LETTERS

Quantum interference between two single photons emitted by independently trapped atoms

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When two indistinguishable single photons are fed into the two input ports of a beam splitter, the photons will coalesce and leave together from the same output port. This is a quantum interference effect, which occurs because two possible paths—in which the photons leave by different output ports—interfere destructively. This effect was first observed in parametric downconversion[1] (in which a nonlinear crystal splits a single photon into two photons of lower energy), then from two separate downconversion crystals[2], as well as with single photons produced one after the other by the same quantum emitter[3–6]. With the recent developments in quantum information research, much attention has been devoted to this interference effect as a resource for quantum data processing using linear optics techniques[2,7–11]. To ensure the scalability of schemes based on these ideas, it is crucial that indistinguishable photons are emitted by a collection of synchronized, but otherwise independent sources. Here we demonstrate the quantum interference of two single photons emitted by two independently trapped single atoms, bridging the gap towards the simultaneous emission of many indistinguishable single photons by different emitters. Our data analysis shows that the observed coalescence is mainly limited by wavefront matching of the light emitted by the two atoms, and to a lesser extent by the motion of each atom in its own trap.

A basic requirement for most quantum computing schemes is the implementation of two-qubit quantum gates[12]. If the qubits are encoded in single photons, the gate can be obtained by using an interference effect between the photons, followed by a measurement-induced state projection[9]. One may also use qubits encoded in solid-state systems such as quantum dots[13], or in atomic systems such as ions[14] or neutral atoms[15]. One way to entangle the atomic qubits without direct interaction, and thus realise quantum gates, is to use them as single photon sources, so that the emitted photons are entangled with the internal states of the emitters. The interference of two photons emitted by such sources projects the state of the two atoms into an entangled state[16]. Many protocols based on this conditional entanglement have been proposed[10,11], and experimental work is under way to implement them[17]. The photons involved in such schemes do not need to be initially entangled, and can even be emitted by different sources[2], but they need to be indistinguishable. However, it is in general not easy to have several (possibly many) independent sources emitting indistinguishable photons. With quantum dots in microcavities[3,6], the dispersion in frequency associated with differences in fabrication is usually much too large for the photons to be emitted at the same frequency. With atoms in cavities[4], each emitter is itself a complicated experiment, and cannot easily be multiplied. In this paper we address this problem by using two single atoms in two neighbouring traps emitting in free space, and we demonstrate that these atoms do emit indistinguishable photons. This scheme can easily be scaled to arrays of traps[18].

Our experiment uses two single rubidium-87 atoms, confined in separate optical dipole traps. These traps are formed in the focal plane of the same high-numerical aperture lens, and loaded from a cloud of cold atoms in an optical molasses[19]. The two traps, each of which has a waist of 1 μm, are separated by a distance of 6 μm. To obtain triggered single photon emission from the two atoms, we simultaneously excite them with a high efficiency (>95%) using a σ^+-polarized pulsed laser beam which drives the $F = 2$, $m_F = 2$ to $F' = 3$, $m'_F = 3$ closed transition[20]. The quantization axis is defined by a magnetic field of several gauss. Both atoms are excited by the

