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Rydberg Atoms and Strongly Coupled Atom-Light Systems

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Abstract. Since the discovery of the Rydberg atom in 1885, research on the Rydberg atom has presented numerous discoveries about the Rydberg atom. As the atoms has valence electron in a high principal quantum number state, Rydberg atoms can interact with each other in a unique way, such as dipole-dipole interactions, Rydberg blockade and anti-blockade. To reach the Rydberg state, it is usually necessary to use a laser to excite the atoms from their ground state. Due to the special characteristics about Rydberg atoms as well as their interactions, it has demonstrated promising of application in different fields, for example, quantum computing and quantum information, as well as nonlinear optics and photonics. However, due to the technical limitations, the demand of deterministic atoms sources and the effect of blackbody radiation are still hindering the research relative to Rydberg atoms. For future study relative to Rydberg atoms, the additions with laser-trapping could be beneficial for fields like quantum electro dynamics and localized electromagnetic field probing.

Keywords: Rydberg atoms; Strongly coupled systems; Atomic physics.

1. Introduction

The Rydberg atoms was first discovered in 1885, as Johann Balmer proposed Balmer's formula to explain the hydrogen atoms' spectra [1], few years later, Johannes Rydberg also proposed Rydberg formula to explain the spectra of general spectroscopic material. The results shown that Rydberg developed his formulae entirely independently of Balmer's and because of the generality of Rydberg's formula, Balmer's formula was an example of Rydberg's formula [2]. Rydberg atoms was defined to be the atoms which has the trait as their valence electron could be in a high principal quantum number (n) state [1].

The study of highly excited Rydberg atoms has yielded a number of fascinating discoveries during the last 20 years, leading to an explosion of activity in Rydberg atom physics. Numerous in-depth reviews have been published on the topic, highlighting different facets of contemporary Rydberg atom physics, including both theoretical and practical aspects. Some of the related topics are dipole-dipole interactions between Rudberg atoms, Rydberg blockade and anti-blockade and quantum information [3]. The application of Rydberg atoms includes using interactions of Rydberg atoms to facilitate large scale quantum entanglement thereby benefits quantum information and quantum simulations; promote the plasma-related experiments, quantum optics, non-linear optics and photonics, etc.

This paper discusses some of the basic features of Rydberg atoms and some of the interactions between Rydberg atoms. In addition, some limitations, applications or future research directions related to Rydberg atoms were discussed.

2. Rydberg Atoms in Strongly Coupled Systems

2.1. Dipole-Dipole interactions

There exist multiple types of Rydberg-Rydberg interactions, such as Van der Waals regime, Förster resonance and the resonant dipole-dipole interaction of two distinct Rydberg states (See Figure 1).

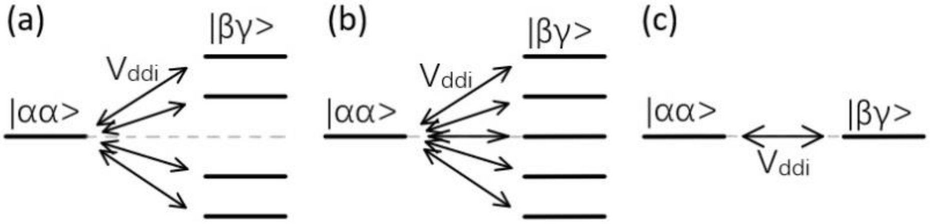

Figure 1. Three types of Rydberg atoms interaction. (a) Rydberg atoms interaction in Van der Waals regime. (b) Rydberg atoms interaction in Förster resonance. (c) Rydberg atoms interaction as the resonant dipole-dipole interaction.

The Hamiltonian interaction term for two Rydberg atoms can be expressed as:

$$V_{ddi}=\frac{1}{4\pi\varepsilon_0}\frac{d_1\cdot d_2-3(d_1\cdot n)(d_1\cdot n)}{R^3} \tag{1}$$

As the distance between two Rydberg atoms is r_2-r_1 and R is defined to be the absolute value of distance between two Rydberg atoms, $n = (r_2-r_1)/R$ and d_i is the electric dipole operator.

