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One-photon atomic cooling with an optical Maxwell demon valve

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Abstract
We discuss the relationship between recent proposals of 'atom diodes' or one-way barriers for ultracold atoms and a Maxwell demon valve: in particular the way in which these proposals make use of dissipation via a one-photon spontaneous emission and avoid violation of the second law.

1. Introduction

The 'very observant and neat-fingered being' conceived by Maxwell, later known as Maxwell's demon, was able to open or close a little hole between two portions, A and B, of a vessel full of air, originally at uniform temperature, so as to accumulate fast molecules in one portion, A, and slow molecules in B [1]. The threat to the second law by this not necessarily malicious creature has triggered ever since the interest of many scientists, including a long list of very eminent ones, and the flow of related papers is far from abating with time after more than 130 years. There are collections of papers on the subject edited in two books [2, 3]. Whereas the first Maxwell demon was supposed to achieve a differential of temperature between the two partitions, according to Maxwell's description 'without expenditure of work', a second version of the demon would achieve a differential of pressure, simply by letting atoms cross in one direction but not in the opposite one, i.e., it would be essentially an inanimate one-way valve without the intelligent attributes of the first demon.

Maxwell's original aim was to show that the second law was only statistical and that it could be violated. A main topic in most discussions about these demons, their heirs and later variants has been their 'exorcism', although the exact meaning of this word varies with the authors, to show that the demons either cannot achieve their objective, or that, if they do, no violation of the second law takes place. A popular practice has been to assume from the start that the second law is globally obeyed, and identify later the step in a cyclic process in which an excess of entropy is produced that compensates the entropy reduction in the gas. Thus, Szilard located the entropy increase in the demon's measurement [4]; Bennett [5], following Landauer, and many others afterwards, in the erasure of the demon's memory, Fahn in the 'decorrelation' [6], Devereux in the motion of the partition [7], and so on. Exorcisms based on quantum mechanics have also been invoked [8]. Many of the arguments depend on specific models or definitions of entropy, so they are not always easy to compare and generalize. Moreover, since the rules of the game (i.e., the attributes and aim of the demon, or the conditions of the environment) are not clearly established or commonly accepted, there is a very broad variety of claims and results, and controversy abounds, for a glimpse see [9–12], sometimes about the analysis of the very same demon model (such as Szilard's one-molecule heat engine). After Szilard's paper and later work by Brillouin [13–15], the link between information—acquired or erased—and entropy has been present in most of the discussions, and appears to be the most broadly accepted source of exorcisms. Yet for the followers of the information entropy school of Shannon [16] and Jaynes [17]—who interpret entropy as missing information about the microstate—this is little more than a tautology.

Instead of emphasizing the various exorcisms, however, which may be a good exercise to meditate about thermodynamics, entropy, the second law, quantum measurement or information, a different route has been to overcome the level of gedanken experiments and propose some feasible realization of sorting devices for atoms, playing the roles of semipermeable membranes, valves or diodes, to achieve pressure and temperature differentials or 'rectification' of atomic motion. This was possibly out of the question in Maxwell's time but may seriously be considered nowadays with the advent of powerful laser cooling and atom manipulation techniques. Even if, strictly speaking, a demon with exactly the fantastic properties assumed by Maxwell, did not exist, proxies achieving sufficiently close objectives in their effect on the gas would be worthwhile for trapping, sorting or cooling. Proposals or actual experiments in this direction have been called and will be called Maxwell's demons in a broad sense, even if they spend and dissipate energy, do work, and do not violate any microscopic or macroscopic law. An example of this trend is the intense activity around rachets or Brownian motors [18], in which rectification occurs thanks to non-equilibrium conditions and periodic potentials with asymmetric units. The fact that they require non-equilibrium, thus not satisfying one of the assumptions of the original demon, does not make them less interesting or useful, in particular they are proposed as the mechanisms behind biological transport, and they are frequently referred to as Maxwell's demons. There are other examples: Balykin and Letokhov [19] have imagined a device rather close to the original Maxwell demon in which an information gathering laser device measures the velocity of the atom. This information would then be processed (in some unspecified way) to open or close an optical gate. They basically study the information gathering step looking at the shift in the laser beam phase provoked by the atom passage and estimate the signal to noise ratio and the temperatures that could be achieved; other proposed optical demons by Milburn [20] or Scully and coworkers [21] discuss a Stern–Gerlach type of separation of ground and excited states; a velocity selection technique has been termed Maxwell's demon cooling [22]; and a proposal to reduce the entropy of a finite system of atoms in a lattice by locating the vacancies and moving the atoms in a controlled way has also been related to the Maxwell demon [23].

