Single-photon absorber in Rydberg media

Jan Kumlin and Hans Peter Büchler

Institute for Theoretical Physics III, University of Stuttgart

University of Stuttgart

SFB/TRR 21
Control of Quantum Correlations in Tailored Matter

Abstract

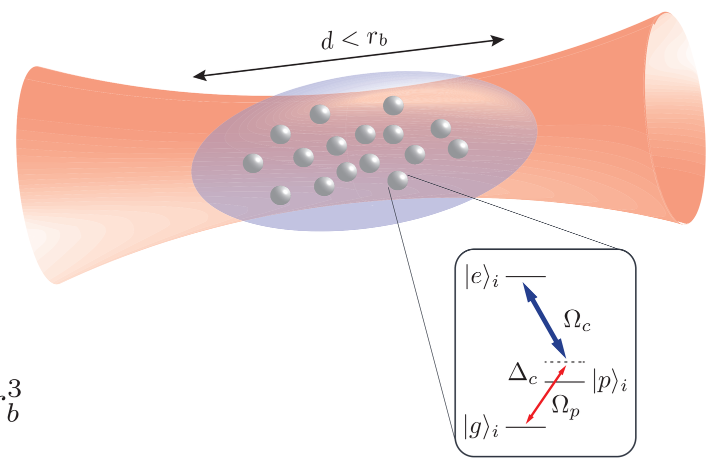
The properties of a dissipative and strongly interacting system of Rydberg atoms give rise to applications like a single-photon absorber [1]. When the atoms are confined in a region smaller than the so-called Rydberg blockade radius, the system can only carry a single excitation. In such a case, a single photon can be absorbed from a pulse leaving the medium transparent for the following ones.
For such a setup, we consider a quantum master equation approach in continuous media where the largest energy scale is the absorption rate of the medium also accounting for the saturation of the medium. We present a general solution for an arbitrary incoming light field extending the results given in [2].

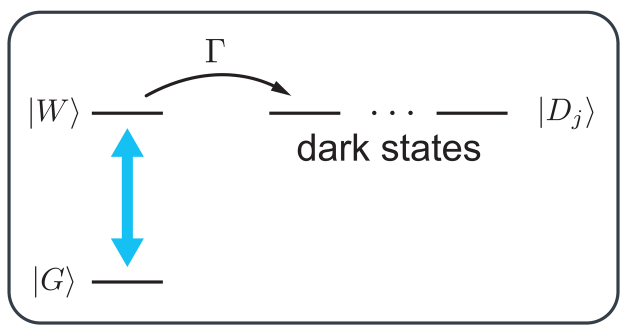
The model

» ensemble of atoms driven resonantly into Rydberg state

» strong interactions due to large dipole-dipole interactions

➤ Rydberg blockade
➢ only one excitation inside volume $V \sim r_b^3$





» describe atomic ensemble as two-level system (TLS) ➢ 'super-atom' $\{|G\rangle, |W\rangle\}$

» collective states $|G\rangle = \otimes_i |g_i\rangle$

$$|W\rangle = \frac{1}{\sqrt{N}} \sum_i |e_i\rangle \otimes_{j\neq i} |g_j\rangle$$

» dephasing Γ into dark states leads to dissipative dynamics

» Γ can be interpreted as an absorption rate

» 1D system with density $n(x)$

» assume Γ to be largest energy scale, neglect coherent dynamics of TLS (i.e. no Rabi oscillations)
➢ only dissipative dynamics!

➤ description via quantum master equation

$$\partial_t \rho = \underbrace{-\frac{i}{\hbar}[H,\rho]}_{\text{propagation}} + \underbrace{\Gamma \int \mathrm{d}x\, n(x) \left(c(x)\rho c^\dagger(x) - \frac{1}{2}\left\{c^\dagger(x)c(x), \rho\right\}\right)}_{\text{non-unitary (dissipative) dynamics}}$$

$H = \int \mathrm{d}k\, \hbar k\, a^\dagger(k)a(k)$ quantum jumps damping

$c^\dagger(x) = a^\dagger(x)|G\rangle\langle E|$ ⟶ $\boxed{c^\dagger(x')c^\dagger(x) \equiv 0}$

$|E\rangle$ state with single excitation that does not couple to the light field ➢ only one excitation allowed!

