LITTLE BIG PHOTON

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A photon, the constituent particle of light, carries only a tiny amount of energy. Furthermore photons do not interact with one another in vacuum, and generally only very weakly in optical media. Nonetheless, it has recently become possible for a single photon to switch on or off hundreds of other photons, or to generate entanglement between thousands of atoms.

▲ A single photon can generate quantum correlations (entanglement) between several thousand atoms.
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Photons come in many beautiful colors and are very useful for transmitting information with little loss over large distances. However, photons are also a little boring: they essentially do not interact with one another. This absence of interactions, or equivalently, the linearity of the optical response, is what allows one to send powerful optical pulses over large distances through optical fibers without much signal distortion. It is also what makes photons good carriers of quantum states, that can be encoded in the photons' polarization, frequency, or time of arrival.

Quantum nonlinear optics

On the other hand, nonlinear optics is arguably much more interesting than linear optics. In nonlinear optics it is possible, *e.g.*, to convert a light beam of one frequency into a beam with exactly twice the frequency. However, even in what are considered strongly nonlinear optical media, a very large number of photons is required to generate an appreciable nonlinear signal. The weakness of optical nonlinearities is illustrated [1] by the fate of the first paper reporting optical frequency doubling: the reported signal was removed by the copy editor because he mistook it for a dust speckle!

Building on those first controlled experiments in nonlinear optics, it took researchers another half century to access a regime one may call *quantum nonlinear* optics [2]. In this regime the optical medium is so strongly nonlinear that it responds differently to two incident photons as compared to one incident photon [3-5]. This regime offers highly complex many-body phenomena similar to the ones that make condensed matter physics so interesting (and its theoretical description so challenging). Strong quantum optical nonlinearities can also enable a variety of applications, where individual photons control much larger systems, such as an all-optical transistor where a single photon controls another, much stronger light beam [4-6].

How can strong, deterministic interactions between individual photons be experimentally realized? In standard materials, the nonlinear response becomes observable when the electric field of the laser beam is sufficiently strong to appreciably displace the electron in the Coulomb field of the nucleus, leading to an anharmonic electron response. However, this regime requires strong light fields containing many photons. To reach the quantum nonlinear regime, one must instead make use of the

▼ **FIG. 1:** Atom-light interaction. The interaction probability of an atom with a photon traveling in a laser beam is given by the ratio of the atomic cross section σ and the beam area A. While the atomic cross section σ can be of order of the optical wavelength squared, λ^2, optical diffraction prevents the laser beam from being focused to an area less than λ^2. (This is the same effect that limits the resolution of optical microscopes.) Therefore the atom-photon interaction probability in free space is (much) less than one. The interaction probability can be made to approach unity by placing mirrors around the atoms, such that a photon bouncing back and forth between the mirrors has many chances of interacting with the atom.

laser beam area A

atom

cross section σ
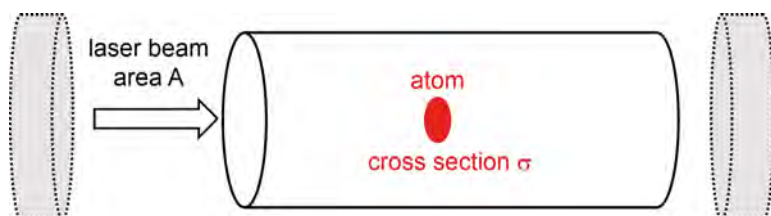
graininess of matter, or equivalently, the fact that one atom can only absorb one photon at a time. Two photons then interact with one another because the first photon modifies the atom's state, and hence the atom's response to the second photon.

What, then, is the limit to the interaction of one photon with one atom? The basic situation is depicted in Figure 1: A weak light beam is focused onto an area A containing an atom with absorption cross section σ. The interaction probability between a photon in that beam and an atom is then simply given by the ratio of areas σ/A. Note that for a strong atomic transition the atom's absorption cross section can be on the order of the optical transition wavelength squared, λ^2, which is several orders of magnitude larger than the geometric size of the atom: The atom constitutes a perfect antenna. Nonetheless, the diffraction limit for focusing light in free space imposes a minimum on the beam area of $A > \lambda^2$, so that the interaction probability σ/A between an atom and a photon is less, and typically much less, than unity. The largest reported value in free space is σ/A≈0.1 [7].

