrt{2}}\left(|L\rangle_2 + |R\rangle_2\right)$$

$$= \frac{1}{2}\left[\, |LL\rangle_{12} + |LR\rangle_{12} + |RL\rangle_{12} + |RR\rangle_{12} \right]$$

$\Delta x_1 = \Delta x_2$



$d - \frac{\Delta x}{2} + \frac{\Delta x}{2} = d$

$d + \frac{\Delta x}{2} + \frac{\Delta x}{2} = d + \Delta x$

$d - \frac{\Delta x}{2} - \frac{\Delta x}{2} = d - \Delta x$

$d - \frac{\Delta x}{2} + \frac{\Delta x}{2} = d$

$$U(t=0, t>0) = e^{-\frac{i}{\hbar}Ht} \quad ; \quad H = \phi(x) = \frac{Gm_1m_2}{x_{12}}$$

$$* \quad U|LL\rangle_{12} = e^{-\frac{i}{\hbar}\phi(x)t}|LL\rangle_{12} = e^{-\frac{i}{\hbar}\frac{Gm_1m_2}{x_{12}}t}|LL\rangle_{12} \longrightarrow x_{12} = d$$

$$U|LR\rangle_{12} = \dots$$

$$U|RL\rangle_{12} = e^{-\frac{i}{\hbar}\phi(x)t}|RL\rangle_{12} = e^{-\frac{i}{\hbar}\frac{Gm_1m_2}{x_{12}}t}|RL\rangle_{12} \longrightarrow x_{12} = d - \Delta x$$

$$U|RR\rangle_{12} = \dots$$

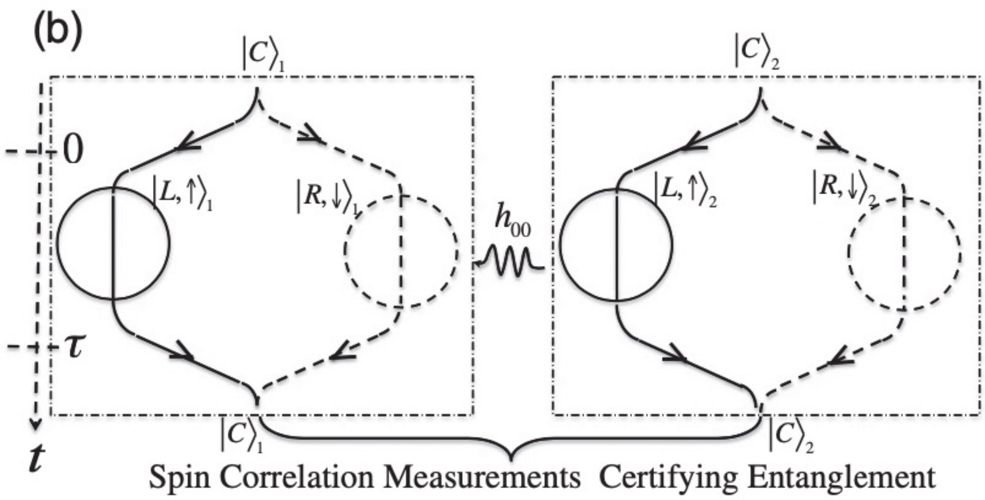
$$|\psi(t>0)\rangle = \frac{1}{2}\left[\underbrace{e^{-\frac{i}{\hbar}\frac{Gm_1m_2}{d}}}_{e^{i\phi}}|LL\rangle_{12} + \underbrace{e^{-\frac{i}{\hbar}\frac{Gm_1m_2}{d+\Delta x}}}_{e^{i\phi_{LR}}}|LR\rangle_{12} + \underbrace{e^{-\frac{i}{\hbar}\frac{Gm_1m_2}{d-\Delta x}}}_{e^{i\phi_{RL}}}|RL\rangle_{12} + \underbrace{e^{-\frac{i}{\hbar}\frac{Gm_1m_2}{d}}}_{e^{i\phi}}|RR\rangle_{12}\right]$$

