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# Quantum Information Processing with Cavity QED

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## ABSTRACT

Strongly coupled cavity QED systems show great promise for coherent processing of quantum information in the contexts of quantum computing, communication and cryptography. We present here current progress in experiments for which single atoms are strongly coupled to the mode of a high finesse optical resonator.

## 1. INTRODUCTION

An exciting development in modern experimental physics is the increasing ability to investigate and manipulate systems at the level of single quanta, with examples of this new capability found in fields ranging from atomic and molecular physics (cavity QED with single atoms and photons,[1] ion traps cooled to the zero point,[2] NMR manipulations of molecular states[34]) to condensed matter physics (Coulomb blockade with discrete electron energies[5]). From the perspective of quantum computation, which relies on the manipulation and storage of pure quantum states, in order to fabricate a useful device it is additionally required that these single quanta can be made to interact in a controlled and coherent fashion with minimal decoherence. More quantitatively, if the coherent, reversible evolution of a quantum system is characterised by rate $g$ , then a necessary requirement is to achieve *strong coupling* for which $g > \beta \equiv \max[\Gamma, T^{-1}]$ with $T$ as the interaction time and $\Gamma$ as the set of decoherence rates for the system.

Our current research explores cavity quantum electrodynamics (QED) in the strong coupling domain as a realization of such a system. Our model cavity QED system is comprised of a single, two-state atom located in an optical cavity formed by two spherical mirrors. For this system $2g$ is the single-photon Rabi frequency and sets the rate of coherent evolution, while $\Gamma \equiv \{\gamma_\perp, \kappa\}$, with $\gamma_\perp$ as the atomic dipole decay rate and $\kappa$ as the rate of decay of the cavity field through the mirrors. It should be noted that although $\kappa$ appears here as a dissipative rate it is not necessarily a source of decoherence: if the exiting photons are considered as part of the quantum system and can efficiently be coupled to the next stage of computation (for instance, a second cavity), $\kappa$ can be seen as providing a quantum channel for exchange of entanglement between spatially separated sites.[6] This possibility for distribution of quantum information via photons makes cavity QED potentially extremely useful for quantum communication, cryptography, and error correction[7] in addition to proposed uses in quantum computation[8].[9] The combination of a small cavity mode volume (to give a large electric field per photon, and hence large coupling strength, $g$ ) and a high finesse cavity (for long photon storage times, and hence small $\kappa$ ) yields the requisite $g > \{\kappa, \gamma_\perp\}$ in our experiments. Finally, regarding the atomic interaction time $T$, several experiments in cavity QED have investigated interactions of atoms with the electromagnetic field at the level of single photon fields,[10–13] however without exception these experiments have employed fast atoms from thermal atomic beams, with short interaction times so that measurements over an ensemble of atoms are required. By contrast, our recent work employs slow laser cooled atoms to enable the monitoring and manipulation of single-atom trajectories in *real-time*,[1415] a major step towards realizing our ultimate goal of localized atoms strongly coupled to the cavity mode as is desirable for quantum computation.

We present here results from two ongoing experiments that explore phenomena uniquely accessible in this regime of true strong coupling.

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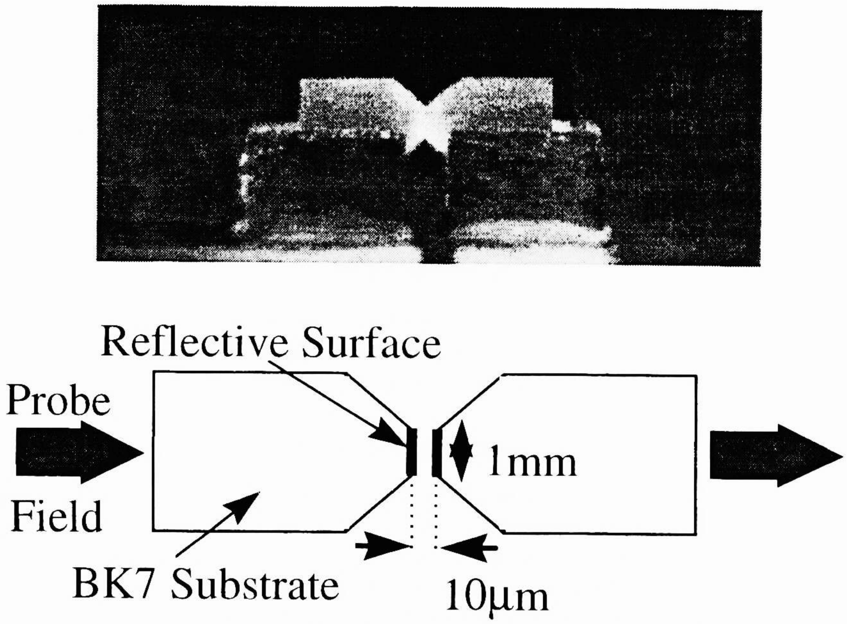


