Canadian Journal of Physics

The density effect on superradiance detected by the field suppression of superradiance

Journal:	<i>Canadian Journal of Physics</i>
Manuscript ID	cjp-2017-0680.R1
Manuscript Type:	Article
Date Submitted by the Author:	13-Mar-2018
Complete List of Authors:	Han, Jianing; University of South Alabama, Physics Maeda, H.; Aoyama Gakuin University
Keyword:	Superradiance, Rydberg atoms, Cold gas, Field suppression, Laser
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

The density effect on superradiance detected by the field suppression of superradiance

Jianing Han ^{*1} and H. Maeda²

¹*Department of Physics, University of South Alabama, Mobile, Alabama 36688.*

²*Department of Phys. and Math, Aoyama Gakuin Univ. 5-10-1 Fuchinobe,
Chuo-Ku, Sagamihara, Kanagawa, 252-5258 Japan.*

(Dated: January 24, 2019)

Abstract

In this article, the density effect on superradiance is investigated through the field suppression of superradiance. It is shown that increasing density, which increases the number of atoms and leads to a greater macroscopic dipole, causes line broadening. In other words, it is harder to stop superradiance by an external electric field at higher density. The results reported here are essential to the superradiance detection and are critical steps towards creating and controlling ultracold plasma.

PACS numbers: 33.20.Bx, 36.40.Mr, 32.70.Jz

* Email address: jhan@southalabama.edu

I. INTRODUCTION

Superradiance, cooperative radiation, was proposed by Dicke in 1954 [1] and intensively studied in the 1970's [2, 3]. A comprehensive review of superradiance can be found in Ref. [7, 8] and references therein. Many applications of superradiance have been investigated. For example, polarized photons in a microcavity [4], ac and dc photonic Josephson effects [5], and superradiant solids have been studied [6]. Recently, superradiance has been observed in a cold Rydberg gas [9].

In this article, we apply an external electric field to superradiance and the suppression of superradiance has been observed, which is similar to the stark switch. Therefore, the electric field can be used as a stark switch to switch the superradiance on and off. The field suppression of superradiance has been observed in free space and in a cavity in Sr, Ba, Na room-temperature gases [10–12]. We propose superradiance triggers the ultracold plasma formation. Therefore, by switching superradiance on and off by the stark effect, plasma can then be switched on and off. Evidences of switching plasma on and off by an external electric field have been reported [13]. This also confirms that superradiance induces fast plasma formation.

This article is arranged in the following way. First, experimental procedures are described in the next section. The field suppression of superradiance, followed by the density effects on superradiance suppression, is then presented.

II. EXPERIMENT

The apparatus and technique are described elsewhere [14]. Briefly, Rb atoms are held in a vapor cell Magneto-Optical Trap (MOT). Three retro-reflected 780 nm trapping lasers and one 780 repump laser establish a population of 2.5×10^6 in the $5p_{3/2}$ state, and the trap volume, about 0.3 mm^3 , is midway between two pairs of rods, which serve as field-ionization electrodes and bias field electrodes. At time zero, the $5p_{3/2}$ atoms are excited to the Rb nd state at a 20 Hz repetition rate with a 480 nm 5 ns blue dye laser pulse. The width of this laser pulse is $\sim 10 \text{ GHz}$. After waiting for a certain delay, t , the atoms are exposed to a $3 \mu\text{s}$ rise-time field-ionization pulse [15, 16]. If we want to check the field suppression, an electric field pulse is added, between the excitation laser pulse and the field ionization pulse, on one

FIG. 1: (a) The energy diagram of this experiment. n is the principal quantum number. l is the angular momentum quantum number. $l = 0$, the s state, or $l = 2$, the d state, is excited at $t=0$ μs . (b) The experimental time sequence of this experiment.

pair of rods. Fig. 1(b) shows that a 4 μs electric field pulse is added. The experimental results, which will be described in following sections, are also verified by adding a continuous DC field. The non-uniform quadrupole field from the anti-Helmholtz coils is turned off 20 ms ahead of the laser pulse. The field ionized ion signal is collected by a pair of microchannel plates (MCPs). The electron signal from MCPs is collected by an oscilloscope. The whole oscilloscope trace is separated to several gates, which are integrated separately and recorded by a computer through a GPIB board. The earth magnetic field is canceled to less than 60 mGauss [17] in this experiment.