Solving the quantum master equation

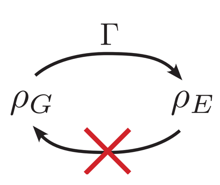
» split the system into $|G\rangle$ subspace and $|E\rangle$ subspace

$$\rho = \begin{pmatrix} \langle G|\rho|G\rangle & 0 \\ 0 & \langle E|\rho|E\rangle \end{pmatrix} = \begin{pmatrix} \rho_G & 0 \\ 0 & \rho_E \end{pmatrix}$$

» two sets of differential equations

$$\partial_t \rho_G = -\frac{i}{\hbar}[H,\rho_G] - \frac{\Gamma}{2}\int \mathrm{d}x\, n(x)\left\{a^\dagger(x)a(x), \rho_G\right\} \quad ➢ \quad i\hbar\partial_t|\Psi\rangle = (H - i\hbar\tilde{\Gamma}/2)|\Psi\rangle$$

$$\partial_t \rho_E = -\frac{i}{\hbar}[H,\rho_E] + \Gamma\int \mathrm{d}x\, n(x) a(x)\rho_G a^\dagger(x)$$



» ansatz for ρ_G and ρ_E

$$\rho_G = |\Psi\rangle\langle\Psi|, \qquad |\Psi\rangle = \sum_n c_n \left[\int \mathrm{d}x\, \phi(x,t)a^\dagger(x)\right]^n |0\rangle$$

$$\rho_E = \sum_{n,n'} \int \mathrm{d}\mathbf{x}_n \int \mathrm{d}\mathbf{y}_{n'}\, \xi_{n,n'}(\mathbf{x}_n, \mathbf{y}_{n'}, t)|\mathbf{x}_n\rangle\langle\mathbf{y}_{n'}|$$

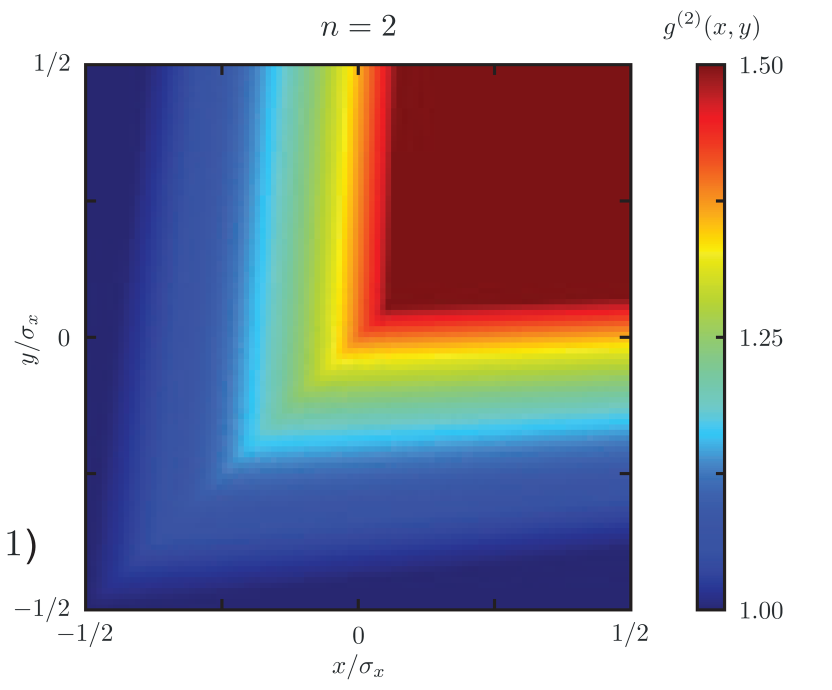
» full solution for $t \to \infty$ with initial conditions $\rho_E(t \to -\infty) = 0$, $\phi(x, t \to -\infty) = \phi_0(x - t)$

$$\xi_{n,n'}(\mathbf{x}_n, \mathbf{y}_{n'}) = c^*_{n+1}c_{n'+1}\sqrt{n+1}\sqrt{n'+1}\prod_i^n \phi_0^*(x_i)\prod_j^{n'}\phi_0(y_j) \int_{-\infty}^{\infty} \mathrm{d}s\, \gamma(s) \exp\left\{-\frac{1}{2}\left(\sum_{i=1}^n \eta(x_i+s) + \sum_{j=1}^{n'}\eta(y_j+s)\right)\right\}$$

