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# Controlled Single-Photon Emission from a Single Trapped Two-Level Atom

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**By illuminating an individual rubidium atom stored in a tight optical tweezer with short resonant light pulses, we create an efficient triggered source of single photons with a well-defined polarization. The measured intensity correlation of the emitted light pulses exhibits almost perfect antibunching. Such a source of high rate, fully controlled single photon pulses has many potential applications for quantum information processing.**

Implementing a deterministic or conditional two qubit quantum gate is a key step towards quantum computation. Deterministic gates generally require a strong interaction between the particles that are used to carry the physical qubits (*1*). Recently, controlled-not gates have been realized using trapped ions and incorporated in elaborate quantum algorithms (*3, 2, 4*). So far, individually addressed two qubit gates have not been demonstrated with neutral atoms. Promising results have been obtained on entangling neutral atoms using cold controlled collisions in an optical lattice (*5*), but the single qubit operations are difficult to perform in such a system.

Another approach is to bypass the requirement for a direct interaction between the qubits, and use instead an interference effect and a measurement-induced state projection to create the desired operation (*6, 7*). An interesting recent development of this idea is to use photon detection events for creating entangled states of two atoms (*8, 9, 10*). This provides “conditional” quantum gates, where the success of the logical operation is heralded by appropriate detection events. These schemes can be extended to realize a full controlled-not gate, or a Bell-state measurement, or more generally to implement conditional unitary operations (*8, 11*). They could be implemented by using, for instance, trapped ions (*12*), or atoms in microscopic dipole traps. These proposals require the controlled emission of indistinguishable single photons by at least two identical emitters.

Various single photon sources have been implemented using solid-state systems as well as atoms or ions. Solid-state systems such as single molecules, nitrogen-vacancy centers in diamond or quantum dots allow high single photon rates (*13*). However, realizing truly identical sources is a major problem for such systems, due to inhomogeneities in both the environment of the emitters, and the emitters themselves. Another approach is provided by sources based on neutral atoms (*14, 15*) or ions (*16*) strongly coupled to a mode of a high-finesse optical cavity. Such sources are spectrally narrow, and the photons are emitted into a well-defined spatial mode, thus opening the way to coherent coupling of the quantum state of single atoms

and single photons. However, the rate at which the system can emit photons is limited by the cavity and is often low in practice. Moreover, the need to achieve the strong coupling regime of cavity quantum electrodynamics remains a demanding experimental requirement.

We present a triggered single-photon source based on a single rubidium atom trapped at the focal point of a high-numerical-aperture lens (N.A. = 0.7). We also show that we have full control of the optical transition by observing Rabi oscillations. Under these conditions our system is equivalent to the textbook model formed by a two-level atom driven by monochromatic light pulses. Previous work has shown that by using holographic techniques one can create arrays of dipole traps, each containing a single atom, which can be addressed individually (17). The work presented here can therefore be directly scaled to two or more identical emitters.

We trap the single rubidium 87 atom at the focus of the lens using a far-detuned optical dipole trap (810 nm), loaded from an optical molasses. The same lens is also used to collect the fluorescence emitted by the atom (Fig. 1). The experimental apparatus is described in more detail in references (18, 19). A crucial feature of our experiment is the existence of a “collisional blockade” mechanism (19) which allows only one atom at a time to be stored in the trap: if a second atom enters the trap, both are immediately ejected. In this regime the atom statistics are sub-Poissonian and the trap contains either one or zero (and never two) atoms, with an average atom number of 0.5.

The trapped atom is excited with 4 ns pulses of laser light, resonant with the  $S_{1/2}, F = 2 \rightarrow P_{3/2}, F' = 3$  transition at 780.2 nm. The laser pulses are generated by frequency doubling pulses at 1560 nm, generated by using an electro-optic modulator to chop the output of a continuous-wave diode laser. A fiber amplifier is used to boost the peak power of the pulses prior to the doubling crystal. The repetition rate of the source is 5 MHz.

Fluorescence photons are produced by spontaneous emission from the upper state, which has a lifetime of 26 ns. The pulsed laser beam is  $\sigma^+$ -polarized with respect to the quantization

axis defined by a magnetic field applied during the excitation. The trapped atom is optically pumped into the  $F = 2, m_F = +2$  ground state by the first few laser pulses. It then cycles on the  $F = 2, m_F = +2 \rightarrow F' = 3, m'_F = +3$  transition, which forms a closed two-level system emitting  $\sigma^+$ -polarized photons. Impurities in the polarization of the pulsed laser beam with respect to the quantization axis, together with the large bandwidth of the exciting pulse (250 MHz), result in off-resonant excitation to the  $F' = 2$  upper state, leading to possible de-excitation to the  $F = 1$  ground state. To counteract this, we add a repumping laser resonant with the  $F = 1 \rightarrow F' = 2$  transition. We check that our two-level description is still valid in the presence of the repumper by analyzing the polarization of the emitted single photons (see supporting online text for further details).

