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Using quantum erasure to exorcise Maxwell's demon: II. Analysis

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Abstract

We present an analysis of the single atom negentropy quantum heat engine to determine the fundamental limits of its operation. The engine has an internal reservoir of negentropy which allows one to extract work from a single thermal reservoir. The process is attended by constantly increasing entropy and does not violate the second law of thermodynamics.

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1. Introduction

Thermodynamics [1], that is usually treated within the framework of classical mechanics, has recently been revisited within the context of quantum optics and interesting and novel features have been predicted in the operation of quantum heat engines (QHEs) [2,3]. In particular, the recent advances in quantum optics such as cavity QED [4], the maser [5], and LWI [6], have been employed to show that it is indeed possible to improve the efficiency of classical heat engines. For example, as has been shown recently in Refs. [7,8], a classical Otto-cycle heat engine can be improved by adding a laser system that is able to extract coherent laser energy from thermally excited atoms.

Also a quantum Carnot engine has been analyzed in which the atoms in the heat bath are given a small bit of quantum coherence [9,10]. The induced quantum coherence becomes vanishingly

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small in the high-temperature limit at which the engine operates, and the heat bath is essentially thermal. However, the phase of the atomic coherence provides a new control parameter that can be varied to increase the temperature of the radiation field and to extract work from a single heat bath.

The present work is an outgrowth of Ref. [11] where it is shown that the internal "spin" states of an atom can be cooled to absolute zero via a state selective Maser scheme, see also Ref. [12]. This process has been employed in the design of a QHE based on cycling a single atom through a micromaser cavity [5] many times [2].

In classical heat engines, useful work is produced by drawing energy from a high-temperature source and depositing entropy in a low-temperature entropy sink. Specifically a working fluid, such as steam, draws energy from a boiler, does work on a piston and deposits entropy in the cooling water. In the QHE presented in Ref. [13], the atomic spin states play the role of the working fluid, a blackbody Hohlraum is the energy source and the atomic spins drive a maser field producing useful work. However there is no lower temperature entropy sink in such a QHE. Instead, the atomic center of mass (COM) degrees of freedom are used to provide a source of negentropy [13–15] which allows the QHE to operate for a finite number of cycles. There is however a constantly increasing entropy in the engine operation such that there is no violation of the the second law.

Negentropy QHE consists of Hohlraum to heat atomic internal degrees of freedom and intelligent Maxwell demon realized via Stern–Gerlach apparatus (SGA) which separated hot and cold atoms. The relation of the single-atom heat engines to the Maxwell demon [19] concept is presented in Ref. [14], and the details of the different implementations can be found in [15]. The separation of hot and cold atoms is responsible for the running of the heat engine. It has been shown that a laser can be viewed as a heat engine [16].

The goal of the present paper is to perform an analysis to determine the fundamental restrictions and limitations of the negentropy QHE using internal degrees of freedom. We describe in details the general process of producing atomic beam pulse for the QHE and find out limitations on how many cycles it is able to perform.

2. Preparation of a single atom wave packet

The schematic of negentropy QHE is shown in Fig. 1. The atoms are initially stored in some material (see Fig. 1(B)). The binding energy of the atoms U_0 is low enough that the thermal radiation cannot effectively excite them. Note here that the process of creating a wave packet has similar physics with atom laser [20].

The atoms interact with the laser pulse to create an atomic pulse. The Hamiltonian of the atom is given by

$$H = H_0 + U(z) + V(z,t) \quad (1)$$

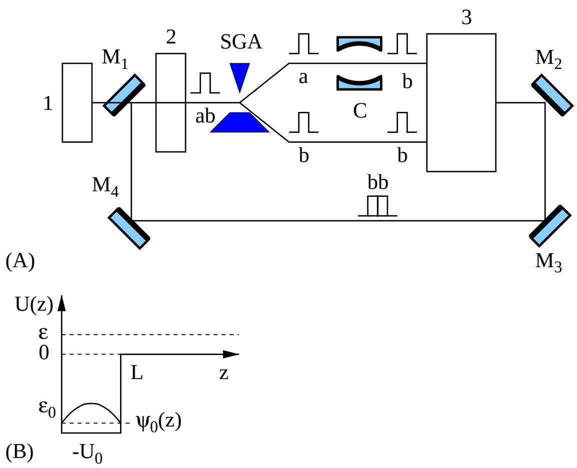

Fig. 1. (A) A schematic of negentropy QHE. (1) is the source of single atom beam. The atom goes through mirror M_1 then Hohlraum (2) where levels a and b become thermally populated. The atom then goes through a Stern–Gerlach apparatus (SGA) that separates hot and cold atoms, sending the atom in state a up, and the atom in state b down. Hot atom in state a goes through a cavity C where it deposits a photon. The system (3) combines the two beams together and doubles the duration of the wave packet. The mirrors M_2, M_3, and M_4 cycle the atomic wavepacket back to Hohlraum. Letters below the pulses denote the internal state of atom, e.g., a means atom is in the upper state. (B) Depicts the potential required to produce the initial atomic wave packet. A laser pulse excites atom from the ground state ε_0 to the excited state ε. Here $\psi_0(z)$ is the initial wave function corresponding to the ground state ε_0.