Observation of dynamic suppression of spontaneous emission in a strongly driven cavity

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We report a Rydberg-atom experiment, demonstrating the dynamic suppression of spontaneous emission in a resonant microwave cavity driven by a resonant external field. If the Rabi frequency of the injected field is larger than the atomic and cavity line widths, the atoms almost completely decouple from the cavity mode due to suppressed field fluctuations at the sideband frequencies of the Mollow triplet. This was achieved with about 100 microwave photons in the cavity. The reduced decay rate is a consequence of non-Markovian dynamics induced by the finite cavity-response time.

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Enhancement [1,2] or suppression [2–5] of spontaneous emission of an atom inside a cavity is one of the phenomena primarily studied in cavity quantum electrodynamics. As Purcell predicted almost 50 years ago [6], this modification of the radiation properties of the atom results from a change in the mode density distribution of the vacuum field inside a cavity as compared with free space.

In addition to these static phenomena, dynamic effects have recently been investigated; an example is linewidth narrowing in the normal modes of a strongly coupled atom-cavity system: in the case of a cavity width much smaller than the spontaneous emission rate, Thompson, Rempe, and Kimble [7] have observed that the oscillatory exchange of energy between atom and cavity field leads to a decay rate of half of that in free space. An efficient mechanism for dynamic suppression of spontaneous emission has been predicted for atoms in a cavity when a strong resonant driving field is present [8]. However, direct observation of this effect for optical transitions is difficult owing to the decay of the atom into sidemodes. A related phenomenon, vacuum-field dressed-state pumping, was reported some time ago [9].

In this paper we give experimental evidence of dynamic suppression of spontaneous emission in a strongly driven cavity. The studies were conducted using microwave transitions between neighboring states of Rydberg atoms. The atoms are placed in a closed superconducting low-order microwave cavity. Therefore, unlike in the case of an optical resonator, the only decay channel available for the atoms is into one cavity mode. We report nearly complete suppression of both spontaneous emission and thermally induced transitions of the atoms if an external resonant field is injected into the cavity. In order to observe this effect, the Rabi frequency has to be larger than the atomic and cavity linewidths. A detailed theoretical analysis of the phenomenon is given in Ref. [10].

Our experimental setup is in principle similar to that used in the micromaser experiment (see, for example, Ref. [11]). The quality factor of the cavity is, however, much smaller. The scheme is shown in Fig. 1. A collimated beam of rubidium atoms is excited to the $53\,^2P_{3/2}$ state of ^{85}Rb by means of three-step diode laser excitation with wavelengths 780.2 nm, 776.0 nm, and 1258.8 nm, respectively. The lasers for the two lower steps are stabilized to the atomic fluorescence signal, while the last step is locked by monitoring the Rydberg atom count rate. The atomic beam has a thermal velocity distribution, the most probable time of flight through the cavity being $T = 67\ \mu$s. Due to the long lifetime of Rydberg levels, the linewidth of the atomic transition is determined by transit time broadening.

After being excited to the $53\,^2P_{3/2}$ state, the atoms traverse a superconducting cylindrical cavity along its axis. The length L of the cavity is 25.3 mm and its diameter D is 20.6 mm. The cavity is operated in the TM_{020} mode at a frequency $\omega_c = 2\pi \times 25.5903$ GHz. This is equal to the resonance frequency ω_0 of the transition between the levels $53\,^2P_{3/2}$ and $53\,^2S_{1/2}$ used in our experiment.

We chose the TM_{020} mode because it provides a constant amplitude of the electric field along the axis of the cavity. In this way we avoid effects relating to position-dependent atom-field coupling. At the entrance and exit holes, power leakage leads to a gradual turn on and turn off of the field amplitude in the rest frame of the atoms. The rise time is about 5 μs. The cavity field is linearly polarized with the electric field vector parallel to the di-

