

Photon-Interfaced Ten-Qubit Register of Trapped Ions

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Establishing networks of quantum processors offers a path to scalable quantum computing and applications in communication and sensing. This requires first developing efficient interfaces between photons and multiqubit registers. In this Letter, we show how to entangle each individual matter qubit in a register of ten to a separate traveling photon. The qubits are encoded in a string of cotrapped atomic ions. By switching the trap confinement, ions are brought one at a time into the waist of an optical cavity and emit a photon via a laser-driven cavity-mediated Raman transition. The result is a train of photonic qubits, each near-maximally entangled by their polarization with a different ion qubit in the string. An average ion-photon Bell state fidelity of 92% is achieved, for an average probability for detecting each single photon of 9%. The technique is directly scalable to larger ion-qubit registers and opens up the near-term possibility of entangling distributed networks of trapped-ion quantum processors, sensing arrays, and clocks.

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There is a current research effort to develop the building blocks of future quantum networks [1–3]: distributed matter-based nodes for the storage and processing of quantum information that are interconnected with photonic links for the establishment of internode entanglement. Such networks have a broad range of envisioned applications [2]. Over distances of a few meters, they offer a path to scale up the qubit number in quantum computers and quantum simulators [4,5]. Over larger distances they offer a fundamentally new platform for secure communication [6], distributed sensing [7,8], and timekeeping [9]. Experiments have demonstrated the entanglement of two remote matter-based qubits via photon transfer, including qubits encoded in ionized atoms [10–12], neutral atoms [13–15], solid state defect centers [16–18], quantum dots [19,20], and superconducting circuits [21]. Entanglement of three remote nitrogen-valence-center qubits was achieved [22].

In order to network intermediate-scale quantum processors, methods are first needed to connect the quantum states of multiple qubits in the processors to those of photons. Those photons can then be used to establish multiqubit entanglement between the processors, providing access to the full computational power of their joint Hilbert space. A few experiments have demonstrated coupling each individual in a register of two [23–25] and three [26] matter qubits to separate photons. Two entangled Bell pairs

between two remote nitrogen-valence-center nodes have been established [25].

In this Letter, we demonstrate a scalable technique to entangle each matter-based qubit in a register to a different propagating photon. Qubits are encoded into a string of electrically trapped atomic ions. By modifying the trapping voltages, each ion in the string is brought sequentially into a photon-interfacing zone, corresponding to the focus of an optical cavity, and emits one photon. A train of photons is ideally obtained: each photon in the train is entangled with a qubit encoded in the ion that emitted it. In future, those photons are then available to entangle, e.g., remote copies of the ion register via photonic entanglement swapping, as demonstrated using one ion qubit in our system over 230 m [12].

Quantum network node functionality is here demonstrated via ion-photon interfacing, as well as ion-qubit memory on the millisecond timescale and single qubit processing. Previously, memory times of tens of milliseconds and universal quantum logic have been demonstrated in our system [27]. Entangling remote registers of trapped-ion qubits is a promising path to realize quantum networks and their most advanced applications [28]. For example, strings of tens of $^{40}\text{Ca}^+$ ions—the species used in the present work—are some of today’s most advanced intermediate-scale quantum computers [29,30], quantum simulators [31,32], and quantum sensor arrays [33] and can also function as optical atomic clocks [34–38].

Our experimental system consists of a string of ten $^{40}\text{Ca}^+$ atoms in a linear Paul trap with an integrated optical cavity for photon collection at 854 nm [Fig. 1(a)]. The cavity axis is close to perpendicular to the ion-string axis, with a relative angle of 85.9° [Fig. 1(b)]. The waist of the relevant vacuum mode of the cavity is $12.31(8) \mu\text{m}$ and the length