A first obstacle for a one-way valve construction is the reversibility of microscopic laws. In a one-dimensional (1D) setting, the transmission of a structureless particle (classical or quantum) through a barrier surrounded by regions where the particle moves freely, is allowed or disallowed in both ways if the Hamiltonian is Hermitian. An option for one-way filtering is to dissipate energy asymmetrically, preferably into some external reservoir not to heat the particles of the gas or the door itself. Skordos and Zurek [24] made a model calculation

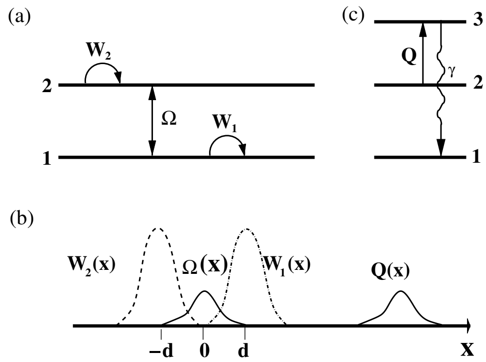

Figure 1. (a) Schematic action of the different lasers on the atom levels; (b) location of the laser potentials; (c) schematic action of a quenching laser.

showing that a dissipative asymmetric trap door does indeed induce a net flow if the gas is initially at rest. (Other one-way membrane models which compress phase space but are energy conserving and time reversible have been proposed [25, 26]; however, they are not Hamiltonian and thus, it is not clear how to implement them in practice.) The importance of dissipation was already stressed by Smoluchowski and Feynman discussing simple models such as the rachet and pawl [27]. More recently, Milburn has discussed a sorting atom–optical demon working as a Stern–Gerlach apparatus to separate ground and excited atoms at equilibrium with respect to their internal energy, passing through a cavity [20]. In order for the device to keep working, the mirror must be reset, for example with a restoring force together with friction, and this entails an entropy cost sufficient to avoid any violation of the second law.

2. Optical one-way barrier

The present authors undertook recently the objective of constructing optical one-way barriers (or 'atom diodes') for ultracold atoms independently [28–32], and without giving at first much thought to any demonic aspect to the enterprise. The goal is of obvious interest for trapping and cooling. Later we could not help but note the similarities with Maxwell's thought experiment. An analysis of the relation is actually worthwhile to understand why and how these devices work. At variance with some of the previous proposals for realizations of optical demons we focus on the translational motion. The proposed device is in its simplest form in the spirit of Maxwell's pressure demon, i.e., an inanimate valve for one-way motion. In a more sophisticated version in which the valve is moved within a trap [30], this may be also used for cooling.

Our approach for introducing a basic and microscopically allowed asymmetry in the transmission/reflection behaviour of the barrier is to use explicitly the internal structure of the atoms. Consider in particular the two-level atom scheme of figure 1(a) and the laser induced potentials represented in figure 1(b) consisting, from left to right, in a state-selective mirror potential W_2 for state 2, a pumping region with Rabi frequency Ω, and a state-selective mirror potential W_1 for state 1. They can be implemented by a highly detuned two photon stimulated Raman adiabatic passage (STIRAP) transition [31], and, neglecting decay from the excited state, the atom dynamics is governed by a Hermitian Hamiltonian. Nevertheless, the fate of atoms incident in the ground state is clearly asymmetrical: ground state atoms from the left are transmitted to the right in the excited state whereas they are reflected when coming from

