Long-range Rydberg-blockade entangling gate mediated by auxiliary atoms

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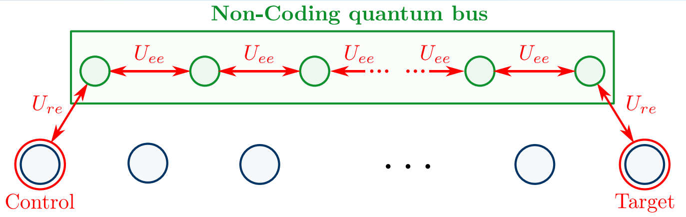
Introduction

Two-qubit entangling gates between nearest neighbour qubits encoded in the ground state manifold of neutral atoms in a lattice can be implemented using Rydberg Blockade [1]. However, as Rydberg blockade becomes less effective with interatomic distance, such protocols fail for atoms separated by a few or more lattice sites. In this work, we propose a protocol implementing CZ and CNOT gates between qubits arbitrarily far apart in the lattice [2].

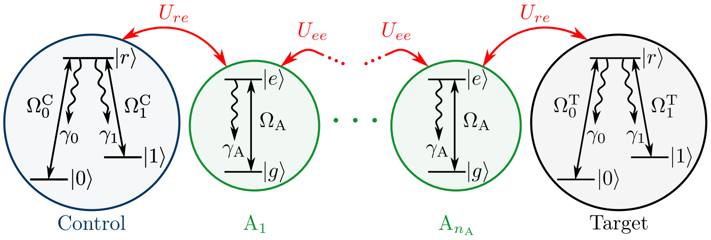
$$U_{\mathrm{CZ}} = |00\rangle\langle 00| - |01\rangle\langle 01| - |10\rangle\langle 10| - |11\rangle\langle 11|,$$
$$U_{\mathrm{CNOT}} = |00\rangle\langle 00| + |01\rangle\langle 01| + |10\rangle\langle 11| + |11\rangle\langle 10|$$

System



- Qubits encoded in 1D chain of atoms
  Quantum bus made of n_{A} ancillary non-coding atoms

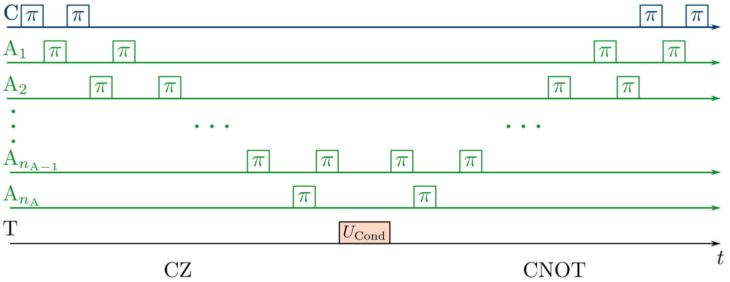
Both types of atom are individually adressable



- Dipole-dipole interaction between atoms in Rydberg state ($|r\rangle$, $|e\rangle$) ⇒ doubly excited state energy shift U ⇒ dipole blockade
- Dissipation of atoms excited to Rydberg states ⇒ master equation

Protocol

- Strong Rydberg blockade regime ($U \gg \Omega$) ⇒ conditional dynamics [1]
- All ancillary atoms initially in $|g\rangle$



CZ

$$\mathrm{C}\ \boxed{\pi}\ \begin{cases} 0 \leftrightarrow r & \text{if } n_{\mathrm{A}} \text{ odd} \\ 1 \leftrightarrow r & \text{if } n_{\mathrm{A}} \text{ even} \end{cases}$$
$$\mathrm{T}\ \boxed{U_{\mathrm{Cond}}} = \overset{1\leftrightarrow r}{\boxed{2\pi}}$$

CNOT

$$\mathrm{C}\ \boxed{\pi}\ \begin{cases} 0 \leftrightarrow r & \text{if } n_{\mathrm{A}} \text{ even} \\ 1 \leftrightarrow r & \text{if } n_{\mathrm{A}} \text{ odd} \end{cases}$$
$$\mathrm{T}\ \boxed{U_{\mathrm{Cond}}} = \underset{0\leftrightarrow r}{\boxed{\pi}}\overset{1\leftrightarrow r}{\boxed{\pi}}\underset{0\leftrightarrow r}{\boxed{\pi}}$$

- Rydberg excitation hopping from one atom to its next nearest neighbour
- At most one Rydberg excitation at a time in the whole system
- $n_{\mathrm{pulse}} = 4n_{\mathrm{A}} + 2 + n_{\mathrm{T}}$ with n_{T}=2 (CZ) or n_{T}=3 (CNOT)

