Quantum Consensus Dynamics by Entangling Maxwell Demon

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Abstract

■ We introduce a Maxwell demon which generates many-body-entanglement robustly against thermal fluctuations, which allows us to obtain quantum advantage.

■ Adopting the protocol of the voter model used for opinion dynamics approaching consensus, the demon randomly selects a qubit pair and performs a quantum feed back control, in continuous repetitions.

■ We derive a lower bound of the entropy production rate by demon's operation, which is determined by a competition between the quantum-classical mutual information acquired by the demon and the absolute irreversibility of the feedback control.

■ Our finding of the lower bound corresponds to a reformulation of the second law of thermodynamics under a class of Maxwell demon which generates many-body entanglement in a working substance.

■This suggests that a general condition for the operation of a successful entangling demon, one for which many-body entanglement stabilization and work extraction are possible, is that the information gain is larger than the absolute irreversibility.

Introduction

■ A modern view of a Maxwell demon is a feedback control in which the dynamics of a system uses outputs of a measurement as inputs in a smart manner.

■ The field of thermodynamics of information has clarified the fundamental bounds on entropy reduction and work extraction in terms of quantities such as the quantum–classical mutual information and absolute irreversibility.

■ However, the thermodynamics of continuous quantum feedback remains a largely unexplored issue.

■ Recently, variants of the original Maxwell demon which operate continuously in time have been demonstrated, showing an enhancement of the work extraction beyond the conventional feedback control with a limitation given by modified second-law-like inequalities.

■ Stepping further along this direction, we propose a new type of Maxwell demon, namely a continuous quantum feedback control, that is capable of generating many-body entanglement in the working substance and study the quantum dynamics and second law of thermodynamics.

■ This provides insights of dynamics in the quantum steady-state engineering studied in quantum information and optics, in the language of thermodynamics of information.