$$= \frac{1}{\sqrt{2}}e^{i\phi}\left[\frac{1}{\sqrt{2}}|L\rangle_1\left(|L\rangle_2 + e^{i\Delta\phi_{LR}}|R\rangle_2\right) + \frac{1}{\sqrt{2}}|R\rangle_1\left(e^{i\Delta\phi_{RL}}|L\rangle_2 + |R\rangle_2\right)\right]$$

$$\neq$$

Entangled state $\longrightarrow$ We need to measure the entanglement!

Gravitational Entanglement Witnessing in SG interferometry



Step 1 : Spin dependent spatial splitting of the center of mass state of the test mass m_j :

$$|C_1\rangle \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1+|\downarrow\rangle_1\right) \longrightarrow \frac{1}{\sqrt{2}}\left(|L\uparrow\rangle_1+|R\downarrow\rangle_1\right)$$

$$|C_2\rangle \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_2+|\downarrow\rangle_2\right) \longrightarrow \frac{1}{\sqrt{2}}\left(|L\uparrow\rangle_2+|R\downarrow\rangle_2\right)$$

$$|C_i\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle_i + |R\rangle_i\right)$$

Step 2 :

$$|\Psi(t=0)\rangle = \frac{1}{\sqrt{2}}\left(|L\uparrow\rangle_1+|R\downarrow\rangle_1\right)\frac{1}{\sqrt{2}}\left(|L\uparrow\rangle_2+|R\downarrow\rangle_2\right)$$

$$|\Psi(t>0)\rangle = \frac{1}{\sqrt{2}}e^{i\phi}\left[\frac{1}{\sqrt{2}}|\uparrow L\rangle_1\left(|\uparrow L\rangle_2+e^{i\Delta\phi_{LR}}|\downarrow R\rangle_2\right) + \frac{1}{\sqrt{2}}|\downarrow R\rangle_1\left(e^{i\Delta\phi_{RL}}|\uparrow L\rangle_2+|\downarrow R\rangle_2\right)\right]$$

Step 3 : Brings back the superposition through the unitary transformation

$$|L\uparrow\rangle_{1,2} \rightarrow |C,\uparrow\rangle$$

$$|R\downarrow\rangle_{1,2} \rightarrow |C,\downarrow\rangle$$

$$|\Psi(t_f)\rangle = \frac{1}{\sqrt{2}}e^{i\phi}\left[\frac{1}{\sqrt{2}}|\uparrow\rangle_1\underline{\left(|\uparrow\rangle_2+e^{i\Delta\phi_{LR}}|\downarrow\rangle_2\right)} + \frac{1}{\sqrt{2}}|\downarrow\rangle_1\underline{\left(e^{i\Delta\phi_{RL}}|\uparrow\rangle_2+|\downarrow\rangle_2\right)}\right]|C_1C_2\rangle$$

Entangled state of the spins of the 2 test masses !

Entangled State:

$$|\uparrow\rangle_1\left(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}}|\downarrow\rangle_2\right) + |\downarrow\rangle_1\left(e^{i\Delta\phi_{RL}}|\uparrow\rangle_2 + |\downarrow\rangle_2\right) \not\propto |\Omega\rangle \otimes |\chi\rangle$$

Product State:

$$|\uparrow\rangle_1\left(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}}|\downarrow\rangle_2\right) + |\downarrow\rangle_1\left(e^{i\Delta\phi_{RL}}|\uparrow\rangle_2 + |\downarrow\rangle_2\right) \propto |\Omega\rangle \otimes |\chi\rangle$$

$$\boxed{\text{If} \quad -\Delta\phi_{LR} = 2\pi n + \Delta\phi_{RL}:}$$

$$= \left[e^{i\Delta\phi_{LR}}|\uparrow\rangle_1 + |\downarrow\rangle_1\right]\left[e^{i\Delta\phi_{RL}}|\uparrow\rangle_2 + |\downarrow\rangle_2\right]$$

