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Observation of Rydberg blockade between two atoms

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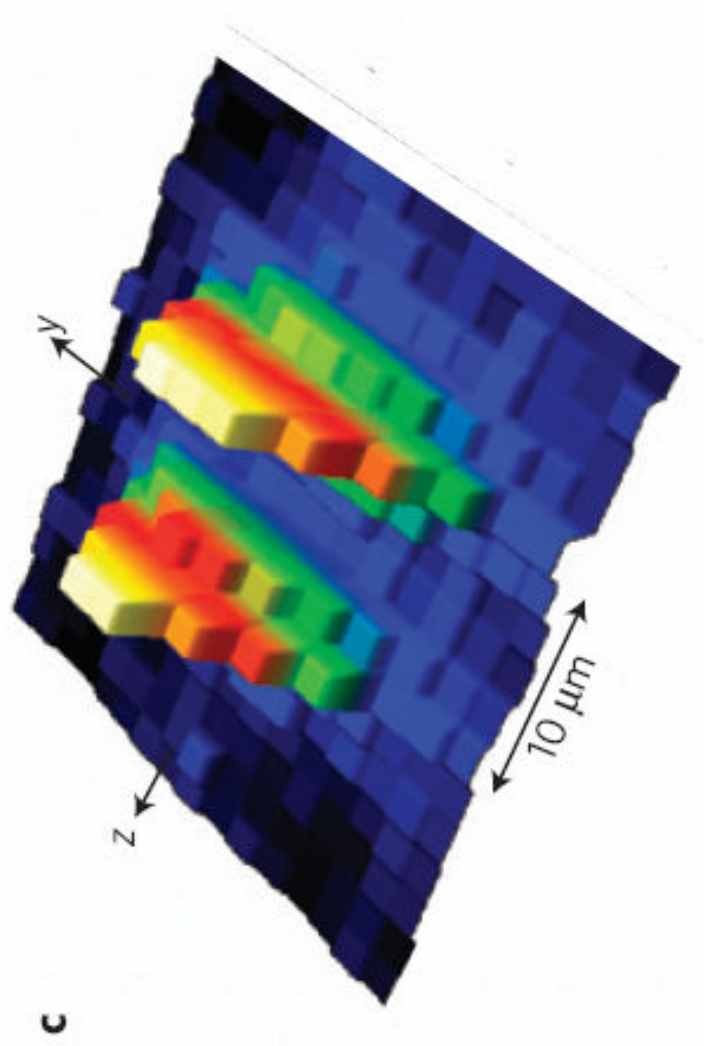
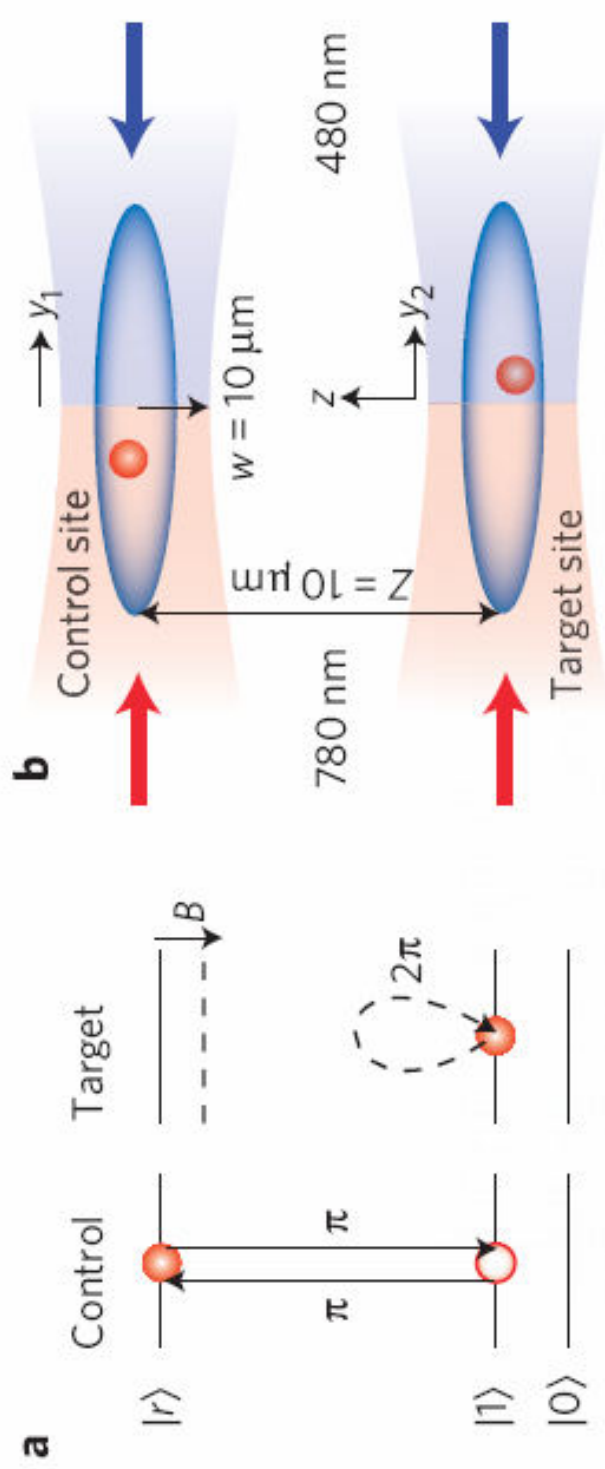
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Observation of collective excitation of two individual atoms in the Rydberg blockade regime

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Outlines

- Rabi Oscillations
- Properties of Rydberg atoms
- Van Der Waals Force and Rydberg Blockade
- The implementation of a CNOT gate
- Preparation of Entanglement between two atoms
- Summary

Rabi Oscillation in two-level systems

- For a two level system, we can write the state as

$$|\Psi(t)\rangle = C_a(t)|a\rangle + C_b(t)|b\rangle$$

- The Hamiltonian can be written as

$$H = H_0 + H_1$$

$$H_0 = \hbar\omega_a|a\rangle\langle a| + \hbar\omega_b|b\rangle\langle b|$$

$$H_1 = -exE(t)$$

$$\begin{aligned} &= -e(|a\rangle\langle a| + |b\rangle\langle b|)\hat{x}(|a\rangle\langle a| + |b\rangle\langle b|) \\ &= -(d|a\rangle\langle b| + d^*|b\rangle\langle a|) \end{aligned}$$

- Solving the Schrodinger's equation

$$\frac{\partial}{\partial t}|\Psi(t)\rangle = -\frac{i}{\hbar}H|\Psi(t)\rangle$$

- The solution is:

$$c_a(t) = \left\{ c_a(0) \left[\cos\left(\frac{\Omega t}{2}\right) - \frac{i\Delta}{\Omega} \sin\left(\frac{\Omega t}{2}\right) \right] + i \frac{\Omega_R}{\Omega} e^{-i\phi} c_b(0) \sin\left(\frac{\Omega t}{2}\right) \right\} e^{i\Delta t/2},$$