**Figure 1.** One of the Fabry-Perot cavities used in our cavity QED experiments, shown in a CCD image above and schematically below.

## 2. THE UNION OF STRONG COUPLING AND COLD ATOMS

A very small Fabry-Perot cavity, shown in Fig. 1, produces the highest coupling $g$ achieved in an optical system to date: two superpolished spherical mirrors of radius of curvature 10 cm form a cavity of length 10.1 $\mu$m and finesse $\mathcal{F}$=1.8 x $10^5$, yielding cavity parameters $(g_0, \kappa, \gamma_\perp, T^{-1})/2\pi$ = (120, 40, 2.6, 0.002) MHz.[15] The atom-field coupling coefficient $g$ varies spatially depending on the position of an atom within the standing-wave structure $\psi(\vec{r})$ of the electromagnetic field inside the cavity, and is given as a function of position by $g(\vec{r}) \equiv g_0\psi(\vec{r})$ , with the optimal coupling $g_0$ determined by the cavity geometry (and the known transition dipole moment). $\kappa$ is the measured linewidth of the $TEM_{00}$ mode of the cavity, $\gamma_\perp$ is the dipole decay rate for the Cs ($6S_{1/2}$,F=4, $m_F$=4) $\rightarrow$($6P_{3/2}$,F=5,$m_F$=5) transition ($\lambda$ = 852.36 nm),[16] and typical transit times for atoms through the cavity mode (waist $w_0 \simeq 15\mu$m) are $T \simeq 75\mu$s.

Cesium atoms are provided by a MOT formed 5mm above the optical resonator. The MOT is loaded for 0.5s, atoms are then sub-Doppler cooled to a temperature of $20\mu K$ and allowed to fall under gravity through the cavity mode. A single atom in the cavity causes a profound change in the spectrum of the atom-cavity system to a transmitted probe beam, as plotted in Fig. 2 for a probe drive strength of 0.5 photons. From a simple Lorentzian lineshape with no atom present (dashed curve), the spectrum evolves to a doubled peaked "vacuum-Rabi" splitting[17] (solid curve) as an atom reaches the region of optimal coupling with $g(\vec{r}) \approx g_0$. Accordingly, a probe beam of fixed frequency $\omega_P$ shows changes in transmission as single atoms transit the cavity. Near the coincident atom-cavity resonance $\omega_P \simeq \omega_{atom} = \omega_{cavity}$ , a decrease in transmission is observed, whereas for a probe detuned by $\simeq \pm g_0$ an increase in transmission relative to that of the empty cavity is seen. Real-time single atom transit signals are shown in Fig. 3(a,b) corresponding to these two probe detunings.

In Ref.[15] we map out the full structure of the vacuum-Rabi spectrum from single atom transits signals such as these, and explore the nonlinear saturation behavior of the system.