Let us define:

$$\boxed{W = \sigma_x^{(1)} \otimes \sigma_z^{(2)} + \sigma_y^{(1)} \otimes \sigma_y^{(2)}}$$

$$W = \begin{pmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 \end{pmatrix}$$

$$|\Psi(t_f)\rangle = \frac{1}{2} e^{i\phi} \begin{pmatrix} 1 \\ e^{i\Delta\phi_{LR}} \\ e^{i\Delta\phi_{RL}} \\ 1 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} e^{i\phi} \\ e^{i\phi_{LR}} \\ e^{i\phi_{RL}} \\ e^{i\phi} \end{pmatrix}$$

Therefore:

$$|\langle W\rangle| = \left| \cos(\Delta\phi_{RL}) - \cos(\Delta\phi_{LR}) + \cos(\Delta\phi_{RL} - \Delta\phi_{LR}) - 1 \right|$$

If $-\Delta\phi_{LR} = 2\pi n + \Delta\phi_{RL}$:

$$|\langle W\rangle| = \left| \frac{\cos(2\Delta\phi_{LR}) - 1}{2} \right| \in [0;1] \longrightarrow \text{Product State}$$

Thus:

$$\boxed{|\langle W\rangle| > 1 \longrightarrow \text{Entangled State}}$$

Quantum Circuit:

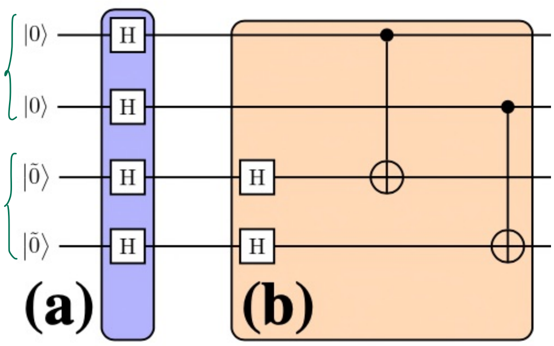
$$|\Psi(t=0)\rangle = \frac{1}{\sqrt{2}}\left(|L\uparrow\rangle_1 + |R\downarrow\rangle_1\right)\frac{1}{\sqrt{2}}\left(|L\uparrow\rangle_2 + |R\downarrow\rangle_2\right)$$

$$= \frac{1}{2}\left[|L\uparrow\rangle_1|L\uparrow\rangle_2 + |L\uparrow\rangle_1|R\downarrow\rangle_2 + |R\downarrow\rangle_1|L\uparrow\rangle_2 + |R\downarrow\rangle_1|R\downarrow\rangle_2\right]$$

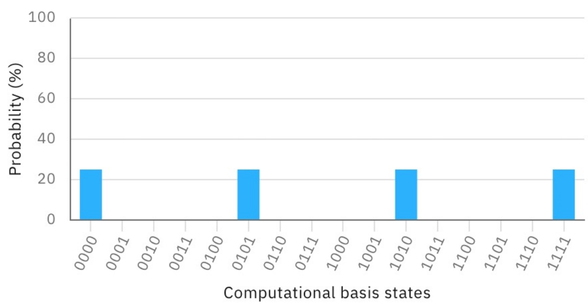
$$= \frac{1}{2}\left[\underset{0000}{|\uparrow\uparrow LL\rangle_{12}} + \underset{0101}{|\uparrow\downarrow LR\rangle_{12}} + \underset{1010}{|\downarrow\uparrow RL\rangle_{12}} + \underset{1111}{|\downarrow\downarrow RR\rangle_{12}}\right]$$

