A Heralded Quantum Gate between Remote Atoms

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Abstract: We implement a probabilistic entangling gate between two distant trapped ytterbium ions and measure an average gate fidelity of 90%.

OCIS codes: (270.5585) Quantum information and processing; (270.5565) Quantum communications

The one-way quantum computing model [1, 2] is an alternative model of quantum computing. Here, a highly entangled multi-partite cluster state is prepared in advance. Then, single qubit operations and local projective measurements on the entangled nodes are used to realize the quantum computation. Classical feed-forward of measurement results and the pattern of measurements on the cluster-state implements the deterministic quantum algorithm. This model is universal, equivalent to the circuit model and offers an alternative way to scale trapped ion quantum computing.

Large entangled clusters states employing trapped ions as the nodes can in principle be produced in a way that scales ultimately linear in the number of nodes [3, 4]. This scheme uses a heralded gate to entangle the long-lived hyperfine "clock" states of distant atoms. The gate operation is mediated through the interference of two photons which are spontaneously emitted by the two ions and carry frequency encoded qubits. The successful operation of the gate is heralded by the coincidence detection of these photons. This entangling gate has many favorable properties. First, the ions do not have to be localized to the Lamb-Dicke regime and the operation is not sensitive to the interferometric phase difference of the optical paths. Also, the qubits are encoded in the atomic hyperfine "clock" states and in two well-separated photonic frequency states, both of which are highly insensitive to external influences. Furthermore, the operation of the gate between remote ions facilitates individual addressing for single qubit operations and measurement. Finally, gates between arbitrary nodes are realized without moving the ions. Employing the gate to create large entangled cluster states and combining it with the easily accessible single qubit rotations and measurements, may allow the realization of a scalable one-way quantum computer.

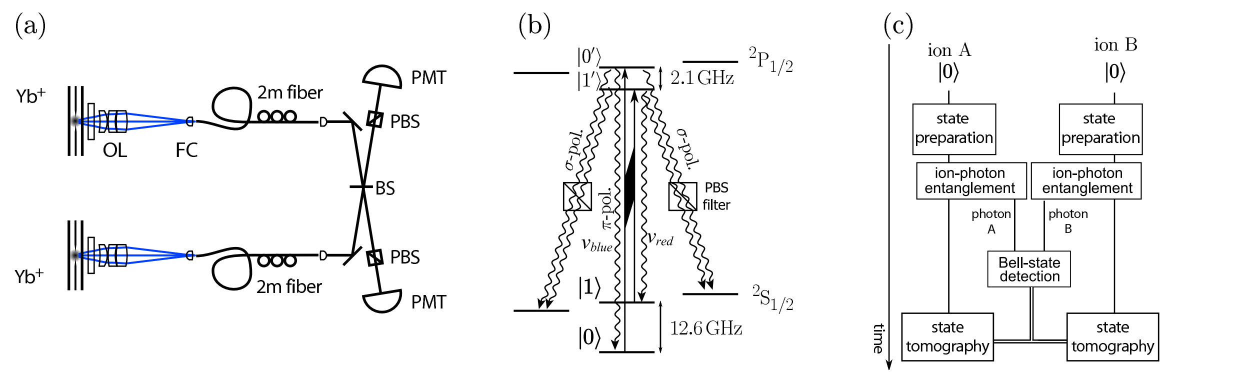

Fig. 1. (a) The experimental apparatus [5, 6]. Two $^{171}\mathrm{Yb}^+$ ions are trapped in identically constructed ion traps separated by one meter. About 2% of the emitted light of each ion is collected by objective lenses (OL) and coupled into two single mode fibers. The output of these fibers is directed to interfere on a polarization independent 50% beam splitter. Polarizers (PBS) only transmit the π-polarized light from the ions. The photons are detected by single photon counting photo multiplier tubes (PMT). (b) Level and excitation scheme. The qubit is encoded in the $^2\mathrm{S}_{1/2}$ hyperfine "clock" states of the $^{171}\mathrm{Yb}^+$ ion and is coherently excited to the $^2\mathrm{P}_{1/2}$ hyperfine excited states by a pulse from an ultrafast laser with a wavelength near $369.5\mathrm{nm}$. Upon spontaneous emission of a π-polarized $369.5\mathrm{nm}$ photon, the frequency state of the photon is entangled with the qubit state of the atom. (c) Gate operation scheme. After initialization in $|0\rangle$, each ion is prepared in one of the input states $|\Psi_a\rangle_1$ and $|\Psi_a\rangle_2$ of the gate. The frequency of each spontaneously emitted photon is entangled with the state of the respective ion. If these two photons are detected in the anti-symmetric Bell state, the quantum state of the two ions is projected on the state $|\Psi_{aa}\rangle \propto Z_1(I - Z_1Z_2)|\Psi_a\rangle_1|\Psi_a\rangle_2$. Here $Z := \sigma_Z$ is the Pauli-z operator.

Here, we demonstrate the experimental realization of this heralded entangling gate. Up to a global phase, we prepare each of the two input qubits in the basis states of a full set of mutually unbiased bases and measure the fidelity of the expected output state. Averaged over these states we observe a fidelity of 90%. For one pair of input states for which we expect the antisymmetric Bell state as output, we perform full tomography of the output state. From the inferred density matrix, we obtain a fidelity $F = 0.87$, a concurrence $C = 0.77$ and the entanglement of formation $R_F = 0.69$.

References

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