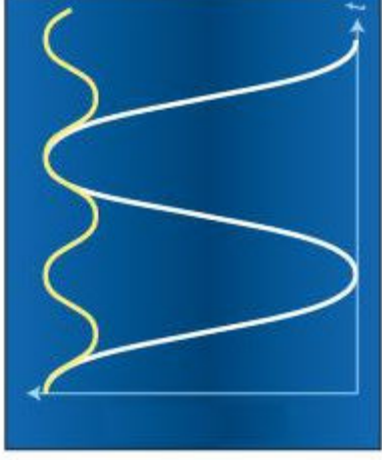
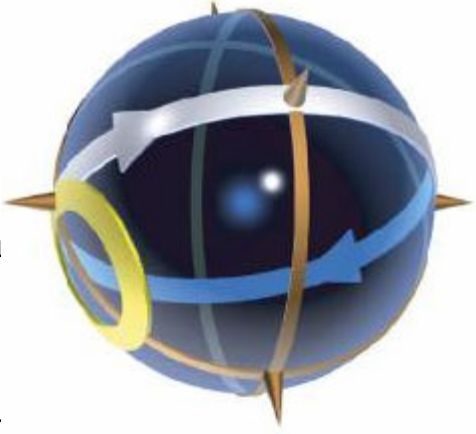
$$c_b(t) = \left\{ c_b(0) \left[\cos\left(\frac{\Omega t}{2}\right) + \frac{i\Delta}{\Omega} \sin\left(\frac{\Omega t}{2}\right) \right] + i \frac{\Omega_R}{\Omega} e^{i\phi} c_a(0) \sin\left(\frac{\Omega t}{2}\right) \right\} e^{-i\Delta t/2},$$

- And the inversion is:

$$w(t) = |c_a(t)|^2 - |c_b(t)|^2 = \left(\frac{\Delta^2 - \Omega_R^2}{\Omega^2} \right) \sin^2\left(\frac{\Omega t}{2}\right) + \cos^2\left(\frac{\Omega t}{2}\right).$$

- The induced dipole can be calculated too:

$$\begin{aligned} P(t) &= e \langle \Psi(t) | \hat{x} | \Psi(t) \rangle = c_a^* c_b d_{ab} e^{i\omega_0 t} + c.c. \\ &= 2 \operatorname{Re} \left\{ \frac{i\Omega_R}{\Omega} d_{ab} \left[\cos\left(\frac{\Omega t}{2}\right) + \frac{i\Delta}{\Omega} \sin\left(\frac{\Omega t}{2}\right) \right] \sin\left(\frac{\Omega t}{2}\right) e^{i\phi} e^{i\omega t} \right\} \end{aligned}$$



Rydberg Atoms

- A Rydberg atom is an excited atom with one or more electrons that have a very high principal quantum number.

- From Bohr's model:
$$r_n = \frac{n^2 \hbar^2}{k e^2 m_e} \propto n^2$$

- Level scheme used in the experiment:

$$|1\rangle \equiv |5s_{1/2}, f = 2, m_f = 2\rangle$$

$$|r\rangle \equiv |79d_{5/2}, m_j = 1/2\rangle$$

OR $|r\rangle \equiv |90d_{5/2}, m_j = 1/2\rangle$

Rydberg Atom Scaling Laws

At $n=80$:
Radius $\sim n^2$
 $r \sim 3\mu\text{m}$

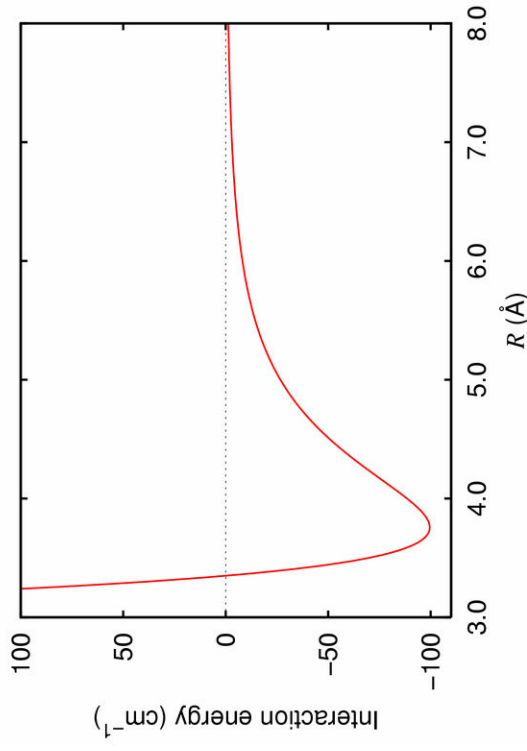
Lifetime $\sim n^3 \cdot n^{4.5}$
 $\tau \sim 600\mu\text{s}$

Dipole Moment $\sim n^2$
 $\mu \sim 10^4 e a_0$

Polarizability $\sim n^7$
 $\alpha \sim 10^3 \text{GHz}/(\text{V/cm})^2$

Van Der Waals Force

- Atoms don't have permanent dipole, but could have induced dipole. This force is also called the London Dispersion force, which is responsible for the long range part of the graph.



- Now consider two Rydberg atoms, and choose the quantization axis along z. The dipole-dipole interaction term is:

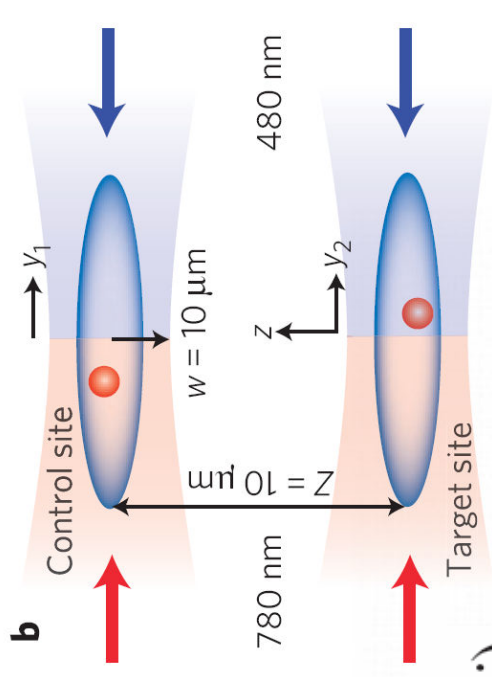
$$V_{\text{dd}} = \frac{e^2}{R^3}(\mathbf{a} \cdot \mathbf{b} - 3a_z b_z)$$

- The interaction term as a coupling:

$$nl_j + nl_j \rightarrow n_s l_s j_s + n_t l_t j_t$$

$$\delta = E(n_s l_s j_s) + E(n_t l_t j_t) - 2E(nl_j)$$

Förster defect



Interaction regimes

- At the largest distances, a nonzero Förster defect causes the dominant long-range interaction to go as R^{-6} (van der Waals type). The R^{-5} quadrupole-quadrupole interaction is normally much smaller.
- For atoms that are closer, the van der Waals interaction becomes large enough to mix the finestructure levels together, particularly for the d levels. This occurs for 30–80 d levels in the 0.8–8 μm range of distances of interest for interactions between optically resolvable Rydberg atoms.
- For atoms at somewhat smaller distances, typically 0.5–5 μm , the dipole-dipole interaction is comparable to the energy differences between nearby states, so the interactions become resonant and vary as R^{-3} .