➢ $\eta(x) = \Gamma \int_{-\infty}^{x} \mathrm{d}z\, n(z)$ ➢ $\gamma(s) = \Gamma \int \mathrm{d}x\, n(x)|\phi_0(x)|^2 \exp\left(-\eta(x+s)\right)$

Second-order correlation function

$$g^{(2)}(x,y) = \frac{\langle a^\dagger(x)a^\dagger(y)a(y)a(x)\rangle}{\langle a^\dagger(x)a(x)\rangle\langle a^\dagger(y)a(y)\rangle}$$



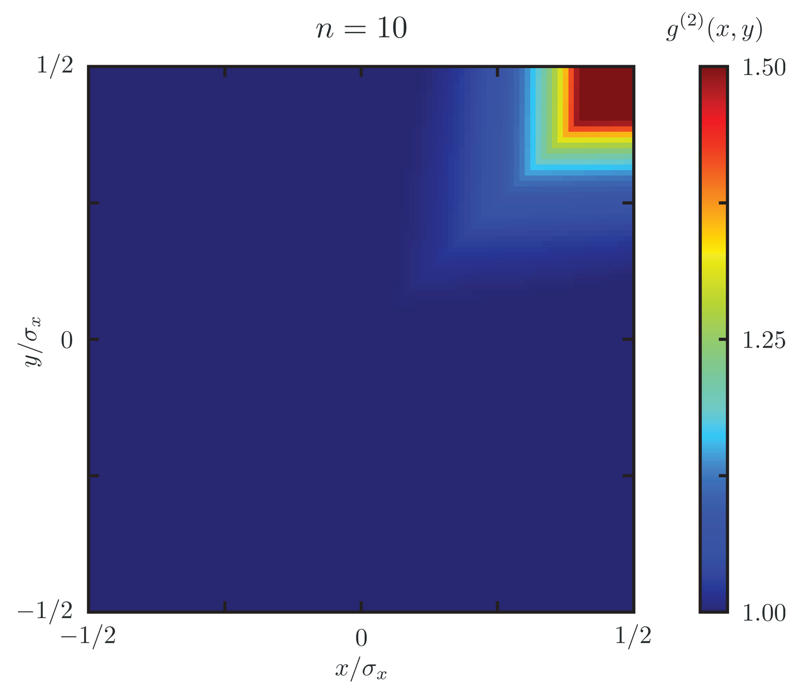
» consider box shaped incoming pulse

$$\phi_0^2(x) = \begin{cases} \frac{1}{\sigma_x}, & -\frac{\sigma_x}{2} \le x \le -\frac{\sigma_x}{2} \\ 0, & \text{otherwise} \end{cases}$$

» coherent state $|c_m|^2 = e^{-n}\frac{n^m}{m!}$

» Gaussian medium of length L $(\sigma_x/L \gg 1)$

» strong absorption $(\mathrm{OD} = 12)$



➤ strong bunching feature at beginning of the pulse!!