Spatial Splitting

Spin



$$|L\rangle \longrightarrow H|L\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right) = |C\rangle$$



$$\longrightarrow \underset{1111}{|\downarrow\downarrow RR\rangle} + \underset{1010}{|\downarrow\uparrow RL\rangle} + \underset{0101}{|\uparrow\downarrow LR\rangle} + \underset{0000}{|\uparrow\uparrow LL\rangle}$$

$$|\Psi(t>0)\rangle = \frac{1}{\sqrt{2}} e^{i\phi}\left[\frac{1}{\sqrt{2}}|\uparrow L\rangle_1\left(|\uparrow L\rangle_2 + e^{i\Delta\phi_{LR}}|\downarrow R\rangle_2\right) + \frac{1}{\sqrt{2}}|\downarrow R\rangle_1\left(e^{i\Delta\phi_{RL}}|\uparrow L\rangle_2 + |\downarrow R\rangle_2\right)\right]$$

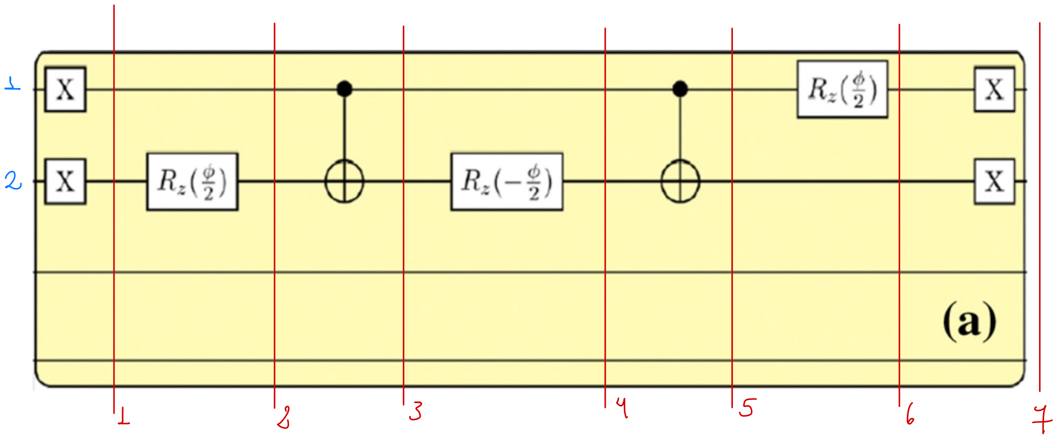
$$= \frac{1}{2}\left[|\uparrow\uparrow LL\rangle \underbrace{e^{i\phi}}_{\text{From } U_1^\dagger} + |\uparrow\downarrow LR\rangle \underbrace{e^{i\phi_{LR}}}_{\text{From } U_2^\dagger} + |\downarrow\uparrow RL\rangle \underbrace{e^{i\phi_{RL}}}_{\text{From } U_3^\dagger} + |\downarrow\downarrow RR\rangle \underbrace{e^{i\phi}}_{\text{From } U_4^\dagger}\right]$$

$$U_1^\dagger|\uparrow\uparrow\rangle = U_1^\dagger \begin{pmatrix}1\\0\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix} = U_1^\dagger\begin{pmatrix}1\\0\\0\\0\end{pmatrix} = \begin{pmatrix}e^{i\phi}\\0\\0\\0\end{pmatrix} \quad ; \quad U_1^\dagger = \begin{pmatrix}e^{i\phi} & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix}$$

In what follows we will work only over the position states. Let us summarize:

$$|\uparrow\uparrow LL\rangle = |\uparrow\uparrow\rangle \; ; \; |\uparrow\downarrow LR\rangle = |\uparrow\downarrow\rangle \; ; \; |\downarrow\uparrow RL\rangle = |\downarrow\uparrow\rangle \; ; \; |\downarrow\downarrow RR\rangle = |\downarrow\downarrow\rangle$$

i) $U_1^\dagger$:



$t=t_0$: $|\uparrow\uparrow\rangle_{12} + |\uparrow\downarrow\rangle_{12} + |\downarrow\uparrow\rangle_{12} + |\downarrow\downarrow\rangle_{12}$

