Rheinland-Pfälzische Technische Universität Kaiserslautern Landau

# Rydberg quantum gates

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Hauptseminar 2

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Rheinland-Pfälzische Technische Universität Kaiserslautern Landau

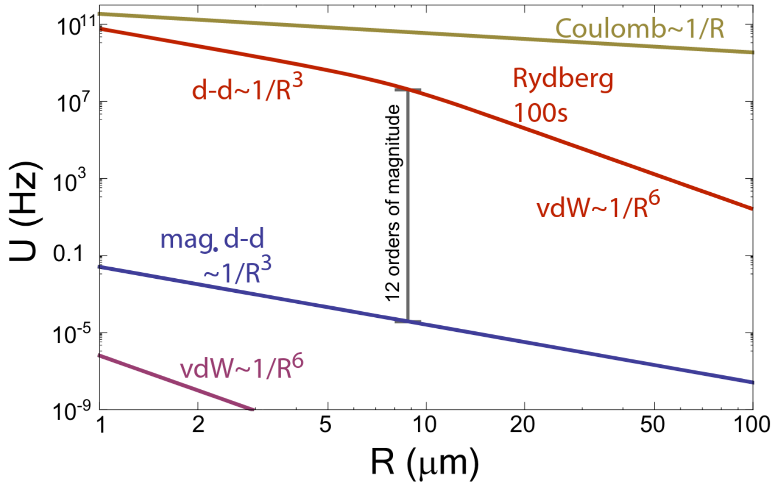
1. Why Rydberg atoms?
2. Quantum phase gate
3. Experimental implementation: CNOT gate
4. Atomic ensembles

# 1. Rydberg atoms

- Excited atoms in a very high principal quantum number $n$
- Size <r> $\sim n^2$

$\Rightarrow$ 1000-10000 times larger

- Dipole matrix element $d \sim n^2$
- Strong interaction

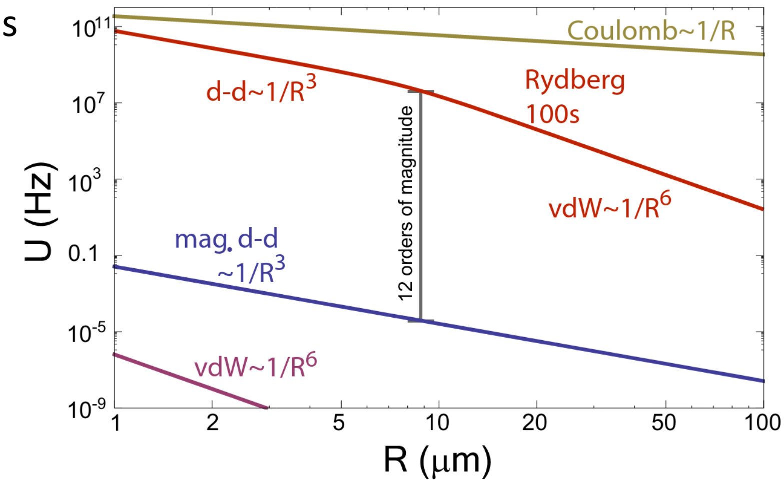



REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010



# 1. Advantages of Rydberg atoms

- Share a lot of advantages with ions
- Radiative lifetime
  - $\tau \sim n^3$
- Interaction can be turned off
  - $\Rightarrow$ unique feature
  - $\Rightarrow$ Qubit stored in lower levels
  - $\Rightarrow$ Rydberg state used only for computing

