Interaction of Laser Cooled Trapped Ions with Optical Cavity Fields

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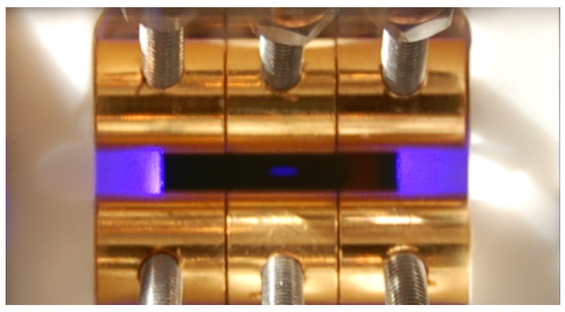
Introduction

Interaction between trapped ions and trapped photons



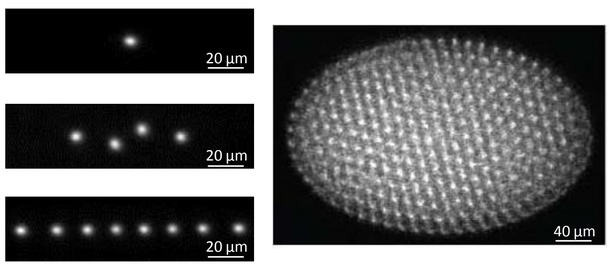
Motivations

- Cavity QED & quantum optics: light-matter interaction at the few quanta level
- Optomechanics & many-body physics: dynamics of ions in optical potentials

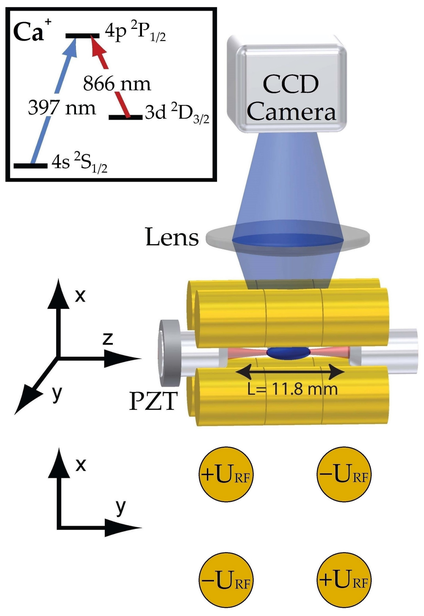
Laser cooled ions

- Can be trapped for hours
- Low temperature (~mK)

⇒Cold enough to form an ordered state, so-called **Ion Coulomb crystals**
→1D, 2D or 3D structures
→Excellent localization, easy to control
→No collisions, long coherence time



Experimental set-up



Calcium Ions Ca^+

- Produced by photo-ionization
- Inside ultra-high vacuum chamber (~10^{-10} mBar)

Linear Paul Trap

- Axial confinement through DC voltage applied on end cap electrodes
- Radial confinement through alternating RF voltage (~MHz) applied on opposite electrode rods

Laser Cooling

- Cooling optical transition at 397nm
- Repumping optical transition at 866nm

⇒Imaging ions by collecting scattered light at 397nm

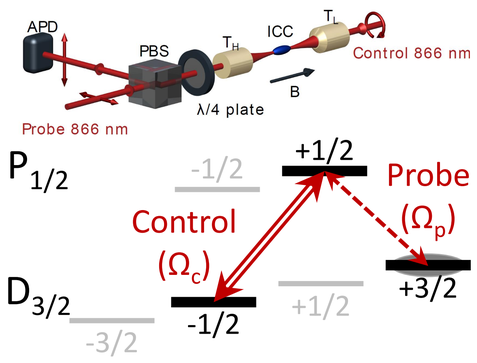
Linear Optical Cavity

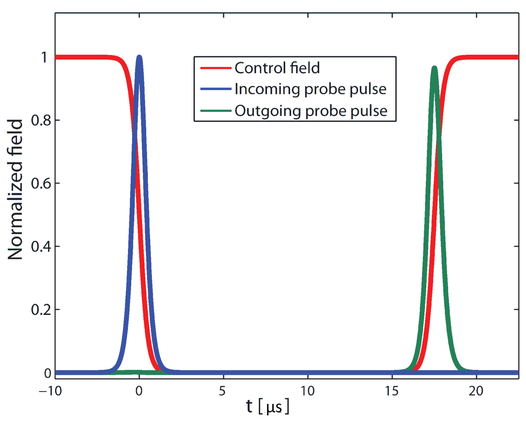
- High reflectivity mirrors
  →Enhance interaction between light and ion
  →Generate standing wave potential

Large crystals for a quantum memory for light

Large crystals

- Coulomb crystals with few 10s of thousand ions
- On-demand storage and retrieval of light pulses composed of a few photons in a collective excitation of the ensemble
- Goals: high efficiency for storage and retrieval, long storage times





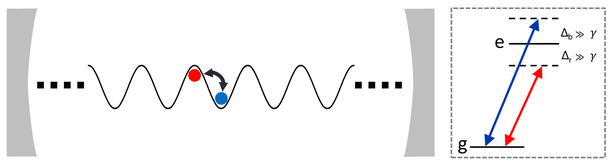
Principle: electromagnetically induced transparency (EIT)