The situation can be improved by placing a resonant optical cavity around the atom, such that the photon traverses the plane containing the atom many times [8,9]. In this case the interaction probability can approach unity, *i.e.*, the atom can be made to absorb the photon with near certainty. Once the atom has absorbed the first photon, it is in an excited state, and cannot absorb a second photon. Thus the absorption of the second photon is conditioned on the presence or absence of the first photon. If one detunes the second photon from atomic resonance, such that the atom constitutes a transparent medium with an index of refraction, one can similarly condition an optical phase shift experienced by the second photon on the presence of the first photon [10].

In practice, one does not use an electronic excited state of the atom because it is typically much too short lived. Rather, the first photon transfers the atom from one stable ground state (*g*) to another stable state (*s*) via an excited state (*d*) with the help of an additional (control) laser beam (see Figure 2b). This process, called electromagnetically induced transparency (EIT) [11], is highly interesting in its own right, as inside an atomic ensemble the light then travels very slowly. EIT allows one not only to dynamically control the speed of light in the medium, but also to reversibly store light in the medium, and retrieve it at a later time. For every photon stored in the medium, one of the atoms in the ensemble has been transferred from the state *g* to the state *s*.

All-optical transistor controlled by a single stored photon

Using these principles it is then possible to realize an all-optical transistor that is controlled by a single stored photon: Consider a situation where an ensemble of
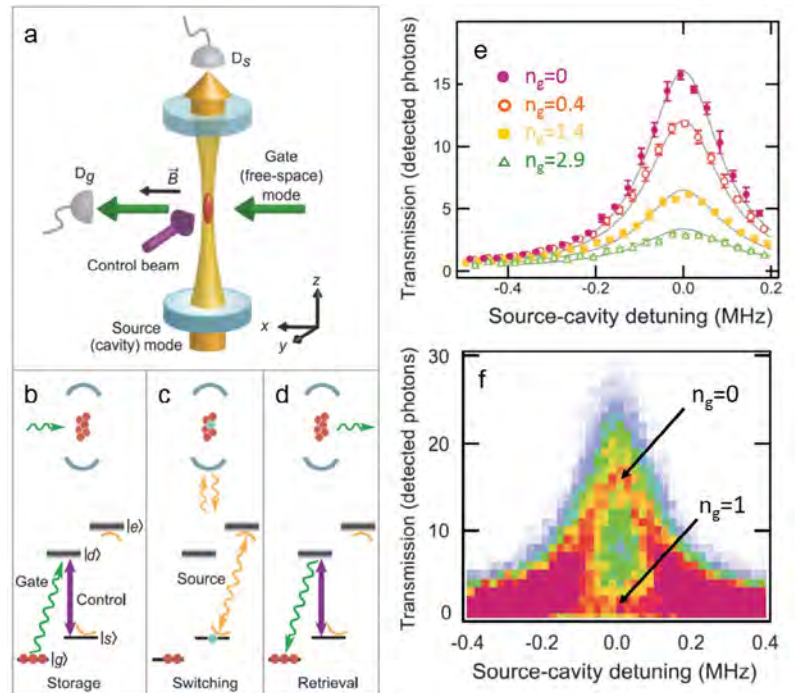
▲ **FIG. 2: All-optical switch and transistor operated with one stored photon. (a)** Setup and **(b to d)** atomic level scheme with experimental sequence. An ensemble of laser-cooled cesium atoms is trapped inside an optical resonator. **(b)** A gate photon is stored in the atomic medium, corresponding to the transfer of one of the atoms to the state |s⟩. **(c)** This collective excitation blocks the transmission of source photons through the cavity and **(d)** can be retrieved later in the gate mode. **(e)** Cavity transmission in the presence of stored gate photons for mean stored gate photon number ⟨n_g⟩ = 0, 0.4, 1.4, and 2.9 (top to bottom). **(f)** Cavity transmission for ⟨n_g⟩ = 0.5 stored gate photons. The horizontal axis indicates the detuning of the source beam from the cavity resonance, and the vertical axis indicates the number of detected transmitted source photons. The color indicates the occurrence rate of a particular detected transmitted source photon number for a given source-cavity detuning. The histogram displays a clear separation between the zero-gate-photon component n_g = 0 with high cavity transmission, and the component n_g = 1 leading to cavity blocking, thus directly showing the quantization of the gate light field.