Two regimes of interaction

- The Hamiltonian for the system can be written as

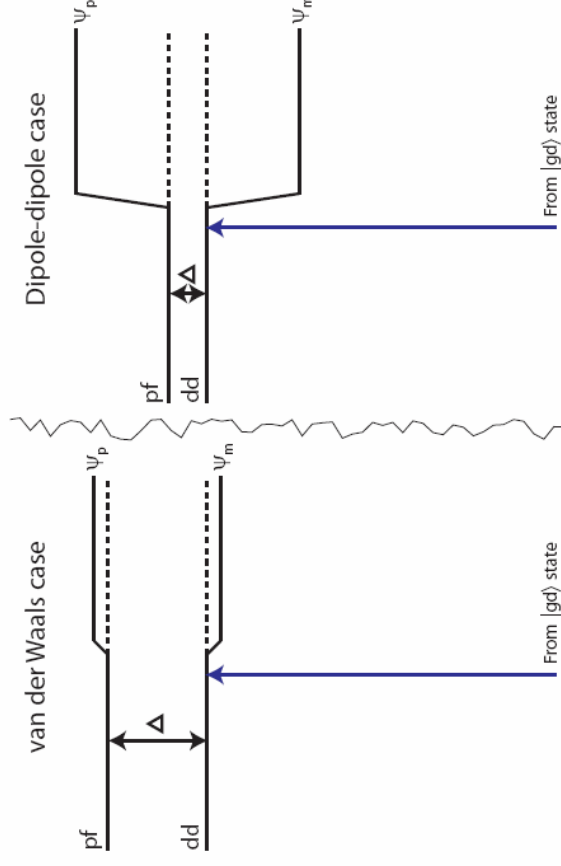
$$H = \hbar \begin{pmatrix} 0 & V & V \\ V & \Delta & 0 \\ V & 0 & \Delta \end{pmatrix}$$

Where the basis is chose to be

$$|d, d\rangle, |p, f\rangle, |f, p\rangle$$

- The interaction term is

$$V_{dd} = \frac{e^2}{R^3}(\mathbf{a} \cdot \mathbf{b} - 3a_z b_z)$$



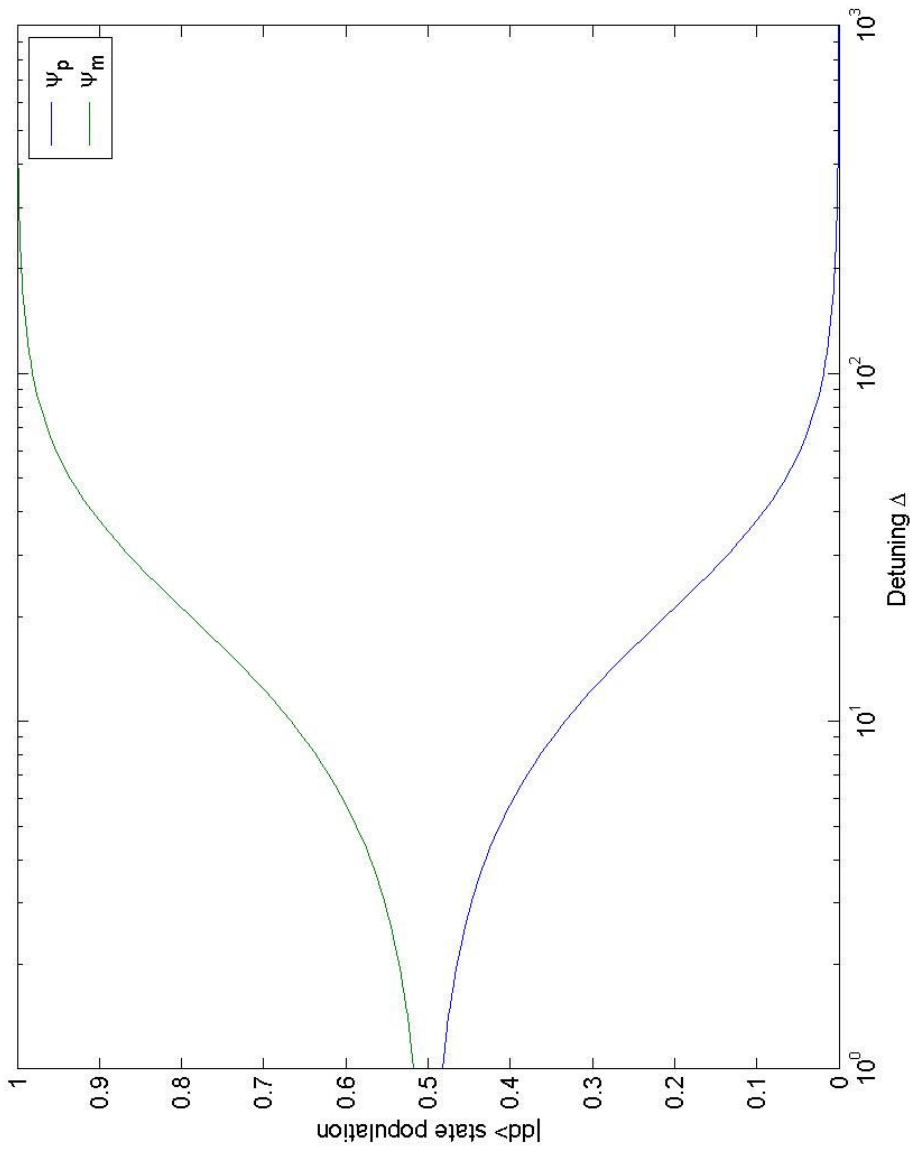
- Diagonalize the Hamiltonian we can have the eigenstate (up to a normalization factor) and eigenenergy:

$$\begin{pmatrix} |\psi_0\rangle \\ |\psi_m\rangle \\ |\psi_p\rangle \end{pmatrix} = \begin{pmatrix} |fp\rangle - |pf\rangle \\ -\frac{\Delta + \sqrt{8V^2 + \Delta^2}}{2V} |dd\rangle + |pf\rangle + |fp\rangle \\ -\frac{\Delta - \sqrt{8V^2 + \Delta^2}}{2V} |dd\rangle + |pf\rangle + |fp\rangle \end{pmatrix}$$

$$\begin{pmatrix} E_0 \\ E_m \\ E_p \end{pmatrix} = \begin{pmatrix} \Delta \\ \frac{1}{2}(\Delta - \sqrt{8V^2 + \Delta^2}) \\ \frac{1}{2}(\Delta + \sqrt{8V^2 + \Delta^2}) \end{pmatrix}$$