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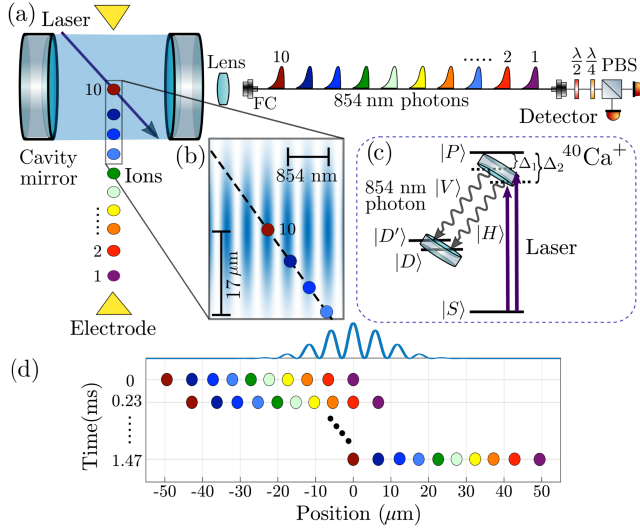


FIG. 1. (a) Concept image. Each 854 nm photon is polarization-entangled with a matching-colored $^{40}\text{Ca}^+$ ion (color indicates entanglement only). Configuration is after ion-string transport: photon 10 was just generated from ion 10. Photons are collected into optical fiber (FC, fiber coupler) and undergo polarization analysis: half-wave ($\lambda/2$) and quarter-wave ($\lambda/4$) plates; polarizing beam splitter (PBS). (b) Enlargement showing 854 nm vacuum cavity standing waves and 85.9° angle to ion string (dashed line). (c) Atomic energy level diagram. $|S\rangle = |4^2S_{1/2}, m_j = -1/2\rangle$, $|P\rangle = |4^2P_{3/2}, m_j = -3/2\rangle$, $|D\rangle = |3^2D_{5/2}, m_j = -5/2\rangle$, $|D'\rangle = |3^2D_{5/2}, m_j = -3/2\rangle$. The frequency difference $\Delta_2 - \Delta_1$ is equal to the one between $|D'\rangle$ and $|D\rangle$ [39,46]. (d) The ion string is stepwise displaced along its axis, bringing ions one at a time to the cavity center and standing wave maximum ($0 \mu\text{m}$). Blue oscillating line: cross section of vacuum cavity standing wave (electric field squared) along the ion-string axis [see dashed line in (b)].

of the ten ion string is $49 \mu\text{m}$, meaning that many ions lie far outside the cavity field. By unbalancing the voltages on the end cap electrodes—which provide confinement along the string axis—different ions can be positioned at the center of the cavity waist. In this Letter, values in parentheses denote one standard deviation of statistical uncertainty in the last digit(s) of the reported number.

First, the ion at one end of the string (ion 1) is ideally placed at the optimal position for photon generation: a maximum of the vacuum standing wave at the center of the cavity waist. A single photon is generated from ion 1 via a bichromatic cavity-mediated Raman transition (BCMRT) [46,47] [Fig. 1(c)], driven via a single-ion-focused 393 nm Raman laser beam with a $1.2 \mu\text{m}$ intensity waist at the ion [26,27]. A Raman laser pulse on the ion ideally generates the maximally entangled state $|\psi(\theta)\rangle = (|D', V\rangle + e^{i\theta}|D, H\rangle)/\sqrt{2}$, where $|D'\rangle$ and $|D\rangle$ are the respective Zeeman states $|3^2D_{5/2}, m_j = -3/2\rangle$ and $|3^2D_{5/2}, m_j = -5/2\rangle$, and $|V\rangle$ and $|H\rangle$ are the vertical and horizontal polarization components of an 854 nm photon emitted into the cavity vacuum mode, respectively. The angle θ is a phase set by

the relative phase of the two frequency components in the bichromatic beam [47].

After the generated photon has exited the cavity, the ion string is moved (shuttled) along the string axis to a new equilibrium position in which the neighboring ion (ion 2) is now in the same optimal position for photon generation and an attempt to generate a photon (photon 2) is made. This process—of bringing each ion one at a time into the position of optimal cavity coupling and attempting to make a photon—is repeated for all cotrapped ions, ideally yielding a train of single photons, each entangled with a different known ion qubit in the string [Fig. 1(d)]. On exiting the cavity through a preferred mirror, photons are collected into a single-mode optical fiber, which implements a rotation U_p on the polarization of each photon, and are then sent to a polarization analysis and detection setup [Fig. 1(a)]. For details on the photon detectors see Ref. [39].

