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Quantum interference in a driven two-level atom

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We show that a dynamical suppression of spontaneous emission, predicted for a three-level atom [S.-Y. Zhu and M. O. Scully, Phys. Rev. Lett. **76**, 388 (1996)] can occur in a two-level atom driven by a polychromatic field. We find that the quantum interference, responsible for the cancellation of spontaneous emission, appears between different channels of transitions among the dressed states of the driven atom. We discuss the effect for bichromatic and trichromatic (amplitude-modulated) fields and find that these two cases lead to the cancellation of spontaneous emission in different parts of the fluorescence spectrum. Our system has the advantage of being easily accessible by current experiments. [S1050-2947(99)50712-9]

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The study of quantum interference as a mechanism for suppression of spontaneous emission has been a subject of considerable interest for many years. It was originally predicted by Agarwal [1], who showed that the decay of an excited degenerate V-type three-level atom can be modified due to interference between the two coupled atomic transitions. The analysis of quantum interference has since been extended to other configurations of three- and multilevel atoms [2]. Quantum interference between coupled transitions can lead to trapping of the population in one of the atomic excited levels, thereby eliminating the population in the other levels. The absence of population stops the decay process from these levels.

Another process that results from quantum interference is the so-called dynamical suppression of spontaneous emission. It was predicted by Zhu and Scully [3] (see also [4]) in a driven V-type system. In this mechanism the decay process can be inhibited without population trapping. They found that quantum interference between two transitions with parallel dipole moments, coupled via the vacuum field and driven by a laser field from an auxiliary level, can lead to the elimination of the spectral line at the driving laser frequency.

In contrast to a simple theoretical picture of the process, that the cancellation results from the interference between two, close in frequency and correlated transitions, experimental work has been proven to be extremely difficult, with only one experiment so far demonstrating this effect [5]. The difficulty stems mostly from the fact that the interference requires two nearly degenerate transitions with parallel or antiparallel dipole moments. This is a real practical problem, as one is very unlikely to find isolated atoms with two coupled dipole moments and quantum states close in energy. In the experiment [5] quantum interference was observed between coupled transitions within a multilevel configuration in sodium dimers driven by a two-photon process. Agarwal [6] has provided an explanation of the observed effect in terms of two-photon transition rates. Recently, Berman [7] has shown that the observed effect can, in fact, be interpreted in terms of population trapping rather than as dynamical suppression.

In this paper, we show that dynamical suppression of spontaneous emission can be obtained in a simple system of a two-level atom driven by coherent laser fields. This is a rather surprising prediction, since one might imagine from the examples discussed above that the interference requires an atom with two coupled and nearly degenerate transitions, and therefore this effect would not appear in the two-level system. However, the driven two-level atom is no longer a two-level system; its energy spectrum is composed of a ladder of dressed states [8] with multichannel transitions among them. The quantum interference actually appears between degenerate transitions of the dressed-atom system.

We consider a two-level atom with ground state $|g\rangle$ and excited state $|e\rangle$ connected by a dipole transition moment $\vec{\mu}$. The atom is driven by a polychromatic field whose central frequency ω_s is detuned from the atomic resonance ω_0 by $\Delta=\omega_0-\omega_s$. The time evolution of the system is given by the master equation of the reduced density operator, which in the interaction picture is given by

$$\frac{\partial\tilde{\rho}}{\partial t}=-i[\Delta S^z+H_{int},\tilde{\rho}]-\frac{1}{2}\Gamma(S^+S^-\tilde{\rho}+\tilde{\rho}S^+S^- -2S^-\tilde{\rho}S^+), \quad (1)$$

where Γ is the radiative damping constant, $S^+(S^-)$ is the atomic raising (lowering) dipole operator, S^z is the atomic inversion, and H_{int} is the interaction between the atom and the driving fields. The explicit form of H_{int} depends on the number of driving fields, their Rabi frequencies, and detunings.

Bichromatic field

First, we consider quantum interference with a bichromatic driving field composed of a strong resonant laser field and a weaker laser field detuned from ω_0 by the Rabi frequency of the strong field. The effect of the strong field alone is to produce dressed states [8]

$$|i,N\rangle=\frac{1}{\sqrt{2}}[|g,N\rangle-(-1)^i|e,N-1\rangle], \quad i=1,2, \quad (2)$$

