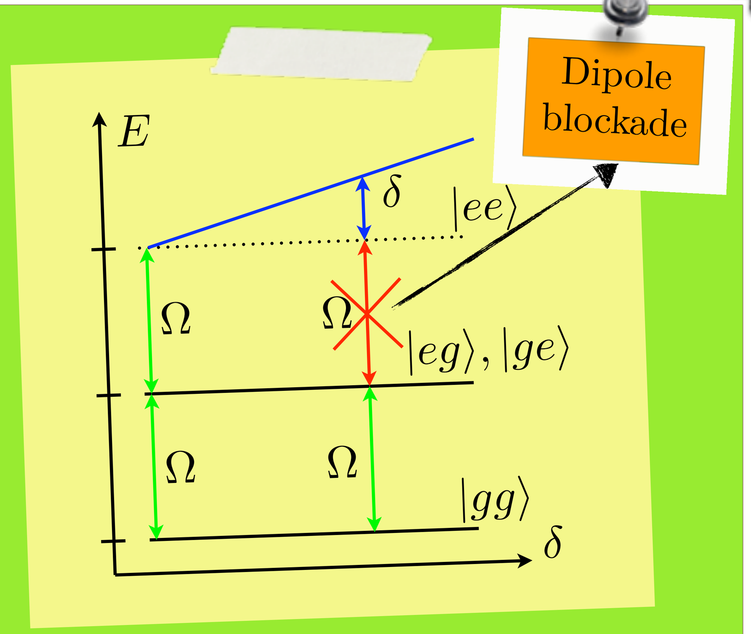
Tunable Entanglement, Antibunching and Saturation Effects in Dipole Blockade

J. Gillet[1], G. S. Agarwal[2] and T. Bastin[1]

[1]Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, 4000 Liège, Belgium
[2]Department of Physics, Oklahoma State University, Stillwater, OK 74078-3072, USA

Introduction

Dipole-dipole interactions between atoms give rise to fascinating applications in quantum information science like quantum logic operations or entanglement production. Those interactions modify the laser excitation of adjacent atoms such that it can be greatly supressed, that is the *dipole blockade* effect. Consider two two-level atoms exposed to a laser field of Rabi frequency 2Ω. We give the interaction Hamiltonian

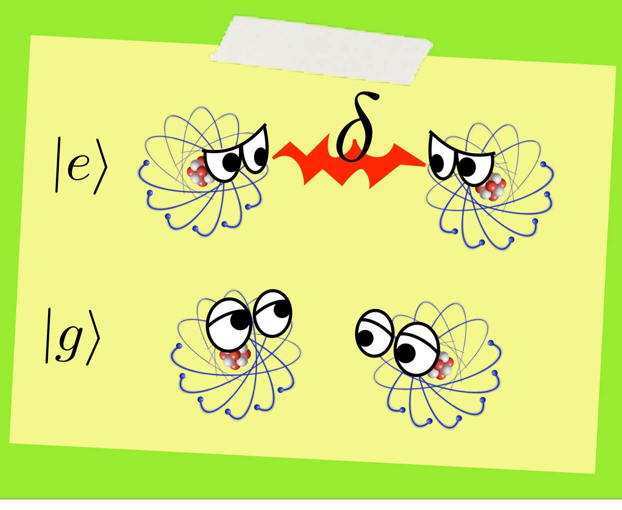


$$H = \hbar\delta|ee\rangle\langle ee| + \hbar\Omega\left(e^{i\mathbf{k}_L\cdot\mathbf{x}_1}S_1^+ + e^{i\mathbf{k}_L\cdot\mathbf{x}_2}S_2^+ + \text{h.c.}\right).$$

The time evolution of the system is governed by the master equation

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] - \gamma\sum_{i=1}^{2}(S_i^+S_i^-\rho + \rho S_i^+S_i^- - 2S_i^-\rho S_i^+),$$

where γ is the total dissipation rate.



