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# Cooperative single-photon subradiant states in a three-dimensional atomic array

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## HIGHLIGHTS

- Cooperative single-photon subradiant states in a three-dimensional atomic array.
- Subradiant state manipulation via spatially-increasing phase imprinting.
- Quantum storage of light in the subradiant state in two-level atoms.

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ABSTRACT

We propose a complete superradiant and subradiant states that can be manipulated and prepared in a three-dimensional atomic array. These subradiant states can be realized by absorbing a single photon and imprinting the spatially-dependent phases on the atomic system. We find that the collective decay rates and associated cooperative Lamb shifts are highly dependent on the phases we manage to imprint, and the subradiant state of long lifetime can be found for various lattice spacings and atom numbers. We also investigate both optically thin and thick atomic arrays, which can serve for systematic studies of super- and sub-radiance. Our proposal offers an alternative scheme for quantum memory of light in a three-dimensional array of two-level atoms, which is applicable and potentially advantageous in quantum information processing.
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## 1. Introduction

Superradiance [1] and associated collective phenomena [2–4] have raised continuous interests in the past sixty years. These collective effects are due to the induced dipole–dipole interaction [5,6] that

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comes from the common field mediating the atomic system. This resonant dipole–dipole interaction is in essence long-ranged, therefore the decay behavior heavily depends on the interatomic distance and the geometry of the atomic ensemble. The spontaneous decay can exhibit superradiance that is more commonly observed in experiments, and also cooperative Lamb shift (CLS) [2,7] and subradiance, that are less observable because of the demanding precision and signal-to-noise ratio in measurements.

Recent studies involve a fast decay of second-order correlation of two photons from the cascade atomic ensemble [8–10], and a redshift of CLS in the embedded Fe atoms in the planar cavity [11], the atomic vapor layer [12], an ionic atomic system [13], and a cold-atom ensemble [14–16]. Subradiant decay can also be measured in diversified atomic systems of ring/disk plasmonic nanocavities [17], ultracold molecules [18], and a large cloud of cold atoms [19]. Interestingly, recent proposals of singly-excited states that can describe single-photon superradiance [20–23] and subradiance [24–26] provide a new direction in investigating these collective effects in a limited but complete Hilbert space. The advantage of the setting of single-photon interacting with the atoms restricts this space to $N$ singly-excited states and one ground state, hugely simplifying the dynamical light–matter interacting systems of for example $2^N$ states of $N$ two-level atoms.

In this paper we propose a complete Hilbert space of cooperative single-photon states that are responsible for the superradiance and subradiance. In Section 2, we introduce these states that can be prepared in a three-dimensional (3D) atomic array with one atom per site. In Section 3, we introduce the theoretical background of our analysis. We then investigate the time evolutions of the subradiant states in Section 4, which can be observable in fluorescence experiments, and we discuss and conclude in Section 5.

## 2. Cooperative single-photon states using De Moivre's formula

When a single photon interacts with two-level atoms of $|g\rangle$ and $|e\rangle$ for the ground and excited states respectively, the so-called timed Dicke state is formed on absorbing this photon [20,27],

$$|\phi_N\rangle = \frac{1}{\sqrt{N}} \sum_{\mu=1}^{N} e^{i\mathbf{k}\cdot\mathbf{r}_\mu} |e\rangle_\mu |g\rangle^{\otimes(N-1)}, \tag{1}$$

where $\mathbf{k}$ is the wavevector of single photon. The above denotes a superposition of one and only one excited state with the rest of $(N-1)$ ground state atoms. This timed Dicke state is symmetrical under exchange of any two atoms, thus shows superradiant decay after the absorption. The dipole–dipole interaction is responsible for the emergence of enhanced decay behavior. However since this symmetrical state is not the eigenstate for this long-ranged dipole–dipole interaction in general, it couples with other nonsymmetrical (NS) and orthogonal states during the process of spontaneous emission. These NS states on the other hand are responsible for both super- and subradiant decays, and can be observed in the emission long after the superradiant decay [22,19]. The possible candidates for these NS states can be found in Refs. [22–26]. Following the proposal of NS states in one-dimensional atomic array [26], we further extend it to a 3D case which is more advantageous in the efficiency of absorbing the photon and has richer physics in super- and sub-radiance due to its dimensionality.

In [26], we utilize the De Moivre's formula to construct the complete Hilbert space of singly-excited states and the extension to a 3D atomic array is straightforward,

$$|\phi_m\rangle_{3D} = \sum_{\mu=1}^{N} \frac{e^{i\mathbf{k}\cdot\mathbf{r}_\mu}}{\sqrt{N}} e^{i\frac{2m\pi}{N}(\mu-1)} |e\rangle_\mu |g\rangle^{\otimes(N-1)}, \tag{2}$$

where we denote them as DM (De Moivre) states and their normalizations are ensured. The orthonormality can be shown as

$${}_{3D}\langle\phi_m|\phi_n\rangle_{3D} = \frac{1}{N} \sum_{\mu=1}^{N} e^{i\frac{2\pi}{N}(\mu-1)(m-n)} = \delta_{m,n}. \tag{3}$$

The De Moivre's formula is intentionally used for finding the nth root of unity, where there exists a complex number $z$ such that $z^n = 1$. For the construction of $N$ singly-excited states, we then take the

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