atoms with two stable ground states is used to store a very weak incoming laser pulse containing on average less than one photon (Figure 2 b-d). Some of the time the incoming laser beam will contain no photons, and all of the atoms will remain in the state *g*. However, if the incoming beam does contain a photon, then this photon will be stored as a state of the atomic ensemble where one of the atoms has been transferred to the state s. Now consider the case where this ensemble is located inside an optical cavity that is made resonant with an optical transition connecting *s* to an excited state *e* (Fig. 2a). The atom in s then acts as an absorbing medium that prevents the cavity of filling up with input light that is applied to the cavity. Thus in the presence of a stored gate photon (*i.e.*, an atom in the state s), a source beam incident onto the cavity is reflected off the input mirror of the cavity, while in the absence of a stored gate photon the source beam is transmitted through the (empty) cavity. This idea constitutes the essence of an all-optical transistor that is controlled by a single stored gate photon [6].

In the experiment, the average transmission through the cavity (shown in Fig. 2e as a function of the detuning of the

signal light from the cavity resonance) decreases smoothly with the average photon number in the gate pulse. However, if one plots a histogram of the transmitted photon number, rather than the average transmission (Fig. 2f), it becomes evident that the average transmission is due to two well-separated components: a high-transmission regime corresponding to the empty cavity with no gate photons having been stored, and a regime with a tenfold reduced transmission corresponding to a stored gate photon. The quantization of the photon number in the stored gate pulse, or equivalently, the discrete nature of the optical excitation in a medium consisting of individual atoms, is directly visible in the histogram of the cavity transmission. One finds that a single stored gate photon can block the transmission of hundreds of source photons [6]. Using a different technique, the direct interaction between atoms containing stored photons, the blocking of the transmission of tens of photons has also been demonstrated [4,5].

Generating entanglement between many atoms with a single photon

A single photon can not only switch on or off hundreds of other photons, it can also create strong entanglement between thousands of atoms [12]. The basic idea is shown in Fig. 3. An ensemble of 3000 laser-cooled atoms, each carrying a spin 1, is trapped inside an optical resonator. Initially, each atom's spin state is independent of the state of the other atoms, and all atomic spins are pointing in the same direction. Thus the N-atom ensemble is in an unentangled state that can be described as a large spin $S=N$ on a sphere. If each atom is prepared such that its spin is pointing along the x axis, then the collective large spin vector also points along the x axis. In this situation, if a measurement of the spin along the z axis is performed,

then on average an equal number of atoms is found pointing along the positive and negative z directions. However, in any particular realization of the spin measurement along z, there are fluctuations in the distribution, since any atom can be found with equal probability in the states up or down. These fluctuations, that scale with the square root of the particle number, have a Gaussian probability distribution about the mean direction (see Figure 3).