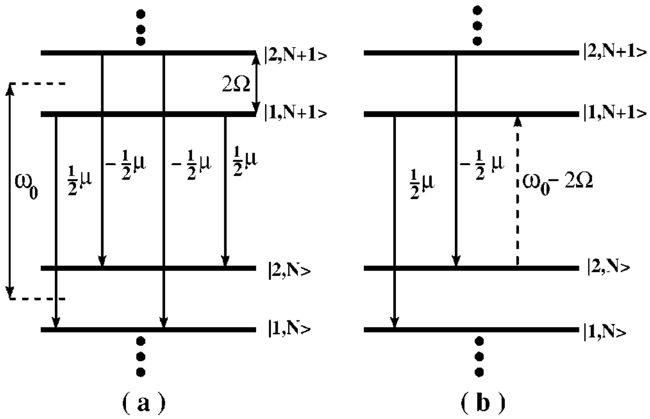

FIG. 1. (a) Dressed states of a strongly driven two-level atom. The arrows indicate the allowed spontaneous transitions with dipole moments $\pm\frac{1}{2}\mu$. (b) A second coherent field (dashed arrow) of frequency $\omega_0-2\Omega$ couples the dipole moments of the two degenerate transitions at ω_0.

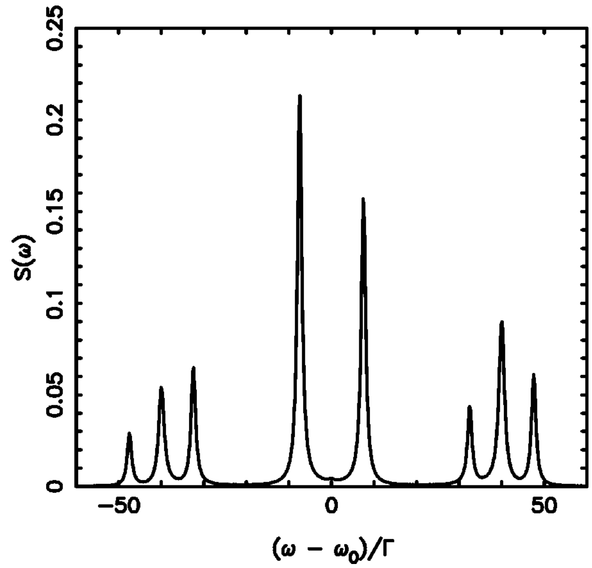

FIG. 2. The fluorescence spectrum for a bichromatic driving field with a strong resonant component of the Rabi frequency $2\Omega=40\Gamma$, and a weaker component of frequency $\omega_2=\omega_0-2\Omega$ and $2\Omega_2=16\Gamma$.

with energies $E_{1,2}=\hbar(N\omega_0\pm\Omega)$, where N is the number of photons in the field mode and 2Ω is the Rabi frequency.

The dressed states, shown in Fig. 1(a), form an infinite ladder of doublets with interdoublet spacing ω_0 and intradoublet spacing 2Ω. We see that in the dressed-atom basis the system is no longer a two-level system. It is a multilevel system with three different transition frequencies, ω_0 and $\omega_0\pm2\Omega$, and four nonvanishing dipole matrix elements $\vec{\mu}_{ij,N}=\langle N,i|\vec{\mu}|j,N-1\rangle$:

$$\vec{\mu}_{11,N}=\vec{\mu}_{12,N}=-\vec{\mu}_{21,N}=-\vec{\mu}_{22,N}=\frac{1}{2}\vec{\mu}, \tag{3}$$

connecting dressed states between neighboring manifolds. There are two antiparallel dipole moments $\vec{\mu}_{11,N}$ and $\vec{\mu}_{22,N}$ that contribute to the transitions at ω_0, which makes this an ideal candidate for quantum interference. However, they are not coupled (correlated), preventing these dipole moments from being a souce of quantum interference. This can be shown by calculating the correlation functions of the dipole moment operators of the dressed-atom transitions $\sigma^{+}_{ijN}=|i,N\rangle\langle N-1,j|$ $(i,j=1,2)$. The correlation functions $\langle\sigma^{+}_{iiN}\sigma^{-}_{jjN}\rangle$ $(i\neq j)$ are equal to zero, showing that the dipole moments oscillate independently.

In order to correlate them, we introduce a second (weaker) laser field of frequency $\omega_0-2\Omega$ and the Rabi frequency $2\Omega_2<2\Omega$, which couples the degenerate transitions with dipole moments $\vec{\mu}_{11,N}$ and $\vec{\mu}_{22,N-1}$, as indicated in Fig. 1(b). Treating the second field perturbatively, at zeroth order the coupling results in new "doubly dressed" states [9]

$$|\bar{N},n\pm\rangle=\frac{1}{\sqrt{2}}(|2,N-n-1,M+n+1\rangle\pm|1,N-n,M+n\rangle), \tag{4}$$

where M is the number of photons in the weaker field mode, and $\bar{N}=N+M$ is the total number of photons. The doubly dressed states are entangled states of the "singly" dressed states (2), and the states of the second driving field.

