Observation of Self-Induced Rabi Oscillations in Two-Level Atoms Excited Inside a Resonant Cavity: The Ringing Regime of Superradiance

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A collection of N Rydberg atoms and a resonant millimeter-wave cavity are shown to exchange energy back and forth at a rate $2(d/\hbar)\mathcal{E}_0\sqrt{N}$, where d is the electric dipole matrix element of the atomic transition and $\mathcal{E}_0$ the "field per photon" in the cavity. This experiment is a demonstration of self-induced Rabi oscillations in a two-level atom system coupled to a single electromagnetic field mode and can also be considered as a very simple illustration of "ringings" in superradiant emission.

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The simplest quantum mechanical model dealing with atom-radiation interaction is the Jaynes-Cummings one,[1] which describes an isolated two-level atom coupled to a single mode of the electromagnetic (em) field resonant with the atomic transition. In this model, atomic radiation appears as a very simple process: If the field—defined as an eigenmode of an em cavity—is undamped and initially empty and if the atom is excited in its upper state, an *oscillatory exchange* of energy between the atomic and field systems is expected,[2] corresponding to a succession of emission and absorption of a single photon by the atom. This exchange should occur at a rate $\Omega_0 = (2d/\hbar)\,\mathcal{E}_0$, where $\boldsymbol{d}$ is the electric dipole matrix element of the atomic transition, $\hbar$ the Planck constant, and $\mathcal{E}_0 = (\hbar\omega/2\epsilon_0 V)^{1/2}$ the "electric field per photon" in the mode (ω and V are, respectively, the transition frequency and the effective volume of the cavity mode). This regime of Rabi oscillation induced by the self-radiated atomic field in the cavity has never been observed so far because it occurs at a rate usually too small compared to the rates T_c^{-1} and T_A^{-1} at which the field and the atoms, respectively, escape from the cavity ($T_c^{-1} = \omega/Q$, Q being the cavity-mode quality factor). Clearly, if the condition

$$\Omega_0 T_c > 1 \tag{1}$$

is not fulfilled, the single-atom–single-photon Rabi oscillation cannot occur since the radiated photon decays in the cavity mirrors before being reabsorbed by the atom. In this case, the cavity mode becomes a "reservoir" in which the atom radiates *irreversibly* at a rate $\Gamma_c = \Omega_0^2 T_c$ which can be *much larger* than the spontaneous emission rate of the same transition in free space. This enhancement of spontaneous emission due to the atomic coupling with a damped resonator, predicted long ago,[3] has been recently observed by our group[4] in an experiment involving Rydberg atoms excited in a millimeter-wave cavity with $Q \cong 10^6$. In Ref. 4, it has been pointed out that a tenfold increase of the resonator Q should allow us to fulfill condition (1) and to observe the fundamental regime of single-atom self-induced Rabi oscillation.

The purpose of this Letter is to report an alternative experiment in which we have observed a closely related self-induced Rabi-oscillation effect in a cavity with a "moderately" high Q. The main idea of the experiment is that an ensemble of N atoms radiates in the cavity a field whose amplitude is $\sqrt{N}$ times larger than a single-photon field, thus increasing the Rabi-exchange frequency to $\Omega_0\sqrt{N}$. Condition (1) for observing this emission regime is then replaced by

$$\Omega_0\sqrt{N}\,T_c > 1 \tag{2}$$

which is much easier to fulfill than Eq. (1), even with relatively short T_c.

The experiment has been performed with sodium Rydberg atoms prepared in a millimeter-wave Fabry-Perot resonator. The advantages of using Rydberg atoms for studying fundamental atom-radiation processes in a cavity are well known[2]: (i) the existence of huge electric dipole matrix elements d between nearby levels makes the intrinsic frequency Ω_0 unusually large; (ii) the resonant frequencies between these levels fall in the millimeter-domain, corresponding to large-size low-order cavities in which it is easy to prepare and to keep during relatively long times the atoms in a region of well-defined and constant atom-field coupling; (iii) Rydberg atoms have long spontaneous emission times, insuring that their coupling to the other modes of the field can be neglected during their interaction with the selected single mode of the cavity. This means that they constitute in these experiments quasi-ideal two-level systems in which all the levels corresponding to the transitions nonresonant with the cavity are irrelevant.