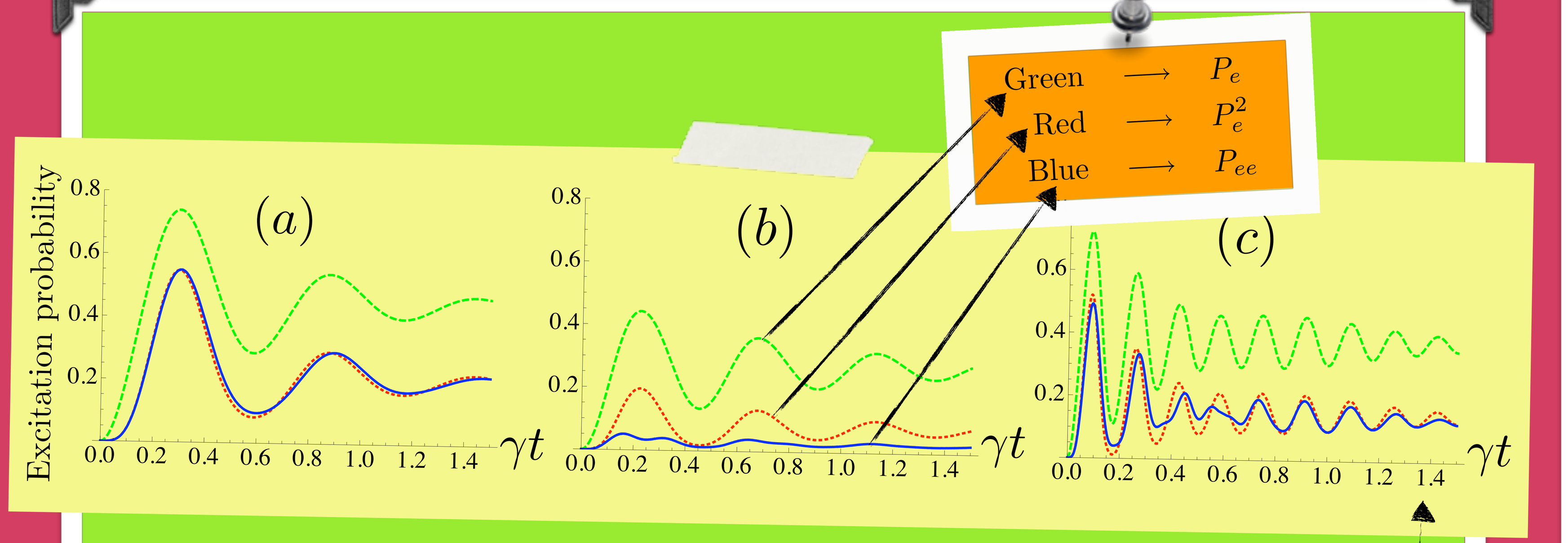
For a given state, we can probe the effects of the dipole blockade with the quantitiy P_{ee}/P_e^2, with

$$P_{ee} = \langle ee|\rho|ee\rangle.$$

$$P_e = \langle e_1|\rho|e_1\rangle = \langle e_2|\rho|e_2\rangle,$$

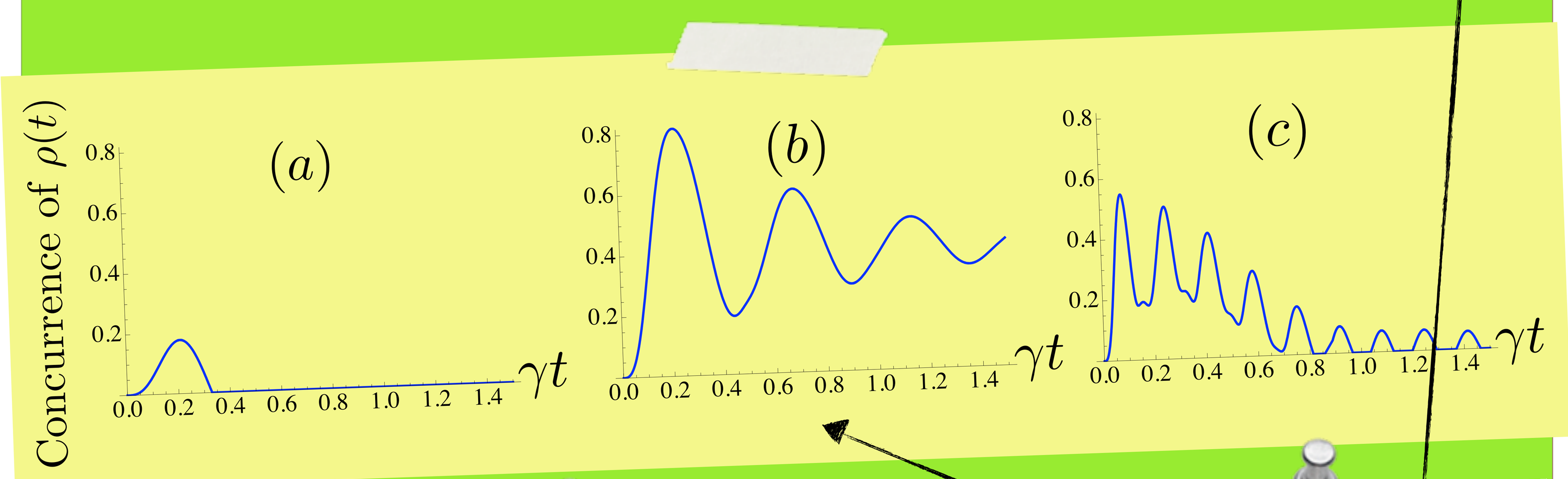
For independant atoms, we have $P_{ee}/P_e^2 = 1$.

