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Quantum optics: Strongly interacting photons

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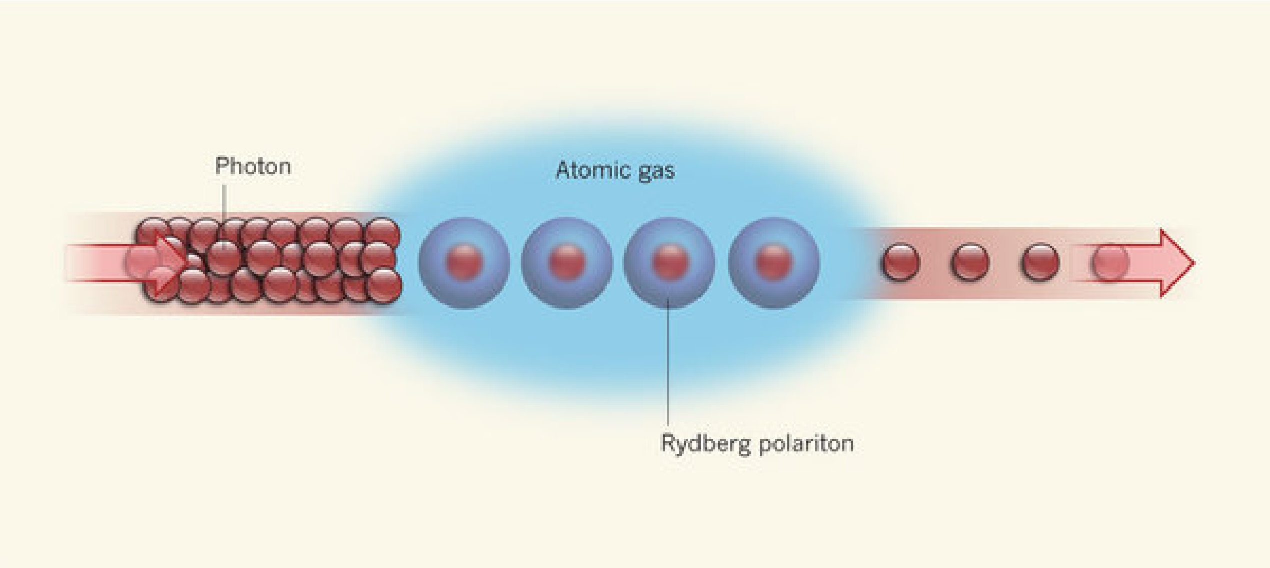
A fine marriage between atomic and optical physics has produced a medium that is transparent to single photons but opaque to multiple photons. The finding heralds the development of devices such as single-photon switches. See Letter **p.57**

Subject terms: Physics

Can photons be made to interact strongly with each other? Until recently, materials with nonlinear optical properties could mediate photon–photon interactions that were weak at best. These weak interactions have previously been artificially enhanced using devices known as optical cavities[1], which make the photons repeat their encounters thousands to millions of times. On page 57 of this issue, Peyronel *et al.*[2] demonstrate a new material in which single photons propagate freely, but interact so strongly with each other that when just two photons are present one is quickly absorbed. The result opens up the possibility of realizing concepts such as single-photon switches, deterministic photon-based quantum logic, and quantum gases of strongly interacting photons[*].

We have known since the dawn of quantum physics a century ago that light consists of particles, called photons, of energy hf, where h is Planck's constant and f is the light's frequency. Photons usually interact extremely weakly with each other, but strongly with the charged particles that comprise matter. In most materials, the optical response is linear — a beam comprised of many photons scatters and moves from place to place in the same way that single photons do. Inside nonlinear materials, however, the optical response is altered when multiple photons are present. The motion of a particular photon depends on the properties — most notably the number — of other photons in its vicinity. Until recently, however, available nonlinear materials required large numbers of photons to be present in order for them to noticeably affect each other. Peyronel *et al.*[2] combined several recent developments in atomic and optical physics to produce a novel nonlinear medium that is transparent to single photons yet opaque to multiple photons (Fig. 1).

