Rydberg excited Calcium Ions for quantum interactions

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The R-ION Consortium

Experiment

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Trapped ions

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Laser system

Theory

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http://www.chistera.eu/projects/r-ion

3rd R-ION Meeting
Innsbruck, Oct 2012
Funding period

August 2011 - today - July 2014

Requested funds

- six postdoc years for theory
- six postdoc years for experiment
- 200 kEUR for consumables
- 70 kEUR travel and subsistence

General aim (Research programme with 3 WPs)

- explore and understand fundamental properties of a new platform for quantum information processing and for quantum simulations
Outline

1. Background - Rydberg states and trapped ions
2. Aim of the project and challenges
3. Experimental developments
   • Laser system
   • Ion trap setup
4. Theoretical progress
   • Many body effects in Rydberg ion laser excitation
   • Rydberg mode shaping and parallel quantum gates
   • Many-body spin systems
5. Summary, Problems and Outlook
Atoms in Rydberg states

- hydrogen-like atoms
- simple level structure
- long lifetime $\tau / n^{3-5}$ ($\tau \approx 100 \mu s$)
- large displacement between charges

Rydberg atoms interact strongly and over large distances, e.g. via permanent or induced dipole interaction (interaction strengths of several MHz achievable).
Dipole blockade

Two atoms

D. Jaksch et al., PRL 85, 2208 (2000)
M. Lukin et al., PRL 87, 037901 (2001)

Rydberg state

ground state


distance energy

Rydberg-Rydberg interaction

radius

» 10 µm

Rydberg state

ground state
Interacting Rydberg Atoms

Two blockaded atoms

\[ R < R_b \]

\[ \left| \begin{array}{c} \text{atom 1} \\ \text{atom 2} \end{array} \right| \]

Rabi oscillations

\[ \sqrt{2\Omega} \]

\[ \left| \begin{array}{c} \text{atom 1} \\ \text{atom 2} \end{array} \right| + \left| \begin{array}{c} \text{atom 1} \\ \text{atom 2} \end{array} \right| \]

Entangled state is created „for free“

Urban et al., Nat. Phys. 5, 115 (2009)

Atomic ensembles

\[ \sqrt{N\Omega} \]

\[ \left| \begin{array}{c} \text{atom 1} \\ \text{atom 2} \end{array} \right| + \left| \begin{array}{c} \text{atom 1} \\ \text{atom 2} \end{array} \right| + \left| \begin{array}{c} \text{atom 1} \\ \text{atom 2} \end{array} \right| \]

Dudin et al., Nature Physics 8, 790 (2012)
Trapped ions

- robust trapping
- storage and manipulation quantum information
- single and two-qubit gates with fidelity > 99% possible
- unity state detection efficiency

Applications
- ultra precise clocks
- precision measurements
- quantum computer
- quantum simulator

Problems
- scalability is a problem
- not because the lack of large ion crystals
- because interactions rely on structure of vibrational modes
  (vibrational mode structure becomes too complex for large crystals)
Aim of this project

Join advantages of **trapped ions**

- trapped, localized qubits
- near unity detection efficiency
- quantum gate operations with >99% fidelity
- reliable state tomography

with **Rydberg excitations and interactions**

- Rydberg blockade mechanism
- long range interactions
- fast gate operation
- **independent** of vibrational modes

... a new approach towards a robust scalable quantum computer
The Challenges

**Experimental challenges**

- need **coherent laser source** with 122 nm wave length (vacuum ultra violet VUV)
- need to combine this with ion trap

**Theoretical challenges**

- need to understand the physics of ionic Rydberg states in a trap
- need to identify physical protocols for the implementation of QIP and many-body spin models
Energy of Rydberg states (n=10-100) determines VUV wavelength.

$^{40}\text{Ca}^+$

Ryd.

$P_{3/2}$

$P_{1/2}$

$D_{5/2}$

$D_{3/2}$

122-131 nm

Rydberg spectrum

$n+1$

$n$

$n-1$

$nP$

$D_{5/2}$
Generation of VUV radiation

- original purpose of laser system: (anti-)hydrogen spectroscopy
- first time that laser is not „experiment“ but tool
Achievements (WP2, WP3)

Frequency stabilisation

all infrared Lasers actively stabilized to < 100 kHz

Optimization of output power

Rydberg excitation wavelength

~1 µW @ 122 nm

ionization wavelength

6 µW @ 121.26 nm

- MgF$_2$ – lens separates laser vacuum and ion trap vacuum
- flexible connection between laser vacuum and ion trap (laser focus can hardly be moved, need to move trap)