- The state $|\psi_0\rangle$ is not coupled in the Rabi flopping (the dark state.)
- In the limit where $V \gg \Delta$ the amplitude of $|dd\rangle$ in the two state is almost equal. (The Dipole-dipole regime)
- In the limit where $V \ll \Delta$ the amplitude of $|dd\rangle$ in state $|\psi_p\rangle$ is almost zero, and the amplitude in state $|\psi_m\rangle$ is almost 1. (the Van Der Waals regime)

Two regimes of interaction



Recap of Scaling laws

- Two regimes: the van der Waals regime, and the dipole-dipole regime.
- Here, we have a two particle state $|\phi\rangle$ that is coupled to another two particle state $|\psi\rangle$ through an interaction term V_{int} , and an energy detuning of Δ . V_{int} is the dipole interaction operator $\sim n^4/R^3$.
- In the regime of van der Waals interactions, the coupling between the atoms is much less than the energy detuning, $\Delta \gg V_{\text{int}}$, of the interaction. The shift in energy is V_{int}^2/Δ . Since $\Delta \sim 1/n^3$, the total scaling of the shift $\sim n^{11}/R^6$.
- For dipole-dipole interactions, the energy detuning Δ is much smaller than the interaction V_{int} . In this case, the scaling is simply n^4/R^3 .