$t=t_1$: $|\downarrow\downarrow\rangle_{12} + |\downarrow\uparrow\rangle_{12} + |\uparrow\downarrow\rangle_{12} + |\uparrow\uparrow\rangle_{12}$

$t=t_2$: $|\downarrow\rangle \underbrace{R_z(\tfrac{\phi}{2})|\downarrow\rangle} + |\downarrow\rangle \underbrace{R_z(\tfrac{\phi}{2})|\uparrow\rangle} + |\uparrow\rangle \underbrace{R_z(\tfrac{\phi}{2})|\downarrow\rangle} + |\uparrow\rangle \underbrace{R_z(\tfrac{\phi}{2})|\uparrow\rangle}$

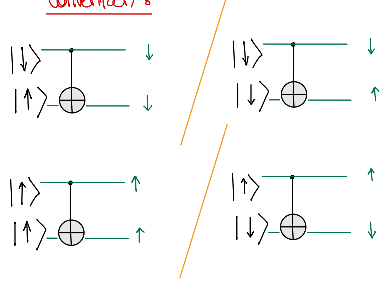
$$\begin{pmatrix}1 & 0\\ 0 & e^{i\phi/2}\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix} \quad \begin{pmatrix}1 & 0\\ 0 & e^{i\phi/2}\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix} \quad \begin{pmatrix}1 & 0\\ 0 & e^{i\phi/2}\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix} \quad \begin{pmatrix}1 & 0\\ 0 & e^{i\phi/2}\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}$$

$$\downarrow$$

$$\begin{pmatrix}0\\1\end{pmatrix}\otimes\begin{pmatrix}0\\e^{i\phi/2}\end{pmatrix} \quad \begin{pmatrix}0\\1\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix} \quad \begin{pmatrix}1\\0\end{pmatrix}\otimes\begin{pmatrix}0\\e^{i\phi/2}\end{pmatrix} \quad \begin{pmatrix}1\\0\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix}$$

$$= e^{i\phi/2}|\downarrow\downarrow\rangle_{12} + |\downarrow\uparrow\rangle_{12} + e^{i\phi/2}|\uparrow\downarrow\rangle_{12} + |\uparrow\uparrow\rangle_{12}$$

Convention:



$t = t_3:$ $\quad e^{i\phi/2}|\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle + e^{i\phi/2}|\uparrow\downarrow\rangle + |\uparrow\uparrow\rangle$

$t = t_4:$ $\quad e^{i\phi/2}|\downarrow\rangle \underbrace{R_z(-\phi/2)|\uparrow\rangle}_{|\uparrow\rangle} + |\downarrow\rangle \underbrace{R_z(-\phi/2)|\downarrow\rangle}_{e^{-i\phi/2}|\downarrow\rangle} + e^{i\phi/2}|\uparrow\rangle \underbrace{R_z(-\phi/2)|\downarrow\rangle}_{e^{-i\phi/2}|\downarrow\rangle} + |\uparrow\rangle \underbrace{R_z(-\phi/2)|\uparrow\rangle}_{|\uparrow\rangle}$

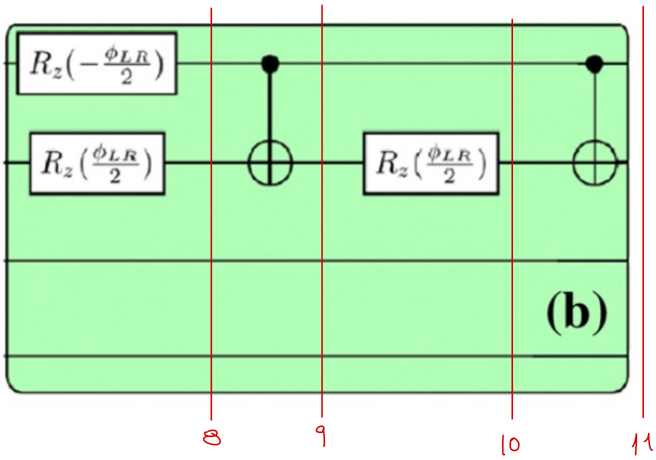
$\quad = e^{i\phi/2}|\downarrow\uparrow\rangle_{12} + e^{-i\phi/2}|\downarrow\downarrow\rangle_{12} + |\uparrow\downarrow\rangle_{12} + |\uparrow\uparrow\rangle_{12}$