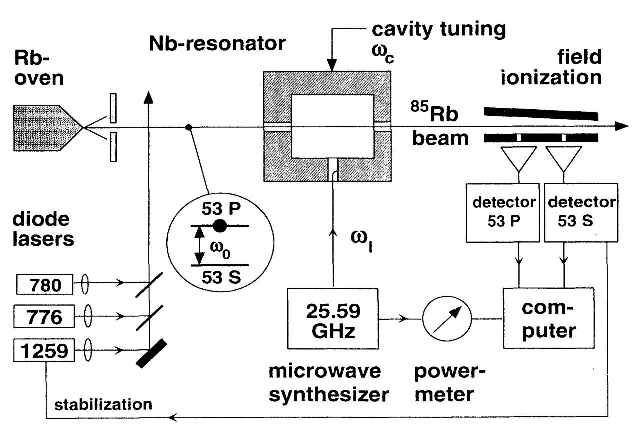

FIG. 1. Scheme of the experimental setup. The three diode-laser wavelengths (in nm) are indicated.

rection of the atomic beam. In order to reduce the number of populated substates, the three diode lasers were polarized in the same direction.

The cavity is made of niobium, which is a superconductor below 9.2 K. It was cooled to a temperature of 4.2 K in a ^{4}He cryostat. A loaded quality factor Q_L of 1.9×10^6 was measured. This corresponds to a cavity decay rate $\kappa = 2\pi \times 6.7$ kHz.

The cavity is driven by an external microwave source coupled through a hole in the sidewall, equidistant from the two end caps. There is a second hole in the opposite side, which is used to determine the resonance frequency and the Q factor of the cavity in transmission.

The microwave source is a 26 GHz synthesizer with a linewidth below 1 kHz. The number of photons n_0 in the cavity mode for a resonant driving field can be determined from the injected power P_I, the transmitted power P_T, and the loaded quality factor Q_L of the cavity:

$$n_0 = \frac{2\sqrt{P_T P_I} Q_L}{\hbar \omega_c^2}. \tag{1}$$

We estimate the uncertainty of n_0 to be 10% due to errors in the measurement of the microwave power. For a detuned driving field of frequency ω_l, the number of photons inside the cavity varies according to a Lorentzian:

$$n = \frac{n_0}{1 + (\omega_c - \omega_l)^2/\kappa^2}. \tag{2}$$

Information on the atom-field interaction is obtained via the level occupation of the atoms leaving the cavity. The Rydberg atoms are detected state selectively by field ionization using two secondary electron multipliers (channeltrons). The detector efficiency η is about 10% [11].

The atom-field coupling constant for the transition $53\,^2P_{3/2}, m = \pm\frac{1}{2} \to 53\,^2S_{1/2}, m = \pm\frac{1}{2}$ was calculated to be $g = 2\pi \times 17$ kHz. Hence the resonant Rabi frequency is $\Omega = 2g\sqrt{n}$. There is strong inhomogeneous broadening of the atomic line due to Stark shifts caused by electric stray fields from rubidium atoms deposited on the inner surface of the cavity. We observe an inhomogeneous line width $\gamma_i \approx 35\kappa$.

Our experimental regime is described by the following relations between the different rates involved:

$$g \gtrsim \kappa > T^{-1}. \tag{3}$$

We start our discussion with the case of a resonant cavity where no external microwave field is applied. Due to the large inhomogeneous broadening of the transition, the maser threshold cannot be reached for our system. Under these circumstances we expect enhanced spontaneous emission [1]. In the microwave regime, transitions induced by blackbody radiation have to be taken into account, too, because of the large number $\bar{n} = 2.9$ of thermal photons in the cavity mode at a temperature of 4.2 K. The blackbody induced transition rate adds to the spontaneous rate. At resonance, the overall enhanced decay rate is given by [10]

$$\Gamma_0 = \frac{2g^2}{\kappa + \gamma_i}(1 + 2\bar{n}) \approx 2\pi \times 16 \text{ kHz}. \tag{4}$$

Since Γ_0^{-1} is small compared with the time of flight T, the atoms leave the cavity in thermal equilibrium. This is demonstrated by the field ionization spectrum in Fig. 2(a). There are peaks in the Rydberg count rate at two values of the ionizing field, corresponding to atoms in the initially occupied $53P$ level and the lower $53S$ level, respectively.

We now apply a strong external microwave field resonant with the atoms and cavity. The field ionization spectrum obtained in this case is displayed in Fig. 2(b). The striking result is a 90% reduction of the lower Rydberg-level ($53S$) count rate, even though the intensity of the resonant cavity field far exceeds the saturation threshold of the $53P \to 53S$ transition. The observed suppression of atomic decay due to the dynamics induced by a strong driving field has first been predicted in Ref. [8].