III. RESULT AND DISCUSSION

One way of understanding the formation of superradiance is the following. Excited atoms, or atoms in a higher energy level than the ground state, will spontaneously decay to lower levels, which is called the spontaneous emission. The transition of the electron from one energy level to the other energy level gives rise to changing electric current, which causes the electromagnetic radiation, or photons. If there is more than one atom, then the nearby atoms will be affected by the decaying atom through the photon electromagnetic field, primarily the magnetic part of the electromagnetic field, emitted by the decaying atom. This argument is based on the Lenz's law. If we call this photon as the perturbing photon, all atoms within $\frac{1}{2}\lambda$ will be affected by this perturbing photon. λ is the photon wavelength emitted by the decaying atom. If there are enough identical perturbing photons, the affected atoms will

FIG. 2: (a) The energy levels of the $24s$ and $23p$ states relative to the ionization limit of the ^{85}Rb atom as a function of an external field F . (b) The transition frequency as a function of the external electric field F for the $24s \rightarrow 23p$ transition. Both $\Delta m = 0$ and $|\Delta m| = 1$ transitions are plotted. (c) The energy levels of the $23d$ and $21f$ state relative to the ionization limit of the ^{85}Rb atom as a function of an external field F . (d) The transition frequency as a function of the external electric field F for the $23d \rightarrow 21f$ transition. $|\Delta m| = 0, 1$.

form a macroscopic dipole, many dipoles oscillating in the same manner. We say that the superradiance is triggered. All atoms in the macroscopic dipole will decay and emit photons with the same frequency and in the same direction as the perturbing photons. If no external electric field presents, all the m states of one angular momentum state are degenerate. In other words, the atoms in one m state can freely change to other m states without extra energy. When the atoms are in a state which is a superposition of different m states and when they decay, they emit the same frequency electromagnetic waves. If one atom in a particular $m=m_0$ state tends to superradiant decay to a lower level, atoms in other m states can easily transit to the m_0 state and superradiant decay to lower energy levels. If we add an external electric field, the external field will deform the orbitals of different m states, different m states separate from each other. In other words, due to the energy difference between different m states, the transition frequencies will be different from each other for different m states. If one atom in a particular $m=m_0$ state tends to superradiant decay to a lower level, atoms in other m states will not be affected. This makes it harder to achieve a macroscopic dipole and harder to trigger superradiance.

Fig. 2 shows the energy levels as a function of the external electric field strength and the

transition frequency as a function of the field strength for the $24s \rightarrow 23p$ and $23d \rightarrow 21f$ superradiance transition. This calculation is done by a numerov technique [18] for the $l + \frac{1}{2}$ states. We use the $24s \rightarrow 23p$ superradiance transition as an example. If there are no external fields, $F = 0$ V/cm, all the different m levels in the $23p$ state are degenerate. As the external field increases, the $23p$ state splits in two states: the $23p$ $m = 0$ state and the $23p$ $m = 1$ state. The transition frequency changes as a function of the external field strength as shown in Fig. 2(b). If we suddenly switch on the external field, suddenly change the external electric field from 0 V/cm to 10 V/cm for instance, the number of photons with the same frequency at 10 V/cm will drop compared to that at 0 V/cm. Therefore, it requires a longer time to build up the macroscopic dipole. This is also displayed in our experimental data. Figs. 3 and 4 show that the superradiance is suppressed, once an external electric field is added. Compared with Figs. 2(a) and (c), it also shows that the higher angular momentum states are more sensitive to the external field due to the closer spacing between the neighboring states. For this reason, the experimental data shows that the higher angular momentum states can be suppressed at a smaller external field than the lower angular momentum states.

Fig. 3 shows two sets of data: superradiance without suppression and superradiance with suppression. Both data sets are plotted as a function of time. It is shown that when the electric field is off, the superradiance is turned on, a sharp rise, at about $1 \mu\text{s}$. The sharp increasing feature stops at about $3 \mu\text{s}$, which indicates the end of the superradiance pulse. In other words, at time zero the Rydberg atoms are pumped to the $23d$ state, and after waiting $1 \mu\text{s}$, a burst of superradiance appears. As discussed earlier, if we add a small electric field, there is no superradiance. However, the $21f$ signal still slowly increases as a function of time, which is due to the spontaneous emission from $23d$ to $21f$. This plot shows that superradiance can be suppressed by a small external electric field. In the next section, it will be shown that at higher density, or after waiting for a longer time, superradiance can still happen under a small external field.

