北京量子信息科学研究院
Beijing Academy of Quantum Information Sciences

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Quantum Computing with Rydberg Atoms

Chen Huang

Quantum Operating System Group, BAQIS
Department of Physics, Imperial College London

Outline

What are the Rydberg atoms?

Rydberg atoms are atoms with one or more electrons in highly excited state (very high principal quantum number n).

Properties

- Dipole-dipole interactions scale as $r^2 = (a_0 n^2)^2 \sim n^4$.
- Radiative lifetimes for alkalis scale as n^3.

Two-body interactions

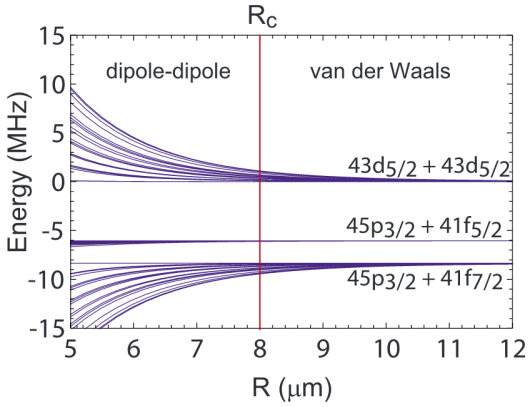
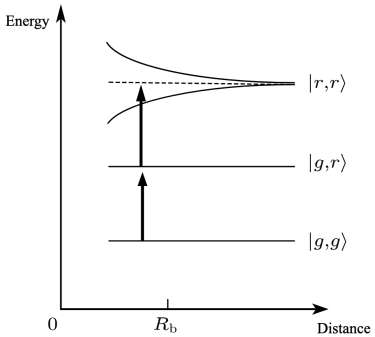


Figure 1: Interaction potentials for $43d_{5/2} + 43d_{5/2}$ Rb Rydberg atoms. The cutoff radius R_c represents the distance scale for the transition from resonant dipole-dipole to van der Waals behavior.

Dipole-dipole interaction

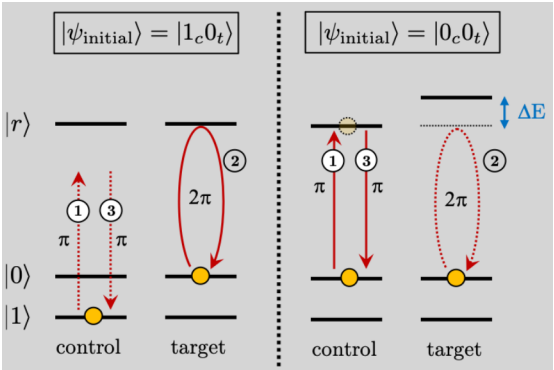
$$V_{\text{dd}} = \frac{1}{4\pi\varepsilon_0 R^3}\left(\vec{p}_1 \cdot \vec{p}_2 - 3(\vec{p}_1 \cdot \hat{R})(\vec{p}_2 \cdot \hat{R})\right) \propto \frac{1}{R^3}$$



Rydberg blockade

When one atom in a pair is excited to a Rydberg state, the strong dipole-dipole interaction shifts the energy levels of nearby atoms, **preventing** them from being excited to the same state. This ensures that only one atom can be in the Rydberg state at a time within a certain volume.

Controlled-Z gate

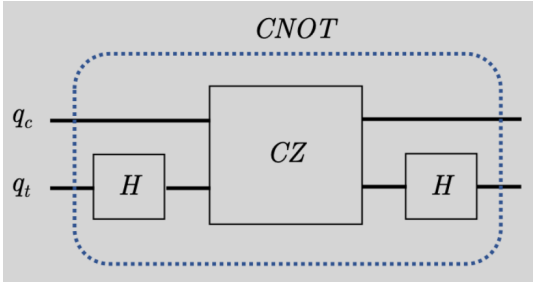


- $|00\rangle \rightarrow -|00\rangle$
- $|01\rangle \rightarrow -|01\rangle$
- $|10\rangle \rightarrow -|10\rangle$
- $|11\rangle \rightarrow |11\rangle$

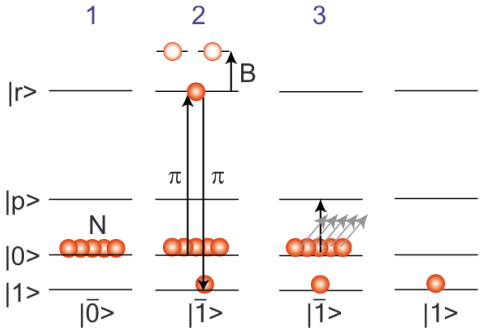
$$U = \mathrm{e}^{i\pi} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- Basis states $|0\rangle$, $|1\rangle$ and Rydberg level $|r\rangle$.
- $|0\rangle$ is coupled to $|r\rangle$ with excitation Rabi frequency Ω.

CNOT gate



Preparation of single-atom states[1]



[1] Saffman and Walker (2002)

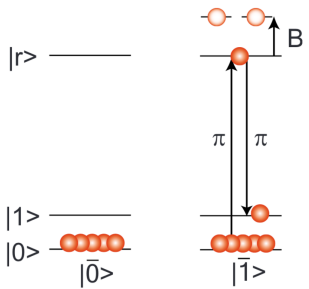
Rydberg coupled ensembles[2]

Extend: 2 atoms $\rightarrow$ N atoms

- Logical 0: $\left|\bar{0}\right\rangle = \prod_{i=1}^{N} \left|0_i\right\rangle$.
- Logical 1: $\left|\bar{1}\right\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \left|0 \cdots 1_i \cdots 0\right\rangle$
  $\Rightarrow$ a closed two-level system with the collectively enhanced Rabi frequency $\Omega_N = \sqrt{N}\Omega$

In the limit of strong blockade, the probability of unwanted double excitation is

$$P_2 = \frac{N-1}{N} \frac{\Omega_N^2}{2B^2}.$$



[2] Lukin et al. (2001)

Summary

1. Rydberg Physics
   - What are the Rydberg atoms?
   - Two-body interactions
   - Rydberg blockade
2. Rydberg Quantum Computing
   - Two-atom blockade gate
     - CZ gate
     - CNOT gate
   - Preparation of single-atom states
   - Rydberg coupled ensembles

Thanks for Listening!