$t = t_5:$ $\quad e^{i\phi/2}|\downarrow\downarrow\rangle_{12} + e^{-i\phi/2}|\downarrow\uparrow\rangle_{12} + |\uparrow\downarrow\rangle_{12} + |\uparrow\uparrow\rangle_{12}$

$t = t_6:$ $\quad e^{i\phi}|\downarrow\downarrow\rangle + |\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\uparrow\uparrow\rangle$

$t = t_7:$ $\quad e^{i\phi}|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle$

ii) $U_2^{\dagger}$:



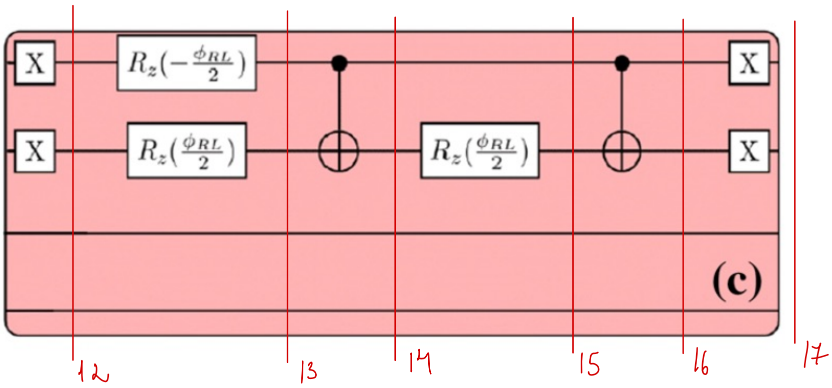
$t = t_8:$ $\quad e^{i\phi}|\uparrow\uparrow\rangle + e^{i\frac{\phi_{LR}}{2}}|\uparrow\downarrow\rangle + e^{-i\frac{\phi_{LR}}{2}}|\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle$

$t = t_9:$ $\quad e^{i\phi}|\uparrow\uparrow\rangle + e^{i\frac{\phi_{LR}}{2}}|\uparrow\downarrow\rangle + e^{-i\frac{\phi_{LR}}{2}}|\downarrow\downarrow\rangle + |\downarrow\uparrow\rangle$

$t = t_{10}:$ $\quad e^{i\phi}|\uparrow\uparrow\rangle + e^{i\phi_{LR}}|\uparrow\downarrow\rangle + |\downarrow\downarrow\rangle + |\downarrow\uparrow\rangle$

$t = t_{11}:$ $\quad e^{i\phi}|\uparrow\uparrow\rangle + e^{i\phi_{LR}}|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle$

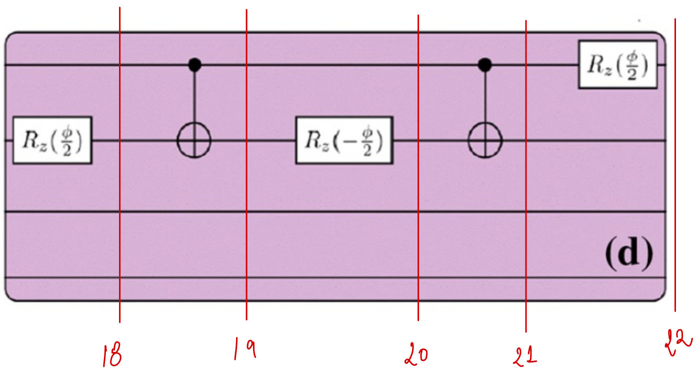
iii) $U_3^\dagger$:



