

# Quantum Interference of Photon Pairs from Two Trapped Atomic Ions

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We collect the fluorescence from two trapped atomic ions, and measure quantum interference between photons emitted from the ions. The interference of two photons is a crucial component of schemes to entangle atomic qubits based on a photonic coupling. The ability to preserve the generated entanglement and to repeat the experiment with the same ions is necessary to implement entangling quantum gates between atomic qubits, and allows the implementation of protocols to efficiently scale to larger numbers of atomic qubits.

PACS numbers: 03.67.-a, 32.80.Pj, 42.50.Vk

Trapped atomic ions are among the most attractive implementations of quantum bits (qubits) for applications in quantum information processing, owing to their long trapping lifetimes and long coherence times. While nearby trapped ions can be entangled through their Coulomb-coupled motion [1, 2, 3, 4, 5, 6], it is more natural to entangle remotely-located ions through a photonic coupling, eliminating the need to control the ion motion. When two atomic ions each emit a single photon [7, 8], subsequent interference and detection of these photons can leave the trapped ion qubits in an entangled state [9, 10]. Moreover, such a photonic coupling can be tailored to operate quantum gates between the ions and efficiently generate extended networks of entangled qubits and cluster states for scalable quantum computation [11, 12, 13, 14, 15, 16]. Here, we report the generation of single photons and the observation of quantum interference between two photons emitted from two trapped atomic ions. The same two ions remain in place for the generation of thousands of two-photon interference events, which, together with the long coherence times available in trapped ion systems [17, 18, 19], points the way toward scaling to large entangled networks of remotely-located qubits.

Remote entanglement of two ions or atoms can be achieved by subjecting two photons emitted by the particles to a Bell-state measurement and is heralded by an appropriate coincidence detection of the photons. The essence of this Bell-state measurement is the quantum interference of two photons, which has been observed previously with photons generated in a variety of physical processes and systems, including nonlinear optical down-conversion [20, 21], quantum dots [22], atoms in cavity-QED [23] and, more recently, two independently trapped neutral atoms [24]. We report the first observation of interference between two photons emitted from multiple trapped atomic ions. This demonstration is important for scaling to extended quantum networks of qubits, which is only feasible if the entanglement can be preserved on a timescale long compared to the average time needed to entangle two qubits. With their unsurpassed trapping and qubit coherence times, trapped ions are well

suited for this purpose [17, 18, 19].

In the experiment, one or two  $^{111}\text{Cd}^+$  ions are trapped in a four-rod linear rf quadrupole trap with rod spacings of 0.5 mm and an end-cap spacing of 2.6 mm [25]. The rf drive frequency is  $\Omega_T/2\pi = 36$  MHz and the center of mass secular trapping frequencies are  $(\omega_x, \omega_y, \omega_z)/2\pi = (0.9, 0.9, 0.2)$  MHz. Residual micromotion at the rf drive frequency is reduced by applying static offset voltages to the trap rods and endcaps. Cadmium atoms from the background vapor are photoionized using a frequency quadrupled ultrafast Ti:sapphire laser centered at 229 nm. The mean lifetime of the ions in the trap is over one hour. Continuous wave (cw) laser light with a wavelength of  $\lambda = 214.5$  nm is used to Doppler cool and excite the ions. This light is generated by frequency quadrupling the light from a cw amplified diode laser at 858 nm and is stabilized to a tellurium reference at a detuning of  $\Delta \approx -\Gamma/2 = -30$  MHz from the atomic  $5s\ ^2S_{1/2} \leftrightarrow 5p\ ^2P_{3/2}$  transition of  $^{111}\text{Cd}^+$ . Doppler cooling localizes the ion to about 300 nm, well outside the Lamb-Dicke limit but better than the resolution of the diffraction-limited imaging optics. Incident  $\sigma^+$ -polarized laser light optically pumps the ion to the  $F = 1, m_F = 1$  ground state and drives the closed optical transition to the  $F = 2, m_F = 2$  excited state, with the quantization axis defined by a magnetic field of 0.5 Gauss.

