Quantum simulator using Rydberg atoms in optical tweezers

Seminar 2

Katja Gosar
Advisor: dr. Peter Jeglič

April 14th 2021

Introduction

- Quantum technologies: communication, computation, simulation, sensing and metrology
- What is quantum simulation?

$$\text{synthetic quantum system} \Longleftrightarrow \text{real-world system}$$

- Why use cold atoms for quantum simulation?
  - $\rightarrow$ controllability
  - $\rightarrow$ scalability

Introduction

1. Atoms in optical tweezers
   - Dipole traps
   - Optical tweezers
   - Preparation of defect-free atom arrays
2. Rydberg atoms
   - Rydberg state excitation and Rabi oscillations
   - Dipole-dipole interaction and Rydberg blockade
3. Quantum simulator
   - Experiment and the Hamiltonian
   - Phase diagram and phase transitions

Dipole traps

Energy of an induced dipole moment in an oscillating electric field with frequency ω

$$U_{\text{dip}} = -\frac{1}{2}\langle \mathbf{pE} \rangle = -\frac{1}{2\epsilon_0 c}\text{Re}(\alpha) I$$

$\alpha(\omega)$ ... polarizability $\rightarrow$ Lorentz's model with resonance frequency ω_0, damping Γ

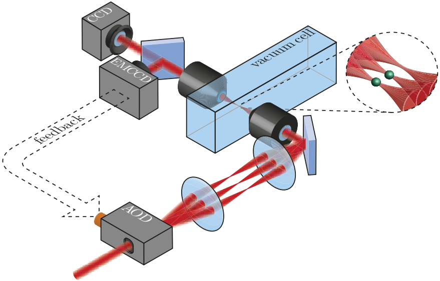
$$U_{\text{dip}}(\mathbf{r}) = \frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta} I(\mathbf{r})$$

$\Delta = \omega - \omega_0$

- $\Delta < 0$ red detuning, attractive
- $\Delta > 0$ blue detuning, repulsive

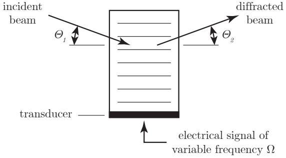
Optical tweezers

individually controlled position and intensity of dipole traps



Endres et al. (2016)

acousto-optic deflector (AOD)

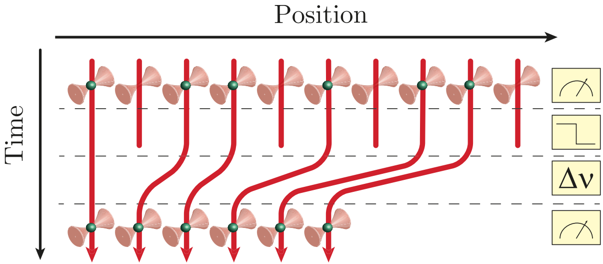


multitone driving → multiple deflected beams

high NA → tight focus → collisional blockade effect → at most one atom per trap

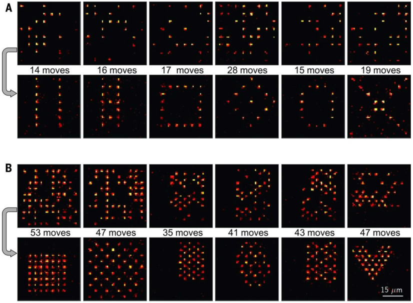
Preparation of defect-free atom arrays

1. loading from MOT (magneto-optical trap) to optical tweezers
2. fluorescence imaging to identify filled traps
3. rearrangement of traps (frequency sweep)

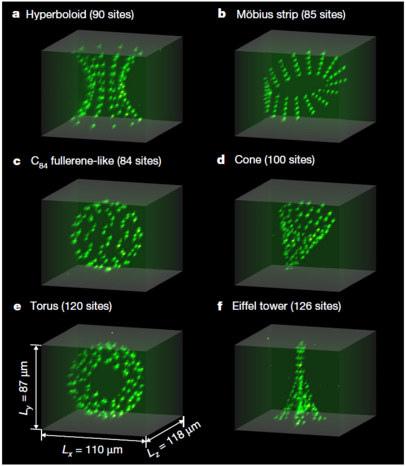


Endres et al. (2016)

Preparation of defect-free atom arrays



Barredo et al. (2016)

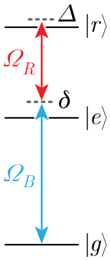


Barredo et al. (2018)

Properties of Rydberg atoms

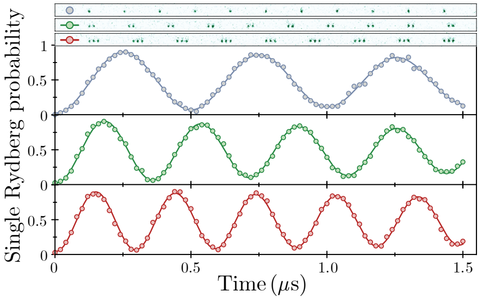
- highly excited valence electron - high principal quantum number n
- small binding energy
- long radiative lifetime
- large polarizibility
- strong dipole-dipole interactions $\rightarrow$ Rydberg blockade

Rydberg state excitation and Rabi oscillations



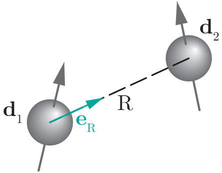
→ effectively a two-level system with Rabi frequency Ω and detuning Δ

