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AN ANALYSIS OF DIPOLE COUPLED TWO LEVEL ATOMS' ENTANGLEMENT CHARACTERISTICS

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ABSTRACT

Microscopic systems consisting of a collection of atoms tend to exhibit a rich variety of cooperative effects, which arise due to the interaction between individual atoms, mediated by the environment. For example, when an atomic ensemble, confined in a region of space smaller than an optical wavelength, is irradiated with a single mode radiation field, each atom in the ensemble in- teracts with the external radiation field as well as with the radiation emitted from all the other atoms. In this case, the intensity of radiation emitted by this collection of atoms shows markedly different behaviour from that arising due to emission from independent atoms. These cooperative effects, which arise mainly due to the dipole-dipole interaction between the atoms, lead to interesting modification in the behaviour of the system, starting from forma- tion of Dicke states, collective emission from the group of atoms which can show either subradiant or superradiant behaviour, depending on the strength of the interaction, geometry of the physical system, Rabi field strengths and the decay rates from different channels. In recent times, several interesting manifestations of the cooperative effects among atoms are being studied, from the view point of practical application in the fields of quantum information, quantum engineering of states for quantum computing, cryptography etc. A complete understanding of the behaviour of such a system necessitates a mi- croscopic formulation of the different interactions between the atoms and the environment in which they are present.

KEYWORD: Dipole, Microscopic, Atomic, Quantum Information, Engineering

INTRODUCTION

When treating a system of many atoms, the net force experienced by any single atom is computed as a collective sum of interactive forces with all the other atoms. Coherent addition of all these inter-atomic interactions gives rise to, what is known as, the cooperative phenomena. Therefore, the model for collective microscopic behaviour of the entire system can be built in terms of a basic building block involving interaction between a pair of atoms. One of the most common interactions of this kind is the dipole-dipole (D-D) interaction.

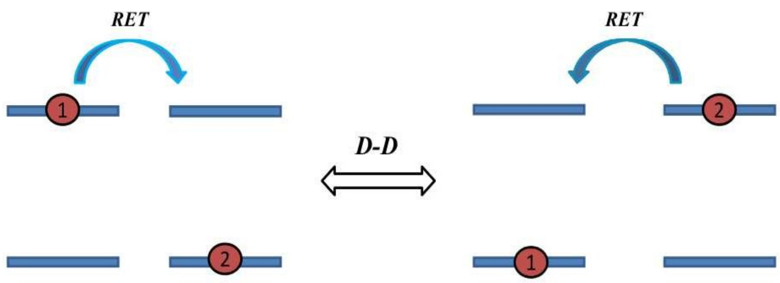

Figure 1-1: Origin of dipole-dipole interaction

Whenever an atom, in its excited state, comes very close (within a wave- length) to another atom in its ground state, energy is transferred to the second atom non-radiatively. This non-radiative energy exchange reverses the role of the individual atoms participating in this interaction, viz., the second atom becomes the excited atom and the first one goes to its ground state. This phenomenon reverses after a while, with the second atom transferring energy to the first one. This kind of energy exchange leads to an interaction between the participating atoms. The nature of this interaction is equivalent to the one derived from the dipole term of the classical electromagnetic interaction, and hence termed 'dipole-dipole interaction' (see figure 1-1). static form of long-range interaction between two dipoles μ→1 and μ→2 separated by a distance r is given by where μ^1, μ^2 are the unit vectors along the two dipole moments, r = |r| and ϵ0 is the vacuum permittivity. Unlike the typical van der Waal's interaction, one can see that the D-D interaction has two characteristic features, i.e., long range since it decays as Ωst ∝ 1/r3, and anisotropic since it depends on the relative angles between the dipoles.

The D-D interaction at smaller inter atomic distances gives rise to a variety of phenomena, which have generated considerable interest in the past. Some of the early reports in this direction include new resonance fluorescence peaks that arise due to D-D interactions, suppression of existing fluorescence peaks, modification of transition rates and level shifts, thus giving rise to significant changes in the multiple jump dynamics and a host of oth- ers. In the context of quantum information, entanglement between the atom pair arising due to dipole-dipole interaction, and their subsequent evolu- tion is another widely studied aspect. Dipole-dipole interaction between Rydberg atoms, which are stronger due to their large dipole moments, application of this to quantum computation schemes, have also generated a lot of interest. Due to the strong and long-range D-D interactions, Rydberg atoms offer efficient tools for quantum engineering. This is due to the fact that, resonant condition can be achieved experimentally in these Ryd- berg atoms, by tuning the levels with microwave or external electric fields. The D-D interaction between the atoms creates an energy shift, depending on the inter-atomic distance, which in turn controls the excitation of the neigh- bouring atoms around a previously excited atom. In effect, the shift created by the D-D interaction allows a single Rydberg excitation in a large atomic sample, inhibiting all other excitations. This is generally referred to as 'dipole blockade'. The dipole blockade regime for two atoms has been recently measured experimentally, in the collective excitation of a pair of individually trapped atoms. Such a result opens up a way to controlling the be- haviour of a few-atom sample.

