

# DETERMINISTIC ENTANGLEMENT OF TWO NEUTRAL ATOMS USING RYDBERG BLOCKADE

Greg Dmochowski

July 28, 2010

# Table of contents

## Theory:

1. What are Rydberg atoms (for)?
2. Rydberg Blockade
3. C-Phase gates from Rydberg Blockade
4. C-Not gate from C-Phase gate
5. Entanglement from C-Not gate

## Experiment:

1. Trapping two neutral atoms
2. Rydberg Rabi Oscillations
3. Observing Rydberg Blockade
4. C-Not gate operation
5. Entanglement

# Rydberg atoms

- Rydberg states are electronic states with very high principle quantum number,  $n$  ( $n \sim 100$ )
  - Atomic 'radius' scales as  $r \sim n^2$
  - Dipole moment scales as  $\mu \sim r \sim n^2$

- Recall dipole-dipole interaction:

$$V_{\text{dip}}(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \left[ \frac{\mu_1 \cdot \mu_2}{|\mathbf{r}|^3} - 3 \frac{(\mu_1 \cdot \mathbf{r})(\mu_2 \cdot \mathbf{r})}{|\mathbf{r}|^5} \right]$$

- i.e. Two Rydberg atoms can have large dipolar interactions even at modest separations
- Quantum gates need strong, long range interactions for fast gate speeds

# Rydberg blockade

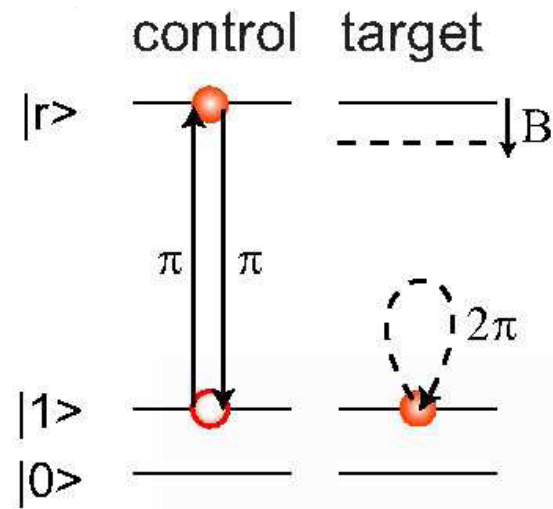
- In general, blockade refers to the prevention of flow or excitation of one particle due to the presence of another particle.
  - ▣ e.g. Coulomb blockade, **photon blockade**
- Here, the presence of one Rydberg atom prevents the excitation of a second, nearby atom to its Rydberg state by way of dipole-dipole interaction.
- Laymen's picture: electric field of large (Rydberg) dipole moment shifts corresponding level of nearby atom out of resonance with excitation beam

# Rydberg blockade as a controlled phase gate

- In absence of 'control' Rydberg state, target atom may undergo  $2\pi$  rotation through its Rydberg state.
- In presence of control Rydberg state, target cannot be excited to its Rydberg state – no phase is incurred.

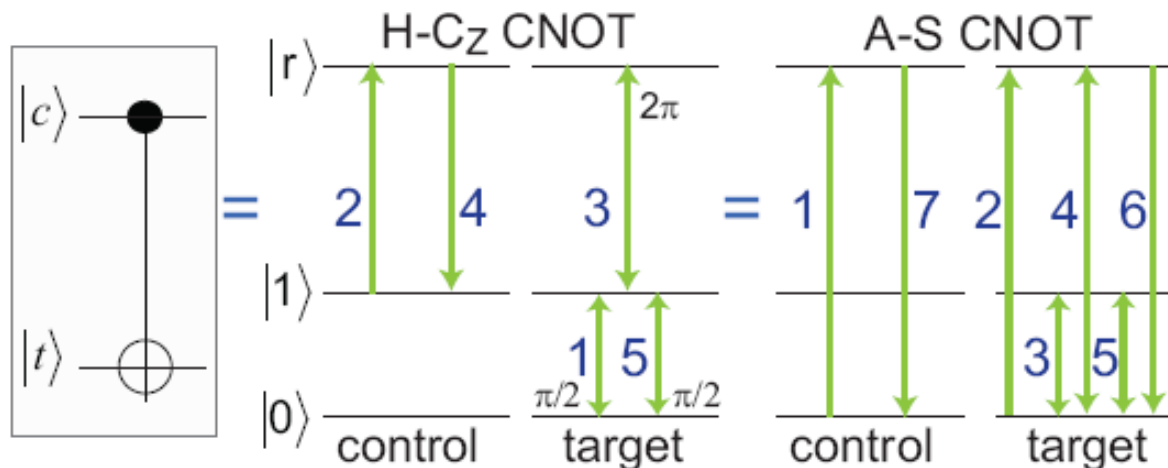
$$|0\rangle_c |1\rangle_t \longrightarrow -|0\rangle_c |1\rangle_t$$

$$|1\rangle_c |1\rangle_t \longrightarrow |1\rangle_c |1\rangle_t$$



# From C-phase to C-Not

- Multiple ways to achieve a C-Not gate from a C-Phase operation
  - ▣ e.g. Hadamard- $C_z$  or Amplitude Swap
- These require additional single-qubit rotations



- (All are  $\pi$  rotations unless otherwise indicated)

# From C-Not to entanglement

- To create entanglement using C-not gate prepare initial states:

$$|ct\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)|0\rangle \quad |ct\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)|1\rangle$$

- Applying C-Not yields Bell states:

$$|B_1\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \text{ and } |B_2\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

- Voila!

