QUANTUM OPTICS

Superradiators created atom by atom

Collective emission is observed from atoms dropping singly through a resonator field

By **Dieter Meschede**

High radiation rates are usually associated with macroscopic lasers. Laser radiation is "coherent"—its amplitude and phase are well-defined—but its generation requires energy inputs to overcome loss. Excited atoms spontaneously emit in a random and incoherent fashion, and for N such atoms, the emission rate simply increases as N. However, if these atoms are in close proximity and coherently coupled by a radiation field, this microscopic ensemble acts as a single emitter whose emission rate increases as N^2 and becomes "superradiant," to use Dicke's terminology (*1*). On page 662 of this issue, Kim *et al.* (*2*) show the buildup of coherent light fields through collective emission from atomic radiators injected one by one into a resonator field. There is only one atom ever in the cavity, but the emission is still collective and superradiant. These results suggest another route toward thresholdless lasing.

The spontaneous emission from a single atom can be modeled as a quantum antenna without preferred emission direction. The radiation field of individual atomic emitters is also considered "incoherent" because no well-defined phase exists. Embedding an atom into the field of a small-volume optical resonator provides some directionality because the radiation is injected mainly into the geometrically determined cavity field [the Purcell effect (*3*)].

A rather different limit is realized in a conventional laser oscillator (see the figure, bottom panel). In order to maintain coherent oscillations, all members of the microscopic antenna ensemble (the macroscopic polarization of the laser medium) must be fully synchronized with the local phase of the laser wave. Coherent laser light is then driven by this phased array and emitted in a direction determined by the mirror assembly.

Laser radiation is a threshold process. The laser switches on when there is sufficient energy to self-organize the ensemble in such a way that the polarization continuously drives the field. The threshold is conditioned on the rate of stimulated emission induced by the field of the laser resonator that must overcome the losses suffered by competition from spontaneous fluorescence. Above the threshold, additionally supplied energy will dominantly feed the laser field and not be lost. In conventional lasers, the number of photons populating the laser resonator field is already very large at threshold.

Cooperative radiation effects do not fundamentally need to overcome any threshold and do not depend on any mirror geometry. Atom ensembles can always show an effective interaction through the constructive or destructive interaction of their individual contributions. What matters is that the atoms couple phase-coherently to a joint mode of the radiation field. For example, such phase-coherent emitters located within a single half wavelength create a superradiant emitter whose emission scales as N^2. A commentary on superradiance by Scully and Svidzinsky (*4*) noted applications such as quantum memories.

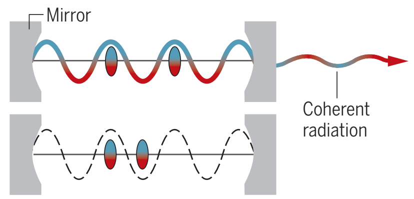
In recent years, control of atomic emitters coupled to a radiation field has seen much experimental progress, such as providing the phase control required for synchronized interaction of atoms and radiation fields. A resonator field not only geometrically facilitates phase-controlled atom-field coupling but also enhances the electromagnetic field amplitude at the emitter. In this situation, stimulated emission into the resonator field can increase to the level that threshold conditions are rendered almost negligible. The effective interaction of two atoms coupled to a joint radiation field is shown in the figure, top panel (*5*). The atomic radiation fields interfere constructively for full-wavelength spacing and destructively for half-wavelength spacing, like phased arrays of radio antennae used to control emission patterns.

Kim *et al.* have now shown how to build up coherent light fields by collective emission from atomic radiators injected one by one into a resonator field (see the figure, middle panel). Phase-stable lasers induce dipole emitters with a superposition of the atomic ground and excited state. Insertion at selected positions supports constructive interference. In their experiment, only a single emitter (a barium atom) is present in the cavity at any time. Nonetheless, the radiation field exhibits the properties of collective emission, the N^2 emission rate. The long-lived resonator field stores the radiation field and effectively couples every atomic dipole with its preceding and following neighbors.

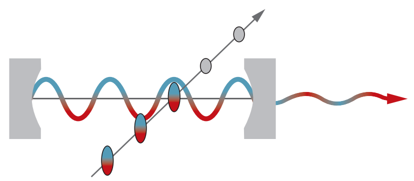
The threshold for the superradiant buildup of a coherent radiation field is again negligible, a consequence of injecting a controlled stable polarization that drives the laser field from the beginning. Such thresholdless lasing is of interest probably not for high-power but for low-power applications. Attempts have been made to reduce thresholds by geometrically optimizing the ratio of stimulated and spontaneous emission. The present experiment may point out alternative routes. ■

Enhancing emission

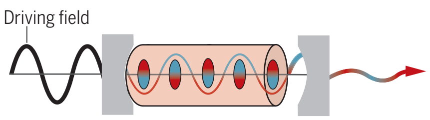
The radiation of single atoms can be focused and amplified with superradiance or lasing. Kim *et al*. now show that single atoms falling through a cavity can also superradiate with negligible threshold.



Interfering atomic radiators: Two phase-coherently driven atoms emit their radiation field into the cavity constructively (superradiantly) for 2π phase difference and destructively (no emission) for π phase difference.



Cavity memory effects: Stimulated emission causes traversing atomic dipoles to deliver their radiation field into the resonator field. Subsequent atoms show collective radiation phenomena because the long-lived cavity field stores the field and thus memorizes preceding atoms.



Lasing: Conventional devices use the macroscopic polarization of a laser medium to drive the laser field. The polarization and coherent laser field switch on in a self-organized way at threshold.

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Institut für Angewandte Physik, Universität Bonn, 53115 Bonn, Germany. Email: meschede@uni-bonn.de

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