$t = t_{17}$:

$$e^{i\phi}|\uparrow\uparrow\rangle + e^{i\phi_{LR}}|\uparrow\downarrow\rangle + e^{i\phi_{RL}}|\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle$$

* $U_4^\dagger$:

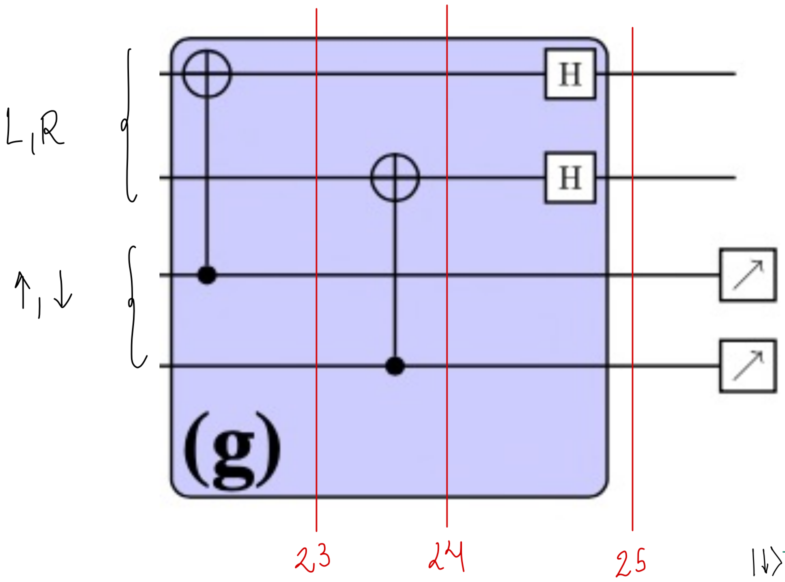


$t = t_{22}$:

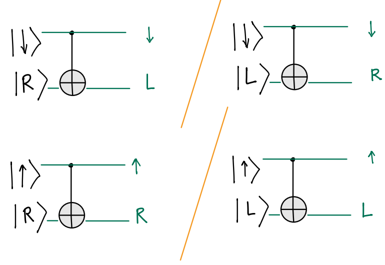
$$\underset{LL}{e^{i\phi}|\uparrow\uparrow\rangle} + \underset{LR}{e^{i\phi_{LR}}|\uparrow\downarrow\rangle} + \underset{RL}{e^{i\phi_{RL}}|\downarrow\uparrow\rangle} + \underset{RR}{e^{i\phi}|\downarrow\downarrow\rangle}$$

Thus, up to now :

$$|\Psi(t>0)\rangle = \frac{1}{2}\Big[\,|\uparrow\uparrow LL\rangle\, e^{i\phi} + |\uparrow\downarrow LR\rangle\, e^{i\phi_{LR}} + |\downarrow\uparrow RL\rangle\, e^{i\phi_{RL}} + |\downarrow\downarrow RR\rangle\, e^{i\phi}\Big]$$



Convention :



$t = t_{25}$:

$$\frac{1}{2}\Big[e^{i\phi}|\uparrow\uparrow\rangle + e^{i\phi^{LR}}|\uparrow\downarrow\rangle + e^{i\phi^{RL}}|\downarrow\uparrow\rangle + e^{i\phi}|\downarrow\downarrow\rangle\Big]\,|C\rangle_1|C\rangle_2$$

$$|\psi(t_f)\rangle = \frac{1}{\sqrt{2}} e^{i\phi} \left[\frac{1}{\sqrt{2}} |\uparrow\rangle_1 \underline{\left(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}} |\downarrow\rangle_2 \right)} + \frac{1}{\sqrt{2}} |\downarrow\rangle_1 \underline{\left(e^{i\Delta\phi_{RL}} |\uparrow\rangle_2 + |\downarrow\rangle_2 \right)} \right] |C_1 C_2\rangle$$