But how did they do it in the lab?!



Rotate some frequency knobs

# References for various knob turning activities

## □ Trapping, ground and Rydberg state Rabi oscillations:

PRL **96**, 063001 (2006)      PHYSICAL REVIEW LETTERS      week ending 17 FEBRUARY 2006      PRL **100**, 113003 (2008)      PHYSICAL REVIEW LETTERS      week ending 21 MARCH 2008

**Fast Ground State Manipulation of Neutral Atoms in Microscopic Optical Traps**      **Rabi Oscillations between Ground and Rydberg States with Dipole-Dipole Atomic Interactions**

D. D. Yavuz, P. B. Kulatunga, E. Urban, T. A. Johnson, N. Proite, T. Henage, T. G. Walker, and M. Saffman      T. A. Johnson, E. Urban, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, and M. Saffman

## □ Rydberg Blockade:



### Observation of Rydberg blockade between two atoms

E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker and M. Saffman\*

## □ C-Not gate:

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



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

L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson,\* T. G. Walker, and M. Saffman

## □ Deterministic entanglement:

Deterministic entanglement of two neutral atoms via Rydberg blockade

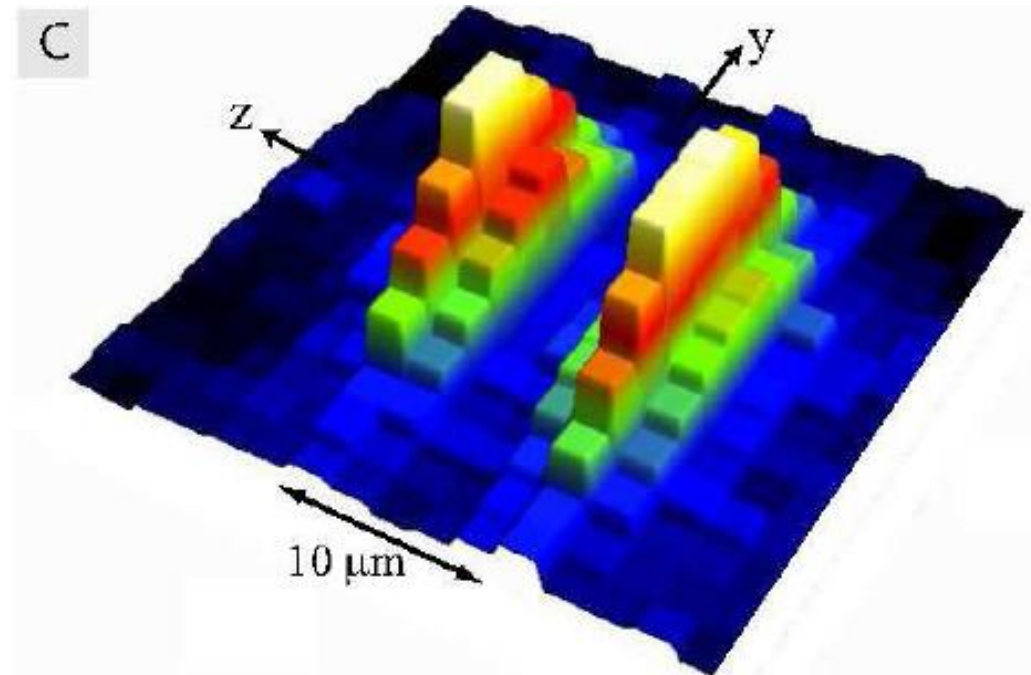
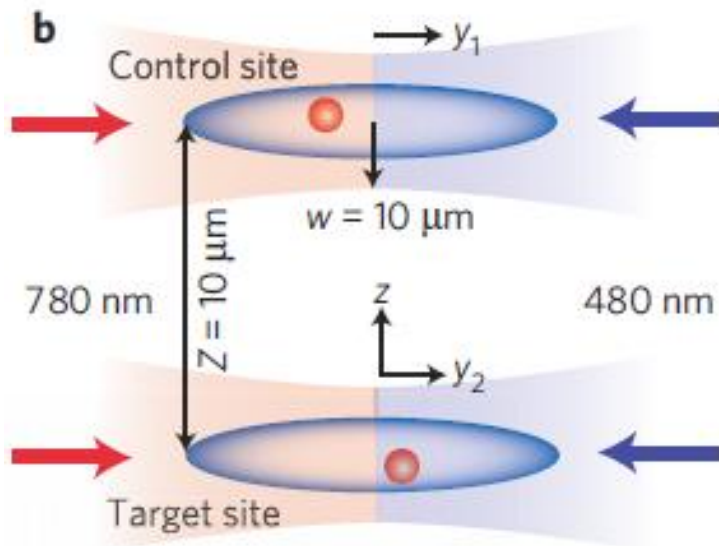
X. L. Zhang, L. Isenhower, A. T. Gill, T. G. Walker, and M. Saffman