**Achievements (WP2, WP3)**

**Linear Paul trap in place**
- trap frequencies
  \[ \omega_{\text{rad}} \approx 2\pi \times 1 \text{ MHz}, \]
  \[ \omega_{\text{ax}} \approx 2\pi \times 120 \text{ kHz} \]
- 1D and 2D ion crystals

**Spectroscopy of low-lying levels**
- axial side bands

![Graph showing trap frequencies](image)

**First observations of Ca\(^+\) - VUV interaction**
- 3 Ca\(^+\)
- 2 Ca\(^+\) + 1 Ca\(^{2+}\)

![Image of spectroscopy results](image)

**Ionisation rate**
\[ \sim 1/\text{min} @ 0.5 \mu\text{W} \]
Achievements (WP2, WP3)

Mixed Ca\(^+\) - Ca\(^{2+}\) ion crystals

Experiment: changing ratio \(\omega_{\text{rad}} / \omega_{\text{ax}}\)

\[
\frac{\omega_{\text{rad}}}{2\pi} = \begin{align*}
212\text{kHz} & \quad 187\text{kHz} & \quad 175\text{kHz} \\
3 \times \text{Ca}^+ & \quad & 
\end{align*}
\]

- direct link to theoretical proposal made within R-ION consortium
Many-body effects in laser excitation

Consider crystal of three ions

- transition takes place at critical gradient
  \[ \beta_0 = \frac{5}{29} \frac{\alpha^2}{M\Omega^2} \]

- Rydberg atom experiences additional confinement

\[ P(n) \ldots \text{polarizability, } n \ldots \text{principal quantum number} \]

\( \rightarrow \) n-dependent critical gradient \( \beta_c(n) \)
- equilibrium configuration of the crystal depends on field gradient and on whether a Rydberg state is excited or not.

Critical gradient for Rydberg ion.

Critical gradient for ground state ion.
- even the excitation of a single ion to a Rydberg state is a many-body phenomenon as the entire crystal has to rearrange

- consequence for laser excitation visible in the Franck-Condon factors

- mechanism allows to exert large forces on trapped ions

Weibin Li and Igor Lesanovsky, PRL 108, 023003 (2012)
Vibrational mode shaping (WP4)

- Rydberg excitation of few ions within long ion chain (100 ions)

Transverse vibrational modes (entries of normal mode matrix)

- Rydberg ions chop long crystal into sub-crystals (F [W. Li, R. Nath, A. Glätzle and I. Lesanovsky, arXiv:1208.2863 (2012)])
Parallelization of quantum gates (WP4)

- Rydberg ion
- Ion in electronically low lying state

- Quantum gates can be executed in parallel on the sub-crystals with high fidelity
Summary

Experiment
- combined laser and trap setup exists
- evolution to second generation (optimized laser and trap)
- first evidence of VUV-laser ion interaction
- first experiments geared towards R-ION theory proposal

Theory
- even Rydberg excitation of a single ion in a crystal is non-trivial
- Rydberg ions can dynamically split large ion crystals
- dynamical mode shaping permits parallel execution of gates
Problems

Experiment

- experiments are difficult (laser itself is an experiment)
- two experiments = at least twice the number of problems
- 6 months down-time due to broken laser source

Theory

- for the moment only blue sky physics
- needs experimental input since there is a number of lose ends (incomplete spectral data, Rydberg ion modelling sufficient?)

Big problem!

- UK is not in Schengen zone + Border Agency is acting unreasonably
- severely hinders exchange of scientist
  (R-ION employs indian and chinese researchers)
Outlook

**Experiment**
- increase laser-power for coherent excitation wavelength
- investigate many-body effects in ionisation
- demonstrate coherent excitation of ionic Rydberg states
- implement quantum gate protocol(s)

**Theory**
- calculate long-range interactions among ions
- devise and characterize quantum gate based on long-range interactions
- engineer and investigate many-body quantum systems
Spin ice in two dimensional ion crystal

Classical spin ice

\[ H_0 = J_z (\sigma_z^1 + \sigma_z^2 + \sigma_z^3 + \sigma_z^4)^2 \]

Quantum fluctuations

\[ H_1 = \sum_{i<j} J_{\perp} (\sigma_+^i \sigma_-^j + \sigma_-^i \sigma_+^j) \]

Realization with Rydberg atoms/ions

- challenge: all ions on a plaquette must interact equally
- exploiting long-range interactions, MW tuning and magic angles