Chapter 1

Introduction

The interaction between a single atom and the mode of an optical cavity constitutes a quantum interface between light and matter: through the coupling between the light field and the atomic dipole, the atom and cavity exchange single energy quanta. The field of cavity quantum electrodynamics (QED) is thus an exciting platform from which to explore the dynamics of fundamental quantum processes in the laboratory. Cavity QED is also an excellent candidate system for the emerging field of quantum information science [1]. In this context, the light-matter quantum interface could be harnessed to transfer information between nodes and channels of a quantum network [2]. Atoms trapped within cavities would function as "quantum nodes" where information could be processed and stored, then mapped to the output cavity mode and coupled into the "quantum channel" of an optical fiber for distribution to other nodes.

Our light-matter interface is of course also a real-world experimental system, and in order to investigate quantum processes, we need to demonstrate control over the system's many degrees of freedom. For example, while the Jaynes-Cummings model of cavity QED [3] treats the atom as a two-level system, the cesium atoms in our laboratory have a multiplicity of hyperfine and Zeeman ground states, each of which couples differently to a cavity; in order to understand our system in terms of a simple model, we would like to prepare the atom reliably in a single ground state. An atom also possesses external degrees of freedom, which describe its center-of-mass motion within the cavity. As the cavity mode has spatial structure, the coupling of an atom to the cavity depends upon its precise location; we would like to be able to cool the atom's vibrational motion (that is, to localize it at the antinode of a trapping potential). In the context of quantum information science, we would like to store information in two ground states of the atom, and so we need the capability to drive unitary transformations in this state space. Finally, we would like to explore the process of mapping quantum states between photons and atoms, a building block for future quantum networks.

This thesis describes recent progress in all of these directions: internal state preparation, center-of-mass ground state cooling, and a coherent mapping of photonic to atomic states.

1.1 A single trapped atom

The Jaynes-Cummings interaction Hamiltonian describes the coupling of a two-level atom to a single cavity mode [3]:

$$\hat{H}_{int} = \hbar g(\hat{a}^\dagger \hat{\sigma} + \hat{a}\hat{\sigma}^\dagger), \tag{1.1}$$

where $\hat{a}^\dagger$ and $\hat{a}$ are photon creation and annihilation operators, $\hat{\sigma}^\dagger$ and $\hat{\sigma}$ are atomic raising and lowering operators, and g is the (spatially dependent) coupling strength. Here we have made the rotating wave approximation, as the cavity field is near-resonant with the atomic transition. When we include terms for excitations in the atom and cavity modes as well as for a classical probe field at frequency ω_p, then we have the Jaynes-Cummings Hamiltonian, written here in the reference frame of the probe:

$$\hat{H}_{JC} = \hbar\Delta_a \hat{\sigma}^\dagger \hat{\sigma} + \hbar\Delta_c \hat{a}^\dagger \hat{a} + \hbar g(\hat{a}^\dagger \hat{\sigma} + \hat{a}\hat{\sigma}^\dagger) + \epsilon \hat{a} + \epsilon^* \hat{a}^\dagger, \tag{1.2}$$

where ω_a and ω_c are the atom and cavity frequencies, $\Delta_a = \omega_a - \omega_p$, $\Delta_c = \omega_c - \omega_p$, and ϵ is the probe field drive strength.

In the absence of a probe ($\omega_p = 0$, $\epsilon = 0$), we can diagonalize this Hamiltonian to find the exact eigenstates and eigenvalues of the system. We work in the tensor