Since the setup of this experiment is basically the same as the one we have used in other atom-cavity experiments,[4-6] we will describe it only briefly here and refer the reader to those references for more details. Figure 1 presents a general sketch of this setup. The sodium Rydberg atoms are prepared in the $36S_{1/2}$ level by stepwise-pulsed laser excitation. They then interact with the Fabry-Perot resonator resonant with a transition towards the less-excited $35P_{1/2}$ level. In order to remove the twofold degeneracy[7] in the upper and lower levels and to study a true two-level atom transition, a small dc magnetic field is applied along the cavity axis and the cavity is tuned to resonance with the $|e\rangle = |36S_{1/2}, M_J = +\frac{1}{2}\rangle \rightarrow |g\rangle = |35P_{1/2}, M_J = -\frac{1}{2}\rangle$ σ_+-polarized transition[6] (the transition matrix element and frequency are, respectively, $d = 592$ a.u. and $\omega/2\pi = 82\,058$ MHz). The resonator parameters are $V = 1.74$ cm^3 and $T_c^{-1} = \omega/Q = 5\times 10^6$ s^{-1}, and the single-atom Rabi nutation frequency of the system is $\Omega_0/2\pi = 20$ kHz. The atom-cavity interaction time is limited by the thermal drift of the atomic beam through the cavity waist ($T_A \cong 6$ μs). After leaving the cavity, the atoms enter a Rydberg-state-selective detector,[4-6] which makes use of the field-ionization effect. This detector allows us to determine the absolute numbers N_e and N_g of atoms in the upper and lower states of the atomic transition. The detector is coupled to an LSI-11 computer which averages the data corresponding to successive pulses. In order to study the evolution of the atom-cavity system during the time the atoms are inside the cavity, we make use of a small electrode (E on Fig. 1) which at a preset delay $t < T_A$ after the laser excitation allows us to apply an inhomogeneous electric field in the cavity. This field Stark shifts the Rydberg states out of resonance with the cavity mode and essentially "freezes" the atomic evolution up to the detection time.[6] By scanning the time t, we can thus reconstruct the atomic evolution during the whole atom-cavity interaction time.

Figure 2 shows as solid lines the recorded evolution of the normalized excited-state population $N_e/(N_e + N_g)$ averaged over 1000 laser shots, for increasing values of the total population $N = N_e + N_g$. For relatively small atom samples [$N = 2000$, Fig. 2(a)], the atomic evolution is irreversible. Condition (2) is then not fulfilled and this case corresponds to the cavity-assisted overdamped superradiant regime studied in detail in previous articles.[2,5,6] The N-atom emission process in the cavity occurs then faster than it would in free space, essentially because of the cavity-enhancement effect discussed above. The emission is, however, not fast enough to overcome field damping and the atoms cannot reabsorb their own radiation. When N is increased [Figs. 2(b)-2(d)], the emission occurs even faster, and oscillations in the atomic population evolution become clearly observable, these oscillations be-

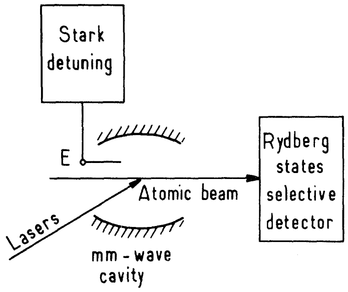

FIG. 1. Sketch of experimental arrangement. The millimeter-wave cavity is made of two copper spherical mirrors of 60-mm radius of curvature and 27-mm-diam aperture, in the cofocal geometry (60 mm between mirrors). The measured cavity finesse is 3200 at 82 GHz.

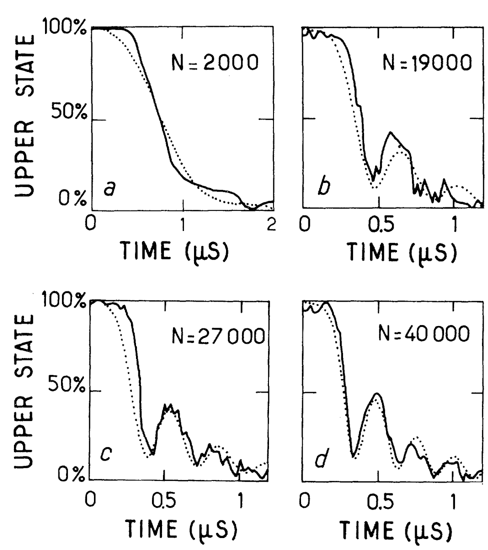

FIG. 2. Evolution of the normalized upper-level population N_e/N as a function of time, for increasing total atom number N. Solid line: experiment; dotted line: theoretical calculation. (a) Overdamped regime; (b)-(d) self-induced ringings with increasing frequency. Note the different time scales of (a) and (b)-(d).

ing damped in a time $\sim 2T_c$.