Alternatively, the ions can be excited with ultrafast  $\sigma^+$  polarized pulses, generated by a picosecond mode-locked Ti:sapphire laser with a center frequency of 858 nm. An electro-optic pulse picker is used to reduce the pulse repetition rate from 81 MHz to 27 MHz with an extinction ratio of better than 100:1 in the infrared. Each of the pulses is then frequency quadrupled to 214.5 nm through phase-matched LBO and BBO nonlinear crystals. The UV (fourth harmonic) is filtered from the fundamental and second harmonic via dichroic mirrors and directed to the ion with a near transform-limited pulse duration of 1 ps, exciting the ion on a timescale much faster than the excited state lifetime of 2.6 ns [25]. The bandwidth of the pulsed laser ( $\approx 0.4$  THz) is small compared to the fine-structure splitting (70 THz), ensuring selective excitation to the  $5p\ ^2P_{3/2}$  excited state.

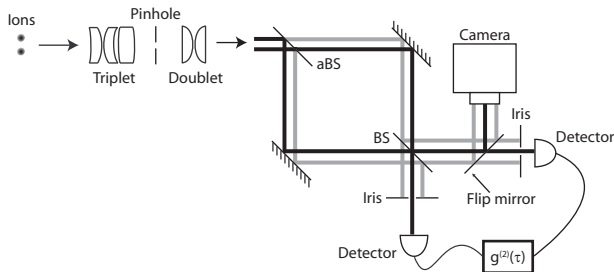


FIG. 1: Schematic of the detection system. The light from two ions is separated by an ancillary beam splitter (aBS) and superimposed on the primary beam splitter (BS). Both beam splitters are used at a  $10^\circ$  opening angle. The non-overlapping ion images are blocked by two irises. For a single ion and opened irises this system is equivalent to the Hanbury Brown and Twiss set-up. A flip mirror (FM) is used to send the beams on a single photon sensitive camera.

The light scattered by the ions is collected using an objective lens with a numerical aperture of 0.23 and a working distance of 13 mm (Fig. 1). The intermediate image generated by the objective is re-imaged using a doublet lens, resulting in an overall magnification of about 1000. The light from both ions is sent on a 50 % ancillary beam splitter, then the transmitted and reflected beam pairs are directed to the primary beam splitter where the light from the two different ions is superimposed. Behind this beam splitter, a removable mirror can be used to send the light onto a camera which is used to monitor the ion fluorescence during loading and for coarse alignment of the beams. On the camera, the ion images have a spot size of about 0.5 mm and are separated by about 2 mm. Two irises are used to select only the superimposed images of the ions. This light is subsequently detected by two photon counting photomultiplier tubes with a quantum efficiency of about 20 % and a time resolution of 1 ns [25]. The overall detection efficiency of a photon emitted by an ion is 0.1 %. In the case of a single trapped ion, the irises are opened and the set-up is equivalent to a single beam splitter with two photodetectors.

This set-up is not sensitive to relative movement of the imaging optics with respect to both ions and leads to a stable spatial overlap of the modes even if the images of both ions move with respect to the beam splitter. The equal path length of the beams of both ions furthermore ensures that the modes match in size and wavefront radius of curvature. From the interference contrast, the two pathlengths were adjusted to match within 1 mm.

To demonstrate that the excitation of an ion with an ultrashort pulse leads to the emission of at most one photon [26], we first trap a single  $^{111}\text{Cd}^+$  ion. We employ a repetitive sequence consisting of a  $150 \mu\text{s}$  cooling interval and a  $50 \mu\text{s}$  measurement interval. During the cooling interval the ion is Doppler cooled with cw-light only, and during the measurement interval the ion sees only ultra-

fast laser pulses with a 37.5 ns pulse separation. The intensity autocorrelation function of the photons emitted during the measurement interval is recorded using a multi-channel scaler and the resulting data are shown in Fig. 2. The periodic ultrafast excitation of the ion

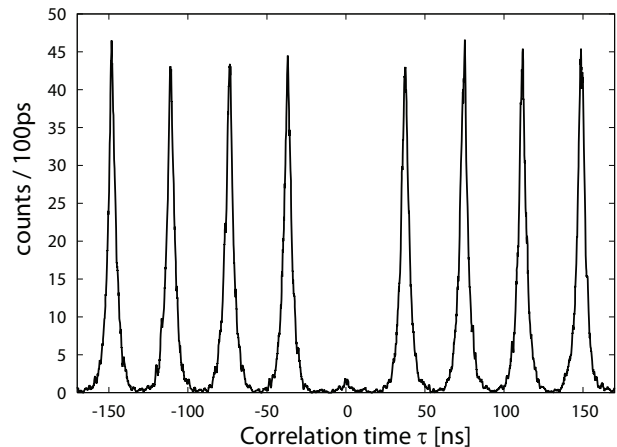


FIG. 2: Intensity autocorrelation of the light emitted by a single ion excited by one-picosecond pulses. The near-perfect antibunching at zero delay shows that at most one photon is emitted from an excitation pulse. The measurement was done with one ion with an excitation probability of about 20 % from each excitation pulse. The data shown were integrated for about 5 min (20 min total time).

