THE QUANTUM INTERNET

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A broad program of research relating to quantum information processing using the methods of cavity quantum electrodynamics (cavity QED) is described. A major theme of the research is to develop the tools needed to realize a quantum network (or *quantum internet*), with atom-cavity systems linked by high-fidelity optical interconnects. Recent progress toward the trapping of a single atom within a high-finesse cavity is discussed, as is a new type of optical trap whose potential is independent of the internal state of the trapped atom.

1 Introduction

The Quantum Optics Group at Caltech is pursuing a broad program of research relating to the implementation of quantum logic and communication, with emphasis on developing the tools needed to realize quantum networks. As illustrated in Figure 1, such a network could consist of atom-cavity systems linked by high-fidelity optical interconnects. Professors Cirac and Zoller and colleagues have proposed and analyzed a complete set of elementary network operations, including local processing of quantum information and the distribution of quantum entanglement (as for example by quantum teleportation).[1] Note that quantum-state transfer between processing nodes of such a network offers a potentially powerful means to overcome scaling problems for quantum computers[2] and to accomplish tasks that are impossible within the realm of classical communication.[3,4,5]

To lay the experimental foundations for such possibilities, we are investigating the interaction of single atoms strongly coupled to the field of high finesse optical cavities at the single photon level.[6,7,8,9] Current work is directed toward trapping and localization of atoms inside small cavities, both by employing novel forces in cavity QED at the single photon level and by way of dipole-force traps within the cavity mode. Here we describe recent progress made on these fronts. We also discuss a new type of optical dipole-force trap for which the AC-Stark shifts of ground and excited states are identical, so that the trapping potential for the center-of-mass becomes independent of the atomic internal state.

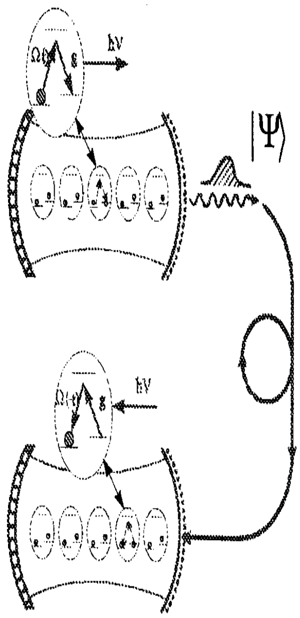

Figure 1. Illustration of the protocol of Ref. [1] for the generation and distribution of entanglement among atoms in remote cavities. By expanding from two cavities to a larger set interconnected by optical fiber, complex quantum networks can be realized.

2 Localized atoms in cavity QED

We have invested considerable effort in recent years in the marriage of cavity QED with laser cooling and trapping of neutral atoms. A significant milestone has been the real-time detection of individual atoms transiting through a high-finesse optical resonator.[6,7,8]

In our experiments, Cesium atoms are dropped from a magneto-optical trap located a few millimeters above a Fabry-Perot cavity. By recording modifications of the cavity transmission as an atom enters the cavity mode, we can monitor the "trajectory" of an individual atom as it transits through the cavity. Indeed, a rather complex technical infrastructure for cavity locking and frequency stabilization has enabled us to record the full complex susceptibility for single atoms coupled to the cavity field [8]. These measurements are already remarkably close to the standard quantum limit for sensing the atom's position (within a factor of roughly 3). Given the ability to monitor the motion of a single atom in a cavity in real time with near quantum-limited sensitivity, we are attempting now to exploit this capability to trap and cool the atom within the cavity. Several strategies are being pursued, as discussed in the following sections.

2.1 *Quantum feedback*

One strategy that we are pursuing involves the implementation of *quantum servo control* of atomic motion.[10,11] Here, a magneto-optical trap (MOT) situated 2mm above a high finesse optical cavity (of finesse 200,000) is switched off and polarization gradient cooling applied, with the Cs atoms then falling down into the cavity mode. The arrival of an individual atom is sensed by an intracavity probe field of photon number $n_1 \ll 1$, which has a small effect on the atomic center-of-mass motion. Having detected an atom by a change in transmission of this probe beam, we then switch it OFF. A trapping beam is next triggered ON as a result of the presence of the atom within the cavity, with its frequency tuned to the lower component of the vacuum-Rabi doublet.

