

Quantum interference of photon pairs from two remote trapped atomic ions

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1 Trapped atomic ions are among the most attractive
 2 implementations of quantum bits for applications in quantum-
 3 information processing, owing to their long trapping lifetimes
 4 and long coherence times. Although nearby trapped ions can
 5 be entangled through their Coulomb-coupled motion^{1–6}, it
 6 seems more natural to entangle remotely located ions through
 7 a coupling mediated by photons, eliminating the need to control
 8 the ion motion. A promising way to entangle ions via a photonic
 9 channel is to interfere two photons emitted from the ions and
 10 then detect appropriate photon coincidence events^{7–9}. Here, we
 11 report the pivotal element of this scheme in the observation of
 12 quantum interference between pairs of single photons emitted
 13 from two atomic ions residing in independent traps.

14 Remote entanglement of two ions or atoms can be achieved
 15 by subjecting two photons emitted by the particles to a Bell-
 16 state measurement and is heralded by an appropriate coincidence
 17 detection of the photons⁷. The essence of this Bell-state
 18 measurement is the quantum interference of two photons, which
 19 has been observed previously with photons generated in a variety
 20 of physical processes and systems, including nonlinear optical
 21 down-conversion^{10,11}, quantum dots¹², atoms in cavity quantum
 22 electrodynamics¹³, atomic ensembles^{14–16} and two nearby trapped
 23 neutral atoms¹⁷. We report the first observation of interference
 24 between two single photons emitted from two remote trapped
 25 atomic ions. The two Yb ions are stored in independent traps in two
 26 vacuum chambers separated by about one metre. The interference
 27 of two single photons emitted by remote ions is the only element
 28 of remote-entanglement schemes that has not previously been
 29 demonstrated. Hence, this demonstration is an essential step
 30 towards future remote-ion-entanglement experiments, which may
 31 ultimately lead to large-scale quantum networks^{18–23}.

32 In the experiment, single ¹⁷⁴Yb⁺ ions are trapped in two
 33 congeneric Paul traps located in separate vacuum chambers as
 34 described in detail in the Methods section. Laser cooling localizes
 35 the ions to within the resolution of the diffraction-limited imaging
 36 optics but well outside the Lamb–Dicke limit. The ions are excited
 37 with ultrafast laser pulses generated by a picosecond mode-locked
 38 Ti:sapphire laser with a centre frequency of 739 nm. Each pulse
 39 is then frequency doubled to 369.5 nm through a phase-matched
 40 lithium triborate nonlinear crystal. An electro-optic pulse picker
 41 is used to reduce the pulse repetition rate from 81 MHz to
 42 8.1 MHz with an extinction ratio of better than 10⁴:1. The second
 43 harmonic is filtered from the fundamental with a prism, split
 44 between the two traps using a beam splitter and aligned to arrive
 45 at the two ions within 100 ps of each other. Each pulse has a near-
 46 transform-limited pulse duration of 2 ps and excites the ions on a
 47 timescale much faster than the excited-state lifetime of 8 ns. The

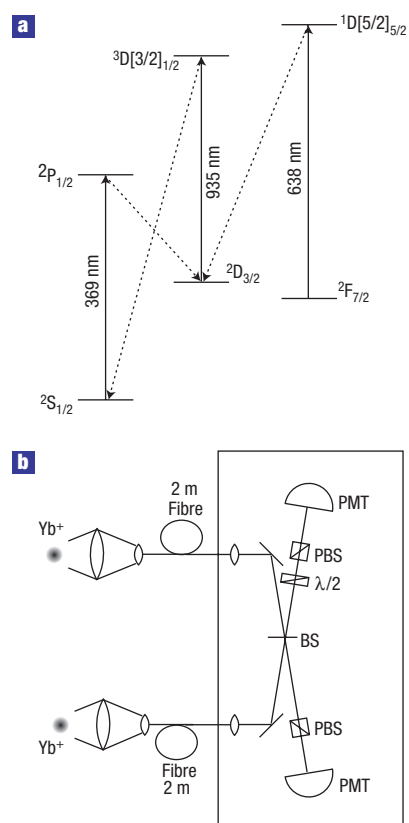


Figure 1 The ytterbium set-up. **a**, Relevant level scheme of ¹⁷⁴Yb⁺. **b**, Schematic diagram of the detection system. The unpolarized light from each ¹⁷⁴Yb⁺ ion is collected using a triplet lens with a numerical aperture of 0.23 and a working distance of 13 mm. It is coupled into a single-mode fused-silica fibre using an aspheric collimation lens with a numerical aperture of 0.6. About 25% of the light collected from each ion is transmitted through the 2 m fibres. The light from both fibres is collimated with a monochromatic lens and mode matched on a polarization-independent beam splitter (BS). Behind the beam splitter, two removable polarizers (PBS) can be used to select parallel polarization. Inserting a $\lambda/2$ plate allows the detection of perpendicularly polarized photons. Subsequently, the light is detected by two photon-counting photomultipliers (PMT) with a quantum efficiency of about 20% and a time resolution of about 1 ns. The photon arrival times at the photomultipliers are recorded using a time-to-digital converter with a resolution of 4 ps (PicoQuant PicoHarp300). The contrast of the interferometer is measured using 369.5 nm laser light to be better than 96%.