- 2 optical fields in 3-level Λ-system
- Probe pulse stored in medium when Control turned OFF
- Probe pulse retrieved when Control turned ON
- Ion Coulomb crystal in cavity:
  - Demonstrated: 100% transparency of 1 Probe photon with 1000 Control photons
  - In progress/next: On-demand storage and retrieval

Pinning of ions by optical lattices

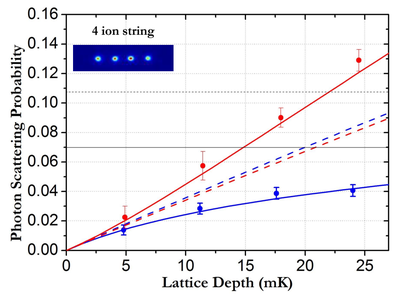
Principle

- Standing wave ⇒$I(z) \propto \sin^2(kz)$
- Ion ~ electric dipole $\vec{p} \propto \vec{E}$
- Inhomogeneous E-field
  ⇒ Force $\vec{F}(z) \propto \nabla|\vec{E}(z)|^2$
  ⇒ Potential $V(z) \propto \sin^2(kz)$



Red detuned: ion at an antinode
Blue detuned: ion at a node

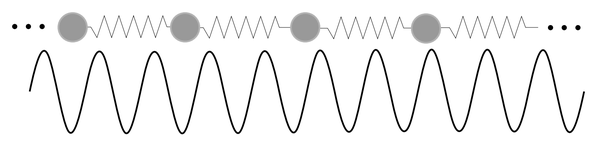
Some results



- Evidence of pinning:
  difference in scattering rate from symmetric blue and red-detuned lattice fields

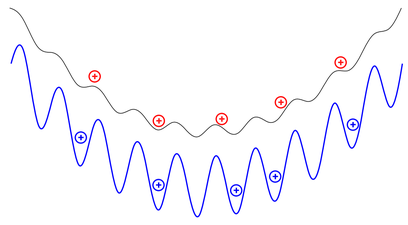
- Single ion pinned at the antinode of a 2nd resonant probe field
  ⇒ Light-ion coupling increased from 50 % to 80 %

Nano-friction: The Frenkel-Kontorova model



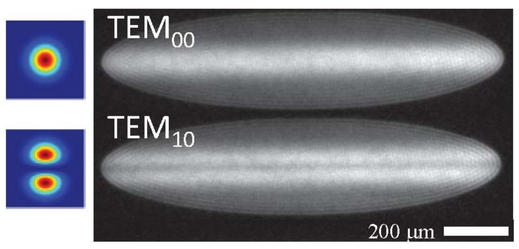
The Frenkel-Kontorova model of dry friction: An infinite chain of spring-connected masses in a sinusoidal potential. A similar model, the Frenkel-Kontorova model for trapped ions in an optical potential, can be simulated in an ion trap.

- Uses the Coulomb repulsion and ion trap confinement to generate effective springs
- Cavity field generates sinusoidal potential
  ⇒ Induces phase transition:
  Stick-slip friction at the nanoscale

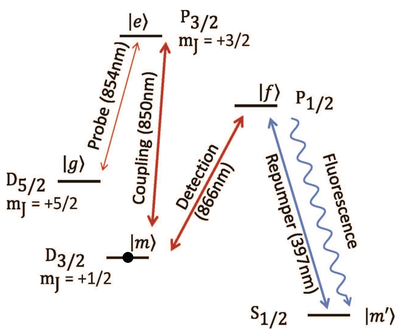


Outlook

- Multimode memory using spatial extension of crystals

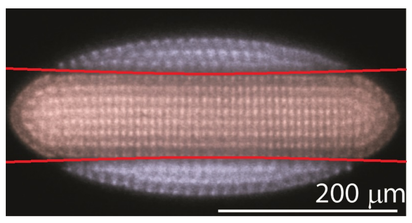


- Towards a few-photon counter by fluorescence cycles of the stored excitations



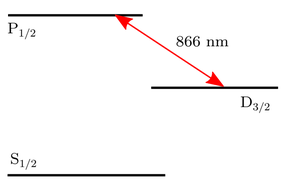
- Use 2-species bi-crystals (e.g. $^{40}Ca^+$ & $^{44}Ca^+$):
  - sympathetic cooling
  - optimize spatial modematching

- Localize ions at antinodes of the standing wave to increase light-ion coupling



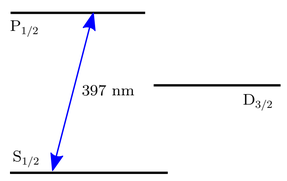
Linear Paul traps incorporating cavities in Aarhus

Red Cavity trap (2006-)



- Optical cavity coated for $D_{3/2}$ to $P_{1/2}$ transition of Ca^+ at 866 nm
- Can trap Ca^+ & Mg^+
- Quantum memory & photon counter

Blue Cavity trap (2015-)



- Optical cavity coated for $S_{1/2}$ to $P_{1/2}$ transition of Ca^+ at 397 nm
- Can trap Ca^+ & Ba^+
- Optomechanics & many-body simulation

Funding

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