

Scalable quantum computation with photons and trapped ions

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Ultrafast laser pulses can be used for fast quantum gates and entangling gates offering an alternative method to scale quantum computing systems. We implement fundamental components of these entangling gates.

Trapped ions are among the most attractive systems for quantum computation, owing to their long trapping lifetimes and long coherence times. However, scaling of these systems to a large number of quantum bits (qubits) is still a challenge. One approach to overcome this scaling problem in ion traps is to use deterministic quantum gates between two nearby ions and shuttle the ions to other trapping zones for storage and further operations as necessary [1]. An alternative approach to scaling up trapped ion quantum computation systems is to use photon-mediated entanglement and entangling gates [2]. With this approach, atoms in many different trapping zones can be entangled without the need to cool the ions near the motional ground state. Even though this approach is probabilistic, it has been shown that it scales efficiently. By uniting atomic and photonic systems, the benefits of atomic quantum memory and the quantum communication of photons are combined.

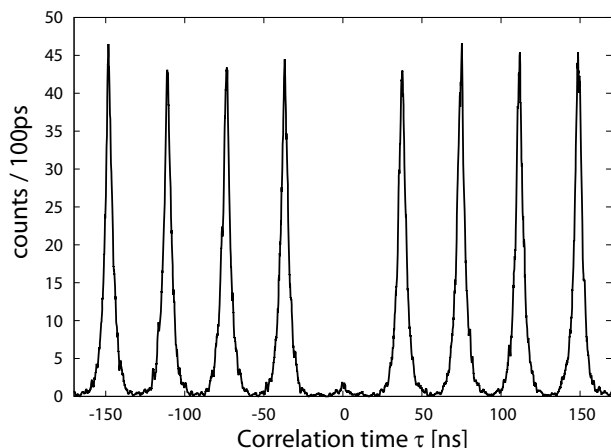


FIG. 1: Intensity autocorrelation of the light emitted by a single ion excited by one-picosecond pulses. The near-perfect antibunching at zero delay shows that at most one photon is emitted from an excitation pulse. This measurement was done with one ion with an integration time of about 5 min (20 min total time).

Remote entanglement of two ions can be achieved by first entangling each ion with an emitted photon [3] and then subjecting these two photons to a Bell-state measurement. The essential elements of this entanglement scheme are that at most one photon is generated in each attempt as well as the quantum interference of these

two photons. Using an ultrafast laser pulse, we demonstrate the excitation of a single ion on a time scale much faster than the lifetime of the excited state. The subsequently emitted photons show near-perfect anti-bunching (Fig. 1), demonstrating that from a single laser pulse at most one photon is scattered by the atom, as required by the entangling scheme.

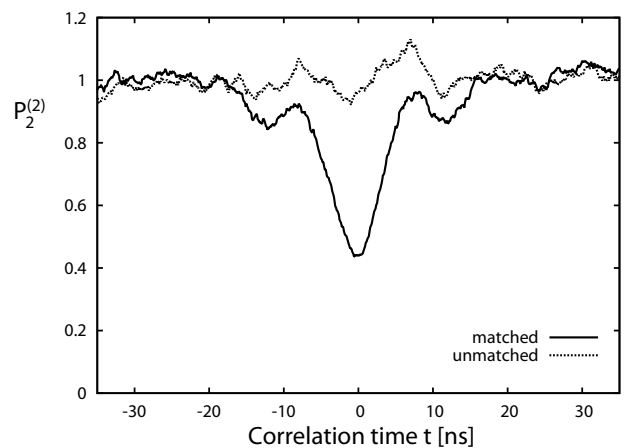


FIG. 2: Joint detection probability of photons emitted by different ions, $P_2^{(2)}$ as calculated from the measured single ion intensity autocorrelation $g^{(2)}$ and the measured joint detection probability. Without mode overlap (dotted line), the photons are uncorrelated and no anti-bunching is observed. 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 [4]. Our results correspond to a mode overlap of at least 57%, and a photon duration of about 5.3 ns.

While the entanglement scheme does not necessitate interferometric stability of the length of the two paths, it does require the spatial modes of the two ions to be matched on the beamsplitter. Due to relative drift of the images of the ions on the beamsplitter we are not able to show mode-matching of the light emitted by ions located in different rf traps. However, for two cadmium ions in the same trap, we demonstrate mode-matching by observing the two-photon interference of the emitted photons [5, 6]. Here we achieve a visibility corresponding to a free-space mode-overlap of 57% (Fig. 2).

The remote entanglement of two ions can be extended

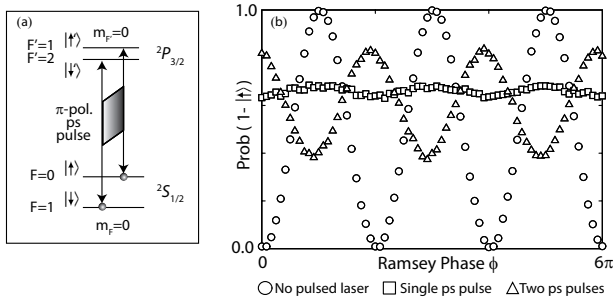


FIG. 3: (a) Atomic energy levels of $^{111}\text{Cd}^+$, relevant for the experiment. (b) Ramsey fringes without pulsed laser interaction (circles), only one excitation pulse (squares), and excitation followed by de-excitation (triangles). The phase shift of 18.9π of the Ramsey fringes following excitation and de-excitation compared to the Ramsey fringes without the laser pulses is due to the qubit frequency shift of $13.904(4)$ GHz during the 680 ps delay between the excitation and de-excitation pulses.

to an entangling gate if both qubit states of the ion can be coherently excited by a single light pulse [2, 7]. We implement fundamental components of these entangling gates by using ultrafast optical pulses to drive picosecond optical Rabi oscillations between the $5s\ ^2S_{1/2}$ and $5p\ ^2P_{3/2}$ states in a single trapped cadmium ion. By adding a second counter-propagating laser pulse we coherently de-excite the ion back to the ground state. When the ultrafast excitation drives an initial superposition stored in the $S_{1/2}$ hyperfine qubit states of the ion, the frequency of the spontaneously emitted photon becomes entangled with the atomic hyperfine qubit, evidenced by the loss and

recovery of contrast in a Ramsey interferometer (Fig. 3, [8]).

Improving the visibility of the two-photon interference, for example by using a different ion species for which optical fibers are available, and combining it with the readily available methods of state detection of trapped ions may allow two ions to be entangled without involving their motion.

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

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