arXiv:1007.0397v1 [quant-ph] 2 Jul 2010

# Trapping two single atoms

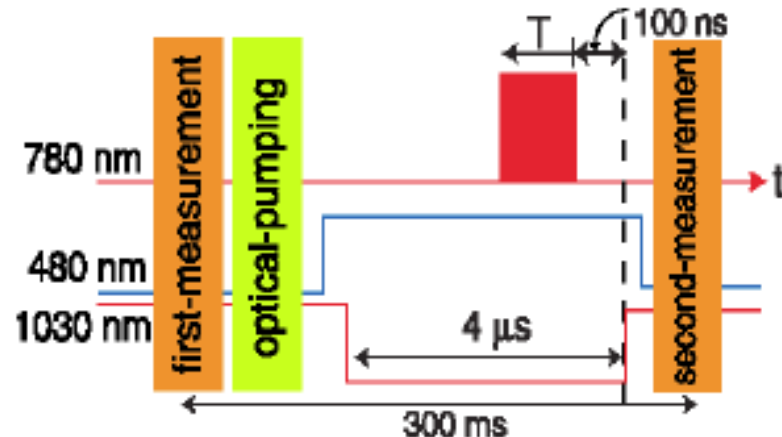
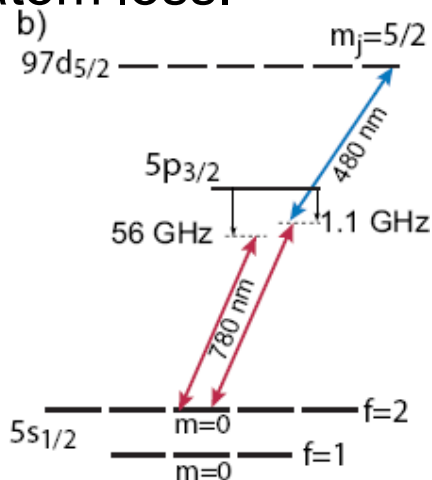
- Far-Off-Resonance-Trap (FORT) is used to confine atoms
- Atoms are loaded from a MOT to the FORT
- Some numbers:
  - 1030nm or 1064nm trapping beam with waist =  $3.2\mu\text{m}$
  - Trapping sites are  $8.7\mu\text{m}, 10\mu\text{m}$  apart
  - $\sigma_{x,y} = 0.3\mu\text{m}, \sigma_z = 4\mu\text{m}$
  - $T \sim 250\mu\text{K}$
- Presence of two single atoms is verified by spatially resolved fluorescence with pre-calibrated thresholds

# Trapping two single atoms



# Rydberg Rabi oscillations

- Two-photon transitions are used
- Measuring ground state population:
  - Photo-ionization of Rydberg level (by FORT beam) is much faster than rate of radiative decay down to ground state
  - ‘blow away’ atoms in Rydberg levels and then measure ground state population using MOT light and cyclic transition
  - This ‘enables detection of Rydberg excitation by monitoring atom loss.’



# Rydberg Rabi oscillations

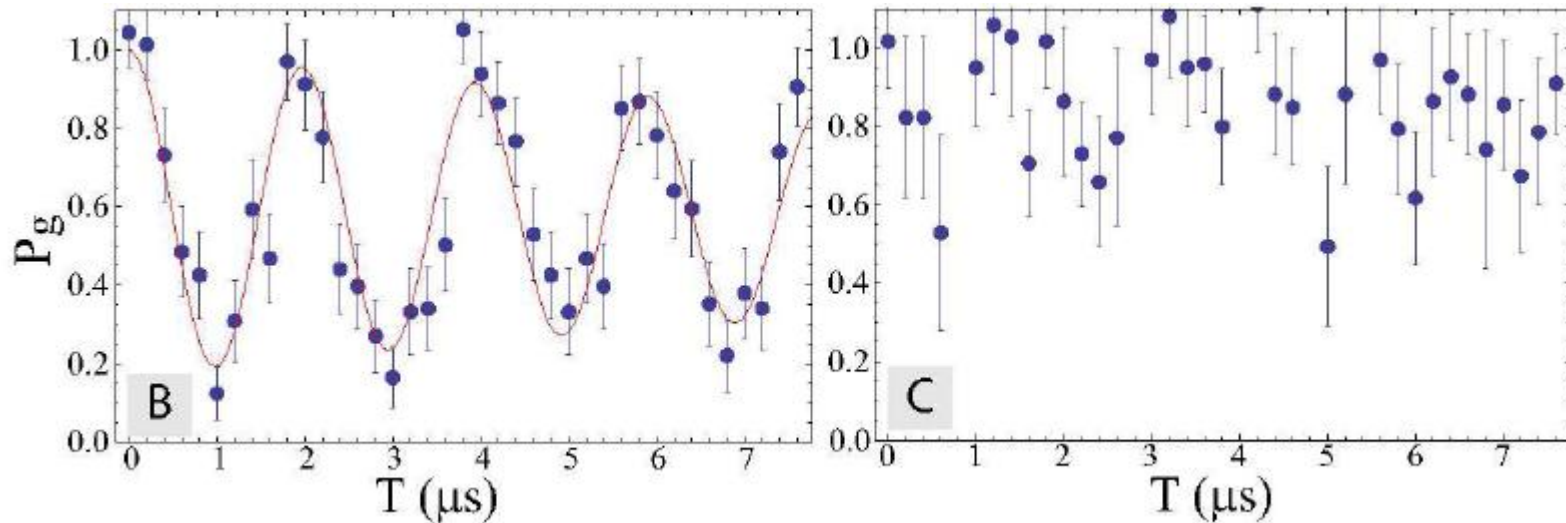


Figure 2: Rabi flopping experiment to  $79d_{5/2}$ . A) experimental sequence, B) measured ground state population during Rabi flopping on the target site and C) crosstalk when the Rydberg excitation lasers are pointed at the empty control site. The Rabi pulse length  $T$  is defined by a 780 nm laser which is switched with a fast AOM (20 ns rise time). The 480 nm light is switched more slowly, before and after each pulse. Each data point is the average of  $\sim 30$  pre-selected single atom experiments, with the bars showing  $\pm 1$  standard deviation. The solid

