CAVITY QUANTUM ELECTRODYNAMICS AT OPTICAL FREQUENCIES

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Quantum electrodynamics (QED) tells us that the electromagnetic field is, on a mode-by-mode basis, quantized according to the harmonic oscillator model. Each mode is ascribed a lowest energy (or dark) state possessing one half quanta of non-removable energy plus an infinite ladder of equally spaced excited states accessed through the addition or removal of energy quanta from the mode. In the optical regime and under normal thermal conditions, electromagnetic field modes are typically in their dark state. Nevertheless, a residual dark-state atom-field coupling remains, and it is this coupling that mediates shifts and spontaneous radiative decay of atomic states. The experimental reality of dark-state atom-field coupling is frequently interpreted as proof of the quantum description of light.

The spatial and spectral properties of the electromagnetic field (even the dark-state field) are determined by all those boundary conditions present in the local environment. Consequently, atom-field interactions, in general, and spontaneous decay, in particular, are expected to exhibit quantitative and even qualitative changes with environment. Cavity QED consists of the study of atom-field interactions under conditions in which the quantum nature of the light field is important and the presence of boundary conditions creates an electromagnetic environment different from that found in free space.

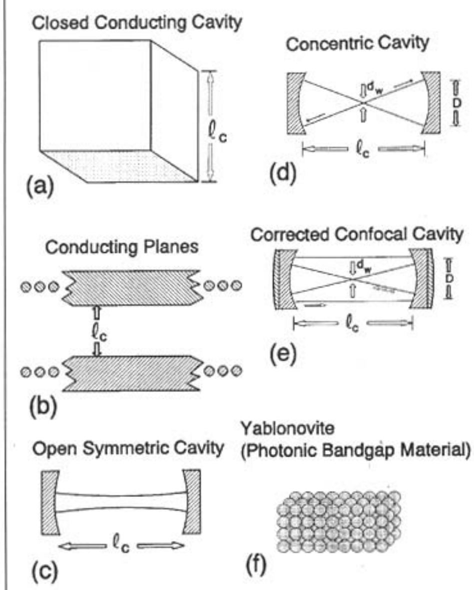

FIGURE 1. EXAMPLES OF "CAVITY QED" ENVIRONMENTS.

One cavity QED effect that has received considerable experimental attention in the optical regime is the environmental modification of spontaneous radiative decay.[1-3] In free space, where the electromagnetic environment may be described in terms of a spectrally and spatially smooth continuum of electromagnetic modes, spontaneous radiative decay proceeds in an irreversible and exponentially damped manner. In some cavities, however, the electromagnetic environment consists of a single weakly damped mode, and "spontaneous decay" consists of a periodic exchange of energy between the atom and the enclosing cavity.[4,5] More generally, the presence of dielectric or metallic boundaries gives rise, in each particular instance, to a unique electromagnetic environment leading to spontaneous emission with characteristics intermediate between the extreme cases mentioned above. Predictably, the various decay dynamics lead to quite different spontaneous emission spectra.[6-8]

Environmentally mediated modifications of spontaneous emission lead concomitantly to novel driven atom dynamics. For example, it has been shown that the presence of significant spectral structure in the electromagnetic environment can lead to entirely new steady states. For example, in suitably structured electromagnetic environments, the atomic steady-state displays a positive inversion (a result impossible in free space[9,10]), dipole forces relating to atomic cooling and trapping are enhanced,[11] and spectral features of driven-atom spontaneous emission undergo novel modifications.[12]

The dynamical and spectral properties of one or a few atoms interacting with a single weakly damped and populated electromagnetic mode are also investigated as a part of cavity QED. Work in this area can be distinguished from that described in the previous paragraphs through the presence of photons, beyond those emitted by the atom or atoms involved, in the mode of interest. Behavior predicted is often qualitatively different from that observed in more typical atom-field interactions. In the optical regime, experimental realization of the conditions frequently considered by theorists working in this area presents great difficulty and in many cases has not yet been achieved. Conditions assumed generally require the spatial localization of atoms to within the volume of a single mode for significant time intervals and decoupling them from other modes and sources of damping. Experiments in the microwave regime, only slightly less difficult, have nevertheless been successful. Microwave effects observed have included one-and two-photon micro masers.[13,14] Numerous effects that relate to the optical regime have been analyzed, including few-atom optical bistability,[15,16] quantum revivals of coherence,[17,18] quantum properties of cavity fluorescence,[12,19-22] and cavity-field-induced level shifts.[23]