The overall detection and collection efficiency for the light emitted from the atom is measured to be  $0.60 \pm 0.04\%$ . This is obtained by measuring the fluorescence rate of the atom for the same atomic transition driven by a continuous-wave probe beam, and confirmed by a direct measurement of the transmission of our detection system (see supporting online text).

For a two-level atom and exactly resonant square light pulses of fixed duration  $T$ , the probability for an atom in the ground state to be transferred to the excited state is  $\sin^2(\Omega T/2)$ , the Rabi frequency  $\Omega$  being proportional to the square root of the power. Therefore the excited state population and hence the fluorescence rate oscillates as the intensity is increased. To observe these Rabi oscillations, we illuminate the trapped atom with the laser pulses during 1 ms. We keep the length of each laser pulse fixed at 4 ns, with a repetition rate of 5 MHz, and measure the total fluorescence rate as a function of the laser power. The Rabi oscillations are clearly visible on our results (see Fig. 2). From the height of the first peak and the calibrated detection efficiency measured previously, we derive a maximum excitation efficiency per pulse of  $95 \pm 5\%$ .

The reduction in the contrast of the oscillations at high laser power is mostly due to fluctua-

tions of the pulsed laser peak power. This is shown by the theoretical curve in Fig. 2, based on a simple two-level model. This model shows that the 10% relative intensity fluctuations that we measured on the laser beam are enough to smear out the oscillations as observed.

The behavior of the atom in the time domain can be studied by using time resolved photon counting techniques to record the arrival times of the detected photons following the excitation pulses, thus constructing a time spectrum. By adjusting the laser pulse intensity, we observe an adjustable number of Rabi oscillations during the duration of the pulse, followed by the free decay of the atom once the laser has been turned off. The effect of pulses close to  $\pi$ ,  $2\pi$  and  $3\pi$  are displayed as inserts on Fig. 2, and show the quality of the coherent control achieved on a single atom.

In order to use this system as a single photon source, the laser power is set to realize a  $\pi$  pulse. To maximize the number of single photons emitted before the atom is heated out of the trap, we use the following sequence. First, the presence of an atom in the dipole trap is detected in real-time using its fluorescence from the molasses light. Then, the magnetic field is switched on and we trigger an experimental sequence that alternates  $115 \mu\text{s}$  periods of pulsed excitation with  $885 \mu\text{s}$  periods of cooling by the molasses light (Fig. 3). The repumping laser remains on throughout, and the trap lifetime during the sequence is measured to be 34 ms. After 100 excitation/cooling cycles, the magnetic field is switched off and the molasses is turned back on, until a new atom is recaptured and the process begins again. On average, three atoms are captured per second under these conditions. The average count rate during the excitation is  $9600 \text{ s}^{-1}$ , with a peak rate of  $29000 \text{ s}^{-1}$  (corresponding to twice the first peak in Fig. 3)

To characterize the statistics of the emitted light, we measure the second order temporal correlation function, using a Hanbury Brown and Twiss type set-up. This is done using the beam splitter in the imaging system (Fig. 1), which sends the fluorescence light to two photon-counting avalanche photodiodes that are connected to a high-resolution time-to-digital conver-

sion counting card in a start-stop configuration (resolution of about 1 ns). The card is gated so that only photons scattered during the  $115 \mu\text{s}$  periods of pulsed excitation are counted, and the number of coincidence events is measured as a function of delay. The histogram obtained after 4 hours of continuous operation is displayed in Fig. 4, and shows a series of spikes separated by the period of the excitation pulses (200 ns). The  $1/e$  half width of the peaks is  $27 \pm 3$  ns, in agreement with the lifetime of the upper state. No background correction is done on the displayed data. The small flat background is attributed to coincidences between a fluorescence photon, and an event coming either from stray laser light (about 175 counts/sec), or dark counts of the avalanche photodiodes (about 150 counts/sec). When these events are corrected for, the integrated residual area around zero delay is  $3.4\% \pm 1.2\%$  of the area of the other peaks.

We calculate (20) that under our experimental conditions, the probability to emit exactly one photon per pulse is 0.981 whereas the probability to emit two photons is 0.019. These two-photon events would show up in the correlation curve as coincidences close to zero delay (still with no coincidences at exactly zero delay). From our calculation, the value for the ratio of the area around zero delay compared to the others is 3.7%, in excellent agreement with the experimental results.

Finally, we discuss the coherence properties of the emitted photons, necessary for entanglement protocols based on the interference between two emitted photons, either from the same atom or from different atoms. As our collection optics are diffraction-limited, the outgoing photons should be in a single spatial mode of the electromagnetic field. As far as temporal coherence is concerned, the main limiting factor appears to be the motion of the atom in the trap, which can be controlled by optimized cooling sequences. We then anticipate that our source should be Fourier-limited by the lifetime of the excited state. We are now working to characterize the coherence of our single-photon source, and to use it to observe multiple atom interference effects.

