Cavity QED experiments with large Coulomb crystals
Why cavity QED with ion Coulomb crystals?

I) Quantum information:
   Stable and faithful light-matter interfaces for coupling of flying and stationary qubits

II) Cavity optomechanics:

III) Plasma physics:
   A tool to investigate the properties of strongly coupled one component plasmas (OCPs).
Outline:

I. Brief reminder of the properties of Coulomb crystals

II. Cavity Quantum ElectroDynamics in short

III. CQED experiments with single ions

IV. CQED experiments with larger Coulomb crystals

V. Applications:
   Quantum memories and photon counters
I. Brief reminder of the properties of Coulomb crystals
Brief introduction to ion Coulomb crystals

Laser cooling of trapped ions:

$\text{Ca}^+:$

$\begin{align*}
397 \text{ nm} & \quad -1/2 \quad +1/2 \quad P_{1/2} \\
866 \text{ nm} & \quad -3/2 \quad -1/2 \quad +1/2 \quad +3/2 \quad D_{3/2} \\
-1/2 & \quad +1/2 \quad S_{1/2}
\end{align*}$
Ion Coulomb crystals

Properties:

- Uniform density: $\sim 10^8 - 10^9$ ions/cm$^3$
- Melting point: $\sim 100$ mK
- Life times of: $\sim$hours @ $P \sim 10^{-10}$ mBar

Unique feature of these solids:

The internal state of individual ions are "unperturbed" by the presence of other ions as well as the trapping fields!

II. Cavity Quantum Electrodynamics in short
Cavity Quantum ElectroDynamics in short

Exploration of the coupling of a quantized cavity EM-field to electromagnetic transitions in a quantum system.

A few important parameters (2-level system)

**Strong coupling regime:**

$g > \gamma, \kappa$

Coupling rate of a single photon to the atomic system: $g$
Quantum system dipole decay rate: $\gamma$
Cavity field decay rate: $\kappa$
Pioneering CQED work

Microwaves:

Atoms

Haroche, ENS; Walther, MPQ

Optical range:

Atoms

Rempe, MPQ; Kimble, Caltech

Ions

Walther, MPQ; Blatt, Innsbruck

Qdots

Imamoglu, ETH
Yamamoto, Stanford

CPB’s

Schoelkopf, YALE;
Wallraff, ETH
Martinis, UCSB
Vion, Saclay

$$g = \mu_e g \cdot \epsilon \sqrt{\frac{\hbar \omega}{2e_0 V}}$$
Atomic interaction with a single photon

Hallmark of CQED!
III. CQED experiments with single ions
A single ion as a nanoscopic probe of an optical field

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† Communications Research Laboratory, 588-2 Iwaoka, Nishi-ku, Kobe 651-24, Japan
Modified spontaneous emission rate from a single atoms by a high finesse optical cavity

Purcell effect: \( \tau_D(Z) = \frac{\tau_{D,\text{free}}}{1 + 2C(Z)} \)

Cooperativity: \( C(Z) = g(z)^2 / 2\kappa\gamma \)

Ref: PRL 92 203002 (2004)
Quantum to classical transition in a single-ion laser

François Dubin\textsuperscript{1,2}, Carlos Russo\textsuperscript{1†}, Helena G. Barros\textsuperscript{1,3}, Andreas Stute\textsuperscript{1,3}, Christoph Becher\textsuperscript{1†}, Piet O. Schmidt\textsuperscript{1∗†} and Rainer Blatt\textsuperscript{1,3}

Tunable ion–photon entanglement in an optical cavity

A. Stute\textsuperscript{1}, B. Casabone\textsuperscript{1}, P. Schindler\textsuperscript{1}, T. Monz\textsuperscript{1}, P. O. Schmidt\textsuperscript{2,3}, B. Brandstätter\textsuperscript{1}, T. E. Northup\textsuperscript{1} & R. Blatt\textsuperscript{1,4}
Micro-cavity designs I (Sussex)
Single Ion Coupled to an Optical Fiber Cavity

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(Received 31 October 2012; published 25 January 2013)
IV. CQED experiments with larger Coulomb crystals
Why Coulomb crystals?

Interaction with a single photon

For multi-particle states:
\[
|g, 1\rangle \equiv |g_1, \ldots, g_{N_{\text{tot}}}, 1\rangle
\]

Ideally:
\[
|e, 0\rangle \equiv \frac{1}{\sqrt{N_{\text{tot}}}} \sum_{i=1}^{N_{\text{tot}}} |g_1, g_2, \ldots, e_i, \ldots, g_{N_{\text{tot}}}, 0\rangle
\]

Actually:
\[
|e, 0\rangle \equiv \sum_{i=1}^{N_{\text{tot}}} c_i |g_1, g_2, \ldots, e_i, \ldots, g_{N_{\text{tot}}}, 0\rangle, \quad \sum_{i=1}^{N_{\text{tot}}} |c_i|^2 = 1
\]

Effective number of ions:
\[
N \equiv \sum_{i=1}^{N_{\text{tot}}} \psi^2(\mathbf{r}_i)
\]

being the cavity mode function (TEM\textsubscript{00})
Why Coulomb crystals?

