P H Y S I C A L   R E V I E W   L E T T E R S

Submicron Positioning of Single Atoms in a Microcavity

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The coupling of individual atoms to a high-finesse optical cavity is precisely controlled and adjusted using a standing-wave dipole-force trap, a challenge for strong atom-cavity coupling. Ultracold Rubidium atoms are first loaded into potential minima of the dipole trap in the center of the cavity. Then we use the trap as a conveyor belt that we set into motion perpendicular to the cavity axis. This allows us to repetitively move atoms out of and back into the cavity mode with a repositioning precision of 135 nm. This makes it possible to either selectively address one atom of a string of atoms by the cavity, or to simultaneously couple two precisely separated atoms to a higher mode of the cavity.

Worldwide, intense research is being devoted to control the position of an array of single atoms. To meet this objective, several techniques are currently being explored with optical [1–5], magnetic [6–8], or electric [9–11] fields. However, none of the experiments performed so far has achieved positioning in combination with strong coupling to a high-finesse optical cavity. Either the atom could not be stopped inside the cavity, or strong coupling was not achieved, or trapping of a discrete number of atoms was probabilistic and cavity addressing was not possible [12–15]. The problems encountered when combining single-atom control with strong coupling are twofold: On the one hand, the small optical cavity required to achieve strong coupling adds a significant complexity, making the experiment challenging. On the other hand, atomic motion in the regime of strong coupling is dramatically different from free-space motion [13,16]. We now report on an experiment where the novel phenomena that a strongly coupled atom experiences inside a cavity are exploited to achieve the above-mentioned objective. Our experiment is the first in which a distinct number of atoms is repeatedly transported in and out of and brought to a halt inside an environment where atoms and cavity can no longer be considered separate entities by virtue of their strong coupling.

The apparatus and the atom transport into the cavity are illustrated in Fig. 1. A cold cloud of ^{85}Rb atoms is prepared in a magneto-optical trap (MOT). From there, these atoms are transferred over a distance of 14 mm into a cavity by means of a horizontally running-wave dipole-force trap, which is formed by a single beam of an Yb:YAG laser (5 W, 1030 nm). This beam is red detuned from the relevant transitions and therefore attracts the atoms towards regions of highest intensity, i.e., towards its focus, which is located between the MOT and the cavity. The atoms oscillate with a period of 200 ms in this trap (waist 40 μm, Rayleigh length 4.8 mm, depth 240 μK), with one turning point at the position of the MOT, and the other in the cavity. This oscillation is stopped as soon as the atoms arrive in the cavity, by switching from the guiding dipole trap to a

standing-wave dipole trap (2 W each direction, waist 16 μm in the center of the cavity). The atoms are trapped in the antinodes of the standing wave that act as potential wells of 2.5 mK depth, with a well-to-well distance of 515 nm. Nanopositioning of the atoms relative to the cavity mode is accomplished by tilting a glass plate in the path of the retro-reflected beam. This changes the optical path length and therefore also the position of the antinodes. The glass plate is mounted on a galvo scanner that provides a measured repeatability of the interference pattern of ±15 nm. This setup has been calibrated interferometrically. Since the trapped atoms follow this motion, they can be shifted to any position along the axis of the dipole-trap beams, as if they were sitting on a conveyor belt [1]. The positioning range is ±250 μm, limited by the
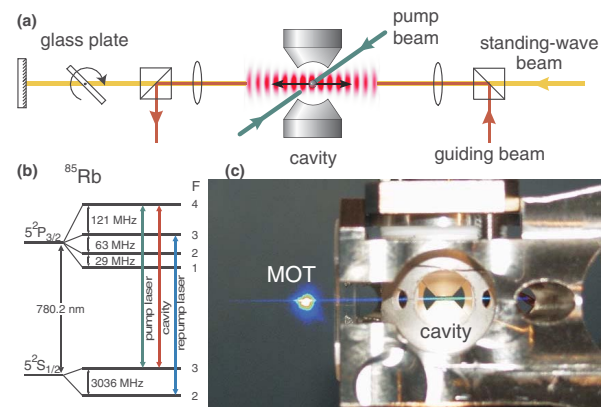

FIG. 1 (color online). Experimental setup: (a) Sketch of the dipole-trap arrangement that is used to guide atoms into the cavity. A standing-wave dipole-force trap allows us to freely adjust the position of an atom within the cavity mode by tilting a thick glass plate in front of the retro-reflecting mirror. Atoms that are trapped in the antinodes are displaced accordingly. (b) Level-scheme of ^{85}Rb including the relevant transitions. (c) Side view of the cavity (cone-shaped mirrors), superimposed with absorption images of an atom cloud in the MOT and in the transport trap illustrating the path of the atoms.

present thickness of the glass plate (3 mm). This allows a precise tuning of the coupling to the cavity.