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20. We have performed a full calculation of the second order correlation function using the Heisenberg-Langevin equations, which gives the areas of the peaks. We have also calculated the photon emission probabilities using density matrix and Monte Carlo methods, which lead to the same result.
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## Supporting Online Material

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Supporting online text

### Polarization analysis of the emitted single photons

As explained in the main text, polarization imperfections lead to a depumping process to the  $F = 1$  ground state. A repumping laser is used to counteract this process and minimize deviations from the two-level behavior.

To check the validity of our two-level description, we have investigated the effect of impurities in the polarization of the pulsed laser beam with respect to the quantization axis. We measure that on average the atom is pumped into the  $F = 1$  ground state by spontaneous emission after 120 excitations. In the presence of the repumping light, a rate equation model of the repumping process (including the repumping laser as well as the pulsed excitation) shows that the atom spends more than 90% of its time on the cycling  $F = 2, m_F = +2 \rightarrow F' = 3, m'_F = +3$  transition, as desired.

In addition, we have measured the polarization of the emitted light, using a polarizer to select fluorescence light either polarized perpendicularly ( $\perp$ ) or parallel ( $\parallel$ ) to the quantization axis. For a narrow collection angle,  $\perp$  would correspond to the circularly polarized photons emitted on the cycling transition, and  $\parallel$  to  $\pi$  polarized photons. Here, the measured contrast  $(R_{\perp} - R_{\parallel}) / (R_{\perp} + R_{\parallel}) = 72(\pm 2)\%$ , where  $R_{\perp}$  and  $R_{\parallel}$  are the count rates perpendicular and parallel to the quantization axis respectively. The largest part of this depolarization is actually due to the very large numerical aperture (N.A. = 0.7) of the collection lens, which decreases to 77% the maximum contrast obtainable for purely  $\sigma$ -polarized fluorescence. From the measured contrast of 72%, we calculate that 3% of the collected photons are  $\pi$ -polarized and we attribute this to

photons induced by the depumping-repumping processes. This number is compatible with the results of the rate equation model discussed in the previous paragraph.

### **Collection and detection efficiency**

The overall collection and detection efficiency of  $(0.60 \pm 0.04)\%$  is obtained by measuring the fluorescence rate of the atom as a function of the power of a continuous-wave probe beam. Since the saturated photon emission rate for a closed two-level system is  $\Gamma/2$ , where  $\Gamma$  is the inverse of the natural lifetime, the collection and detection efficiency can be obtained directly from the measured count rate.

This value is compatible with that obtained from a direct evaluation of the transmission of our detection system. The transmission of our lens is measured to be 87% and its collection solid angle is  $0.15 \times 4\pi$  sr. Because the emission pattern for  $\sigma^+$ -polarized photons is not isotropic, the effective solid angle of collection must be corrected by a factor of 85%. The transmission of the optical elements in the imaging system is 58%. Finally the light passes through a pinhole before illuminating the avalanche photodiode. The largest uncertainty is in the combination of the pinhole transmission and photodiode quantum efficiency, which is estimated to be around 10%. Multiplying all factors gives an overall collection and detection efficiency compatible with the 0.6% quoted above.

**Figure 1.** Schematic of the experiment. The same lens is used to focus the dipole trap and collect the fluorescence light. The fluorescence is separated by a dichroic mirror and imaged onto two photon counting avalanche photodiodes (APD), placed after a beam-splitter (BS). The insert shows the relevant hyperfine levels and Zeeman sublevels of rubidium 87. The cycling transition is shown by the arrow. Also shown is the nearby  $F' = 2$  level responsible for the depumping.

**Figure 2.** Total count rate (squares) as a function of the average power of the pulsed beam, for a fixed pulse length of 4 ns and a repetition rate of 5 MHz. The solid line is a theoretical curve using a simple two-level model that includes spontaneous emission and intensity fluctuations. The inserts show the time spectra for the laser intensities corresponding to  $\pi$ ,  $2\pi$  and  $3\pi$  pulses.

**Figure 3.** Fluorescence signal measured by one of the two photodiodes during the experimental sequence, averaged over 22958 cycles. Peaks are observed corresponding to the  $115 \mu\text{s}$  periods of pulsed excitation, separated by periods of lower fluorescence induced by the molasses light during the  $885 \mu\text{s}$  of cooling. The exponential decay of the signal is due the lifetime of the atom in the trap, which is 34 ms under these conditions. Insert: A close-up of the signal clearly shows the alternating excitation and cooling periods.

**Figure 4.** Histogram of the time delays in the start-stop experiment. The histogram has been binned 4 times leading to a 4.7 ns time resolution. No correction for background has been made. The absence of a peak at zero delay shows that the source is emitting single photons. During the 4-hour experimental run, 43895 sequences were completed, which corresponds to a total of 505 seconds of excitation. A total of  $4.83 \times 10^6$  photons were detected by the two photodiodes.







