State-Insensitive Cooling and Trapping of Single Atoms in an Optical Cavity

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Single Cesium atoms are cooled and trapped inside a small optical cavity by way of a novel far-off-resonance dipole-force trap (FORT), with observed lifetimes of $2-3$ seconds. Trapped atoms are observed continuously via transmission of a strongly coupled probe beam, with individual events lasting $\simeq 1$ s. The loss of successive atoms from the trap $N \geq 3 \rightarrow 2 \rightarrow 1 \rightarrow 0$ is thereby monitored in real time. Trapping, cooling, and interactions with strong coupling are enabled by the FORT potential, for which the center-of-mass motion is only weakly dependent on the atom's internal state.

A long-standing ambition in the field of cavity quantum electrodynamics (QED) has been to trap single atoms inside high-Q cavities in a regime of strong coupling [1]. Diverse avenues have been pursued for creating the trapping potential for atom confinement, including additional far off-resonant trapping beams [2], near-resonant light with with $\bar{n} \simeq 1$ intracavity photons [3, 4], and single trapped ions in high-finesse optical cavities [5, 6], although strong coupling has yet to be achieved for trapped ions. A critical aspect of this research is the development of techniques for atom localization that are compatible with strong coupling, as required for quantum computation and communication [7, 8, 9, 10, 11, 12].

In this Letter we present experiments to enable quantum information processing in cavity QED by (1) achieving extended trapping times for single atoms in a cavity while still maintaining strong coupling, (2) realizing a trapping potential for the center-of-mass motion that is largely independent of the internal atomic state, and (3) demonstrating a scheme that allows continuous observation of trapped atoms by way of the atom-field coupling. More specifically, we have recorded trapping times up to 3 s for single Cs atoms stored in an intracavity far-off resonance trap (FORT) [13], which represents an improvement by a factor of 10^2 beyond the first realization of trapping in cavity QED [2], and by roughly 10^4 beyond prior results for atomic trapping [3] and localization [4] with $\bar{n} \simeq 1$ photon. We have also continuously monitored trapped atoms by way of strong coupling to a probe beam, including observations of trap loss atom by atom over intervals $\simeq 1$ s. These measurements incorporate auxiliary cooling beams, and provide the first realization of cooling for trapped atoms strongly coupled to a cavity. Our protocols are facilitated by the choice of a "magic" wavelength for the FORT [14, 15, 16], for which the relevant atomic levels are shifted almost equally, thereby providing significant advantages for coherent state manipulation of the atom-cavity system.

A major obstacle to the integration of a conventional red-detuned FORT within the setting of cavity QED is that excited electronic states generally experience a positive AC-Stark shift of comparable magnitude to the negative (trapping) shift of the ground state [13]. This leads to the unfortunate consequence that the detuning and

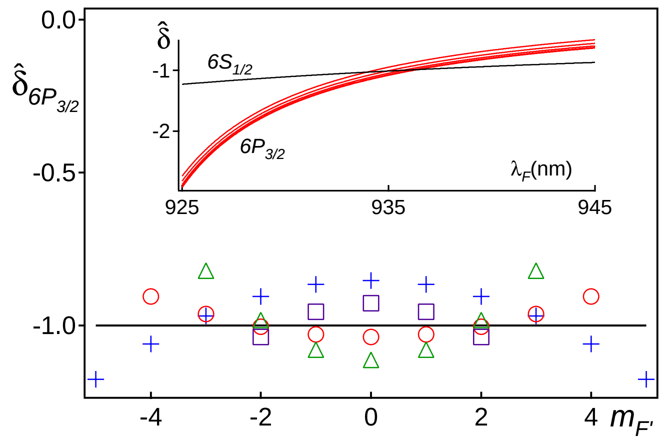

FIG. 1: AC-Stark shifts $(\hat{\delta}_{6S_{1/2}}, \hat{\delta}_{6P_{3/2}})$ for the $(6S_{1/2}, 6P_{3/2})$ levels in atomic Cs for a linearly polarized FORT. The inset shows $(\hat{\delta}_{6S_{1/2}}, \hat{\delta}_{6P_{3/2},F'=4})$ as functions of FORT wavelength λ_F. The full plot gives $\hat{\delta}_{6P_{3/2}}$ versus $m_{F'}$ for each of the levels $6P_{3/2}, F' = 2, 3, 4, 5$ for $\lambda_F = 935.6$ nm. In each case, the normalization is $\hat{\delta} = \delta/[\delta_{6S_{1/2}}(\lambda_F = 935.6 \text{ nm})]$ [17].

