Applications of Post-selected Closed Timelike Curves in Quantum Information Processing

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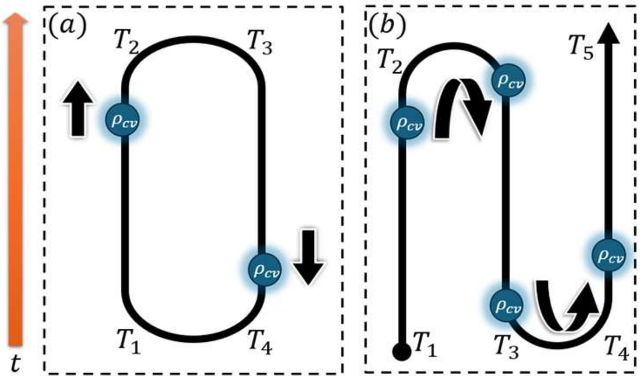
Abstract

Post-selected closed timelike curve (PCTC) theoretically enables the teleportation of information from the future to the present quantum state. We analyze PCTC with weak value amplification (PCTC-WVA), finding that the Fisher information (FI) increases by 89% compared to the case without PCTC. Additionally, we demonstrate that PCTC is crucial for work extraction: without it, the efficiency of the quantum Szilárd engine approaches zero. By analyzing readout errors and controlled-Z (CZ) errors arising from real devices, we show that the ideal case, after performing noise simulation, closely aligns the experimental statistics, confirming the reliability of the PCTC framework.

PCTC

In a CTC, particles loop back to their past before advancing to the future—equivalent to time travel for a linear observer. A quantum circuit can simulate this by sending the particle's state back to its past and then forward again. It's worth mentioning that PCTC builds on CTC by post-selecting those timelines that wouldn't produce the grandfather paradox, thereby ensuring that all timelines conform to self-consistency.



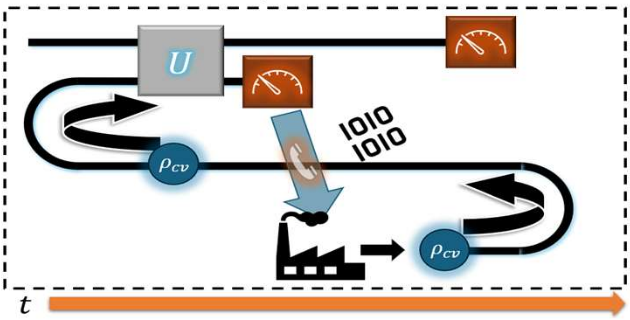
Metrology

We consider single-parameter estimation of an unknown θ in quantum metrology. After evolving the quantum state, we perform N measurements. By applying the Cramér–Rao bound to estimator θ, we obtain a lower bound for its variance, i.e.,

$$Var(\theta) \geq \frac{1}{NI(\theta)} \geq \frac{1}{NI_Q(\theta)}.$$

Here, Fisher information (FI) $I(\theta)$ measures the precision in estimating the parameter θ. We note that QFI is obtained by performing the optimal measurement Quantum FI (QFI) $I_Q(\theta)$ and hence is the upper bound of the FI $I(\theta)$, which is defined as

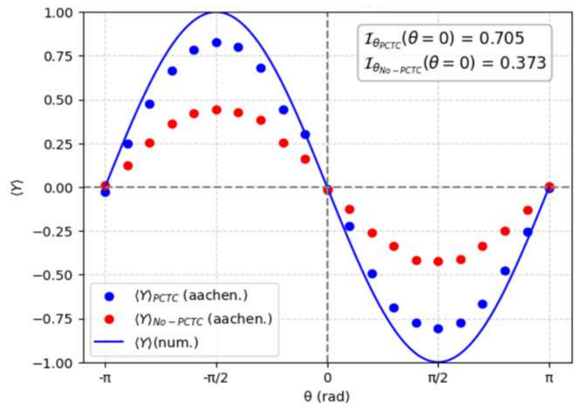
$$I(\theta) = \sum_i \frac{1}{P_i(\theta)} \left(\frac{\partial P_i(\theta)}{\partial \theta} \right)^2.$$



Advantage in Metrology via PCTC

$$P_i(\theta) = A_i \sin(\theta + \theta_0) + c_i.$$

We used the above formula to fit the probability distribution and calculate the FI. The experiment was conducted on IBM's aachen quantum processor.



Optimization of Quantum Heat Engines

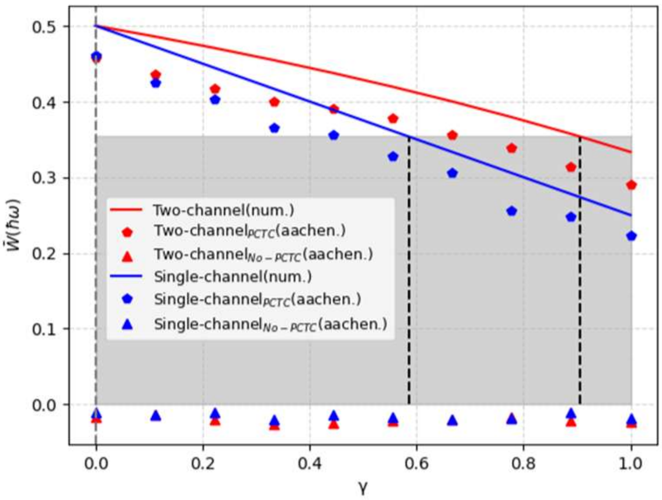
Consider a two-level system, in which $|0\rangle$ is the ground state and $|1\rangle$ is the excited state,

$$U_{a|x} \rho_{a|x} U_{a|x}^{\dagger} = |0\rangle\langle 0|.$$

$$\Delta W_{a|x} = Tr\left[H_W \Lambda(\rho_{a|x})\right] - Tr\left[H_W U_{a|x} \Lambda(\rho_{a|x}) U_{a|x}^{\dagger}\right].$$

Dephasing channel:

$$\Lambda(\rho) = \frac{1-\gamma}{2}\rho + \frac{\gamma}{2}\sigma_z \rho \sigma_z.$$



Heat engine	theoretical	experiment
$e_{\text{total two-channel}}$	5%	4.6%
$e_{\text{total single-channel}}$	2%	3.8%
Metrology	theoretical	experiment
e_{total}	14.5%	18%

References

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3. F.-J. Chan, *et al.*, Phys. Rev. A **106**, 052201 (2022).