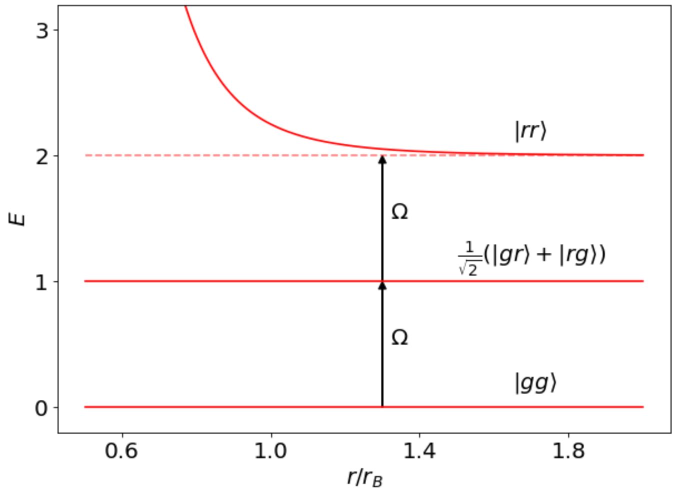



REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010

# 1. Rydberg blockade

- $H = \frac{\Omega}{2}(\hat{\sigma}_1^x + \hat{\sigma}_2^x) - u(\hat{\sigma}_1^{rr} + \hat{\sigma}_2^{rr})$

- $u = \frac{C_6}{r^6}$ => $r_B = \sqrt[6]{\frac{|C_6|}{\Omega}}$








# 2. Quantum gates

- Single qubit gates
  -> rotation on Bloch sphere
- Two qubit gates
  -> controlled gates
- Universal set required for computing
  -> e.g. H, S, T, CNOT

| Operator | Gate(s) | Matrix |
|---|---|---|
| Pauli-X (X) | X | $\begin{bmatrix}0&1\\1&0\end{bmatrix}$ |
| Pauli-Y (Y) | Y | $\begin{bmatrix}0&-i\\i&0\end{bmatrix}$ |
| Pauli-Z (Z) | Z | $\begin{bmatrix}1&0\\0&-1\end{bmatrix}$ |
| Hadamard (H) | H | $\frac{1}{\sqrt{2}}\begin{bmatrix}1&1\\1&-1\end{bmatrix}$ |
| Phase (S, P) | S | $\begin{bmatrix}1&0\\0&i\end{bmatrix}$ |
| π/8 (T) | T | $\begin{bmatrix}1&0\\0&e^{i\pi/4}\end{bmatrix}$ |
| Controlled Not (CNOT, CX) | | $\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$ |
| Controlled Z (CZ) | Z | $\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-1\end{bmatrix}$ |
| SWAP | | $\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$ |
| Toffoli (CCNOT, CCX, TOFF) | | $\begin{bmatrix}1&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0\\0&0&1&0&0&0&0&0\\0&0&0&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&1\\0&0&0&0&0&0&1&0\end{bmatrix}$ |

wikipedia.org/wiki/Quantum_logic_gate

# 2. Quantum phase gate

- Bloch sphere: Rotation around the z-axis

- $P(\varphi) = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{pmatrix}$, $|0\rangle \rightarrow |0\rangle$ and $|1\rangle \rightarrow e^{i\varphi}|1\rangle$

$\varphi = \pi$ => Z-gate: $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$\varphi = \frac{\pi}{2}$ => Phase flip gate: $\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$

$\varphi = \frac{\pi}{4}$ => $\frac{\pi}{8}$ - gate: $\begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$



VOLUME 85, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 2000

**Fast Quantum Gates for Neutral Atoms**

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(Received 7 April 2000)

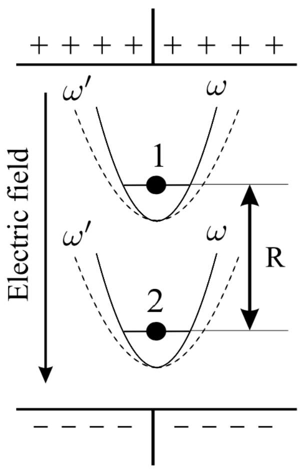
We propose several schemes for implementing a fast two-qubit quantum gate for neutral atoms with the gate operation time much faster than the time scales associated with the external motion of the atoms in the trapping potential. In our example, the large interaction energy required to perform fast gate operations is provided by the dipole-dipole interaction of atoms excited to low-lying Rydberg states in constant electric fields. A detailed analysis of imperfections of the gate operation is given.