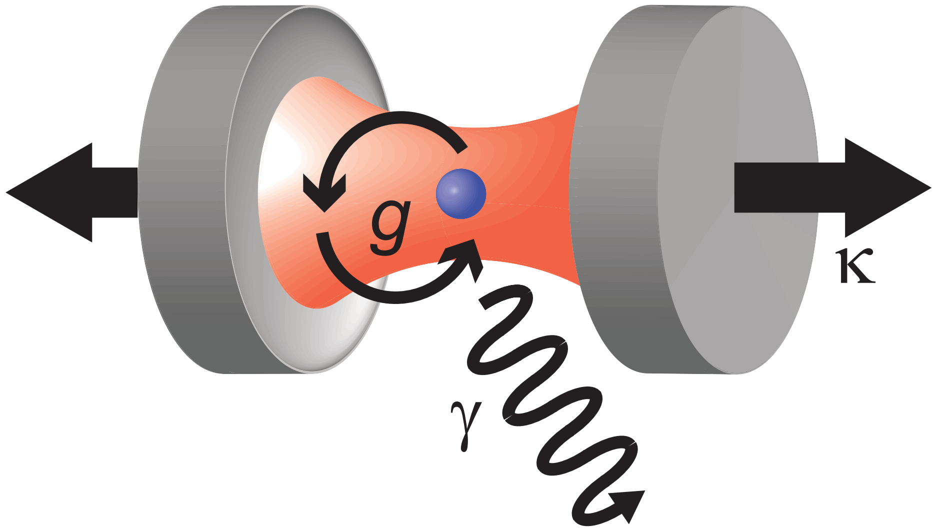

Figure 1.1: Coupling rates for a model cavity QED system. Atom and cavity couple coherently to one another at rate g. There are two incoherent mechanisms: the cavity field decays at rate κ, and the atom decays spontaneously at rate γ.

product basis where $|g,n\rangle$ and $|e,n-1\rangle$ are n-excitation states with an atom in the ground (excited) state and n $(n-1)$ photons in the cavity. The interaction term couples each pair of n-excitation states, leading to eigenstates and eigenvalues

$$\begin{aligned} |\pm_n\rangle &= (\delta \pm \sqrt{4g^2 n + \delta^2})|g,n\rangle + 2g\sqrt{n}|e,n-1\rangle, \\ E_{\pm n} &= \frac{\hbar}{2}(2n\omega_c - \delta \pm \sqrt{4g^2 n + \delta^2}), \end{aligned}$$

where $\delta = \omega_c - \omega_a$, and $|\pm_n\rangle$ is unnormalized. For the on-resonant case $\delta = 0$, $|\pm_n\rangle$ form the Jaynes-Cummings ladder of eigenstates, with the anharmonic dressed state splitting $2\hbar g\sqrt{n}$ between $E_{\pm n}$ at each rung of the ladder. A more realistic model for our system adapts the Jaynes-Cummings Hamiltonian to include multiple Zeeman and hyperfine states of the atom and two polarization modes of the cavity [4, 5].

To complete our cavity QED model, we need to include dissipation, through which the atom and cavity couple irreversibly to the environment. Dissipation can occur either through spontaneous emission, at rate γ, or cavity transmission, at rate κ. Figure 1.1 provides a schematic depiction of the three relevant coupling rates

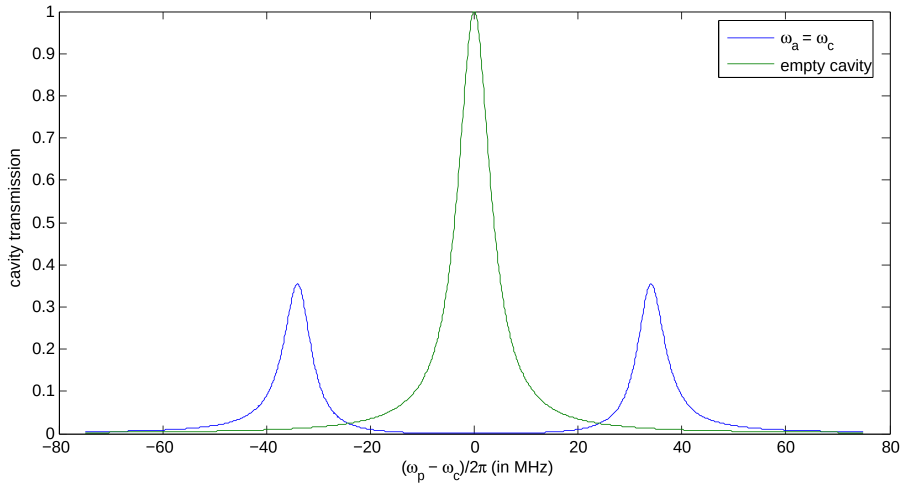

Figure 1.2: Steady-state transmission of the atom-cavity system as a function of probe detuning in the weak driving limit. Parameters are $g = 2\pi \times 33.9$ MHz, $\kappa = 2\pi \times 3.8$ MHz, $\gamma = 2\pi \times 2.6$ MHz, $\omega_a = \omega_c$. The cavity transmission is normalized to the maximum empty cavity transmission; empty cavity transmission as a function of probe detuning is plotted for comparison.