leads to peaks at multiples of the pulse separation time of 37.5 ns. The half width of these peaks is given by the 2.6 ns lifetime of the excited state. In contrast to pulsed coherent or pulsed thermal light, the peak at zero time delay is almost entirely suppressed. This near-perfect antibunching is highly non-classical and demonstrates that at most one photon is emitted after each excitation pulse. The residual peak at zero time delay has a height of about 2 % of the other peaks and originates from diffusely scattered light of the pulsed laser. 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 ( $< 10^{-3}$  for our parameters).

Two-photon interference is a purely quantum phenomenon and can be understood qualitatively if one considers the ways in which two photons impinging on different input ports of a beam splitter can emerge from separate output ports. There are two possibilities: both photons are reflected, or both are transmitted. For two photons which have the same polarization and frequency and which are exactly matched on the beam splitter, these two cases interfere destructively, leading to the effect that the photons always emerge together from the beam splitter [27, 28]. Here we demonstrate two-photon interference by exciting two  $^{111}\text{Cd}^+$  ions located in the same trap with near-resonant cw light.

To separate the interference effect of photons emitted by different ions from the emission properties of the individual ions using cw excitation, we first investigate the photon statistics of a single ion (dashed curve in Fig. 3). In this case, the intensity autocorrelation function,  $g^{(2)}(\tau)$ , shows the well known signal of damped Rabi oscillations [29, 30]: when a photon is detected at time  $t$ , the atom is projected onto its ground state and begins a damped Rabi oscillation which determines the probability to observe a second photon at time  $t + \tau$ . Theoretically, the probability of detecting two photons at the same time vanishes, and background counts are measured to contribute less than 1 % of the signal. However, the instrument response function of the photomultiplier tubes has a width of about 1 ns, limiting the antibunching observed in the measurement. This antibunching means that the photons of one ion reach the beam splitter one by one, however, the next photon of the same ion can be detected after a short time.

We now investigate the joint detection probability of two photons for light emitted by two ions,  $P^{(2)}$ . In this case, an observed joint detection event can originate from two photons emitted successively by one ion,  $P_1^{(2)} = g^{(2)}$ , or two photons emitted by different ions,  $P_2^{(2)}$ . For a symmetric set-up — equal emission rates of both ions and a 50 % beam splitter — the joint detection probability is

$$P^{(2)} = \frac{g^{(2)} + P_2^{(2)}}{2}. \quad (1)$$

If the modes of the ions do not overlap on the beam splitter, the photons from different ions are completely uncorrelated. However, due to the single ion contribution to the joint detection probability, we still observe anti-bunching, although of reduced depth, as can be seen in Fig. 3 (dotted line). If the spatial modes of the two ions are matched on the beam splitter, the photons reaching the beam splitter at the same time from different ions interfere, thus reducing the number of coincidence detections. This effect is clearly visible in the joint detection probability depicted in Fig. 3 (solid line).

Assuming a symmetric set-up, we can separate the two-photon interference effect eminent in the joint detection probability of two photons from different ions from the contribution of the single ion,  $g^{(2)}$ , by solving for  $P_2^{(2)}$  in eq. (1). The results are shown in Fig. 4. For non-overlapping photon modes the joint detection probability  $P_2^{(2)}$  is basically flat and demonstrates that photons of different ions are not correlated. If the modes of the two photons overlap, we expect to find a Gaussian dip where the half width is given by the duration of a photon and the depth is determined by the mode overlap [28]. We measure a half width of about 5.3 ns and a contrast of about 57 %, corresponding to a mode-overlap of 57 % (75 % amplitude matching). We attribute the non-perfect mode overlap in the experiment to phase front