- Two atoms at fixed position

- Interaction strength $u(R)$ between Rydberg states

- Stored in atomic ground states $|g\rangle_j = |0\rangle_j$ and $|e\rangle_j = |1\rangle_j$

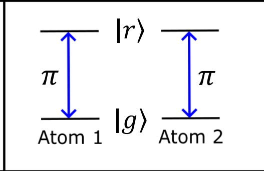
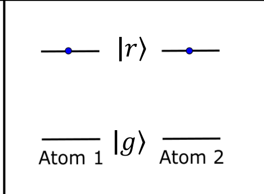
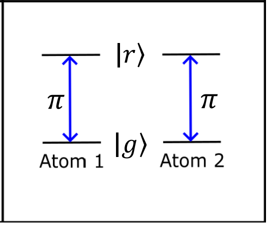
- $|g\rangle_j$ coupled to Rydberg state $|r\rangle_j$ by $\Omega_j$



# 2. Quantum phase gate: model A

- $\Omega_1 = \Omega_2 = \Omega$ and $\Omega \gg u$

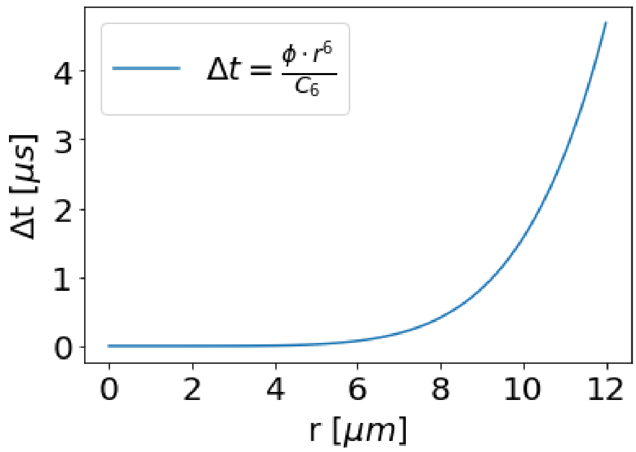
1. Apply $\pi$ pulse: $|g\rangle_1 |g\rangle_2 = |gg\rangle \rightarrow -|rr\rangle$
2. $\big|rr(\Delta t)\rangle = e^{-iE\Delta t}|rr(0)\rangle$
3. Apply $\pi$ pulse again: $-e^{i\varphi}|rr\rangle \rightarrow e^{i\varphi}|gg\rangle$

