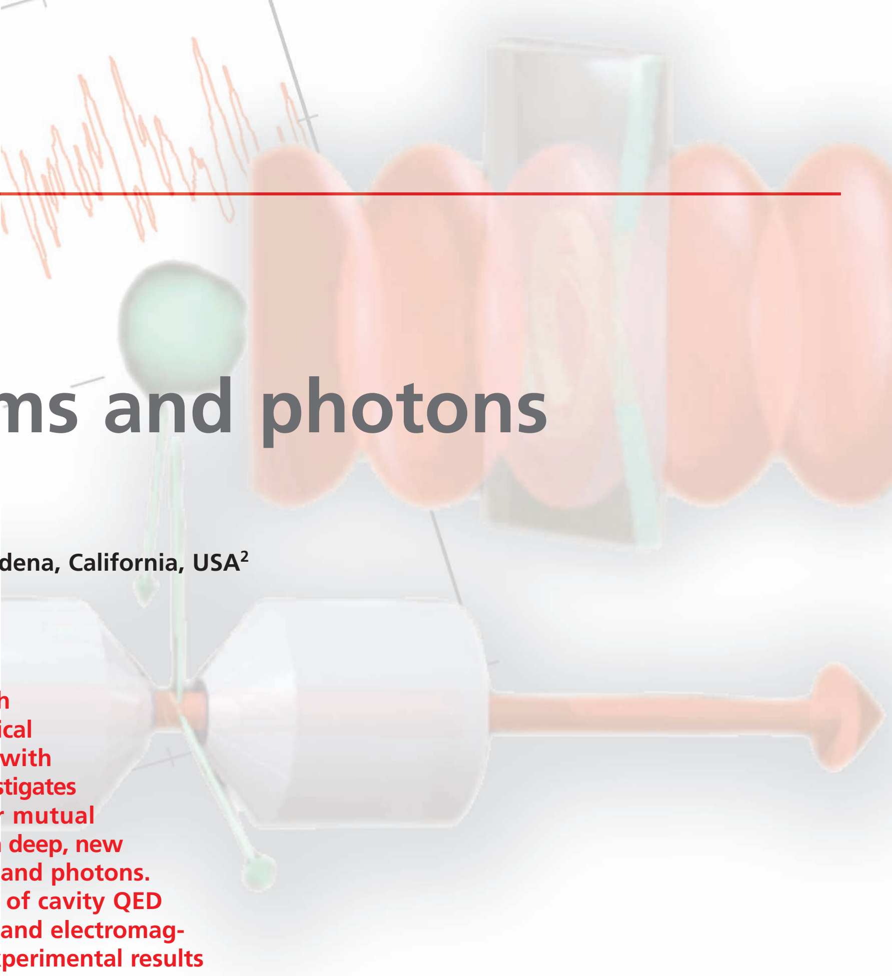

Optical physics with single atoms and photons

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In recent years, remarkable advances in laser-based techniques for cooling, confining, and coherently manipulating atoms have provided a rich set of tools for the investigation of quantum optical effects. The synthesis of these new techniques with cavity quantum electrodynamics (QED), which investigates atom-photon interactions as mediated by their mutual coupling to an electromagnetic resonator, has born deep, new insight into the interplay between single atoms and photons. This article offers an introduction to the science of cavity QED in the regime of strong coupling between atom and electromagnetic field. We also provide a survey of recent experimental results from our research group including the demonstration of a "one-atom laser" consisting of a single, driven atom bound to an optical cavity.

1 Introduction

1.1 Cavity QED fundamentals

The strength of the resonant interaction between an atom and a photon is governed by the size of the transition strength of the atom and the electric field associated with the photon (or, in other words, how "tightly packed" that single photon's energy is around the atom). It follows that the comparatively small electric field of a freely-propagating single photon only weakly affects the state of an atom located in a region of space through which the field passes. Cavity quantum electrodynamics seeks to enhance this interaction by establishing electromagnetic boundary conditions (a cavity) around the atom such that the electric field associated with the presence of just one photon within the cavity mode is sufficient to saturate completely the atomic response and, conversely, that the presence of a single atom within the cavity is able to alter appreciably the intracavity electric field.