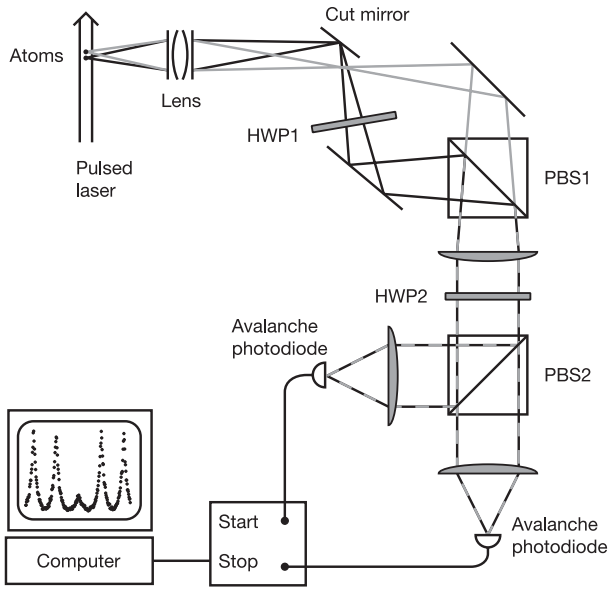

Figure 1 | Experimental set-up. The two atoms are trapped in two dipole traps separated by 6 μm, and they are excited by the same pulsed laser beam. The trap depth is 1.5 mK, and the trap frequency along the axis of the pulsed laser beam is 120 kHz. The emitted photons are collected by the same lens that is used to create the dipole traps. The light from one of the traps is separated off using a cut mirror placed close to the image plane of the objective. In the plane of the cut mirror, the spot corresponding to each trap has a waist of ~90 μm, and the two images are separated by 500 μm. The half-wave plate HWP1 is oriented such that, at polarizing beam splitter PBS1, the light beams from the two atoms are recombined into the same spatial mode, but with orthogonal polarizations. There are then two configurations to detect the photons: either the axis of HWP2 is set so that the two orthogonal incident polarizations are equally mixed in each output of PBS2, as in a 50/50 beam splitter, or the axis is set so that the polarizations are unchanged, and then PBS2 simply separates the two beams coming from the two atoms without mixing them. Two avalanche photodiodes are placed in the two output ports of PBS2. The measured overall collection and detection efficiency is 0.6% for each photodiode[21].

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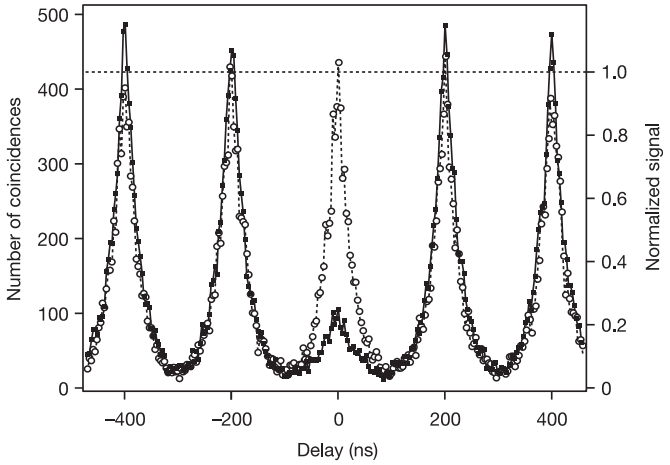

Figure 2 | Histograms of the time delays of the arrival of two photons on the avalanche photodiodes, in the start–stop configuration. Black squares correspond to the 50/50 beam-splitter configuration (interfering beams). Open circles correspond to the beam-separator configuration (independent beams). These histograms have been binned three times, leading to a 3.6-ns resolution. The total accumulation time is about five hours, corresponding to about 6,600 events with two photons arriving on the beam splitter at around zero delay. The solid and dashed lines are a guide to the eye. The normalized signal is obtained by dividing the number of counts by the average value of the peak height in the beam-separator configuration.

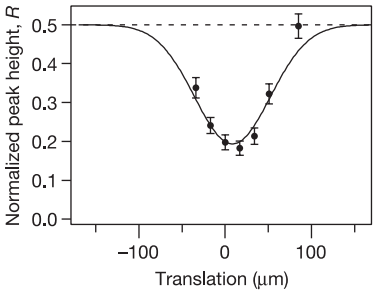

Figure 3 | Influence of wavefront matching. The ratio of the height of the residual peak at zero delay in the beam-splitter configuration to the average height of the peaks in the beam-separator configuration, as a function of the relative distance between the two beams, translated parallel to each other. The solid curve is the expected ratio, calculated from the measured beam waist of the two beams. The amplitude and the centre of this curve are adjusted to fit the data. Error bars show ±1 s.d.

same short (less than 4 ns) π-pulse. Each one then spontaneously emits a single photon[21] with a lifetime of 26 ns. The photons are collected by the same objective lens that is used to focus the dipole trap beams[19], and detected using a pair of avalanche photodiodes. Between the objective and the photodiodes, an optical set-up composed of two half-wave plates and two polarizing beam-splitter cubes (HWP1, HWP2 and PBS1, PBS2) is inserted in the beam path (see Fig. 1). It can be configured either as a 50/50 beam splitter that mixes the light from the two atoms on each detector, or as a beam separator that sends the light from each atom to only one of the detectors. The avalanche photodiodes are connected to a high-resolution counting card in a start–stop configuration. This allows us to measure the number of coincident photodetections as a function of the delay between the arrival times of the two photons on the photodiodes, with a resolution of about 1.2 ns. In the 50/50 beam-splitter configuration, the detectors cannot distinguish which atom has emitted a photon, and we expect to observe the coalescence effect. In the beam-separator configuration, each avalanche photodiode monitors only the light emitted by one of the two atoms, and coincidence counts can be due only to independent emissions by both atoms.

