# Toolbox for Microwave-driven Quantum Logic with Trapped Ions

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Trapped atomic ions are a well-advanced physical system for investigating fundamental questions of quantum physics and for quantum information science and its applications. When contemplating the scalability of trapped ions for quantum information science one notes that the use of laser light for coherent operations gives rise to technical and also physical issues that can be remedied by replacing laser light by long wavelength radiation in the microwave (MW) and radio-frequency (RF) regime radiation employing suitably modified ion traps.

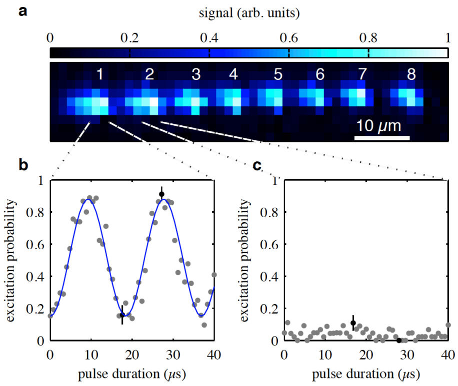


FIG. 1. Coherent single-qubit excitation within a quantum byte. (a) Spatially resolved resonance fluorescence (near 369 nm) of eight $^{171}Yb^+$ ions held in a linear Paul trap. (b) Rabi oscillations between hyperfine states $\left|^2S_{1/2}, F=0\right\rangle$ and $\left|^2S_{1/2}, F=1, m_F=+1\right\rangle$ of the electronic ground state are observed only for ion 1 when irradiating all ions at the microwave addressing frequency of this ion. (c) The non-addressed ion 2 (and 3 through 8 as well) are left virtually unaffected.

Magnetic gradient induced coupling (MAGIC) makes it possible to coherently manipulate trapped ions using exclusively MW and RF radiation. After introducing the general concept of MAGIC, I shall report on recent experimental progress using $^{171}Yb^+$ ions confined in a suitable Paul trap as effective spin-1/2 systems interacting via MAGIC. It will be shown that the spin-spin coupling topology can be experimentally tailored to best suit a desired quantum simulation or computation: The magnitude of coupling can be adjusted by variation of the magnetic field gradient and the trapping potential. The sign of coupling, and turning the coupling on and off is attained by simple state preparation using MW pulses. Taking advantage of simultaneous between between three qubits a quantum Fourier transform has been implemented with a speed-up of factor 3 as compared with a decomposition of the QFT into 2-qubit gates.

In general, executing a quantum gate with a single qubit, or a subset of qubits, affects the quantum states of all other qubits. This reduced fidelity of the whole quantum register may preclude scalability. We demonstrate addressing of individual qubits within a quantum byte (eight qubits interacting via MAGIC) using MW radiation and measure the error induced in all non-addressed qubits (cross-talk) associated with the application of single-qubit gates [1]. The measured cross-talk is on the order $10^{-5}$ and therefore below the threshold commonly agreed sufficient to efficiently realize fault-tolerant quantum computing.

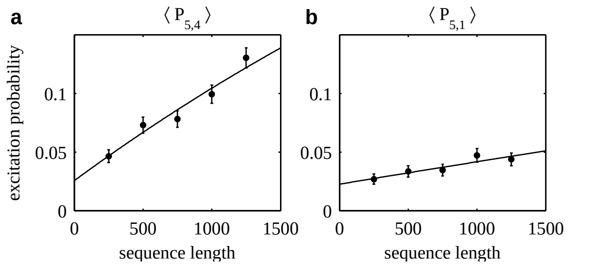


FIG. 2. Exemplary error accumulation during benchmarking. A benchmarking sequence is addressed to ion 5 and the spurious excitation of all other ions is measured. Exemplary data for ions 4 and 1 are shown. Next-neighbour cross-talk causes the excitation probabilities of the next-neighbour ion 4 (a) to accumulate faster than the ones of the non-next-neighbour ion 1 (b). From these data we deduce cross-talk errors per single gate of the order $10^{-5}$.

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