Enhanced spontaneous emission into the mode of a cavity QED system

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We study the light generated by spontaneous emission into a mode of a cavity QED system under weak excitation of the orthogonally polarized mode. Operating in the intermediate regime of cavity QED with comparable coherent and decoherent coupling constants, we find an enhancement of the emission into the undriven cavity mode by more than a factor of 18.5 over that expected by the solid angle subtended by the mode. A model that incorporates three atomic levels and two polarization modes quantitatively explains the observations. © 2007 Optical Society of America

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Cavity QED has been identified as an environment to transfer information and entanglement between matter and light qubits.[1,2] Information inside the system must exit through one of the two available channels: cavity decay, at a rate κ, or spontaneous emission, at a rate γ_{tot}. These decay mechanisms allow for the creation of quantum interconnects and information protocols, since they enable information flow into and out of the quantum system. Spontaneous emission has then a dual role in cavity QED; it is a source of decoherence, but it is also a useful way to extract information out of the system. The detection of a spontaneously emitted photon in cavity QED is an unambiguous probe of the state of the atomic part of the atom–cavity system.

Work in the past has focused on the bad cavity limit where the enhancement and suppression of spontaneous emission is easy to identify (see, for example, the article by Hinds in Ref. 3). Other studies of spontaneous emission in cavity QED include geometries that allow observation of the atoms from the side[4] and studies of the atomic fluorescence into the mode of the cavity with the atoms driven by a laser that propagates perpendicular to the cavity axis.[5,6] This Letter presents our investigations of light generated by a spontaneous emission process into a mode of a driven optical cavity in a system in the intermediate coupling regime of cavity QED, where the dipole coupling between a single atom and the mode of the cavity, g, is comparable with the dissipation rates κ and γ_{tot}.

It is difficult to identify the origin of light exiting the mode of the cavity in the intermediate regime of cavity QED. The light can come from the drive, spontaneous emission, or stimulated emission. We follow Birnbaum *et al.*[7] by using the polarization of the cavity-emitted photon to gain information on the origin of the photon and the state of the atomic system. Our cavity QED system consists of a high-finesse optical resonator where one or a few atoms interact with two degenerate TEM_{00} cavity modes with orthogonal linear polarizations. We use the internal structure of the atoms to inform us when a photon originates in a fluorescence event. Instead of utilizing ^{85}Rb atoms in their stretched states ($m_F=F$ with $\Delta m=1$) to form a closed two-level system when driven with circularly polarized light, we prepare the atoms into the $m_F=0$ ground state and drive the optical transition with π polarization ($\Delta m=0$). Next, we look at the light emitted out of the cavity, separating it into the two linear polarizations, one parallel to and the other orthogonal to the drive (see Fig. 1 for a schematic of the apparatus). The presence of any light of orthogonal polarization signals that it comes originally from a spontaneous emission event of an atom that decays, emitting circularly polarized light with $\Delta m=\pm 1$.

A model for the atoms that captures the essential physics of the system needs to consider more than two atomic levels as sketched in the inset of Fig. 1. The modes of the cavity couple to a single atom with coupling constants g and G that depend on the electric dipole moment of the transition, with $G=g/\eta$. The factor (η) takes into account the Clebsh–Gordon coefficients of the electric dipole moment that joins