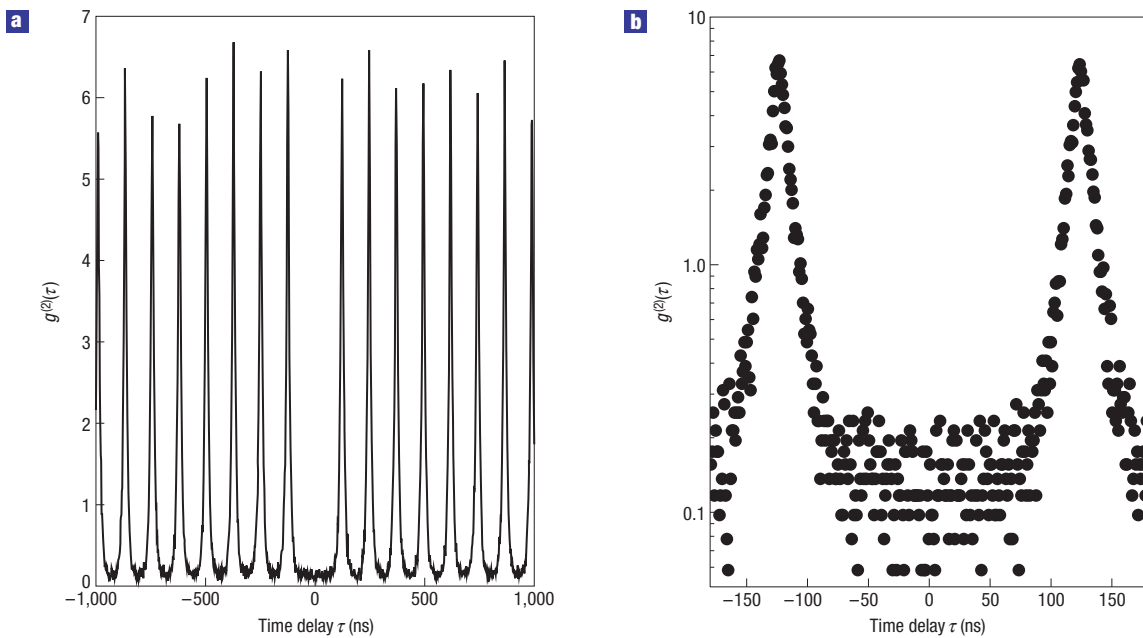


Figure 2 Intensity autocorrelation of the light emitted by a single ion excited by picosecond pulses. **a**, The periodically emitted photons from the pulsed excitation lead to peaks at multiples of the 124 ns pulse repetition time. **b**, The near-perfect photon antibunching, revealed by the logarithmic scale, proves that at most one photon is emitted from an excitation pulse. The correlation function is evaluated from the stored photon arrival times using 2 ns binning. The probability to detect a photon from one excitation pulse is 6×10^{-4} . The data shown were integrated for 3 h.

1 pulse energy can be adjusted to simultaneously excite both ions
2 with near-unit probability.

3 Two re-entrant viewports at opposing sides of each trap are
4 used to simultaneously image the ions in free space and couple
5 light scattered from the ions into single-mode optical fibres. In free
6 space, a telescope is used to image scattered photons on a camera
7 to monitor loading and to verify the presence of a single $^{174}\text{Yb}^+$ ion
8 in each trap. Fibre coupling is realized from the opposite side of the
9 trap using a second objective lens to collect spontaneously emitted
10 photons (Fig. 1b). Each beam is focused onto a single-mode fibre
11 using an aspheric lens. About 25% of the spontaneously emitted
12 photons collected by the objective are transmitted through the 2 m
13 fibre. The ion light transmitted through the single-mode fibres
14 is collimated and mode matched on a polarization-independent
15 beam splitter. The light emerging from the beam splitter is detected
16 using photomultipliers. Removable polarizers and a removable $\lambda/2$
17 wave plate allow detection of unpolarized photons, or photons
18 of parallel or perpendicular polarization. The arrival times of the
19 photons at the photomultipliers are recorded using a time-to-
20 digital converter.

