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THESIS DEFENSE: Harnessing Quantum Dynamics: Heat Engines, Negative Temperatures, and Dynamical Spectroscopy

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In this thesis, our main objective is to utilize different kinds of quantum dynamics as resources. To do so, we investigate thermodynamics, non-equilibrium steady states, and dynamical spectroscopy in order to categorize the dynamics of quantum systems as having either no external drive (self-drive), a weak external drive, or a strong external drive, respectively.In the first part, we explore the dynamics of quantum heat engines. In that, we consider dynamics that are driven by time-indep-\\endent Hamiltonian, i.e., without external driving. We show that when a working system non-locally interacts with two baths at different temperatures, the engine can operate in a one-step cycle, yielding Carnot efficiency at maximum power. This advantage is exclusively because non-local operations are more powerful than local ones. To study such engines in a more systematic manner, we develop a resource theory of heat engines. This provides a framework to study quantum engines operating with a working system composed of a finite number of quantum particles and restricted to few observations, i.e., in the one-shot finite-size regime. We also propose an experimentally feasible model of an engine using an atom-cavity system that yields Carnot efficiency at maximum power. In the second part, we consider open quantum dynamics, where a system weakly interacts with environments. In particular, we study the Lindblad master equation-based dynamics of quantum systems weakly coupled to two thermal baths at different temperatures. In general, these dynamics lead to non-equilibrium steady states. By selectively coupling a quantum system to two different thermal baths, a synthetic thermal bath can be engineered, and the temperature of such a synthetic bath can be made negative. With this, we explore steady-state quantum thermodynamics with negative temperatures. We show that the zeroth and the Clausius state of the second law remain unaltered in the case of baths with negative temperatures. However, the Kelvin-Planck statement of the second law updates in this case to incorporate the following. (i) There is spontaneous heat flow from a bath with a negative temperature to a bath with a positive temperature. In this sense, the baths with a negative temperature are `hotter' than the ones with a positive temperature. (ii) There is spontaneous heat flow from a bath with a less negative temperature

to a bath with a more negative temperature. We also introduce a continuous heat engine operating between a positive and negative temperature bath. Our analysis shows that the heat-to-work conversion efficiency for such an engine is always unity. We study the thermodynamic implications of our results. The third part of the thesis explores systems driven by strong external fields. In such circumstances, we encounter transient quantum dynamics, which cannot be described by thermodynamics. This kind of dynamics is utilized for dynamical spectroscopy. Particularly, we have studied high harmonic generation where a strong laser field interacts with matter. By utilizing the high harmonic generation mechanism, we characterize the topological features of solids.

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