hence the effective coupling between an atomic transition and the cavity mode become strong functions of the atom's position within the trap [16]. However, due to the specific multi-level structure of Cesium, the wavelength λ_F of the trapping laser can be tuned to a region where both of these problems are eliminated for the $6S_{1/2} \rightarrow 6P_{3/2}$ transition, as illustrated in Fig. 1 [14, 15, 16, 17]. Around the "magic" wavelength $\lambda_F = 935$ nm, the sum of AC-Stark shifts coming from different allowed optical transitions results in the ground $6S_{1/2}$ and excited $6P_{3/2}$ states both being shifted downwards by comparable amounts, $\delta_{6S_{1/2}} \simeq \delta_{6P_{3/2}}$, albeit with small dependence on $(F', m_{F'})$ for the shifts $\delta_{6P_{3/2}}$.

The task then is to achieve state-independent trapping while still maintaining strong coupling for the $6S_{1/2} \rightarrow 6P_{3/2}$ transition. Our experimental setup to achieve this end is schematically depicted in Fig. 2 [2]. Significantly, the cavity has a TEM_{00} longitudinal mode located nine mode orders below the mode employed for cavity QED at 852 nm, at the wavelength $\bar{\lambda}_F = 935.6$ nm, allowing the implementation of a FORT with $\delta_{6S_{1/2}} \simeq \delta_{6P_{3/2}}$. The

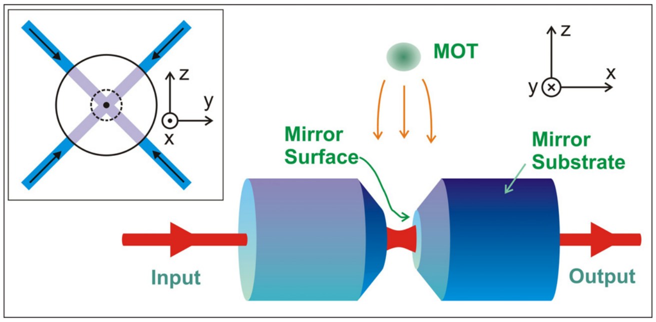

FIG. 2: Schematic of experiment for trapping single atoms in an optical cavity in a regime of strong coupling. Relevant cavity parameters are length $l = 43.0\ \mu$m, waist $w_0 = 23.9\ \mu$m, and finesse $\mathcal{F} = 4.2 \times 10^5$ at 852 nm. The inset illustrates transverse beams used for cooling and repumping.

field to excite this cavity mode is provided by a laser at $\bar{\lambda}_F$, which is independently locked to the cavity. The finesse of the cavity at $\bar{\lambda}_F$ is $\mathcal{F} \sim 2200$ [18], so that a mode-matched input power of 1.2 mW gives a peak AC-Stark shift $\delta_{6S_{1/2}}/2\pi = -47$ MHz for all states in the $6S_{1/2}$ ground manifold, corresponding to a trap depth $U_0/k_B = 2.3$ mK, which was used for all experiments.

Principal parameters relevant to cavity QED with the system in Fig. 2 are the Rabi frequency $2g_0$ for a single quantum of excitation and the amplitude decay rates (κ, γ) due to cavity losses and atomic spontaneous emission. For our system, $g_0/2\pi = 24$ MHz, $\kappa/2\pi = 4.2$ MHz, and $\gamma/2\pi = 2.6$ MHz, where g_0 is for the $(6S_{1/2}, F = 4, m_F = 4) \to (6P_{3/2}, F' = 5, m'_F = 4)$ transition in atomic Cs at $\lambda_0 = 852.4$ nm. Strong coupling is thereby achieved $(g_0 \gg (\kappa, \gamma))$, resulting in critical photon and atom numbers $n_0 \equiv \gamma^2/(2g_0^2) \simeq 0.006$, $N_0 \equiv 2\kappa\gamma/g_0^2 \simeq 0.04$. The small transition shifts for our FORT mean that g_0 is considerably larger than the spatially dependent shift δ_0 of the bare atomic frequency employed for cavity QED, $g_0 \gg \delta_0 \equiv |\delta_{6P_{3/2}} - \delta_{6S_{1/2}}|$, whereas in a conventional FORT, $\delta_0 \sim 2|\delta_{6S_{1/2}}| \gg g_0$.