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Results and discussion

Gate fidelity : imperfect blockade

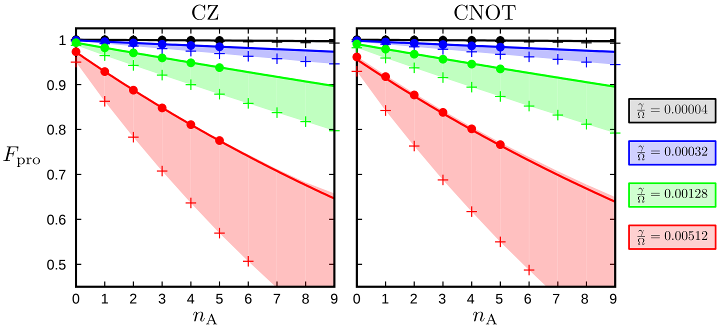
- Gate error proportional to probability of double excitation $P_2 \propto \Omega^2/U^2$
- Process fidelity ($\gamma_i = 0,\ i = 0, 1, \mathrm{A}$)

$$F_{\mathrm{pro}}^{\gamma_i=0}\left(\frac{U}{\Omega}\right) = 1 - \alpha\left(\frac{U}{\Omega}\right)^{-2}$$

with $0.1 \lesssim \alpha \lesssim 2$ a constant whose value depends only on n_{A} and U_{Cond}

Gate Fidelity : effects of dissipation

- $U_{rr}/\Omega = U_{re}/\Omega = U_{ee}/\Omega = 200 \Rightarrow 1 - F_{\mathrm{proc}} < 10^{-4}$
- $\gamma_0 = \gamma_1 = \gamma/2$ and $\gamma_{\mathrm{A}} = \gamma$



dots : process fidelity F_{pro} [3]

crosses : lower bound on process fidelity as given by Hofmann [4]
shaded area is delimited by upper and lower bounds on F_{pro}

- Process fidelity ⇔ cumulated time spent by the atoms in Rydberg states

$$F_{\mathrm{pro}}\left(\frac{U}{\Omega}, \{\gamma_i\}\right) \approx F_{\mathrm{pro}}^{\gamma_i=0}\left(\frac{U}{\Omega}\right) e^{-(\gamma_0+\gamma_1)t_{\mathrm{q}}} e^{-\gamma_{\mathrm{A}} t_{\mathrm{A}}(n_{\mathrm{A}})} \quad \text{(solid line)}$$

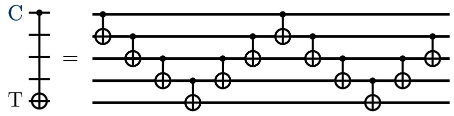
$$\mathrm{CZ}\ :\ t_{\mathrm{q}} = \frac{2\pi + 6\,t_{\mathrm{eff}}^{\pi}}{2}, \quad t_{\mathrm{A}}(n_{\mathrm{A}}) = \frac{4\pi n_{\mathrm{A}} + 4n_{\mathrm{A}}t_{\mathrm{eff}}^{\pi} - 2t_{\mathrm{eff}}^{\pi}}{2}$$

$$\mathrm{CNOT}\ :\ t_{\mathrm{q}} = \frac{2\pi + 7\,t_{\mathrm{eff}}^{\pi}}{2}, \quad t_{\mathrm{A}}(n_{\mathrm{A}}) = \frac{4\pi n_{\mathrm{A}} + 4n_{\mathrm{A}}t_{\mathrm{eff}}^{\pi} + \pi - 2t_{\mathrm{eff}}^{\pi}}{2}$$

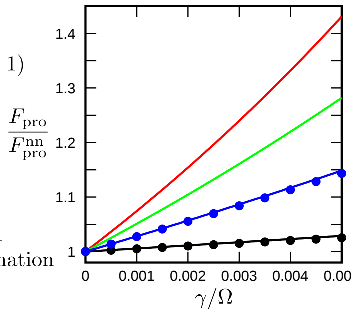
with t_{eff}^{π} the effective time spent in Rydberg state during a π-pulse (estimated to 0.39 by numerical simulation)

Comparison with sequence of nearest neighbour CNOTs

- CNOT between qubits separated by $n_{\mathrm{A}} - 1$ other qubits using sequence of nearest neighbours CNOTs [5] ⇒ process fidelity $F_{\mathrm{pro}}^{\mathrm{nn}}$



- Advantages of our protocol
  - Lower number of pulses
    $4n_{\mathrm{A}} + 5$ instead of $20(n_{\mathrm{A}} - 1)$
  - Improved fidelity



$\gamma_0 = \gamma_1 = \gamma/2$, $\gamma_{\mathrm{A}} = \gamma$
$n_{\mathrm{A}} = 2,\ 3,\ 4,\ 5$
dots : numerical simulation
solid line : theoretical estimation

Perspectives and experimental considerations

- Optimized pulses to improve process fidelity
- Experimental implementations
  - Same species for both qubit and ancillary atoms [6,7,8]
  - Two different atomic species for qubit and ancillary atoms [9]