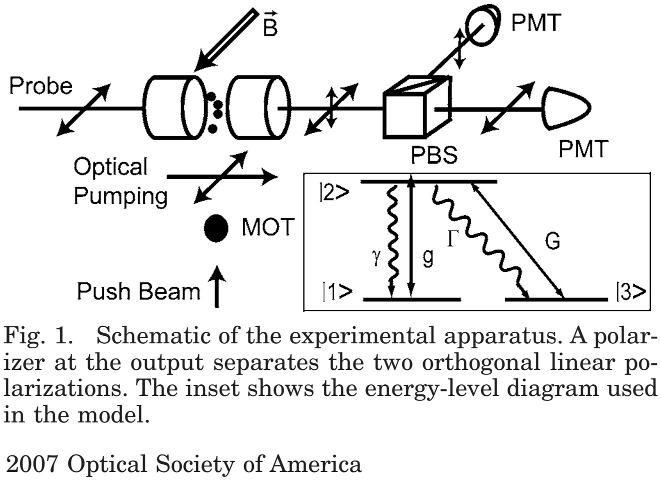

Fig. 1. Schematic of the experimental apparatus. A polarizer at the output separates the two orthogonal linear polarizations. The inset shows the energy-level diagram used in the model.

the two levels, as well as any other factors that affect the coupling. The inset shows the relevant energy-level diagram. The respective decay rates, γ and Γ, are also related by $\Gamma = \gamma/\eta$. The system is driven weakly on-axis by a classically horizontally polarized field ϵ/κ normalized to photon flux units.

We consider N three-level atoms fixed with degenerate ground states maximally coupled to a two-mode cavity with orthogonal linear polarizations. The effective Hamiltonian for the between-jump evolution in quantum trajectory theory[8] is

$$\begin{aligned} H = {} & \frac{\epsilon}{\kappa}(a - a^\dagger) + i\hbar g\left(a\sum_{i=1}^{N}|2\rangle_i\langle 1| - a^\dagger\sum_{i=1}^{N}|1\rangle_i\langle 2|\right) \\ & + i\hbar G\left(c\sum_{i=1}^{N}|2\rangle_i\langle 3| - c^\dagger\sum_{i=1}^{N}|3\rangle_i\langle 2|\right) - i\hbar\,\kappa(a^\dagger a + b^\dagger b) \\ & - i\hbar\,\frac{\gamma+\Gamma}{2}\sum_{i=1}^{N}|2\rangle_i\langle 2|, \end{aligned} \tag{1}$$

where a is the annihilation operator for the driven horizontally polarized cavity mode, b is the annihilation operator for the vertically polarized cavity mode, and $c = (a + ib)/\sqrt{2}$.

The state of the system to first order in ϵ/κ is

$$\begin{aligned} |\Psi\rangle = {} & |0000\rangle + c_{0010}|0010\rangle + c_{1000}|1000\rangle + c_{0100}|0100\rangle \\ & + c_{1001}|1001\rangle + c_{0101}|0101\rangle; \end{aligned} \tag{2}$$

the labels in the probability amplitudes, $|n_a, n_b, n_2, n_3\rangle$, denote the photon number for the a mode, b mode, number of atoms in $|2\rangle$, and number of atoms in $|3\rangle$, respectively; and with the number of atoms in $|1\rangle$, $n_1 = N - n_2 - n_3$. The atomic portion of the state is a collective state referring to N atoms that are symmetric with respect to the exchange of any pair of atoms.

We find the equations of motion for the coefficients using the Hamiltonian and solve them in steady state starting with N atoms in $|1\rangle$. The driven mode transmission is proportional to the steady-state solution of $|c_{1000}|^2_{ss}$, while the undriven mode transmission is proportional to $|c_{0101}|^2_{ss}$.

We use two dimensionless numbers to characterize the influence of an atom in the system: $C_1 = g^2/\kappa(\gamma + \Gamma)$, and $\tilde{C} = G^2/\kappa((\gamma+\Gamma))$. The transmitted intensities normalized to the empty cavity intensity of the driven mode are

$$T_d = \frac{1}{(1 + 2C_1N/(1 + 2\tilde{C}_1))^2}, \tag{3}$$

$$T_u = \left(\frac{2\tilde{C}_1}{1 + 2\tilde{C}_1}\right)\left(\frac{C_1N/(1 + 2\tilde{C}_1)}{(1 + 2C_1N/(1 + 2\tilde{C}_1))^2}\right). \tag{4}$$

The first factor in Eq. (4) is the ratio of enhanced spontaneous emission to the orthogonal mode to the total spontaneous emission, also known as the beta factor in laser theory.[9,10] The second factor is the probability of having an atom in the excited state under low excitation. The dependence on N in the theory, which assumes very weak excitation, shows that the absorption of a photon from the driven mode takes the system into a collective state with one excited atom among N. When the photon is emitted into the undriven mode, the transition is not collective and does not grow with $\sqrt{N}$. The individual atoms do not return to the same original state where they started.

