Ion Trap Cavity Quantum Electrodynamics

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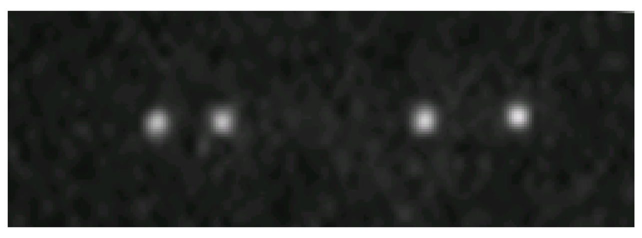
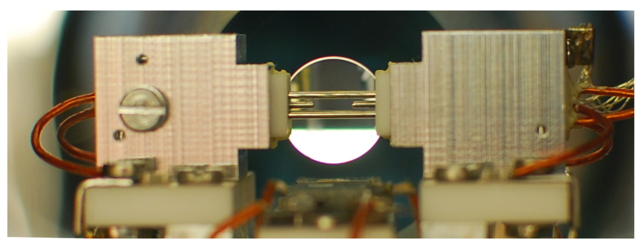
Overview/Motivation

We trap Barium ions within a high finesse optical cavity (F≈70000) to provide an enhancement of photon emission into the cavity mode. The cavity provides a single atom cooperativity of approximately unity which will provide a substantial enhancement of photon emission into the cavity mode. This will make our system well suited for atom-photon networking protocols, cavity based cooling methods and cavity based detection.





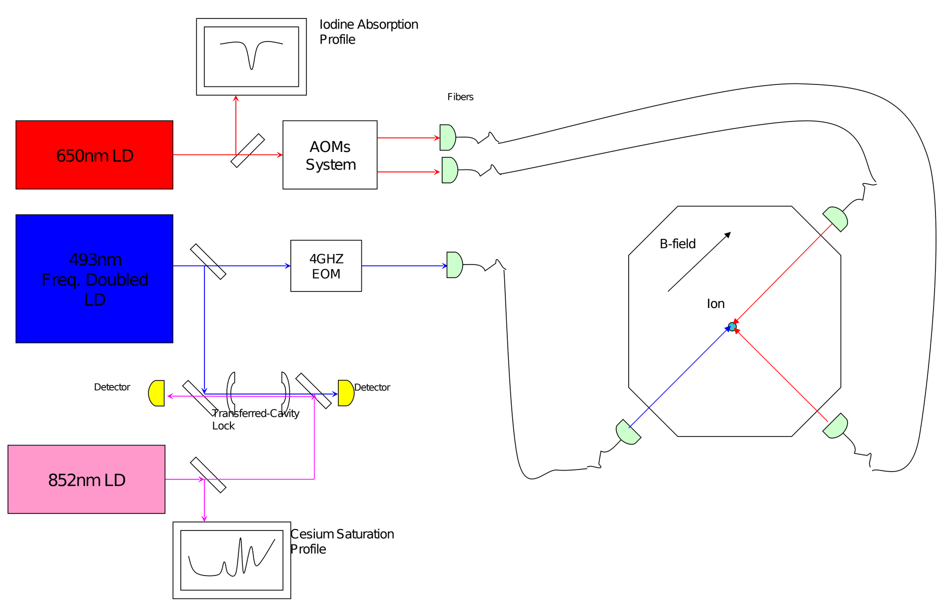
Images showing five trapped Barium ions (one is dark in this image) in linear paul trap (left image) and linear paul trap in vacuum chamber.

Key aspects of our system:

- All relevant Barium ions are in the visible spectrum which makes it well suited for coupling to a high finesse cavity.
- Cavity has high finesse (> 50000) at both $S_{1/2}$ to $P_{1/2}$ and $D_{3/2}$ to $P_{1/2}$ transitions.
- Cavity linewidth is sufficiently narrow to resolve ion vibrational levels.
- Long lived meta-stable D levels and very large fine-structure splitting (50 THz) - Flexible choice of detection schemes and qubit manipulation.