A cavity can be used to achieve this feat by restricting a photon to exist within only a very small volume of space. This volume, known as the cavity mode volume V_m, in conjunction with the resonant frequency of the cavity ω_c and the intrinsic moment μ of the atom for electric dipole transitions, determines a frequency

$$g_0 = \sqrt{\frac{\mu^2 \omega_c}{2\hbar \varepsilon_0 V_m}}, \qquad \text{(Eq. 1)}$$

which characterizes the strength of the coupling between atom and field. In order to visualize the physical significance of this rate, consider a photon deposited into a coupled atom-cavity system (**figure 1**). If this single quantum of excitation is given no route by which to depart the system, it will coherently excite and de-excite the atom in a repeated manner, smoothly oscillating between atomic and photonic excitation at a rate $2g_0$. The atom and the field effectively become partners in a new, coupled quantum system which exhibits behavior quite distinct from its constituent parts.

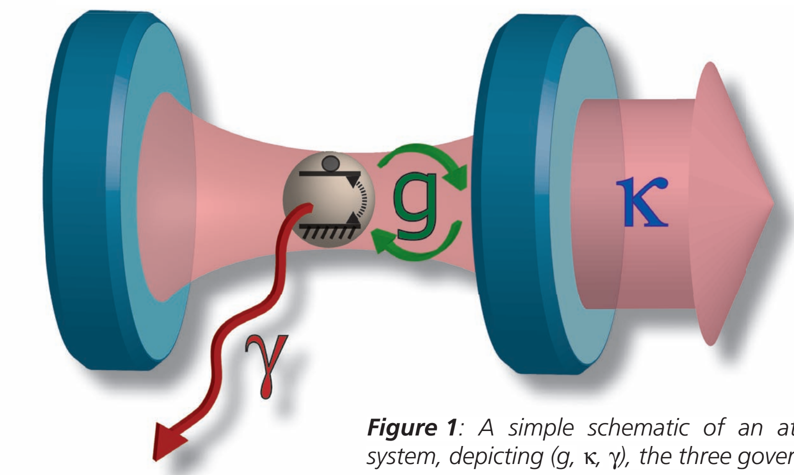

***Figure 1**: A simple schematic of an atom-cavity system, depicting (g, κ, γ), the three governing rates in cavity QED*

Of course, no real atom or cavity is completely free of channels through which excitation can escape. In fact, both exhibit incoherent decay from their respective excited states at characteristic rates γ, the atomic linewidth, and κ, the cavity linewidth. It follows that in order to study the interesting atom-photon interaction (at rate g_0), we require that this be the dominant rate in the system, or equivalently

$$g_0 \gg (\gamma, \kappa). \qquad \text{(Eq. 2)}$$

This is known as the *strong coupling crite-*

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[1] This topic was awarded the Berthold Leibinger Zukunftspreis 2006

[2] We dedicate this manuscript to Professor Herbert Walther, whose life and historic achievements provide a foundation for modern optical science and an enduring legacy for generations to come.

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rion for cavity QED. Under this condition, the coupled system is given ample time to exhibit coherent atom-photon dynamics before this coherence is lost to the environment.

1.2 Experimental realization

The discussion above is broadly applicable to an assortment of electromagnetic cavity geometries which can be coupled to a wide variety of atomic and atom-like quantum systems, with resonant frequencies ranging from the microwave to the optical regime [1, 2]. However, the remainder of this article will focus on our group's research on cavity QED in the optical domain, using ultra-high finesse Fabry-Perot resonators coupled to the D2 line of atomic cesium at $\lambda = 852{,}4$ nm [3].