$\{g,\ \kappa,\ \gamma\}$. Mathematically, we can treat dissipation by incorporating the Jaynes-Cummings Hamiltonian into a master equation $\dot{\rho} = \mathcal{L}\rho$ for the density matrix of the system, where $\mathcal{L}$ is the Liouvillian superoperator [6]:

$$\mathcal{L} = -i[H_{JC}, \rho] + \kappa(2\hat{a}\rho\hat{a}^\dagger - \hat{a}^\dagger\hat{a}\rho - \rho\hat{a}^\dagger\hat{a}) + \gamma(2\hat{\sigma}\rho\hat{\sigma}^\dagger - \hat{\sigma}^\dagger\hat{\sigma}\rho - \rho\hat{\sigma}^\dagger\hat{\sigma}). \tag{1.3}$$

For a restricted basis set, the master equation can be solved numerically to find the steady state density matrix and expectation values of various operators. In the weak driving limit, in which the system is restricted to $n = \{0,\ 1\}$, the master equation can be solved analytically [7].

Figure 1.2 depicts the weak driving solution for the steady-state intracavity photon number, proportional to the cavity transmission, as a function of probe frequency ω_p ($\omega_a = \omega_c$) for the parameters in our current cavity QED experiment. Note that the frequencies of the two peaks correspond to the eigenvalues $E_{\pm 1}/\hbar = \pm g$, while the linewidth of each peak is approximately $\frac{\kappa+\gamma}{2}$. When $g \gg \kappa, \gamma$, the two-peaked structure — known as the vacuum-Rabi splitting — is well-resolved. Our experiments

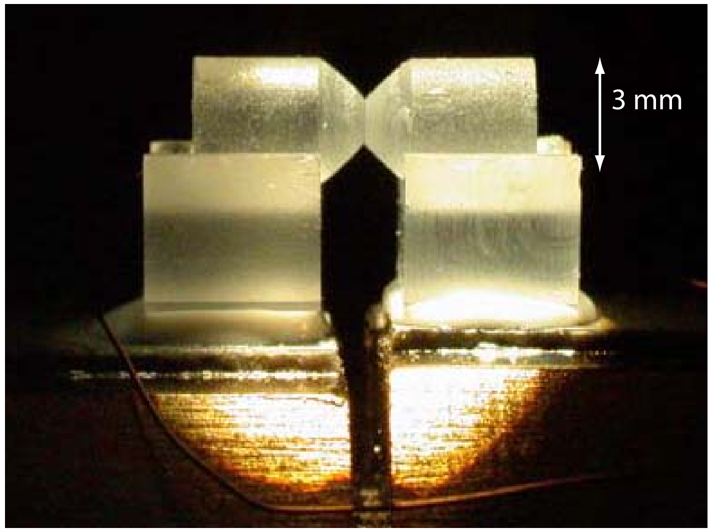

Figure 1.3: Photograph of the most recent cavity constructed for use in the lab 1 experiment. The cavity mirrors, fabricated on BK7 substrates, are only 9.2 μm apart; the mirror faces are 1 mm in diameter, with a 10 cm radius of curvature, and coned so that they can be brought close together. The substrates are held in BK7 v-blocks glued to shear-mode piezoelectric transducers, with a copper mounting block beneath.

operate in this *strong coupling* regime, where coherent coupling dominates dissipative rates.

We construct the optical cavities that we use in the lab from high-finesse mirrors [8]; an example cavity is shown in Figure 1.3. In order to meet the strong coupling criterion, we want to maximize g, the scalar product of the atomic dipole and the electric field within the cavity:

$$g = \vec{\mu} \cdot \vec{E} = \mu \sqrt{\frac{\hbar \omega_a}{2 \epsilon_0 V_m}}, \tag{1.4}$$

where V_m, the cavity mode volume, is proportional to the cavity length and to the square of the mode waist. Thus, we should minimize the mode volume by building short cavities and using mirrors with a small radius of curvature. However, the full-width half-maximum (FWHM) linewidth of a cavity is given by the ratio of its free spectral range to finesse [9]:

$$2(\kappa/2\pi) = FWHM = \frac{FSR}{\mathcal{F}} = \frac{c}{2d\mathcal{F}}, \tag{1.5}$$

where d is the cavity length. Thus, as we build smaller cavities, the requirements on the mirror quality become increasingly stringent in order to maintain $g \gg \kappa$.