To determine the minimum number of cavity photons necessary to achieve suppressed emission, we varied the intensity of the external microwave source, keeping its frequency at resonance with atoms and cavity. The result is shown in Fig. 3. At -100 dBm we still observe the full spontaneous and thermal decay rate. Strong suppression sets in at a power level of -73 dBm, which corresponds to only about 100 microwave photons in the cavity. The fact that such a small number of photons can lead to

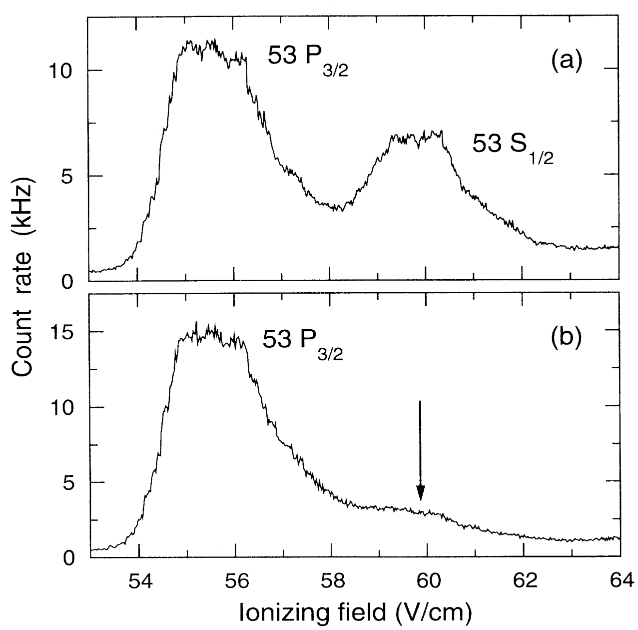

FIG. 2. (a) Field ionization spectrum without external microwave field. Atoms that leave the cavity in the $53\,^2P_{3/2}$ state are ionized in a field of 56 V/cm; atoms in the $53\,^2S_{1/2}$ state are ionized at 60 V/cm. The $53\,^2S_{1/2}$ state is populated by spontaneous transitions and transitions induced by the thermal field in the cavity. (b) Field ionization spectrum with a strong external driving field. The $53\,^2S_{1/2}$ signal (arrow) has almost completely disappeared, indicating the suppression of spontaneous and thermally induced transitions. In both cases the cavity is resonant with the atomic transition. The atomic beam density corresponds to an average number of nine atoms inside the cavity.

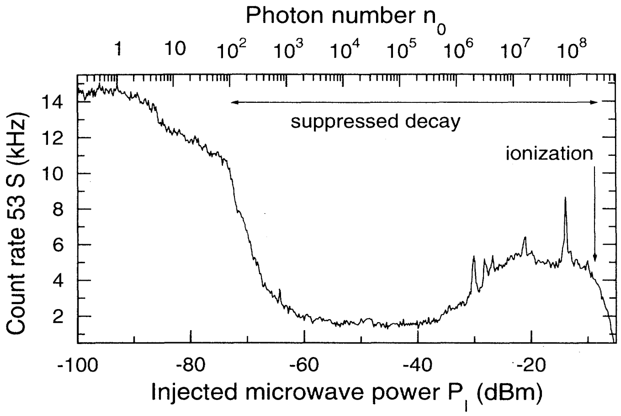

FIG. 3. Count rate in the lower Rydberg level (53S) as a function of the intensity of the external microwave field. Both cavity frequency ω_c and microwave frequency ω_l are resonant with the atomic transition frequency ω_0.

drastic changes in the system behavior is a consequence of the strong coupling of Rydberg atoms to the electromagnetic field. At -30 dBm the lower level occupation rises again to about 30% of its value at zero external field. In addition, at certain intensities pronounced peaks are observed. Finally, at -10 dBm the intracavity field is strong enough to ionize the atoms.

There is a simple physical interpretation of the observed suppression of decay in terms of the dressed atom picture. First, we have to explain the surprising fact that the strong resonant field itself does not induce any transitions. This can be understood by noting that the atoms enter and leave the cavity field adiabatically, if the detuning $\Delta = \omega_0 - \omega_l$ of the driving field is larger than the inverse rise time of the field in the rest frame of the atoms [12]. Due to the relatively large inhomogeneous broadening, this condition holds for the majority of atoms. Therefore, starting in the upper level ($53P$) at zero field, each atom slowly passes through a succession of stationary states while entering the cavity field.