21 To demonstrate that the excitation of an ion with an ultrashort
22 pulse leads to the emission of at most one photon, we first
23 analyse the light scattered by a single $^{174}\text{Yb}^+$ ion by blocking the
24 fluorescence from one of the two traps. We use a repetitive sequence
25 consisting of a $40 \mu\text{s}$ measurement interval and a $10 \mu\text{s}$ cooling
26 interval. During the cooling interval, the ion is Doppler cooled only
27 with continuous-wave (cw) light, whereas during the measurement
28 interval, the ion is excited only by ultrafast laser pulses with a
29 124 ns pulse separation. From the arrival times of the photons at the
30 photomultipliers, the intensity autocorrelation function, $g^{(2)}(\tau)$,
31 is evaluated and shown in Fig. 2. The periodic ultrafast excitation
32 of the ion leads to peaks at multiples of the pulse separation
33 time. As the ions are excited on a timescale much faster than the
34 excited-state lifetime, the spontaneously emitted photons have an

exponential envelope²⁴. Therefore, the peaks in the autocorrelation
function have a two-sided exponential decay where the $1/e$ half
width is given by the 8 ns lifetime of the excited state. In contrast
to pulsed coherent or pulsed thermal light, there is no peak at
zero time delay (Fig. 2). This near-perfect antibunching is highly
non-classical and clearly demonstrates that at most one photon is
emitted after each excitation pulse. Theoretically, the probability to
scatter two photons from one ion excited with one pulse is limited
by the emission probability of an excited atom during the excitation
pulse ($\approx 10^{-4}$ here). This very clean single-photon source is a good
starting point for the observation of two-photon interference and
is necessary for high-fidelity photon-mediated ion entanglement.

Two-photon interference is a purely quantum phenomenon
and can be understood qualitatively by considering the four
possibilities in which two photons impinging on different input
ports of a beam splitter can emerge from the output ports. In
two of these possibilities, the two photons leave from different
ports and thus can generate a coincidence event: both photons are
reflected, or both are transmitted. For two photons that have the
same polarization, frequency and are spatially mode matched on
the beam splitter, these two cases interfere destructively. This leads
to the effect that the photons always emerge together from the beam
splitter and no coincidence events are observed²⁵. This can also be
understood from the bosonic nature of the two-photon system⁹.

To observe two-photon interference, the single ions in both
traps are excited simultaneously by picosecond laser pulses and
the fluorescence photons are combined on the beam splitter. The
polarizers after the beam splitter are used to measure the
coincidences of parallel polarized photons. To measure
coincidences of perpendicularly polarized photons in the two
output ports of the beam splitter, a $\lambda/2$ wave plate is added in
front of one polarizer. The resulting cross-correlation functions
are shown in Fig. 3. For perpendicular polarization, the photons
are distinguishable and do not interfere; thus, we find a peak at

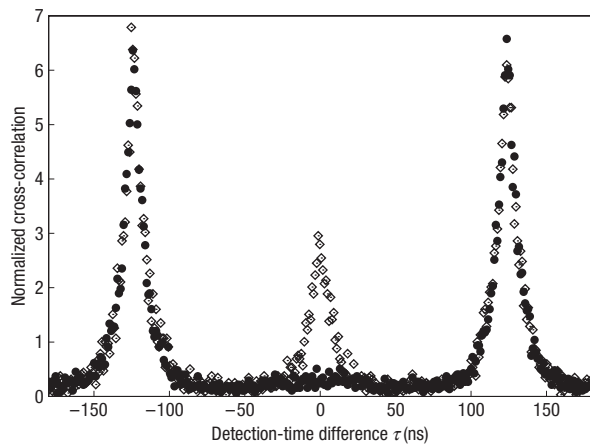


Figure 3 Normalized intensity cross-correlation of photons emitted by two ions.

For perpendicular linear polarization (diamonds) the photons from the two ions are distinguishable; thus we observe a peak at zero delay. In contrast to the peaks at longer delay times, for which the two photons can be emitted by the same ion, the two photons leading to a coincidence at zero delay must be emitted by different ions. Thus, the peak at zero delay has half the area of the peaks at longer delay times. Integrating all photon pairs with a detection-time difference of $|\tau| < 8$ ns results in a coincidence detection probability of 1.4×10^{-8} per excitation pulse (or 2×10^{-8} for the photon pairs with a less than 16 ns detection-time difference). For parallel linear polarization (circles), the two-photon interference suppresses the coincidence detection of two photons on different output ports of the beam splitter. Including dark counts, the number of photon pairs with less than 8 ns and 16 ns detection-time differences is reduced by 86% and 81%, respectively. Each curve was integrated for about 4 h and evaluated using a 1 ns binning.

