Cavity QED with optically transported atoms

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Ultracold \(^{87}\)Rb atoms are delivered into a high-finesse optical micro-cavity using a translating optical lattice trap and detected via the cavity field. The atoms are loaded into an optical lattice from a magneto-optic trap (MOT) and transported 1.5 cm into the cavity. Our cavity satisfies the strong-coupling requirements for a single intracavity atom, thus permitting real-time observation of single atoms transported into the cavity. This transport scheme enables us to vary the number of intracavity atoms from 1 to \(>100\) corresponding to a maximum atomic cooperativity parameter of 5400, the highest value ever achieved in an atom-cavity system. When many atoms are loaded into the cavity, optical bistability is directly measured in real-time cavity transmission.

Many applications in quantum information science require the coherent and reversible interaction of single photon fields with material qubits such as trapped atoms. Quantum states can be transferred between light and matter—respectively offering long range communication and long-term storage of quantum information. This important paradigm is the heart of cavity QED systems, which are largely focused on creating laboratory systems capable of reversible matter-photon dynamics at the single photon level \(\textit{[1]}\). To achieve this, a small high-finesse build-up cavity is used to tremendously enhance the electric field per photon and hence the interaction strength of a single photon with the cavity medium (e.g. atoms). For a single atom in the cavity, the interaction strength is given by the single photon Rabi frequency, \(2g_0\), and coherent dynamics is achieved for \(g_0^2/(\kappa \Gamma) \gg 1\), where \(\kappa\) is the cavity field decay rate and \(\Gamma\) is the atomic spontaneous emission rate.

There have been spectacular recent successes in cavity QED research brought about by the merging of optical cavity systems with ultracold neutral atoms \(\textit{[2]}\), including real-time observation \(\textit{[3, 4, 5]}\) and trapping \(\textit{[6, 7, 8, 9]}\) of single atoms in optical cavities, real-time feedback control on a single atom \(\textit{[10]}\), and single photon generation \(\textit{[11, 12]}\). Together with the remarkable experimental work in microwave cavity QED \(\textit{[13]}\) and the future prospects for cavity QED with trapped ions \(\textit{[14, 15]}\), the field is well-poised to contribute significantly to the development of quantum information science. Indeed, current cavity QED parameters are sufficient for existing quantum gate protocols with fidelities \(>99.9\%\) percent \(\textit{[10, 17, 18, 19]}\), and the systems are principally limited by the lack of a scalable atomic trapping system to provide adequate control over atom motional degrees of freedom.

Our strategy for overcoming this limitation is to employ optical dipole trapping fields independent from the cavity and orthogonal to its axis as illustrated in Fig. 1 \(\textit{[28]}\). Atoms are trapped in the anti-nodes of the standing wave formed by two focused counter-propagating laser beams. Translating the standing wave controllably introduces atoms in this 1-D chain in and out of the cavity mode. This trapping geometry will ultimately allow entanglement of \(>100\) distinguishable atoms in two such parallel chains or in a single chain using nearest-neighbor interactions.

In this Letter, we describe an experimental realization of a cavity QED system with optically trapped and transported atoms. Single and multiple atoms are transported into the cavity and detected—in the latter case, we observe optical bistability in the cavity output due to the cooperative interaction of the atoms with the cavity field. By adjusting the initial loading conditions of the optical traps, the number of intracavity atoms, \(N\), can be varied from 1-106 atoms. Our unique combination of strong coupling parameters and large maximum intracavity atomic density \((10^{10}\ \text{cm}^{-3})\), provide for a measured atomic cooperativity, \(C=N g_0^2/(\kappa \Gamma)\), up to 5400, the highest value ever achieved in an atom-cavity system. The cooperativity parameter is an important figure of merit both for single atom \((N = 1)\) protocols and for many-atom, ensemble based protocols including light storage and single photon generation \(\textit{[21, 22, 23, 24]}\).