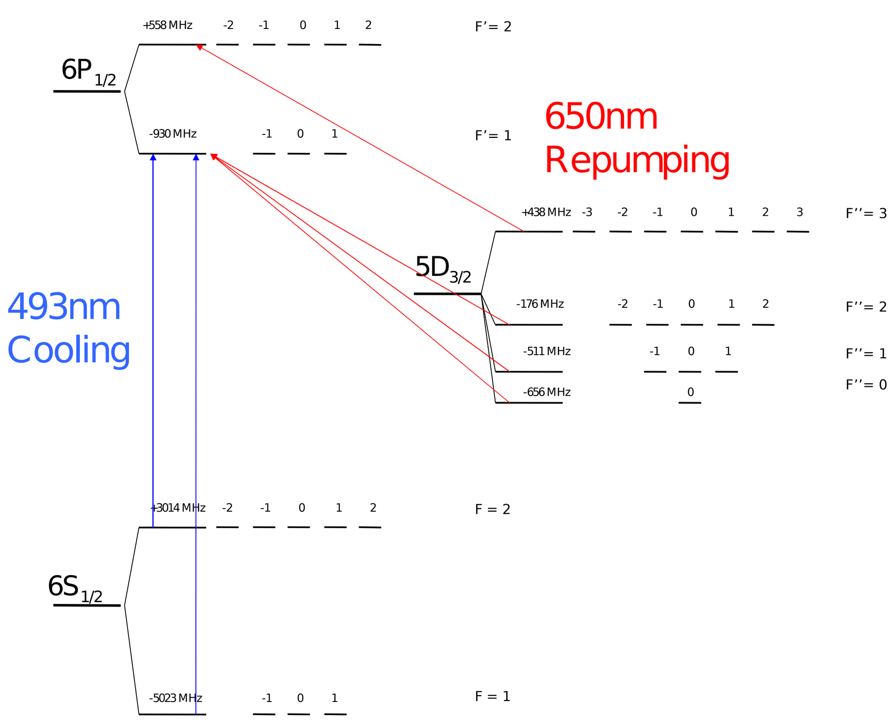
Trapping Barium

Setup



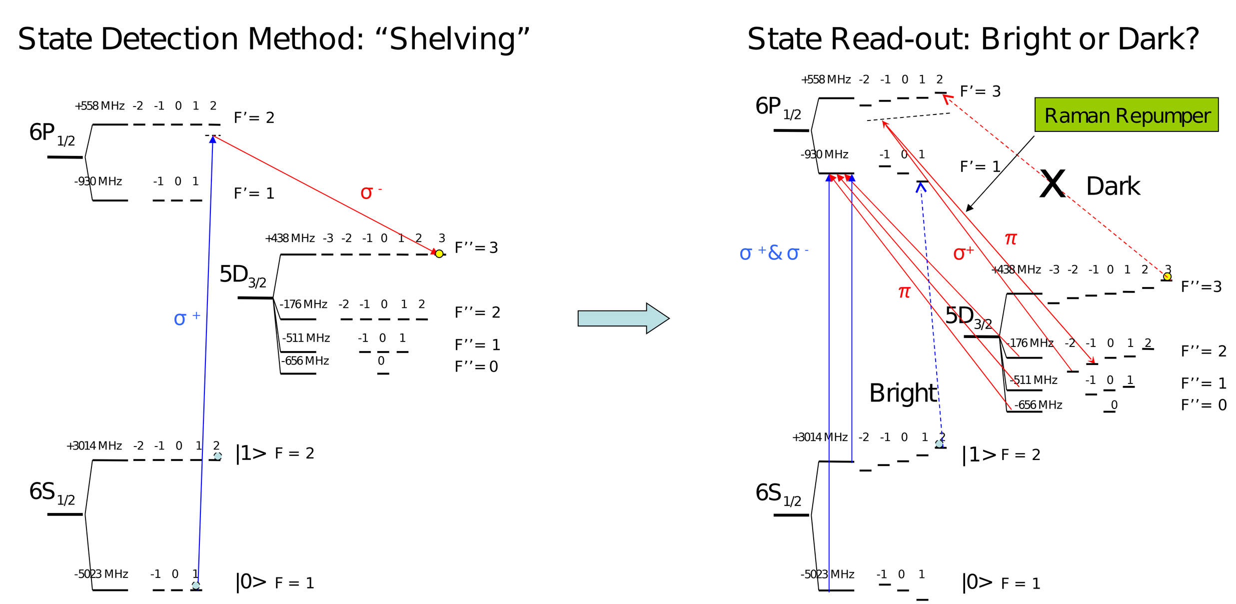
$^{137}Ba^+$ confined in a linear RF Paul trap with axial confinement up to 600 kHz and radial confinement up to 2 MHz. All cooling and state manipulation are provided by diode lasers which are locked to a reference cavity that is stabilized to a Cesium cell. Frequency-doubled diode lasers (493nm) address the $6S_{1/2}$-$6P_{1/2}$ transition for Doppler cooling and state manipulation. Diode lasers at 650nm address the $5D_{3/2}$-$6P_{1/2}$ transition for repumping, shelving, and Raman state manipulation.

