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# Spectroscopy of systems of two identical atoms: effects of quantum interference

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**Abstract.** Several effects of quantum interference in spectroscopy of a system of two atoms are discussed. (i) In the system of spatially separated atoms in a one-dimensional (1D) geometry (a single-mode waveguide or photon crystal), a (meta)stable excited entangled state can be formed, its decay being very sensitive to the distance between the atoms and to perturbations which cause a difference between their resonance frequencies. (ii) In a system of closely located atoms in 3D space, the extreme sensitivity of absorption and fluorescence spectra to the direction of the applied magnetic field is demonstrated. These theoretical predictions can be useful for the quantum information processing and ultrasensitive measurements.

A system of two identical atoms is the simplest example that exhibits (i) the effect of entanglement which is of primary importance for the quantum information processing, and (ii) an extreme sensitivity of the absorption and emission spectra to the mutual position of the atoms. Only few experiments so far demonstrated these properties, but still far from their real potentiality. For instance, in Ref. [1], the fluorescence spectra of two trapped ions showed a weak dependence on the distance $r$ between them, varied near $r \approx 2\lambda_{eg}$, where $\lambda_{eg}$ was the wavelength of the used optical transition. On the other hand, theory predicts the two opposite limiting cases $r \gg \lambda_{eg}$ and $r \ll \lambda_{eg}$ are more promising.

1D case of spatially separated atoms. If one of the atoms is initially excited its spontaneous decay leads to excitation of another atom, refection from it, and finally, if the distance between the atoms is equal to a whole number of the half-wavelengths of the optical transition, to the formation of a stable entangled state [2]. In the "ideal" case, this excited state is stable, and is formed with the 1/2 probability. In reality this state is meta-stable since any small deviation from the ideal condition leads to its decay. Such a perturbation can be caused by a deviation of the interatomic distance from the `ideal' one, and/or by different surroundings that lead to a detuning of the atom's transition frequencies [3]. So, the system can be useful both as a candidate for a long-lived entangled state, and as a precise tool for weak perturbation measurements.

3D case of closely spaced atoms in a magnetic field: Fluorescence spectra. A system of two identical atoms with the ground state $|g>$ and the excited state $|e>$ is an example exhibiting the effects of Dicke super- and subradiance. The two excited states of this system

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are $|Q_1\rangle = |e_1 g_2\rangle$ and $|Q_2\rangle = |e_2 g_1\rangle$. The dipole-dipole interaction between the states $|Q_1\rangle$ and $|Q_2\rangle$ leads to their superpositions producing two entangled eigenstates, symmetric and antisymmetric. The symmetric state $(|Q_1\rangle + |Q_2\rangle)/\sqrt{2}$ is superradiant, decaying twice faster than the one-atom excited state whereas the antisymmetric state $(|Q_1\rangle - |Q_2\rangle)/\sqrt{2}$ is subradiant, decaying much slower (by the parameter $(r/\lambda_{eg})^2$ if the distance $r$ between the atoms is smaller then the wavelength of the $|e\rangle \to |g\rangle$ transition. Now, the main idea is that a sufficiently strong magnetic field, directed at the magic $\alpha = \arccos(1/\sqrt{3}) \approx 54.7^0$ hinders the dipole-dipole interaction, so the fluorescent spectra become most simple. Moreover, they are very sensitive to a small deviation of the magnetic field from the magic angle. In this way, the vector separation between the atoms can be found. The second idea is the measurement of the gated fluorescence from the subradiant state only. Its relative yield gives an estimate for the distance between the atoms. So, the full nanoscopy of pairs of atoms can be achieved.

A procedure for switching from superradiance to subradiance. After selective excitation of the superradiant state and application of the strong magnetic field the following procedure can be applied. Its first act makes atoms non-identical in a sense of their transition frequencies. This can be achieved, e.g., by introducing a transverse gradient in the magnetic field. If this action is adiabatic then the superradiant state transfers to the product state, say $|e_1 g_2\rangle$. The second act is the instantaneous switching of the gradient direction that does not change the state but changes its energy. In the final act, the gradient is adiabatically turned off. Calculations show that the final state will be subradiant with the lifetime increased by $\sim(\lambda_{eg}/r)^2$ times. So, the actual goal of keeping quantum information for a long time with the use of subradiant states can be realized.

Narrow dip in the natural linewidth absorption profile. The first act above leads also to an interesting effect of the quantum interference in the absorption spectrum [4]. A typical example is shown in the figure 1 (where $\Gamma$ is the radiation width and $k = 2\pi/\lambda_{eg}$). The dip's depth and the shape of the absorption profile depend on the distance between the atoms.

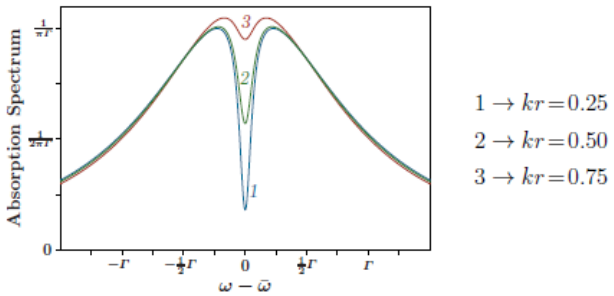


**Fig. 1.** Narrow dip in the natural linewidth absorption profile.

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