In this article, we will concentrate on cavity QED effects that are related to optical systems and have been or should soon be experimentally realizable. While microwave cavity QED work will be mentioned as necessary, a fuller account can be found in review papers that collectively cover both optical and microwave cavity QED.[13,24-31]

ATOM-CAVITY COUPLING

Cavities are broadly divided into two categories—good and bad. Cavities in the former category have photon leak rates that are slower than the spontaneous emission rate of cavity atoms. In bad cavities, spontaneously emitted photons disappear from the spatial region of the emitting atom before reabsorption is likely and spontaneous emission proceeds irreversibly. In the optical regime, good cavities are extremely difficult to realize experimentally and success has only recently been reported.[32] Good cavities are special in that emitted photons are localized long enough to be reabsorbed. As a result, good cavities generally lead to some form of nonexponential spontaneous decay. In this section, we concentrate on determining spontaneous emission rates in bad cavities. Note that even "bad" cavities can produce large modifications to spontaneous decay rates.

As originally written by Einstein in the context of a thermal environment, the rate $W_{e\to g}$ at which excited-state two-level atoms undergo radiative transitions to their ground state is given by

$$W_{e\to g} = BU(\omega_a) + A \tag{1}$$

(where ω_a is the atomic transition frequency and $U(\omega)$ is the electromagnetic energy density per unit volume and frequency. The first term, $BU(\omega_a)$, represents transitions stimulated by the electromagnetic energy density $U(\omega)$, while the second term, **A**, represents transitions that occur spontaneously via the dark-state atom-field coupling.

Using Eq. 1 and thermodynamic arguments, one can show that the rate of spontaneous emission and the rate of stimulated emission are equal when each available electromagnetic mode is populated by one real photon. The fact that this is so has led to the popular picture in which spontaneous transitions are viewed as being stimulated by an electromagnetic energy density that is associated with the dark (or vacuum) state and is equal in magnitude to that physically present when each mode is populated by one photon.

Quantum electrodynamic calculations of single-mode radiative dynamics confirm the general picture already implicit in Eq. 1, *i.e.*, atoms display both stimulated and spontaneous emission into the mode with the former rate being proportional to the photon occupation number of the mode, while the latter rate is independent of it. The same calculations confirm the equality of stimulated and spontaneous emission rates into a given mode when the mode is occupied by one photon. It is intuitively clear and easily demonstrated that stimulated emission into a given mode depends on the characteristics of the mode in the vicinity of the atomic radiator. In particular, stimulated (and hence spontaneous) emission rates into a specific mode are affected by the polarization and energy density of the modal field at the location of the radiator.

To calculate the overall rate of spontaneous emission in a cavity environment, we must sum over the rates associated with individual modes. In light of the discussion above, we can write the cavity spontaneous emission rate as

$$A_c(\xi) = B_a \sum_{\substack{cavity\\modes}} \epsilon_m \sigma_m(\xi) \tag{2}$$

where ξ represents the spatial and spectral coordinates of the atom, ϵ_m represents the relative angular coupling of the atom to the field of mode m, $\sigma_m(\omega,\vec{r})$ is the spectral energy density of mode m when occupied by a single photon, and B_a represents an environment-independent constant proportional to fixed quantities such as the atomic matrix element and so on. By evaluating Eq. 2 for the case of free space, we find that $A = B_a\hbar\omega_a\rho(\omega_a)/3$, where $\rho(\omega)$ is the free-space density of modes per unit volume and frequency. Solving for B_a and using Eq. 2, we have

$$A_c(\xi) = \frac{3\pi^2c^3}{\hbar\omega^3}\left[\sum_{\substack{cavity\\modes}} \epsilon_m\sigma_m(\xi)\right] \tag{3}$$

The summation over cavity modes appearing in Eq. 3, though related to the cavity density of modes in an indirect way, has (except in the case of free space) no simple connection to it. One must conclude that those commonly heard motivations for cavity-modified spontaneous emission rates that are based on cavity-mediated changes in the density of electromagnetic modes are only loosely correct.

