A quantum detector for photon entanglement

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We use a single trapped ⁴⁰Ca⁺ ion as a resonant, polarization-sensitive absorber to detect and characterize the entanglement of tunable narrowband photon pairs from a spontaneous parametric down-conversion source. Single-photon absorption is marked by a quantum jump in the ion and heralded by coincident detection of the partner photon. For three polarization basis settings of absorption and detection of the herald, we find maximum coincidences always for orthogonal polarizations. The polarization entanglement is further evidenced by tomographic reconstruction of the biphoton quantum state.

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The realization of quantum networks is a primary goal in quantum information science [1], remote entanglement being the basic resource required to establish quantum channels between their nodes [2]. Promising schemes for experimental implementations are based on single atomic qubits as nodes, where quantum information is stored and processed, and single photons to communicate between the nodes and generate entanglement. Therefore the very basic requirement is to be able to efficiently and reversibly transfer quantum states between atoms and photons at the single particle level. In that sense, controlled emission and absorption of single photons by a single atomic particle are key enabling tools for quantum optical information technologies [3 4].

In studies of single-photon emission, achievements include control of the shape, frequency, polarization, and bandwidth of the generated single photons [5 11], and the demonstration of atom-photon entanglement [12 15]. Based on the latter, distant entanglement of single atoms has been established [16] and employed [17] by the projective measurement of two photons, each entangled with its emitting atom. A fully bi-directional atom-photon interface implies the transfer of quantum states also by controlled absorption of a single photon [3]. Then the entanglement shared by a photon pair as they come from a spontaneous parametric down-conversion (SPDC) source could be transferred to two distant nodes of the network, entangling them with each other [18]. Experimental progress in this direction includes designing optical systems that optimize the atom-photon coupling in free space [19 23], detecting the attenuation and phase shift of a weak laser beam by a single atom [24 25], and transferring photons between atoms in cavities [26 27].

Controlling both emission and absorption will pave the way towards implementing quantum networking scenarios, where transmission of quantum information across the network is directly linked with its local processing in atoms [18 28 29]. In this context, single trapped ions provide optimal conditions for quantum information processing, meeting the requirements [30] of high-fidelity state manipulations and detection schemes, as well as the controlled interaction of several qubits [31 36]. At the same time, entangled SPDC photon pairs offer robust and simple generation of high-purity entanglement at large rate and thereby serve as an optimal resource for communication over quantum channels [34 37]. In our previous work [38 39] we operated for the first time a hybrid quantum system integrating single trapped ions and SPDC photon pairs. We demonstrated absorption of single photons by the ion [38] and showed that the absorption of one photon from a pair can be heralded by the coincident detection of its partner photon [39]; time and frequency correlation of the photon pair are manifested in the heralded absorption process.

Here we report an experiment where the polarization entanglement of the SPDC photon pairs is manifested through quantum tomography measurements, using the single ion as a polarization-sensitive single-photon detector, prepared by optical pumping in a suitably oriented magnetic field. We find a fidelity of 93% to the maximally entangled Bell state of the photon pairs. This opens up the perspective of heralded storage of photon polarization in a single ion.

A schematic representation of our experimental setup is displayed in Fig. 1. A single ⁴⁰Ca⁺ ion is confined and laser cooled in a linear Paul trap which is placed between two high numerical aperture laser objectives (HALOs) [40]. The ion is addressed by various laser beams for cooling and optical pumping. The HALOs serve for efficiently collecting the ion’s laser-excited fluorescence on a photomultiplier (PMT) and for coupling the ion to single photons in a single optical mode. The SPDC photon source consists of a periodically poled, type II phase-matched KTP crystal which is continuously pumped at
Photon entanglement is therefore manifest if the ion absorbs one basis state but not the other. Photon entanglement in a Bell singlet state $|\Psi^-\rangle$, in which the polarizations of the two photons are anti-correlated in all linear or circular bases. In the measurement we use the $D-A$ (diagonal-antidiagonal linear) basis pairs. Transfer of the photon polarization to the ion in a certain basis is obtained if the ion absorbs one basis state but not the other. Photon entanglement is therefore manifested by maximum coincidence of polarization-sensitive absorption and trigger photon detection in orthogonal polarization states.

Fig. 1b presents the laser excitation sequence used to control the ion’s interaction with a single down-conversion photon. (I) Each period starts with Doppler cooling of the ion motion to the Lamb-Dicke limit (wave packet expansion $\ll$ laser wavelength) with laser light at 397 nm and 866 nm. (II) Thereafter, the internal state of the ion is prepared for polarization-sensitive absorption of SPDC photons: laser light at 850 nm populates the $D_{5/2}$ level while at the same time, laser light at 854 nm optically pumps the ion into specific Zeeman sub-levels of that manifold. The prepared state is controlled by the polarization $E$ and propagation direction $k$ of the 854 nm pumping light with respect to the orientation of the magnetic field $B$ that sets the quantization axis: with $\sigma$-polarized light on axis with the magnetic field ($k \parallel B$) we prepare a mixture of the states either with magnetic moments $m = \{+\frac{5}{2}, +\frac{3}{2}\}$, or with $m = \{-\frac{3}{2}, -\frac{5}{2}\}$. With $\pi$-polarized light propagating perpendicular to the magnetic field orientation ($k \perp B \parallel E$), we prepare an incoherent mixture of the states with $m = \{-\frac{5}{2}, +\frac{5}{2}\}$.