Setup

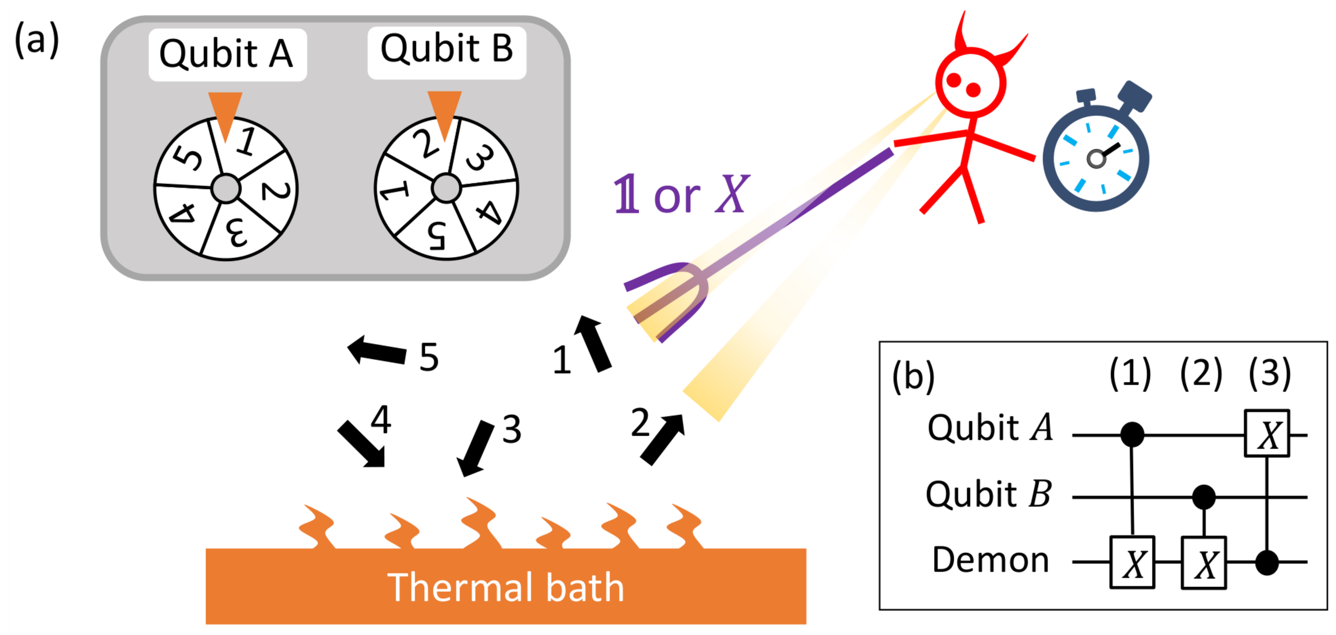

Fig. 1. Entangling maxwell demon adopting a protocol of the voter model (a) The demon selects a random pair of qubit A and B among many, and induces a copy process in which qubit A copies the state of qubit B in certain basis, continuously repeating the selection and copy process with a rate Γ_{copy}. A thermal bath induces bit-flip with a rate Γ_{flip}. **(b)** Quantum circuit realizing the copy proceess.