The apparatus (see Fig. 1) consists of two main components: the source of atoms and the cavity. A titanium:sapphire laser (Ti:Sapph) provides most of the light needed for the experiment at 780 nm. The laser frequency is locked using a Pound–Drever–Hall (PDH) technique on saturation spectroscopy of ^{85}Rb.

A rubidium dispenser delivers Rb vapor to a magneto-optical trap (MOT) in a glass cell 20 cm below a cubic chamber that houses the cavity. The glass cell has a silane coating to decrease the sticking of Rb to the walls and to maximize the capture efficiency of the MOT.[11] Each of the six 30 mW beams of the MOT has a $1/e$ (power) diameter of 20 mm. A second laser repumps the atoms that fall out of the cycling transition in the trap. A pair of anti-Helmholtz coils generates a magnetic field gradient of 6 G/cm, and three sets of independent coils zero the magnetic field at the trapping region.

The cavity defines a TEM$_{00}$ mode with two 7 mm diameter mirrors with different transmission coefficients. The input transmission [15 parts in 10^6 (ppm)] is smaller than the output (250 ppm) to ensure that most of the signal escapes from the cavity on the detector side. The separation between the mirrors is 2.2 mm, so the coupling coefficient between the driven mode and the π dipole transition of Rb is $g/2\pi = 1.5$ MHz. The finesse of the cavity is $\mathcal{F} \approx 11{,}000$ with $\kappa/2\pi = 3.2$ MHz. The mirrors are glued directly to flat piezoelectric transducers for controlling the length of the cavity. Our experimental system is in the intermediate regime of cavity QED, where $g \approx (\kappa, \gamma_{\mathrm{tot}}/2)$ with $(g, \kappa, \gamma_{\mathrm{tot}}/2)/2\pi = (1.5, 3.2, 3.0)$ MHz, $\gamma_{\mathrm{tot}} = \gamma + \Gamma$, giving $C_1 = 0.12$. The Clebsch–Gordon coefficients for the ($F = 3$, $m_F = 0 \rightarrow F' = 4$, $m_F = 0 \pm 1$) give an optimal value for $\eta = \sqrt{8/3}$. The value would be larger if some of the emitting atoms were not maximally coupled.

We stabilize the cavity length with a PDH technique using a 820 nm laser. The frequency of this laser is locked to the stabilized 780 nm laser by using a transfer cavity. We separate the two wavelengths at the output of the physics cavity with a grating and use appropriate interference filters to further ensure the separation of the two colors. We launch the atoms from the MOT toward the cavity with a pulsed near-resonant push beam from below and prepare them with an optical pumping beam. The cavity drive is resonant with the D_2 line between ($F = 3$, $m_F = 0 \rightarrow F' = 4$, $m_F = 0$) states. The repetition rate sets the number of atoms delivered to the cavity as more or less atoms accumulate in the MOT during the waiting period. We take data by recording the transmitted light in the two orthogonal linear polarizations for resonant excitation. There is a slight nondegeneracy of the two orthogonal modes of less than 0.5 MHz (smaller than the full width at half-maximum of the transmission). The birefringence of the cavity is less than 1×10^{-4} on its axis.