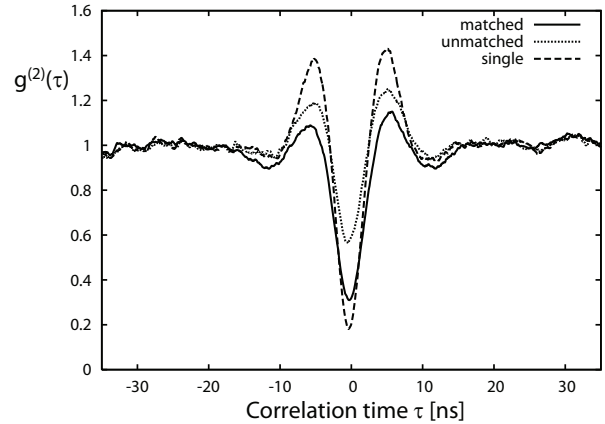


FIG. 3: Intensity autocorrelation and joint detection probability for cw-excitation (raw data), integrated for about 60 minutes for each curve. Each ion leads to a total count rate of  $4 \times 10^4$ /s. The one ion intensity autocorrelation (dashed line) shows strong antibunching with  $g^{(2)}(\tau=0) = 0.18$ . From this value we expect the joint detection probability at zero delay for light from two ions without mode overlap (dotted line) to be 0.59, which is in good agreement with the experimental value of 0.57. If the modes of the two ions are matched (solid line) two-photon interference leads to a significant reduction of coincidence detections. In this case the joint detection probability drops to 0.31 at  $\tau = 0$ .

distortions of the beams from the two ions. These originate mainly in the limited surface quality of the vacuum windows and the lenses, considering the short radiation wavelength of 214 nm.

It is a challenge to realize satisfactory and stable mode overlap in free space. While the set-up is suited to reject common mode movement of the trap with respect to the beam splitter, changes in the ion separation strongly affect the mode overlap. The resulting coincidence detections lead to false positive events in the Bell-measurement and thus limit the fidelity of any entanglement scheme. Upon excitation of two ions with the pulsed laser we were not able to demonstrate two-photon interference, even though an estimate shows that heating of the ion by the pulsed laser should not be an issue. Possible explanations are slight shifts in the separation of the ions or degradation of the vacuum and heating of the ions due to electrons released from the trap by the high-energy photons of the pulsed laser. While our present mode overlap is sufficient to entangle two ions, the rejection of other spatial modes, which can be achieved with a single-mode optical fiber, should strongly improve the mode overlap, producing a higher fidelity of the heralded entanglement process.

In conclusion, we demonstrated a single photon source based on the ultrafast excitation of a single trapped ion and we measured two photon quantum interference of

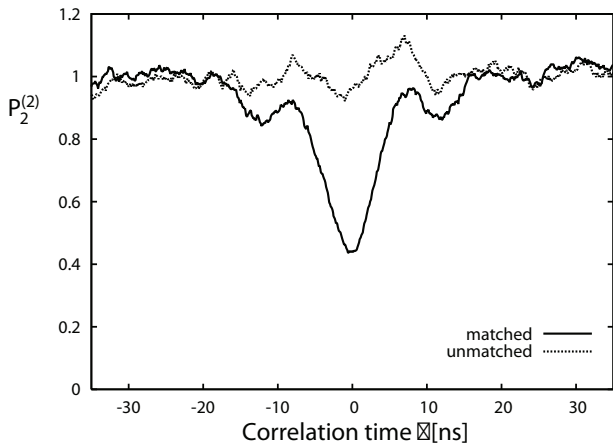


FIG. 4: Joint detection probability of photons emitted by different ions,  $P_2^{(2)}$ , as calculated from the measured single ion intensity autocorrelation,  $g^{(2)}$ , and the joint detection probability shown in Fig. 3. Without mode overlap (dotted line), the photons are uncorrelated and no anti-bunching is observed. When mode overlap is achieved (solid line), two-photon interference clearly reduces coincidence detections. The anti-bunching is expected to have a Gaussian shape where the depth is given by the mode overlap while the width is determined by the photon duration [28]. Our results correspond to a mode overlap of at least 57%, and a photon duration of about 5.3 ns.

photons emitted by two trapped ions. The contrast of the observed interference is sufficient to demonstrate entanglement of two ions in this set-up. In the future, single-mode fibers should greatly improve the mode overlap and thus lead to the entanglement of remote ions with high fidelity. Building upon this, entangling gates provide a means to scale the probabilistic entanglement from two qubits to the generation of networks of entangled qubits. 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.

This work is supported by the National Security Agency and the Disruptive Technology Office under Army Research Office contract W911NF-04-1-0234, and the National Science Foundation Information Technology Research Program.

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