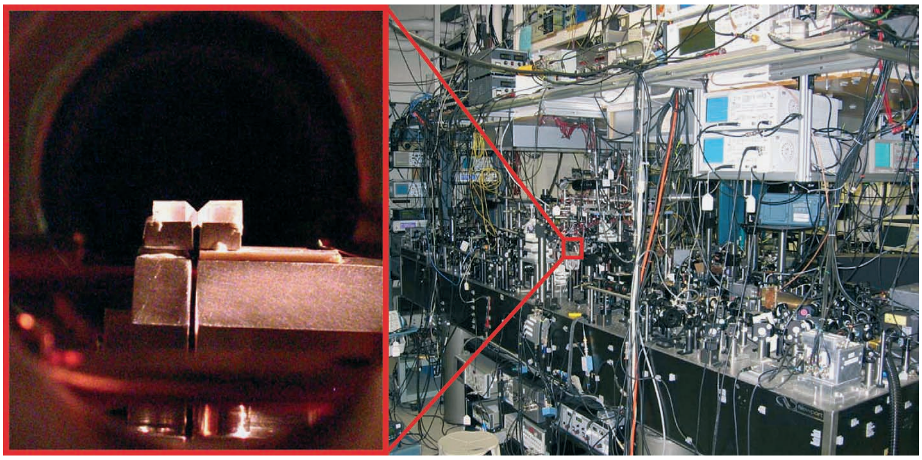

***Figure 2**: At the heart of the Caltech cavity QED laboratory is a high finnese Fabry-Perot resonator within an ultra-high vacuum chamber*

The cavity in our lab (**figure 2**) consists of two state-of-the-art superpolished spherical mirror substrates which have been custom coated with a highly reflective dielectric stack such that their total transmission, scattering and absorption losses add up to only 7 parts-per-million. These mirrors have a radius of curvature of 20 cm and are actively stabilized to a distance 42.2 µm apart, ensuring a small mode volume and thereby a large coupling constant, g_0. The relevant rate parameters for our atom-cavity system are

$$(g_0;\ \kappa;\ \gamma) = (34;\ 3.8;\ 2.6)\ \text{MHz}, \qquad \text{(Eq. 3)}$$

which is well within the regime of strong coupling.

This cavity sits atop a passive vibration isolation stack in an ultra-high vacuum chamber at a pressure of 10^{-8} Pa. Also within this chamber is a reservoir of atomic cesium which provides a small background vapor of atoms which can be trapped and optically cooled to a few microKelvin above absolute zero using standard laser cooling techniques [4]. The resulting cloud of cold atoms, located millimeters above the two cavity substrates, is released to fall under gravity such that, on average, just a few atoms pass within the narrow aperture between the mirrors and transit through the mode of the cavity.

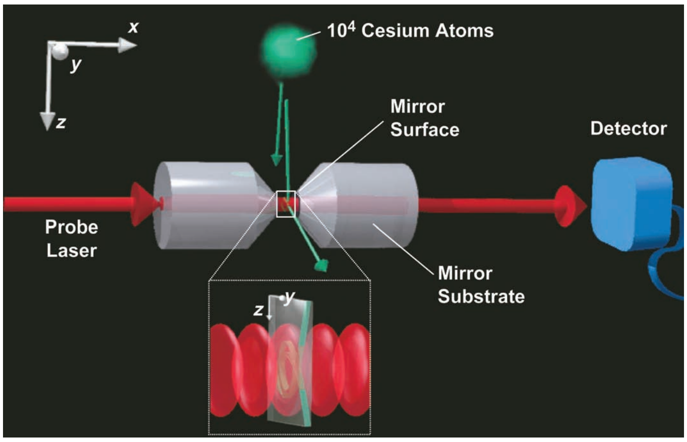

***Figure 3**: The atom-cavity microscope: A single cesium atom is bound in orbit by way of its interaction with one photon inside an optical cavity. As the atom moves within the cavity mode, it modulates the transmission of a weak probe laser. By detecting and recording the transmitted light, it is possible to reconstruct the trajectory of the atom*

