into a bedload flow initially formed only of larger moving beads (*13*). After a while, a quasi-continuous layer of small particles developed beneath larger moving beads and above quasi-immobile larger beads (see the figure, panel B).

In the regime of partial mobility, processes are restricted to the surface of the bed, and all particles experience long periods of rest. This condition is characteristic of gravel transport. The propensity for grains of similar size to block each other leads to accumulations of similar-sized grains in restricted areas of the channel bed. Two phenomena command attention. Mobile materials collect in patches of similar size in the streambed, a phenomenon that mediates the overall sediment flux (*14*), while the largest stones in streambeds—usually only marginally mobile—congregate into clusters, chains, and cell-like arrangements that dramatically increase the overall stability of the bed (*15*).

The second case is particularly interesting from the granular perspective, because the stone structures represent a natural case of force chains that have been studied in the laboratory for more than a decade (*16*). In the extreme case of steep mountain channels containing relatively large stones, stone lines become channel-spanning force chains, forming a distinctive step-and-pool morphology that maintains a stable channel in situations when any unconstrained stone would be swept away.

Heuristic models have been constructed for the development of surface structures, but the mechanisms that promote patch development and bed surface structures require additional experimental study before physically sound models may be developed. Stone lines and cells on the surface are relatively long-lived because, during most flows, their ultimate strength is not tested. This allows time for additional mechanisms to strengthen them further, beyond the state achieved by force chains in continuously deforming media. Hence, failure mechanisms are of particular interest. When extreme flows do break the stability of steep channels, life-threatening debris flows result.

Granular physics provides a good basis for improving our understanding of bedload transport at relatively high rates. However, surface phenomena that would simulate partial bedload transport remain essentially uninvestigated in granular physics. While imparting insight into the bedload problem, experiments on these phenomena would also open a new perspective in granular physics.

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17. P.F. acknowledges the support of *Cemagref* and the University of British Columbia, Department of Geography, where this Perspective was written while on sabbatical leave. This work was partly funded by the French Institut National des Sciences de l'Univers and Agence Nationale de la Recherche grant ANR-05-ECCO-015. M.C. is supported by the Natural Sciences and Engineering Research Council of Canada.

10.1126/science.1178516

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PHYSICS

The Super of Superradiance

Marlan O. Scully[1,2] and Anatoly A. Svidzinsky[1]

Cooperative single-photon emission from an atom ensemble will provide insights into quantum electrodynamics and applications in quantum communication.

In 1954, Robert Dicke introduced the concept of superradiance in describing the cooperative, spontaneous emission of photons from a collection of atoms. The concept of superradiance can be understood by picturing each atom as a tiny antenna emitting electromagnetic waves. Thermally excited atoms emit light randomly, and the emitted intensity is a function of the number of atoms, N. However, when the atomic "antennas" are coherently radiating in phase with each other, the net electromagnetic field is proportional to N, and therefore, the emitted intensity goes as N^2. As a result, the atoms radiate their energy N times faster than for incoherent emission. It is this anomalous radiance that Dicke dubbed "superradiance" (*1*–*3*).

An even more interesting kind of radiation speedup can occur when a single photon is stored uniformly in a cloud of N atoms (see the figure, panel A). Suppose you have one atom that decays with a rate γ. Then suppose there are N such atoms close together in an atom cloud with only one of the atoms excited (but we don't know which one). Because there is only one atom excited, you might expect the decay rate to be γ. But if the atoms are symmetrically organized within the cloud, the decay rate is actually $N\gamma$ (*1*). This enhanced single-photon emission rate is "the greatest radiation anomaly" inherent in superradiance. Single-photon superradiance has become a subject of current interest (*4*–*12*), and promises to yield new tools for storing quantum information and deeper insight into the physics of virtual processes.

Dicke's point is that the N atoms act like one big atom and decay collectively. This is intuitive when the atoms are close together compared to the wavelength of radiation λ. When the same symmetric state is formed but the atomic cloud size is larger than λ, there is no longer constructive cooperation in radiation emission. The atoms will trap the light, decreasing the emission rate.

Nevertheless, it is possible to produce a state such that the large cloud also emits radiation with an enhanced rate proportional to $N\gamma$ (*4*, *5*). This is important because in quantum optics the sample is usually large compared to λ.

However, things are a bit trickier here. More subtle and interesting physics come into play, extending from quantum information and a new kind of cavity quantum electrodynamics (QED) (*13*), to new insights into quantum field theory (*9*–*12*).

The essential new physics is the transition from the coherent antenna array to the single-photon state in which cooperative emission is due to N entangled atoms (not N coherent