Collective coupling: $g_{\text{eff}} = gN^{1/2}$ => Collective strong coupling regime accessible ($g_{\text{eff}} > \kappa, \gamma$)

N can be varied “continuously” from 1 to ~ 2000

Good overlap between cavity mode and ions in Coulomb crystals

Micro-meter positioning control


The $^{40}\text{Ca}^+$ ion:

The $^{40}\text{Ca}^+$ ion:

$S_{1/2}$

$P_{1/2}$

$D_{3/2}$

397 nm

866 nm
Why Coulomb crystals?

Collective coupling: \( g_{\text{eff}} = gN^{1/2} \) => Collective strong coupling regime accessible \( (g_{\text{eff}} > \kappa, \gamma) \)

N can be varied “continuously” from 1 to ~ 2000

Good overlap between cavity mode and ions in Coulomb crystals
Micro-meter positioning control


The \(^{40}\text{Ca}^+\) ion:

397 nm

866 nm
The Cavity Trap Setup

The cavity:
- $L = 11 \text{ mm}$
- $w_0 = 37 \mu\text{m}$
- $R_1 \approx 99.85\%$
- $R_2 > 99.99\%$
- $F \sim 3200$
- $\kappa = 2\pi \times 2.1 \text{ MHz}$

The $^{40}\text{Ca}^+ \text{ ion:}$

- $\gamma = 2\pi \times 11.2 \text{ MHz}$
- $g = 2\pi \times 0.53 \text{ MHz}$

The trap:
- $2r = 5.2 \text{ mm}$
- $z_0 = 5.0 \text{ mm}$
- $z_E = 5.9 \text{ mm}$

The cavity-atom coupling:
- $g_{\text{eff}} = gN^{1/2} > \gamma, \kappa \Rightarrow N > \sim 430$

Coop. par.: $C = Ng^2/(2\kappa\gamma)$:
- $C \approx 0.006$ ($N = 1$) $\rightarrow C \approx 10$ ($N = 1500$)
**Experimental Sequence**

**Laser cooling:**

- **Ca\(^+\):**
  - \(S_{1/2}\)
  - \(-1/2\) \rightarrow \(+1/2\)
  - \(-3/2\) \rightarrow \(+1/2\)
  - \(-1/2\) \rightarrow \(+3/2\)
  - \(+3/2\) \rightarrow \(-1/2\)

- \(P_{1/2}\)
  - \(-1/2\) \rightarrow \(+1/2\)

- \(D_{3/2}\)
  - \(-1/2\) \rightarrow \(+3/2\)

- **Laser lines:**
  - 397 nm
  - 866 nm
Experimental Sequence

Optical pumping:

Ca$^+$:

-1/2 +1/2 P_{1/2} +3/2 D_{3/2}

~97% population

397 nm

866 nm
Experimental Sequence

Cavity probing:

$\text{Ca}^+$:

-1/2  +1/2  $P_{1/2}$

-3/2  -1/2  +1/2  +3/2  $D_{3/2}$

-1/2  +1/2  $S_{1/2}$

Single photon detector (866 nm)

866 nm
Observation of single photon Rabi splitting

\[ \nu_{\text{cav}} = \nu_{\text{atom}} : \]

**Reflection signal**

**Probe detuning (MHz)**

First exp.:


Nature Physics 5, 494 (2009)
Detailed information on the coupling to TEM modes

Cavity TEM mode waist: \( w_0 = 37 \mu m \)

Detailed information on the coupling to TEM modes

\( \text{TEM}_{00}(x) \)
\( \text{TEM}_{00}(y) \)

\( \text{TEM}_{10}(y) \)

\( \text{TEM}_{10}(x) \)


Electromagnetically Induced Transparency (EIT)

2-level atoms

3-level atoms

Absorption

Dispersion
EIT in a cavity

2-level atoms in cavity

3-level atoms in cavity
Observation of triplet structure in reflection

\[
\begin{align*}
\text{Ca}^+: & \quad -\frac{1}{2} \quad +\frac{1}{2} \quad \text{P}_{\frac{1}{2}} \\
\Omega_c (\sigma^+) & \quad \Omega_p (\sigma^-) \\
-\frac{3}{2} & \quad -\frac{1}{2} \quad +\frac{1}{2} \quad +\frac{3}{2} \quad \text{D}_{\frac{3}{2}} \\
-\frac{1}{2} & \quad +\frac{1}{2} \quad \text{S}_{\frac{1}{2}} \\
\end{align*}
\]
EIT feature vs. coupling laser power

Non-Lorenzian line shapes due to Gaussian mode profile
> 90 % transparency for $\Delta \nu_{\text{HWHM}} \sim 100 \text{ kHz}$

$\gamma_c \sim 1 \text{ kHz}$

Nature Photonics, 5, 633 (2011)
Cross Kerr effect and photon blockade

Schmidt and Imamoğlu, opt. Lett. 21, 1936 (1996);

\[ \text{Ca}^+: \]

\[
\begin{array}{cccc}
-3/2 & -1/2 & +1/2 & +3/2 \\
\hline
\Omega_b (\sigma^+) & & & \\
\hline
-1/2 & +1/2 & P_{3/2} & \\
\hline
\Omega_c (\sigma^+) & & & \\
\hline
-3/2 & -1/2 & +1/2 & +3/2 \\
\hline
\Omega_p (\sigma^-) & & & \\
\hline
-1/2 & +1/2 & S_{1/2} & \\
\hline
\end{array}
\]

If the light shift due to \( \Omega_b \) is larger than the EIT width then EIT ceases \( \Rightarrow \) Photon blockade!