The cavity is 490 μm long so that transverse optical access is granted, and the mirror reflectivity is unbalanced, so that photons generated inside are emitted mainly through one of its mirrors. With the two mirrors (of 5 cm radius of curvature) having transmission coefficients of $T_0 = 2$ ppm and $T_1 = 95$ ppm, strong coupling to the TEM$_{00}$-mode is reached with $(g_0, \kappa, \gamma) = 2\pi \times (5, 5, 3)$ MHz, and to the TEM$_{01}$-mode with $(g_0, \kappa, \gamma) = 2\pi \times (4.3, 2.5, 3)$ MHz. Here, g_0 is the atom-cavity coupling constant in a cavity antinode averaged over all the relevant atomic transitions, κ the cavity-field decay rate, and γ the polarization decay rate of the atom. Note that we have deliberately chosen a regime (with $g_0 \simeq \kappa$) where the photons are emitted from the cavity before they are reabsorbed due to vacuum-Rabi oscillations. Moreover, the cavity length (and therefore its mode volume) was chosen to be large enough to accommodate transverse pumping and trapping beams, resulting in $g_0 \simeq \gamma$. We emphasize that single-photon generation schemes, like those demonstrated in Munich [17,18], work very well in such cavities. Moreover, single atoms inside the cavity lead to a ~10-fold reduction of the intensity of a resonant light beam transmitted through the cavity, demonstrating strong coupling for the known γ and κ.

To continuously monitor the atom-cavity coupling, we tune the cavity resonance close to the $5^2S_{1/2}(F = 3)$ to $5^2P_{3/2}(F' = 4)$ transition and continuously excite the atom with a pair of counter-propagating lin $\perp$ lin polarized laser beams. These pump-laser beams run perpendicular to the cavity axis and have the same frequency as the cavity, so that resonant Raman scattering of photons into the cavity mode takes place, although the atoms are Stark-shifted out of resonance by the dipole trap. In particular, the transition

$$|F = 3, n = 0\rangle \overset{\text{laser}}{\to} |F = 4, n = 0\rangle \overset{\text{cavity}}{\to} |F = 3, n = 1\rangle$$

keeps the atomic state unchanged, but changes the intracavity photon number n by one, so that the initial and final states differ, which is characteristic for Raman transitions. With the TEM$_{00}$ mode of the cavity driving one branch of this transition, the photon-scattering rate from the atom-cavity system is in first approximation given by the enhanced spontaneous emission rate, $T_1(c/(2L))(g_{\text{eff}}/\kappa)^2 = 640$ ms^{-1}, with $g_{\text{eff}} = \Omega_l g_0/2\Delta_{ls}$ the effective atom-cavity coupling strength, where $\Omega_l = 2\pi \times 30$ MHz is the Rabi frequency of the driving laser and $\Delta_{ls} = 2\pi \times 100$ MHz is the dynamic Stark shift from the trapping laser. We estimated that in our experiment about 20 photons/ms are actually detected (due to detector efficiency, transmission loss, etc.).

As we show elsewhere [19], this cavity and pump beam configuration provides efficient cooling of the atoms in the center of the cavity mode. Here, this is used to efficiently load atoms into the cavity. When the dilute cloud of atoms

guided from the MOT arrives inside the cavity, the standing-wave potential is turned on. This gives rise to a random distribution of atoms among various potential wells in the vicinity of the cavity mode. Some atoms are hot enough to ripple along the dipole-trap axis like a marble across a washboard, in a random walk. As soon as such an atom enters the cavity mode, it scatters photons into the cavity and is subject to light forces which cool the atom into a potential well. The atom then remains trapped inside the cavity, where it continues to scatter photons. One after another, atoms are loaded into (or lost from) the cavity. This manifests itself in a stepwise increase (or decrease) of the photon-scattering rate into the cavity, which is therefore an unambiguous measure for the number of trapped atoms.