Measurements of distance between two atoms

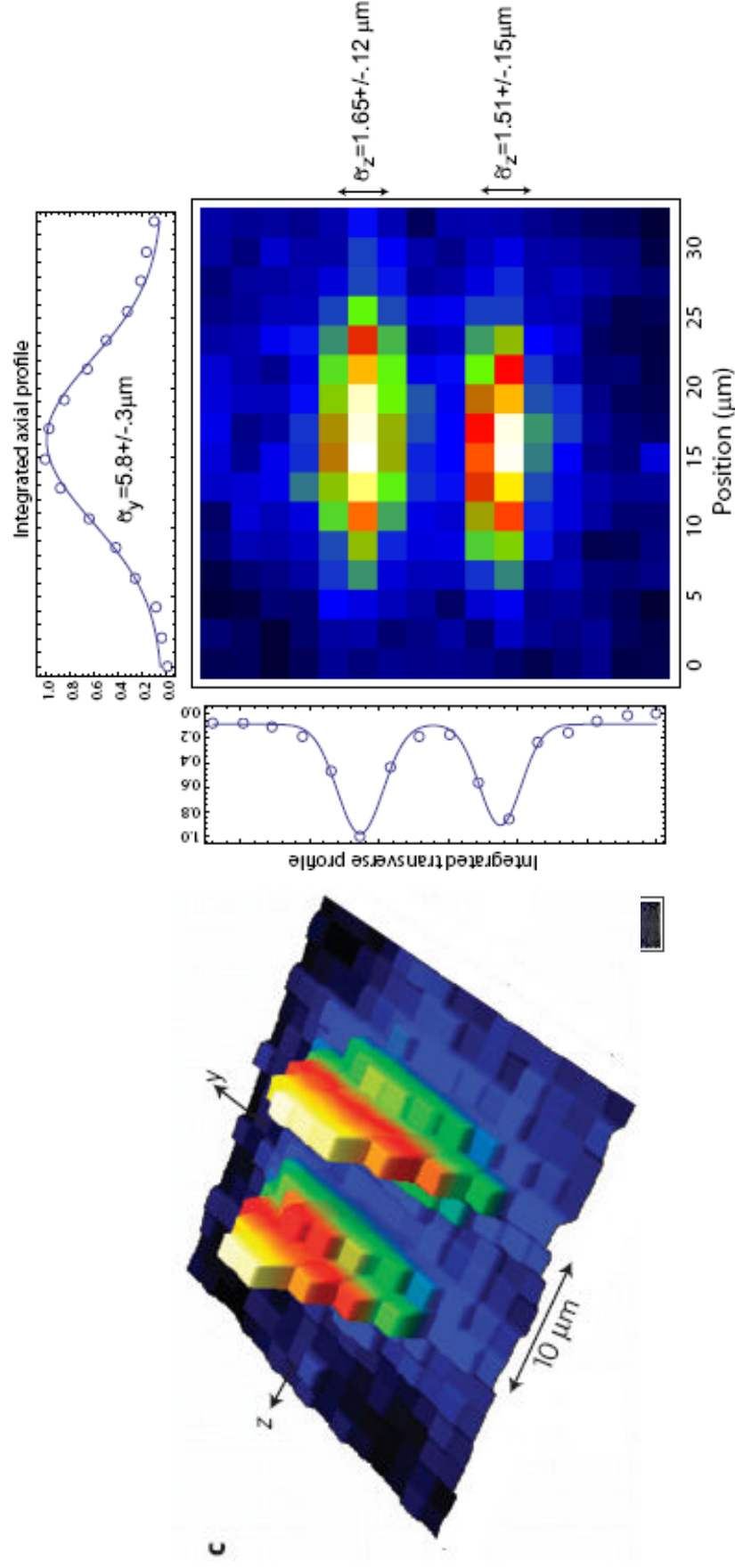
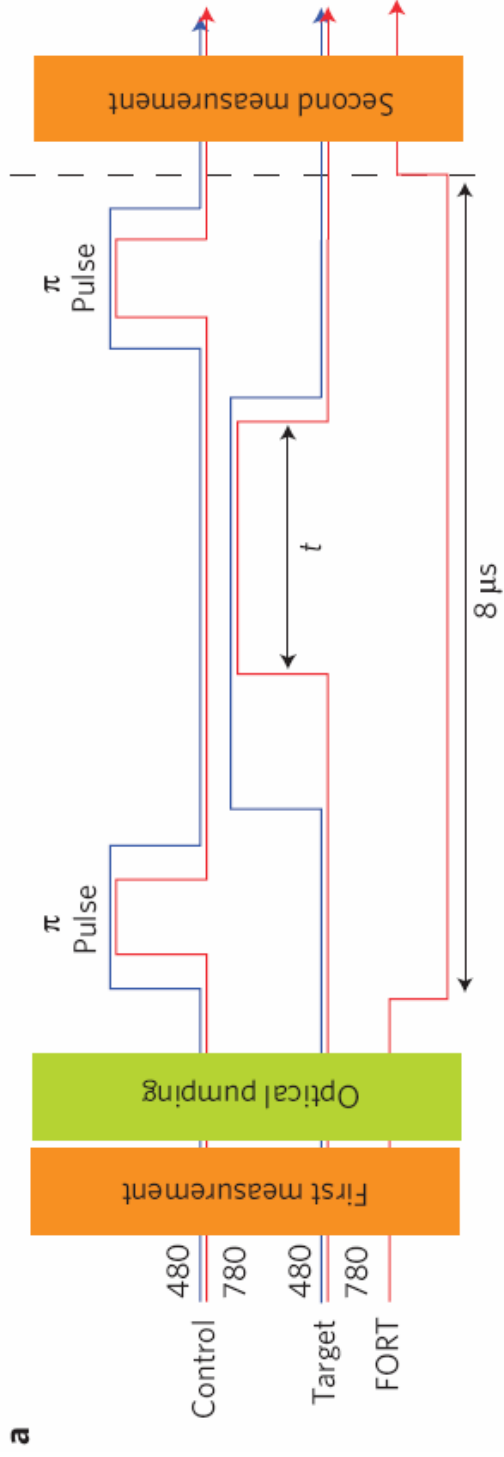
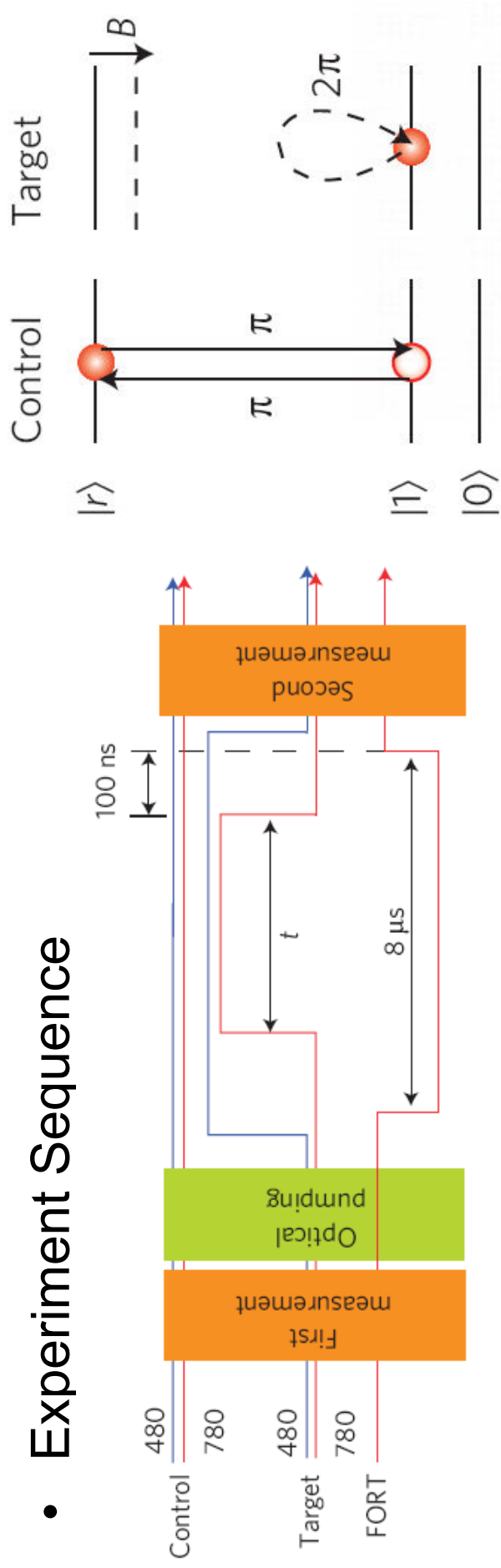
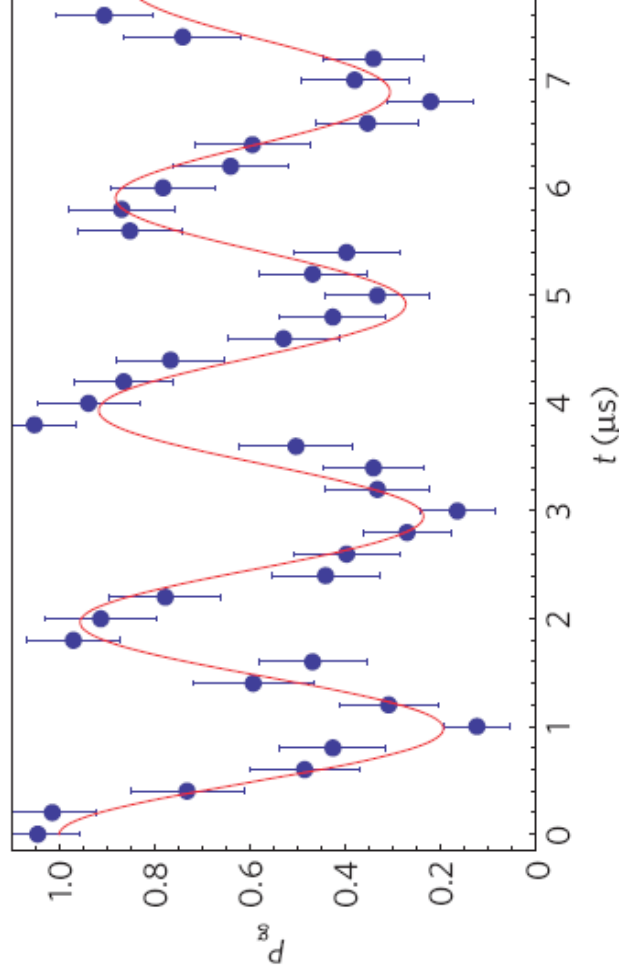


FIG. 1: Single atom distributions from averaging 146 single atom loading events. Each exposure was 30 ms long. The vertical separation between the centers of the trapping sites is $Z = 10.2 \mu\text{m}$. The inferred widths of the atomic distributions after removal of the imaging optics blurring are $\sigma_x = 0.45 \mu\text{m}$ and $\sigma_y = 5.6 \mu\text{m}$.