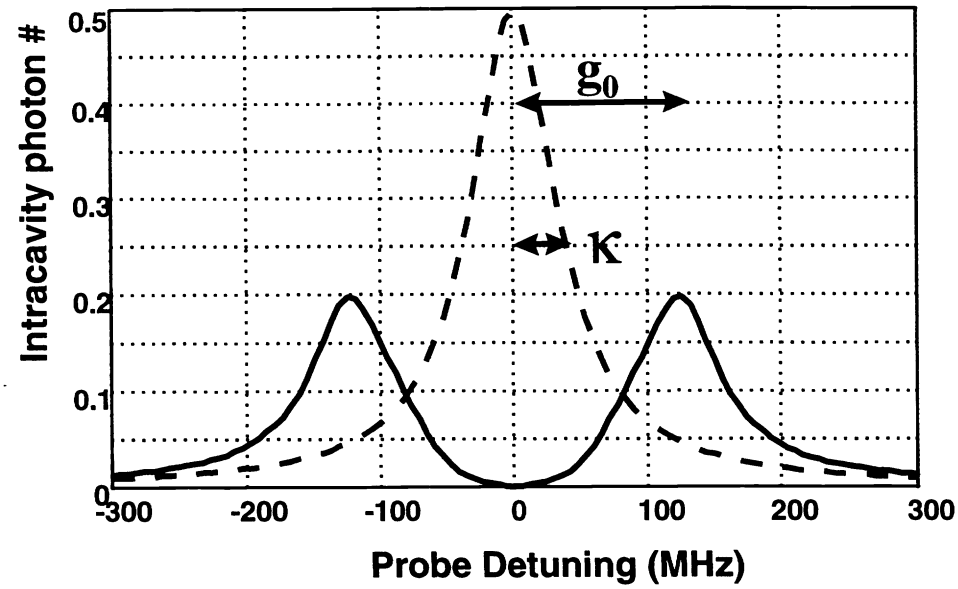


**Figure 2.** Transmission vs. detuning for a probe field of photon number =0.5, with no atom present (dashed curve), and with a single, optimally coupled atom (solid curve).

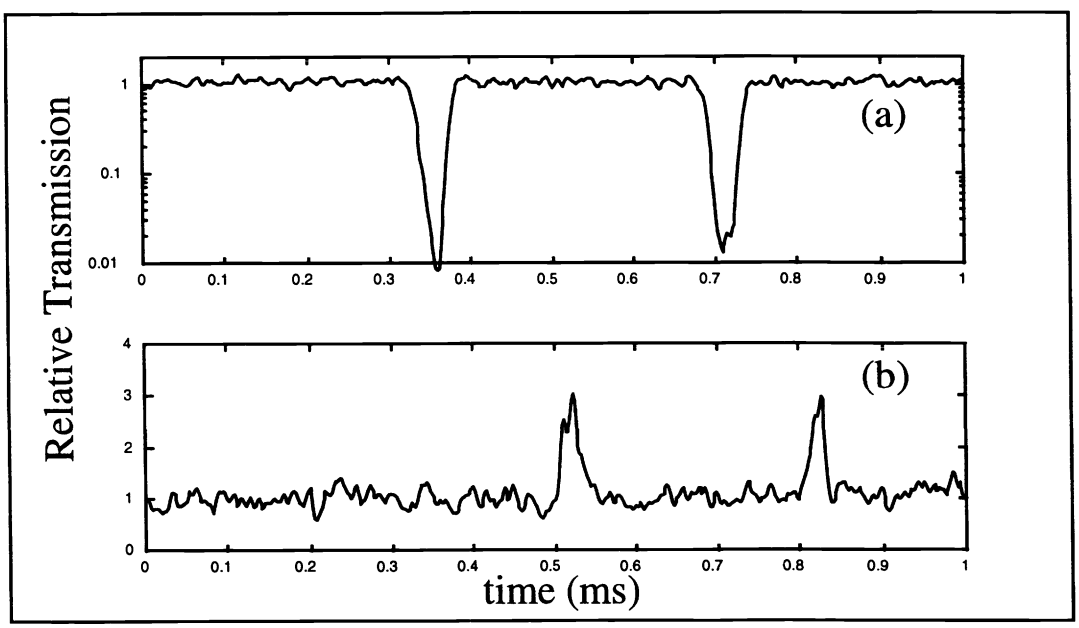


**Figure 3.** Real-time changes in transmission of the atom-cavity system produced by the transit of individual atoms through the cavity mode. In (a) the probe is tuned close to the coincident atom-cavity resonance (detuned by -20MHz), and decreases in transmission by two orders of magnitude are observed. In (b) the probe is detuned by $\simeq -g_0 = 120$ MHz. Here atom transits give increases in transmission.

## 3. TRAPPING SINGLE ATOMS WITH SINGLE PHOTONS

The strong coupling described above can be exploited to confine single atoms in a cavity field with $\lesssim 1$ photon. The vacuum-Rabi frequency spectrum of Fig. 3 indicates a shift in the system's energy eigenvalues to $\pm\hbar g_0$ at the atom position corresponding to optimal coupling, creating a potential minimum (maximum) for an atom in the corresponding lower (upper) dressed state. A probe detuned by $\simeq -g_0$ drives the atom to the lower dressed level, giving rise to a pseudo-potential with depth $\hbar g_0/k_B \approx 7\text{mK}$,[18] greater than the kinetic energy of the slow atoms. Evidence for these single-photon mechanical light forces is observed in an asymmetry of the vacuum-Rabi spectrum recorded in Ref.[15]: blue detuned probe fields force the atomic trajectories away from the regions of optimal coupling, giving rise to smaller changes in transmission than otherwise expected.

