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Rydberg assisted light shift imbalance induced blockade in an atomic ensemble

Yanfei Tu [a,*], May E. Kim [b], Selim M. Shahriar [a,b]

[a] Department of Electrical Engineering & Computer Science, Northwestern University, Evanston, IL 60208, USA
[b] Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208, USA

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ABSTRACT

Previously, we had proposed the technique of light shift imbalance induced blockade which leads to a condition where a collection of non-interacting atoms under laser excitation remains combined to a superposition of the ground and the first excited states, thus realizing a collective state quantum bit which in turn can be used to realize a quantum computer. In this paper, we show first that the light shift imbalance by itself is actually not enough to produce such a blockade, and explain the reason why the limitation of our previous analysis had reached this constraint. We then show that by introducing Rydberg interaction, it is possible to achieve such a blockade for a wide range of parameters. Analytic arguments used to establish these results are confirmed by numerical simulations. The fidelity of coupled quantum gates based on such collective state qubits is highly insensitive to the exact number of atoms in the ensemble. As such, this approach may prove to be viable for scalable quantum computing based on neutral atoms.

1. Introduction

In most protocols for quantum computing or quantum information processing, the fundamental building block is the quantum bit (qubit). A single, neutral atom behaving as a two-level system can be used as a qubit. Compared to ions, neutral atoms have the advantage that they are highly decoupled from electromagnetic perturbations. However, coupling two qubits using neutral atoms is difficult to achieve. One approach for such coupling makes use of the Rydberg blockade [1–7]. In another approach, a cavity mode is used to couple atoms held inside the cavity [8–11]. A key parameter in this approach is the single photon Rabi frequency, which must be much larger than atomic and cavity decay rates. This constraint can only be met by making the cavity very small, which in turn makes it difficult to hold many qubits inside.

One approach for circumventing this constraint is to make use of atomic ensembles. The single photon Rabi frequency for an ensemble scales as $\sqrt{N}$, where N is the number of atoms, thus making it possible to make use of a much larger cavity. However, in order to use an ensemble for quantum computing, it is necessary to ensure that it behaves as an effective two-level system.

When exposed to only a single photon (or in a Raman transition, where one leg is exposed to a single photon), an ensemble of two-level atoms does indeed behave like a single two-level system. This property has been used to realize quantum memory elements using such an ensemble [12,13]. However, any protocol that aims to create a two qubit logic gate (such as a CNOT gate) between two ensembles, necessary for realizing a quantum computer, must make use of additional, classical laser fields. Under such excitations, an ensemble no longer behaves like a two-level system. Instead, it exhibits a cascade of energy levels that are equally spaced. When exposed to a classical field, all levels in the cascade get excited [14], making it impossible to realize a quantum logic gate. In order to overcome this constraint, it is necessary to create conditions under which the cascade is truncated to a two-level system.

Previously, our group had proposed a scheme for producing such a blockade, using imbalances in light shifts experienced by the collective states [15,16]. In that model, the light shifts were calculated by using a perturbation method, keeping terms up to second-order in laser intensity. However, it turns out that when the collective excitation is viewed as a product of individual atomic states, an accurate representation for classical laser fields, and in the absence of any interaction between the atoms, the blockade effect disappears. We have verified this conclusion by numerically simulating the evolution of collective states for small values of N. It is still possible to produce such a blockade for a laser field described as a superposition of photon number states.

* Corresponding author.
E-mail address: yanfeitu@gmail.com (Y. Tu).

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However, when the mean photon number in such a field is very large, such as in a classical laser field, the blockade tends to vanish. Thus, in order to produce a blockade under excitation with a classical laser field, we must make use of some interaction between the atoms. In this paper, we propose to make use of interaction induced via excitation to Rydberg states to achieve this goal.

The rest of the paper is organized as follows. In Section 2, we review briefly the formulation of collective excitation of lambda-type atoms. In Section 3, we summarize the model we had developed previously for light shift blockade (LSB) of collective excitation using second-order perturbation approximation. In Section 4 we discuss how an alternative formulation of collective excitation allows us to determine the effect of light shift exactly, and identify conditions under which LSB is not possible. In particular, we show that when all excitation fields are classical, there is no blockade. In Section 5, we show how the interaction between two Rydberg states can be used to realize LSB even under classical excitation. In Section 6, we generalize this process for N atoms and show how LSB works for N-atom ensembles. Finally, in Section 7, we summarize our results, and present an outlook for using this approach for realizing a multi-qubit quantum computer.

2. Collective state model

In order to avoid the deleterious effect of spontaneous emission, it is useful to realize a qubit based on two states that are long-lived. A convenient example for such a system consists of a Zeeman sublevel in one of the ground hyperfine state (e.g. $m_F=0$, $F=1$, $5^2S_{1/2}$ in ^{87}Rb) and another Zeeman sublevel in another ground hyperfine state (e.g. $m_F=0$, $F=2$, $5^2S_{1/2}$ in ^{87}Rb). These levels can be coupled by two laser fields to an intermediate state (e.g. $m_F=1$, $F=2$, $5^2P_{1/2}$ in ^{87}Rb). When the interaction is highly detuned with respect to the intermediate state, the laser fields cause a Raman transition between the two low lying states, thus producing an effective two-level system.