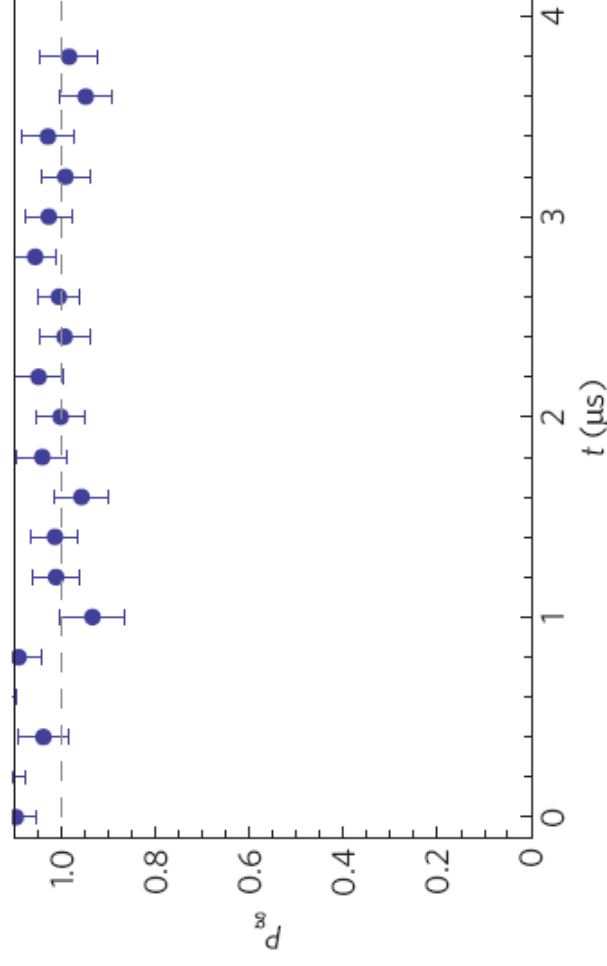
Implementation of a CNOT gate

- Experiment Sequence





- Measured ground-state population during Rabi flopping on the target site.



- Measured control-site crosstalk when the Rydberg excitation lasers are pointed at the empty target site. The error bars represent one standard deviation.

Figure 2 | Single-atom Rabi oscillations to $79d_{5/2}$.

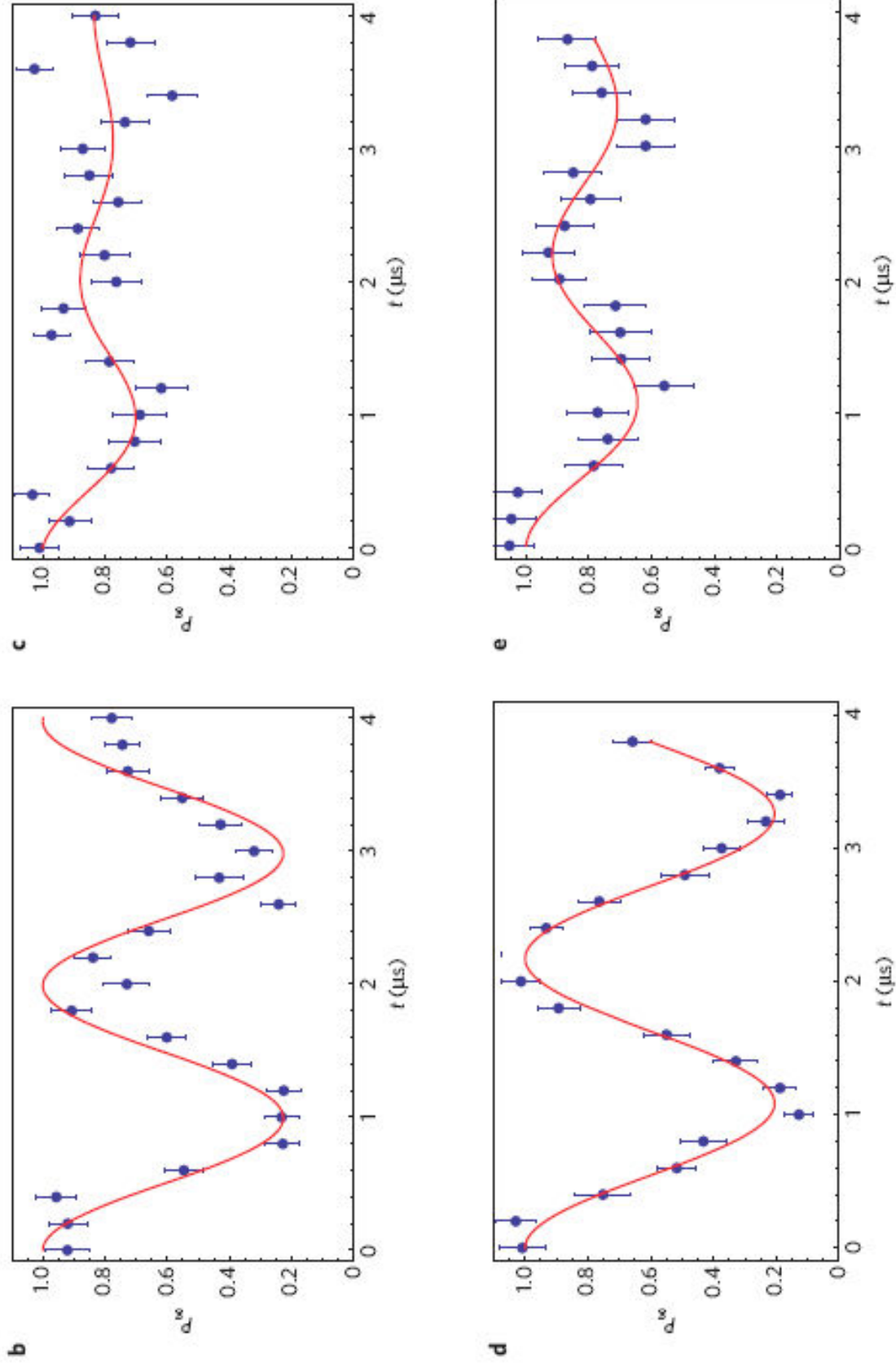


Figure 3 | Rydberg blockade experiment between control and target atoms. **a**, Experimental sequence. **b**, Rabi oscillations on site 2 when no π pulses are applied to site 1. **c**, Blocked oscillations on site 2 when the π pulses are applied to site 1. **d,e**, The same as in **b,c**, but with the roles of sites 1 and 2 reversed. The red lines are curve fits to the function $(1 - a) + a \cos(2\pi f t) e^{-t/\tau}$. The fit parameters (a, f (MHz), τ (μs)) were: (0.44, 0.51, 5.7) for **b**, (0.17, 0.45, 3.0) for **c**, (0.40, 0.46, ∞) for **d** and (0.21, 0.45, 2.3) for **e**. The error bars are standard deviations with 50 data points at each value of t .

Efficiency of the blockade

- The residue Rabi flopping in the target site can be calculated as:

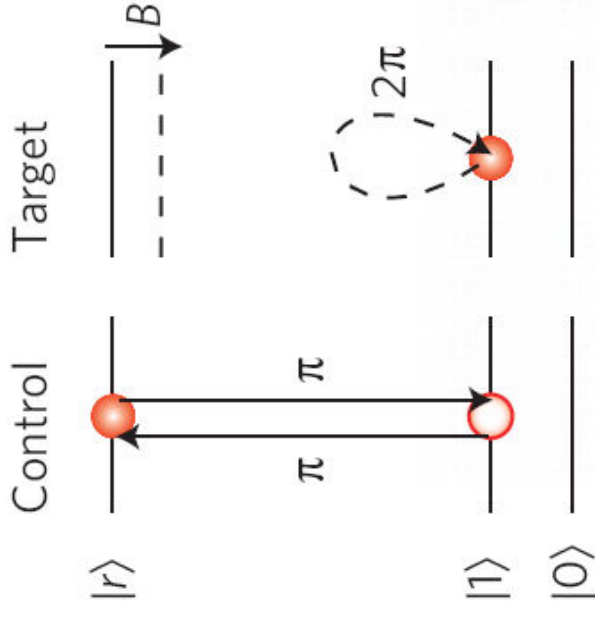
$$P_2 = \Omega^2 / \Omega^2 + 2B^2$$

Where B is the effective blockade shift.

