Feedback on the Motion of a Single Atom in an Optical Cavity

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(Received 22 January 2002; published 4 April 2002)

We demonstrate feedback on the motion of a single neutral atom trapped in the light field of a high-finesse cavity. Information on the atomic motion is obtained from the transmittance of the cavity. This is used to implement a feedback loop in analog electronics that influences the atom's motion by controlling the optical dipole force exerted by the same light that is used to observe the atom. In spite of intrinsic limitations, the time the atom stays within the cavity could be extended by almost 30% beyond that of a comparable constant-intensity dipole trap.

DOI: 10.1103/PhysRevLett.88.163002 PACS numbers: 32.80.–t, 42.50.–p

The principle of feedback is universal and finds widespread applications in science and technology. For example, feedback can stabilize a system subject to random perturbations from the environment, even in the quantum domain [1,2]. An interesting target of feedback control is the motion of a single particle such as an ion [3] or a neutral atom [4]. Here, feedback provides new avenues not accessible to, e.g., standard laser cooling and trapping techniques. In contrast to these techniques, which employ a predetermined set of operations, feedback allows one to control the particle depending on the outcome of a measurement performed on the particle. A prime example is stochastic cooling of charged particles in accelerator rings [5]. This technique has also been proposed to cool an ensemble of atoms [6] and, recently, a single trapped particle [7]. So far, feedback control of a single neutral atom has not been realized.

The key to feedback control is to observe the moving particle with high spatial and temporal resolution. High spatial resolution was achieved for a molecule embedded in a solid [8] or an ion trapped in a radio-frequency field [9]. For an atom, high spatial and temporal resolution can be obtained by placing a high-finesse optical cavity around the atom and driving the system with a laser [10,11]. If the cavity waist is small, the transmittance of the cavity depends strongly on the position of the atom [12,13]. At the same time, the intracavity light itself influences the atomic motion [14,15]. This allows one to catch an atom entering the cavity by switching the laser intensity to a higher value when the atom is detected in an antinode of the cavity mode [16,17]. The atom is then stored in the dipole trap until heating has increased its kinetic energy to a value comparable to the trap depth.

This Letter reports on feedback, applied while the stored atom moves inside the cavity. To illustrate the idea, suppose that the atom has passed the deepest point of the potential and moves uphill, thereby transforming its kinetic energy into potential energy. Most of the potential energy can be removed when the trap depth is reduced immediately after the atom has turned around. The atom will then slowly move back towards the center, where the trap depth is increased again. By repeating the sequence, and under ideal conditions, the atom comes to a rest at the center. Such a cooling strategy requires knowledge of the velocity of the atom, which is derived from the time derivative of the position. Therefore, we call this strategy "differentiating feedback." The strategy resembles parametric cooling, but has the advantage that the modulation of the trap potential is automatically synchronized with the atomic motion. Note also that feedback cooling would be a natural extension of cavity-mediated cooling, which is caused by the delayed response of the intracavity intensity due to the high Q of the cavity [14,18,19].

Another strategy that will be presented here attacks the random momentum kicks due to spontaneous photon scattering from the trap light. These kicks disturb the otherwise regular motion of the atom in the dipole potential and lead to heating. This heating is large when the atom is in the region of high intensity at the cavity mode center. Since here the dipole force vanishes, the light field can equally well be turned off. Therefore, it is favorable to devise a trapping strategy that uses a low intensity and, hence, heats the atom only little when it is located near the trap center, but switches to a high intensity and, hence, a larger dipole force if the atom is further away. The pump power is now a direct function of the position, and we call this strategy "proportional feedback."

In our experiment, these two feedback strategies and a few deterministic strategies are implemented. The experiment is constrained by both technical and fundamental obstacles: The shot noise of the low-power ($\approx 10^{-12}$ W) light beam limits the amount of information on which the feedback can react. The random character of the atomic motion in a near-resonant light field and the shallow optical potential, which is only slightly larger than the atom's kinetic energy, impose further limits. Despite these difficulties, it is possible to extend the time an atom spends inside the cavity by means of feedback.