A quantitative analysis of the atomic evolution in this experiment is readily obtained by using the Bloch vector picture.[2,5] Let us recall that it amounts to describing the collective atomic system in the cavity as a classical vector of length $J=N/2$ rotating in an abstract space. This vector is defined by its polar angles θ and φ with respect to a reference Oz axis in this space. The $\theta=0$ and $\theta=\pi$ directions correspond to a fully excited ($N_e=N$) or fully deexcited ($N_g=N$) atomic system, respectively. The projection $(N/2)\cos\theta$ of the Bloch vector along the Oz direction measures half the population difference $(N_e-N_g)/2$, whereas its transverse component corresponds to the electric dipole of the atomic system, φ representing the phase of this dipole relative to an arbitrary reference. The evolution of the Bloch angle θ is ruled by the following equation:

$$\frac{d^2\theta}{dt^2}+\frac{1}{2T_c}\frac{d\theta}{dt}-\frac{N\Omega_0^{\,2}}{4}\sin\theta=0, \qquad (3)$$

which is formally identical to the equation describing the motion of a damped pendulum in a potential well proportional to $\cos\theta$. Initially, this pendulum starts from $\theta\cong 0$ and swings down to the $\theta=\pi$ position. Depending upon the respective magnitudes of T_c^{-1} and $\Omega_0\sqrt{N}$, the evolution follows either the overdamped regime or the self-oscillating regime discussed above. In order to get this optical pendulum started at time $t=0$, the model must incorporate a description of the quantum and blackbody field fluctuations. It can be shown that these fluctuations are adequately described by choosing for θ at time $t=0$ a random "tipping angle" obeying a Gaussian probability law with an average $\theta_0=2(1+\bar{n}/N)^{1/2}$, where $\bar{n}=[\exp(\hbar\omega/k_BT)-1]^{-1}$ is the average number of blackbody photons in the cavity mode at the temperature T of the experiment (k_B is the Boltzmann constant; in our experiment $T=300$ K and $\bar{n}=76$). In order to compute the evolution of the atomic system averaged over a large number of pulses, one has to determine the solution of Eq. (3) with a set of initial values of θ and weigh the corresponding trajectories according to the above mentioned Gaussian statistics.

The dotted lines superimposed on the experimental traces of Fig. 2 represent the results of these calculations for the average value of $\frac{1}{2}[1+\cos\theta(t)]$. They are in excellent agreement with the experimental curves.

It should be stressed that the parameters used in the theoretical calculations ($N,Q,V,d,\bar{n}$) are all independently calculated or measured and that the fit between experiment and theory does not depend upon any adjustable quantity.

Let us remark that in our theoretical calculations, it has been necessary to take into account the blackbody field fluctuations which help in triggering the emission process at time $t=0$. Let us note, however, that this thermal field is not essential in this experiment. As pointed out earlier,[6] its effect is to speed up the system starting phase {by changing θ_0 from $2/\sqrt{N}$ to $2[(1+\bar{n})/N]^{1/2}$}, without altering the nature and the shape of the atomic evolution. In particular, the oscillation frequency of the atomic populations *does not depend* upon T. (This holds only inasmuch as $N\gg\bar{n}$ and basically reflects the fact that the self-induced field in the cavity, which governs the oscillations, strongly dominates the random thermal field.) We can thus be sure that—although our experiment has been performed in a cavity containing a large absolute number of blackbody photons—we are basically testing here effects which would be the same at $T=0$ K.

The collective self-nutation regime of emission for an ensemble of two-level atoms observed here had been analyzed previously in various theoretical papers, and discussed at length in the context of superradiance theories.[8] It is then generally referred to as the "ringing" regime of superfluorescent emission. In the case of free-space (mirrorless) superradiance, these ringings have up to now eluded a quantitative comparison between experiments and theory,[9] since the simple Rabi nutation effect is then obscured by multimode diffraction and propagation phenomena. Our experiment demonstrates that it is much easier to observe and study these ringings by inducing superradiance *inside a cavity,* where the atoms are essentially coupled to a single mode of the field. This provides another illustration of the advantages of using Rydberg atoms in millimeter-wave cavities for precise quantitative checks of fundamental atom-radiation effects.

Experiments aiming at the observation of similar ringings for a single atom are presently in progress in our laboratory.

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