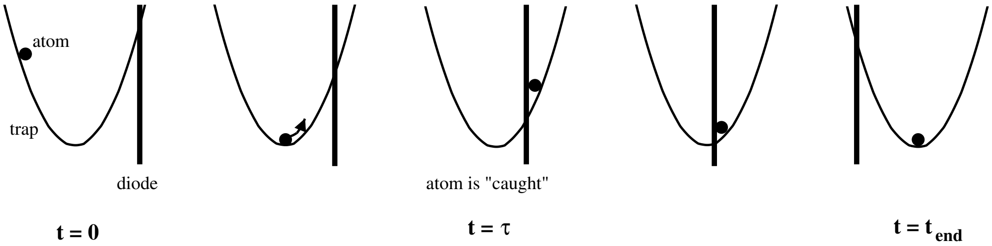

Figure 2. Schematic representation of the cooling method for a single particle: snapshots for different times; the passing direction of the diode is from left to right.

the right. This asymmetry may be enough for some applications but it will hardly be capable of providing an efficient valve in the long run since the transmitted atoms may return to the laser illuminated region in their excited state due to collisions or external forces. Of course microscopic reversibility still holds in the sense that time-reversed, leftwards trajectories are allowed for atoms incident in the excited state which end up in the ground state. The physical mechanism that comes in our help to break time-reversal symmetry is spontaneous decay. This can be speeded up by a quenching laser [32] (with induced potential $Q(x)$, see figures 1(b) and (c)) coupling the excited level 2 with another atomic level 3 which decays with a large decay rate γ to the ground state 1: the excited atom is pumped to state 3, emits a photon and suffers a recoil. However, due to the masses and frequencies involved, most of the excess energy of the excited state is carried away by the photon and the recoil kinetic energy is far too small to induce excitations of the internal state of the atom by collision. A limitation of this dissipative mechanism may be photon reabsorption, but it will be small for effectively 1D configurations or generally at sufficiently low densities. We have in summary described an ultracold-atom valve which works thanks to the asymmetric atomic excitation and the dissipation of one photon per atom. Used between two chambers it may lead to pressure differentials. Sweeping it through a harmonic trap may lead to atom cooling using one spontaneously emitted photon per atom [30] as described in the next section.

3. Cooling

We now outline the general idea of the cooling method. Let us consider a cloud of independent atoms confined in a harmonic trap and assume that the motion of the atoms can be described classically. In addition, we assume that the one-way barrier can be approximated as a perfect diode in the sense that every atom which crosses the diode is caught for sure and cannot cross back, i.e. the emission of a photon happens immediately and recoil is neglected. These idealizations are useful to determine the maximal amount of entropy reduction for the gas.

During the cooling process (see figure 2), the diode sweeps slowly through the potential and captures the atoms near their classical turning points. If the diode catches the atom, the atom will undergo an irreversible process which involves the scattering of a spontaneous photon. Then the moving diode, which becomes a hard wall for the captured atom, transports it to the bottom of the potential without increasing its kinetic energy. (A similar process occurs by moving down a racket slowly with a tennis ball at rest on it.) Thus the particles are cooled by a one-way barrier that is slowly swept through the cloud.

In contrast to ordinary laser cooling where repeated scattering of photons is used to slow particles, in our scheme each atom only scatters on average one photon, independently of the initial temperature T_{init}. In principle, every emitted photon can be detected as a function of time. From the detection time we know the corresponding barrier position and therefore the potential energy of the captured atoms. If the diode is moving slowly enough, the atom is caught always with kinetic energy approximately zero, so by measuring the emitted photons as a function of time, we can approximately reconstruct the initial atomic energy distribution.

We can assume the 'worst case' scenario in which the ensemble is such that the atom is always caught with zero kinetic energy. Thus the initial entropy of the cloud is greater than zero and the final entropy is zero: after the cooling every atom is in the same atomic state (with the atom at rest) independent of its initial state. Even in this extreme situation the second law holds as seen by taking into account the information that could be gathered by a photon detector, realizing the original scheme of Szilard.

4. Summary

The cooling method based on an optical realization of a Maxwell demon valve is in summary a process making use of dissipation via a single one-photon spontaneous emission per atom. It decreases the entropy of the gas at the expense of the photons, which, when measured, provide, if required, additional information on the gas, although of course, no photon detection is really needed for the cooling.

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