For the Van der Waals regime, two Rydberg atoms have identical state and there exists no degeneracy between their combined paired state with other paired states. By applying the nondegenerate perturbation theory, the energy shift is then represented as:

$$\Delta E_{\alpha\alpha}=\sum_{\beta,\gamma\ldots}\frac{|\langle\alpha\alpha|V_{ddi}|\beta\gamma\rangle|^2}{E_{\alpha\alpha}-E_{\beta\gamma}} \tag{2}$$

Where $E_{\alpha\alpha}$ and $E_{\beta\gamma}$ are the energy of the states |αα> and |βγ> and the sum includes all dipole coupled states with |α>. If the system contains more than 2 Rydberg atoms, the Van der Waal interactions are additive.

When the combined paired state of two Rydberg atoms is approximately degenerate with another paired state and omitting the non-resonant coupling effect, both paired states could be kept and coupled via dipole-dipole interaction with a slight difference in their energies called Förster defect ($\Delta=E_{\alpha\alpha}-E_{\beta\gamma}$) [4]. However, it is feasible to generate two degenerate states in practical by using a moderate electric field to the paired Rydberg atoms. And under the application of the moderate electric fields, the interaction of two paired states could be adjusted to either weak Van der Waals regime interaction (two paired state isolated apart by large energy difference) or the strong Förster resonance interaction (two degenerate paired state) [4].

For the resonant dipole-dipole interaction between two paired states, each state consists two Rydberg atoms α and β, one is in nS Rydberg state and the other is in n′P Rydberg state [4]. Once those two Rydberg atoms paired up, |αβ> state will be degenerate with |βα> state, causing the coupling of two degenerate states via the dipole-dipole Hamiltonian.

General explanation for the effects of Rydberg atoms dipole-dipole interactions is provided by the above explanations. However, in some situation such as numerous proximity Rydberg states for large n will no longer result in typical Van der Waal regime [4], necessitating a full numerical calculation of the pair's energy spectrum for an accurate comparison with experiments.

2.2. Rydberg Blockade and Anti-blockade

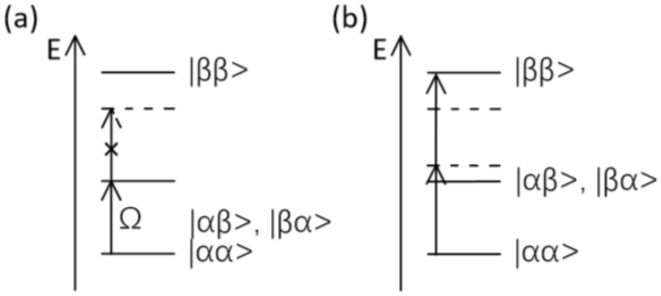

Figure 2. (a) Schematic of Rydberg blockade. (b) Schematic of Rydberg anti-blockade.

For a Rydberg atom in |α> ground state coupled with another Rydberg atom in |β> exited state by a resonant laser with Rabi frequency Ω, the combined ground state |αα> is still coupled to the single excited state |αβ> or |βα>, where only one of two atoms is excited in the combined state [4]. Nevertheless, the double excited state |ββ> is not coupled with exited state |αβ> or |βα> by the resonant laser with Rabi frequency Ω due to the Van der Waal interaction between those two exited atoms, resulting in a higher energy state and causing the Rydberg blockade [4] as shown in Figure 2.

There were a few experiments that demonstrated Rydberg blockade, such as Wisconsin experiment, Palais au experiment and Sandia experiment [4]. Wisconsin experiment demonstrated that the control atom's state governs the target atom's Rydberg excitation and shows the typical Rydberg blockade effect [4]. The Palais au experiment and Sandia experiment both demonstrates that there exists a $\sqrt{2}$ scaled augmentation of the collective Rabi oscillation and a suppression of the change to excite two atoms simultaneously [4].

In contrast to the Rydberg blockade, there also exists Rydberg anti-blockade, which typically has two types [5]. The first type is achieved when the weak Rydberg-Rydberg interaction strength is substantially less than the magnitude of the Rabi frequency [5]. The second type is achieved by adjusting the Rydberg-Rydberg interaction using the blue-detuned laser to reach for the scenario that the total detuning for an arbitrary Rydberg atom equals to the total Rydberg-Rydberg interaction strength for an arbitrary pair of Rydberg atoms [5].