Due to the small transition probability when an external field is added, superradiance can be suppressed by an external electric field. We now show that increasing the density, superradiance can still happen under a constant external electric field. Superradiance is triggered by a strong spontaneous photon field, after which the microscopic dipole is formed. This macroscopic dipole is $n\vec{p}$, where $\vec{p}$ is the transition dipole moment of one atom, and n

FIG. 3: The $21f$ signal as a function of the time with an electric field on and off. The $23d$ state is originally excited. The field strength is 3 V/cm .

is the number of atoms. An external field splits energy levels and as a result, the oscillation frequencies will be different between any two individual levels and the magnitude of the macroscopic dipole moment will decrease. If the density increases, the number of atoms, n , in a $(\frac{\lambda}{2})^3$ volume increases [19]. Therefore, a macroscopic dipole can still be formed for each two individual levels. Here we use the $24s \rightarrow 23p$ superradiance as an example. Fig. 4 is the $23p \ m = 1$ state signal as a function of the total number of Rydberg atoms with the electric field on and off. When the field is off and the total number of atoms is about 1.3×10^5 , superradiance appears. If an external field is added, the superradiance at this number of atoms is suppressed. If we increase the density to 1.5×10^5 , superradiance can be triggered at higher density. Here the sample size is constant, or the excitation volume is constant. The sample is in a cylindrical shape. The diameter of the sample is determined by the diameter of the Rydberg excitation laser beam, $\sim 200 \text{ } \mu\text{m}$, and the length of the cylinder is determined by the MOT diameter, $\sim 800 \text{ } \mu\text{m}$.

Whether or not the dipole-dipole interaction in a many-body system, atoms in a MOT or a cluster, will suppress superradiance is discussed here. The dipole-dipole interaction introduces a preferred polarization axis, which is different from atom to atom, for the atom which is interacting with nearby atoms through the dipole-dipole interaction. Therefore, it is believed that dipole-dipole interactions, or higher densities, suppress superradiance. However, according to Lenz's law, the atoms within $\frac{\lambda}{2}$ of a spontaneous photon can still be affected by the electromagnetic field. Whether or not the superradiance can be completely suppressed is determined by whether or not the dipole field strength is greater than the photon field strength in a randomly oriented atomic sample. In the density range and

FIG. 4: The $23p\ m = 1$ signal as a function of the total number of Rydberg atoms with the electric field on and off. The $24s$ is originally excited. When the electric field is on, the field strength is: 13.3 V/cm. The data are taken at a $4\ \mu\text{s}$ delay.

the principal quantum number range, $n < 25$, that we studied in this article, no density suppression has been observed. Increasing the density in the density range that we study, increasing the number of atoms in a certain volume, enhances superradiance by enhancing the macroscopic dipole.

Fig. 5 shows the superradiance signal as a function of the external field strength. The two traces in Fig. 5(b) are the lowest and the highest density trace from Fig. 5(a). Here the sample size is constant. Different sample sizes are tested. In this experiment, the excitation laser beam diameter remains constant and the MOT size remains constant. The density of the sample is tuned by changing the intensity of the repump laser beam. It is shown that higher densities have a greater width than the lower densities, which indicates greater density enhances superradiance.

To clarify, the dipole-dipole interaction in a molecule will not affect superradiance. Similar to the fact that an atom can reorient itself under an external field, a molecule has the freedom of reorientation under an external field. Therefore, superradiance in molecules is very common. For instance, the first superradiance experiment is done in HF molecules [2].

The superradiance suppression signal for isolated atoms may be different from the superradiance suppression signal for dipole-dipole interacting atoms in a many-body system. The dipole-dipole interaction in s states will cause the mixing of p states by diagonalizing the matrix composed by the dipole-dipole coupled states, and p states are more sensitive to the electric field; therefore, superradiance in a dipole-dipole coupled many body system is easier to be suppressed by an external electric field.

FIG. 5: In both (a) and (b), the $23d$ state is originally excited. (a) Superradiance signal as a function of the external electric field strength measured at different densities. The size of the atomic sample is constant. This figure shows that the superradiance can be suppressed by an external electric field. The line-width of the curve with 3.1×10^5 is about 8 MHz based on the fact that when $F = 0.75$ V/cm, the frequency shift of the $23d \rightarrow 21f$ transition is about 4 MHz. With a higher total number of atoms, the width is broader. (b) This figure shows two electric field scans taken at two densities and both are selected from (a).