2 The atom-cavity microscope

An important consideration when studying the quantum dynamics of these atoms as they interact with the cavity is that the kinetic energy, E_K, associated with their motion as they fall can be, on average, comparable to the maximum energy associated with the atom-cavity coupling, $\hbar g_0$. As a consequence, the presence of a single intracavity photon can significantly affect the center-of-mass motion of a strongly coupled atom. In fact, under certain conditions where $\hbar g_0 > E_K$ and the length of the cavity is very slightly shifted from resonance with the bare atomic transition, the force exerted on the atom by just a single intracavity photon can be sufficient to keep the atom trapped within the cavity for an experimentally significant period of time. This effect was observed by our group in 2001 (**figure 3**) with single-atom trap lifetimes approaching T = 0.5 ms [5]. An atom that is trapped via its interaction with the intracavity field moves dynamically through the Gaussian mode of the cavity. As the strength of the field varies spatially with the mode shape, so too does the effective rate of coupling between atom and cavity $g(\mathbf{r}) = g_0 U(\mathbf{r})$, where g_0 is the maximal atom-cavity coupling from equation 1 and $U(\mathbf{r})$ is a dimensionless function which describes the shape of the cavity mode.

These variations in atom-cavity coupling modulate the intracavity field as the atom's position changes. This modulation can be detected on the light collected from the output of the cavity into free space and from this signal it is possible to reconstruct the trajectory of the atom as it orbits within the cavity (**figure 4**), where the atom is "bound" to the cavity by way of single photons.

This "atom-cavity microscope" offers an appealing first step towards the ability to observe and control atomic motion within a cavity QED setting. However, it is also limited in that it relies upon QED atom-photon interaction effects, thereby precluding the ability to study independently the state of a trapped atom.

3 The single atom laser

3.1 Far off-resonance trapping

In order to decouple the trapping mechanism from the cavity QED interaction, in 1999 our group demonstrated a "far off-resonance trap" (FORT) for atomic confinement within the cavity [6]. The FORT is an all-optical trap, generated by driving another TEM_{00} mode of the cavity which is a few free spectral ranges (i.e. frequency spacings of the axial cavity modes, as in figure 3) away from the cavity QED wavelength. The wavelength of this trap is carefully chosen to only minimally perturb the

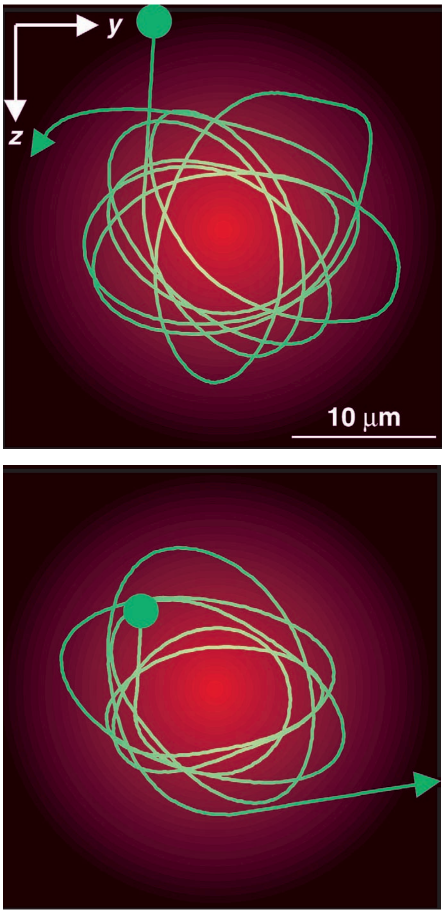

***Figure 4**: Two trajectories, reconstructed using the atom-cavity microscope technique, show the paths of individual cesium atoms (animations available at www.its.caltech.edu/~qoptics/atomorbits)*

internal structure of the atom [7]. Using this technique, we have observed atomic confinement which lasts, on average, for T = 3 s (which is a factor of 10^8 longer than the relevant time scale for atom-photon interactions, g_0^{-1}).