Time Evolution



We plotted the time dependant behavior of two atoms initialy in the ground state using the master equation. When the interaction is small, the atoms behave almost independantly, but when it grows, the blockade effect becomes important. We see that increasing the power of the laser lifts off the blockade.

In order to know the amount of entanglement in the system, we plotted below the concurrence of the system. The blockade regime is associated with great values of entanglement. When the laser power is raised, the amount of entanglement drops.



(a) $\Omega/\gamma = 5, \delta/\gamma = 5$
(b) $\Omega/\gamma = 5, \delta/\gamma = 30$
(c) $\Omega/\gamma = 15, \delta/\gamma = 30$

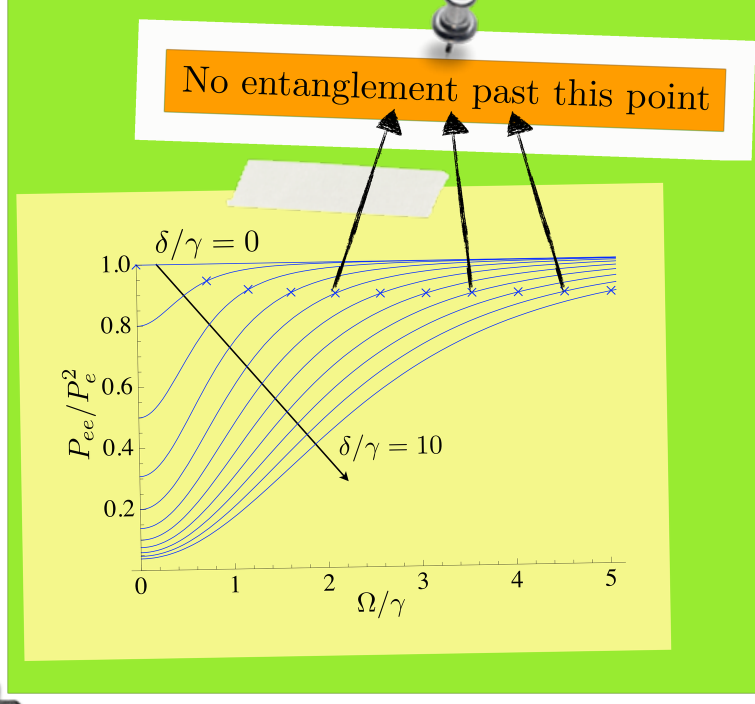
♣Let's play with the dipole blockade!
♡ How many times does the letter 'e' appear in all figures?
♠ Answer on the side.

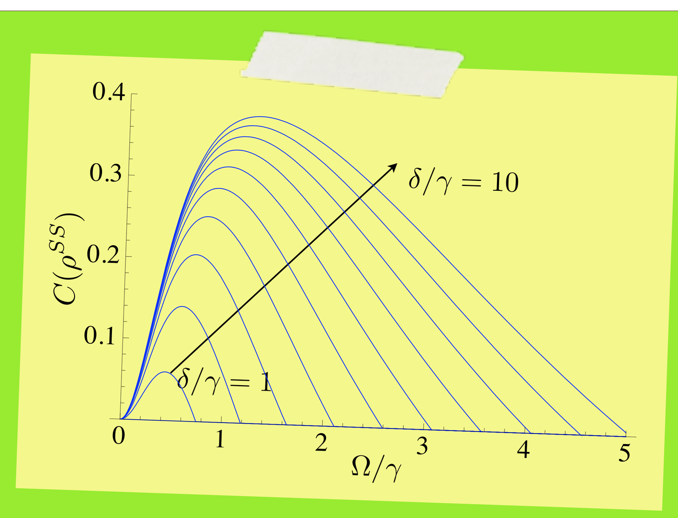
Steady-State

When the atoms reach an equilibrium, the system is in its steady-state. We found the analytical expression of that state, which allows us to check the atoms behavior very easily. We find

$$\left.\frac{P_{ee}}{P_e^2}\right|_{SS} = \frac{64\Omega^4 + 4(4\Omega^2+\gamma^2)|\alpha|^2}{(8\Omega^2+|\alpha|^2)^2},$$

with $\alpha = -(\delta + 2i\gamma)$. That quantity is plotted below. We observe that for a small laser power, the blockade becomes very important as the interaction grows. For greater powers, the atoms tend to behave independantly.