The measurements are performed by repeating the following procedure. First, we detect the simultaneous presence of one atom in each trap in real time by measuring their fluorescence from the molasses light used to load the traps. We then trigger a sequence that alternates a burst of 575 pulsed excitations, lasting 115 μs, with a 885-μs cooling period using the molasses light. This alternation is repeated 15 times before stopping and recapturing a new pair of atoms. During the excitation periods, the π-pulses irradiate both atoms every 200 ns, and the counting card accumulates the number of double detections produced by the two avalanche photodiodes. This sequence maximizes the number of single photons that we can obtain before the two atoms are heated out of the trap[21]. After the 15 bursts of pulsed excitations, we measured a probability of 65% to keep each atom in its trap. At the end of the sequence, we switch the molasses back on and wait on average about 300 ms until we detect two atoms again. Two histograms are accumulated for the same number of repetitions: one in the 50/50 beam-splitter configuration, and one in the beam-separator configuration.

The two histograms are shown in Fig. 2, without background subtraction. Both histograms consist of a series of peaks separated by 200 ns, the repetition period of the pulsed laser. The width of the peaks is determined by the 26-ns lifetime of the excited state. In the beam-separator configuration, all peaks are identical, and always correspond to a double detection with one photon coming from each atom. Hence, their height gives a natural calibration of the experiment. A histogram in the 50/50 beam-splitter configuration can be normalized by dividing by the height of the peaks in its corresponding histogram measured in the beam-separator configuration. The normalized signals that are obtained are then independent of collection efficiency, detection efficiency and experiment duration, and allow histograms taken under different conditions to be compared. In the 50/50 beam-splitter configuration, the peak at zero delay is clearly much smaller than the other peaks. As each atom is a very good source of single photons[21], this peak also consists only of events where both atoms have emitted a photon. In contrast, the other peaks consist of events where two photons are successively emitted, either by the same atom, or by both atoms. Because the peaks at non-zero delay are almost the same in both configurations, we can deduce that almost all registered counts are due to events where both atoms were present.

In the case of perfect coalescence, the peak at zero delay in the 50/50 beam-splitter configuration would be absent: as the two photons leave via the same port, there can be no coincidences. We attribute the residual peak that we observe in Fig. 2 to an imperfect overlap of the spatial modes of the two photons, which then do not interfere. To illustrate this effect experimentally, we varied the overlap between the two modes in a controlled way by translating one beam relative to the other (translation of the cut mirror; see Fig. 1). Figure 3 shows the normalized height R of the residual peak at zero delay, as a function of the separation between the two images. For a given spatial overlap K between the amplitude of the two modes, the ratio R is expected to be $(1–K^2)/2$ (see Methods section and Supplementary Information). The solid line is a gaussian fit based on the experimental value of the beam size in the image plane, and considering the maximal wavefront overlap K_{max} as an adjustable parameter. The agreement with the coincidence data is very good, which confirms the crucial role of good mode matching of the two beams in our experiment. We obtain from the fit the maximum wavefront overlap $K_{max} = 0.78 \pm 0.03$. This imperfect overlap is consistent with the errors we measure on the beam positions and waists.

Finally, we analyse the structure of the time spectrum around zero delay. The small peak at zero delay from Fig. 2 is displayed on a larger scale in Fig. 4. The dashed line corresponds to a model where the

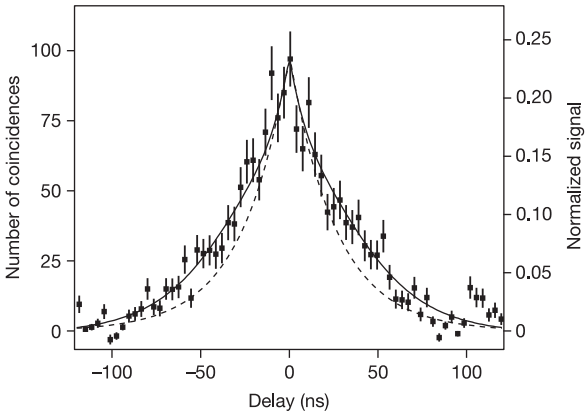

Figure 4 | Zoom of the histogram of Fig. 2 in the 50/50 beam-splitter configuration, around zero delay. This curve is obtained from Fig. 2 by subtraction of the contribution from the background and neighbouring peaks. The squares represent the experimental data. The solid line is a fit by the model described in the Methods section, taking into account the finite temperature of the atoms and the spatial overlap. The dotted line is the expected signal for zero temperature. The error bars correspond to $\pm\sqrt{N}$ statistical photon counting noise.

wavepackets of the two photons are identical and arrive at the same time on the beamsplitter, but with imperfect spatial overlap of the two beams. This curve does not correctly reproduce the experimental data: the experimental dots seem to sit on a slightly wider curve. Due to their finite temperature, the atoms move in the trapping potential and experience a range of light-shifts. This changes their internal energy, and thus modifies the frequency of the emitted photon. For two photons at different frequencies, the correlation signal would exhibit a beat note as already seen in ref. 4. If the two photons now have a distribution of frequencies, the correlation signal consists of a beat note averaged out over this distribution. This gives rise to a slightly broader structure for the signal, which is well fitted by the solid line predicted by our simple model (see details in the Methods section).

