Heisenberg Limit Superradiant Super-resolving Metrology

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We propose a superradiant metrology scheme to achieve Heisenberg limit super-resolving displacement measurement by encoding multiple light momenta into a three-level atomic ensemble. We use $2N$ coherent pulses to prepare a single excitation superradiant state in a superposition of two timed Dicke states [1] that are $4N$ light momenta apart in the momentum space (Fig.1). The phase difference between these two states induced by a uniform displacement of the atomic ensemble has $1/4N$ sensitivity. Experiments are proposed in crystal and in ultracold atoms.

The basic mechanism is shown in Fig.1. We first prepare a collection of three-level atoms (ground state $|c\rangle$, excited state $|b\rangle$ and auxiliary state $|a\rangle$) in a single-photon superradiant state $|b\rangle$ where we define $b_k \equiv N^{-1/2} \sum_j e^{ikr_j} |c_1, c_2 \cdots b_j \cdots c_N\rangle$. A $\pi/4$-pulse splits it into an equal superposition of $b_0$ and $a_0$. Then $\pi$-pulses with momentum $k_1$ (represented by unitary transformation $U_1$) and $k_2 = -k_1$ ($U_2$) alternatively drive the system to a superposition of $b_{-2Nk_1}$ and $a_{2Nk_1}$. A displacement $r_0$ attaches opposite phases to these two states and a reverse operation can retrieve this phase as a population difference $P = P_b - P_a = -\cos(4Nk_1 \cdot r_0)$. In Fig. 2, we draw $P$ for $N=16$ (black) and $32$ (red) where the fluctuations come from the imperfections of the pulses in phase and in amplitude.