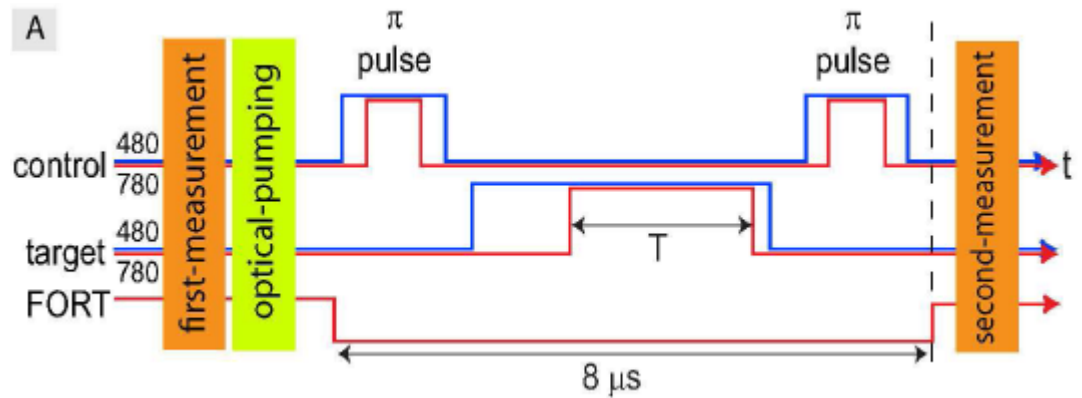
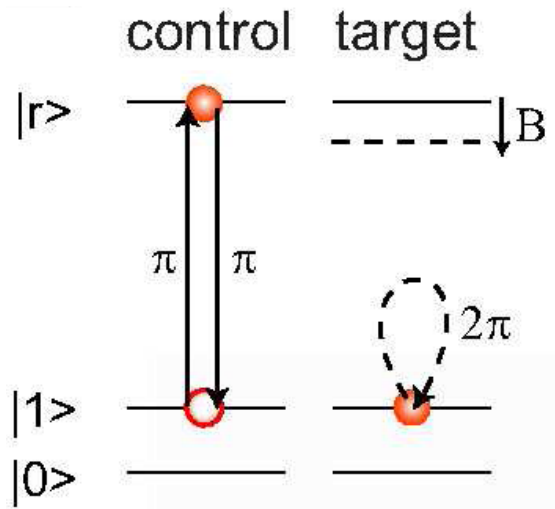
LETTERS

PUBLISHED ONLINE: 11 JANUARY 2009 | DOI: 10.1038/NPHYS1178

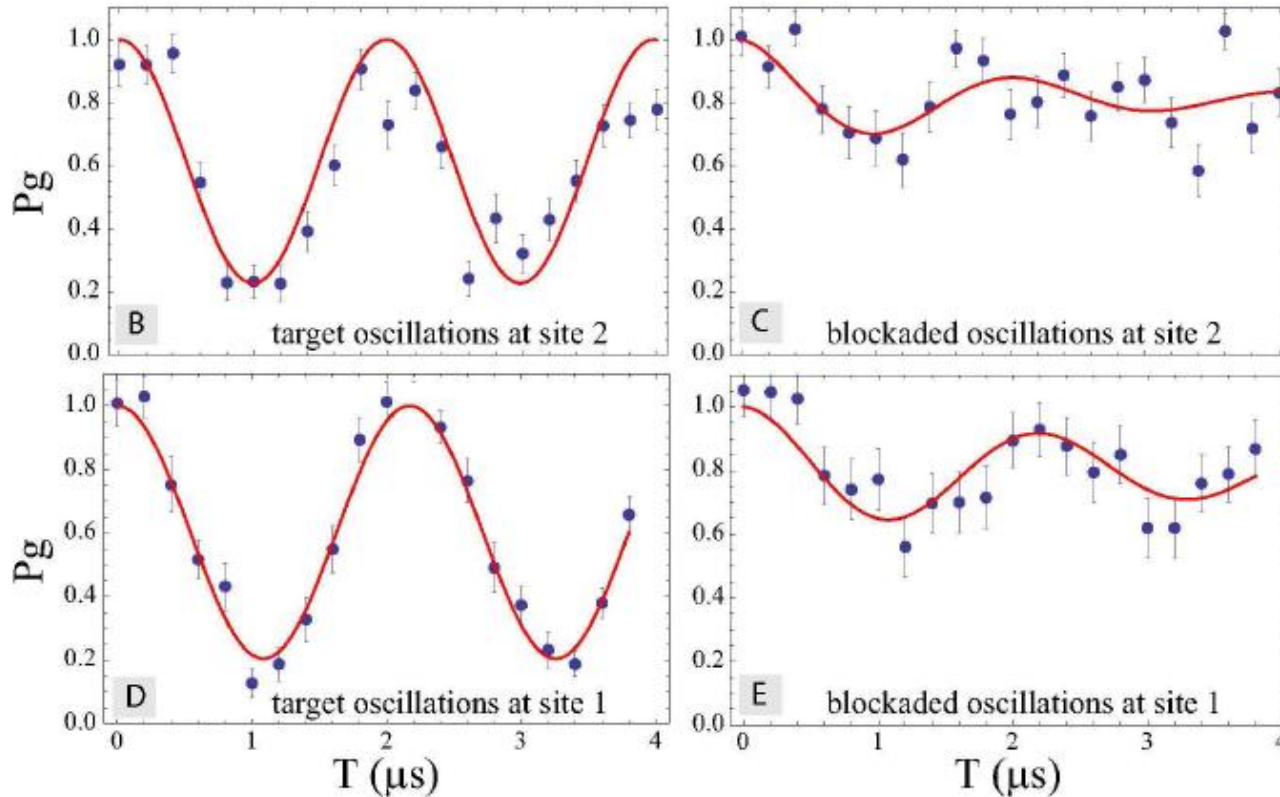
Observation of Rydberg blockade between two atoms

