Cooling, coherent manipulations and decoherence of two-species trapped-ion arrays for Quantum Information Processing.

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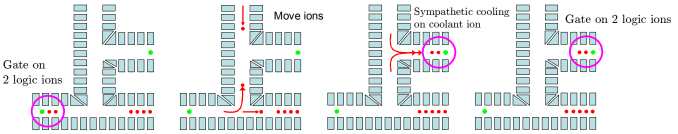
Experimental investigation of scalable ion trap QIP proposal.

We focus on two of the requirements for scaling up an ion trap quantum information processor:

1) Ability to move information around.
2) High fidelity logic gates.

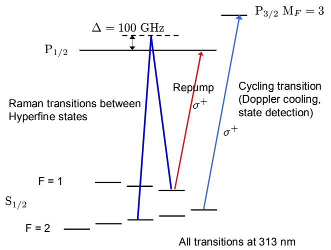
For 1) proposal: Move the ions themselves, resulting in negligible perturbation of the internal states.
Moving ions heats them up, which decreases the fidelity of 2-qubit gates using motional mode, therefore require re-cooling of motion while preserving quantum information.



Experiments: Demonstrations of multiple high-fidelity single and two-ion gates while moving ions around.

$^9\mathrm{Be}^+$ logic ion

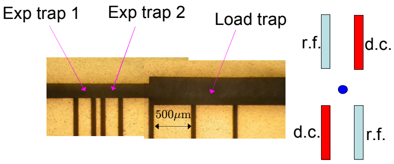
Magnetic field of 119.4 Gauss



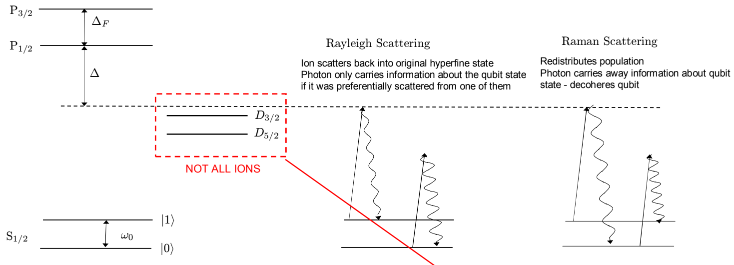
All transitions at 313 nm

Challenges:
Quantum control and movement of arrays of ions containing multiple types of ion, here Berylium for logic, and Magnesium for sympathetic re-cooling

Segmented linear Paul trap



Spontaneous photon scattering limits to logic gate fidelity



Rayleigh Scattering

Ion scatters back into original hyperfine state
Photon only carries information about the qubit state if it was preferentially scattered from one of them

Raman Scattering

Redistributes population
Photon carries away information about qubit state - decoheres qubit

Single qubit gates do not involve motional states

In general, for quantum logic gates via Raman transitions $\omega_0 \ll \Delta$
For "clock" qubits, the scattering matrix elements are the same for each qubit state.

If these conditions are met, **Rayleigh scattering doesn't decohere the spin state**, Raman scattering does.

D states place an lower limit on the achievable fidelity, $\sim 10^{-4} \rightarrow 10^{-6}$ for two qubit gates

$$P^{(1)}_{\mathrm{error}} \leq P_{\mathrm{Raman\ scatter}} = \frac{2\pi\gamma}{3}\frac{\Delta_F}{\Delta(\Delta-\Delta_F)} = \frac{2\pi\gamma|\Omega_R|}{g^2}$$

$\propto 1/\text{speed of gate}$

$\propto$ laser power

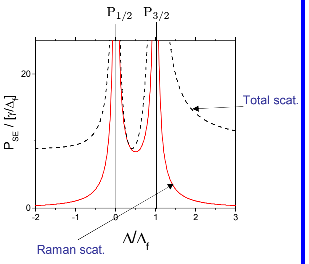
$$(\sim 1/\Delta^2)$$

Raman scattering also decoheres the spin state during two-qubit gates based on state-dependent forces

$$P^{(2)}_{\mathrm{error}} \leq (4/\eta)P_{\mathrm{Raman\ scatter}}$$

Extra time/laser power required

Lamb-Dicke parameter



$$\Delta \gg \Delta_F$$

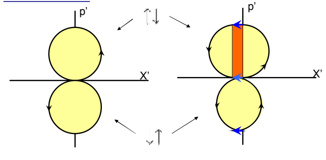
Amplitudes for Raman scattering via $P_{3/2}$ and $P_{1/2}$ destructively interfere - the total scattering rate is then dominated by Rayleigh scattering
- To maintain gate speed, need more power

Two qubit gates also make use of motional states

Ion recoils from emission of Rayleigh photons.
The recoil kick modifies the phase space trajectory, which results in an single qubit phase acquired by each ion.
The kick direction and phase acquired are random, therefore this dephases the qubits.