By fitting the experimental data shown in Fig. 4 with our model, we extract the overlap of the spatial modes $K = 0.7 \pm 0.05$ and the temperature of the atoms $T = 180 \pm 20\,\mu$K. In a separate experiment, we measured the temperature of the atoms in the dipole trap, which is initially close to $120 \pm 10\,\mu$K. Each pulse followed by the spontaneous emission of the photon increases the energy of the atom by one recoil. We calculate that after the first 115 μs of pulsed excitations the temperature rises by 60 μK, in good agreement with the temperature obtained from the fit above. We also checked experimentally that each cooling period resets the temperature of the atom to its initial value. A comparison of the fit with the dashed curve, which corresponds to zero temperature, confirms that at present the imperfect interference is due mainly to the imperfect optical wavefront matching, and not to the motion of the atoms in the traps.

Thus we have experimentally demonstrated the coalescence of two photons emitted by two independent trapped atoms. The contrast of the interference is limited by the overlap (in free space) of the spatial modes of the fluorescence light emitted by the two atoms. By coupling the light from each of the atoms into identical single-mode optical fibres, this overlap could be greatly improved, though this may be at the cost of a reduced counting rate. The shape of the residual signal around zero delay is well explained by a broadening due to the finite temperature of the atoms in the trap. Better wavefront overlap and further cooling of the atoms will improve the overall quality of this interference and will make this system suitable as a resource for entangling two atoms.

METHODS

Derivation of the experimental signal. If $f_k(\mathbf{r})\varepsilon_k(t)$ is the field emitted by the atom k ($k = 1, 2$), ref. 22 shows that the probability of detecting one photon at $\mathbf{r}_A$ and of detecting the other one at $\mathbf{r}_B$, in the 50/50 beam-splitter configuration, after a delay τ, is proportional to:

$$w^{(2)}(\tau, \mathbf{r}_A, \mathbf{r}_B) = \int |f_1(\mathbf{r}_B) f_2(\mathbf{r}_A)\varepsilon_1(t+\tau)\varepsilon_2(t) - f_2(\mathbf{r}_B) f_1(\mathbf{r}_A)\varepsilon_2(t+\tau)\varepsilon_1(t)|^2 \mathrm{d}t$$

which can be understood as the interference of two paths. Assuming a temporal form of the field $\varepsilon_k(t) = H(t)e^{-\frac{\Gamma}{2}t}e^{i\omega_k t}$ where $H(t)$ is the step function, we obtain:

$$w^2(\tau) \propto e^{-\Gamma|\tau|}(1 - K^2 \cos\Delta\omega\tau)$$

where $K = |\int \mathrm{d}\mathbf{r} f_1^*(\mathbf{r}) f_2(\mathbf{r})| / \sqrt{\int \mathrm{d}\mathbf{r}|f_1(\mathbf{r})|^2 \times \int \mathrm{d}\mathbf{r}|f_2(\mathbf{r})|^2}$ is the spatial overlap of the electric field, and $\Delta\omega$ is the frequency difference between the two emitted photons. The double detection probability for $\tau = 0$ is proportional to $(1–K^2)$, and so is the normalized ratio R defined in the text. The proportionality factor is determined in the absence of interferences ($K = 0$): in this case, the two photons behave as distinguishable particles and have a probability of 1/2 of leaving the 50/50 beam splitter through two different ports. Thus, the normalized ratio R is $(1–K^2)/2$.

Model including the finite temperature of the atoms in the trap. To take into account the finite temperature of the atoms in the trap, we integrate the expected signal for two photons interfering with a frequency difference $\Delta\omega$ and a spatial overlap K (see above), over the probability distribution of frequency differences. To obtain this probability distribution, we solve the equations of motion for a thermal ensemble of single atoms in the trap experiencing pulsed excitations during 115 μs, followed by a decay in a random direction. After each pulse, we calculate the lightshifts of all the atoms in the ensemble. We repeat this for 575 pulses to obtain the distribution of lightshifts. This distribution is found to be well represented by a function of the form $U^2 e^{-\frac{2U}{k_B T}}$. The value of $\Delta\omega$ is proportional to the difference in lightshifts experienced by the atoms when they emit the photons. We then calculate the auto-correlation of the lightshift distribution to get the probability distribution of $\Delta\omega$. By averaging over this distribution of lightshift differences, we obtain the normalized coincidence rate signal as an analytical function with only two fitting parameters, the spatial overlap and the temperature of the atoms.