The geometry allows only π excitations ($\Delta m=0$) and no Faraday rotation of the light as the incoming polarization is aligned with an external uniform magnetic field. The observed light at the orthogonal polarization must come from spontaneous emission. This light is emitted into the well-defined spatial mode of the cavity, facilitating its detection. The weak input field drive (ϵ/κ) is polarized horizontally to better than 1×10^{-5} and aligned to the magnetic field to better than ±4°. The output of the cavity is split into two orthogonal polarization beams with a Glan laser polarizer. Small changes in the magnetic field alignment or in the optical pumping of the atoms do not make qualitative changes in the results and only minor quantitative ones.

As each launch of atoms (every 150 ms) traverses the cavity, we record the transmission of both polarizations (horizontal and vertical) in a digital storage scope to average over 20 launches of atoms. The individual atoms take about 10 μs to traverse the mode of the cavity. The batch of atoms crosses the cavity mode in about 500 μs. The temperature of the atoms is less than 0.5 mK.

We parameterize the change in the transmission using the cooperativity $C=C_1N/(1+2\tilde{C}_1)$ of the driven mode. We extract C using the change in the normalized transmission of the driven cavity mode [Eq. (3)]. The normalized transmission of the driven mode, T_d (horizontal polarization), decreases monotonically as the number of atoms passing through increases. The undriven mode (vertical polarization) shows a maximum on the transmission, T_u, as the number of atoms increases (see Fig. 2). We extract a value of $\tilde{C}_1=0.026\pm0.005$ with the only adjustable parameter in the model $\eta=2.1\pm0.4$. This value is consistent with the expected value. The maximum of the transmission in the undriven mode happens at the point where the atomic inversion is highest for a given drive: $C=0.5$. This value of the cooperativity also coincides with the point where the driven mode starts to show vacuum Rabi splitting as a function of N.

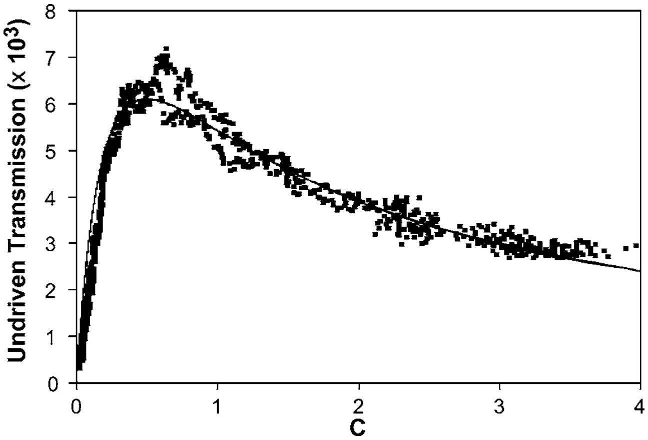

Fig. 2. Variation of the cavity transmission of the undriven mode (vertical polarization) as a function of cooperatively C. The continuous line is the prediction from the model. The vertical scale is normalized to the empty cavity transmission ($C=0$) of the driven mode. The range of the number of atoms is $0\leqslant N\leqslant36$.

The emitted light in the vertical mode comes from an atom in the excited state. Its decay is through the coupling into the undriven mode, and it shows enhanced spontaneous emission mediated by G [Eq. (4)]. The ratio between the undriven and driven transmission, T_u/T_d, at the peak of the former ($C\approx0.5$ in Fig. 2) is 0.024 ± 0.004, where the uncertainty includes the statistical error. The fraction subtended by the mode of the cavity at the mirrors is 1.3×10^{-3}, which would be the fractional transmission, T_u/T_d, in the absence of enhancement. Since we see a larger amount, 0.024, we take the ratio of these two numbers as the enhanced spontaneous emission into the undriven mode, 18.5±3, in agreement with the model.

The labeling of the photons by polarization permits us to identify an emission out of the cavity generated by an excited atom spontaneous decay. The dependence of the light on the number of atoms shows a maximum when the available weak drive maximizes the atomic inversion. The specific quantum dynamics of the photon with orthogonal polarization remain to be explored, but the intrinsic relation between the state of the atom and the atomic polarization should allow exploration of atom–photon correlations in cavity QED.[2]

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