In detail, the experimental sequence consists of the following steps (with laser pulse durations given in brackets). First, the ions are initialized via Doppler cooling (8 ms) followed by optical pumping into the state $|S\rangle = |4^2S_{1/2}, m_j = -1/2\rangle$ (40 μs) and a wait time (60 μs). Second, a Raman pulse (80 μs) is applied to the ion at the cavity maximum (ion 1 in the first instance). Third, a change in the end cap electrode voltages is initiated that leads to a new ion-string equilibrium position in which the neighboring ion is at the cavity maximum. A 60 μs wait time now occurs to allow for ion transport [39]. Steps two and three are then repeated until a Raman pulse has been applied to each ion in the string.

In the last step, the ions are moved back to their initial position and ion-qubit measurement is carried out. For that, the $|D'\rangle$ -state electron population of all ions is moved to the $|S\rangle$ state via a $6.4 \mu\text{s}$ π pulse using a laser at 729 nm on all ions. Next comes an optional 729 nm $\pi/2$ pulse implemented on the $|S\rangle$ to $|D\rangle$ transition on all ions. The optional pulse is implemented when the ion qubits are to be measured in the Pauli σ_x or σ_y basis: the optical phase of the pulse determines in which of the two bases the measurement is made. The optional pulse is not implemented when the ion qubit is to be measured in the σ_z basis. Finally, single-ion resolved qubit state detection is performed via electron shelving for 5 ms on all ions simultaneously, at which point the experimental sequence is concluded. The chosen ion-qubit and photon-qubit measurement bases are fixed throughout a single execution of the experimental pulse sequence. The sequence is repeated for all nine combinations of Pauli measurement bases for two qubits—set by different combinations of wave plate settings for the photon qubits and laser pulses for the ion qubits—allowing for tomographic reconstruction of all 100 possible combinations of two-qubit ion-photon pair density matrices ρ_{ij} (ion i , photon j).

The pulse sequence was repeated 54 000 times over 45 min, corresponding to the same number of attempts to

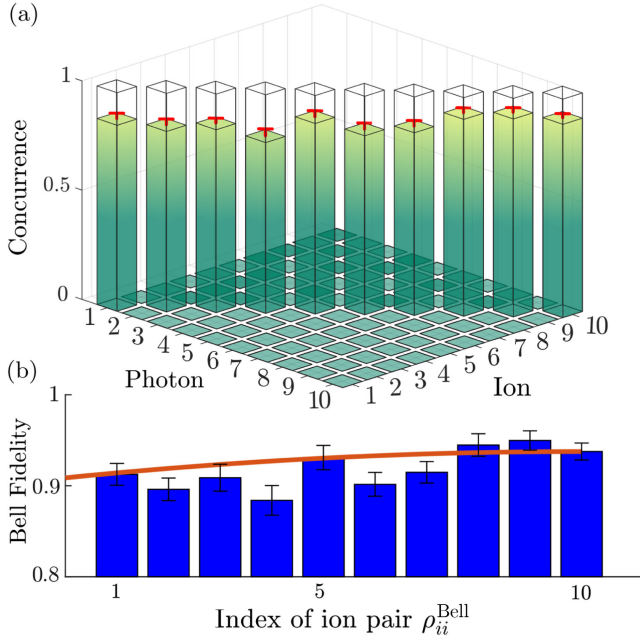


FIG. 2. (a) Concurrence of all 100 tomographically reconstructed ion-photon states ρ_{ij} . The highest and lowest value for matched ion-photon states $\rho_{i=j}$ are 0.91(2) and 0.78(3), respectively. (b) Blue bars with errors: Bell state fidelities of the ion-photon states ρ_{ii}^{Bell} . Orange curve: model based on calibrated ion-qubit decoherence. All errors bars are derived from Monte Carlo analysis of tomographic data.

generate a photon from each ion. From the dataset, all two-qubit ion-photon density matrices ρ_{ij} are tomographically reconstructed. The concurrences [48] of all 100 ion-photon pairs [Fig. 2(a)] show that all matched ion-photon pairs (ρ_{ii}) are strongly entangled, while all unmatched pairs ($\rho_{i,j \neq i}$) are not entangled: there is no evidence that any photon is entangled with any other ion other than the one that was in the focus of the Raman laser when the photon was generated. Up to the precision of our measurements, ions not in the focus do not significantly participate in the BCMRT process such that they neither emit nor absorb cavity photons.