Our current experiment seeks to utilize this potential as a trap for single atoms. Experimentally, a weak probe field near the atom-cavity resonance is monitored, and as an atom enters the cavity the corresponding drop in transmission is used to trigger OFF this resonant field, and ON a second field detuned by $\simeq -g_0$ to create the trapping potential. In the absence of mechanical effects the longest possible transit times would be $\simeq 100\mu$s, and to date using our triggering strategy we have observed atoms held within the cavity for $> 300\mu$s. An example of such an atom is shown in Fig. 4. By detuning the cavity from the atomic resonance to reduce spontaneous emission heating, we hope to further extend this time. Such data shows progress toward trapping atoms, but more fundamentally demonstrates the use of strong coupling to exercise control at a fundamental level over a system's evolution.

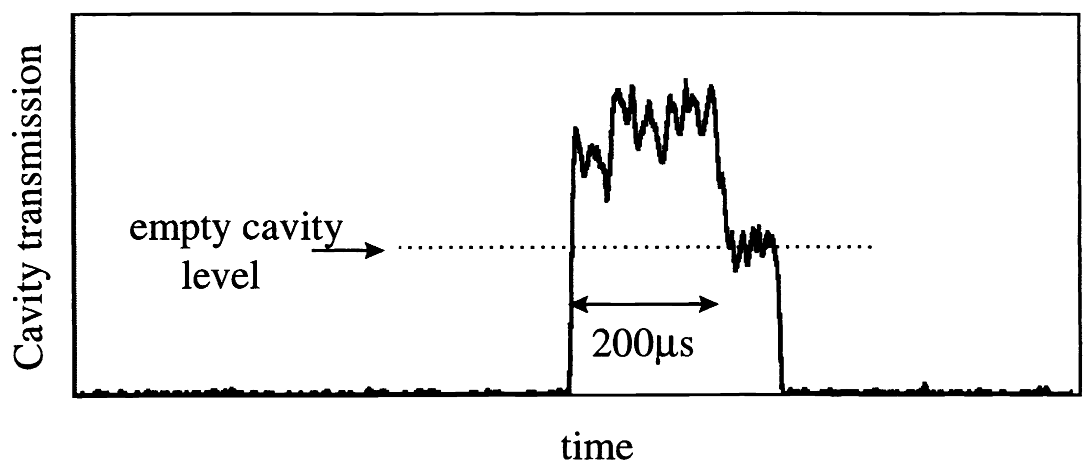


**Figure 4.** Lengthening the interaction time of an atom in the cavity. A probe detuned by $\simeq -g_0$ is triggered ON in the presence of an atom falling into the cavity mode. Transit times have been extended from $100\mu s$ in the absence of forces from this probe field to $>300\mu s$ . The transit shown has been extended to $\sim 200\mu s$. duration.

Other mechanisms for lengthening the atom-cavity interaction time are being investigated. Once an atom is confined within the cavity mode structure, cooling the atomic motion is clearly desirable, with a Sisyphus-like cooling mechanism induced by the finite response time of the cavity to atomic motion[19] being one candidate for future experiments. Another possibility is to use our real-time information on the atomic trajectory to feed back to the trapping potential and cool the atom (changing for example the detuning or intensity of the probe field). Yet another promising approach would be to apply a far-detuned probe field forming a dipole-force trap, to contain the atom independently of the cavity QED interactions.

## 4. CONTINUOUS MEASUREMENT OF SINGLE ATOM TRAJECTORIES

A second experiment, with cavity parameters $(g_0, \kappa)/2\pi = (11, 3.2)$ MHz, focuses on the use of strong coupling in novel approaches to quantum measurement. As implied above, continuous measurement of the cavity transmission can be used to monitor the spatial trajectory of an individual atom as it falls through. The sensitivity of such observations is set by the spatial gradient of $g(\vec{r}) = g_0 \cos k_L x \exp - \left(y^2 + z^2\right)/w_0^2$. For our near-planar cavities $k_L \gg 1/w_0$, so we achieve the greatest sensitivity to atomic displacements along the cavity axis. With $g_0 \simeq 11$ MHz, it should ultimately be possible to reach the Standard Quantum Limit for monitoring the position of a free mass. In the context of cavity QED, reaching this limit would enable unique experiments to investigate the strong conditioning of system evolution on measurement results, as well as a true realization of quantum feedback control.