Our setup is similar to that described in Ref. [11]. Rubidium-85 atoms are launched towards the cavity by a pulsed atomic fountain at a repetition rate of about 0.3 Hz. On their way up, the atoms are optically pumped into the $m_F = 3$ Zeeman sublevel of the $5^2S_{1/2}F = 3$ state. The flux is kept so low that only in one out of 17 shots a strongly coupled atom is observed in the cavity. The entrance velocities of the atoms vary between ≈ 0.08 and 0.26 m/s, depending on the arrival time in the cavity. The cavity has a finesse of 4.4×10^5 and is near resonant with the atomic transition to the $5^2P_{3/2}F = 4$, $m_F = 4$ state at a wavelength of 780 nm. Our system is characterized by half the single-photon Rabi frequency for an atom in an antinode, and the decay rates of the cavity field and the atomic dipole, $(g_0, \kappa, \gamma)/2\pi = (16, 1.4, 3)$ MHz, respectively. A circularly polarized laser pumps the TEM_{00} mode of the cavity at a rate η, normalized so that η^2/κ^2 is the mean number of photons in the resonant cavity without an atom. The frequency of the laser is tuned $2\pi \times 5$ MHz below the cavity resonance and $2\pi \times 45$ MHz below the atomic transition. For these detunings, an atom in the standing wave increases the cavity transmittance. Improving on our previous experiments [17], the cavity frequency is stabilized using a second laser resonant with a different longitudinal cavity mode at 785 nm. This light is insensitive to the presence of an atom so that the stabilization can be operated continuously. In contrast to Ref. [20], the stabilization laser is weak and does not influence the motion of the atom. The dipole force exerted by the near-resonant pump field, however, induces a fast oscillation of the atom in the direction of the cavity axis. This leads to an interesting interplay of cavity-mediated cooling and diffusion [21,22], but this is not relevant in the context of this Letter. Only the motion in the plane perpendicular to the cavity axis is slow enough to allow external feedback. In this plane, the dipole force does not change the atom's angular momentum, nor can the atom's angular position be measured. Both drawbacks can in principle be overcome by using higher order transversal modes [23].

In order to implement the feedback loop, analog electronics was set up to react on the changes of the cavity transmittance; see Fig. 1. To this end, the intensity of the light transmitted through the cavity is detected with a photon counter. The overall efficiency for detecting a photon that escapes the cavity mode amounts to about 10%.

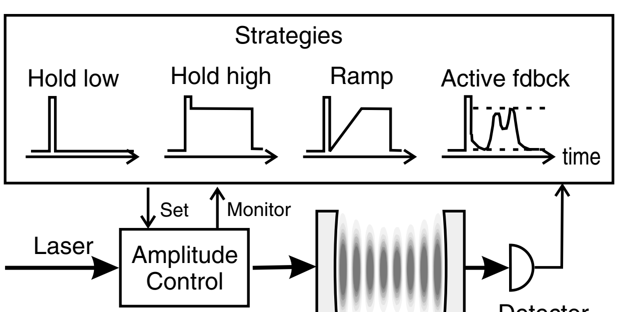

FIG. 1. Experimental setup showing the cavity and the control unit with the different strategies. "Hold low," "hold high," and "ramp" are deterministic. In the feedback strategies, the pump power after the initial stopping pulse depends on the motion of the atom, but is bound as indicated by the two dashed lines. The atomic fountain (not shown) injects slow ^{85}Rb atoms from below into the cavity.

The photon clicks are recorded by a computer and simultaneously sent to a count-rate-to-voltage converter (CRVC). The CRVC signal is passed through a 10 kHz low-pass filter and is used for the trigger and feedback electronics. The 10 kHz is large enough to pass the changes caused by the radial motion of the atom. The signal is then divided by the measured input power to obtain the transmittance $\bar{T}$. It is normalized to unity for the resonant cavity without an atom. $\bar{T}$ depends on the atomic position and the pump power. In particular, saturation of the atom decreases $\bar{T}$.

Once an atom is detected in the cavity, several strategies can be applied. Each will be discussed below. They are all subject to the boundary condition that the observation light beam should not be turned off completely and that the photon detector should not be saturated. This establishes lower and upper limits for the power of the pump laser. The final signal is then sent to an acousto-optic modulator (AOM) controlling the input power. The intracavity power will follow the input power within the cavity response time, $(2\kappa)^{-1}$, which is much shorter than the time it takes an atom to travel a distance $w_0 = 29$ μm, the cavity mode waist.