Entanglement generation

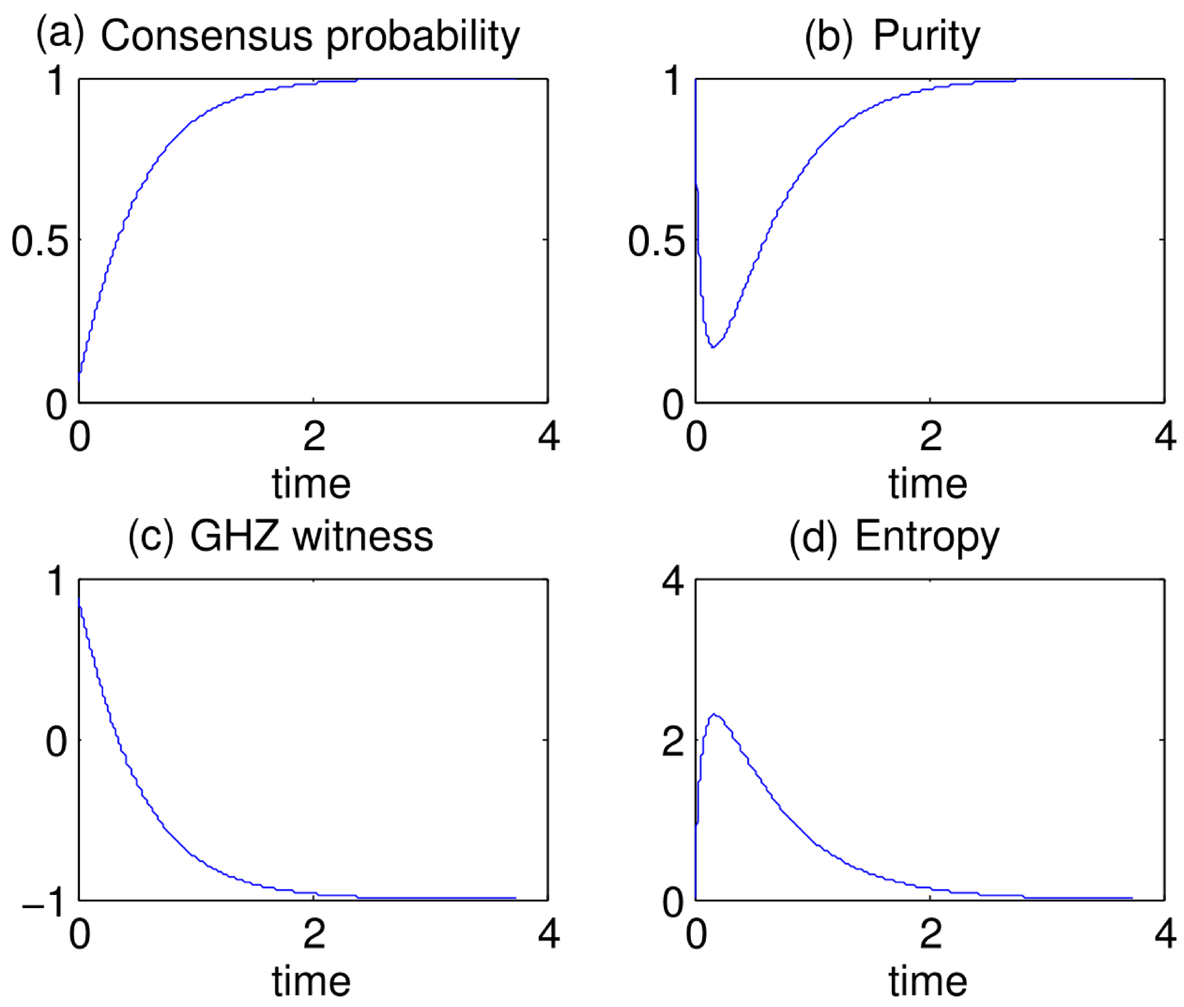

Fig. 2. Entanglement generation by the consensus dynamics in the absence of bit-flip noise. The quantum feedback controls induce consensus among the qubits **(a)**, while enhancing GHZ entanglement **(c)**. They reduce [or increase] von Neumann entropy of the qubits depending on time **(d)**, accompanying the enhancement [or reduction] of coherence **(b)**. Here, 5 qubits are considered , and the initial state is symmetric superposition $\sum_{s_1,\cdots,s_N=0,1}|s_1\cdots s_N\rangle$. The time is measured in $\Gamma_{\text{copy}}^{-1}$.