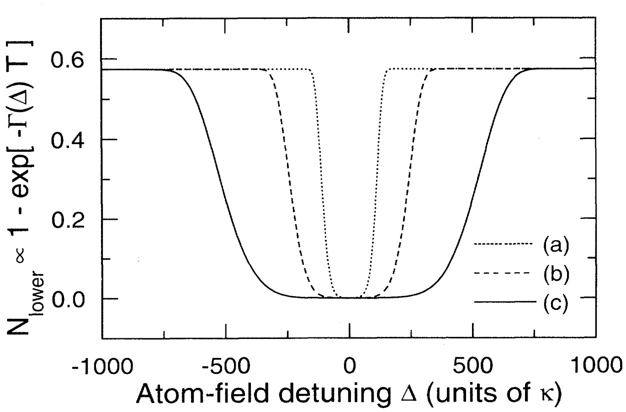

FIG. 4. Lower level occupation of atoms leaving the cavity, calculated from dressed atom model in the limit of a strong driving field; (a) $n_0 = 2 \times 10^6$; (b) $n_0 = 2 \times 10^7$; (c) $n_0 = 2 \times 10^8$; atoms and cavity are in resonance.

Consequently, inside the cavity the atom is in one of its eigenstates $|\pm\rangle$ in the presence of a strong driving field, the so-called semiclassical dressed states [12]:

$$\begin{aligned} |+\rangle &= \cos(\theta)\,|53P\rangle + \sin(\theta)\,|53S\rangle, \\ |-\rangle &= -\sin(\theta)\,|53P\rangle + \cos(\theta)\,|53S\rangle, \end{aligned}$$

where $\tan 2\theta = \Omega/\Delta$. For $\Delta > 0$ ($\Delta < 0$) the atom is found in $|+\rangle$ ($|-\rangle$). By analogy, an atom leaving the cavity in the same dressed state ends up in the initially occupied $53P$ level. In this picture it is clear that atoms detected in the lower ($53S$) level are due to the decay of the dressed states inside the cavity. Our experimental results demonstrate that this decay can be suppressed by a strong driving field.

As shown in Refs. [8] and [10], intensity-dependent decay rates are a consequence of the finite response time κ of the cavity mode, leading to a non-Markovian atom-reservoir interaction. Memory effects average and thereby reduce the decay terms in the Bloch equations. A more pictorial explanation of the phenomenon is obtained by noting that, if the atom is in a dressed state, atomic decay is triggered by vacuum fluctuations or thermal photons at the sideband frequencies $\omega \pm \bar{\Omega}$. If the generalized

