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## LETTER TO THE EDITOR

## Improvement by laser quenching of an ‘atom diode’: a one-way barrier for ultra-cold atoms

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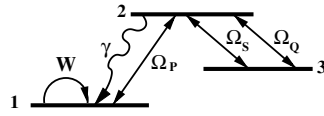
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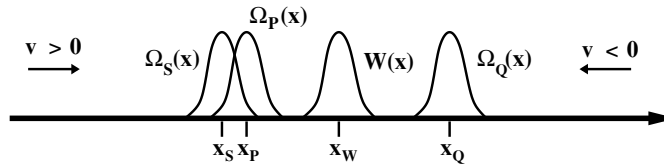
### Abstract

Different laser devices working as ‘atom diodes’ or ‘one-way barriers’ for ultra-cold atoms have been proposed recently. They transmit ground state level atoms coming from one side, say from the left, but reflect them when they come from the other side. We combine a previous model, consisting of the stimulated Raman adiabatic passage (STIRAP) from the ground to an excited state and a state-selective mirror potential, with a localized quenching laser which produces spontaneous decay back to the ground state. This avoids backwards motion, provides more control of the decay process and therefore a more compact and useful device.

Atom optics is devoted to the understanding and control of coherent atomic waves interacting with electromagnetic fields or material structures, and much of its current development is inspired by analogies with electronics and photonics. Many optical elements such as lenses, mirrors, splitters, or interferometers have been proposed and demonstrated [1, 2]. Ultra-cold atoms can also be transported coherently along waveguides, and this opens up the possibility of developing atom circuits or chips [3–5]. To that end, basic circuit elements and operations have to be implemented; among them, an important one is the ‘diode’ or ‘one-way barrier’, which lets atoms, typically in the ground state, pass in one direction but blocks them in the opposite direction, within a ‘working’ velocity range. Such a device may have a significant impact for trapping and cooling in waveguides or other geometries. In a series of recent papers [6–9], the present authors and co-workers have proposed and analysed the properties of different laser devices and atom-level schemes which achieve on paper the goal of one-way transmission. The possibility of using them for phase-space compression in a cooling procedure complementary to the existing ones [7, 8] is an exciting prospect that deserves further research and motivates several ongoing experimental and theoretical efforts in which this paper may be framed.



**Figure 1.** Atomic level structure for a diode model.



**Figure 2.** Spatial localization of the lasers. In the calculations  $x_S = -15 \mu\text{m}$ ,  $x_P = 15 \mu\text{m}$ ,  $x_W = 85 \mu\text{m}$  and  $x_Q = 155 \mu\text{m}$ .

In this letter, we tackle a significant practical improvement for some of the proposed diode implementations: the use of a quenching laser to induce at will excited state decay. A good diode must involve an irreversible decay step so that time-reversed trajectories associated with backwards motion in the ‘forbidden’ direction do not occur. For example, in a simple one-dimensional (1D) diode scheme, ground state atoms coming from the left within a broad velocity range are transmitted to the right in some excited state whereas ground state atoms from the right are blocked by a state-selective mirror. While this may be enough for some purposes, the absence of an irreversible decay from the excited state would mean, according to the unitarity of the collision matrix, that an excited atom could cross the device leftwards. Since excited atoms could come back towards the diode because of collisions or external forces, a truly one-way device, reliable when atom returns are possible, requires the irreversible decay of the excited atoms in a timescale smaller than the return time. This condition may occur naturally by a direct spontaneous decay. Nevertheless, long lived excited states need a long time to decay or, equivalently, the atom has to travel a long distance to decay, which leads to a spatially wide ‘atom diode’, a drawback for cooling applications. To remedy this problem, it is possible to force at will the irreversible decay via a quenching laser, as is explored and demonstrated here.

In our model the atom has the three-level structure of figure 1 with spontaneous decay from  $2 \rightarrow 1$ . We assume that the atomic motion is effectively 1D and use a combination of ‘Stokes’ and ‘pumping’ STIRAP lasers [10] with position dependent Rabi frequencies  $\Omega_S$ , and  $\Omega_P$ , a state-selective mirror laser and a quenching laser with Rabi frequencies  $W$  and  $\Omega_Q$ , respectively. Their spatial location is shown in figure 2. A similar model of the three-level atom diode has been proposed in [6] without quenching potential, but with spontaneous decay from  $3 \rightarrow 1$ . In that case the decay rate  $3 \rightarrow 1$  must be small enough such that the probability for spontaneous decay is negligible before the rightward travelling atom has passed the state-selective mirror (see [6] for details), but the small decay rate implies a spatially wide ‘atom diode’ region.

