Single Electron Trapping in an Ion Crystal

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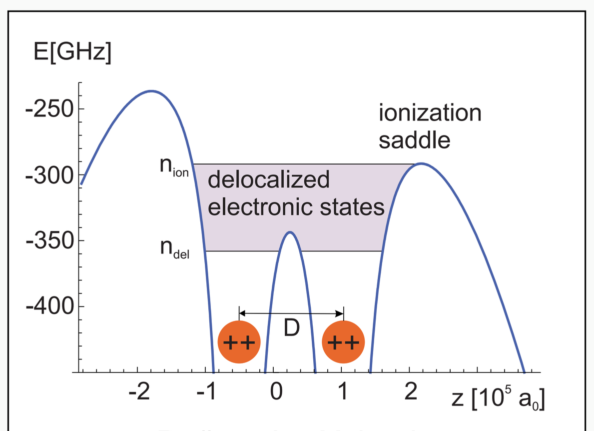
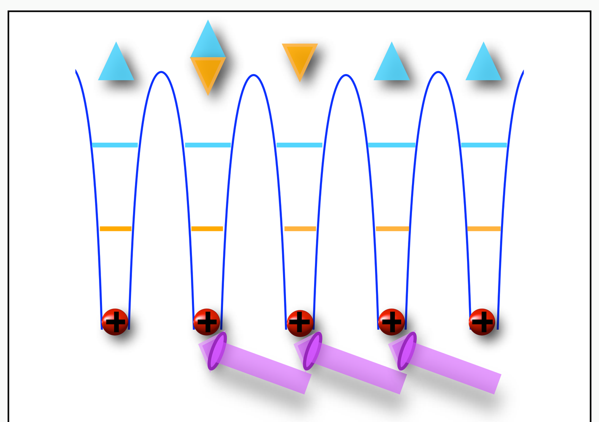
Introduction

- When ions are excited to a Rydberg state in ion traps, weakly bound electrons render the system exotic properties, such as binding repulsive interacting ions into giant ionic molecules and achieving spin models as well as quantum gates in one dimensional Rydberg ions.
- Traditionally, ion traps are used to confine single ions or crystals of ions of the same charge. Simultaneous trapping of ions and electrons seems not possible at first glance because either Paul trap or Penning trap confine only particles of a certain charge while the oppositely charged ones are repelled from the trap.
- We demonstrate that a single electron can be trapped in the centre of a small-number ion crystal in a linear Paul trap.
- The successful trapping of the electron can be monitored by changes of ion's equilibrium position and oscillating frequency.



Rydberg Ion Molecule
Lesanovsky, Mueller & Zoller, PRA **79**, 010701(R)(2009)



Rydberg Ion Chain
Mueller, Liang, Lesanovsky & Zoller, NJP **10**, 093009(2008)

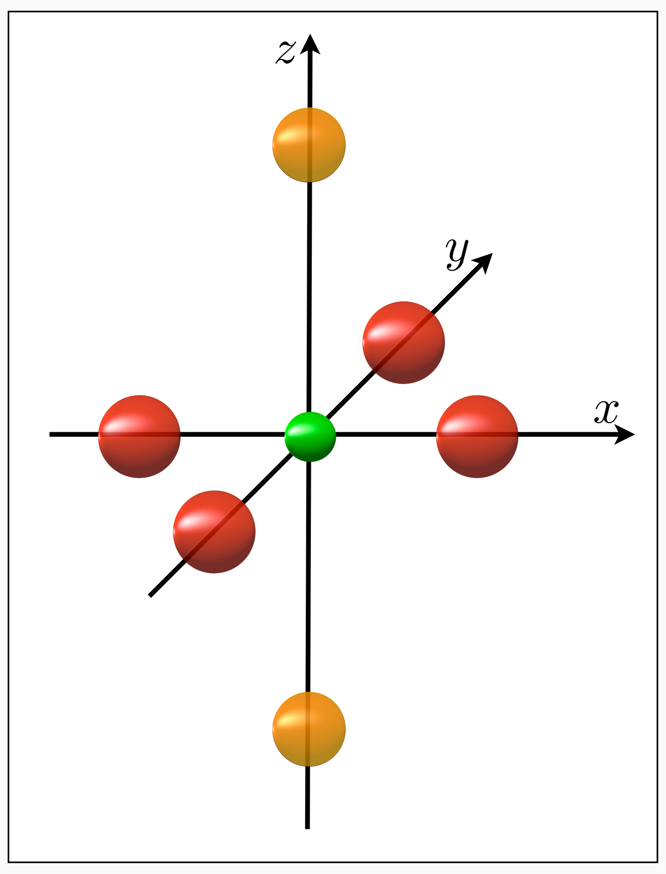
Electron-ion crystal

- The electric potential of a radio-frequency (Paul) trap is

$$\Phi(\mathbf{r},t)=\alpha\cos\Omega t(x^2-y^2)-\beta(x^2+y^2+z^2)$$

where Ω is the driving frequency of RF field, and electric gradient α and β is determined by the trap.