The states ρ_{ii} are rotated with respect to each other by single qubit Pauli σ_z rotations. A numerical search is done to find the angles of these rotations; details can be found in [39]. Specifically, the function $\sum_{m,n} F(U_z^m \rho_{mm} U_z^{m\dagger}, U_z^n \rho_{nn} U_z^{n\dagger})$ is maximized over those angles, where U_z^k is a σ_z rotation on ion-qubit k (and identity on the photonic qubit) and F is the mixed state fidelity function [49]. The obtained rotation angles increase as a function of the ion number and are consistent with the effect of the independently measured magnetic field gradient across the string of $4.4(2) \text{ G m}^{-1}$ [39]. Two steps of manipulation bring the states ρ_{ii} into the Bell-state form ($|\psi(0)\rangle$). First, the states $\rho_{ii}^{\text{rot}} = U_z^i \rho_{ii} U_z^{i\dagger}$ are computed, where U_z^i are the rotations found to maximize the previous function. Second, the

function $\sum_m F(U_p \rho_{mm}^{\text{rot}} U_p^\dagger, |\psi(0)\rangle)$ is maximized over U_p : a single arbitrary one-qubit rotation of the photonic qubits that is attributed to the polarization rotation applied by the optical fiber going to the photon analysis and detection station. The states $\rho_{ii}^{\text{Bell}} = U_p \rho_{ii}^{\text{rot}} U_p^\dagger$ are now in the Bell-state form.

The Bell-state fidelities $\langle \psi(0) | \rho_{ii}^{\text{Bell}} | \psi(0) \rangle$, which range from 0.88(2) to 0.95(1), are shown in Fig. 2(b) and compared with a model of ion-qubit decoherence based on Gaussian dephasing. That model, which considers the coherence time of the $|D\rangle$ - $|D'\rangle$ qubit of 5.5(1) ms [39], is applied to the last ion-photon state generated ($\rho_{10,10}^{\text{Bell}}$), and predicts a 0.02 drop in Bell fidelity between $\rho_{10,10}^{\text{Bell}}$ and $\rho_{1,1}^{\text{Bell}}$. A significant increase in coherence time is expected by mapping the ion-qubit states into the $|S\rangle$ -state ground-state manifold and performing spin echoes, as we demonstrated for two ions [27]. The highest Bell fidelities observed here are consistent with those observed for one and two ion strings in our previous works [12,27]. We attribute errors, which are not due to ion-qubit decoherence, to a range of sources that each contribute infidelities at the level of ≤ 0.01 , including errors in 729 nm laser pulses and polarization analysis optics, as well as errors on one ion due to photon generation attempts on another [39]. A detailed study of the fidelity errors at that level is beyond the scope of this Letter. For a comparison between the Bell-state fidelities and concurrences for the states ρ_{ii}^{Bell} , see Ref. [39].

Figure 3 shows a histogram of all the single photon detection events, in which ten single photon wave packets are clearly visible. The photons detected in, e.g., the first (last) 80 μs -long time window are the ones expected to have been produced due to the corresponding Raman laser pulse applied to the first (tenth) ion, respectively. The total number of detected counts in the ten windows are $c_i = [5789, 5388, 5009, 4740, 4577, 4441, 4267, 4689, 5130, 5869]$, and the corresponding photon detection probabilities ($P_i = c_i/54000$) are shown as an inset in Fig. 3.