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1. Hong, C. K., Ou, Z. Y. & Mandel, L. Measurement of subpicosecond time intervals between two photons by interference. *Phys. Rev. Lett.* **59,** 2044–2046 (1987).
2. de Riedmatten, H., Marcikic, J., Tittel, W., Zbinden, M. & Gisin, N. Quantum interference with photon pairs created in spatially separated sources. *Phys. Rev. A* **67,** 022301 (2003).
3. Varoutsis, S. *et al.* Restoration of photon indistinguishability in the emission of a semiconductor quantum dot. *Phys. Rev. B* **72,** 041303(R) (2005).
4. Legero, T., Wilk, T., Hennrich, M., Rempe, G. & Kuhn, A. Quantum beat of two single photons. *Phys. Rev. Lett.* **93,** 070503 (2004).
5. Kiraz, A. *et al.* Indistinguishable photons from a single molecule. *Phys. Rev. Lett.* **94,** 223602 (2005).
6. Santori, C., Fattal, D., Vučković, J., Salomon, G. S. & Yamamoto, Y. Indistinguishable photons from a single-photon device. *Nature* **419,** 594–597 (2002).
7. Dowling, J. P., Franson, J. D., Lee, H. & Milburn, G. J. Towards scalable linear-optical quantum computers. *Quantum Inf. Process.* **3,** 205–213 (2004).
8. Pan, J.-W., Bouwmeester, D., Weinfurter, H. & Zeilinger, A. Experimental entanglement swapping: entangling photons that never interacted. *Phys. Rev. Lett.* **80,** 3891–3894 (1998).
9. Knill, E., Laflamme, R. & Milburn, G. J. A scheme for efficient quantum computation with linear optics. *Nature* **409,** 46–52 (2001).
10. Lim, Y. L., Beige, A. & Kwek, L. C. Repeat-until-success linear optics distributed quantum computing. *Phys. Rev. Lett.* **95,** 030505 (2005).
11. Barrett, S. D. & Kok, P. Efficient high-fidelity quantum computation using matter qubits and linear optics. *Phys. Rev. A* **71,** 060310 (2003).
12. Zoller, P., Cirac, J. I., Duan, L. & García-Ripoll, J. J. in *Les Houches, Session LXXIX, 2003—Quantum Entanglement and Information Processing* (eds Estève, D., Raimond, J.-M. & Dalibard, J.) 187–222 (Elsevier, Amsterdam, 2004).
13. Paillard, M. *et al.* Spin relaxation quenching in semiconductor quantum dots. *Phys. Rev. Lett.* **86,** 1634–1637 (2001).
14. Monroe, C., Meekhof, D. M., King, B. E., Itano, W. M. & Wineland, D. J. Demonstration of a fundamental quantum logic gate. *Phys. Rev. Lett.* **75,** 4714–4717 (1995).
15. Schrader, D. *et al.* Neutral atom quantum register. *Phys. Rev. Lett.* **93,** 150501 (2004).

16. Simon, C. & Irvine, W. T. M. Robust long-distance entanglement and a loophole-free Bell test with ions and photons. *Phys. Rev. Lett.* **91,** 110405 (2003).
17. Blinov, B. B., Moehring, D. L., Duan, L.-M. & Monroe, C. Observation of entanglement between a single trapped atom and a single photon. *Nature* **428,** 153–157 (2004).
18. Bergamini, S. *et al.* Holographic generation of microtrap arrays for single atoms by use of a programmable phase modulator. *J. Opt. Soc. Am. B* **21,** 1889–1894 (2004).
19. Schlosser, N., Reymond, G., Protsenko, I. & Grangier, P. Sub-poissonian loading of single atoms in a microscopic dipole trap. *Nature* **411,** 1024–1027 (2001).
20. Dingjan, J. *et al.* A frequency-doubled, pulsed laser system for rubidium manipulation. *Appl. Phys. B* **82,** 47–51 (2006).
21. Darquié, B. *et al.* Controlled single-photon emission from a single trapped two-level atom. *Science* **309,** 454–456 (2005).
22. Legero, T., Wilk, T., Kuhn, A. & Rempe, G. Time-resolved two-photon quantum interference. *Appl. Phys. B* **77,** 797–802 (2003).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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