- Particles with same charges can be trapped while inverse charged particles are repelled from the trap.
- Six Ions are trapped in a linear Paul trap, where four doubly charged ions are confined in x-y plane and two singly charged ions are sitting symmetrically on z-axis. A static magnetic field B_z is applied in z-direction in order to confine the electron in x-y direction. Assuming one electron is located in the vicinity of trap center, ions' potential is



$$V_{IE} = \sum_{i=1}^{6} Q_i[\frac{a}{2}(x_i^2+y_i^2)+\frac{b}{2}z_i^2] + \sum_{i=1}^{6}\sum_{j>i}\frac{Q_iQ_j}{|R_i-R_j|}-\sum_{i=1}^{6}\frac{Q_i}{|R_i|}$$

where Q_i, and R_i are charges and positions of ions and

$$a=\frac{4\pi\varepsilon}{e^2}\left(\frac{2e^2\alpha^2}{M\Omega^2}+\frac{e^2B_z^2}{4M}-2e\beta\right)$$

$$b=\frac{4\pi\varepsilon}{e^2}\times 4e\beta$$

Ions' Equilibrium

- At equilibrium, ion's coordinates can be found

$$(x_0,0,0)\ (0,x_0,0)\ (-x_0,0,0)\ (0,-x_0,0)\ (0,0,z_1)\ (0,0,-z_1)$$

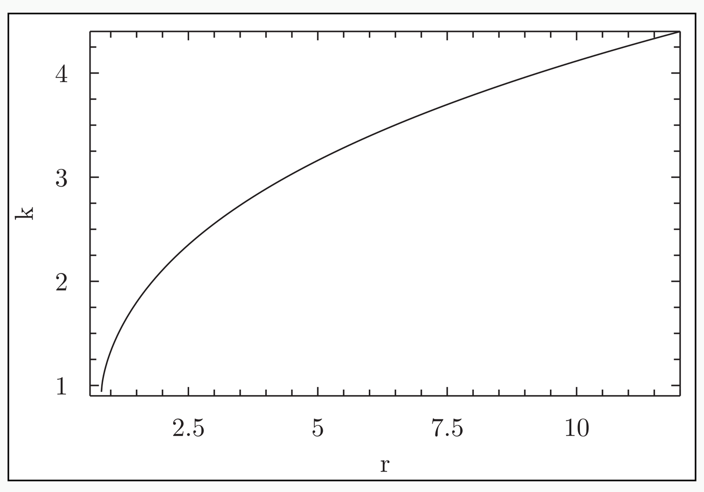
- Let $z_1=kx_0$, equilibrium positions of ions are found by solving

$$\frac{\partial V_{IE}}{\partial R_i}=0 \text{ and } \frac{\partial^2 V_{IE}}{\partial R_i^2}>0$$

Solve k as a function of $r=a/b$.

