Superradiance by chirally interacting single atoms in a cavity

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Superradiance is fundamentally different from the ordinary spontaneous emission in that its emission power scales as the square of the number of emitters. In recent studies, new approaches to superradiance have been demonstrated. Atomic phase imprinting to an ensemble of cold atoms by a laser pulse – even by a single-photon pulse – induced an immediate superradiant output but in the same direction as the input, making it difficult to separate them. In another approach, up to two emitters were prepared in a cavity and their quantum states were individually manipulated to exhibit controlled collective emission.

In this presentation, we introduce a new type of phase-controlled superradiance, where the output is completely separated from the input and tens of atoms participate in superradiance as we control atomic states individually. In our experiment, single two-level atoms are prepared in the same quantum superposition state and then made to traverse a cavity one by one (Fig. 1). A single atom in the cavity then emits a photon collectively with the past atoms that have already gone through the cavity. Such collective interaction among time-separated atoms has never been observed before. The interaction is one-sided or chiral in that the preceding atoms can affect the following atoms, not vice versa. We observe the emission power increases as the square of the number \( N \) of the atoms traversing the cavity during the cavity-field decay time. The \( N \)-squared dependence occurs even when the number of photons in the cavity exceeds unity without exhibiting any lasing threshold. So, our results can also be viewed as thresholdless lasing. Currently, the largest \( N \) is about 30, but it can be easily scaled up further by optimizing experimental parameters. We prepared the single atoms in the same quantum superposition state by controlling their position in a nanometer resolution with a nanohole-array atom aperture. Interestingly, the emission power per atom is twice larger than that in the usual superradiance due to the chirality. This chiral interaction feature can be utilized to build a chiral atom-atom interaction system to study quantum many-body chirality physics. Moreover, the thresholdless lasing property can be utilized in making more efficient lasers.

Figure 1 (a) Experimental Schematic. Single two-level atoms (barium) are injected through a nanohole-array apperture and then excited by a pump field to the same quantum superposition state. (b) Nanohole array aperture. Hole diameter is 180nm and the hole-to-hole distance is 791nm, the same as the \(^{1}S_{0}^{1}P_{1}\) transition wavelength of atomic barium. (c) Atomic phases imprinted by the pump laser. Consider three atoms going through nanoholes 1, 2 and 3, respectively, as marked in (b). Although atom 3 has the opposite imprinted phase to the others, it goes through an antinode opposite in phase to the antinodes atoms 1 and 2 go through. As a result, all three atoms would have identical atom-cavity relative phases.