The different control strategies are depicted in Fig. 1. Not shown is "reference," in which we take no action other than passive observation of the passing atom. All other strategies share a fixed initial stopping pulse at a pump power of $\eta^2 = 10\kappa^2$, triggered at $t = 0$ when an atom is observed at an antinode, and has a duration of 0.15 ms which is chosen to be $\approx 1/4$ oscillation period in the dipole trap in order to remove a seizable fraction of the atoms kinetic energy. The control strategies have a fixed maximal duration of 2 ms. They are as follows: (1) "hold low," in which after the stopping pulse the pump power is switched to the low level $\eta^2 = 2.4\kappa^2$ that was used to detect the atom; (2) "hold high," idem, but now the pump power is kept at a high level $\eta^2 = 7\kappa^2$; (3) "ramp," in which the pump power is ramped up from the low to the high level in 1 ms, then remaining constant until $t = 2.15$ ms. (4) "Proportional feedback," in which the pump power switches to the high level if $\bar{T} < 0.19$ and to the low level if $\bar{T} > 0.19$; see Fig. 2 for a typical result. (5) "Differentiating feedback," in which the pump power is switched to the high level if the atom is seen to move away from the axis ($d\bar{T}/dt < 0$), and to a low level if the atom moves towards the center ($d\bar{T}/dt > 0$). Note that strategies (1)–(3) are completely deterministic. Strategies (4) and (5) were implemented by a proportional and differentiating circuit, respectively, reacting on $\bar{T}$ with such high gains that the output switches between the upper or lower limit and rarely has intermediate values.

To evaluate the results, the recorded photon clicks are binned over 10 μs long intervals. The resulting signal was divided by the pump power, normalized to unity for the resonant cavity without an atom, and subsequently nearest-neighbor averaged to obtain the transmittance T. In order to determine when an atom enters and exits the cavity, T is compared with two threshold levels, L and

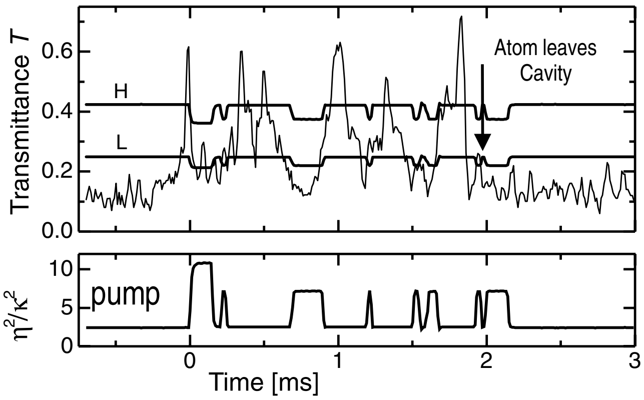

FIG. 2. A typical result for the measured transmittance, T, of the cavity (upper graph) and the corresponding pump power (lower graph) as a function of time during a proportional feedback sequence. T is large if the atom is near an antinode. The irregular behavior of T indicates the nonconservative motion of the atom. L and H are threshold levels used to evaluate the data.

H; see Fig. 2. Level L is 1.2× the empty-cavity T plus a correction that is proportional to the expected Poissonian noise. Level H is 1.7× level L. It is assumed that an atom resides in the cavity if $T > H$, or if $T > L$ for more than 0.1 ms. The entrance time is set to the moment when T first exceeds L. The exit time, t_e, is defined with respect to the trigger time, $t = 0$, and is tentatively set to the moment when T drops below L. If T returns above L within 0.1 ms, it is decided that the atom still resides in the cavity. In addition, if within 0.5 ms after the tentative leave of an atom, a second signal qualifies as an atom in the cavity, it is assumed that this is the same atom returning from an excursion to the outer region of the cavity mode. The 0.5 ms interval is chosen on the basis of simulations where this near-absent behavior was observed.

In total, we have recorded several thousand events for which we determined the entrance time and the exit time, t_e. Results are listed in Table I, and three exit-time histograms are plotted in Fig. 3. The overall structure looks similar in all cases. As the initial 0.15 ms stopping pulse is not perfect, approximately 2/3 of the atoms are not slowed down enough and, hence, can escape the cavity during the stopping pulse. The probability for an atom to stay longer defines the capture probability. It is determined for each strategy and is tabulated in Table I. It represents an average over all events, and hence, over all entrance velocities. It is observed that the capture probability is higher for the slow atoms that arrive late in a fountain shot. The capture probability is smallest without the stopping pulse, as measured in "reference." That even without a stopping pulse atoms are sometimes captured is probably due to momentum kicks by the probe light in the cavity. The random character of these kicks allows one to catch some of the slowest atoms. If a stop pulse is applied, the capture probability is much higher and independent of the feedback strategy applied afterwards. For each strategy, the mean exit time, $\langle t_e \rangle$, is determined by averaging the t_e of the atoms that stay in the cavity longer than 0.15 ms. To exclude systematic effects, the different types of measurement were alternated irregularly during data acquisition every 1 to 2 h. No correlation is observed between capture probability and t_e.

TABLE I. Number of trigger events, capture probabilities, and mean exit times $\langle t_e \rangle$ for different strategies and their standard error. The total measuring time for these 6642 trigger events is more than 100 h.