Following the analysis of Parkins[12], we make use of the fact that the lower peak of the vacuum-Rabi splitting corresponds to an attractive pseudo-potential, with the average "well depth" increasing with increasing probability for occupation of the lower dressed state, at least in the limit of intracavity fields with photon number $n_2 < 1$. By exciting a population to the lower dressed-state manifold, the trapping beam creates a confining potential sufficient to localize the atom. By way of this active control strategy we have observed localization of single atoms within the cavity for times $\approx 300\ \mu s$ in a setting for which an atom would have otherwise fallen through the cavity mode in less than $100\ \mu s$. Of course in addition to a trapping force, the atom is heated as well, which explains the rather modest increase in the time of localization. [13]

2.2 *Trapping with single photons*

A second experiment to achieve trapping within an optical cavity is illustrated in Figure 2. In the upper diagram, the magneto-optical trap MOT 2 has been formed from a primary MOT 1 located 25 cm above and dropped into the lower ultrahigh vacuum chamber (10^{-10} Torr) containing the cavity of finesse 470,000. After switching off MOT 2, the atoms are further cooled by polarization-gradient cooling to a temperature of $1\ \mu K$ and then released to fall into the $45\ \mu m$ gap between the mirrors. As the atoms enter the gap, a set of optical lattice beams lying in a plane perpendicular to the cavity axis are switched on to remove the residual fall velocity, thus producing very cold atoms with velocities of a few $\frac{cm}{sec}$ within the cavity mode (of waist $w_0 = 20\ \mu m$).

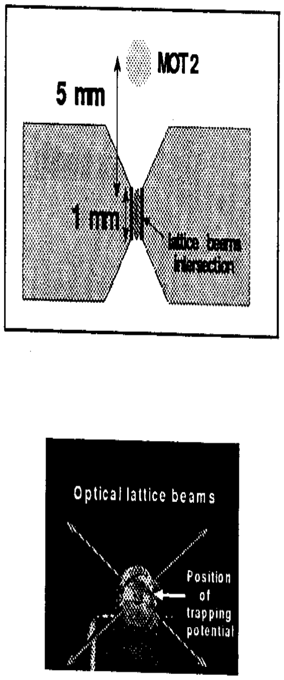

Figure 2. Experimental setup for trapping an atom in an optical cavity.

Because the kinetic energy of such a cold atom is much smaller than the coherent coupling energy $\hbar g_0$, it is possible to achieve long localization times via the single-photon trapping and cooling mechanisms discussed above (see Refs. [12,13,14]). A recent example of our success in this endeavor is given in Figure 3, where an atom is localized within the cavity for a time $T_0 \simeq 1$ msec. Note that the atom would have otherwise fallen through the cavity in less than $100\ \mu$sec. Here the probe laser has been tuned 30 MHz below the common atom-cavity resonance to a frequency corresponding to the energy of the lower dressed state for the optimally coupled atom-cavity system. A pseudo-potential is thereby created which localizes the atom within the cavity (here for a time $T_0 > 1$ msec).

The longest times T_0 that we have observed with the probe frequency ω_p tuned to the lower component of the vacuum-Rabi splitting near $\pm g_0$ are $T_0 \sim 2$ msec. On the other hand, if the probe frequency is instead tuned to be near the common atom-cavity frequency $\omega_p \approx \omega_{cavity} \approx \omega_{atom}$, considerably shorter localization times are observed, with $T_0 \sim 0.6$ msec. This disparity in T_0 between 'up-going' and 'down-going' signals as well as the actual magnitude of the observed localization times can be understood by way

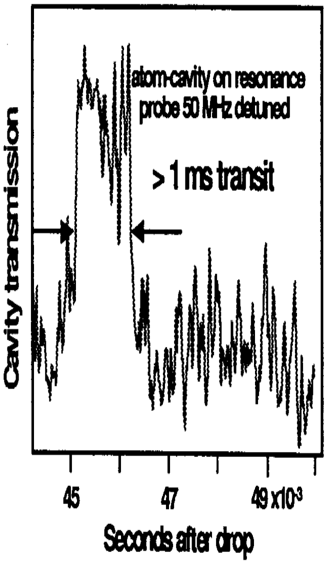

Figure 3. Record of cavity transmission versus time showing an increase in transmission due to a single atom localized within the cavity.