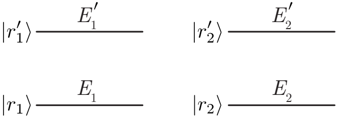
$$\Omega_N = \sqrt{N}\Omega$$



Bernien et al. (2017)

Dipole-dipole interactions



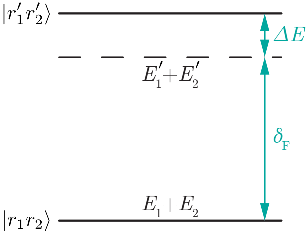


$$V_{dd} = \frac{e^2}{4\pi\epsilon_0}\frac{\mathbf{d}_1\cdot\mathbf{d}_2 - 3(\mathbf{d}_1\cdot\mathbf{e}_R)(\mathbf{d}_2\cdot\mathbf{e}_R)}{R^3}$$

$\delta_F \gg V(R)$:

$$\Delta E \approx C_6/R^6$$

Van der Waals interaction

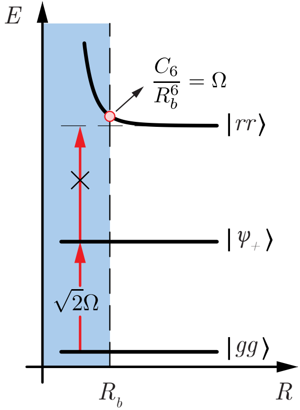


Rydberg blockade

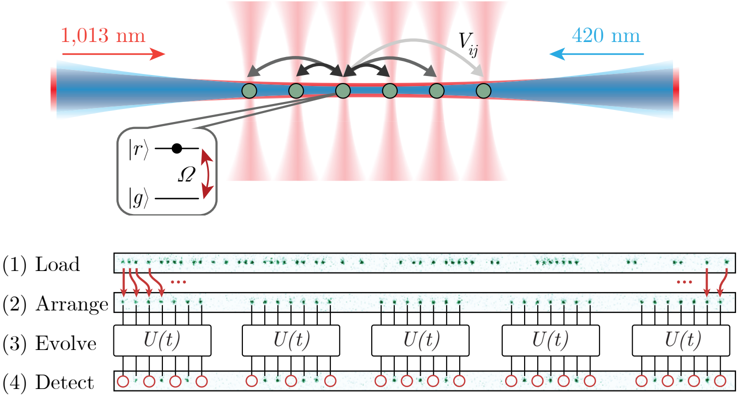
$$\Delta E \approx C_6/R^6$$

Van der Waals interaction

$\rightarrow$ max. one excited atom within Rydberg radius R_b



Quantum simulation experiment



Bernien et al. (2017)

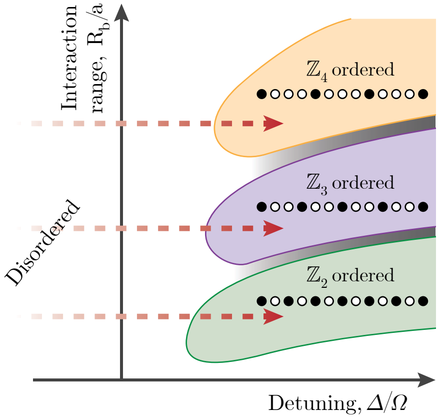
Hamiltonian

$$H = \frac{1}{2}\hbar\Omega \sum_i \sigma_x^i - \hbar\Delta \sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

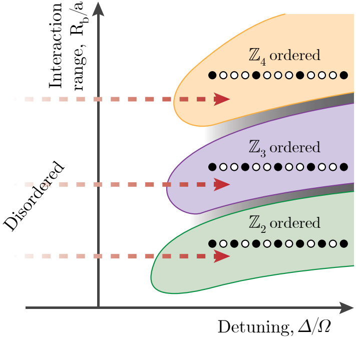
- Ω ... Rabi frequency (intensity of the beams)
  $\sigma_x^i = |g_i\rangle\langle r_i| + |r_i\rangle\langle g_i|$
- Δ ... detuning
  $n_i = |r_i\rangle\langle r_i|$
- V_{ij} ... interaction (Rydberg blockade)

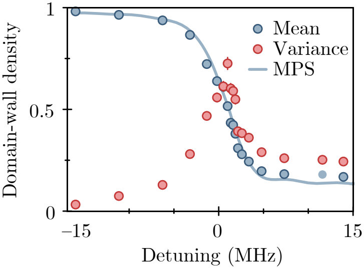
Phase diagram

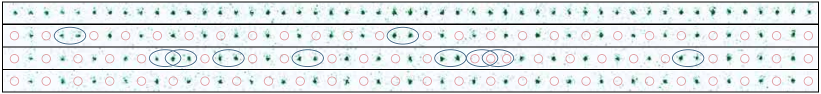
$$H = \frac{1}{2}\hbar\Omega \sum_i \sigma_x^i - \hbar\Delta \sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$



Phase transition







Bernien et al. (2017)

Conclusions

$$\left.\begin{array}{l}\text{optical tweezers} \rightarrow \text{atom positions} \\ \text{Rydberg states} \rightarrow \text{interactions}\end{array}\right\} \text{quantum simulator}$$

Applications:

- quantum spin systems (Ising model, XY model)
- non-equilibrium dynamics
- topological states
- optimization algorithms
- quantum computing