Strategy	Trigger events	Capture probability	$\langle t_e \rangle$ [μs] 150 +
Reference	1098	0.217 ± 0.012	259 ± 19
Hold low	871	0.339 ± 0.016	298 ± 18
Hold high	1113	0.371 ± 0.015	328 ± 16
Ramp	724	0.327 ± 0.017	364 ± 33
Proportional feedback	590	0.368 ± 0.020	395 ± 23
Differentiating feedback	2246	0.340 ± 0.010	401 ± 15

Let us now discuss the results of the various strategies. As can be seen in Fig. 3 and in Table I, the difference between the $\langle t_e \rangle$ for hold low and hold high is only slightly larger than one standard error. To explain this, consider the ideal case for a very slow atom heading exactly towards the cavity axis and perfect timing. We express the kinetic plus potential energy of the atom, E, as a fraction of the actual trap depth $U(\eta^2)$, where the potential energy reference is the trap minimum. Ideally, the stopping pulse would reduce E/U from the initial value, $E/U(2.4\kappa^2) \approx 1$, to about $U(2.4\kappa^2)/U(10\kappa^2) \approx 0.4$ shortly after the stopping pulse, both for strategies (1) and (2). From this, and because the value of the trap depth divided by the spontaneous-emission diffusion coefficient depends only weakly on the intracavity intensity, one would expect identical $\langle t_e \rangle$. Clearly, in the nonideal case $E/U > 0.4$, as, e.g., the atoms have initial kinetic energy and angular momentum. Now E/U also depends on the final trap depth. For hold low, $U(2.4\kappa^2)/k_B = 0.16$ mK, is shallower than for hold high, where $U(7\kappa^2)/k_B = 0.34$ mK. Therefore, a somewhat

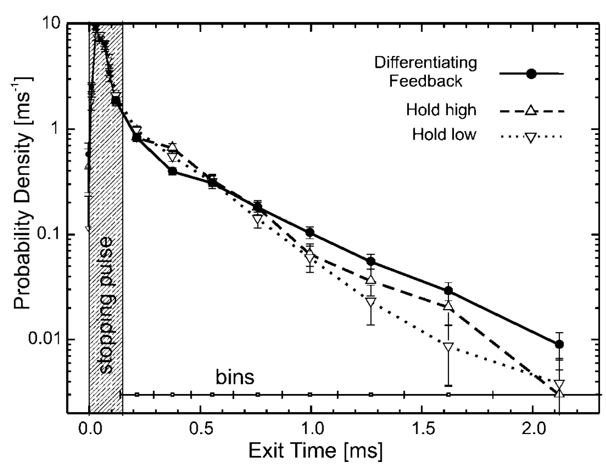

FIG. 3. Histogram of exit times. The width of the histogram bins is shown at the bottom. The hatched area indicates the 0.15 ms long stopping pulse.

longer $\langle t_e \rangle$ for the hold high strategy as observed in the experiment seems reasonable.

An atom can escape only if its motional energy is larger than the trap depth. The former grows with the integrated heating rate, whereas the latter is only a function of the intensity at the moment of escape. Therefore, an atom can be expected to stay longer in the cavity with the strategy "ramp," in which the pump power increases linearly after the trigger. Indeed, $\langle t_e \rangle$ for ramp is larger than that for hold low or hold high.

Let us now discuss the results of the two feedback strategies. As explained in the introduction, proportional feedback minimizes heating near the mode center while simultaneously providing a strong trapping force if the atom moves away, whereas the differentiating feedback attempts to take away motional energy of the atom. Both strategies have $\langle t_e \rangle$'s exceeding those of the deterministic strategies (1)–(3), showing that feedback can indeed be exploited to control the motion of a single neutral atom. The mechanism behind the increase in $\langle t_e \rangle$ for proportional feedback is reduced heating. The increase in $\langle t_e \rangle$ for differentiating feedback could be due to cooling, but the increase can also be accounted for by the fact that in our implementation of differentiating feedback the pump power switches to a low value if the atom approaches an antinode. The finite bandwidth of $\bar{T}$ and, hence, the finite response time then causes the pump power to be low if the atom arrives at the antinode. This reduces momentum diffusion as in the proportional feedback strategy. As differentiating feedback does not increase the value of $\langle t_e \rangle$ beyond that for proportional feedback, cooling is not evident here.

In conclusion, we have for the first time implemented feedback on the motion of a single neutral atom, thereby extending the time the atom spends in the cavity by up to 30%. In a next-generation experiment, the laser's double function of probe and lever could be split. Two independent laser beams would allow one to optimize a near-resonant laser as a probe and a far-detuned laser as a trap. Once cooling is successful, quantization of the motion can become important. It might even be possible to cool an atom into the motional ground state. This would have many applications, e.g., in quantum information processing.

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