Nano Positioning of Single Atoms in a Micro Cavity

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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 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.

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Worldwide, intense research is devoted to control the position of an array of single atoms. To meet this objective, several techniques are presently explored with optical, magnetic, or electric 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. 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. 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 Figs. A cold cloud of 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. 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 MOT and cavity. The atoms oscillate with a period of 200 ms in this trap, 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 Watt, waist 16 µm in the centre 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. Nano positioning 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. 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 2 ppm and 1 ppm, strong coupling to the TEM00-mode is reached with \( g_0, \kappa, \gamma = 2 \pi \times (5, 5, 3) \) MHz, and to the TEM01-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 aver-

![Experimental setup](image-url)
aged over all the relevant atomic transitions, \( \kappa \) the cavity-field decay rate and \( \gamma \) the polarization decay rate of the atom. Note that we have deliberately chosen a regime (with \( g_0 \approx \kappa \)) 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 \( g_0 \approx \gamma \). We emphasize that single-photon generation schemes, like those demonstrated in Munich \cite{17,18}, work very well in such cavities.

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 linearly 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

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|F = 3, n = 0 \rangle_{\text{laser}} \rightarrow |F = 4, n = 0 \rangle_{\text{cavity}} \rightarrow |F = 3, n = 1 \rangle
\]

keeps the atomic state unchanged, but changes the intra-cavity 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, \( T_1 \times c/(2L) \times (g_{\text{eff}}/\kappa)^2 = 640 \text{ ms}^{-1} \), with \( g_{\text{eff}} = \Omega_0 g_0/2\Delta_{ls} \) the effective atom-cavity coupling strength, where \( \Omega_0 = 2\pi \times 30 \text{ MHz} \) is the Rabi frequency of the driving laser and \( \Delta_{ls} = 2\pi \times 100 \text{ MHz} \) the dynamic Stark shift from the trapping laser.

As we show elsewhere \cite{19}, this cavity and pump beam configuration provides efficient cooling of the atoms in the centre 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 \( \mu \text{K} \)-deep potential wells show a good overlap with the resonant cavity mode in the centre 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 intra-cavity trap together with the standing-wave trap forms a 2D optical lattice. The atoms finally trapped therein have a lifetime of 3 s (without pump laser) and of more than 15 s if continuously excited by the pump-laser. 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 figure 2A, where a single atom is swept to and fro once a second over a distance of 75 \( \mu\text{m} \). (B) Same situation but starting with two atoms that are lost one after the other.

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 3A 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 \( \mu\text{m} \). 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 3B shows the mean deviation (RMS value) of these positions relative to the position found in the first or second transit (for both sweep directions separately). Due to 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, 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.

A possible reason for this uncertainty is the small but non-vanishing 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, w0 = 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 41 μK-deep cavity trap.

Finally, we have investigated the effect of the atom transport on the lifetime with and without pump light. Figure 4A shows the probability for an atom to survive 0.5 s of sweeping 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 2π × 500 μm/(λy AG/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 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 centre of the mode. Second, for high sweep frequencies, the strong cooling force in the centre of the cavity efficiently compensates for the parametric heating, as the atoms now have a significant chance to survive even for sweep frequencies around 100 Hz. However, the data show that a loss-less controlled transport works best without pump light and with moderate velocity.

For the coupling of two (or more) atoms, it is advantageous to use higher transverse modes of the cavity. Figure 5A shows the trace of a single atom that is repetitively swept across the TEM01 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 pronounced 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 figure 5B. If two atoms are initially captured, our loading scheme ensures a probability of 50% to have them in different maxima of the TEM01 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 simultaneously to the cavity mode. The atoms can therefore be addressed individually via the cavities, with long coherence time [22]. More-over, the unitarity of the employed photon generation scheme also works in a cavity with much smaller losses.

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 addressed by and strongly coupled to a cavity [17, 18, 20, 21, 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 deterministically 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, 24, 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 [24, 25].

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