Cooling scheme



Barium Ion as a Qubit

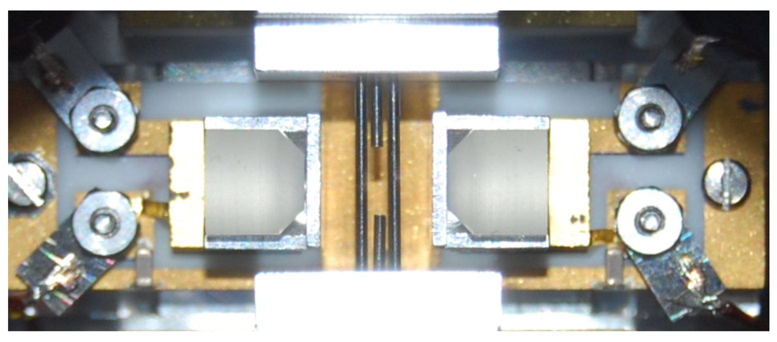
The qubits states are currently chosen to be |F=1,M_f=1> and |F=2, M_F=2> hyperfine ground states of $^{137}Ba^+$. Cooling is easily achieved using the scheme depicted below.



State detection is currently achieved by shelving the ion in the |3,3> hyperfine state of the $D_{3/2}$ level and repumping only to the F=1 hyperfine states of the $P_{1/2}$ level. Such a detection scheme is limited by the small hyperfine splittings of the $D_{3/2}$ level which leads to significant off resonant scattering out of the shelved state. This can be eliminated by using Raman coupling between Zeeman sublevels as shown. The large fine-structure splitting Barium decouples the |3,3> state from the Raman beams and detection is only limited by off-resonant pumping into the |3,3> state.

Cavity QED

Cavity parameters



The parameters:

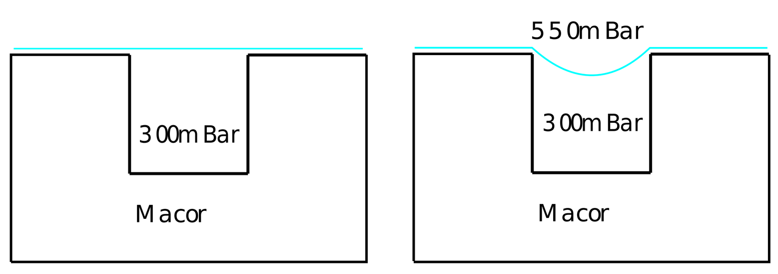
- $\kappa \approx 2\pi \times 300$kHz
- $\gamma \approx 2\pi \times 10$MHz
- g $\approx 2\pi \times 1.7$MHz

$$\left.\begin{array}{l}\kappa \approx 2\pi \times 300\text{kHz}\\ \gamma \approx 2\pi \times 10\text{MHz}\\ g \approx 2\pi \times 1.7\text{MHz}\end{array}\right\} g^2/\kappa\gamma \approx 1$$