The data in Fig. 3 show an efficiency profile: photons emitted by ions closer to the center of the string were detected with lower probability. To predict this profile a master-equation model of the photon generation process is developed that yields the expected photon efficiency and wave packet shape emitted into the cavity for each ion [39]. In the model, the coupling strength of the photon generation process is reduced by the coupling of the Raman laser to motional sidebands of the ion string in the radial direction (the laser is perpendicular to the ion string and cavity axes). The reduction is greater for ions closer to the center of the string because they participate more in the motion of the lower frequency modes, which have higher Lamb-Dicke factors and higher mean phonon numbers after Doppler cooling. Model parameters are set to values obtained from independent calibrations, except for the detection path efficiency ξ , which includes all photon

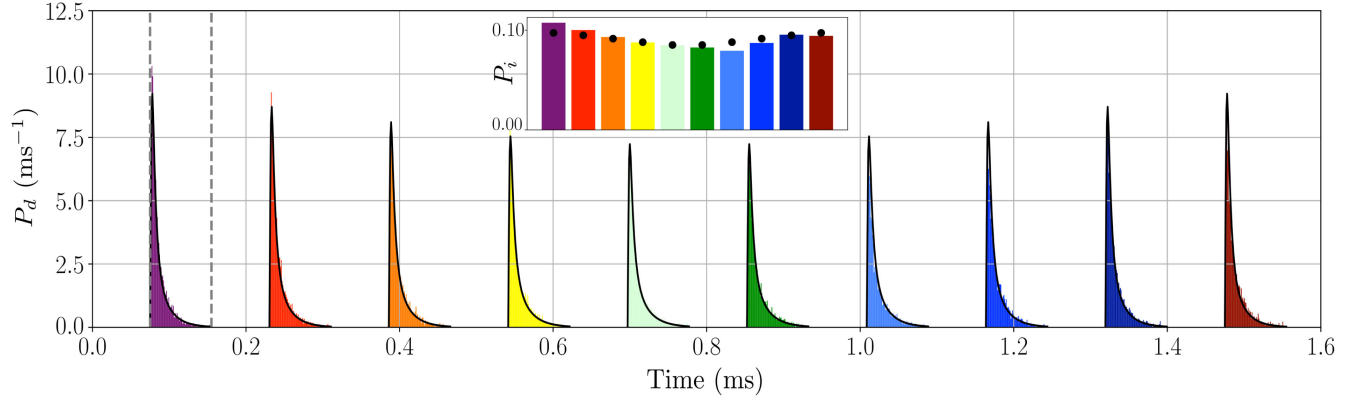


FIG. 3. Histograms of photon arrival times. Probability densities (P_d) are shown on the vertical axis: number of counts normalized by the number of attempts and by the $0.2 \mu\text{s}$ time-bin width. Ten single photon wave packets are visible; color denotes the ion that is expected to have produced the photon (c.f. Fig. 1). Solid black lines: numerical simulations. Dashed vertical lines show an example time window: counts within are associated with photon 1. Inset: photon detection efficiency. Colored bars: measured values P_i obtained by integrating each color-matched wave packet over its time window. Black points: model based on the finite temperature of the ion string.

losses after the photon is emitted into the cavity. ξ is obtained by fitting the model output to data in Fig. 3 [39], yielding $\xi = 0.16$.

The measured single photon wave packets and efficiencies are qualitatively well described by the predictions of the described master-equation model (Fig. 3). The middle ions (5 and 6) are predicted to have a photon generation efficiency lower by a factor of 0.87 compared to the outer ions (1 and 10). This effect could be eliminated in future, and the overall efficiency improved, by ground-state cooling the radial modes [50], after which the model predicts an average increase in photon generation efficiency per ion by a factor of 1.21.

The fitted ξ value is two standard deviations lower than the upper limit of $\xi_{\text{max}} = 0.20(2)$, that was determined from independent calibrations of the detection path efficiency [39]. The predominant loss mechanisms are unwanted scattering and absorption losses in the cavity mirrors, yielding a $0.43(3)$ probability for a photon in the cavity to exit via the preferred mirror.

In the rest of the Letter, results are presented from independent investigations into two additional error sources, beyond ion-string temperature, that could each have reduced photon generation efficiencies from individual ions fractionally by 1% or more. It is not practical to determine the size of each of these errors in the ten-ion experiment of Fig. 3 by comparison of extended error models with the data: the different errors led to similar effects that are not distinguished in data and there are too many parameters to find a reliable match. Instead, the focus is on giving estimates for the size of their effects individually and in combinations, as well as specifying how to mitigate these errors in future experiments. All subsequent calculations include the effect of ion temperature used to model the data in Fig. 3.