For a full description of the atomic dynamics corresponding to figures 1 and 2, including the possibility of several spontaneous emission cycles, the following 1D master equation must be examined [12–14]:

$$\frac{\partial}{\partial t} \rho = -\frac{i}{\hbar} \{H_{3L} \rho - \rho H_{3L}^\dagger\} + \gamma \int_{-1}^1 du \frac{3}{8} (1+u^2) \exp\left(i \frac{m v_{\text{rec}}}{\hbar} u x\right) |1\rangle \langle 2| \rho |2\rangle \langle 1| \times \exp\left(-i \frac{m v_{\text{rec}}}{\hbar} u x\right), \quad (1)$$

where  $v_{\text{rec}}$  is the recoil velocity,  $m$  is the mass, and the initial condition is taken as a pure state. Using  $|1\rangle \equiv (1\ 0\ 0)^T$ ,  $|2\rangle \equiv (0\ 1\ 0)^T$ , and  $|3\rangle \equiv (0\ 0\ 1)^T$ , the non-Hermitian conditional Hamiltonian is

$$H_{3L} = \frac{p_x^2}{2m} + \frac{\hbar}{2} \begin{pmatrix} W(x) & \Omega_P(x) & 0 \\ \Omega_P(x) & -i\gamma & \Omega_S(x) + \Omega_Q(x) \\ 0 & \Omega_S(x) + \Omega_Q(x) & 0 \end{pmatrix}. \quad (2)$$

All potential terms are chosen as Gaussian functions with equal widths  $\Delta x = 15\ \mu\text{m}$  and maximal heights  $\hat{\Omega}_P$ ,  $\hat{\Omega}_S$ ,  $\hat{W}$ ,  $\hat{\Omega}_Q$ ,

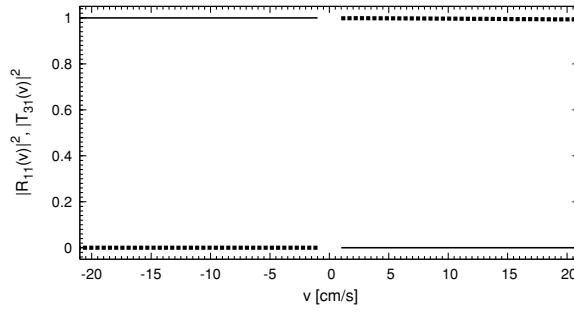
$$\begin{aligned} W(x) &= \hat{W} \Pi(x, x_W), & \Omega_S(x) &= \hat{\Omega}_S \Pi(x, x_S) \\ \Omega_P(x) &= \hat{\Omega}_P \Pi(x, x_P), & \Omega_Q(x) &= \hat{\Omega}_Q \Pi(x, x_Q), \end{aligned}$$

where  $\Pi(x, x_0) = \exp[-(x - x_0)^2 / (2\sigma^2)]$ . It is important that the distance  $x_W - x_P$  is not too small because otherwise the mirror potential spoils the STIRAP transfer, and of course  $x_Q \gg x_W$  must hold such that the atom crossing rightwards has passed the mirror potential before it decays to state 1.