The cavity sits on a vibration isolation stack inside an ultra-high-vacuum (UHV) chamber. We collect $\sim 10^6$ cold cesium atoms from background vapor in a magneto-optical trap (MOT) inside a "source" chamber, then apply an interval of polarization-gradient cooling to bring atom temperatures to around 10 μK [10]. The atoms are released, fall under gravity through a differential pumping tube into the "cQED" chamber, and are collected a few millimeters above the cavity in a second MOT, where they undergo another stage of polarization-gradient cooling. When the atoms are released a second time, some of them fall between the cavity mirrors and transit the standing-wave cavity mode. From Figure 1.2, we see that in the strong coupling regime, the transmission of a probe laser on resonance with the empty cavity will be suppressed in the presence of a single atom. These atom signals, first observed via heterodyne detection in 1996 [11], are known in lab parlance as "downgoers" due to their shape as a function of time; the width of each dip corresponds to the time it takes the falling atom to traverse the cavity mode (tens of μs). Conversely, a probe laser tuned to one of the vacuum-Rabi sidebands at $w_p = \pm g$ would be transmitted by the cavity only in the presence of an atom, and these signals are known as "upgoers."

In order to trap the falling atoms, a standing wave far-off-resonant trap (FORT) [10] provides a series of conservative potential wells along the cavity axis. As the atoms fall through the gap between the mirrors, they are cooled into the wells by a pair of lasers driving cesium transitions from the side of the cavity. After a brief interval, the suppression of a resonant probe laser is used to confirm the presence of a trapped atom.

A watershed in the development of cavity QED in our research group was the successful trapping of atoms initially for $\tau \sim 30$ ms in 1999 [12], followed by $\tau =$

2–3 s in the spring of 2003, where these extended lifetimes were enabled by a state-insensitive FORT at 935.6 nm [13]. In the next few years, single trapped atoms were then used to create a single-atom laser [14, 15], to generate a deterministic source of single photons [16], and to map out the vacuum Rabi splitting of a single atom [17]. Additionally, when multiple atoms were loaded into the FORT, it was possible to observe them leaving the trap one by one [18]. Meanwhile, the ability to drive coherent Raman transitions between cesium hyperfine ground states, based on ideas developed by then-graduate-student David Boozer, offered promising new prospects [19].

1.2 My history in the group

When I arrived at Caltech in June 2002, I joined Theresa Lynn, Kevin Birnbaum, and visiting graduate student Dominik Schrader in lab 1. At the time, the two Kimble group cavity-QED experiments were pursuing different strategies for trapping atoms within optical cavities. In lab 11, Joe Buck and Jason McKeever were cooling atoms into a FORT, struggling to improve the short trapping lifetimes demonstrated in 1999 [12]. Meanwhile in lab 1, Christina Hood and Theresa had demonstrated an "atom-cavity microscope" in which the atom's strong coupling to the cavity field provided a trapping force [20, 21]. Theresa and Kevin now hoped to build upon this result by applying active feedback to the intracavity field in order to control the atom's motion within the trap in real time.

Theresa and Kevin had begun a complete rebuild of the lab 1 experiment in 2000, after a series of failures in the previous system. They patiently taught me the fundamentals of experimental cavity QED as we constructed a new set of diode lasers and servos, coupled light into the new cavity, and characterized atom transits through the cavity mode. In order to control the atomic motion in real time, we planned to feed the detected signal at the cavity output into a field-programmable gate array (FPGA), which would then determine the strength of probe light at the cavity input. Unfortunately, numerical simulations carried out in parallel with our work in the lab indicated that we would be unlikely to observe significant improvements in the lifetime of the atom in the cavity under the action of feedback [22, 23]. Moreover, the experimental system itself presented unforeseen technical challenges. After Theresa's graduation in 2003, Kevin and I worked together on the feedback experiment through the fall of 2004, but at that point it was decided to cancel the project.

Instead, the lab 1 cavity and vacuum chamber would be rebuilt again with three specific aims: to design an asymmetric, "single-sided" cavity, i.e., with one mirror more transmissive than the other, in order to improve data collection and explore new quantum information schemes; to address problems of birefringent stress that had plagued all previous cavity-building efforts; and to improve the background pressure in the vacuum chamber in the hope of achieving longer atom storage times. As Kevin shifted his efforts in his final year to theory for the lab 11 experiment, I took charge of this new project, focusing in particular on designing and assembling a new vacuum chamber and obtaining new cavity mirrors. I supervised two Caltech undergraduates, Yat Shan Au and Travis Bannerman, as they worked on various aspects of this project during their junior and senior years; Cambridge SURF student Toby Burrows also joined us for the summer of 2005. New graduate students Andrey Rodionov and Dalziel Wilson arrived in lab 1 that summer, and Dal assumed responsibility for the lab the following year.

