Quantum thermodynamics with quantum information flow: Theory and experiment

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Quantum thermodynamics is an active research area bridging quantum information and nonequilibrium statistical physics. A key to characterize universal behaviors of entropy production is the fluctuation theorem, which leads to the second law of thermodynamics in the regime far from equilibrium. The fluctuation theorem in classical systems has been thoroughly studied under various feedback control setups by incorporating classical information contents, which sheds modern light on "Maxwell's demon" [1]. However, an intriguing situation in quantum systems, such as continuous (or iterative) measurement and feedback, remains to be investigated.

In this talk, I will first present our theoretical results on the generalized fluctuation theorem and the second law under continuous measurement and feedback [2]. The key ingredient is a newly introduced concept to measure quantum information flow, which we call quantum-classical-transfer (QC-transfer) entropy. QC-transfer entropy can be naturally interpreted as the quantum counterpart of transfer entropy that is commonly used in classical time series analysis.

I will then present our recent collaborating work on an experiment [3]. Specifically, we employ a state stabilization protocol involving repeated measurement and feedback on an electronic spin qubit associated with a Silicon-Vacancy center in diamond, which is strongly coupled to a diamond nanocavity. This setup allows us to verify the fundamental laws of nonequilibrium quantum thermodynamics, including the second law and the fluctuation theorem, both of which incorporate QC-transfer entropy as mentioned above. We further assess the reducible entropy based on the feedback's causal structure and quantitatively demonstrate the thermodynamic advantages of non-Markovian feedback over Markovian feedback. These results reveal a fundamental connection between information and thermodynamics in the quantum regime.

References

[1] J. M. Parrondo, J. M. Horowitz, and T. Sagawa, Nature Physics **11**, 131 (2015).
[2] T. Yada, N. Yoshioka, and T. Sagawa, Phys. Rev. Lett. **128**, 170601 (2022).
[3] T. Yada*, P-J. Stas*, A. Suleymanzade, E. Knall, N. Yoshioka, T. Sagawa, and M. Lukin, arXiv:2411.06709 (2024). *: co-first authors