The experiment begins 1.5 cm above the optical cavity
with a laser-cooled sample of $^{87}$Rb atoms collected in a beam-loaded MOT as previously described in [2]. The cavity itself consists of two 1 mm diameter super-polished mirrors with 10 cm radii of curvature separated by 75 $\mu$m. The measured finesse of the cavity is $F = 420,000$. The relevant cavity QED parameters for our system are $(g_0, \kappa, \Gamma)/(2\pi) = (27, 2.4, 6)$ MHz, placing our system well into the strongly coupled regime and yielding a single atom cooperativity parameter, $C_1 = g_0^2/(\kappa \Gamma) = 51$.

Maintaining the cavity on resonance requires cavity length stability better than $\Delta L < 0.1\lambda/F \sim 200$ fm ($\lambda = 780$ nm is the resonant wavelength of the cavity) and represents a significant challenge. To achieve the required stability while providing the necessary length adjustability, both mirrors are mounted directly on a flat rectangular piezoelectric transducer (PZT) which in turn is attached to a copper block. The block is suspended inside a vacuum chamber by 4 Cu-Be springs to provide an in-vacuo isolation system with a 3.5 Hz resonance. Both the copper block and the PZT have holes drilled vertically to accommodate the optical lattice beams. The length of the cavity is controlled by applying a voltage to the PZT. The isolation system together with low-noise electronics provides excellent passive stability (<10 fm/s drift) of the cavity length.

Optical dipole traps connecting the MOT with the cavity are used to transport the atoms to the cavity. We employ both travelling wave and standing wave beam configurations to confine the atoms. In the former case, the atoms are confined transversely and are guided under the influence of gravity into the cavity. For the standing-wave configuration, two counter-propagating beams are used to form a 1-D lattice, and the atoms are confined vertically at the anti-nodes of the trap beams. The vertical motion of the atoms can then be controlled by varying the difference frequency $\delta$ of the beams using two phase-locked acousto-optic modulators, which creates a ‘walking-wave’ with velocity $v = \lambda \delta / 2$, where $\lambda$ is the trapping wavelength [21]. The optical traps are loaded directly from the MOT, following sub-doppler cooling of the atoms to $\sim 4$ $\mu$K.

In our first experiment, the trapping laser beam is generated from a diode laser operating at 782.5 nm (2.25 nm above of the rubidium D2 line). A single travelling wave of 16 mW of laser power is focused to a 1/c$^2$ intensity waist of $w_0 = 30$ $\mu$m at the cavity. This yields a transverse trap depth of 72 $\mu$K at the cavity. At the location of the MOT, the transverse trap depth is only 4 $\mu$K due to the divergence of the beam to a waist of 130 $\mu$m. We load up to $10 \times 10^5$ $^{87}$Rb atoms into our MOT, and typically 10% are transferred into the optical guide. After the MOT light is extinguished, the atoms fall under gravity towards the cavity while being compressed transversely in the guide.

The atoms delivered to the cavity are detected as modifications in the transmission of a weak cavity probe beam, tuned to the $5S_{1/2} F = 2 \rightarrow 5P_{3/2} F = 3$ transition in $^{87}$Rb. For our cavity, the critical photon number (the average number of photons producing an intracavity intensity of $I_{sat}$) is $\langle n_0 \rangle = \Gamma^2/(8\kappa_0^2) = 0.006$, and single atoms are readily detected with probe strengths up to 1.9 pW corresponding to intracavity fields of $\langle n \rangle \sim 1$. The probe beam is detected with balanced-heterodyne detection with typical bandwidth of 30 kHz. The cavity length is adjusted such that the cavity’s resonant frequency $\omega_c$ is typically detuned $\delta_c = (2\pi)4 \times 10^6$ rad/s below both the atom’s ($\omega_{1a}$) and the probe beam’s ($\omega_1$) frequency.

The cavity transmission is shown in Fig. 2 as the atom cloud falls through the cavity for several different input powers. Although the atomic density time-profile through the cavity is approximately gaussian with a width ($\sim 1.5$ ms FWHM) determined by the cloud temperature, the cavity transmission switches very abruptly and at different times for different powers. For the weakest probe powers, the individual atom transits are observed as spikes in the transmission at the leading and trailing edges of the cloud.