E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker and M. Saffman\*

# Observing Rydberg Blockade



# Observing Rydberg Blockade



Separation between atoms:  $10.2 \mu\text{m}$

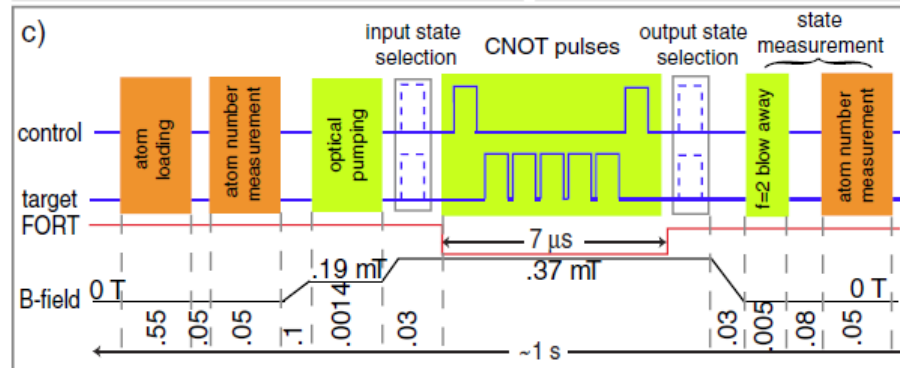
Blockade Shift:  
 $B/2\pi = 9.3 \text{ MHz}$

Rabi frequency:  
 $\Omega/2\pi = 0.67 \text{ MHz}$

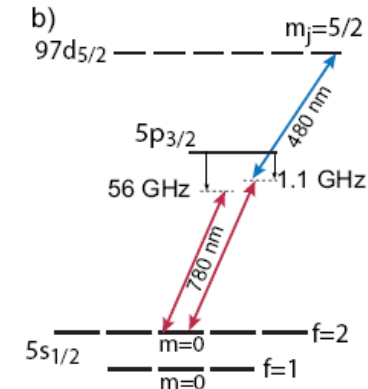
Therefore, double excitation probability:  
 $P_2 \approx \Omega^2/(2B^2) = 2.6 \times 10^{-3}$   
...or 0.1!

**Figure 3 | Rydberg blockade experiment between control and target atoms.** **a**, Experimental sequence. **b**, Rabi oscillations on site 2 when no  $\pi$  pulses are applied to site 1. **c**, Blocked oscillations on site 2 when the  $\pi$  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  $(1-a) + a\cos(2\pi ft)e^{-t/\tau}$ . The fit parameters ( $a, f$  (MHz),  $\tau$  ( $\mu\text{s}$ )) were: (0.44, 0.51, 5.7) for **b**, (0.17, 0.45, 3.0) for **c**, (0.40, 0.46,  $\infty$ ) 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  $t$ .

# C-Not gate from C-Phase operation



- Atoms pumped into  $|f = 2, m_f = 0\rangle$
- Ground state pi pulses are then selectively applied to prepare desired initial state
  - ▣ Hadamard- $C_z$ :  $|0(1)\rangle$  are  $|f = 1(2), m_f = 0\rangle$
  - ▣ Amplitude swap:  $|0(1)\rangle$  are  $|f = 2(1), m_f = 0\rangle$
- Measure output state:
  - ▣ Atoms left in  $f=2$  are blown away with unbalanced radiation pressure
  - ▣ “and a measurement is made to determine if the selected output state is present”
  - ▣ e.g. If you want to check for  $|f=2, f=1\rangle_{ct}$  then apply pi pulse to control atom, send in blow away light and then measure if atoms remain in both sites