To avoid a fluctuating atom number, we apply a filtering procedure. Some 10 ms after the atoms have been loaded into the standing-wave trap, and when on average one atom has been caught, we interrupt the trap for 10 ms and turn it back on adiabatically. During this interruption, only very cold and well-localized atoms remain captured in the weak dipole trap formed by the red-detuned light field that is used to stabilize the cavity length, while all other atoms are lost. The light of this additional trap is detuned from the Rubidium resonance by eight free spectral ranges of the cavity, i.e., by 5 nm. Moreover, its 44 μK-deep potential wells show a good overlap with the resonant cavity mode in the center of the cavity. This helps to localize cold atoms in the antinodes of the cavity mode. Our preparation sequence usually results in 0, 1, or 2 atoms coupled to the cavity. From the photon-scattering rate, we can determine the exact atom number within a few milliseconds. Note that the weak intracavity trap together with the standing-wave trap forms a 2D optical lattice. The atoms finally trapped therein have a lifetime of 3 s (without the pump laser) and of more than 15 s if continuously excited by the pump laser.
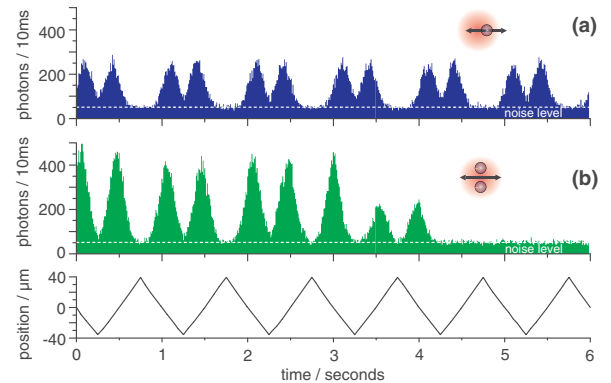

FIG. 2 (color online). Controlled coupling of individual atoms to the cavity: Count rate of the photons emerging from the TEM$_{00}$-mode of the cavity while (a) a single atom is swept to and fro once a second over a distance of 75 μm. (b) Same situation but starting with two atoms that are lost one after the other.

This is an unprecedented trapping time for a neutral atom under permanent observation inside a cavity.

As we load a well-known number of atoms into the cavity, we can also adjust the atom-cavity coupling to any value by tilting the glass plate. This is demonstrated in Fig. 2(a), where a single atom is swept to and fro once a second over a distance of 75 μm through the cavity mode. Figure 2(b) shows the same situation, but starting with two atoms (twice the peak-count rate) that are lost one after another. This shows that we are able to manipulate a single atom for many seconds.

To demonstrate and analyze the repositioning capabilities of our setup, we have performed a series of experiments where we modulate the atomic position with several frequencies and amplitudes, and finally bring the atom back to its initial position. Figure 3(a) depicts the situation where the atom is initially sitting on the cavity axis. We sinusoidally sweep the atom to and fro for a period of 0.5 s with a sweep amplitude of 25 μm. We stop this modulation at the initial position, and, as expected, the final photon-count rate equals the initial count rate, i.e., the atom has been brought back to its starting point. We have now measured such traces for 71 individual atoms, and we swept each atom 19 times through the cavity. For each atom transit, we have determined the standing-wave position that leads to the optimum photon-count rate. Figure 3(b) shows the mean deviation (root-mean-square or RMS value) of these positions relative to the position found in the first or second transit (for both sweep directions separately). Because of the noise of our measurement technique, the positions initially scatter over a range of

± 2 μm (in the third and fourth transit). However, the more important feature is the gradual increase of the mean deviation from transit to transit by an amount of 135 nm. This slow increase is a measure of how well we can reproduce the atomic position. We therefore conclude that the atom is brought back to its starting point within ± 135 nm from one transit to the next. A possible reason for this uncertainty is the small but nonvanishing probability for the atom to hop to another potential well in the outer turning points.

A similar method was applied to study the initial spatial distribution of the atoms, i.e., their average coupling to the cavity after the filter phase. A statistical investigation of 68 traces yields a width of the lateral distribution of ± 7.7 μm along the axis of the dipole trap. This is small compared to the cavity waist, $w_0 = 29.5$ μm. We therefore conclude that the average atom-cavity coupling is reduced by at most 7% due to an initial lateral displacement. This indicates that during the filter phase the atoms had a temperature of only 5 μK in the 44 μK-deep cavity trap.

Finally, we have investigated the effect of the atom transport on the lifetime with and without pump light. Figure 4 shows the probability for an atom to survive 0.5 s of sweeping its position to and fro as a function of the sweep frequency for different sweep amplitudes. Without pump light, the survival probability is high for slow sweeps. However, a fast loss of atoms occurs as soon as the product of sweep frequency and amplitude exceeds 500 μm Hz. With the sweep being sinusoidal, this indicates strong losses if the maximum sweep velocity of the trap exceeds $2\pi \times 500$ μm $/(\lambda_{\text{YAG}}/2) = 6100$ potential wells per second. We know that residual back reflections of the laser cause an intensity modulation at the same frequency. Therefore we attribute the sharp onset of losses to parametric heating, which is affecting the atom once the lowest trap frequency is met.