The rate of coincidences for a given polarization setting is evaluated by computing the second-order time correlation function $g^{(2)}(\tau)$ between the trigger photon detection events on the APD and the very first fluorescence photon detected on the PMT, when the ion started to emit fluorescence photons in phase III of the sequence [39]. A peak at time delay $\tau = 0$ signals the correlation of absorption and trigger photon detection; in absence of correlation the background rate is measured.

A measurement in the $R-L$ basis corresponds to preparing the ion in the $m = \{+\frac{5}{2}, +\frac{3}{2}\}$ or $\{-\frac{3}{2}, -\frac{5}{2}\}$ Zeeman levels, sending the SPDC photons with $k \parallel B$, and setting the waveplates in the filter arm such that circularly polarized trigger photons are detected. Rotation of the HWP in that arm then controls the relative orientation of the two circular polarizations. It should be emphasized that the polarization of the photons sent to the ion is not changed, neither filtered in this measurement. Fig. 2 (top) shows the observed number of coincidences for different HWP angles. We observe a maximum of around

427 nm. It emits polarization-entangled photon pairs in a 200 GHz wide spectral band centered at the frequency of the $D_{5/2} - P_{3/2}$ electronic transition of $^{40}$Ca$^+$. For details see text.

**FIG. 1**: (Color online) (a) Experimental setup consisting of SPDC photon source (top) and ion trap (bottom). (b) Laser excitation scheme for ion-photon interaction and corresponding levels in $^{40}$Ca$^+$. For details see text.
FIG. 2: (Color online) Dependence of absorption-trigger coincidences on trigger photon polarization for 3 different polarization bases, $R-L$ (top), $H-V$ (middle), and $D-A$ (bottom). Data points (crosses) are extracted at $\tau = 0$ from the absorption-trigger correlation function $g^{(2)}(\tau)$ on a 10 $\mu$s time grid; the corresponding background (circles), produced by accidental coincidences, is the average over the whole $g^{(2)}$ function. Error bars correspond to one standard deviation assuming Poissonian counting statistics. The curves are sinusoidal fits with a fixed period and offset angle. In the right-hand column we show the Poincaré sphere with the setting of the ion (blue) and of the trigger photon detector (red, with black arrows indicating variation by rotating the HWP).

1 coincidence/min (73 coincidences with 15 background events in 60 min) and a minimum within the background level for orthogonal and same polarizations, respectively, which reflects the expected anti-correlation of the photon polarizations. From a sinusoidal fit we find 56(6)% visibility before background subtraction.

For measuring the correlations in the $H-V$ basis, optical pumping into the outer Zeeman sub-levels $m = \{-\frac{5}{2}, +\frac{5}{2}\}$ is applied, for which the magnetic field is rotated by 90°, pointing now upwards in Fig. 1a. The SPDC photons propagate with $k \perp B$ and can be absorbed if they are $H$-polarized but not if they are $V$-polarized. The trigger photons are detected with linear polarization along a direction varied by the HWP. The result, as displayed in Fig. 2 (middle), exhibits a maximum of around 0.56 coincidences/min (92 with 24 background in 120 min) for $H-V$ and a minimum at the background level for $H-H$. The visibility derived from the sinusoidal fit is 52(11)%.

To finally verify the presence of polarization correlations also in the $D-A$ basis, preparation of the ion for absorption of linear polarization is used as before. To achieve the 45° rotation relative to the $H-V$ basis, in this case the incoming photon state is rotated, using the fiber polarization controllers. The waveplates in the filter arm are set accordingly and we measure coincidences, varying the observed trigger polarization from $D$ to $A$ with the HWP. The result is plotted in Fig. 2 (bottom). The maximum rate of coincidences is 0.4/min (67 with 21 background in 120 min) for $D-A$, and for $D-D$ the rate reduces to the background level. The sinusoidal fit gives a fringe visibility of 50(9)% before background subtraction. In all these measurements, the visibility is mainly determined by the background events, arising due to heralds with lost partners and spontaneous decay from the D$_{5/2}$ manifold. Nevertheless, the minimum points of the fringes are always, within the experimental error, at the independently determined background level.

Having shown that the ion may be used as a polarization analyzer in the 3 principal bases spanning the Poincaré sphere, we now apply the standard procedure of quantum tomography [13]. This allows reconstructing the density matrix of the two-photon quantum state. To this end we perform coincidence measurements in 16 independent basis combinations, including now different basis settings at the ion and in the filter arm. Using a maximum-likelihood state estimation, we derive the density matrix $\rho$ shown in Fig. 3. In this analysis, we use the pure number of coincidences after subtraction of the background counts. From $\rho$, we derive the overlap fidelity with the maximally entangled singlet state $F = \langle \Psi^- | \rho | \Psi^- \rangle = 0.93(4)$, as well as the concurrence $C = 0.93(6)$ and tangle of formation $T = 0.86(11)$.

In summary, we achieve controlled interaction of a single atom with entangled photons from a photon pair source, whereby the time correlation of the photon pairs is employed for heralding the absorption process. Preparing the single atom as a polarization-sensitive absorber in the three principal bases, we demonstrate that the polarization entanglement of the photon pairs is manifested in the absorption-herald correlation; this is confirmed by performing a full tomography of the quantum state. More generally, we use a single isolated quantum system, a trapped ion, to characterize the properties of another fundamental quantum system, entangled
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