# C-Not gate from C-Phase operation

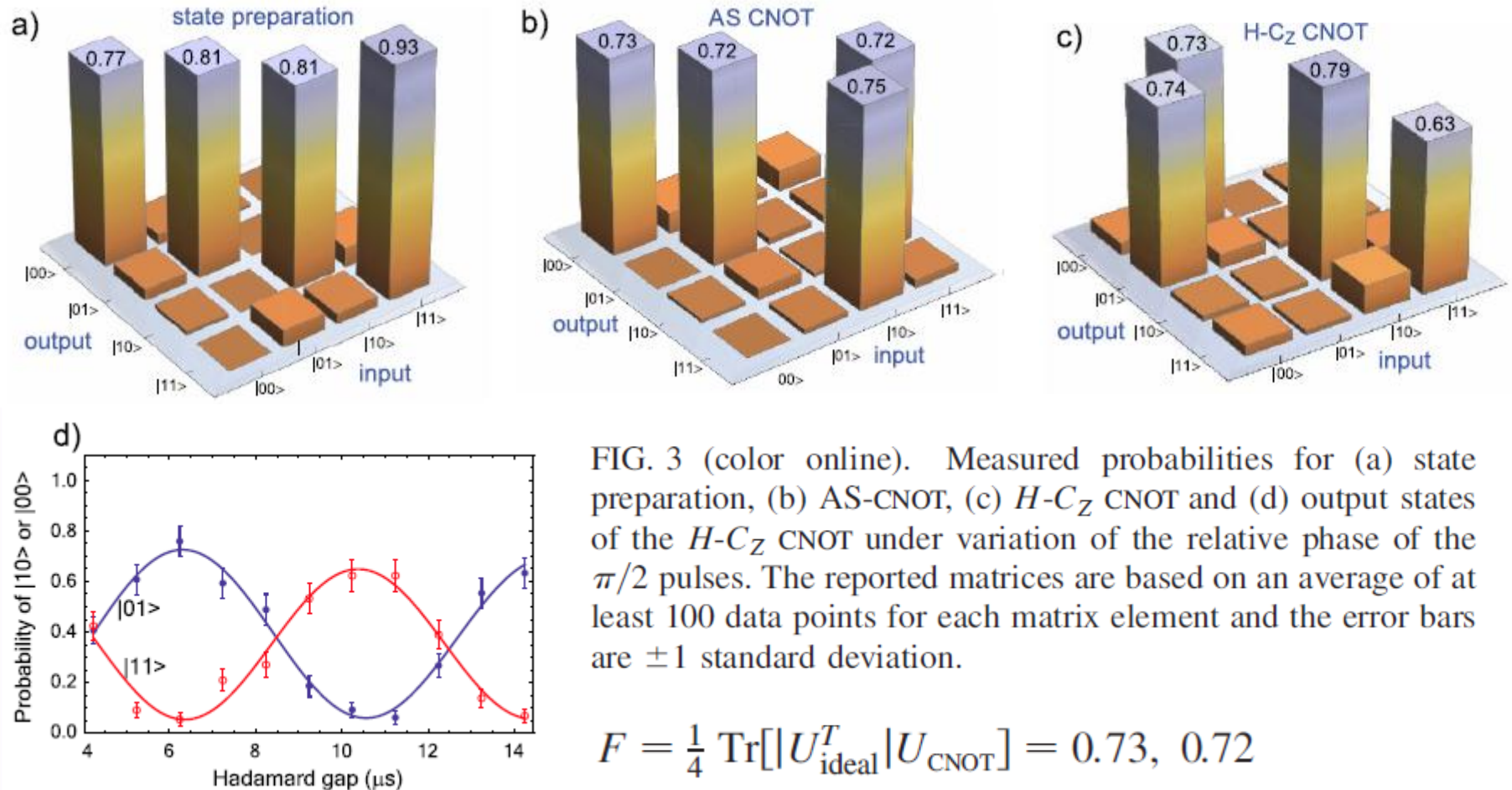


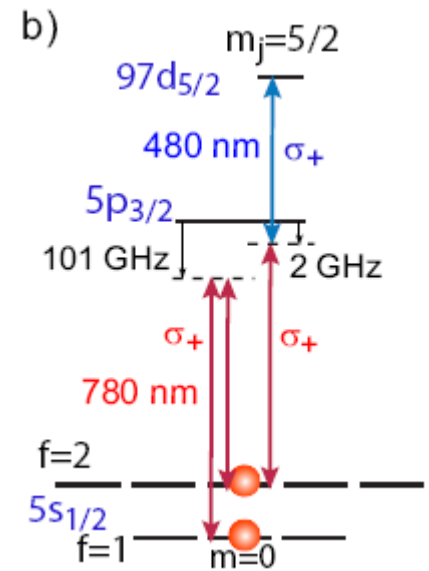
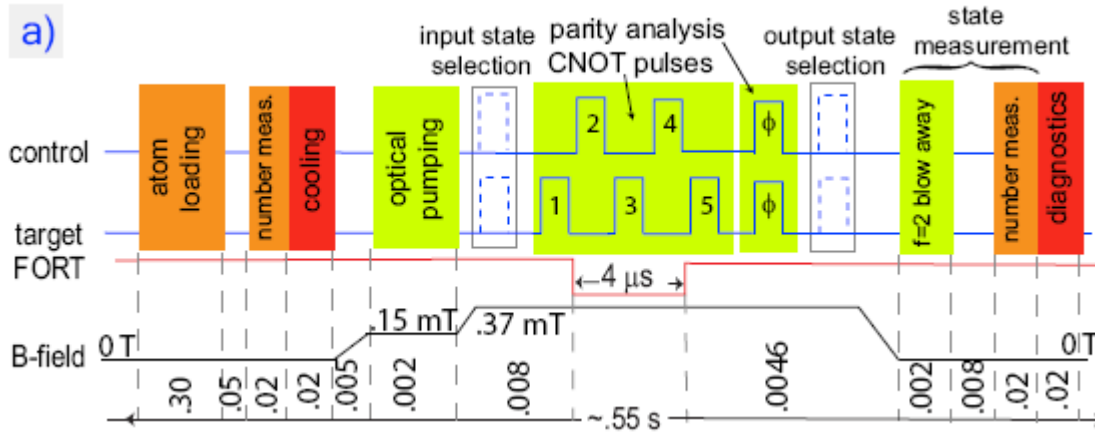
FIG. 3 (color online). Measured probabilities for (a) state preparation, (b) AS-CNOT, (c)  $H$ - $C_Z$  CNOT and (d) output states of the  $H$ - $C_Z$  CNOT under variation of the relative phase of the  $\pi/2$  pulses. The reported matrices are based on an average of at least 100 data points for each matrix element and the error bars are  $\pm 1$  standard deviation.

$$F = \frac{1}{4} \text{Tr}[|U_{\text{ideal}}^T |U_{\text{CNOT}}] = 0.73, 0.72$$

# Accounting for low fidelity

- Sources of error:
  - ▣ Imperfect optical pumping, drift of laser pulses
  - ▣ Blockade 'leakage' (Double excitation probability: 0.1)
  - ▣ Imperfect pulse areas
- These yield the possibility of occupying Rydberg states at the end of pulse sequence, and FORT beams will photo-ionize these atoms...hence, lost.