Perfect Gate:

Recoil Kick:



Erroneous gate:

$$\hat{U}_\varepsilon = \begin{bmatrix} 1 & & & \\ & e^{i(\phi+\Delta\phi)} & & \\ & & e^{i(\phi-\Delta\phi)} & \\ & & & 1 \end{bmatrix}$$

$$\boxed{F = 1 - \frac{P_{\mathrm{Rayleigh}}}{4}\langle|\beta|^2\rangle}$$

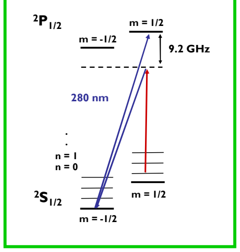
β is the recoil momentum kick

Theoretical comparison of decoherence for different ions (Ozeri et. al. PRA **75**, 042329 (2007)).

Sympathetic cooling with two-species ion arrays

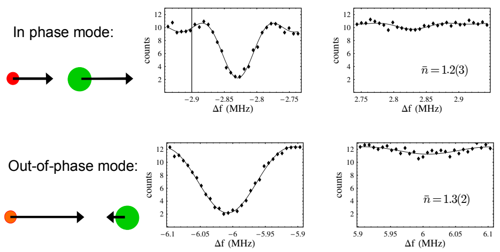
- Spectral addressing of ions – Magnesium transitions at 280 nm are 33 nm detuned from the nearest Beryllium transition (313nm), hence laser cooling Magnesium don't affect quantum logic stored in Be.
- Coulomb interaction means vibrational modes are shared between ions

$^{24}\mathrm{Mg}^+$ coolant ion



Two-ions

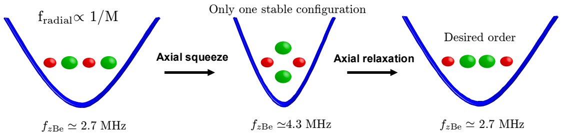
Cooling $^9\mathrm{Be}^+$ qubits with a $^{24}\mathrm{Mg}^+$ coolant ion



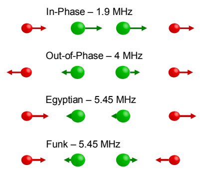
Cooling and re-ordering a two-species, 4 ion array

For sideband cooling and quantum logic gates, a prerequisite is knowing the frequencies of the normal modes. For a four ion, mixed ion array, this depends on ion order. Therefore it is crucial to be able to re-order the crystal

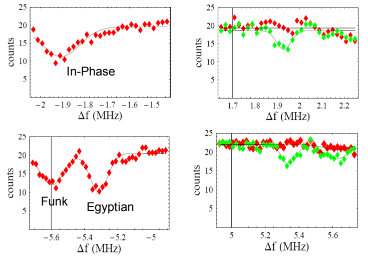
Make use of the fact that the radial pseudopotential strength is mass dependent, whereas d.c. axial potential isn't as axial confinement increases, heavier ions will "pop out" radially



Axial modes of ordered array



Preliminary Raman Sideband Cooling results

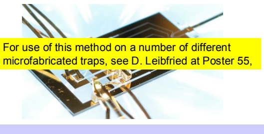


Experimental issues: Stray electric fields mean some radial modes have motion components along axis.
Radial modes may be hot due to re-ordering, and small coupling to Beryllium Doppler cooling

Doppler Re-cooling temperature measurement method for testing microfabricated traps

Idea: measure temperature of a hot ion by time-resolved fluorescence measurements as a function of time after Doppler cooling is turned on.
Advantages: doesn't require ground state cooling of ions, or even Lamb-Dicke regime cooling.
simple laser requirements – only a single Doppler cooling beam required.

Experimental comparison of heating measurements with $^{25}\mathrm{Mg}^+$ by Doppler re-cooling and by traditional Raman thermometry agree.



For use of this method on a number of different microfabricated traps, see D. Leibfried at Poster 55,