The question remains whether the shape of the electron distribution or different m states will affect the superradiance amplitude. In the present discussion, we assume that the shape of the electron distribution does not affect superradiance. In other words, all m states have equal probabilities of creating superradiance and the created superradiance photons have the same polarization and the propagation direction determined by the macroscopic dipole field.

IV. CONCLUSION

In conclusion, we have shown that an electric field can suppress superradiance. Moreover, it has been shown that the superradiance is harder to be stopped by an external field at higher densities, which indicates that if there is an external field from an ion in the atomic sample, the superradiance is less likely to be stopped at higher density. This conclusion supports the idea that superradiance induces ultracold plasma [20, 21].

It's a pleasure to acknowledge Dr. Tom Gallagher for helpful discussions and his contribution. The authors wish to thank Xiangdong Zhang for helping with the data collection process, and helpful discussions. We would like to thank Wenhui Li and Duncan Tate for helpful discussions. It is a pleasure to acknowledge the support from the Army Research Office (USA) under contract no. W911NF-16-1-0583, the University of South Alabama Faculty

Development Council (USAFDC), and the travel support from DOE (USA) Implementation Award # 08-0217.

- [1] R. H. Dicke, Phys. Rev. **93**, 99(1954).
- [2] N. Skribanowitz, I. P. Herman, J. C. MacGillivray, and M. S. Feld, Phys. Rev. Lett. **30**, 309(1973).
- [3] J. C. MacGillivray, and M. S. Feld, Phys. Rev. A **14**, 1169(1976).
- [4] An-Chun Ji, X. C. Xie, and W. M. Liu, Phys. Rev. Lett. **99**, 183602(2007).
- [5] An-Chun Ji, Qing Sun, X. C. Xie, and W. M. Liu, Phys. Rev. Lett. **102**, 023602(2009).
- [6] Xue-Feng Zhang, Qing Sun, Yu-Chuan Wen, Wu-Ming Liu, Sebastian Eggert, and An-Chun Ji, Phys. Rev. Lett. **110**, 090402(2013).
- [7] Q. H. F. Vrehen and H. M. Gibbs, Topics in Current Physics: Dissipative Systems in Quantum Optics (Springer, Berlin, Heidelberg, New York 1982).
- [8] M. Gross and S. Haroche, Phys. Reports **93**, 301(1982).
- [9] J. Han, and Haruka Maeda. Can. J. Phys. **92**, 1130 (2014).
- [10] T. Becker, R.-H. Rinkleff, and A. Steudel, Appl. Phys. B **49**, 257-262 (1989).
- [11] T. Becker, and R.-H. Rinkleff, Phys. Rev. A **44**, 1806(1991).
- [12] D. Bartholdtsen, T. Becker, and R.-H. Rinkleff, Phys. Rev. A **46**, 5801(1992).
- [13] Wenhui Li, Michael W. Noel, Michael P. Robinson, Paul J. Tanner, Thomas F. Gallagher, Daniel Comparat, Bruno Laburthe Tolra, Nicolas Vanhaecke, Thibault Vogt, Nassim Zahzam, Pierre Pillet, and Duncan A. Tate, Phys. Rev. A **70**, 042713(2004).
- [14] W. Li, I. Mourachko, M. W. Noel, and T. F. Gallagher, Phys. Rev. A **67**, 052502 (2003).
- [15] T. F. Gallagher, L. M. Humphrey, W. E. Cooke, R. M. Hill, and S. A. Edelstein, Phys. Rev. A **16**, 1098(1977).
- [16] M. Gross, P. Goy, C. Fabre, S. Haroche, and J. M. Raimond, Phys. Rev. Lett. **43**, 343(1979).
- [17] Jianing Han, Yasir Jamil, D. V. L. Norum, Paul J. Tanner, and T. F. Gallagher, Phys. Rev. A **74**, 054502 (2006).
- [18] M. L. Zimmerman, M. G. Littman, M. M. Kash, and D. Kleppner, Phys. Rev. A **20**, 2251 (1979).
- [19] Jianing Han et. al. .

- [20] J. O. Day, E. Brekke, and T. G. Walker, Phys. Rev. A **77**, 052712(2008).
- [21] Matthieu Viteau, Amodsen Chotia, Daniel Comparat, Duncan A. Tate, T. F. Gallagher, and Pierre Pillet, Phys. Rev. A **78**,

For Review Only