of a simple 'Sisyphus'-type picture based upon the spatially dependent level structure in cavity QED. Our observations are also consistent with detailed numerical simulations of single-photon trapping in such an experiment.[15]

2.3 Cavity QED in a FORT

With cold, localized atoms as described in the preceding section, we have next explored trapping within a far-off-resonance trap (FORT) [16,17] to provide an essentially classical ponderomotive potential for trapping an atom 'indefinitely'. Here, the FORT beam is derived from an external semiconductor diode laser that resonantly excites a red-detuned mode of the cavity at frequency ω_F two longitudinal-mode orders below the mode at ω_c exploited for the cavity QED interactions; that is, $\omega_F = \omega_c - 2\Delta_{FSR}$ with Δ_{FSR} as the cavity free spectral range which is roughly 8nm for the cavity of Figure 2. In this case, the standing-wave patterns of the two modes (ω_F, ω_c) are such that there are coincident antinodes at the center of the cavity; hence, the trapping potential of the FORT has a minimum at the position of maximum cavity QED coupling in this region.

In fact, in the week just before ICOLS, we had some success in trapping atoms inside the cavity with this FORT. An example of a 'typical' event is given in Figure 4. The timing sequence is illustrated in the traces in the upper frame without atoms present. The lower frame gives an expanded view of the time at which the FORT is turned off, and the cavity probe field switched back on. In this trace, an atom was presumably trapped in the FORT for 15 msec and is then detected by way of a reduction in cavity transmission. Control measurements with various beams switched on or off (including most importantly, the FORT) support the conclusion that signals such as in Figure 4 arise from actual trapping of a single atom in the FORT and not from some other source of extraneous, cold atoms.

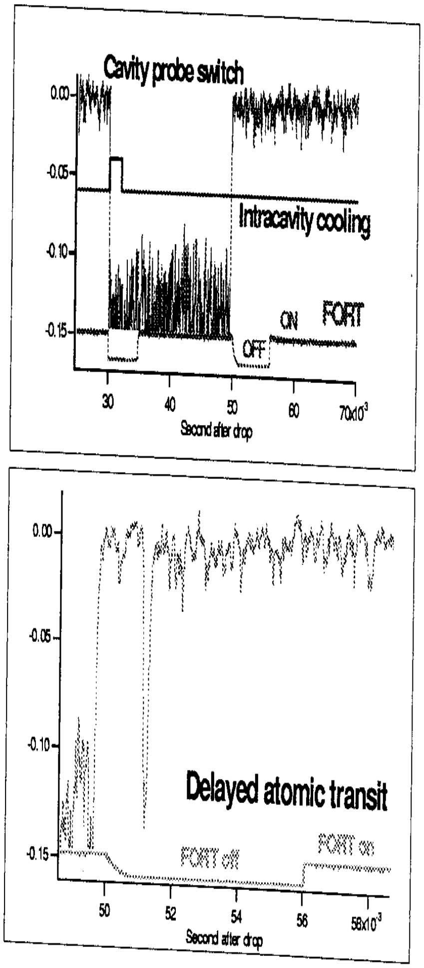

Figure 4. Trapping an atom inside an optical cavity with a FORT.

However, more significantly, in the week following ICOLS, we have been able to trigger the FORT from transit signals generated by the arrival of individual atoms. We have now achieved a clear demonstration of trapping of single atom within the cavity for time $T \approx 30$ msec, with the clear prospect of moving to trapping times $T \sim 1$ sec. The ultimate trapping time in our current apparatus is set by the background pressure of 10^{-10}Torr to be of order 100 sec.

Some sense of the advance that a transit time $T \approx 10$ msec represents relative to other experiments in the area of cavity QED is obtained by noting that the optical information per transit $I = \frac{g_0^2 T}{\kappa}$ (with g_0 as the coherent coupling constant and κ as the cavity decay rate) is $I \approx 10^7$, whereas for other experiments (which employ atomic beams) $I \approx 1$. Stated somewhat differently, these measurements already indicate a separation of time scales between the internal (atomic dipole coupled to cavity field) and external (center-of-mass motion) degrees of freedom of roughly 10^6.

2.4 A zero transition-shift FORT

Numerous demonstrations have now been made of atom confinement in optical dipole traps. The typical scheme is to use a trapping laser whose wavelength lies far to the red of any allowed transition from the atomic ground state, so that the AC Stark shift of the ground state is negative and maximized at the points of highest laser intensity. Atoms thus experience an optical dipole force that attracts them to local maxima of the laser field.