In addition to the FORT field, the input to the cavity consists of probe and locking beams, all of which are directed to separate detectors at the output. The transmitted probe beam is monitored using heterodyne detection, allowing real-time detection of individual cold atoms within the cavity mode [19]. The cavity length is actively controlled using a cavity resonance at $\lambda_C = 835.8$ nm, so the length is stabilized and tunable independently of all other intracavity fields [2]. The probe as well as the FORT beam are linearly polarized along a direction $\hat{l}_+$ orthogonal to the x-axis of the cavity [18, 20].

Cold atoms are collected in a magneto-optical trap (MOT) roughly 5 mm above the cavity mirrors and then released after a stage of sub-Doppler polarization-gradient cooling [13]. Freely falling atoms arrive at the cavity mode over an interval of about 10 ms, with kinetic energy $E_K/k_B \simeq 0.8$ mK, velocity $v \simeq 0.30$ m/s, and transit time $\Delta t = 2w_0/v \simeq 150\ \mu$s. Two additional orthogonal pairs of counter-propagating beams in a $\sigma^+ - \sigma^-$ configuration illuminate the region between the cavity mirrors along directions at $\pm 45°$ relative to $\hat{y}, \hat{z}$ (the "$y - z$ beams") and contain cooling light tuned red of $F = 4 \to F' = 5$ and repumping light near the $F = 3 \to F' = 3$ transition [21]. These beams eliminate the free-fall velocity to capture atoms in the FORT and provide for subsequent cooling of trapped atoms.

We employed two distinct protocols to study the lifetime for single trapped atoms in our FORT.

(1) *Trapping "in the dark"* with the atom illuminated only by the FORT laser at $\bar{\lambda}_F$ and the cavity-locking laser at λ_C. For this protocol, strong coupling enables real-time monitoring of single atoms within the cavity for initial triggering of cooling light and for final detection.

(2) *Trapping with continuous observation of single atoms* with cavity probe and cooling light during the trapping interval. In this case, atoms in the cavity mode are monitored by way of the cavity probe beam, with cooling provided by the auxiliary $y - z$ beams.

(1) In our first protocol, the $F = 4 \to F' = 5$ transition is strongly coupled to the cavity field, with zero detuning of the cavity from the bare atomic resonance, $\Delta_C \equiv \omega_C - \omega_{4\to5} = 0$. In contrast to Ref. [2], here the FORT is *ON* continuously without switching, which makes a cooling mechanism necessary to load atoms into the trap. The initial detection of a single atom falling into the cavity mode is performed with the probe beam tuned to the lower sideband of the vacuum-Rabi spectrum ($\Delta_p = \omega_p - \omega_{4\to5} = -2\pi \times 20$ MHz). The resulting *increase* in transmitted probe power when an atom approaches a region of optimal coupling [22, 23] triggers *ON* a pulse of transverse cooling light from the $y - z$ beams, detuned 41 MHz red of $\omega_{4\to5}$. During the subsequent trapping interval, all near-resonant fields are turned *OFF* (including the transverse cooling light). After a variable delay t_T, the probe field is switched back *ON* to detect whether the atom is still trapped, now with $\Delta_p = 0$.

Data collected in this manner are shown in Fig. 3(a), which displays the conditional probability P to detect an atom given an initial single-atom triggering event versus the time delay t_T. The two data sets shown in Fig. 3(a) yield comparable lifetimes, the upper acquired with mean intracavity atom number $\bar{N} = 0.30$ atoms and the lower with $\bar{N} = 0.019$ [24]. The offset in P between these two curves arises primarily from a reduction in duration δt of the cooling pulses, from 100 μs to 5 μs, which results in a reduced capture probability. Measurements with constant δt but with $\bar{N}$ varied by adjusting the MOT parameters allow us to investigate the probability of trapping an atom other than the "trigger" atom and of capturing more than one atom. For example, with $\delta t = 5\ \mu$s as in the lower set, we have varied $0.011 \lesssim \bar{N} \lesssim 0.20$ with no observable change in either P_T or the trap lifetime τ. Since a conservative upper bound on the relative probability of trapping a second atom is just $\bar{N}/2$ (when $\bar{N} \ll 1$), these data strongly support the conclusion that our measurements are for single trapped atoms. We rou-