The cavity spontaneous emission rate may be enhanced or suppressed relative to its free-space value. Total suppression of spontaneous emission[3] may be achieved, at least in principle, by placing an atom in an environment wherein modal polarizations or spectral energy densities lead to a null summation in Eq. 3. We now consider specific physical environments and the modifications to spontaneous emission that they produce.

The Cavities

Consider an atom within a closed, conductive-walled, cavity (see Fig. 1a) having a characteristic spatial dimension of ℓ_c and quality factor Q. If the cavity is sufficiently small relative to the atomic transition wavelength λ and its Q is sufficiently high, the atom will experience an electromagnetic environment consisting primarily of distinct electromagnetic modes. If spectrally adjacent modes possess negligible spectral energy density at the atomic transition frequency, the atom's spontaneous emission rate may be strongly suppressed relative to its free-space value (see Eq. 3). We consider the opposite situation in which the atom is resonant with one particular cavity mode. We assume, for simplicity, that the mode is non-degenerate and exhibits maximal angular coupling to the atom (*i.e.* $\epsilon_m = 1$). Under these conditions, the summation of Eq. 3 consists of one term whose magnitude is given by

$$\epsilon\sigma \approx \frac{\hbar\omega_a}{V_{mode}\Delta\nu_{mode}}, \tag{4}$$

where V_{mode} and $\Delta\nu_{mode}$ are the mode volume and spectral width, respectively, and we have averaged $\sigma(\xi)$ over a cubic wavelength. It follows that[1]

$$A\text{ (small closed cavity)} = (3Q\lambda^3/8\pi V_c)A.$$

The cavity emission rate will actually exhibit a variation with position within the cavity reflecting the generally non-uniform spatial distribution of modal spectral energy. For wavelength-scale cavities with reasonable Q factors, substantial enhancements of the radiative emission rate can be expected. Self consistency with the assumption of irreversible decay, however, demands that the predicted emission rate remains much smaller than the linewidth of the cavity resonance. If this is not the case, Eqs. 2 and 3 are no longer valid and reversible spontaneous emission may be expected. The small closed cavity, though conceptually simple, has been difficult to realize experimentally. Fairly recently, cavity mediated changes in optical spontaneous emission rates have been observed in micron-size dielectric spheres.[34] Such structures exhibit high-Q "whispering mode" resonances.

An experimentally convenient means of modifying spontaneous emission rates is to place atoms near or between conducting planes (see Fig. 1b), as was demonstrated early on by Drexhage.[2] An especially interesting situation involving plane boundaries arises when one considers the region between two closely spaced, parallel, conductors. When the plate spacing ℓ_c is less than $\lambda/2$, there are no allowed electromagnetic modes with electric fields oriented parallel to the conducting planes. This fact has been used to provide striking demonstrations of the suppression of spontaneous emission.[35,36] In these cases, atoms have been placed in excited states whose decay depends entirely on coupling to electric fields oriented parallel to the plates. In terms of Eq. 3, the spontaneous emission rate vanishes because the angular coupling factor ϵ is uniformly zero. Effects produced by dielectric planar boundaries[37-40] have been studied, as have atomic-energy-level shifts in the presence of planar conductors.[41] Although experimentally convenient for some purposes, planar boundaries create fairly complex electromagnetic environments differing appreciably the free-space environment only for a wavelength or so around the planar surface.

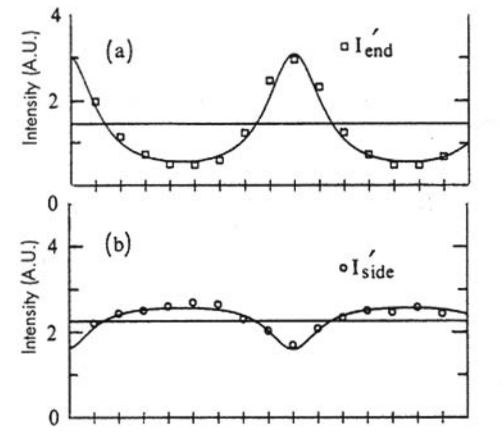

FIGURE 2. INTENSITY OF FLUORESCENCE EMITTED BY A WEAKLY-DRIVEN CAVITY-CONTAINED ATOM AS A FUNCTION OF CAVITY MIRROR SPACING. (a) INTENSITY EMITTED OUT THE END OF THE CAVITY. (b) INTENSITY EMITTED OUT THE SIDE. (FROM REF. 44; REPRINTED WITH PERMISSION.)

