Geometry dependent suppression of collective quantum jumps in Rydberg atoms

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1. System

• The large dipole moment of Rydberg atoms can lead to a Rydberg blockade [1] and collective quantum jumps [2] with applications for quantum information processing [3].

• We consider a system of $N$ driven, damped two-level atoms. Making the electric dipole and rotating wave approximations the Hamiltonian in the interaction picture is

$$H = \sum_{j=1}^{N} \left[ -\mu_0 \mathbf{E}_0 \mathbf{j}_0 \cdot \mathbf{\sigma}_j + \hbar \Omega \left( \mathbf{j}_j^{(\sigma)} - \mathbf{j}_j^{(1-\sigma)} \right) \right]$$

where $\mu_0$ is the Pauli lowering operator for the $j$th atom, $\mathbf{E}_0$ is the driving laser from the atomic resonance, $\Omega$ is the Rabi frequency, and $\mathbf{\sigma}$ is a constant that accounts for the long-range interaction between the Rydberg atoms in their excited states.

• Considering a system of two atoms the double excited state is shifted upward in energy by the term in the Hamiltonian as shown in Fig. 1. Shifts between multi atom systems vary in size as a result of their geometric configurations.

\begin{equation}
\begin{bmatrix}
|gg\rangle \\
|eg\rangle \\
|ge\rangle \\
|ee\rangle
\end{bmatrix} = \mathbf{V} \begin{bmatrix}
|gg\rangle \\
|eg\rangle \\
|ge\rangle \\
|ee\rangle
\end{bmatrix}
\end{equation}

Figure 1: When $\Delta > 0$ the double excited state is shifted out of resonance and excitation is suppressed as seen on the right. This is the familiar Rydberg blockade effect. When $\Delta = 0$ the double excited state is on resonance via a two photon transition. The shifts are also dependent on the arrangement of atoms as seen on the right.

• We include damping using a master equation derived in the Born-Markov approximation:

$$\dot{\rho} = -i [H, \rho] + \sum_{\sigma \neq 1} \left( 2 \mathbf{\sigma} \rho \mathbf{\sigma}_\sigma - \mathbf{\sigma}_\sigma \rho - \mathbf{\sigma}_\sigma \rho \right)$$

describes independent spontaneous emission and

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describes collective spontaneous emission where $\mathbf{J}_j = \sum_{\sigma \neq 1} \mathbf{\sigma}_\sigma$.

• We compare the average jump length of collective quantum jumps for various separation distances. Limiting cases were also checked for fully independent and fully collective collapse operators.

2. Methods

• We numerically solve the master equation for the system by means of a quantum trajectory simulation implemented using the Quantum Tools in Python (Qutip) [4, 5].

• The intermediate case was accomplished by introducing a $\gamma_j$ term that was used to define the spontaneous emission of a set of dipoles [6, 7].

$$\gamma_j = \frac{1}{2} \left( |\Delta|^2 \sum_{\sigma \neq 1} \mathbf{\sigma}_\sigma \rho - \mathbf{\sigma}_\sigma \rho - \mathbf{\sigma}_\sigma \rho \right)$$

where $\Delta_j = \hbar \Omega_j / 2 \pi / \lambda_j$, $\tau_j = \gamma_j \rho / \Delta_j$, and $\mathbf{\sigma}_\sigma$ is the $\sigma_j$ matrix which calculates the $\gamma_j$ matrix and used to determine the collapse operator for our system by $J_j = \sum_{\sigma \neq 1} \mathbf{\sigma}_\sigma$, where $J_j$ is the $\sigma_j$ collapse operator.

• For a system that is separated by a large distance, the eigenvalues of our $J_j$ matrix approach one leaving our system like independent emission. At the other limit, where our distances become very small the eigenvalues of the $\gamma_j$ matrix would approach zero except for one which approaches 1.

Independent case: $\{1, 0, 0, 0\} \Rightarrow \lambda = 1$

Collective case: $\{1, 1, 1, 1\} \Rightarrow \lambda = N$

3. Quantum Trajectory Results

• To explore the state of a single quantum trajectory a Monte Carlo method was implemented in QuTiP. The average energy of the system is computed as a function of time. This simulation was run for various separation lengths. As the atoms get closer together their emission type becomes more like collective spontaneous emission and the quantum jumps seem to disappear.

4. Quantum Jumps

• The excitation population is show as the emission type changes. As the atoms move closer together they emit collectively, and they jumps are inhibited.

5. Future Work

• We plan to explore the properties of these collective quantum jumps as a function of geometry as well as distance. As the atoms move closer together becomes more collective which inhibits the collective jumps. The larger the shift in the energies the more likely there is for jumps to occur. The $\lambda_j$ increases as distance is shorted. We want to see for what conditions are jumps still show as distance is varied and $\lambda_j$ competes with the collective emission.

References