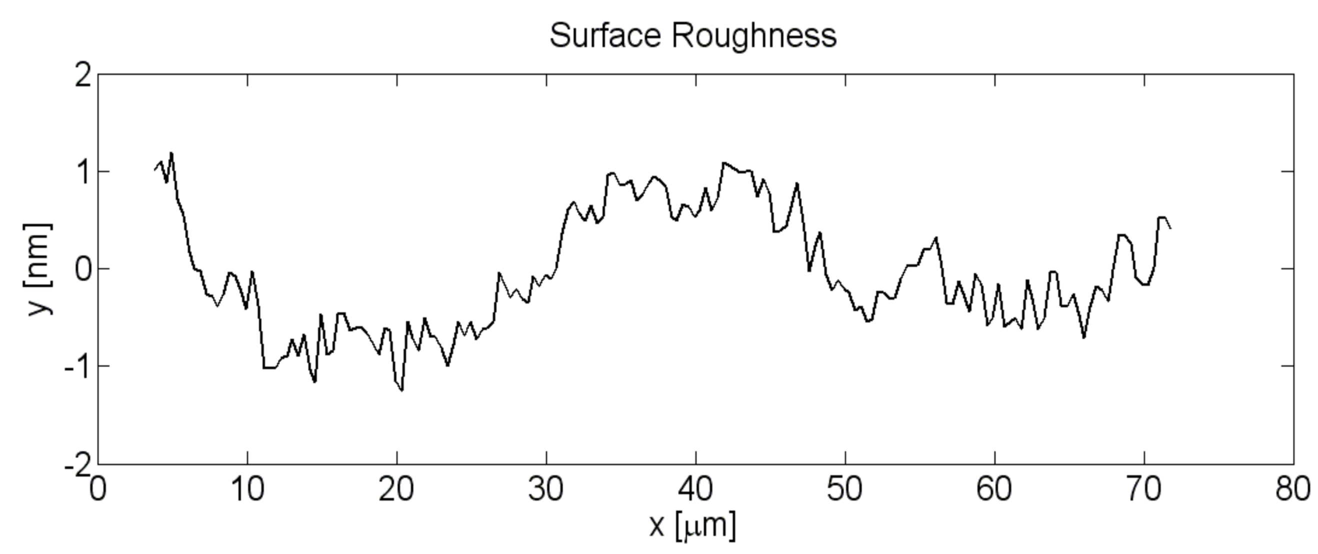
- L = 5mm
- R = 2.5cm
- F = 70,000

A cavity enables coherent information exchange between light and matter which requires good coupling between ion and the cavity field. Our current cavity provides a single atom cooperativity greater than one which enables substantial enhancement of photon emission into the cavity mode suitable for fast, efficient remote entanglement schemes.
Three parameters that determine the coupling efficiency: ion-cavity coupling rate (g), spontaneous emission rate of the ion (γ), and field decay rate of the cavity (κ). For strong coupling regime: g must be much faster than γ and κ. To achieve this, it is desirable to reduce the cavity mode volume. To this end we have developed a mirror fabrication technique that provides mirror curvatures on the order of 1mm. This allows us to enter into the single atom strong coupling regime with a cavity finesse as low as 5000 and still keeping ion-mirror distance to ≈ 1mm.

Micro cavities



The mirrors are produced by placing a 100 micron thick glass cover slip over a macor substrate that has some 1mm blind holes drilled into it. These are then heated to 800°C under 500 mBar, which is sealed when the glass melts. Then air is added to a pressure of 550 mBar, which places a pressure difference between the hole side and the air side, which deforms the molten glass to a hemispherical shape.



Roughness measurement limited by resolution of the optical profiler used. AFM measurements give 0.3 nm roughness. This gives a surface limited finesse of (90,000).

$$\left.\begin{array}{r}\text{R = 1 mm}\\ \text{L = 1.9mm}\\ \text{F = 20000}\end{array}\right\} \Rightarrow \left.\begin{array}{r}g = 2\pi \times 14\text{ MHz}\\ \gamma = 2\pi \times 10\text{ MHz}\\ \kappa = 2\pi \times 2\text{ MHz}\end{array}\right\} \quad g^2/\kappa\gamma \approx 10$$