2.3. Preparation of Rydberg States

One way to prepare a single Rydberg atom is to use the magneto-optical trap and acousto-optic deflector to construct a tweezer array [6]. Firstly, the sample atoms have been prepared in a designated internal ground state, then the ground state atoms are transferred into tweezer array from the magneto-optical trap and it employs a feedback process to remove the entropy related to the probabilistic trap loading [6]. After that, the magneto-optical trap has been turned off to let the atoms couple with the tweezer array laser to get excited into Rydberg state [6]. Finally, the magneto-optical trap is turned back on and the excited Rydberg atoms is therefore ejected from the trap [6].

On the other hand, the bulk preparation of Rydberg atoms could be achieved by exciting any atoms simultaneously in an ensemble of N atoms to the Rydberg state via the laser and microwave radiation [7]. This allows the preparation of a large amount of Rydberg atoms become N times faster than exciting the single atom each time thereby improving the efficiency [7].

3. Appliactions of Rydberg Atoms in Strongly Coupled Systems

3.1. Quantum Information and Quantum Gates

Cold Rydberg gases are a desirable tool for quantum information processing and quantum simulation because of the possibility to construct quantum many-body states through Rydberg atom interactions

[3]. Quantum gates and the two-qubit state can be both implemented with ultracold neutral atoms [8]. Controlling two qubits' interaction is necessary to build two-qubit quantum gates and this can be accomplished for neutral atoms by briefly excitation to Rydberg states [8]. Due to the Rydberg blockade effect, when exciting an ensemble of atoms, there is only one atom that gets excited. Therefore, the collective states can store quantum information through the dipole blockade, or it could be used to invert the state or change the phase of the target qubit as a quantum gate [8].

3.2. Nonlinear Optics and Photonics

The aim of Rydberg quantum optics is to manipulate light at the single photon level by taking use of the strongly interacting characteristics of Rydberg atoms. Single photon sources, single photon transistors, and photonic phase gates are a few examples of this technology [9]. A designated phase shift was preferred by some of the photonic phase gate, and it could be fulfilled by using the Rydberg blockade [9]. Also, multiple single-photon sources were also achieved by using Rydberg atoms, as using two-photon transition to excite an atom to an excited Rydberg state [9]. Rydberg quantum optics has gone a long way in just a decade, and Rydberg ensembles are currently recognized as the only known medium with a non-linearity big enough to eliminate the need for a cavity when implementing an all-optical quantum gate [9].

3.3. Current Limitations and Future Directions

Currently, the false transfers caused by blackbody radiation and the inability to trap Rydberg atoms significantly impede numerous research [10]. Also, two major problems in Rydberg-atom cavity quantum electrodynamics research have been the rapid transit of thermal atoms across the cavities and the demand of deterministic atom sources [10]

Rydberg atoms have been demonstrated to be extremely sensitive sensors of their electromagnetic surroundings, the addition of laser-trapping capabilities to these experiments, which is compatible with all states of high angular momentum will enable the creation of highly sensitive and precisely localized probes of the local fields [10]. Also, by using the superconducting circuits as well as the laser-trapped Rydberg atoms, it is feasible to construct a coherent interface between optical photons and microwave photons in the hybrid cavity quantum electro dynamics research [10].

4. Conclusion

In summary, by laser excitation of an atom from its ground state, the valence electrons of the atom can be excited to a high principal quantum number state, making that atom a Rydberg atom. Due to the special properties of the Rydberg atoms, unique interactions between Rydberg atoms can occur, such as dipole-dipole interactions, Rydberg blockade and anti-blockade. These properties and interactions lead to a wide range of applications such as quantum information and computation as well as nonlinear optics and photonics. Also, with the facilitation of laser-trapping, it is promising for Rydberg atoms to probe localized electromagnetic filed and assist quantum electro dynamics studies. However, there are still limitations that need to be addressed in order to facilitate further research, such as the demand of deterministic atomic sources and the effects of blackbody radiation. It can be trusted that with the relevant research and development of the Rydberg atom and advanced physics, the existing limitations could be resolved and the frontiers of research on the Rydberg atom will be further expanded.

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