# TWO-PHOTON DRESSED STATES AND FLUORESCENCE SPECTRUM OF A DRIVEN THREE-LEVEL ATOM

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Three-state dressing has been observed in a driven three-level artificial atom in circuit QED [**?**], leading to later work investigating the spectrum of the associated fluorescence [**?**, **?**]. In this work we develop a theoretical approach to the fluorescence spectrum similar to that of Shamailov et. al. [**?**] but for this simpler three-level system.

We consider a three-level ladder-type model with a ground state $|g\rangle$, final state $|f\rangle$, and an intermediary state $|e\rangle$, with respective energies $E_g, E_f$, and $E_e$. For an applied external drive to reach resonance with the $|f\rangle$ state, two photons of energy $\hbar\omega_{gf}/2 = (E_f - E_g)/2$ must be absorbed. The Hamiltonian for the driven system is

$$\hat{H} = E_g|g\rangle\langle g| + E_e|e\rangle\langle e| + E_f|f\rangle\langle f| + \hbar\frac{\Omega}{2}\left(e^{-i\omega_d t}|e\rangle\langle g| + \xi e^{-i\omega_d t}|f\rangle\langle e| + \text{H.c.}\right), \tag{1}$$

where $\omega_d$ is the driving frequency, $\Omega$ is the driving field strength (Rabi frequency), and $\xi$ is the ratio of dipole moments for the two dipole transitions, $|g\rangle \leftrightarrow |e\rangle$ and $|e\rangle \leftrightarrow |f\rangle$. In a frame rotating at $\omega_d$, this Hamiltonian is represented by the time-independent matrix [**?**]:

$$\hat{H} = \begin{pmatrix} 0 & \frac{\Omega}{2} & 0 \\ \frac{\Omega}{2} & -\left(\frac{\alpha}{2}+\delta\right) & \xi\frac{\Omega}{2} \\ 0 & \xi\frac{\Omega}{2} & -2\delta \end{pmatrix}, \tag{2}$$

with $\delta = \omega_d - \omega_{gf}/2$ the detuning of the drive frequency from the two-photon transition and $\alpha = \omega_{ef} - \omega_{ge}$, where $\hbar\omega_{ij} = E_j - E_i$. We explore the effect the drive strength and detuning have on the fluorescence spectrum, which we compute from a Lindblad master equation with decay operator $\hat{\sigma}_-^T = |g\rangle\langle e| + \xi|e\rangle\langle f|$. The numerically computed spectra are then interpreted by diagonalising Eqn. (2) to find the dressed states. If the system is driven at the frequency $\omega_{ge}$ of the lower transition, we see a Mollow triplet formed, similar to that of a two-level system [Fig.1 (Left)] [**?**]. As the drive frequency moves closer to the two-photon transition, significant population is moved to the $|f\rangle$ state and the central peak splits into a triplet while the two side peaks split into doublets [Fig.1 (Left and Right)]. We explain this development in the fluorescence spectrum in terms of transitions between dressed states.

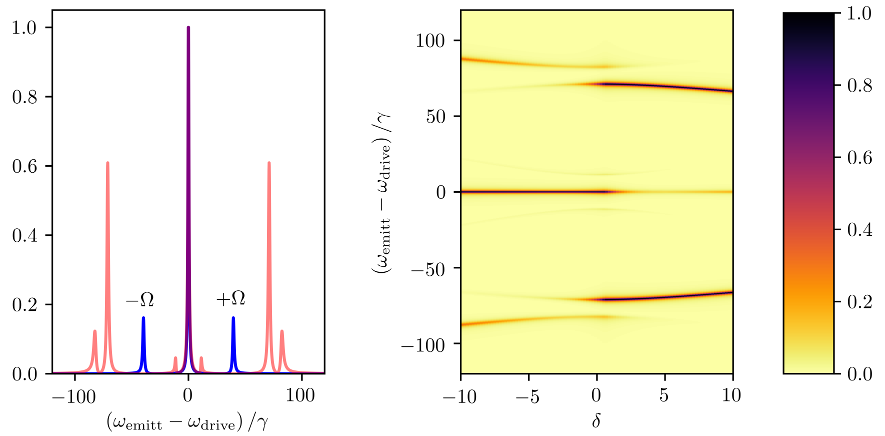


**Figure 1: (Left)** Fluorescence spectrum when the drive is resonant with the ground to first level transition, $\omega_d = \omega_{ge}$ (blue), and resonant with the two-photon transition, $\omega_d = \omega_{gf}/2$ (red). As expected, the side-peaks for the Mollow triplet occur at $\pm\Omega$. **(Right)** As the drive frequency approaches the two-photon resonance, the side peaks split and move due to the dressed-state shifting of the three energy levels. The parameters for both plots are $(\Omega/\gamma, \xi/\gamma, \alpha/\gamma) = (40.0, 1.0, 120.1)$.

## References

[1] Koshino, K., Terai, H., Inomata, K., Yamamoto, T., Qiu, Z., Wang, Z., and Nakamura, Y. "Observation of the Three-State Dressed States in Circuit Quantum Electrodynamics". *Physics Review Letters*, 110, 263601, 2013.

[2] Gasparinetti, S., Pechal, M., Besse, J.C., Mondal, M., Eichler, C. and Wallraff, A. "Correlations and entanglement of microwave photons emitted in a cascade decay". *Physical Review Letters*, 119(14), p.140504, 2017.

[3] Gasparinetti, S., Buijs, R. D., Wallraff, A., et. al. "Two-photon resonance fluorescence of a weakly nonlinear artificial atom", *unpublished*.

[4] Shamailov, S. S., Parkins, A. S., Collett, M. J, and Carmichael, H. J. "Multi-photon blockade and dressing of the dressed states". *Optics Communications*, 283(5):766-722, 2010.

[5] Mollow, B. R, "Power Spectrum of Light Scattered by Two-Level Systems", *Physical Review*, 188(5):1969-1975, 1969.

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