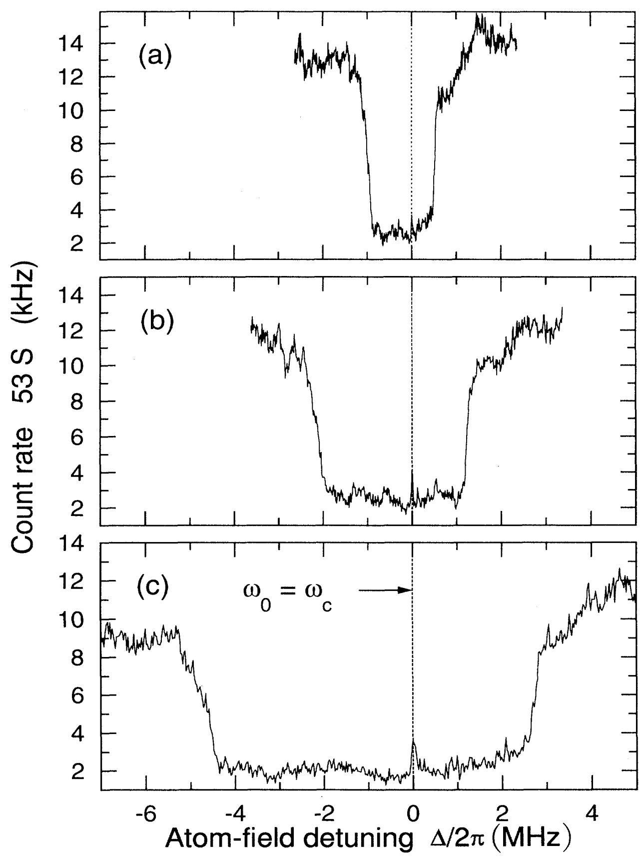

FIG. 5. Count rate in the lower Rydberg level (53S) as a function of the detuning of the external microwave field. The three traces correspond to different microwave intensities: (a) -30 dBm ($n_0 = 2 \times 10^6$); (b) -20 dBm ($n_0 = 2 \times 10^7$); (c) -10 dBm ($n_0 = 2 \times 10^8$).

Rabi frequency $\bar{\Omega} = \sqrt{\Omega^2 + \Delta^2}$ exceeds the cavity and inhomogeneous atomic linewidths, i.e., $\bar{\Omega} > \gamma_i + \kappa$, the sidebands are shifted out of resonance with the cavity. Therefore, fluctuations at these frequencies and hence atomic decay are strongly suppressed. This argument yields an approximate threshold condition $n_0 \gtrsim 50$, in agreement with Fig. 3.

As a further quantitative test of the theory, we measured the suppression of decay as a function of the detuning Δ. From Ref. [10] one obtains a theoretical upper level decay rate

$$\Gamma(\Delta) \approx \frac{2g^2\kappa(1+2\bar{n})}{4\bar{\Omega}^2} \frac{(\bar{\Omega}+|\Delta|)^2}{\kappa^2+(\bar{\Omega}-|\Delta|)^2}. \tag{5}$$

The number of atoms leaving the cavity in the lower state is proportional to $[1-\exp(-\Gamma\tau)]$ (Fig. 4). It should be noted that the actual Rabi frequency Ω inside the cavity depends on the detuning by analogy with Eq. (2). With increasing detuning the power coupled into the cavity, and thus Ω, decreases, which is why suppression is observed only over a limited tuning range.

Three representative experimental spectra of the lower state Rydberg count rate as a function of the atom-field detuning are shown in Fig. 5. The agreement with the theoretical curve (Fig. 4) is remarkable, considering that velocity effects and inhomogenous broadening have not been taken into account.

It is worthwhile to compare quantitatively the width w of the range where suppression of decay occurs with the theoretical prediction. From Eq. (5) we obtain for $\Omega_0 = 2g\sqrt{n_0} \gg \kappa$

$$\frac{w}{\kappa} = \left(\sqrt{\frac{2\ln 2}{1+2\bar{n}}C_1}\,\frac{16}{\kappa T}\,n_0\right)^{1/3}. \tag{6}$$

$C_1 = g^2T/4\kappa$ is the one-atom bistability parameter. The experimental values of w as a function of the injected power are shown in Fig. 6 together with the theoretical curve. For strong fields above -40 dBm, the predicted slope agrees with experiment. At lower intensities the width increases with $\sqrt{n_0}$, in correspondence with weak field theory.

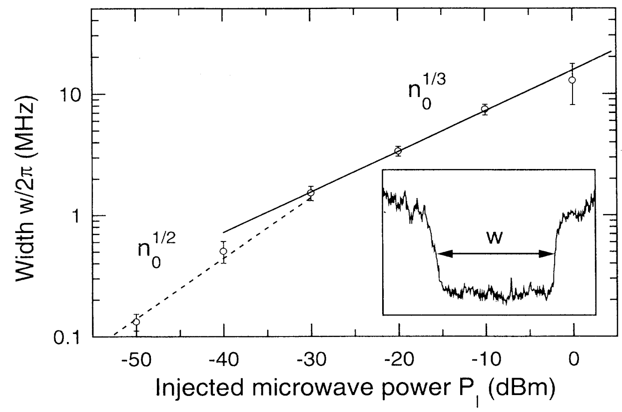

FIG. 6. Measured width of the range where dynamic suppression is observed. The solid line represents the theoretical result in the strong field case ($\Omega_0 \gg \kappa$). The dashed line shows the behavior for weak driving fields.

To summarize, we have described the first experimental demonstration of dynamic suppression of spontaneous transitions by a strong driving field. We have given an explanation of the phenomenon, using the dressed atom model in conjunction with a frequency-dependent reservoir. The observations are in good agreement with this model.

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