- The observed Rabi frequency is:

$$\Omega / 2\pi = 0.51 \text{ MHz}$$
- And the amplitude of the Rabi flopping implies:

$$\bar{B} / (2\pi) = 1.1 \text{ MHz}$$



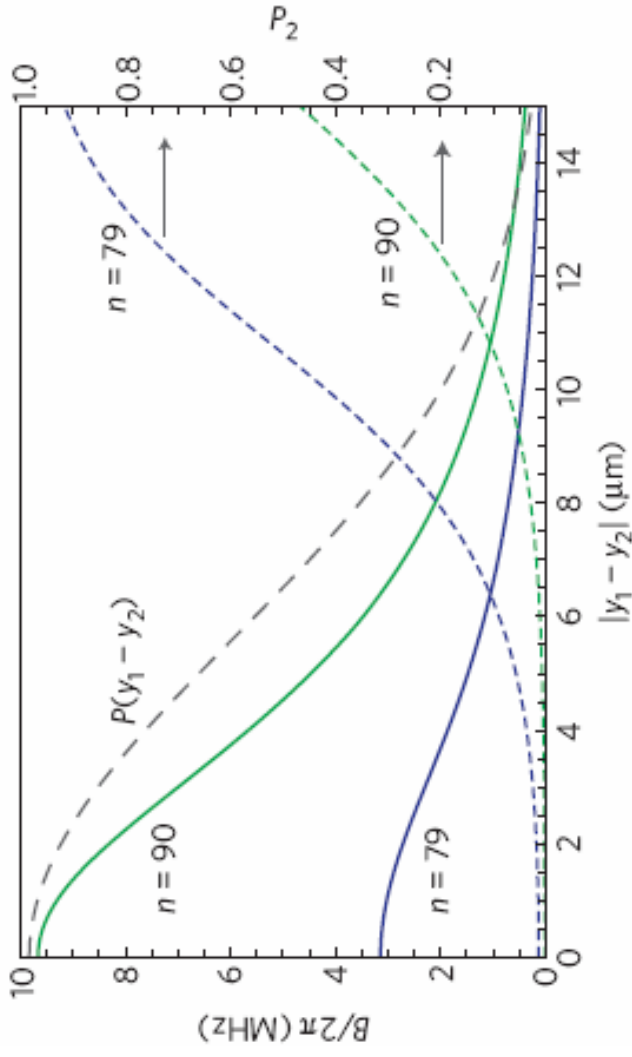


Figure 4 | Theoretical interaction strength. Blockade shift (solid lines) and P_2 (dashed lines) as a function of relative position $|y_1 - y_2|$ for $n = 79$ (blue) and $n = 90$ (green) Rydberg levels. The long-dashed line shows the relative probability of $y_1 - y_2$, which is a Gaussian with variance $2\sigma_y^2$.

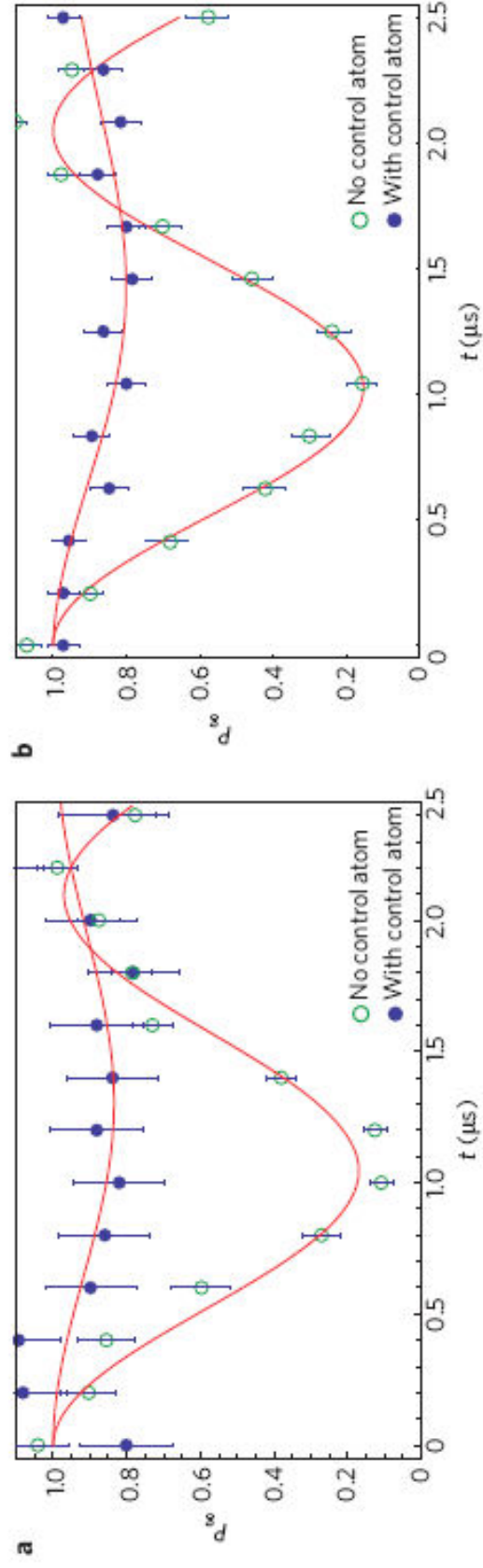


Figure 5 | Rydberg blockade by excitation of the $|90d_{5/2}\rangle$ Rydberg level. a. The experimental data for Rydberg excitation of the target atom with and without a control atom present. **b.** A Monte Carlo simulation accounting for experimental imperfections. The amplitude of the curve fit to the blocked oscillations is $a = 0.09$ (experiment) and $a = 0.11$ (simulation).