- Stationary point is

$$x_s=\left[\frac{4\sqrt{2}-2}{4a}+\frac{2}{a(1+k^2)^{3/2}}\right]^{1/3}$$

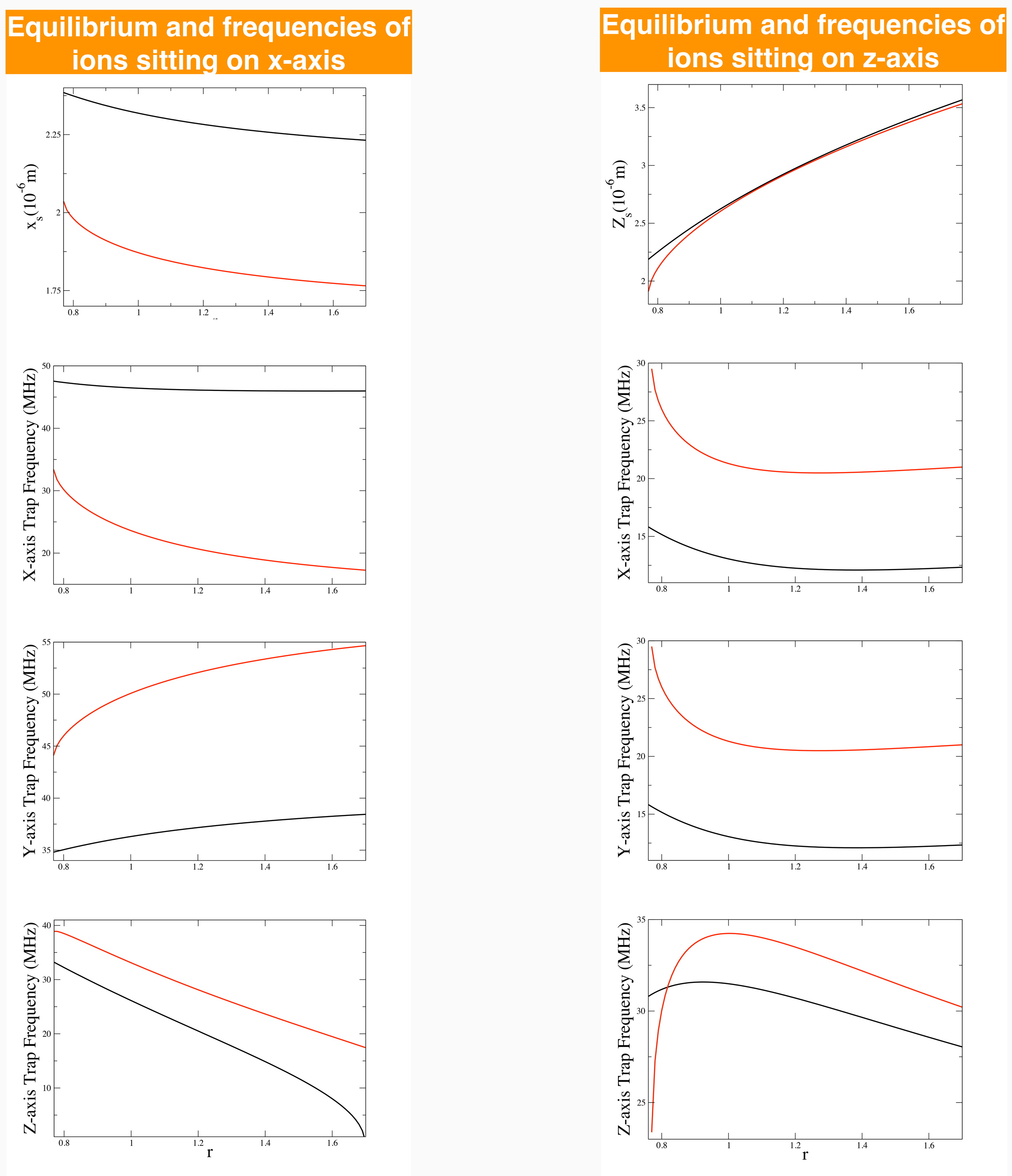


Ion's local trapping frequency

- Expand ion's potential as Taylor series to second order, local potential for ions in the vicinity of equilibrium is

$$U_0\approx U_{c0}+\frac{M\omega_x^2}{2}(x-x_s)^2+\frac{M\omega_y^2}{2}(y-y_s)^2+\frac{M\omega_z^2}{2}(z-z_s)^2$$

- Considering Ca^+, for $\Omega=2\pi\times 20\mathrm{MHz}$, $a=2\times 10^{17}/m^3$ and $B_z=1\mathrm{T}$



Electron trapping

- Electron's potential near trap center, in a good approximation, is

$$V_e\approx\frac{m\omega_\rho^2}{2}\rho^2+\frac{m\omega_z^2}{2}z^2+\omega\hat{L}_z-e\alpha\cos\Omega t(x^2-y^2)$$

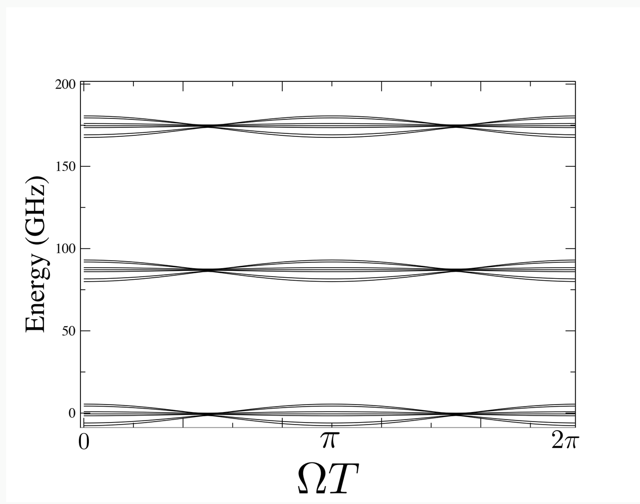
with

$$\omega_\rho^2=\frac{2}{m}\left[\frac{(eB_z)^2}{8m}+e\beta+\frac{e^2}{4\pi\varepsilon}\frac{1-2k^3}{k^3x_s^3}\right]\quad \omega_z^2=\frac{2}{m}\left[\frac{e^2}{4\pi\varepsilon}\frac{4k^3-2}{k^3x_s^3}-2e\beta\right]\quad \omega=\frac{eB_z}{2m}$$

the above frequency are in GHz region while RF field is in 100MHz, indicating that we can solve the time-dependent part adiabatically. The time-independent Hamiltonian can be solved exactly and time-dependent part could be solved perturbatively.

$\Omega=2\pi\times 20\mathrm{MHz}$ $\quad B_z=1\mathrm{T}$

$\beta=9\times 10^6\mathrm{V/m^2}$ $\quad \alpha=1.0\times 10^9\mathrm{V/m^2}$



Outlook

- Electron dynamics has to be studied consistently. When energy splittings close to driving frequency, perturbation becomes invalid, especially near degeneracy.
- Ion is assumed always in its equilibrium. However, the coupling among RF field and electron may cause instability, which can be investigated via, e.g. molecular dynamics.
- Electron trapping will be studied in the future. During this process, both frequency and equilibrium position of ions change dramatically, which migh bring interesting dynamics.