Figure 1: A stream of single photons.



Peyronel *et al.*[2] have directed a beam of overlapping photons into an atomic gas in which single photons are converted into collective excitations known as Rydberg polaritons. The polaritons, which can be thought of as spheres comprising many atoms and one photon, strongly absorb additional photons. On exiting the gas, the polaritons are converted back to individual, non-overlapping photons.

The largest nonlinear optical effects achievable in atoms occur when a light field renders the atoms transparent. Consider a sample of atoms that have three energy levels: a ground state E_g, an excited state E_r and an intermediate level E_e (see Fig. 1b of the paper[2]). Photons of frequency f_1 that are directed into the sample and obey the Bohr equation, $hf_1=E_e-E_g$, will normally be absorbed. However, when a strong 'control' laser of frequency f_2 is also shone on the sample, the atoms become transparent to frequency f_1 if the condition $h(f_1+f_2)=E_r-E_g$ is satisfied. This electromagnetically induced transparency (EIT; ref. 3) puts the atoms and photons into collective excitations called polaritons. In Peyronel and colleagues' experiment, the control laser changes the transmission of the atomic gas from essentially zero to 60%. The EIT condition is extremely sensitive: photons that obey it are transmitted with high probability, whereas those that violate it are absorbed normally. This is basically an optically controlled switch[4].

When the upper level *r* is a state of large principal quantum number *n* (a Rydberg state[5]), the EIT condition can be easily violated by weak interactions between the atoms. For an *n* of about 100, a single Rydberg atom will cause a violation of the EIT condition for all other atoms within a 'blockade radius' of 10 micrometres. This Rydberg blockade produces record nonlinearities, as shown recently by Adams and colleagues[6], and has been used to entangle neutral atoms separated by micrometre-scale distances[7, 8]. A Rydberg polariton can be thought of as a 10-μm sphere containing many ground-state atoms and one Rydberg atom — or, equivalently, many atoms and one photon. Should other photons enter a volume already occupied by a Rydberg polariton, the blockade effect causes a violation of the EIT condition, so the photons are absorbed rather than transmitted. Note that if the atom density is low, as in previous experiments[6], the absorption probability may still be small.

The final, essential ingredient needed to generate strong photon–photon interactions at the two-photon level is an atomic cloud of such high density that when two or more photons enter a blockade volume, all but one are absorbed within that volume, leaving a single Rydberg polariton. This 'photon blockade' is the novelty of Peyronel and colleagues' study. Their experiment reveals that a multi-photon incident light beam is converted, within a few micrometres, into a beam of single photons, with a small (less than 0.09) probability that two photons will leave the atomic gas at the same time. Interestingly, even though their sample is large enough for several Rydberg polaritons to co-exist, the authors find that (and explain why) only one photon at a time is found within the entire sample.

An exciting feature of this experiment is that there are several clear avenues towards improving the properties of the medium. Cooler, denser atomic gases and lasers that have a narrower frequency range would improve the EIT transmission to nearly 100% and reduce the overlap of photons from the single-photon source. A looming challenge is to reconfigure the experiment so that the two-photon nonlinearity delays rather than absorbs excess photons6. This type of nonlinearity, which preserves the number of photons, would be extremely useful for quantum-information purposes.

In one respect, Peyronel and colleagues have demonstrated a quality single-photon light source that has a rate of emission in the megahertz regime, as Dudin and Kuzmich have shown[9] using a related approach. The key capability of this experiment[2] — engineering strong photon–photon interactions at the two-photon level — should also lead to various other new possibilities. For example, single-photon switches, photon detectors of high quantum efficiency, and non-destructive photon detection can easily be foreseen as extensions of this work. The physics of strongly interacting photons has a bright future.

Notes

Notes **References** **Author Information** **Comments**

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