Open-sided, spherical-mirror, optical cavities provide another means of perturbing atomic radiative dynamics. Cavities of this type are especially important because of their demonstrated ability to support reversible spontaneous emission.[32,42]

Consider a symmetric resonator (Fig. 1c) of length ℓ_c, finesse $\mathcal{F}$, and mirror radius $R_m >> \ell_c$. We assume that one mode of the cavity is resonant with the atomic transition frequency. Taking the diameter of the mode to be approximately constant, its volume $V_{mode} \approx \lambda \ell_c^{3/2} R_m^{1/2}/\sqrt{2}$ and by definition, its linewidth $\Delta\nu_{mode} \approx \pi c/\mathcal{F}\ell_c$. It follows using Eqs. 3 and 4 that

$$A_c \text{ (symmetric optical cavity)} \approx \frac{\mathcal{F}}{2^{3/2}} \frac{\lambda}{(\ell_c R_m)^{1/2}} A.$$

One sees immediately that achieving large emission rates becomes increasingly difficult as the cavity becomes large. Nevertheless, a millimeter-scale cavity of finesse 10,000 may produce a cavity-mode spontaneous-emission rate on the order of the total free-space emission rate.

Confocal and concentric optical cavities (Figs. 1d and 1e) are special in that they are characterized by "hour-glass" modes having a very small waist at the center of the cavity. These cavities are frequently referred to as mode degenerate because of the spectral degeneracy of their transverse spatial modes; their hour-glass modes are often seen to be superpositions of the standard transverse Gaussian cavity modes. For our purposes, it is more straightforward to simply treat the hour-glass modes as single discrete modes.

Atoms can be coupled to hour-glass modes much more strongly than they can to constant diameter modes of similar volume and linewidth. In determining the emission rate of an atom at the waist of an hour-glass mode, we note that the spectral energy density at the waist has the same value one would expect from a mode of constant diameter (equal to the small waist diameter d_w) and length ℓ_c (see Fig. 1d and 1e). In the actual mode, the beam diameter becomes quite large at the cavity mirrors. Using Eqs. 3 and 4, and the mode parameters for a spherical mirror confocal cavity, we find that

$$A_c \text{ (spherical mirror confocal cavity)} \approx \frac{24}{\pi^2} \left[\frac{\lambda}{\ell_c} \mathcal{F} \right]^{1/2}.$$

Focusing properties of spherical mirrors limit the minimum spot size in the confocal geometry.[43] Replacing the confocal cavity mirrors with multi-element corrected optical reflectors can in principle lead to spot sizes limited only, as in the concentric cavity case, by diffraction associated with the finite diameter cavity mirrors.

Creating a diffraction-limited confocal cavity is an interesting optical design problem. For concentric or corrected confocal cavities, Eqs. 3 and 4 indicate that

$$A_c \approx \text{(corrected confocal cavity)} \approx \frac{4}{\pi} \left[\frac{D^2}{\ell_c^2} \right] \mathcal{F}$$

(At the center of a concentric cavity, the rate is about twice as large as for the corrected confocal.)

An advantage of the confocal geometry over the concentric is that in the former case the atom can be located within a relatively large active region wherein hour-glass modes centered on the atom always exist. In the latter case, there is only one small-waist mode and the atom (and the cavity for that matter) must be positioned with near wavelength-scale accuracy. From the expressions given above, it is clear that mode-degenerate cavities of centimeter scale can produce large emission rates with relatively low finesses. Mode degenerate cavities of the confocal and concentric variety have been employed in experiments relating to spontaneous emission level shifts[44] and cavity-modified driven-atom dynamics.[9]

All open-sided cavities have the characteristic of leaving atoms within the cavity partially coupled to the free-space modes. The rate of spontaneous emission into these modes is generally estimated by assuming that it scales as the fraction of solid angle over which the atom "sees" the free-space background. The accuracy of this method probably increases with the size of the cavity and does not take angular coupling factors into account, *e.g.*, the atom may be oriented so as to be poorly coupled to the free-space modes and thereby minimize their importance. Atomic coupling to the free-space modes tend to damp effects related to reversible spontaneous emission.