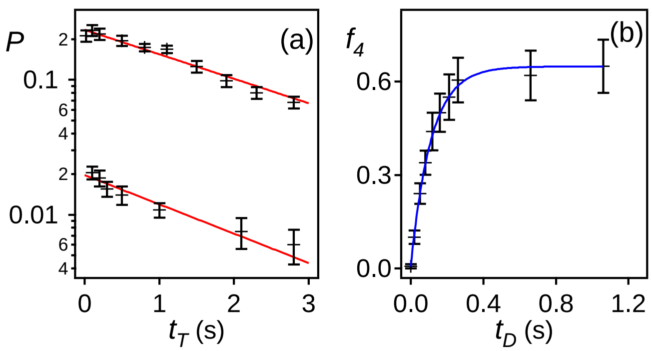

FIG. 3: (a) Detection probability P as a function of trapping time t_T. The upper data set is for mean intracavity atom number $\bar{N} \approx 0.30$, while the lower set is for $\bar{N} \approx 0.019$ atoms. Exponential fits (solid lines) yield lifetimes $\tau_{\rm upper} = (2.4 \pm 0.2)$ s and $\tau_{\rm lower} = (2.0 \pm 0.3)$ s. (b) The fractional population $f_4(t_D)$ in $F = 4$ following depletion of this level at $t_D = 0$. An exponential fit (solid line) gives $\tau_R = (0.11 \pm 0.02)$ s.

tinely observe lifetimes 2 s $< \tau <$ 3 s depending upon the parameters chosen for trap loading and cooling.

Fig. 3(b) explores scattering processes within the FORT that transfer population between the $6S_{1/2}, F = (3, 4)$ ground-state hyperfine levels. For these measurements, the $F = 4$ level is initially depleted, and then the population in $F = 4$ as well as the total $3 + 4$ population are monitored as functions of time t_D to yield the fractional population $f_4(t_D)$ in $F = 4$. The measured time $\tau_R = (0.11 \pm 0.02)$s for re-equilibration of populations between $F = (3, 4)$ agrees with a numerical simulation based upon scattering rates in our FORT, which predicts $\tau_R = 0.10$ s for atoms trapped at the peak FORT intensity in an initially unpolarized state in the $F = 3$ level.

Turning next to the question of the mechanisms that limit our FORT lifetime, we recall that parametric heating caused by intensity fluctuations of the trapping field can be quite important [2, 25]. From measurements of intensity fluctuations for our FORT around twice the relevant harmonic frequencies ($\nu_{axial} = 570, \nu_{radial} = 4.8$) kHz, we estimate a lower bound to the FORT lifetime of $\tau_p^{axial} > 1.6$ s [26]. Since this estimate suggests that parametric heating could be a limiting factor in Fig. 3, we performed subsequent measurements in which the intensity noise was reduced below the shot-noise level of our detection system, giving a lower bound $\tau_p^{axial} > 9$ s. Unfortunately, the measured FORT lifetime increased only modestly to $\tau = (3.1 \pm 0.4)$ s, indicating that other mechanisms are partially responsible for the observed decay.

A second suspect is a heating process described by Corwin *et al.* [27] associated with inelastic Raman scattering in an elliptically polarized FORT field [20]. We calculate rates Γ_s for spontaneous Raman scattering in our FORT to be 2.5 to 7 s^{-1} for transitions that change the hyperfine quantum number F, and between 0.8 and 2.5 s^{-1} when only m_F changes [28]. Based on Eq. 3 in Ref. [27] (a two-state model), we estimate an upper limit to the heating rate from this mechanism, $\Gamma_{IR} \lesssim 0.2\Gamma_s$, giving heating times as short as 0.7 s for the fastest calculated scattering rate. However, we have also undertaken a full multilevel simulation of the optical pumping processes, which indicates much slower heating, $\Gamma_{IR} \sim 0.02$ s^{-1}. We are working to resolve this discrepancy.

A third suspect that cannot be discounted is the presence of stray light, which we have endeavored to eliminate. For lifetimes as in Fig. 3, we require intracavity photon number $\bar{n} \ll 10^{-5}$, which is not trivial to diagnose. A final concern is the background pressure in the region of the FORT. Although the chamber pressure is 3×10^{-10} Torr (leading to $\tau \simeq 30$ s), we have no direct measurement of the residual gas density in the narrow cylinder between the mirror substrates (diameter 1 mm and length 43 μm), except for the trap lifetime itself.