3.2 A one-atom laser

This system – a single atom bound and coupled to an optical cavity – can be viewed in analogy with a conventional laser where the gain medium has been reduced to its conceptual limit: one quantum emitter. However, whereas conventional (semiclassical[3]) lasers operate in the regime of weak coupling (the addition or subtraction of one emitter or of one quantum of excitation will not appreciably impact the dynamics of the overall system), this "one-and-the-same" atom laser operates in the regime of strong coupling.

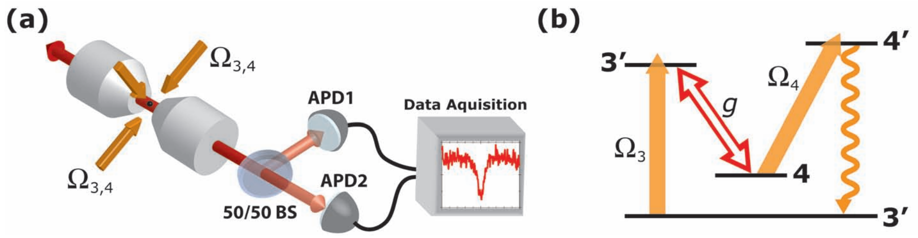

***Figure 5**: (a) Schematic of the one-atom laser. (b) Pumping and level diagram for the one-atom laser. Shown are the cesium $6S_{1/2}$,F=3,4 hyperfine ground states as well as the $6P_{3/2}$,F'=3',4' hyperfine excited states. Classical laser fields Ω_3 und Ω_4 pump the one-atom laser, while the cavity collects and stores emission near the F' = 3' → F = 4 transition*

Therefore, a quantum mechanical model is required to describe its behavior. By driving the atom with two classical laser fields, resonant with the $6S_{1/2}$ to $6P_{3/2}$ optical transition in cesium (**figure 5**) and tightly focused through the aperture between the mirror substrates, our group was able to experimentally demonstrate the operation of this type of one-atom laser [8].

An important feature of this system, in contrast with semiclassical laser sources, is that it exhibits no lasing threshold. As the intensity of the pumping light is gradually increased from zero, emission into the free space output mode of the cavity immediately "turns on", as recorded by two single photon-counting avalanche photodiodes. Moreover, as the intensity of the pumping light continues to increase, emission from the cavity begins to saturate and is eventually "clamped" as a consequence of the single atom-character of the system.

Another signature of the one-atom laser is that the photon statistics of the light emitted from the cavity are decidedly non-classical (as opposed to the coherent state of light emitted from conventional laser sources). The quantum-statistical characteristics of our source are captured in the second order intensity correlation function $g^{(2)}(\tau)$, with our measurements shown in **figure 6**. This function is proportional to the probability that, conditioned on the detection of a photon at time $t_1 = 0$, a second photon was detected at a time $t_2 = \tau$, which can be before or after t_1. Coherent states of light exhibit Poissonian counting statistics which means that the detection of any photon is uncorrelated with the detection of any other and, therefore, that $g^{(2)}(\tau) = 1$ for all times τ (thus also for two or more photons at the same time, where $\tau = 0$).

On the contrary, the correlation function associated with the state of light emitted from the one-atom laser exhibits a sharp dip to « 1, centered at $\tau = 0$. This dip, which represents sub-Poissonian photon statistics and photon antibunching, is a signature of the manifestly quantum character of the system and implies that the stream of photons emitted from the cavity arrives at the detectors in an orderly fashion, one photon at a time. In fact, it is exceedingly rare (occurring much less often than would be observed with emission from a conventional laser) for two photons to be emitted within the same counting interval.

These non-classical properties of this source, as measured in our laboratory, are in good agreement with a detailed theoretical model based on a full analysis of the quantum dynamics of the system [9]. On a practical level, the demonstration of a one-atom laser in the regime of strong coupling is both an intellectually satisfying exploration of the extension of semiclassical laser operation into the manifestly quantum realm as well as an experimentally significant advance which offers a useful, stationary source of non-classical light in the form of a collimated, Gaussian beam.

