Photon statistics in superradiance

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While the most widely known feature of the cooperative spontaneous emission of atomic ensembles (Dicke’s superradiance [1]) is related to the modification of radiative lifetime, its further striking evidence is represented by a pulsed stochastic nature of superradiant pulses [2]. Motivated by explosive development of photon-correlation spectroscopy to study temporal fluctuations of light intensity at single-photon level (second-order photon correlation function $g^{(2)}(\tau)$ leading to observation of photon bunching or antibunching) we have investigated the statistics of superradiant photons by numerical Monte-Carlo simulations [3-4].

A collection of $N$ two-level systems incoherently and continuously pumped at the rate $\gamma_{\text{pump}}$ is coupled with strength $g$ to a single damped cavity mode with photon lifetime $(2\kappa)^{-1}$. A weak coupling regime is assumed, i.e. $g<\kappa$. The polarization of the atoms can be additionally destroyed at the elastic dephasing rate $\gamma_{\text{deph}}$.

Fig. 1: (a) Second-order correlation function $g^{(2)}(\tau)$ of photons emitted from a single mode cavity resonantly interacting with two incoherently pumped two-level systems shows giant photon bunching with $g^{(2)}(\tau=0)=1$. (b) Photon bunching can be explained by pumping the system from the ground state $|1,-1\rangle$ via the dark state $|0,0\rangle$ into the upper state $|1,1\rangle$, followed by emission of a photon pair through the bright state $|1,0\rangle$. See Ref. [4] for simulation details and parameters.

It comes out that in the absence of dephasing the magnitude of photon bunching $g^{(2)}(\tau=0)=30$ is largest for $N=2$. This is a rather unexpected result in context of a common view that superradiant effects are enhanced for larger $N$. As expected for superradiant phenomena, the bunching maximum is strongly suppressed for higher elastic dephasing or pump rates (often denoted as excitation-induced dephasing). For $N=2$ and in the absence of dephasing, incoherent pumping through the subradiant (dark) state into the upper fully inverted state on a time-scale $\sim \gamma_{\text{deph}}^{-1}$ leads to the subsequent emission of photon pairs via the superradiant (bright) state on a time-scale $\sim (g/\kappa)^4$ leading to a strong bunching peak. The emission rate of the second photon $4g^2/\kappa$ is twice as large as compared to emission rate $2g^2/\kappa$ of a single two level system, which in same fingerprint of superradiance in macroscopic atomic ensembles. In fact, the analysis of semiclassical Langevin equations of superradiance also predicts a strong bunching peak in the second order intensity autocorrelation function, which is the macroscopic counterpart of $g^{(2)}(\tau)$ obtained from true single-photon statistics [4].

The resonant coupling of optical emitters to a single cavity mode considered so far is very difficult to achieve in solid-state based systems like quantum dots even for $N=2$, due to their strong inhomogeneous broadening [3]. Therefore we have performed extended simulations assuming that the dots can be tuned through the resonance with each other and the cavity mode, keeping in mind the possibility to shift quantum dot excitonic energy levels by applying external magnetic or electric fields. Our preliminary results show the pronounced dependence of bunching peak amplitude on the detuning, which will hopefully trigger the development of a new experimental technique – the photon bunching spectroscopy [4].