In order to create quantum correlations (entanglement) between the atoms, the atoms must communicate with one another. It turns out that non-classical correlations between several thousand atoms can be accomplished using just one photon that is transmitted through the ensemble and interacts with all atoms. The principle is as follows: The atoms are confined in an optical resonator to enhance the light-atom interaction. When linearly polarized light (v) is incident onto the ensemble, then atomic spin quantum noise leads to a small random Faraday rotation that is correlated with the z component of the atomic spin. In particular, when the atomic spin points exactly along the equator of the Bloch sphere, then the linear polarization is not affected. However, whenever the atomic-spin noise points a little away from the equator, a small Faraday rotation leads to a finite probability for observing a transmitted photon with orthogonal polarization (h). Whenever this photon is detected, we know that the atomic spin state must be pointing away from the equator. Surprisingly, such a detection event projects the atoms into a strongly entangled state with a doughnut-shaped probability distribution (see Figure 3). This quasi-probability distribution (a so-called Wigner distribution) has a negative value in the middle, which is a strong signature of non-classicality. The doughnut shape means that the collective atomic
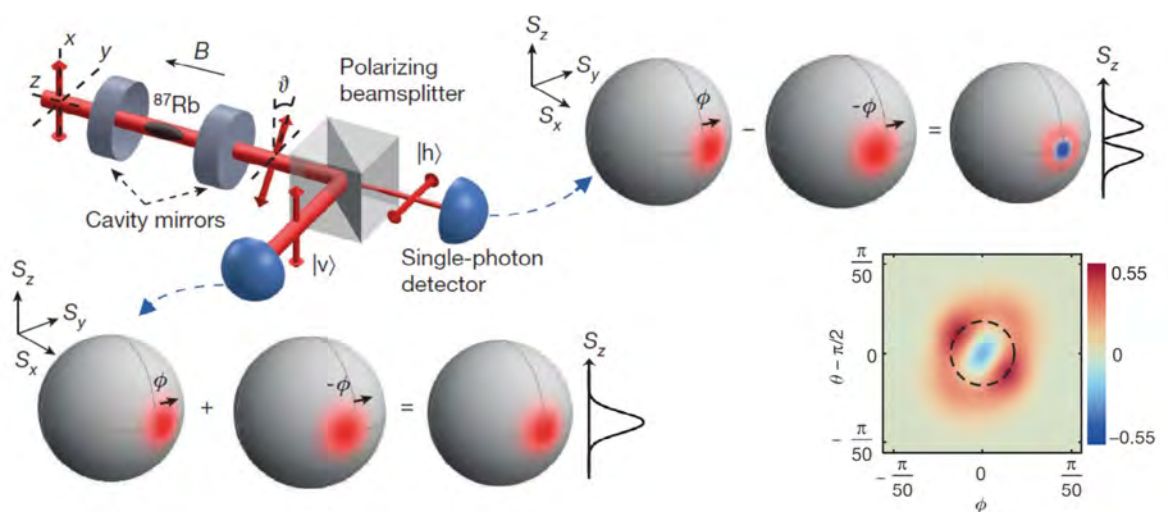
▶ **FIG. 3:** A single photon generating an entangled state of almost 3000 rubidium atoms. The laser-cooled atoms are trapped inside an optical resonator that enhances the interaction between the atomic ensemble and light. The atoms are prepared in a superposition of two spin states with their spin aligned along x and are initially uncorrelated. An incident vertically polarized photon entering the resonator from the left experiences a weak polarization rotation due to atomic spin quantum noise along the z direction, and the detection of a horizontally polarized transmitted photon heralds an entangled state of collective atomic spin. The Bloch spheres show the ideal Wigner distribution functions for the collective spin S upon registering the corresponding single-photon detection events. When the detector for horizontal polarization registers one photon, the state of 3000 atoms is projected into a strongly entangled state with a negative Wigner function (blue area), a strong signature of non-classicality. Inset: Zoom-in on experimentally attained Wigner function for 3000 atoms.

spin is never found pointing towards the equator of the sphere, not even after having been rotated by an arbitrary angle about the *x* axis [13]. This is impossible to achieve with a classical probability distribution of spin directions.

Notably, the measurements also show that a record number of 2800 atoms, over 90% of the ensemble must be mutually entangled with one another [12]. While a single photon cannot possibly "flip the spin" of many atoms, the information gain associated with the detection of just one photon can still drastically change the state of the macroscopic atomic system: With judicious control, even a little photon can have a big impact. ∎

Biography

Vladan Vuletić obtained his Ph.D. in 1997 at the University of Munich working in the group of T.W. Hänsch on the trapping and laser cooling of atoms. After postdoctoral work at Stanford University he was appointed Assistant Professor at Stanford University in 2000. In 2003 he moved to the Massachusetts Institute of Technology where his group experimentally studies many-body entanglement and quantum measurements using ultracold atomic gases.
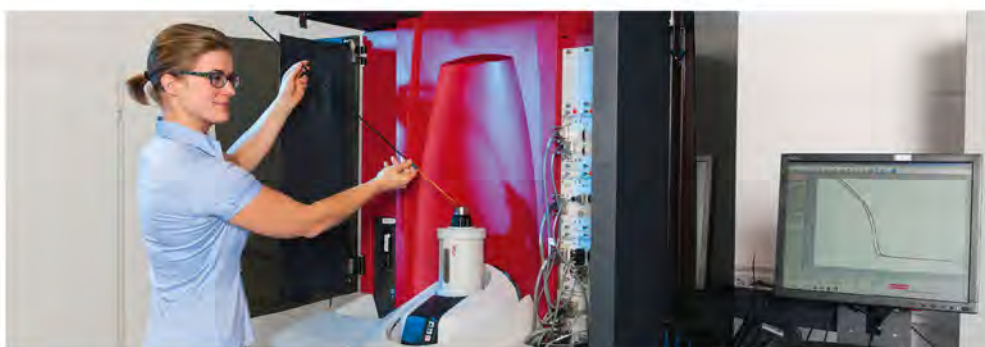
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