➤ 'size' of bunching feature decreases with increasing mean photon number

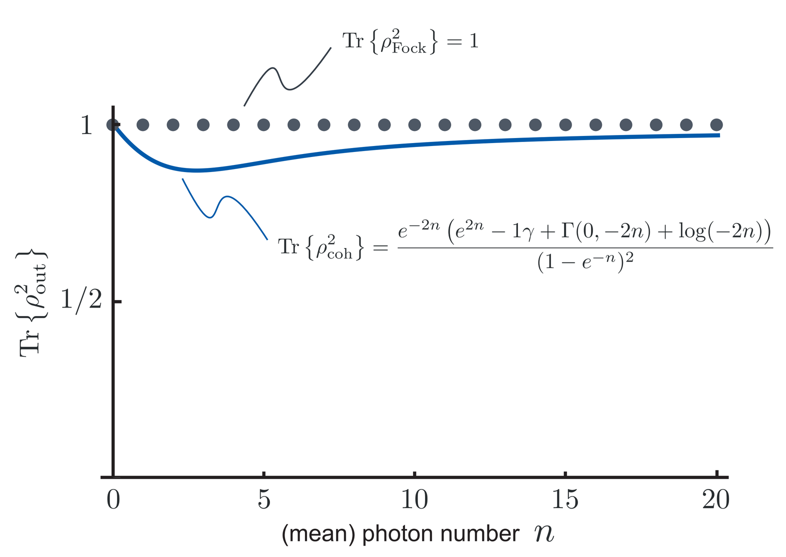
Purity of the outgoing state

$$\mathrm{Tr}\left\{\rho_{\mathrm{out}}^2\right\} = \sum_{n,n'} \frac{|c_{n+1}|^2|c_{n'+1}|^2}{(1-|c_0|^2)^2}(n+1)(n'+1)\int \mathrm{d}s \int \mathrm{d}t\, \partial_s r(s)\partial_t r(t)\left(R(s,t)\right)^{n+n'}$$

➢ $r(s) = \int \mathrm{d}x\, \phi_0^2(x)e^{-\eta(x+s)}$ ➢ $R(s,t) = \int \mathrm{d}x\, \phi_0^2(x)e^{-\frac{1}{2}\eta(x+s)-\frac{1}{2}\eta(x+t)}$

Weak absorption limit

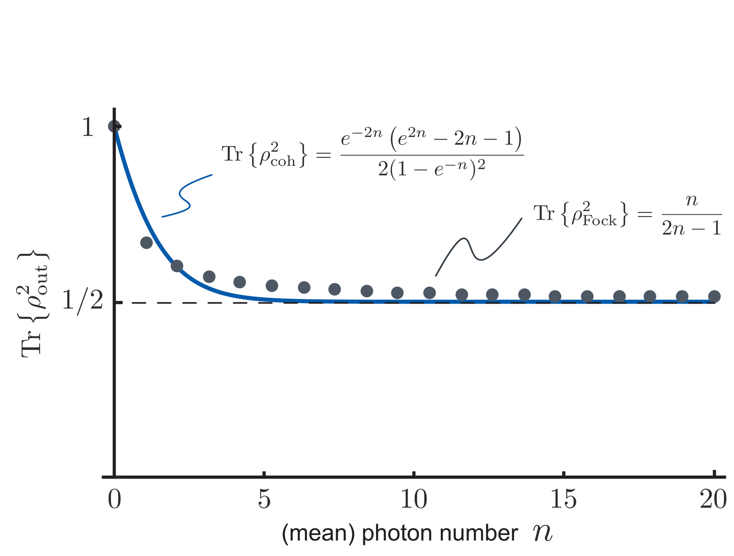
$$\mathrm{Tr}\left\{\rho_{\mathrm{out}}^2\right\} = \sum_{n,n'} \frac{|c_{n+1}|^2|c_{n'+1}|^2}{(1-|c_0|^2)^2}\frac{4(n+1)(n'+1)}{(n+n'+2)^2}$$



$$\mathrm{Tr}\left\{\rho_{\mathrm{out}}^2\right\} \xrightarrow{n\to\infty} 1$$

Strong absorption limit

$$\mathrm{Tr}\left\{\rho_{\mathrm{out}}^2\right\} = \sum_{n,n'} \frac{|c_{n+1}|^2|c_{n'+1}|^2}{(1-|c_0|^2)^2}\frac{2(n+1)(n'+1)}{(n+n'+1)(n+n'+2)}$$



$$\mathrm{Tr}\left\{\rho_{\mathrm{out}}^2\right\} \xrightarrow{n\to\infty} 1/2$$ ➢ mixed state

References

[1] J. Honer, R. Löw, H.Weimer, T. Pfau, and H.P. Büchler, PRL **107**, 093601 (2011)

[2] A. V. Gorshkov, R. Nath, and T. Pohl, PRL **110**, 153601 (2013)