zero delay. This peak has half the area of the others, because at zero delay each ion can only contribute one photon, whereas for non-simultaneous pulses each ion can produce both photons in the correlation measurement. Integrated over photon pairs detected within 8 ns of each other (one lifetime), this peak consists of 1,087 coincidences corresponding to a coincidence detection probability of 1.4×10^{-8} per excitation pulse or an absolute coincidence rate of about 0.1 s^{-1} . For parallel polarization of the two photons, the two-photon interference eliminates coincidence detections. In our case, the remaining peak at zero delay, after subtracting the dark-count background, has an amplitude of about 5% of the perpendicularly polarized signal, corresponding to a 95% contrast of the interferometer. Integrating all photon pairs that are detected within 8 ns of each other, including dark counts, we detect 14% of the photon pairs that we observe for perpendicular polarization.

To use this two-photon interference to produce remote-ion entanglement, an attribute of each photon—polarization²⁶ or frequency²³—must be entangled with the internal state of its parent ion. A coincidence detection of two photons would then project the system onto the antisymmetric superposition state and herald the entanglement of the ions^{7–9}. The interference contrast observed here, including dark counts, would lead to a potential entanglement fidelity of about 90%. The fidelity is limited by the ratio between photon detection events and dark counts. This ratio can be improved by lowering detector dark counts, achieving a higher detection efficiency or by collecting photons from a larger effective solid angle. The most promising way to implement this entanglement scheme with distant ytterbium ions uses the ground-state hyperfine clock states of $^{171}\text{Yb}^+$ to encode the atomic qubit. To realize this experimentally, additional laser

frequencies are necessary for cooling of $^{171}\text{Yb}^+$. In addition, efficient state initialization and state detection in any qubit basis must be implemented to generate and verify the entanglement²⁷.

In summary, we demonstrate a near-perfect single-photon source on the basis of the ultrafast excitation of a single trapped ion and two-photon quantum interference of photon pairs emitted by two remote trapped ions. The contrast of the observed interference in principle allows the entanglement of ions with a fidelity of about 90%, clearly surpassing the threshold needed to violate a Bell inequality. Building on this, entangling gates could provide a means to scale the probabilistic entanglement from two qubits to the generation of networks of entangled qubits and cluster states. The tremendous advantages of the trapped-ion system—extremely long storage and coherence times and high readout fidelity—should make the scalable entanglement of many qubits feasible.

METHODS

The experimental apparatus consists of two congeneric radiofrequency (rf) Paul traps located in separate vacuum chambers. These four-rod linear quadrupole traps have rod spacings of 0.5 mm and end-cap spacings of 2.6 mm. The rf drive frequency is $\Omega_{\text{r}}/2\pi \approx 37$ MHz and the centre-of-mass secular trapping frequencies are $(\omega_x, \omega_y, \omega_z)/2\pi \approx (1, 1, 0.2)$ MHz. Residual micromotion at the rf drive frequency is carefully reduced by applying static offset voltages to the trap rods. Yb atoms from a thermal beam are photoionized by resonantly exciting the $^1\text{S}_0 \leftrightarrow ^1\text{P}_1$ transition near 399 nm using a diode laser and subsequently promoting the electron to the continuum with a 369.5 nm cw laser²⁷, which is also used to Doppler cool the ions. This 369.5 nm laser light is generated by frequency doubling the light from a cw amplified diode laser at 739 nm and is stabilized to an iodine reference at a detuning of ≈ 10 MHz from the atomic $^2\text{S}_{1/2} \leftrightarrow ^2\text{P}_{1/2}$ transition of $^{174}\text{Yb}^+$ (linewidth ≈ 20 MHz) (Fig. 1a). The ions reside in a magnetic field of about 10 G to prevent pumping into dark states. From the excited state, the ion can decay to the $^2\text{D}_{3/2}$ state with a probability of 0.05 (ref. 28). A diode laser near 935 nm is used to repump the ion via the $^3\text{D}[3/2]_{1/2}$ state to the ground state. About once an hour the ion reaches the $^2\text{F}_{7/2}$ state, which is cleared by a diode laser near 638 nm. The mean storage time of the ions in the trap is several days. All of the data presented here was obtained with the same two ions.

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Competing financial interests

The authors declare no competing financial interests.

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Author: Please provide text to define the terms in $g^{(2)}(\tau)$ here. In addition, please check the use of τ in the x axes of figures 2 and 3; in figure 2, it seems to represent 'Time delay', whereas in figure 3, it seems to represent 'Detection-time difference'. Should τ in figure 3's x axis be changed to ' $|\tau|$ '? Once this has been clarified, if appropriate, the text 'Time delay' and 'Detection-time difference' will be removed from the x axes according to style.

Page 4

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