# Deterministic entanglement



- Optical pumping into  $|f = 2, m_f = 0\rangle$
- Basis:  $|0\rangle \equiv |f = 1, m_f = 0\rangle, |1\rangle \equiv |f = 2, m_f = 0\rangle$

# Deterministic entanglement

## □ Ground and Rydberg Rabi oscillations

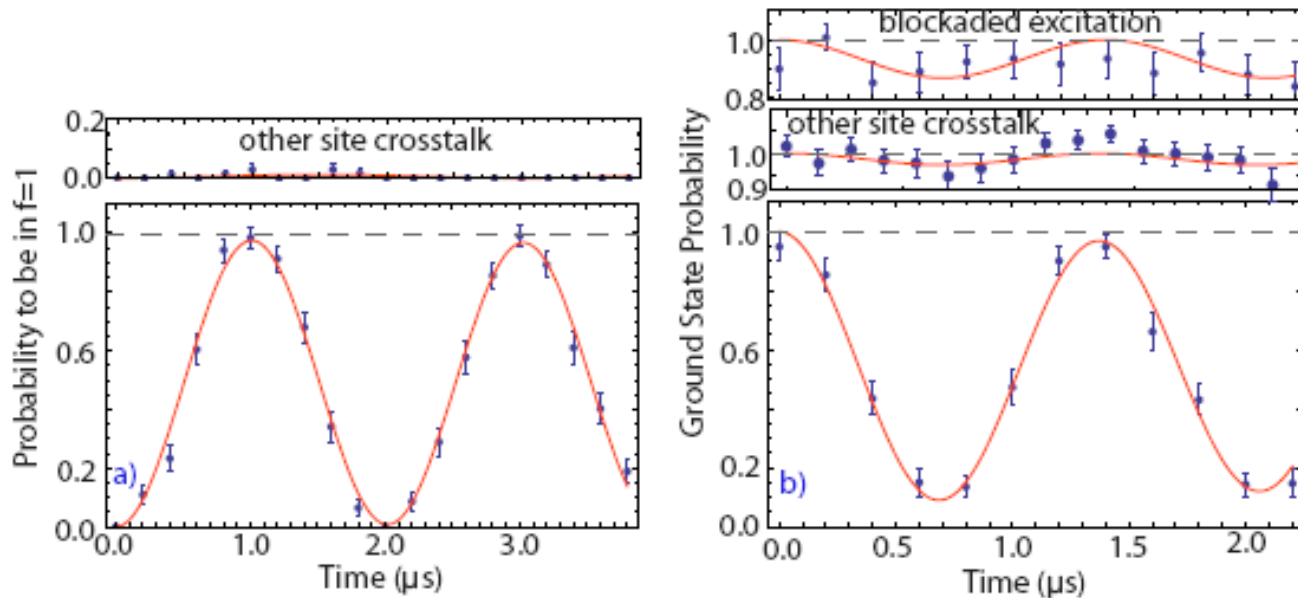


FIG. 2: (color online) a) Ground Rabi flopping on targeted site with neighboring site crosstalk in upper panel and b) Rydberg Rabi flopping on targeted site, with neighboring site crosstalk and flopping blocked by prior excitation of the neighboring site in upper panels. The flopping curves are based on an average of about 100 measurements for each point.

# Deterministic entanglement

## □ State preparation and C-Not

$$|U_{\text{CNOT}}| = \begin{pmatrix} 0.08 & 0.93 \pm .06 & 0 & 0 \\ 0.88 \pm .06 & 0.02 & 0.02 & 0.02 \\ 0 & 0 & 0.90 \pm .07 & 0.05 \\ 0.02 & 0.05 & 0.07 & 0.94 \pm .06 \end{pmatrix}$$

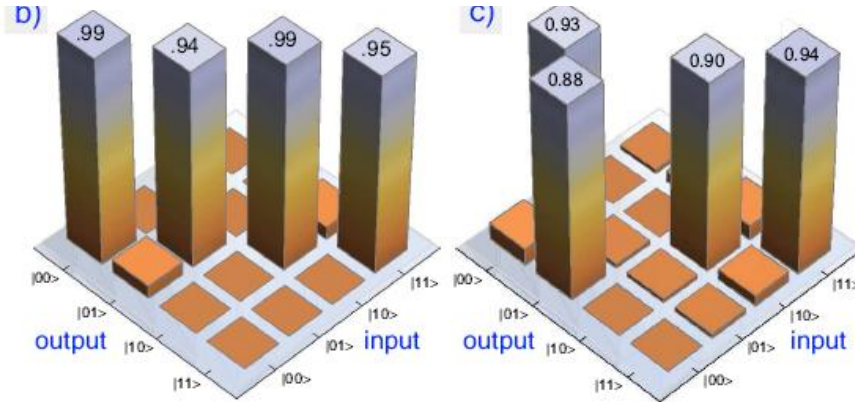


FIG. 3: (color online) a) Experimental sequence, pulses 1 and 5 are ground Rabi  $\pi/2$  pulses; pulses 2 and 4 are Rydberg  $\pi$  pulses; pulse 3 is a Rydberg  $2\pi$  pulse. Measured probabilities for state preparation b) and  $H - C_Z$  CNOT c). The reported matrices are based on an average of about 100 data points for each matrix element.