This is generally known as the Λ-system, illustrated schematically in Fig. 1. Here, the two ground states are $|a\rangle$ and $|c\rangle$, and the intermediate state is $|g\rangle$. The states $|a\rangle$ and $|g\rangle$ are coupled by a field with a Rabi frequency of Ω_1 and a detuning of δ_1. Likewise, states $|c\rangle$ and $|g\rangle$ are coupled by a field with a Rabi frequency of Ω_2 and a detuning of δ_2. In the basis of states $|a\rangle$, $|c\rangle$ and $|g\rangle$, the Hamiltonian under electric dipole and rotating wave approximation, and

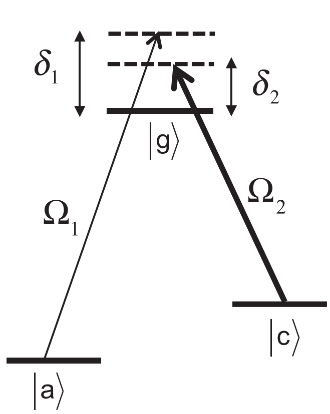

Fig. 1. Three-level scheme of single atom in an ensemble.

rotating wave transportation, is given by

$$\widetilde{H} = \hbar \begin{bmatrix} \Delta/2 & 0 & \Omega_1/2 \\ 0 & -\Delta/2 & \Omega_2/2 \\ \Omega_1/2 & \Omega_2/2 & -\delta \end{bmatrix}, \tag{1}$$

where $\delta \equiv (\delta_1 + \delta_2)/2$ is the average detuning and $\Delta \equiv (\delta_1 - \delta_2)$ is the two-photon detuning. In what follows, we will assume that δ is very large compared to Ω_1 and Ω_2, as well as the decay rate, Γ, of the state $|g\rangle$. We will further assume that the two lasers are co-propagating.

For N such non-interacting atoms, the ensemble can be modeled using symmetric collective states, also known as symmetric Dicke states [14]. The first few states are defined as follows:

$$|A\rangle \equiv |a_1, a_2, \cdot\cdot, a_N\rangle,$$

$$|G_1\rangle \equiv \frac{1}{\sqrt{N}} \sum_{j=1}^{N} |a_1, a_2, \cdot\cdot, g_j, \cdot\cdot, a_N\rangle,$$

$$|C_1\rangle \equiv \frac{1}{\sqrt{N}} \sum_{j=1}^{N} |a_1, a_2, \cdot\cdot, c_j, \cdot\cdot, a_N\rangle,$$

$$|G_2\rangle \equiv \frac{1}{\sqrt{^N C_2}} \sum_{j,k(j\neq k)}^{^N C_2} |a_1, a_2, \cdot\cdot, g_j, \cdot\cdot, g_k, \cdot\cdot, a_N\rangle,$$

$$|C_2\rangle \equiv \frac{1}{\sqrt{^N C_2}} \sum_{j,k(j\neq k)}^{^N C_2} |a_1, a_2, \cdot\cdot, c_j, \cdot\cdot, c_k, \cdot\cdot, a_N\rangle,$$

$$|G_{1,1}\rangle \equiv \frac{1}{\sqrt{2\,^N C_2}} \sum_{j,k(j\neq k)}^{2\,^N C_2} |a_1, a_2, \cdot\cdot, g_j, \cdot\cdot, c_k, \cdot\cdot, a_N\rangle,$$

$$|G_{2,1}\rangle \equiv \frac{1}{\sqrt{3\,^N C_3}} \sum_{j,k,l(j\neq k\neq l)}^{3\,^N C_3} |a_1, a_2, \cdot\cdot, g_j, \cdot\cdot, g_k, \cdot\cdot, c_l, \cdot\cdot, a_N\rangle,$$

$$|G_{1,2}\rangle \equiv \frac{1}{\sqrt{3\,^N C_3}} \sum_{j,k,l(j\neq k\neq l)}^{3\,^N C_3} |a_1, a_2, \cdot\cdot, g_j, \cdot\cdot, c_k, \cdot\cdot, c_l, \cdot\cdot, a_N\rangle. \tag{2}$$

where

$$^N C_M \equiv \binom{N}{M} \equiv N!/\left[M!(N-M)!\right].$$

In Reference [17], we have shown that the system remains confined to a generalized form of these symmetric collective states, independent of the relative separation between the atoms (and hence the size of the ensemble), as long as it is assumed that each atom sees the same amplitude of the Rabi frequency, and the same laser frequency (i.e., any residual Doppler shift of the Raman transition frequency due to the motion of the atoms is negligible). The generalized form of the symmetric states is formally the same as those in Eq. (2), except that the excited states incorporate the relevant spatial phases of the fields at the location of a given atom. This can be understood by noting that any phase factors accompanying the Rabi frequencies in the Hamiltonian of Eq. (1) can be transformed out to produce a version of the Hamiltonian where the Rabi frequencies are real. The transformation necessary for this transfers the phases to the basis states. We refer the reader to Reference [17] for details.