The abrupt non-linearity in the cavity transmission is
due to the absorptive optical bistability of the system resulting from the collective interaction of many radiating atoms with the cavity field. For many atoms, the transmission of the probe beam is given by the steady state optical bistability equation \( Y = X \left[ (1 + 2C\chi)^2 + (\delta_c/K)^2 \right] \) where \( X = \left( I_{in}/I_{sat} \right) \) and \( Y = \left( I_{out}/I_{sat} \right) \) are the output and input intensities, \( I_{in, out} \), normalized to the saturation intensity \( I_{sat} \) and cavity transmission \( T \) and \( \chi = 3 \ln[(1 + \sqrt{1 + 8X})]/2X^{2/3} \). For \( C \geq 15 \), this equation predicts two stable output powers for a given input power as shown in the theoretical trace of Fig. 2b as well as hysteresis in the switching power due to the unstable branch with negative slope.

To measure the bistability directly, we allow the atomic cloud to fall into the cavity with the probe beam off, then we quickly ramp the probe up to a high value and then down to zero again while the atoms are in the cavity. The results are shown in Fig. 2b., where the hysteresis is clearly evident in the 10-fold difference in the switching power. This data is taken from a single experimental run in real time. The data agrees very well with the theoretical curve for high input powers. The agreement at lower power is less satisfactory although the noise floor of the heterodyne detection complicates the analysis of these data.

Coming back to the traces in Fig. 2a, the different switching times can be understood as follows: as the atomic cloud falls through the cavity, the intracavity atomic density (and hence the cooperativity \( C = NC_1 \)) first increases then decreases. For constant input power, the growing cooperativity shifts the bistability curve to the right until the transmission falls to the lower branch. Then, as the cloud continues through the cavity, \( C \) falls and the transmission then jumps back to the higher branch. For higher input powers, the switching points occur at higher intracavity densities and the time window for the drop in transmission becomes more narrow.

Indeed, the intracavity density at the instant when the cavity output power drops can be determined by implicitly solving the bistability equation for \( C \) with a known input. By increasing the probe power, we can map out the cooperativity and the atom number vs time. Fig. 3 shows data collected in this manner. Cooperativities of up to 5400 were measured corresponding to an maximum intracavity atom number of \( \sim 100 \) and an atomic density \( \sim 10^{10} \text{ cm}^{-3} \) inside the cavity. For these data, a Ti:Sapphire laser at 850 nm with 400 mW of power focused to 22 \( \mu \text{m} \) was used to increase the trap depth to 238 \( \mu \text{K} \), which increased the number of atoms loaded into the cavity. In addition, a repumping beam was added perpendicular to the cavity axis to prevent atoms that are pumped into the \( F = 1 \) ground state by the cavity probe beam from becoming dark to the probe light. The maximum switched probe output power is 8 nW, corresponding to an intracavity intensity of \( 7 \times 10^4 I_{sat} \). It is remarkable that such a large intensity can be extin-

![FIG. 3: (top): Data points from transmission curves of several different powers are fitted to bistability curves to extract cooperativity data. From left to right the curves show output power vs. cooperativity for input powers of 240, 758, 2400, 7580, and 31214 pW. (bottom): The atomic cooperativity vs. time is plotted as the atomic cloud falls through the cavity.](image-url)
beams lead to parametric heating in the lattice configuration \[30\]. Indeed, a new solid state pump laser for the Ti:Sapphire has shown significant lifetime improvements in an independent experiment.

In conclusion, we have realized a cavity QED system with optically trapped and transported atoms. Groups of atoms can be deterministically delivered to the cavity mode. The successful demonstration of this scalable trapping geometry opens exciting opportunities in the implementation of quantum gate protocols. Additionally, the strong coupling parameters of our cavity and the large maximum intracavity atomic density, provide for a measured atomic cooperativity, \(C\), up to 5400, the largest observed to-date for atom-cavity systems.

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