| Step | Model A |
| --- | --- |
| 1 |   |
| 2 |   |
| 3 |   |



# 2. Quantum phase gate: model A

- No individual adressing required



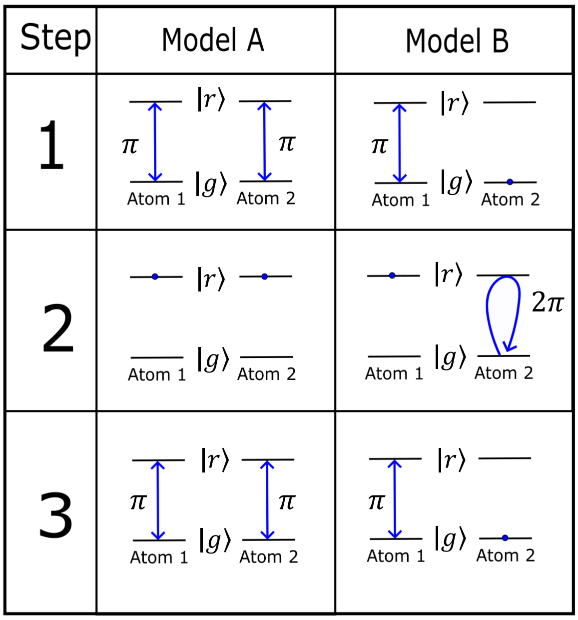

- Inaccurate: $u$ depends on $R$
  => very sensitive

- Strong mechanical effects while in state $|rr\rangle$

# 2. Quantum phase gate: model B

- $u \gg \Omega_j,\ \Omega_1 \neq \Omega_2$

1. Apply $\pi$ pulse to the first atom
2. Apply $2\pi$ pulse to the second atom
3. Apply $\pi$ pulse to the first atom



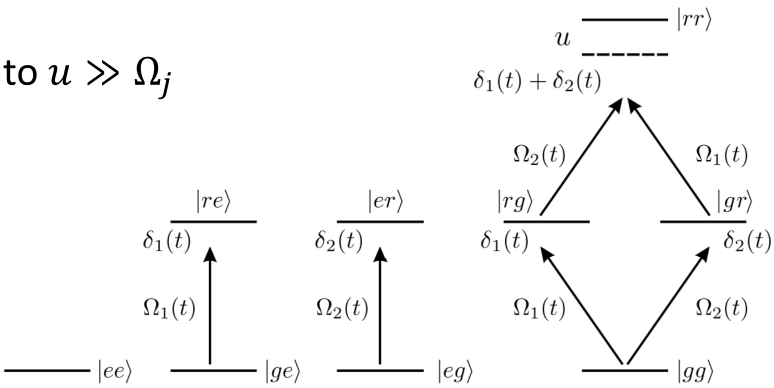



# 2. Quantum phase gate: model B

1. $|gg\rangle \rightarrow i|rg\rangle$
2. Second pulse detuned due to $u \gg \Omega_j$

   $i|rg\rangle \rightarrow ie^{i\varphi}|rg\rangle$

   $\varphi \approx \frac{\pi\Omega_2}{2u} \rightarrow 0$
3. $ie^{i\varphi}|rg\rangle \rightarrow e^{i(\pi-\varphi)}|gg\rangle$



# 2. Quantum phase gate: model B

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- The state $|rr\rangle$ is never populated
- Only weakly sensitive to $R$
- $\Delta t \approx \frac{2\pi}{\Omega_1} + \frac{2\pi}{\Omega_2}$

=> easier to design robust quantum gates



# 3. First implemenation of a CNOT gate

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PRL **104,** 010503 (2010) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2010

**Demonstration of a Neutral Atom Controlled-NOT Quantum Gate**

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(Received 5 August 2009; published 8 January 2010)

We present the first demonstration of a CNOT gate between two individually addressed neutral atoms. Our implementation of the CNOT uses Rydberg blockade interactions between neutral atoms held in optical traps separated by $>8\ \mu$m. Using two different gate protocols we measure CNOT fidelities of $F = 0.73$ and 0.72 based on truth table probabilities. The gate was used to generate Bell states with fidelity $F = 0.48 \pm 0.06$. After correcting for atom loss we obtain an *a posteriori* entanglement fidelity of $F = 0.58$.

DOI: 10.1103/PhysRevLett.104.010503 PACS numbers: 03.67.Lx, 03.67.Bg, 32.80.Ee, 32.80.Qk

# 3. Controlled-NOT quantum gate

$$
\begin{array}{cc|c}
|0\rangle & |1\rangle & \\
\hline
1 & 0 & |0\rangle \\
0 & \sigma^x & |1\rangle
\end{array}
\qquad
\begin{pmatrix}1 & 0\\ 0 & \sigma^x\end{pmatrix}
$$

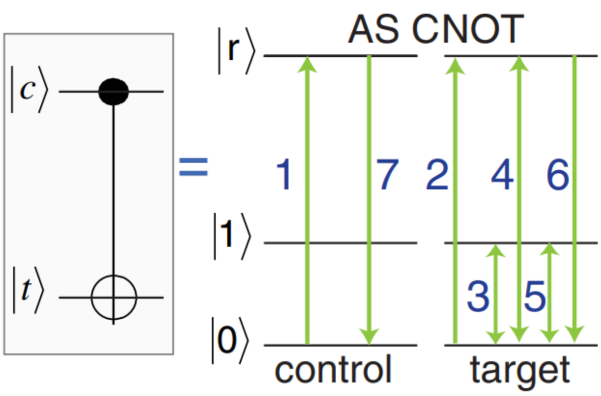
| input | | output | |
|---|---|---|---|
| control | target | control | target |
| 0 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 |
| 1 | 1 | 1 | 0 |