Paper 2: Entanglement with Rydberg blockade

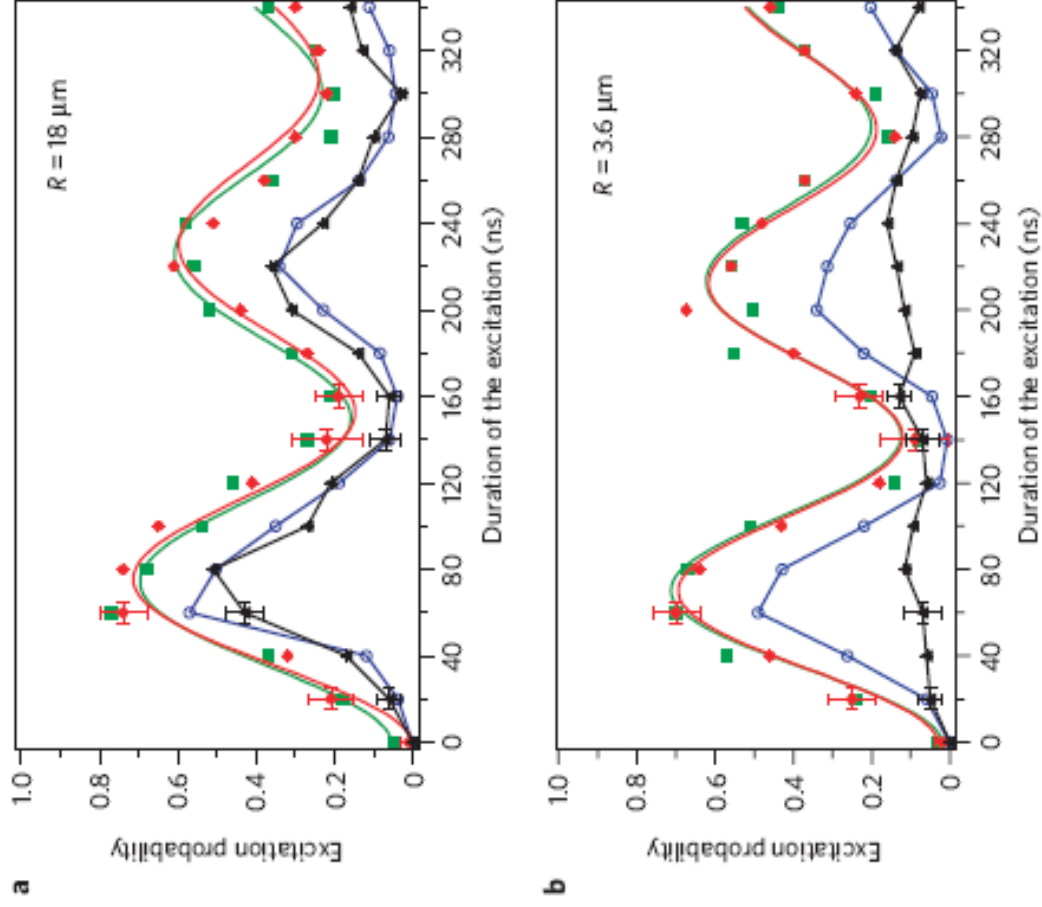


Figure 3 | Rydberg excitation of one and two atoms. In **a** and **b**, the red circles and the green squares represent the probability to excite atom a and atom b respectively, when the other atom is absent. We fit the data by the function $A - Be^{-\frac{1}{2} \cos \Omega t}$, shown as solid red and green lines. The error bars on the data are the r.m.s. statistical error on the measured probability, as well as the error in the estimation of the pulse duration. The blue open circles are the product of the probabilities to excite atom a and atom b when the other one is absent. The triangles are the probability to excite the two atoms simultaneously when they are driven by the same pulse.

a, Atoms separated by $18 \mu\text{m}$. The frequencies of the Rabi oscillations are 6.5 and 6.4 MHz for atom a and b respectively. The agreement between the triangles and the blue circles indicates that the atoms do not interact.

b, Blockade of the Rydberg excitation when the two atoms are separated by $3.6 \mu\text{m}$. Owing to the interaction between the atoms, this double excitation is greatly suppressed.

- The excitation in the two-atom system can be described by:

$$(\hbar\Omega/2)(e^{ik\cdot\mathbf{r}_a}|r, g\rangle\langle g, g| + e^{ik\cdot\mathbf{r}_b}|g, r\rangle\langle g, g|)$$

- Then it is convenient to write the eigenstate:

$$|\Psi_{\pm}\rangle = (1/\sqrt{2})(e^{ik\cdot\mathbf{r}_a}|r, g\rangle \pm e^{ik\cdot\mathbf{r}_b}|g, r\rangle)$$

- Where only the $|\Psi_{+}\rangle$ state could be excited, with an enhancement in the Rabi frequency $\sqrt{2}\Omega$ (collective enhancement).

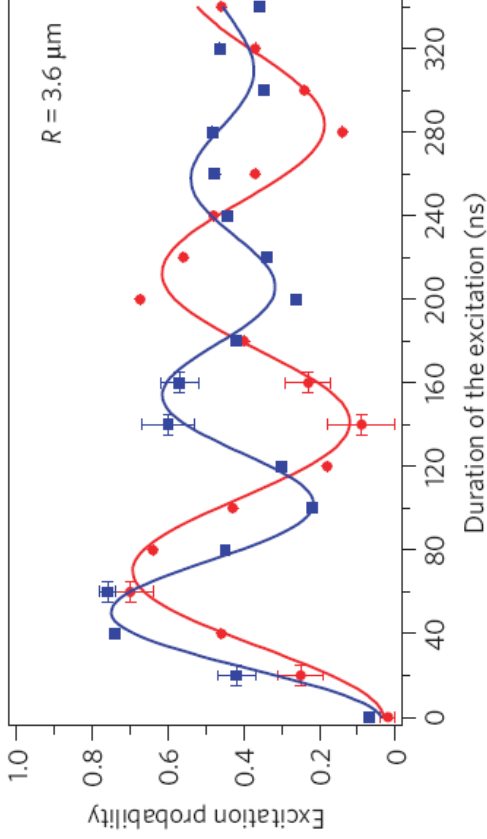


Figure 4 | Excitation of one atom versus collective excitation of two atoms separated by 3.6 μm . The circles represent the probability to excite atom a when atom b is absent (same curve as in Fig. 3b). A fit to the data yields a frequency of this Rabi oscillation $\Omega/2\pi = 7.0 \pm 0.2$ MHz. The error comes from the fit and corresponds to one standard deviation. The squares represent the probability to excite only one atom when the two atoms are trapped and are exposed to the same excitation pulse. The fit gives an oscillation frequency $\Omega'/2\pi = 9.7 \pm 0.2$ MHz. The ratio of the oscillation frequencies is 1.38 ± 0.03 , close to the value $\sqrt{2}$ expected for the collective oscillation of two atoms between $|g, g\rangle$ and $|\Psi_{+}\rangle$.

Summary

- Rydberg blockade between two atoms localized in spatially separated trapping sites is observed. The excitation of one atom to a Rydberg level blocks the subsequent excitation of a second atom.
- Extended the range of strong interactions between just two atoms to a distance that is ten times larger than the wavelength of the light needed for internal-state manipulation.
- Provided a physical mechanism needed to deterministically entangle two atoms on fast timescales, compatible with sub-microsecond operation of a quantum gate.