Considerable attention has recently been focused on the electromagnetic environment within spatially periodic optical "crystals" (see Fig. 1f). It has been suggested[45] and demonstrated[46] that such materials give rise to photonic band structure of the same general type as associated with electrons in periodic media. Interest has focused on the possibility of creating optical materials possessing photonic band gaps, *i.e.*, spectral regions throughout which electromagnetic fields cannot propagate. Within photonic band gaps, electromagnetic modes are essentially absent and radiative dynamics should be strongly modified.[47,48] More generally, any modification of the electromagnetic continuum within a spatially periodic optical structure may, through its perturbation of the basic atom-field radiative coupling, affect the operation of optical devices. Related work involving semiconductor diode lasers has been reported.[38]

EXEMPLARY EXPERIMENTS AND CALCULATIONS

A few of the many interesting optical effects currently being studied in the field of cavity QED will be described. Consider a single two-level atom that is in free space and is weakly driven by a resonant monochromatic laser field occupying a single free-space mode. In an experiment,[43] an open-sided concentric cavity was positioned so that its center coincided with the atom. The cavity subtended only about 5% of the full solid angle about the atom and was oriented perpendicular to the weak laser field. The leakage rate of photons from the cavity through the open sides and endmirrors was sufficiently large to ensure the cavity mode was essentially unpopulated at all times (emitted photons did not therefore exert appreciable back action on the atoms). The atomic fluorescence intensity emitted through one end and out of the side of the cavity were measured as the length of the 5-cm long cavity was varied over a range of approximately one micron.

The results are shown in Figure 2. Peaks in the intensity radiated out the end of the cavity (Fig. 2a) indicate enhanced spontaneous emission into the cavity mode. The simultaneous dips in side fluorescence indicate a reduced level of atomic excitation concomitant to the increase in the overall spontaneous emission rate. Putting aside our sophisticated perspective for a moment, the fact that atomic dynamics are appreciably modified by moving the distant mirrors of an empty cavity a minute fraction of their separation, is indeed intriguing.

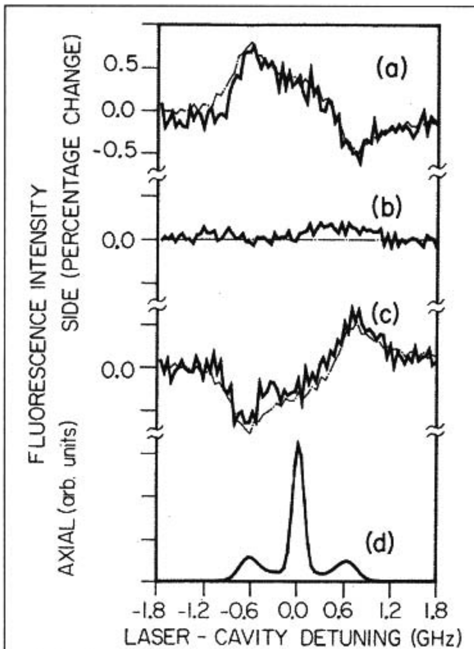

FIGURE 3. FLUORESCENCE INTENSITY EMITTED BY A STRONGLY DRIVEN ATOM (a)-(c) OUT THE SIDE OF A CAVITY (d) OUT THE END OF A CAVITY AS A FUNCTION OF CAVITY MIRROR SPACING. (a)-(c) REPRESENT LASER-ATOM DETUNINGS OF 320, 0, AND -320 MHZ, RESPECTIVELY. (FROM REF. 9; REPRINTED WITH PERMISSION.)