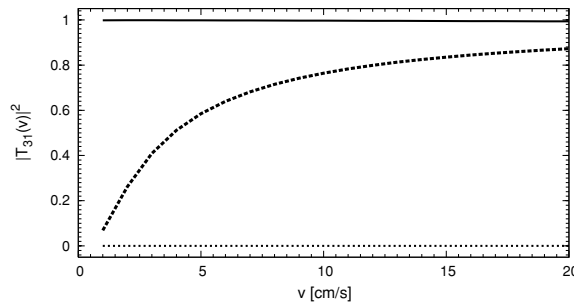
In the quantum-jump approach, the master equation (2) is solved by averaging over ‘trajectories’ with time intervals in which the wavefunction evolves with the conditional Hamiltonian interrupted by random jumps (decay events) [12]. Therefore the dynamics before the first spontaneous photon emission is described by a simple Schrödinger equation using the conditional Hamiltonian  $H_{3L}$ . Note that the STIRAP process  $1 \rightarrow 3$  is characterized by its stability with respect to atom velocity and the fact that it is not much affected by the decay  $2 \rightarrow 1$ , since the adiabatic state realizing the transfer is not composed by 2 at all. Also, because of the position of the quenching laser promoting spontaneous decay from 2 and the assumed level structure, it will be extremely unlikely to have more than one pumping-emission cycle. Thus, the dynamics under the conditional Hamiltonian will be essentially enough to determine the quality and behaviour of the diode. In particular, it will help us to select good values for the laser parameters. So let us examine the stationary Schrödinger equation with  $H_{3L}$ . Using  $\alpha$  and  $\beta$  to denote the channels associated with the internal states,  $\alpha = 1, 2, 3$ ,  $\beta = 1, 2, 3$ , let us denote as  $R_{\beta\alpha}(v)$  the reflection amplitude for an atom incident with velocity  $v$  (positive or negative, see figure 2) in channel  $\alpha$  and reflected in channel  $\beta$ . Similarly, let  $T_{\beta\alpha}(v)$  be the transmission amplitude from  $\alpha$  to  $\beta$ .

First, we examine the case without quenching potential ( $\Omega_Q = 0$ ) but with  $\gamma > 0$ . The parameters  $\hat{\Omega}_P = \hat{\Omega}_S$  have to be chosen large enough such that all ground state atoms incident from the left are transmitted into state 3 (i.e.  $|T_{31}(v)|^2 \approx 1$  for  $v > 0$ ) whereas from the right they are reflected in a velocity interval (i.e.  $|R_{11}(v)|^2 \approx 1$  for  $v < 0$ ). Figure 3 shows that this is true for the chosen parameters. Note the stability of the results with respect to velocity because of the adiabatic passage.

Without a quenching laser, the process  $3 \rightarrow 1$  from the right, however, would be also permitted and in fact very efficient. We shall now include the quenching laser and calculate again the transmission probability for the process  $1 \rightarrow 3$ , namely,  $|T_{31}(v)|^2$  for  $v > 0$ . Figure 4 shows that by increasing  $\hat{\Omega}_Q$  it is possible to suppress totally  $|T_{31}(v)|^2$ . Since reflection for ground state atoms coming from the left is still negligible, this means that the norm of a wavefunction of atoms incident in level 1 from the left is absorbed totally under the time-dependent Schrödinger equation with the non-Hermitian Hamiltonian  $H_{3L}$ . Physically,



**Figure 3.** Reflection probability  $|R_{11}(v)|^2$  (solid line), transmission probability  $|T_{31}(v)|^2$  (dashed line)  $\hat{\Omega}_Q = 0$ . Here and in the following figures,  $\hat{\Omega}_P = \hat{\Omega}_S = 10^6 \text{ s}^{-1}$ ,  $\hat{W} = 2 \times 10^7 \text{ s}^{-1}$ ,  $\gamma = 10^5 \text{ s}^{-1}$ , and  $m$  is the mass of neon.



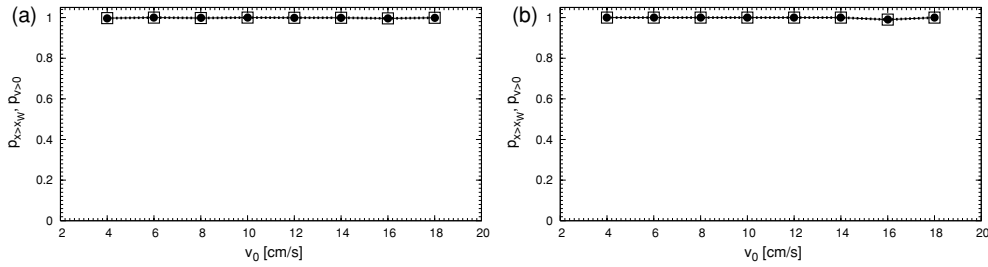
**Figure 4.** Transmission probability  $|T_{31}(v)|^2$  for different  $\hat{\Omega}_Q$ :  $\hat{\Omega}_Q = 0$  (solid line),  $\hat{\Omega}_Q = 10^4 \text{ s}^{-1}$  (thick dotted line),  $\hat{\Omega}_Q = 10^5 \text{ s}^{-1}$  (dotted line).