If we carry out the same experiment with pump light, we see two effects: First, the survival probability is very high
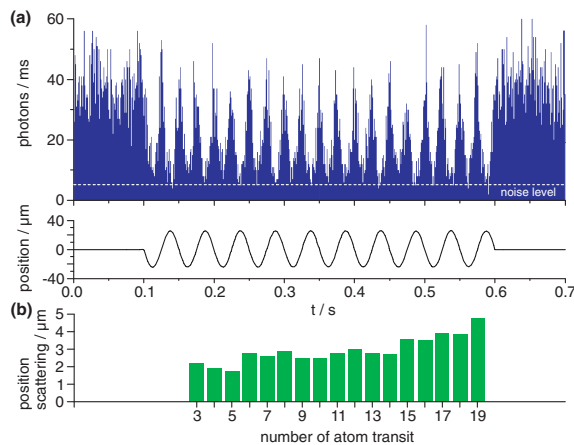

FIG. 3 (color online). Repeatability of atomic positions: Count rate of photons emerging from the cavity while the atomic position is modulated with 20 Hz over a distance of ± 25 μm, and finally brought back to its initial value (a). The 5 kHz noise level is due to photons of the cavity dipole trap at 785 nm still passing the 780 nm filters used for shielding the photon counters. (b) RMS deviation from the initial atomic position, averaged over 71 single-atom traces. The ± 2 μm initial spread stems from noise, but the gradual 135 nm increase from transit to transit reflects the repeatability of the positioning scheme.
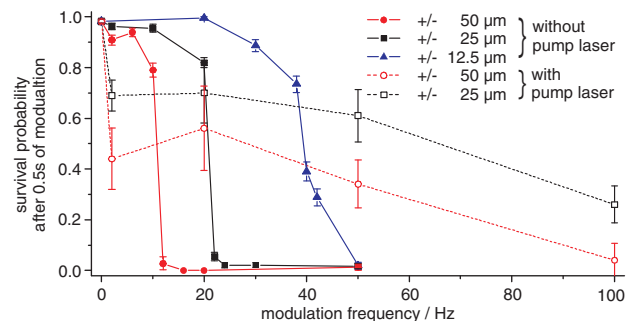

FIG. 4 (color online). Survival probability for moving atoms after 0.5 s of sweeping to and fro, plotted as a function of the sweep frequency for three different sweep amplitudes. Measurements were performed with (open symbols) and without (closed symbols) pump laser. The different behavior reflects the influence of the pump laser on the dynamics of the atom.
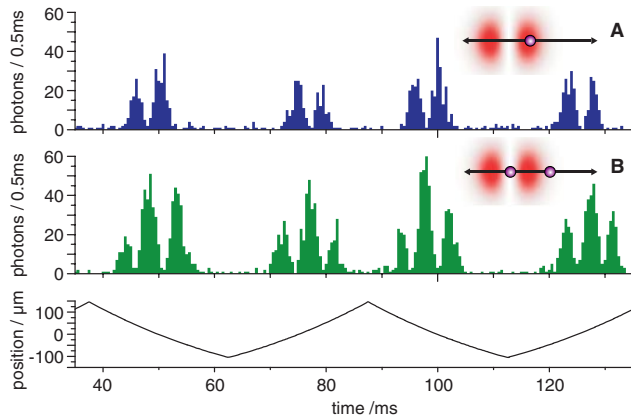
FIG. 5 (color online).   Controlled coupling to the TEM_{01}-mode.
(a) Photon-count rate from the TEM_{01}-mode while a single atom
is swept to and fro with a frequency of 20 Hz over a distance of
250 μm. (b) Same situation, but starting with two atoms whose
distance corresponds exactly to the distance between the two
maxima of the TEM_{01}-mode. The probability for this arrange-
ment is strongly enhanced due to our loading scheme.

without modulation (0 Hz), but it is reduced significantly
even for low sweep frequencies, i.e., atoms are heated and
can get lost once they leave the center of the mode. Second,
for high sweep frequencies, the strong cooling force in the
center of the cavity efficiently compensates for the para-
metric heating, as the atoms now have a significant chance
to survive even for sweep frequencies around 100 Hz.
However, the data show that a lossless controlled transport
works best without pump light and with moderate velocity.