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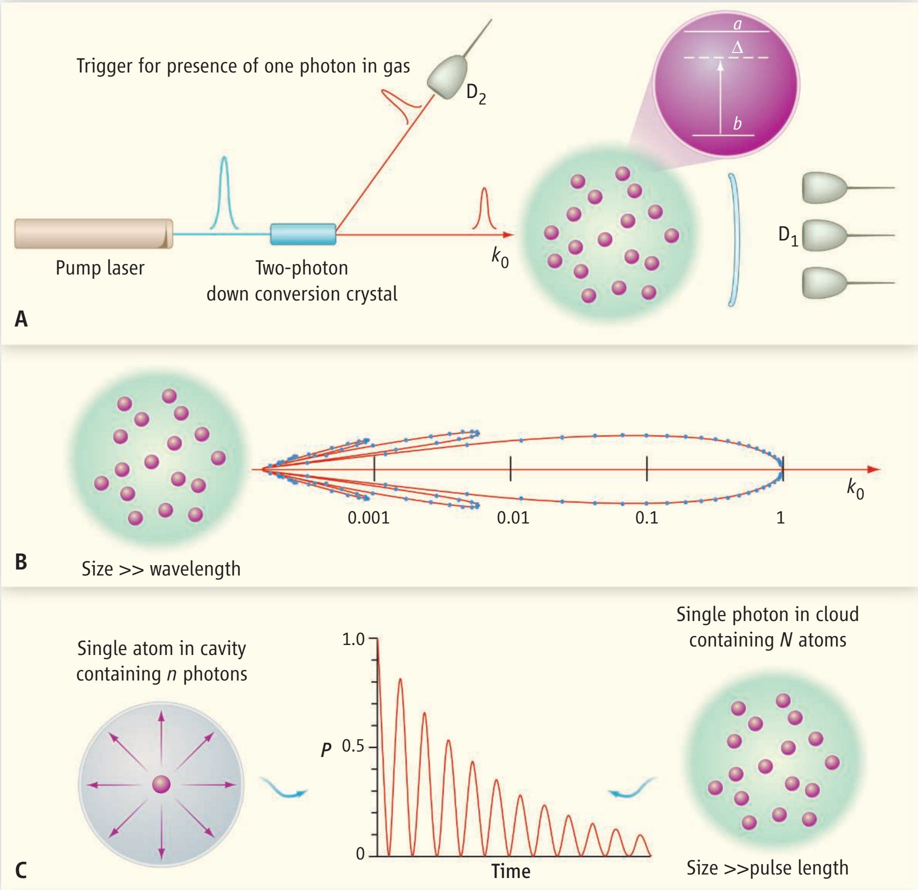
emitters). This is made possible by conditioned preparation of the initial atomic states (see the figure, panel A) (*4*, *5*).

With the large sample, however, it is not so clear why the emitted photon should go in the same direction as the exciting photon given that there is no antenna dipole associated with the atoms (see the figure, panel B). One atom is excited, but we do not know which one. The answer is associated with timing: The atoms at the front of the sample are excited first and those at the back, last (*4*, *5*). These excitations appear as spatial phase factors. It is this timing that yields directionality in the emitted radiation. Without the timed excitation, the radiation will be substantially trapped in the gas (*11*).

In particular, in the conditioned excitation case, the decay rate continues to be proportional to the number of atoms; but it also involves the diffraction factor $(\lambda/R)^2$, where R is the radius of the sample. This is the case for gas clouds that are large compared with λ but small compared with the size of the radiation pulse length L_p. However, when $R > L_p$, the coupled atom-radiation system shows absorption-emission oscillations (see the figure, panel C) that are similar to those observed in cavity QED (*13*), where the Rabi oscillation frequency is determined by the volume of the cavity and the number of photons in the cavity. In the present case, the oscillation frequency is determined by the volume of the cloud and the number of atoms (*14*). This surprising result is indeed a new kind of cavity QED.



Collective action. (**A**) Conditioned excitation prepares the timed uniform state in three logical steps (*4*): (i) Consider a pair of short single-photon pulses produced by a down converter (which absorbs one "blue" photon and emits two lower-energy "red" photons). A count in detector D_2 ensures that a photon of wave vector $\sim k_0$ is entering the atomic cloud at some time t_0. (ii) The atoms are detuned from resonance by an amount Δ so that the excitation probability is weak and every atom is equally likely to be excited but at different times, depending on its position. (iii) Most of the time the photon will pass through the gas, and a count is registered in the "perfect" detector D_1; lack of a count tells us one atom is excited, but we don't know which one. Then, conditioned on a count in D_2, but not in D_1, the detuning Δ is switched to zero. The atoms are now resonant with k_0 and emit spontaneously. (**B**) For a large atomic sample, the conditioned preparation depicted in (A) results in a radiation pattern that is strongly peaked in the k_0 direction. To a good approximation, the timed excitation yields emission speedup, which is proportional to the number of atoms and the solid diffraction angle given by the squared ratio of the wavelength to the sample size. Evolution of the single-photon timed state in the large sample has much in common with evolution of the symmetric state for a small atomic cloud. (**C**) For a very large cloud, the photon is reabsorbed and reemitted many times and the atomic state oscillates with a frequency that goes as $\sqrt{N}$. This is to be compared to the cavity QED scenario (*13*) in which an atom is cycled between the ground and excited states with a frequency which goes as $\sqrt{n}$, where n is the number of photons in the cavity. P is the probability that the atom is excited.

Another fascinating aspect of single-photon superradiance is the collective N-atom Lamb shift, which is due to the rapid emission and reabsorption of (virtual) photons (*10*–*12*). As the decay rate is enhanced by collective emission, so too is the frequency shift associated with the virtual photons. Furthermore, the virtual photons dramatically change the evolution of trapped states (*11*). They provide new decay channels, which ultimately result in a slow decay of the otherwise trapped state. However, for the rapidly decaying states, these virtual processes are relatively unimportant (*11*). In such a case, virtual photons excite other states with only a relatively small probability, depending on the size of the atomic cloud. In addition, the essentially new many-particle Lamb shift is not divergent. That is, the usual single-atom Lamb shift calculations involve infinities, high-frequency cutoffs, and so forth. However, in the many-atom version, the most interesting physics comes from this "infinity-free QED."

A single photon stored in a large cloud of atoms provides new insights into the radiation physics of single-photon superradiance, virtual photons, and more. The single-photon states also have potential for application to quantum informatics.

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