Entanglement protection

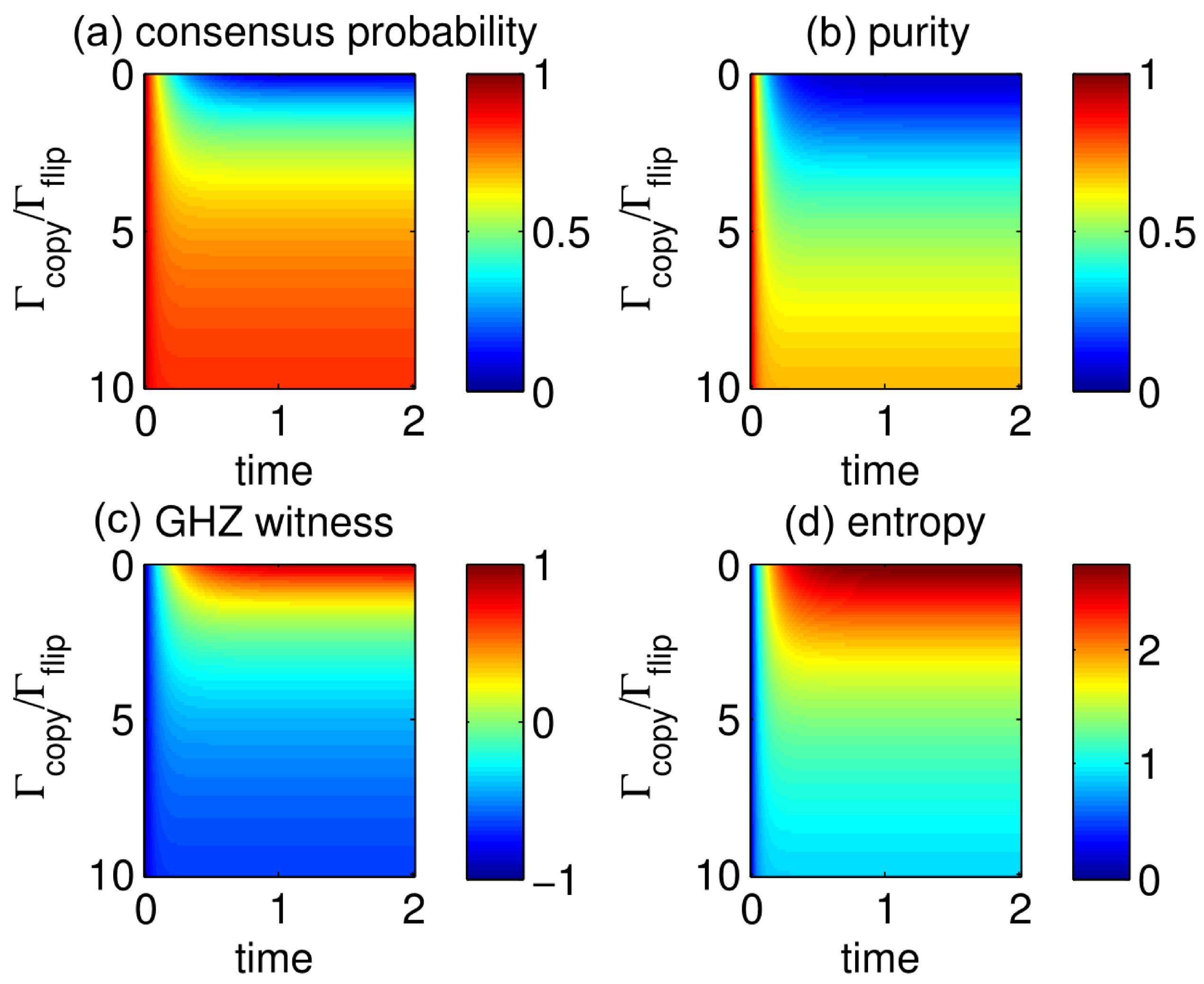

Fig. 3. Entanglement stabilization against bit-flip noise. Here, the initial state is 5-qubit GHZ state, $|00000\rangle+|11111\rangle$. When $\Gamma_{\text{copy}}>\Gamma_{\text{flip}}$, the consensus **(a)**, entanglement **(c)**, coherence **(b)**, and entropy **(d)** is protected against the thermal fluctuations. The time is measured in $\Gamma_{\text{flip}}^{-1}$.

■ Combining the two properties of entanglement generation and protection, the GHZ state can be generated even in the presence of bit-flip noises.

Entropy production by demon

■ We find that the entropy production by the copy processes, $\dot{S}_{\text{copy}}$, are lower bounded as

$$\dot{S}_{\text{copy}} \geq N_{\text{copy}}\Gamma_{\text{copy}}(-\overline{I_{\text{QC}}}+\overline{\lambda_{\text{fb}}})$$

N_{copy}: number of possible copy pairs.

$\overline{I_{\text{QC}}}$: quantum-classical mutual information for quantum system and classical measurement outcomes

$\overline{\lambda_{\text{fb}}}$: absolute irreversibility.

➢ Determined by how much the feedback-operated states are different for distinct selections.

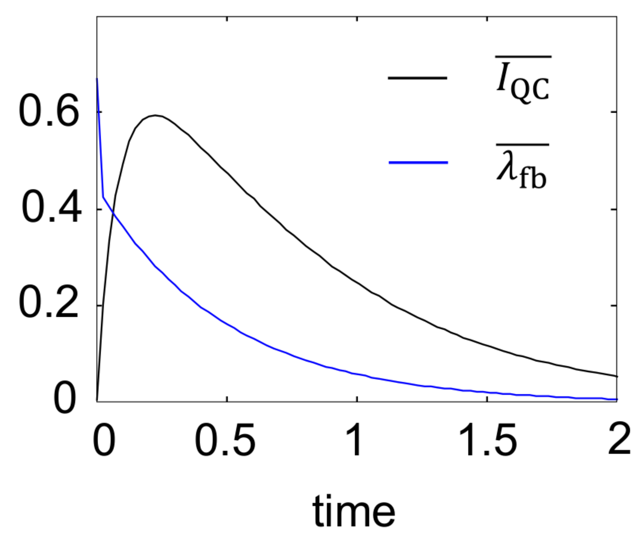

Fig. 4. Competition of $\overline{I_{\text{QC}}}$ and $\overline{\lambda_{\text{fb}}}$, responsible for the entropy in Fig. 2(d).

Conclusion

■ Inspired by the voter model and realized by stochastic and continuous quantum feedback controls, we have introduced a quantum coherent consensus dynamics and we have shown that it is able to generate GHZ-entanglement robustly against bit-flip noises.

■ We have also formulated the second law of thermodynamics under this new class of entangling Maxwell demon and obtained that the lower bound of the entropy production rate is determined by a competition between the quantum-classical information and the absolute irreversibility of the feedback control.

■ Our finding will be helpful for stabilizing a many-body entangled state and for the exploration of the quantum information engine whose working substance is in a many-body entangled state.

Reference: Sungguen Ryu, Rosa López and Raúl Toral. ArXiv:2102.00777. Accepted in New Journal of Physics