The first additional error source are displacements z of individual ions from the center of the Raman laser beam focus, along the string axis, due to imperfect setting of end cap voltages. The position of each ion is estimated to have been set to within a displacement of $z = \pm 0.24(3) \mu\text{m}$. The model is extended to estimate the drop in photon generation efficiency for each ion caused by such displacements, as a fraction of the value achieved without them [39]. The extension considers the center of the Raman beam to provide both the Rabi frequency for which the photon generation process (BCMRT) is resonantly driven and the maximum ion-cavity coupling strength. For $z = \pm 0.24 \mu\text{m}$, a photon generation efficiency drop by a factor of between 0.90 (end ions) and 0.89 (middle ions) across the string is predicted, largely due to the photon generation process being driven off-resonantly for displaced ions. To increase these factors to more than 0.99, the model predicts that ions should be positioned to within $\pm 0.1 \mu\text{m}$ of the laser beam center, which should be feasible by taking more data during ion positioning to reduce statistical uncertainty.

A second additional source of imperfections are coherent oscillations of the string's axial center-of-mass (COM) mode, generated by the shuttling voltage steps [51,52]. That oscillation is in a direction perpendicular to the tightly focused Raman laser beam, yielding a time-dependent Rabi frequency and cavity coupling strength, for the ion whose turn it is to generate a photon. Independent experiments with a single ion show that ion 10—shuttled the largest number of times before photon generation—could have an oscillation amplitude of up to $A_{\text{com}} = 0.2 \mu\text{m}$. This value is an upper bound for the oscillation amplitude of ion 10. Because of uncertainties in the axial COM frequency, we do not know the amplitude values more precisely for this or other ions in the string [39]. An amplitude $A_{\text{com}} = 0.2 \mu\text{m}$

is expected, by further model extensions [39], to cause a drop in photon generation efficiency for ion 10 by a factor of 0.98, compared to the case $A_{\text{com}} = 0$ and $z = 0$. Combining, e.g., $A_{\text{com}} = 0.2 \mu\text{m}$ with a displacement of $z = \pm 0.24 \mu\text{m}$ for ion 10 is predicted to decrease this factor to 0.84. If not mitigated, shuttling-induced oscillations can increase for longer strings that contain more ions, which demand more voltage steps. Preliminary tests show that oscillation amplitudes can be significantly reduced by timing the shuttling steps with respect to the oscillation frequency such that, e.g., every second step largely cancels the oscillation generated by the previous one. No effort was made to time the shuttling steps in the ten-ion experiment to minimize oscillations. Moreover, we expect that simply adding a low-pass electric filter with a cutoff at 40 kHz immediately before the end cap electrodes would reduce A_{com} for a single voltage step by more than an order of magnitude, at the expense of increasing the shuttling wait time by a factor of maximally 1.1. Without compromising photon efficiency [46], significantly shorter photon separations could be achieved through stronger ion-cavity coupling (e.g., using micron-scale cavities [53,54] and faster, energy-neutral ion shuttling [51,52]).

In summary, a method was demonstrated that enables each qubit in a ten-qubit ion register to be entangled with a distinct fiber-coupled photon. These photons can serve as a flexible interface for establishing entanglement between, e.g., remote copies of ion registers, or other matter-based qubit platforms, via photonic entanglement swapping [10–12]. Such links may span from meters—for modular quantum processing [4]—to hundreds of kilometers via telecom-wavelength conversion [26,27,55]. The method is directly scalable to registers with many tens of ion qubits supporting universal quantum processing [33], and to hundreds or even thousands of qubits when integrated with microfabricated, multizone trap architectures [56,57]. As establishing remote entanglement requires many repeated attempts, key next steps are to combine the techniques presented here with methods that extend ion-qubit coherence times, such as dynamical decoupling [58], and with in-sequence cooling protocols [59] to stabilize photon generation efficiency.

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