Even more nonintuitive modifications to the atom-field dynamics were demonstrated in an experiment[9] conducted with essentially the same experimental arrangement, but with the concentric cavity replaced with a confocal one (of only technical importance) and the weak driving laser with a strong one. As above, the side and end fluorescence intensity are measured as a function of the cavity mirror spacing. The side fluorescence was measured for three different atom-driving field detunings. Results are shown in Figure 3. Increases in side fluorescence intensity indicate increases in the excited-state atomic population. The concomitant increase in end fluorescence (see bottom trace) implies, paradoxically, that the cavity-mediated increase in excited-state population is affected through an increase in spontaneous emission. Analysis of this counter-intuitive result indicates that, under appropriate cavity conditions, the atomic steady state can approach total inversion. This experiment reveals an entirely new regime of driven-atom dynamics.

Recently, the first optical observation of reversible spontaneous radiative decay was reported.[32] As alluded to above, one expects a periodic interchange of energy between an atom and the cavity mode. In the frequency domain, this interchange manifests itself as a splitting (referred to as the "Vacuum-Rabi" or "Single-Photon" splitting) of the cavity resonance into two components split by the interchange frequency. Observation of this single-atom effect is an experimental triumph and required a small 1-mm cavity having a finesse on the order of 10^5—extremely high for optical systems. Measurements of the cavity mode splitting are shown in Figure 4. Interestingly, it has been shown that the intrinsically quantum single-atom splitting shown in Figure 4 follows in the case of many atoms from dispersion theory applied to a cavity containing a linear absorber.[49]

Finally, we mention an effect not yet observed.[17,18] In the semiclassical picture, when an atom is coupled to a single-mode resonant driving field, it undergoes Rabi oscillations, *i.e.*, it cycles back and forth between its ground and excited states at a well-defined frequency (the Rabi frequency). Sans relaxation, this oscillation will persist indefinitely. In the case of an atom driven by a single weakly populated cavity mode, the situation is predicted to change dramatically. The atom experiences an initial Rabi oscillation that soon damps out—without coupling to any other modes. More interesting, as time progresses, the oscillation is predicted to reappear! This effect has been designated quantum collapse and revival. The detailed character of the effect depends on the precise initial quantum state of the cavity field, indicating that the effect is intrinsically quantum. While this effect has been seen (just barely) in the microwave regime,[50] an optical realization is not yet in hand.

Why Bother?

Cavity QED deals with situations involving few atoms and/or photons wherein one frequently observes behavior at variance with that expected on the basis of insight gleaned from more macroscopic systems. It is reasonable to anticipate the continued work in the field of cavity QED will reveal entirely unexpected domains of atom-field dynamics that are of both fundamental and practical importance.

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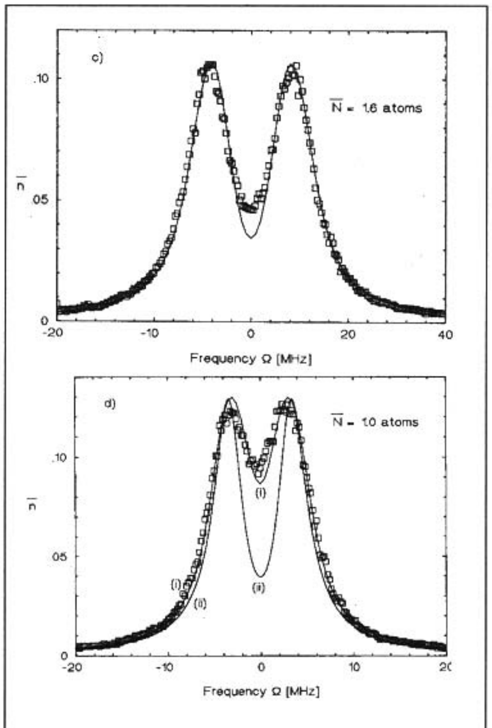

FIGURE 4. INTENSITY TRANSMITTED THROUGH A HIGH FINESSE OPTICAL CAVITY AS A FREQUENCY FOR DIFFERENT AVERAGE NUMBERS OF ATOMS IN THE CAVITY. REVERSIBLE SPONTANEOUS EMISSION GIVES RISE TO THE SPLITTING. (FROM REF. 32; REPRINTED WITH PERMISSION.)

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