At the single photon level this would enable

I) Single photon transistor

Very challenging!!

[Diagram of energy levels and light shift interactions]
Sketch of experimental setup

\[
\text{Ca}^+:
\]

\[
\begin{array}{cccccc}
-3/2 & -1/2 & +1/2 & +3/2 \\
\hline
\Omega_b (\sigma^+) & & & & P_{3/2} \\
-1/2 & +1/2 & & & \\
\Omega_c (\sigma^+) & & & & P_{1/2} \\
-3/2 & -1/2 & +1/2 & +3/2 \\
\hline
-1/2 & +1/2 & & & D_{3/2} \\
\end{array}
\]

\[\Delta = 4.3 \text{ GHz}\]
Probe reflectivity

Probe detuning (kHz)

-3/2  -1/2  +1/2  +3/2  P_{3/2}

-1/2  +1/2  P_{1/2}

-3/2  -1/2  +1/2  +3/2  D_{3/2}

Ω_p (σ⁻)
\[ \Omega_c (\sigma^+) \quad \Omega_p (\sigma^-) \]

Probe reflectivity vs. Probe detuning (kHz)

-3/2  -1/2  +1/2  +3/2  \( P_{3/2} \)

-1/2  +1/2  \( P_{1/2} \)

\[ \Omega_c (\sigma^+) \quad \Omega_p (\sigma^-) \]

-3/2  -1/2  +1/2  +3/2  \( D_{3/2} \)

Probe +Control
Probe reflectivity vs. Probe detuning (kHz)

- $\Omega_b (\sigma^+)$
- $\Omega_c (\sigma^+)$
- $\Omega_p (\sigma^-)$

Levels:
- $-3/2$
- $-1/2$
- $+1/2$
- $+3/2$

Pulse Levels:
- $P_{3/2}$
- $P_{1/2}$

25 $\mu$W
Probe reflectivity vs. probe detuning (kHz) for different laser powers:
- 25 µW
- 50 µW
- 100 µW

The graph shows the probe reflectivity behavior at various detunings for these laser powers.
Probe reflectivity vs. Probe detuning (kHz) for different power levels: 25 µW, 50 µW, 100 µW, and 200 µW. The +Control line shows the behavior of the probe with control.
Photon blockade vs. blockade laser power

Corresponds to ~25,000 blockade photons in cavity at a detuning of 4.3 GHz.

The same shift obtainable for a few photons tuned close to resonance!

Nature Photonics, 5, 633 (2011)
Very recent results with neutral atoms

All-Optical Switch and Transistor Gated by One Stored Photon

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The realization of an all-optical transistor where one ‘gate’ photon controls a ‘source’ light beam, is a long-standing goal in optics. By stopping a light pulse in an atomic ensemble contained inside an optical resonator, we realize a device in which one stored gate photon controls the resonator transmission of subsequently applied source photons. A weak gate pulse induces bimodal transmission distribution, corresponding to zero and one gate photons. One stored gate photon produces fivefold source attenuation, and can be retrieved from the atomic ensemble after switching more than one source photon. Without retrieval, one stored gate photon can switch several hundred source photons. With improved storage and retrieval efficiency, our work may enable various new applications, including photonic quantum gates, and deterministic multiphoton entanglement.
V. Applications:

Quantum memories and photon counters
Quantum memories

Idea behind the quantum memory

Entanglement of Atomic Ensembles by Trapping Correlated Photon States

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(Received 8 December 1999)

(a)

\( \Phi_{\text{in}} \rightarrow \Phi_{\text{out}} \)

\( \Phi_{\text{out}} \rightarrow \Phi_{\text{in}} \)

Adiabaticity requirement:

\[ g_{eff}^2 = g^2 N \gg \kappa \gamma \]
Quantum memories

Large crystals:

Improve coupling strengths of ions to a cavity photon

Figure of merrit (the cooperativity):

\[ C = \frac{Ng^2}{2\kappa\gamma} \]

single photon - single ion coupling strength

Storage fidelity:

\[ F = \frac{C}{1+C} \]

Nature Physics 5, 494 (2009)
Storage fidelity vs. radial extension of crystal

Efficiency

Photon Counters

Original idea:

V) Photon Counters

Our scheme:

V) Photon Counters

Our scheme:

Collection time: 150 µs

THE END !