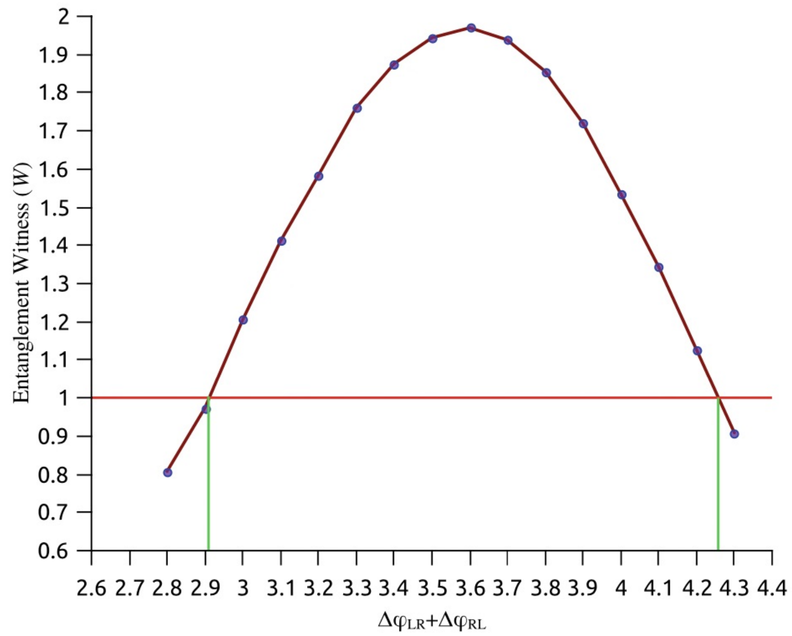


Fig. 5 Entanglement witness ($\mathcal{W}$) vs $\Delta\phi_{LR} + \Delta\phi_{RL}$ plot. Data points in the upper half of the horizontal red line denote entangled states. The section of the X-axis in between two vertical green lines are the corresponding $\Delta\Phi_{LR} + \Delta\phi_{RL}$ values for which the state is entangled

$$2.9113 < \underline{\Delta\phi_{LR} + \Delta\phi_{RL}} < 4.2647$$

$$\downarrow$$

$$46.7439\,n < \tau < 68.4742\,n$$

PHYSICAL REVIEW LETTERS **130,** 267001 (2023)

Editors' Suggestion   Featured in Physics

Millisecond Coherence in a Superconducting Qubit

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Improving control over physical qubits is a crucial component of quantum computing research. Here we report a superconducting fluxonium qubit with *uncorrected* coherence time $T_2^* = 1.48 \pm 0.13$ ms, exceeding the state of the art for transmons by an order of magnitude. The average gate fidelity was benchmarked at 0.99991(1). Notably, even in the millisecond range, the coherence time is limited by material absorption and could be further improved with a more rigorous fabrication. Our demonstration may be useful for suppressing errors in the next generation quantum processors.

DOI: 10.1103/PhysRevLett.130.267001

References :

[4] On the possibility of laboratory evidence for quantum superposition of geometries
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[b] *CPT, Aix-Marseille Université, Université de Toulon, CNRS, F-13288 Marseille, France*

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[2] Manabputra, Behera, B. K., & Panigrahi, P. K. (2020). A simulational model for witnessing quantum effects of gravity using IBM quantum computer. Quantum Information Processing, 19, 1-12.

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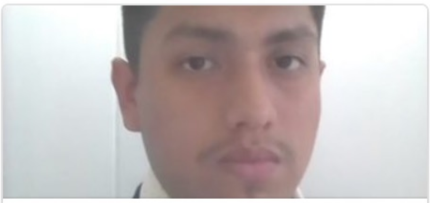
Our Team !!



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