We now compute the transition dipole moments $\vec{\mu}_{n\pm,n\pm}$ between the doubly dressed states corresponding to the transition at ω_0, and find that the dipole moments are equal to zero. Thus, in the doubly driven atom the effective dipole moments at ω_0 are zero due to quantum interference between the two dipole moments of opposite phases.

In order to show that the cancellation does not result from a population trapping, we calculate the steady-state populations $P_{n\pm,\bar{N}}=\langle\pm n,\bar{N}|\rho|\bar{N},n\pm\rangle$ of the doubly dressed states. From the master equation (1), we find that the steady-state-reduced populations $P_{n\pm}=\Sigma_{\bar{N}}P_{n\pm,\bar{N}}$ are all equal, indicating that the population is equally distributed between the dressed states. In this case the cancellation of the dipole moments at ω_0 is not accompanied by population trapping, and therefore is an example of the dynamical suppression of spontaneous emission.

Similarly, it can be shown that the cancellation of the spectral line at ω_0 appears also for frequencies of the second laser $\omega_2\approx\omega_0\pm2\Omega/n$, $n=2,3,\ldots$; i.e., when the laser is coupled to subharmonics of 2Ω [10]. As before, for the $n=1$ case, the cancellation does not result from a population trapping and thus is also an example of the dynamical suppression of spontaneous emission.

In Fig. 2, we show the fluorescence spectrum for the $n=1$ case. It is evident that there is no the central component of the spectrum, i.e., there is no fluorescence at the atomic transition frequency.

Recently, an experiment has been performed [11] verifying the fluorescence spectrum for the $n=1$ case. The experiment has demonstrated the double dressing of the atom. However, the experiment did not explicitly explore the vanishing of the central component of the spectrum, and in fact a large line of the bandwidth of the experimental resolution has been observed at ω_0. The presence of the central line has been explained as arising from the elastic scattering of the strong field on isotopes of the Ba atoms presented in the atomic beam.

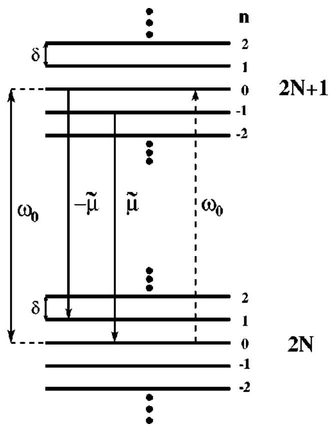

FIG. 3. Dressed states of a two-level atom driven by a symmetric bichromatic field. Solid arrows indicate two dipole transitions with the dipole moments $\pm\tilde{\mu}=\pm\frac{1}{2}J_{-1}(-4\Omega/\delta)$ corresponding to the frequency $\omega_0-\delta$. The dashed arrow indicates an additional coherent field of frequency ω_0, which couples the $\pm\tilde{\mu}$ dipole moments.

Amplitude-modulated field

In the case of two driving fields, the dynamical suppression of spontaneous emission appears at the frequency of the strong driving field. Here, we discuss a further scheme that offers much promise for an experimental observation of the effect. We assume that the atom is driven by an amplitude modulated (AM) field, which is equivalent to a trichromatic field with a central component of frequency ω_0, and two sidebands of frequencies $\omega_0\pm\delta$, where δ is the modulation frequency. The sideband fields can be weaker (a weakly AM field) or stronger (a strongly AM field) than the central component.

We first drive the atom with the sideband fields, which is equivalent to the case of the atom driven by a bichromatic field of frequencies $\omega_0\pm\delta$. The effect of the bichromatic field is to produce dressed states [12]

$$\left|2N,\frac{\Omega}{\delta},m\right\rangle=\sum_{n=-\infty}^{\infty}J_{n-m}\left(-\frac{2\Omega}{\delta}\right)|n,2N\rangle \tag{5}$$

corresponding to energies $E_{2N,m}=\hbar(2N\omega_0+m\delta)$, $m=\pm1$, $\pm2,\dots,$ and where 2Ω is the (on resonance) Rabi frequency of the bichromatic field.