4 Deterministic single photon generation

By adding an extra layer of control to the experiment – specifically, by repeated alternation of the two classical driving fields in figure 5 – we have also demonstrated that it is possible to operate the one-atom laser in a pulsed regime, reliably and deterministically depositing one photon into the cavity mode with each alternation [10]. The single photon pulses emitted from the cavity have a well-defined, user-controlled temporal shape determined by the shape of the classical pulse used to generate them. Because strong coupling highly favors exchange of excitation between atom and cavity as opposed to decay into free space, the process takes place with near unit efficiency and, as a result of the long trap lifetimes provided by the FORT, an average of 14 000 individual photons can be generated from each atom. Photon statistics show that the emitted light suffers from very little contamination by two or more photons – indeed, the presence of one-and-only-one atom in the cavity

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[3] Most lasers can be described by a semiclassical theory – part quantum mechanics, part classical electromagnetic theory. The "one atom laser" is not semiclassical, but entirely quantum mechanical.

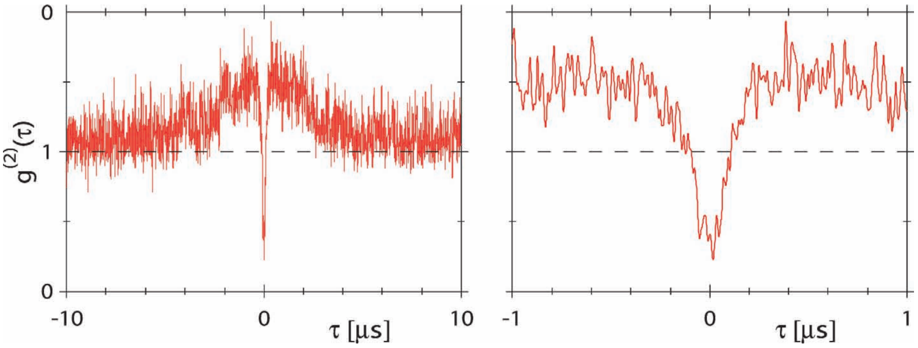

***Figure 6**: The second-order intensity correlation function $g^{(2)}(\tau)$ for emission from the one-atom laser over (a) 20 µs and (b) 2 µs timescales. The behavior of this function near $\tau = 0$ is evidence of manifestly quantum photon statistics*

ensures the repeated emission of exactly one photon with over a 150-fold suppression of the probability to emit two or more photons as compared to pulses of conventional coherent state light.

Single photon sources of this type have a variety of applications, particularly in the burgeoning fields of quantum communications, cryptography and computation [11, 12]. Although still being quite far away from industrially feasible implementations, our research is motivated in part by such applications. For example, a variety of proposals have been made for the use of strongly coupled atom-cavity systems as functional nodes in a quantum network, following the original analysis in [13].

5 Conclusion and outlook

Towards the goal of exploring cavity QED in the context of quantum information, our group has been working to refine control over the quantum degrees of freedom in our system. For example, we have recently verified the reversibility of the single photon generation process described above. It was shown that it is possible to transfer delicate, quantum superposition field states[4] onto the internal states of an atom in the cavity, subsequently store the superposition in the atom for ~250 ns and then transfer the state back onto the intracavity field [14].

This type of process, as well as techniques which we have developed to exercise control over the quantum state of the atom's center-of-mass motion [15] and the internal quantum state of the atom, constitute a growing set of tools which we expect will continue to shine new insight on atom-photon interactions at the most fundamental level.

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[4] The electromagnetic field can be in the quantum mechanical state of, e.g., one photon, two photons, three photons, etc.. However, it is also possible for the field to be in a "superposition" of, for instance, both one and two photons simultaneously, until you "collapse" the superposition into just one or two photons through a measurement. Quantum computers rely on this idea – a quantum bit can be both "on" and "off" at the same time until you measure it.

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