(2) Toward the goals of continuous observation of single trapped atoms [3, 4] and of implementing Λ-schemes in cavity QED [7, 8, 9, 29], we next present results from our second protocol. Here, the $F = 4 \rightarrow F' = 4$ transition is strongly coupled to the cavity field, with $\Delta'_C \equiv \omega_C - \omega_{4\rightarrow 4} = 0$. In contrast to our protocol **(1)**, the FORT and the transverse $y - z$ beams are left *ON* continuously, with the latter containing only light near the $F = 3 \rightarrow F' = 3$ resonance, with detuning Δ_3. Significantly, we observe trap loading with *no cooling light near the* $F = 4 \rightarrow F' = 5$ *transition.*

An example of the resulting probe transmission is shown in Fig. 4, which displays two separate records of the continuous observation of trapped atoms. Here, the probe detuning $\Delta'_p = \omega_p - \omega_{4\rightarrow 4} = 0$ and the probe strength is given in terms of $\bar{m} = |\langle \hat{a} \rangle|^2$ deduced from the heterodyne current, with $\hat{a}$ as the annihilation operator for the intracavity field. We believe that the $y - z$ repumping beams (which excite $F = 3 \rightarrow F' = 3$) provide cooling, since without them the atoms would "roll" in and out of the near-conservative FORT potential (indeed no trapping occurs in their absence). In addition, this is a continuous cooling and loading scheme, so that we routinely load multiple atoms into the trap.

The most striking characteristic of the data collected in this manner is that $\bar{m}$ versus t always reaches its deepest level within the $\simeq 10$ ms window when the falling atoms arrive, subsequently increasing in a discontinuous "staircase" of steps. As indicated in Fig. 4, our interpretation is that there is a different level for $\bar{m}$ associated with each value N of the number of trapped atoms (with the level decreasing for higher N), and that each step is due to the loss of an atom from the cavity mode. In addition, we observe a strong dependence both of the initial trapping probability and of the continuous observation time on the detuning of the transverse beams, with an optimal value $\Delta_3 \simeq 25$ MHz to the *blue* of the $3 \rightarrow 3$ transition, which strongly suggests blue Sisyphus cooling [30].

We stress that observations as in Fig. 4 are made possible by strong coupling in cavity QED, for which individual intracavity atoms cause the displayed changes in probe transmission. While $\bar{m}$ in Figure 4 is only $\simeq 0.01$,

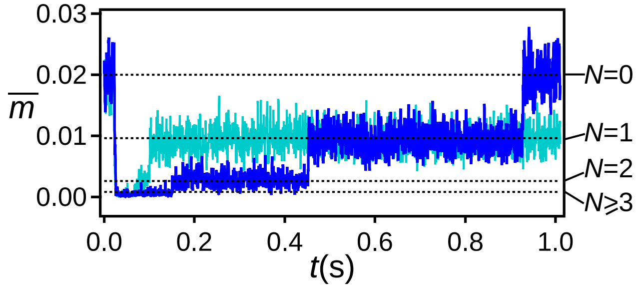

FIG. 4: Two traces of the continuous observation of trapped atoms inside a cavity in a regime of strong coupling. After an initial sharp reduction around $t = 0$ as atoms are cooled into the cavity mode, the intracavity field strength $\bar{m}$ increases in a discontinuous fashion as trapped atoms escape from the cavity mode one by one. RF detection bandwidth = 1 kHz, $\Delta'_C = 0 = \Delta'_p$, and $\Delta_3/2\pi = 25$ MHz (*blue*).

it represents an output flux $\simeq 5 \times 10^5$ photons per second. The probe is also critical to the cooling, although it is not clear whether this beam is acting as a simple "repumper" [30] or is functioning in a more complex fashion due to strong coupling. We have not seen such striking phenomena under similar conditions for cavity QED with the $F = 4 \to F' = 5$ transition. Note that our ability to monitor the atom as well as to cool its motion are enabled by the state-insensitive character of the trap, since the net transition shifts are small, $(g_0, \Delta_3) \gg \delta_0$.

In summary, we have demonstrated a new set of ideas within the setting of cavity QED, including state insensitive trapping suitable for strong coupling. Trapping of single atoms with $g_0 \gg (\delta_0, \kappa, \gamma)$ has been achieved with lifetimes $\tau \simeq 2-3$s. Since intrinsic heating in the FORT is quite low (~ 11 μK/s due to photon recoil), we anticipate extensions to much longer lifetimes. Continuous observations of multiple atoms in a cavity have been reported, and involve an interplay of a strongly coupled probe field for monitoring and a set of $y-z$ cooling beams. Our measurements represent the first demonstration of cooling for trapped atoms strongly coupled to a cavity. Beyond its critical role here, state insensitive trapping should allow the application of diverse laser cooling schemes, leading to atomic confinement in the Lamb-Dicke regime with strong coupling, and thereby to further advances in quantum information science.

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