In Fig. 3, we present the dressed states of this system, which are composed of a ladder of multiplets, separated by ω_0, with each manifold containing an infinite number of states separated by δ. As was shown by Freedhoff and Chen [12], transition dipole moments between dressed states of the $2N+1$ and $2N$ manifolds are

$$\left\langle 2N+1,\frac{\Omega}{\delta},m\left|\vec{\mu}\right|2N,\frac{\Omega}{\delta},m'\right\rangle =\frac{\vec{\mu}}{2}\left[\delta_{mm'}+(-1)^m J_{m-m'}\left(-\frac{4\Omega}{\delta}\right)\right]. \tag{6}$$

Thus, for $m\neq m'$, both positive and negative dipole moments contribute to the transitions, as is indicated in Fig. 3. Therefore, at these frequencies quantum interference could (in principle) lead to inhibition of spontaneous emission. However, similar to the case of monochromatic driving, the dipole moments oscillate independently and thus no such interference can be observed. We now apply the central component of frequency ω_0, and the Rabi frequency $2\Omega_0$, which couples the degenerate antiparallel dipole moments, as is shown in Fig. 3. The effect of the third field is to produce ''triply'' dressed states [13]

$$|m\pm,2N+M\rangle=\sum_{n=-\infty}^{\infty}J_{n-m}\left(\mp\frac{2\Omega}{\delta}\right)|2N+M,n\pm\rangle, \tag{7}$$

where M is the number of photons in the central mode. The dressed states (7) are valid for arbitrary strengths of the modulation. However, their energies are different depending on whether the field is weakly or strongly modulated. For example, for a strongly AM field the dressed states (7) group into manifolds separated by ω_0. Each manifold is composed of an infinite number of doublets, with an interdoublet separation δ and with intradoublet splitting $2\Omega_0$.

Using the summation rules for Bessel functions, we find that the transition dipole moments corresponding to the frequencies $\omega_{mm'}=\omega_0+(m-m')\delta$ are

$$\vec{\mu}_{mm'}=\langle\pm,m,2N+M|\vec{\mu}|2N+M-1,m'\pm\rangle=\frac{1}{2}\vec{\mu}\,\delta_{mm'}. \tag{8}$$

From this we see that the dipole moments corresponding to the transitions with $m\neq m'$ are all equal to zero, indicating a suppression of spontaneous emission at those frequencies.

We now project the master equation (1) onto the dressed states (7) and find that the steady-state populations are all equal, $P_{m+}=P_{m-}=\frac{1}{2}$, indicating that the effect is due to the dynamical suppression of spontaneous emission. The feature is best seen in the fluorescence spectrum, which we plot in Fig. 4 for a strongly modulated field. The spectrum is composed of a central line and a series of doublets separated by δ and with intradoublet splitting $2\Omega_0$. There are no spectral components at $\omega=\omega_0\pm m\delta$, $m\neq0$, corresponding to the central lines in the sidebands, as they are suppressed by quantum interference.

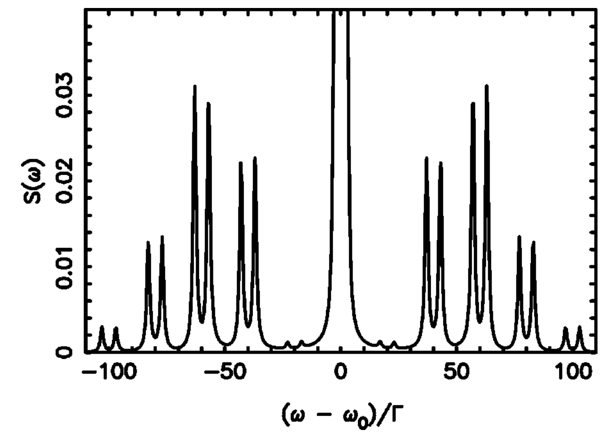

FIG. 4. The fluorescence spectrum for a strongly AM field with $2\Omega=40\Gamma$, $\delta=20\Gamma$, and $2\Omega_0=2\Gamma$. The central peak has a maximum at 0.5.

Quantum interference with an amplitude-modulated driving field, considered in this paper, may be the best candidate to investigate experimentally the dynamical suppression of spontaneous emission in a two-level atom; for example, in an experiment similar to that of Ref. [11]. In this case the effect appears at frequencies different from the driving fields, which avoids the contributions to the observed spectrum from the coherent scattering.

In summary, we have shown that the dynamical suppression of spontaneous emission can be observed in a two-level atom suitably driven by coherent laser fields. The effect results from the interference between degenerate transitions of the dressed-atom system. A strong driving field produces dressed states that form a ladder of manifolds with parallel and antiparallel dipole moments between two neighboring manifolds. A second driving field applied to this singly dressed atom couples degenerate dipole moments of the system and produces superpositions with zero effective dipole moments. This effect leads to the suppression of some components of the fluorescence spectrum.

Finally, we point out that the effect discussed in this paper has been termed ‘‘suppression of spontaneous emission’’ [3,4]. This could suggest that the effect corresponds to the cancellation of spontaneous decay of the atom. In fact, the spontaneous emission is cancelled only at some particular frequencies. Therefore, a more proper term could be ‘‘suppression of spectral components’’ [14].

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