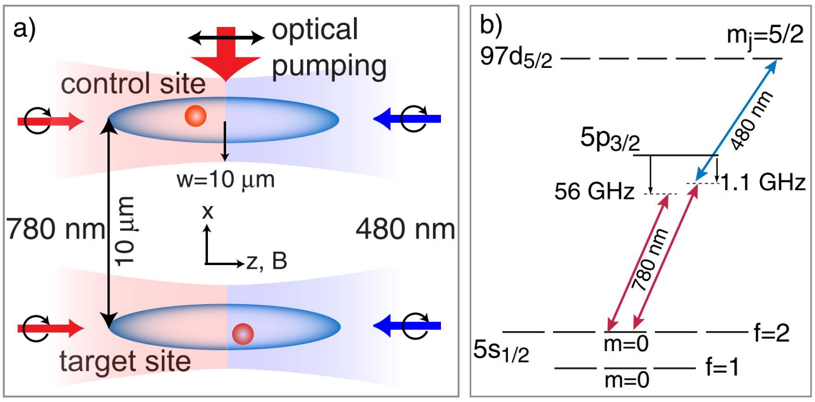
# 3. First implementation of a CNOT gate

- Amplitude swap CNOT
- Control atom in state $|1\rangle$
  - => pulses 1 and 7 are detuned
  - => target atom is swapped by 2-6



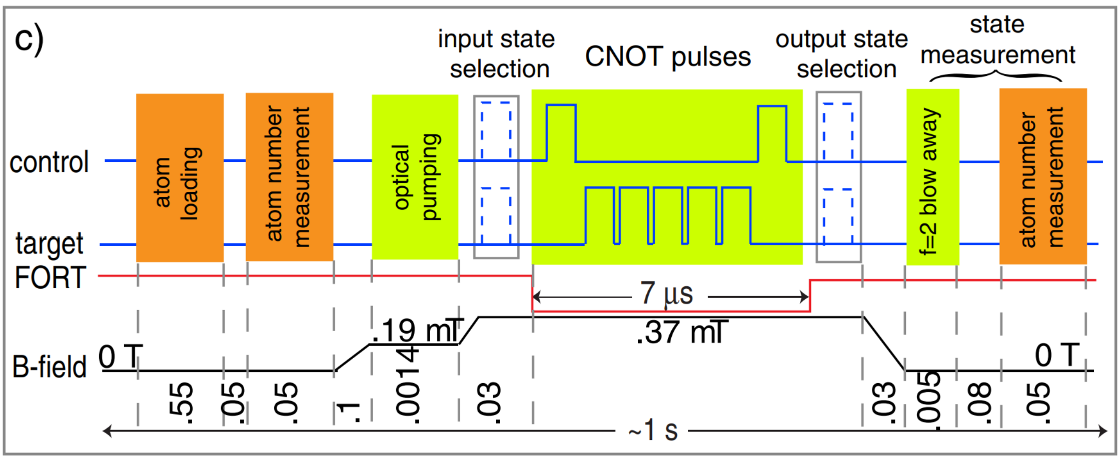
# 3. First implementation of a CNOT gate

- Trapping the atoms at
  $R \approx 10 \mu m$
- Optical pumping to initial state
- Two different detunings
  =>two photon excitation





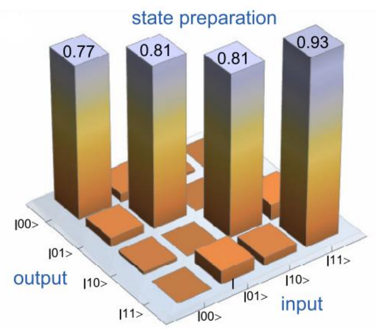

# 3. First implementation of a CNOT gate

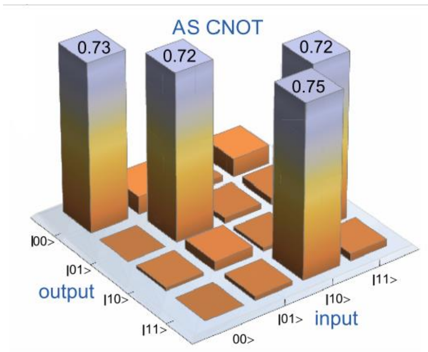



**10 % loss due to collisions between measurements**

# 3. Fidelity

- $F = 0$ for orthogonal states, 1 for identical states
- $F = \mathrm{Tr}[\hat{\rho}\hat{\sigma}]$