nearly all atoms incident in state 1 from the left will emit a spontaneous photon. Because the emission will take place very likely close to the quenching potential, the atom will finally travel to the right in the ground state, as confirmed below by solving the master equation. All other probabilities represented in figure 3 remain unchanged; in particular, the atoms coming from the right in the ground state 1 are unaffected by the quenching laser but blocked by the selective mirror potential. Note also that even atoms incident from the right in 3 will be blocked if the decay provoked by the quenching laser occurs in a timescale which is enough for the atom to arrive at the mirror potential in state 1.

In principle, if  $\hat{\Omega}_Q$  is too large there could be reflection of an atom incident in level 1 from the left but this possibility plays no role for the parameters examined here. So the quenching laser has a range of intensities and velocities for which the desired effect (perfect decay of atoms in level 3) is stable. This regime is also discussed for a single pumping laser without diode in [11].

To confirm that the quenching laser is indeed improving the device significantly we shall solve the 1D master equation (2) using the quantum trajectory approach. The initial state at  $t = 0$  is  $\rho(0) = |\Psi_0\rangle\langle\Psi_0|$ , namely a Gaussian wave packet with mean velocity  $v_0$  in the ground state,

$$\Psi_0(x) = \frac{1}{\mathcal{N}} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \exp \left[ -\frac{\Delta v_0 m}{2\hbar} (x - x_0)^2 + i \frac{v_0 m}{\hbar} x \right],$$



**Figure 5.** Probabilities  $p_{x>x_w}$  (filled circles) and  $p_{v>0}$  (boxes) versus  $v_0$ .  $\Delta v_0 = 0.1 \text{ cm s}^{-1}$ ,  $x_0 = -115 \text{ } \mu\text{m}$  ( $v_0 > 0$ ) or  $x_0 = 255 \text{ } \mu\text{m}$  ( $v_0 < 0$ ).  $t_{\text{max}} = 600 \text{ } \mu\text{m}/v_0$ ,  $\hat{\Omega}_Q = 10^5 \text{ s}^{-1}$ . (a)  $v_{\text{rec}} = 0$  (averaged over  $N = 1000$  trajectories), (b)  $v_{\text{rec}} = 3 \text{ cm s}^{-1}$  (averaged over  $N = 100$  trajectories).

where  $\mathcal{N}$  is a normalization constant. Let  $t_{\text{max}}$  be a large time such that the resulting wave packet  $\Psi_j(t_{\text{max}})$  of almost every quantum ‘trajectory’  $j$  separates into right and left moving parts far from the interaction region. By averaging over all trajectories we get  $p_{x>x_w} = \int_{x_w}^{\infty} dx \langle x | \rho_{11}(t_{\text{max}}) | x \rangle$ , which is the probability to find the atom on the right-hand side and in the ground state, and also  $p_{v>0} = \int_0^{\infty} dv \langle v | \rho_{11}(t_{\text{max}}) | v \rangle$ , which is the probability to find the atom moving to the right at time  $t_{\text{max}}$  in the ground state. The results, shown in figure 5, confirm the prediction of the stationary Schrödinger equation with the conditional Hamiltonian: a perfect transfer is produced from ground to ground state. The error bars (defined by the difference between averaging over  $N$  and over  $N/2$  trajectories) are smaller than the symbol size.

In summary, a quenching laser has been included in an atom diode laser device. Using quenching to force decay to the ground state after crossing the diode provides a significant improvement over previous schemes based on small direct spontaneous decay. With quenching, possible crossings in the wrong direction are suppressed and the atom which has crossed the diode in the allowed direction needs less time to decay, or in other words, the spatial region occupied by the atom diode is much narrower than in the case of direct decay. Quenching could be used in realistic atomic systems such as calcium, strontium, or ytterbium which are currently of interest for frequency standards.

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