We can also compute the concurrence of the steady state analyticaly. We get

$$C(\rho^{SS}) = \text{Max}\left\{0, \frac{\sqrt{2}\Omega^2(\lambda_+ - \lambda_-) - 8\Omega^4}{16\Omega^4 + (4\Omega^2+\gamma^2)|\alpha|^2}\right\},$$

with

$$\lambda_\pm = \sqrt{8\Omega^4 + \delta^2|\alpha|^2 \pm \delta|\alpha|\sqrt{16\Omega^4 + \delta^2|\alpha|^2}}.$$

The concurrence is plotted above. For a fixed laser power value, the concurrence grows with the interaction. We see that for a given intercation value, we can tune the laser intensity to maximize the entanglement. We find that there is always entanglement in the system if

$$0 < 4\Omega^2 < \delta|\alpha|.$$

Photon-Photon Correlations

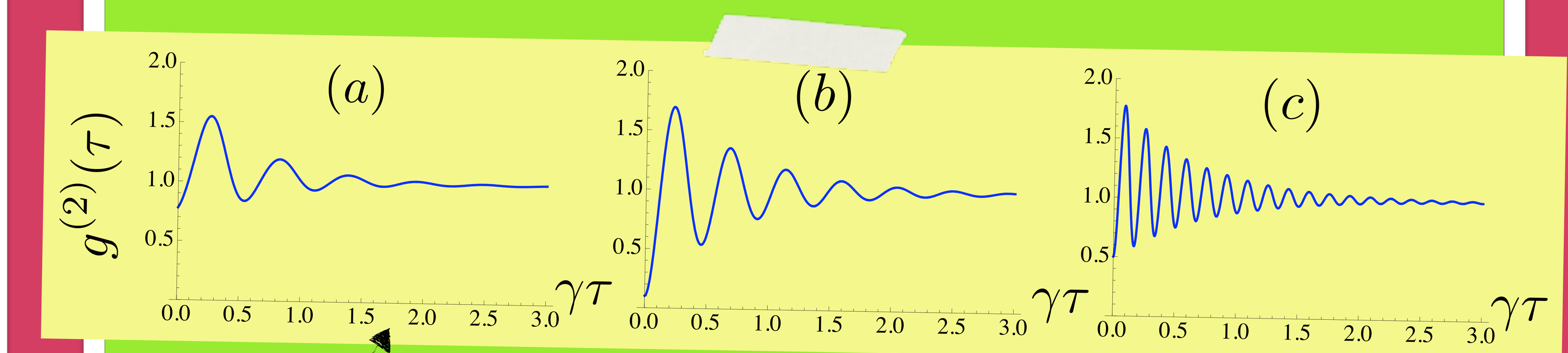
The photon-photon correlation function is defined as

$$g^{(2)}(\mathbf{r}_1,t;\mathbf{r}_2,t+\tau) = \frac{P(\mathbf{r}_2,t+\tau|\mathbf{r}_1,t)}{P(\mathbf{r}_2,t)},$$

where $P(\mathbf{r},t)$ is the probability of detecting a photon at $\mathbf{r}$ and t, and $P(\mathbf{r}_2,t+\tau|\mathbf{r},t)$ the probability of finding another photon later at $\mathbf{r}_2$ and $t+\tau$ if the first one was recorded. We plot that quantity below, for some disposition of the detectors. From the slope of $g^{(2)}$ at small τ, we observe an antibunching behavior in all cases, though stronger when the interaction is higher. For another particular configuration of the detectors we have

$$g^{(2)}(\mathbf{r}_1,0;\mathbf{r}_2,0) = \left.\frac{P_{ee}}{P_e^2}\right|_{SS},$$

which gives us a direct measure of the dipole blockade.



Conclusion

We provide a model able to analyze quantitatively the dipole blockade effect on a two two-level atom system. We show that it is an efficient mechanism for the production of entanglement and tunable with the laser intensity. We observe that the dipole blockade can be lifted in strong driving conditions. Finally we show that for some detector positions, the photon-photon correlation function can continuously monitor the interaction between atoms, which provides an efficient tool in the analysis of dipole blockade [1].

[1] J. Gillet, G. S. Agarwal and T. Bastin, Phys. Rev. A **81**, 013837 (2010)

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◇ The letter 'e' appears twelve times.