Dynamically induced resonance fluorescence of a two-level atom in a cavity

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Resonance fluorescence is an interesting manifestation of the interaction between a quantum mechanical radiator and the vacuum-field fluctuations surrounding the radiator under a coherent resonant excitation. In this work, we study the fluorescence spectra and the dynamics of a strongly driven Jaynes-Cummings system (JCS), where the JCS refers to a two-level atom interacting with a single mode cavity. Such a system is now drawing much attention as a candidate for a single-trapped-atom laser [1] and cavity-QED-based quantum computing [2] in the low damping limit. Our quest is to understand the resonance fluorescence if the driving field is strong enough to influence the JCS level structure. A naive expectation is that high lying states in the so-called Jaynes-Cummings ladder (JCL) could be excited and transitions between adjacent levels would contribute to the resonance fluorescence. We show that such expectation is partially true at best, and that much more information on the system dynamics is embedded in the fluorescence.

In our model a single-mode cavity resonantly coupled with a two-level atom is driven by a classical field of arbitrary-strength as described by a Hamiltonian

$$H = (1/2)\hbar\omega_a\sigma_z + \hbar\omega_c a^+ a + i\hbar g(a^+\sigma_- - a\sigma_+) + i\hbar\mathcal{E}(a^+ e^{-i\omega_L t} - a e^{i\omega_L t}), \qquad (1)$$

where ω_a, ω_c, ω_L are the atomic transition, the cavity resonance, the driving field frequencies, respectively, which are set equal to ω_0 throughout this work. The atom-cavity coupling strength is denoted by g with $\mathcal{E}$ the coupling strength of the driving field to the cavity, proportional to the driving-field amplitude, $\sigma_\pm$ and σ_z the atomic pseudospin operators and $a^+(a)$ the creation (annihilation) operator of the cavity mode. Time evolution of the system was obtained numerically from the master equation

$$\dot{\rho} = (1/i\hbar)[H,\rho] + (\gamma/2)(2\sigma_-\rho\sigma_+ - \sigma_+\sigma_-\rho - \rho\sigma_+\sigma_-) + \kappa(2a\rho a^+ - a^+ a\rho - \rho a^+ a) \qquad (2)$$

where ρ is the density operator, γ the decay rate of the atom through the coupling to free-space vacuum-field modes other than the privileged cavity mode and 2κ the cavity-loss rate. The Fourier transform of $\langle\sigma_+(t)\sigma_-(t+\tau)\rangle$ was calculated using the quantum regression theorem in the steady state.

In Fig. 1, we plot the incoherent part of the fluorescence spectrum in the strong atom-cavity coupling limit ($\gamma, 2\kappa \ll g$). In addition to the familiar doublet (marked a) due to the vacuum

Rabi oscillations, there occur anomalous spontaneous transition lines (*b, c, e, f*) in the fluorescence spectrum which cannot be explained in terms of the transitions between neighboring JCL manifolds. These new lines correspond to the transitions between quasi-energy levels [3]. In fact, there is no stationary state when the JCS system is strongly driven. The quasi-stationary states are dynamically induced by the excitation field, and thus let us call this fluorescence "dynamic resonance fluorescence" (DRF). The DRF lines in Fig. 1 are characterized by the decay from energy manifolds n to $(n-m)$ $(m \geq 2)$ in the quasi-energy picture. It should be compared with the conventional JCL transitions from energy manifolds $n+1$ to n, yielding fluorescence frequencies given by $\omega_0 \pm (\sqrt{n+1} \pm \sqrt{n})g$ (e.g. *d* in Fig. 1). Although the DRF is due to the transitions between *non-adjacent* manifolds, it is still of a single-photon process, made possible by the dynamic Stark effect. In this work we explain the origin of all the anomalous peaks in the DRF. Most of these resonance lines disappear when the atomic and cavity damping effects become significant. In that case, the DRF changes from the doublet (in the low excitation) to the Mollow triplet (in the high excitation) via a quintuplet (quadruplet + singlet) which is the signature of the bimodal intracavity photon number distribution. Moreover, the photon statistics inside the cavity exhibits a laserlike behavior as the driving field intensity is increased.

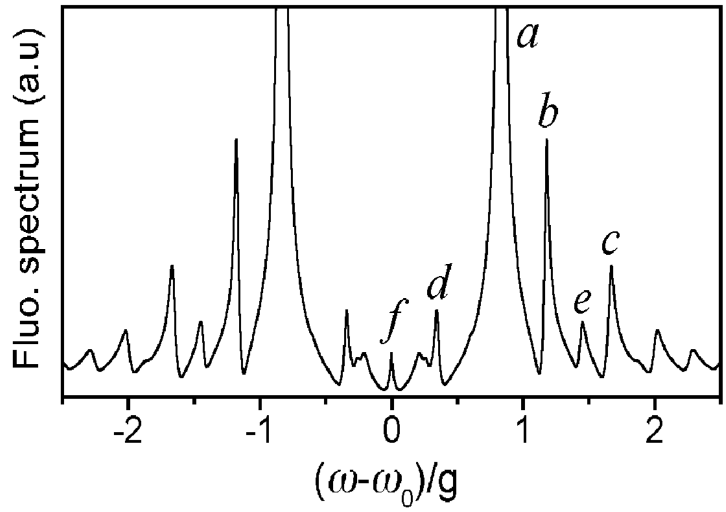

Figure 1: Resonance fluorescence when $\epsilon \equiv 2\mathcal{E}/g = 0.47$ and $\gamma/g = 2\kappa/g = 10^{-2}$.

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