For the coupling of two (or more) atoms, it is advanta-
geous to use higher transverse modes of the cavity.
Figure 5(a) shows the trace of a single atom that is repeti-
tively swept across the TEM_{01} mode of the cavity over a
distance of 250 μm, at a sweep frequency of 20 Hz. The
cavity mode shows two transverse intensity maxima, and
we can clearly distinguish the coupling of the atom to these
two maxima on its way through the cavity. The most pro-
nounced feature, however, is the vanishingly small photon-
count rate when the atom is between these two maxima.
This illustrates that we can control the position of an atom
so precisely that it decouples from the cavity once we move
it between two maxima of a higher-order mode.

Most promising is the extension of this scheme to two
atoms coupled to the same cavity mode, which is shown in
Fig. 5(b). If two atoms are initially captured, our loading
scheme ensures a probability of 50% to have them in
different maxima of the TEM_{01}-mode profile. It is now
sufficient to sweep them to and fro along the dipole-trap
axis to couple either each atom individually or both simul-
taneously to the cavity mode. The atoms can therefore be
addressed individually via the cavity or, as the distance
between the mode maxima of 42 μm can be easily re-
solved with optical microscopes, one can address them
individually from the side using independent laser pulses.

The degree of control achieved over the atom-cavity
coupling is a large step towards quantum information
processing with a quantum register consisting of neutral
atomic qubits, where each individual atom can be ad-
dressed by and strongly coupled to a cavity [17,18,20–
22]. In particular, a cavity like ours (with unbalanced
mirror reflectivity and an adjustable number of atoms in
it) is ideally suited to generate single photons from one
atom [17,18,21] or two photons from two atoms, etc., with
long coherence time [22]. Moreover, the unitarity of the
employed photon generation scheme is a way to determin-
istically entangle an atom and a photon, so that long-
distance entanglement and teleportation between selected
pairs of atoms in separate cavities are now possible in
principle [23–25]. We are confident that our positioning
scheme also works in a cavity with much smaller losses.
Here, the deterministically controlled coupling of two
atoms to the same mode (as demonstrated above) is a
sine qua non for cavity-mediated quantum-gate operations
[20,26].

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[1] S. Kuhr *et al.*, Science **293**, 278 (2001).
[2] R. Dumke *et al.*, Phys. Rev. Lett. **89**, 097903 (2002).
[3] O. Mandel *et al.*, Nature (London) **425**, 937 (2003).
[4] S. Bergamini *et al.*, J. Opt. Soc. Am. B **21**, 1889 (2004).
[5] J. A. Sauer *et al.*, Phys. Rev. A **69**, 051804(R) (2004).
[6] W. Hänsel *et al.*, Phys. Rev. Lett. **86**, 608 (2001).
[7] R. Folman *et al.*, Adv. At. Mol. Opt. Phys. **48**, 263 (2002).
[8] P. Horak *et al.*, Phys. Rev. A **67**, 043806 (2003).
[9] G. R. Guthörlein *et al.*, Nature (London) **414**, 49 (2001).
[10] A. B. Mundt *et al.*, Phys. Rev. Lett. **89**, 103001 (2002).
[11] D. Kielpinski, C. Monroe, and D. Wineland, Nature
(London) **417**, 709 (2002).
[12] J. McKeever *et al.*, Phys. Rev. Lett. **90**, 133602 (2003).
[13] P. Maunz *et al.*, Nature (London) **428**, 50 (2004).
[14] A. Boca *et al.*, Phys. Rev. Lett. **93**, 233603 (2004).
[15] P. Maunz *et al.*, Phys. Rev. Lett. **94**, 033002 (2005).
[16] P. Münstermann *et al.*, Phys. Rev. Lett. **82**, 3791 (1999).
[17] A. Kuhn, M. Hennrich, and G. Rempe, Phys. Rev. Lett. **89**,
067901 (2002).
[18] M. Keller *et al.*, Nature (London) **431**, 1075 (2004).
[19] S. Nußmann *et al.*, quant-ph/0506067 [Nature Physics (to
be published)].
[20] T. Pellizzari *et al.*, Phys. Rev. Lett. **75**, 3788 (1995).
[21] J. McKeever *et al.*, Science **303**, 1992 (2004).
[22] T. Legero *et al.*, Phys. Rev. Lett. **93**, 070503 (2004).
[23] C. Cabrillo *et al.*, Phys. Rev. A **59**, 1025 (1999).
[24] S. Bose *et al.*, Phys. Rev. Lett. **83**, 5158 (1999).
[25] D. E. Browne, M. B. Plenio, and S. F. Huelga, Phys. Rev.
Lett. **91**, 067901 (2003).
[26] A. Rauschenbeutel *et al.*, Phys. Rev. Lett. **83**, 5166 (1999).