Two principal complications stand in the way of reaching this goal, however. The first obstacle stems from severe heating of the atomic motion when the cavity transmission is probed with a laser too close to atomic resonance.[17] The second comes from the fact that we so far have no clean way of distinguishing between variations in the cavity transmission caused by atomic motion along the standing wave, and contributions from either transverse atomic motion or optical pumping among atomic internal (Zeeman) states. At present, we have managed to overcome the first difficulty and have begun to work on the second.

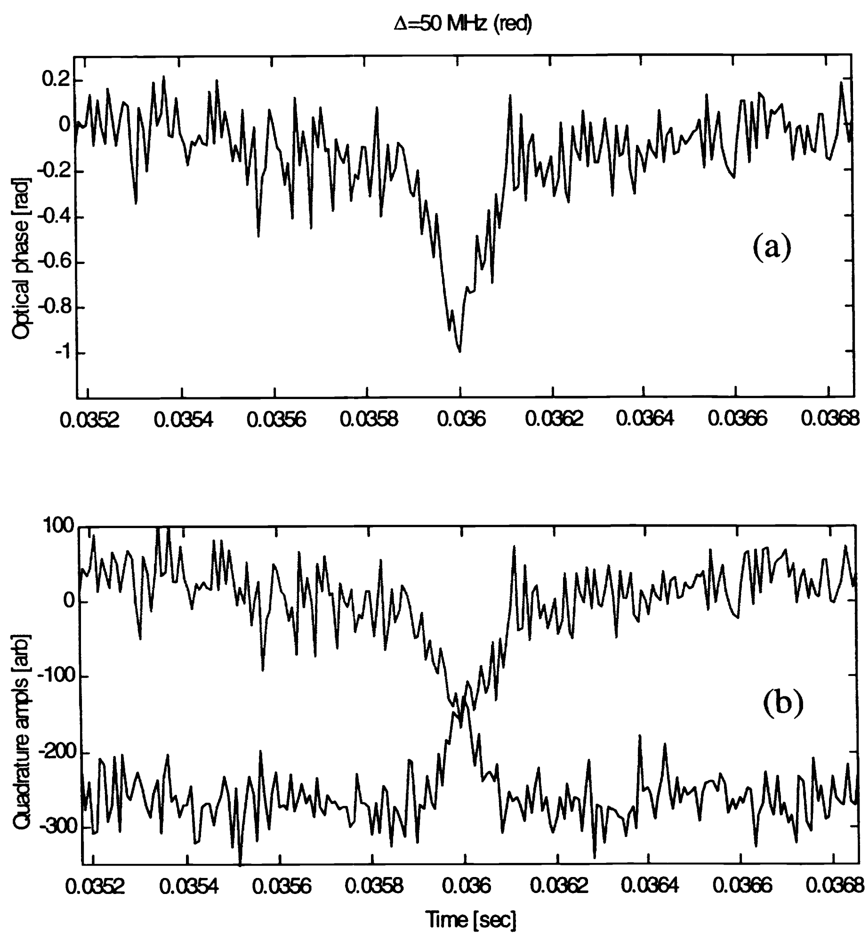


**Figure 5.** Time variation of each quadrature amplitude of the transmitted field (b), and the resulting optical phase (a) for this single atom event.

Our recent measurements minimize back action on the atomic motion by detuning the probe field far from atomic resonance.[21] In order to maintain sensitivity to the atomic position, we now have to determine the *phase* of the transmitted field with high bandwidth and shot-noise limited accuracy. In this experiment both quadratures of the output field are simultaneously recorded in balanced heterodyne detection, giving the first measurement of the real-time evolution of the complex field amplitude brought by single atom transits. Fig. 5 shows the time variation of each quadrature amplitude of the transmitted field, as well as the resulting optical phase for a single atom event. Note that 1 radian of optical phase shift is generated by a single atom, with the probe field detuned 50 MHz to the red of atomic resonance. At -100 MHz detuning, a phase shift of 0.5 rad can still be observed with signal-to-noise ratio $\sim 3$ at 300kHz bandwidth, very near the shot-noise limit.

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