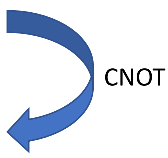




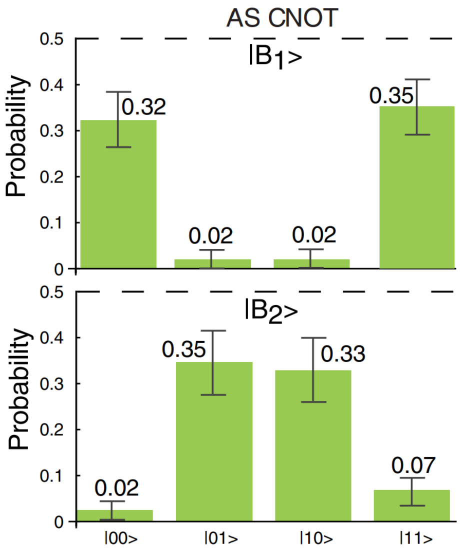

# 3. Is it quantum?

- Has to be able to create entangled states
- Use $\frac{\pi}{2}$-pulse to prepare input states:
- $|00\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle + i|1\rangle\right)|0\rangle$ and $|01\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle + i|1\rangle\right)|1\rangle$
- $|B1\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$ and $|B2\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle + |10\rangle\right)$



# 3. Entanglement

- Entanglement measurable: $F = 0.58$




- Satisfying result since
  - $T = 200\ \mu K$
  - Large separation R



# 4. Ensembles

VOLUME 87, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JULY 2001

**Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles**

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(Received 7 November 2000; published 26 June 2001)

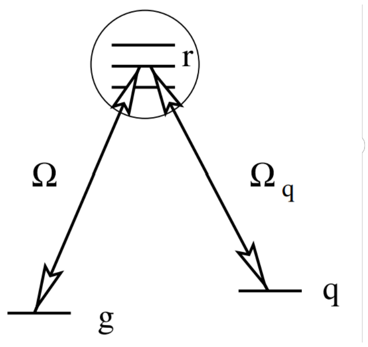
We describe a technique for manipulating quantum information stored in collective states of mesoscopic ensembles. Quantum processing is accomplished by optical excitation into states with strong dipole-dipole interactions. The resulting "dipole blockade" can be used to inhibit transitions into all but singly excited collective states. This can be employed for a controlled generation of collective atomic spin states as well as nonclassical photonic states and for scalable quantum logic gates. An example involving a cold Rydberg gas is analyzed.

DOI: 10.1103/PhysRevLett.87.037901 PACS numbers: 03.67.Lx, 03.75.Fi, 42.50.Gy, 73.23.–b

# 4. Ensembles



- Prepare all atoms in specific sublevel $g$
- Use metastable sublevels q for storage of qubits
- One ensemble as a qubit
  => Same computation possible as in Model 2A



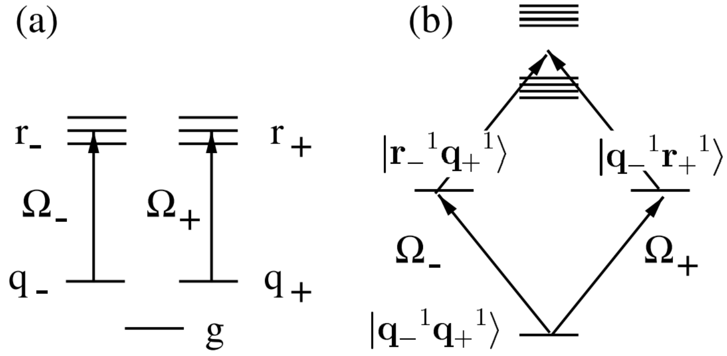



# 4. Ensembles



- Easier coupling to light
=> operations between distant ensembles

- Easier trapping



# Summary

- Advantages of Rydberg atoms:
  - Strong interaction
  - Interaction can be turned on/off
  - Rydberg blockade
  - Long decoherence time
  - Rydberg atoms or Ensembles possible

- Rydberg gates experimentally feasible
  - Fast computation time
  - Universal set of quantum gates necessary