For integration with cavity QED, the problem with this simple approach is that excited (as opposed to ground) states generally experience a positive AC Stark shift of comparable magnitude to the negative shift of the ground state. This has at least two unfortunate consequences. First, atoms are *repelled* from the trap when they happen to spend time in an excited state. Second, the effective detuning between an atomic transition and the cavity mode becomes a strong function of the atom's position within the trap.

It turns out that a clever choice can be made for the wavelength of the trapping laser such that both of these problems are eliminated [18].

In our work in cavity QED with laser-cooled ^{133}Cs atoms, strong coupling between atom and cavity is established via the $S_{1/2}(F=4, m_F=4) \rightarrow P_{3/2}(F=5, m_F=5)$ transition at $\lambda \simeq 852.359$ nm. When a red-detuned trapping laser is applied to the Cs atom, these levels are both shifted by the AC Stark effect as shown in Figure 5. Here the dotted curve shows the ground state $S_{1/2}(F=4, m_F=4)$ shift, and the solid curve shows the excited state $\mathrm{P}_{3/2}(F=5, m_F=5)$ shift, versus wavelength of a circularly-polarized trapping field.

Near the transition resonance at 852 nm, these level shifts allow for trapping of the Cs atom with a traditional dipole-force trap. For small red detunings of the trapping laser (*e.g.* $\lambda \sim 860$ nm), the ground state has a negative energy shift so ground-state atoms will be trapped in local maxima of the laser field. At such wavelengths, however, excited state atoms experience a positive energy shift and will therefore be repelled from the laser field.

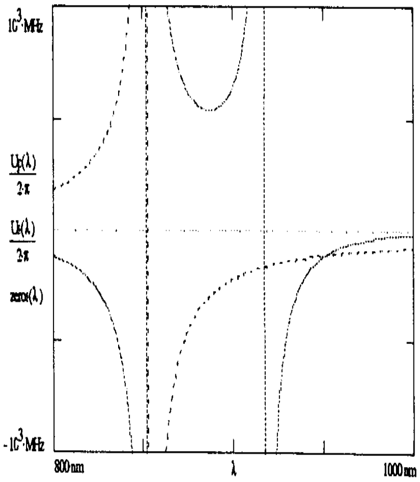

Figure 5. AC stark effect for a cesium atom in a laser field.

Fortunately, the cavity-QED excited state $P_{3/2}(F=5, m_F=5)$ is also coupled to the $D_{5/2}(F=6, m_F=6)$ state with a transition wavelength ~ 917 nm. Hence, the $P_{3/2}(F=5, m_F=5)$ experiences an additional *negative* AC Stark shift when the trapping laser has a small blue detuning from the $P \rightarrow D$ transition. This negative shift and the positive shift from the $S \rightarrow P$ coupling simply add. As a result, it can be seen from Fig. 5 that there is a region of applied wavelengths from 920 nm upward for which cesium atoms will be trapped in the laser field in both the ground and excited states, since each of these acquires a negative shift in its energy.

In fact, there exists a special wavelength for the trapping laser (near 952 nm for the particular choice of polarizations and levels considered here), for which the S and P states (of the cavity-QED transition) are shifted by an *identical* amount. Hence both the S and P states are trapped in local maxima, and the frequency of the $S \rightarrow P$ transition should be unaffected by the existence of a trapping field at this special wavelength. The level shifts are of sufficient magnitude that strong confining forces will be achieved for as little as ~ 1 mW of trapping laser power (assuming a cavity build-up factor

~ 1000 at 952 nm).

We have further extended these ideas to combine both the AC-Stark shifts of the FORT with the cavity QED level structure, thereby obtaining a specific example of the 'well-dressed' states of Ref.[19].

3 Continuous quantum variables

Beyond quantum information processing with internal atomic states and photons serving as *qubits*, we are also investigating algorithms for continuous quantum variables. A recent example is our realization of *genuine* quantum teleportation for the quadrature amplitudes of a beam of light.[20] These same experimental capabilities should enable super-dense quantum coding.[21] Moreover, in concert with the emerging capabilities in cavity QED described in the preceding sections, it should be possible to teleport the center-of-mass wavefunction for atoms trapped in optical cavities.[22]

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