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Using coherence as a resource in a two-mode BEC thermal quantum engine

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Converting disordered energy (heat) into ordered energy (work) is a fundamental objective in thermodynamics. In classical systems, disorder reflects practical limits on the knowledge of the microscopic state of a large system. Quantum systems, however, introduce an additional uncertainty arising from the fundamental structure of quantum mechanics [1]. Features such as coherence and entanglement, which have no classical counterpart, can be used to surpass classical limits or enable new thermodynamic protocols [2]. Williamson and collaborators [3] demonstrated that work can be extracted from a two-mode Bose-Einstein Condensate (BEC) initialized in a coherent state, even when the initial and final states have the same energy and the number-state probability distribution P(n). This establishes coherence as a purely quantum source of work.

The thermodynamic transformation in [3] represents only half of a thermal engine cycle. Here, we extend this idea by constructing closed thermodynamic cycles for a two-mode BEC, where the work steps utilise coherences and are performed by adjusting the coupling, detuning, and interaction strength as a function of time. We examine possible zero-temperature initial states, focusing on coherent states, and analyse their evolution through processes that reduce coherence while conserving energy and number statistics. This allows us to distinguish systematically between classical and quantum contributions to the extracted work. By closing the cycle and returning the system to its initial configuration, we establish a repeatable framework for quantum heat engines and quantify the role of coherence as a thermodynamic resource.

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[3] L. A. Williamson, F. Cerisola, J. Anders, and M. J. Davis, "Extracting work from coherence in a two-mode Bose–Einstein condensate", Quantum Science and Technology 10, 015040 (2024).

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