Meanwhile, during 2004 I also began my transition to lab 11, where Andreea Boca and Russell Miller had assumed responsibility for the experiment and David Boozer and Kevin were working on the corresponding theory. Following the work of Carmichael and Tian [24] and of Parkins et al. [25, 26, 27], Christina Hood had predicted a "photon blockade" effect due to the anharmonicity of the Jaynes-Cummings ladder [21], and guided by Kevin's numerical simulations, we set out to observe this effect in the lab 11 cavity [28, 4, 29]. Specifically, by probing on the lower vacuum-Rabi sideband, we were able to demonstrate that once a photon had entered the cavity, the atom-cavity system blocked the transmission of a second photon. Kevin realized that by measuring the second-order correlation function $g^2(\tau)$ along the "dark" axis of our cavity, that is, orthogonal to the axis of our probe beam, we could observe highly sub-Poissonian statistics and photon antibunching.

Kevin, Andreea, and Dave all graduated in the spring of 2005, and Andreea and Dave continued their work on the cavity QED experiment as postdocs. We turned to the question of cooling the center-of-mass motion of the intracavity atoms, which we hoped would both extend the trap storage times and allow us to access the quantum regime for the atom's external degrees of freedom. By introducing a new pair of Raman lasers at 945.6 nm, we were able to demonstrate resolved sideband cooling to the atom's vibrational ground state along the cavity axis [30]. This was also an important application of a new, efficient state-detection scheme, in which we could identify whether an atom was in the $F = 3$ or $F = 4$ hyperfine manifold.

Since the single photon generation experiment a few years earlier [16], we had been interested in the reverse process: mapping the information in a photonic state into the cavity, onto the hyperfine ground states of a trapped atom. After all, one advantage of using a cavity to generate single photons on demand was that the output photons were created in a well-defined optical mode, and thus were ideal carriers for quantum information in quantum networking schemes [2]. By using pulses of attenuated laser light to provide a phase-coherent input of photons, we were able to characterize the reversible nature of this process in our cavity — that is, the interplay between coherent and incoherent transfer mechanisms [31].

We have made a number of attempts over the past few years to prepare atoms in a particular Zeeman level via optical pumping, but these attempts have met with only limited success. In mid-2007, we implemented a new Raman-based optical pumping scheme, which has the advantage that we can prepare atoms in any desired Zeeman state [32]. After Andreea's departure that summer, Russ and I characterized the effectiveness of this method in the lab. We also implemented a new conditional loading process for our experiment, allowing us now to load multiple atoms into the cavity with every MOT drop, then heat the extra atoms out of the trap until only one remains. In principle, this will allow us in the future to carry out experiments with exactly one atom present, with possible extensions to higher atom number.

Most recently, we have been exploring the possibility for generating atom-photon entanglement, and specifically, entanglement between the atom's hyperfine ground state and the polarization of an output cavity photon. This project has included a series of Rabi flopping measurements aimed at characterizing the underlying mechanisms for decoherence in our experiment. We have also developed and demonstrated a technique for mapping superpositions of Zeeman states within a hyperfine manifold onto superpositions of states between hyperfine manifolds, with the goal of measuring atom entanglement directly through state detection.

1.3 Overview

Chapter 2 of this thesis focuses on our implementation of ground-state cooling. Our central result is the nearly complete suppression of the red vibrational sideband of a Raman spectrum after cooling; I also present more recent results from second-order sideband cooling at 936 nm. This chapter contains a summary of the current experimental setup in lab 11, including recent changes to the apparatus.

Chapter 3 presents the results of our reversible state transfer experiment as well as several technical developments necessary for its implementation.

In Chapter 4, we return to the topic of Raman transitions: first in the context of our new optical pumping scheme, which relies on incoherent Raman transitions, and then in a discussion of conditional loading, where Raman transitions allow us to determine the intracavity atom number in real time.

With these techniques for atom preparation in hand, in Chapter 5 I present our Rabi flopping and decoherence measurements, and the results of our effort to map Zeeman to hyperfine states. I discuss the outlook for entanglement generation and for the use of microwaves in our experiment.

In Chapters 6 and 7, I return to the work of my first three years in lab 1. I discuss technical insights gleaned from this experience and highlight what in hindsight seem to be useful lessons for those assembling new cavity QED experiments.