Interaction of Laser Cooled Trapped Ions
with Optical Cavity Fields
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**Introduction**

**Interaction between trapped ions and trapped photons**

**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**

**Large crystals for a quantum memory for light**

- 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

**Pinning of ions by optical lattices**

**Principle**
- Standing wave \( \Rightarrow I(z) \propto \sin^2(kz) \)
- Ion \( \rightarrow \) electric dipole \( \propto \vec{E} \)
- Inhomogeneous E-field \( \Rightarrow \) Force \( F(z) \propto \nabla|\vec{E}(x)|^2 \)
- Potential \( V(z) \propto \sin^2(kz) \)

**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 \( \Rightarrow \) Light-ion coupling increased from 50% to 80%

**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. \(^{40}\text{Ca}^+ \& ^{44}\text{Ca}^+\)):
  - Sympathetic cooling
  - Optimize spatial modematching
- Localize ions at antinodes of the standing wave to increase light-ion coupling

**Nanofriction: 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
  \( \Rightarrow \) Induces phase transition: Stick-slip friction at the nanoscale

**Linear Paul traps incorporating cavities in Aarhus**

**Red Cavity trap (2006-)**
- Optical cavity coated for \( D_{3/2} \) to \( P_{1/2} \)
- Optical cavity coated for \( S_{1/2} \) to \( P_{1/2} \)
- Can trap \( \text{Ca}^+ \& \text{Mg}^+ \)
- Quantum memory & photon counter

**Blue Cavity trap (2015-)**
- Optical cavity coated for \( D_{3/2} \) to \( P_{1/2} \)
- Can trap \( \text{Ca}^+ \& \text{Ba}^+ \)
- Optomechanics & many-body simulation

**Funding**

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

**Calcium ions Ca\(^{+}\)**
- Produced by photo-ionization
- Inside ultra-high vacuum chamber (~10^-9 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 397 nm
- Repumping optical transition at 866 nm
  \( \Rightarrow \) Imaging ions by collecting scattered light at 397 nm

**Linear Optical Cavity**
- High reflectivity mirrors
  \( \Rightarrow \) Enhance interaction between light and ion
  \( \Rightarrow \) Generate standing wave potential

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