In order to understand these cooperative effects in a sizeable system of many atoms, it is necessary to have a microscopic formulation of the interaction between the atoms and the radiation field. A first step in this direction would be to understand the dynamics of a two atom system interacting with a single mode radiation field, wherein the cooperative effects among the atoms become important. Though the system of two atoms interacting with a single mode radiation field is well studied, we present an overview of the system of two atoms interacting with a radiation field, for maintaining continuity with the later work that is reported in this thesis. After gaining understanding of the behaviour of the two atom system, the next step would be to extend it to include a third atom, which would bring the study closer to a real system. Though a fully quantum mechanical picture describes the energy exchange phenomena more effectively, such an approach becomes cumbersome as the size of the system increases. With this in mind, we present a detailed study using the semi classical approach, wherein the atoms are treated quantum mechanically and the field is treated as a classical variable.

Intensity and radiation statistics of three two-level atoms

Superradiance, is the coherent spontaneous emission of radiation generated due to the cooperative effects among atoms [1], whereas spontaneous emission is a random process, in which the emitted radiation obeys an exponential law, with the natural radiative lifetime $1/\gamma$. In 1954, Dicke [2] theoretically predicted that when the number of atoms N, in a given volume, becomes sufficiently large, the collection of atoms starts to radiate spontaneously much faster, with decay time proportional to $1/N\gamma$, with an emission stronger than that arising from N independent atoms. Further, the enhanced mean radiated intensity is scattered anisotropically, i. e., radiation is emitted in a well defined direction. Depending upon the geometry of the sample, the emission could be proportional to the square of the number of atoms (N2) in the ensemble, instead of N, as is the case for independent atoms. The emission from a system is defined to be superradiant if its radiative decay rate is greater than the single atom decay rate and it is said to be subradiant if it is the other way round.

Formulation

Let us consider a system of three dipolar coupled identical atoms, where the excited state $|ei\rangle$ and the ground state $|gi\rangle$ (i=1, 2, 3) are separated by an energy interval h¯ω. As the atom-atom couplings are in different in both line and loop config- urations, the results for field intensities and radiation statistics for the two configurations are found to be markedly different. In the absence of applied radiation field, the Hamiltonian (5.1) can be expanded in the standard basis, $|ijk\rangle$, with i, j, k = 0, 1. The presence of dipole coupling **Ω** between the atoms causes a mixing of the energy levels leading to creation of entangled states. Depending on the number of atoms that are in the excited state, two different type of entangled states manifest. In the first case, only one atom is in the excited state and in the second, two atoms are in the excited state generating different types of W-states. The GHZ - state is also generated in both the configurations.

The intensity characteristics of light emit- ted by three atoms in a line configuration

As mentioned earlier, in the line configuration, we consider a system of three identical dipole coupled two-level atoms placed symmetrically along a line. The positions of these atoms are given by R1, R2 and R3, and further we consider the case where interatomic spacing *d* between each adjacent pair is taken to be equal as depicted in Fig. 5-1, with $\Omega_{12} = \Omega_{23}$.

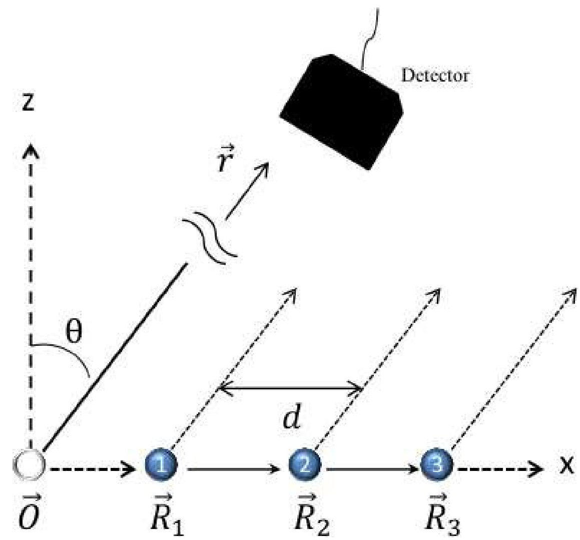

Figure: Schematic diagram of the system of 3 two-level atoms located at positions $\boldsymbol{R}_1$ to $\boldsymbol{R}_3$ with the detector placed at position $\boldsymbol{r}$, recording photons in the far field regime.

CONCLUSION

The nature of initial entangled states influences its radiative characteristics leading to superradiant/subradiant emission of photons. The effect of dipole-dipole coupling and the angular distribution of the emission of photons by entangled atoms from different entangled states is examined. For the case of loop configuration, it is interesting to note that the intensity emitted from the symmetric |W2,1⟩ state exhibits non classical nature for the chosen dipole coupling strength and nearly independent of the observation angle, meaning thereby that the emitted radiation is nearly isotropic. In con- clusion, the fact that entanglement arises due to superposition of states, with the degree of entanglement being controlled by the nature of superposition, of- fers the possibility of its signature on the radiation pattern. It is interesting to note that distinct entangled configurations, in a tripartite system studied here, indeed revealed distinct radiation pattern as also intensity-intensity correla- tion. This opens a way for optical probing of the entanglement characteristics.

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