Fidelity:

$$\frac{1}{4} \text{Tr}[|U_{\text{ideal}}^T|U_{\text{CNOT}}] = 0.91 \pm .06$$

TABLE I: Error sources for the CNOT truth table and entanglement results. Spontaneous emission refers to scattering from  $5p_{3/2}$  during Rydberg excitation and Doppler broadening causes imperfect Rydberg excitation.

error sources (two qubits)	Ref. [10]	this work
optical pumping	0.1	0.02
atom losses before CNOT pulses	0.09	0.02
blockade error at 175 $\mu\text{K}$	0.01	0.01
spontaneous emission	0.04	0.04
Doppler broadening	0.04	0.04
Total CNOT error (added in quadrature)	$\sim 0.15$	$\sim 0.06$
<b>measured results</b>		
background loss (two atoms)	0.28	0.19
gate trace loss ( $1 - \text{Tr}[\rho]$ )	0.17	$\sim 0.01$
CNOT fidelity raw	0.52	0.74
CNOT background loss corrected	0.72	0.91
CNOT background & trace corrected	0.86	0.92
entanglement fidelity raw	0.34	0.58
entanglement background loss corrected	0.48	0.71
entanglement background & trace corrected	0.58	0.71

# Deterministic entanglement

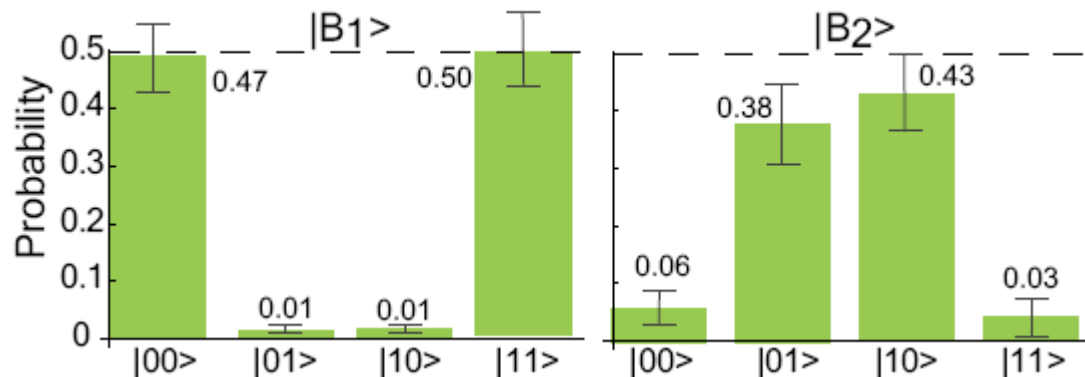
- Prepare initial states:

$$|ct\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)|0\rangle \quad |ct\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)|1\rangle$$

- Applying C-Not yields Bell states:

$$|B_1\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \text{ and } |B_2\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

- Measure:



# Verifying entanglement

- Use the parity signal:  $P = P_{00} + P_{11} - P_{01} - P_{10}$
- Parity signal should vary as:

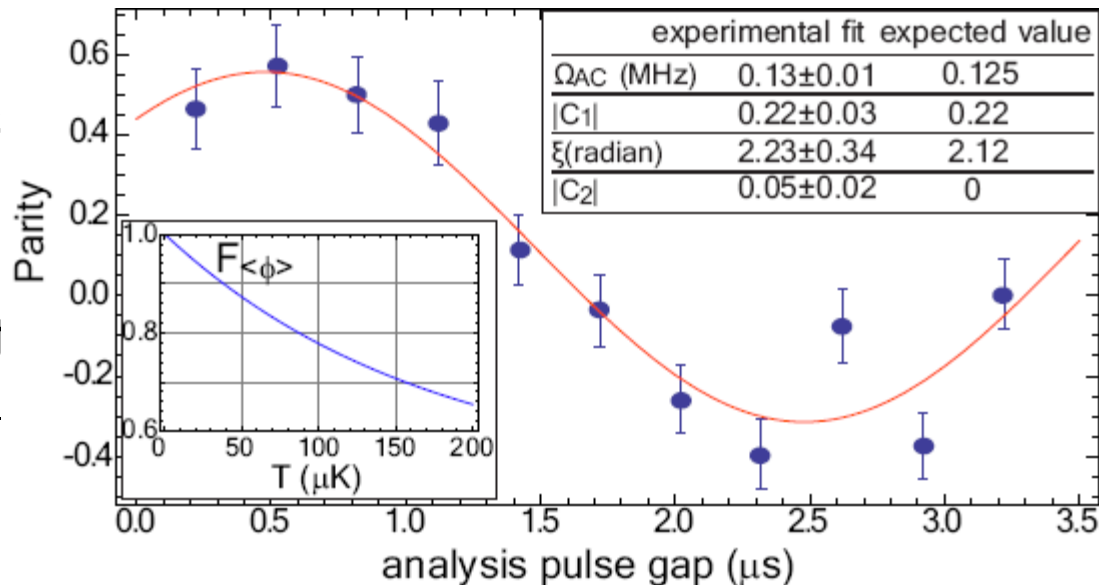
$$P = 2\text{Re}(C_2) - 2|C_1| \cos(2\phi + \xi)$$

where  $C_2$  is coherence between  $|01\rangle$  and  $|10\rangle$   
and  $C_1$  is the coherence between  $|00\rangle$  and  $|11\rangle$

A suff

Fidelity

$F$



$$5 < F \leq 1$$

.04

# Conclusion

---

Frequency knobs are a bit more complicated than wave plates

# Comparison of Rydberg blockade

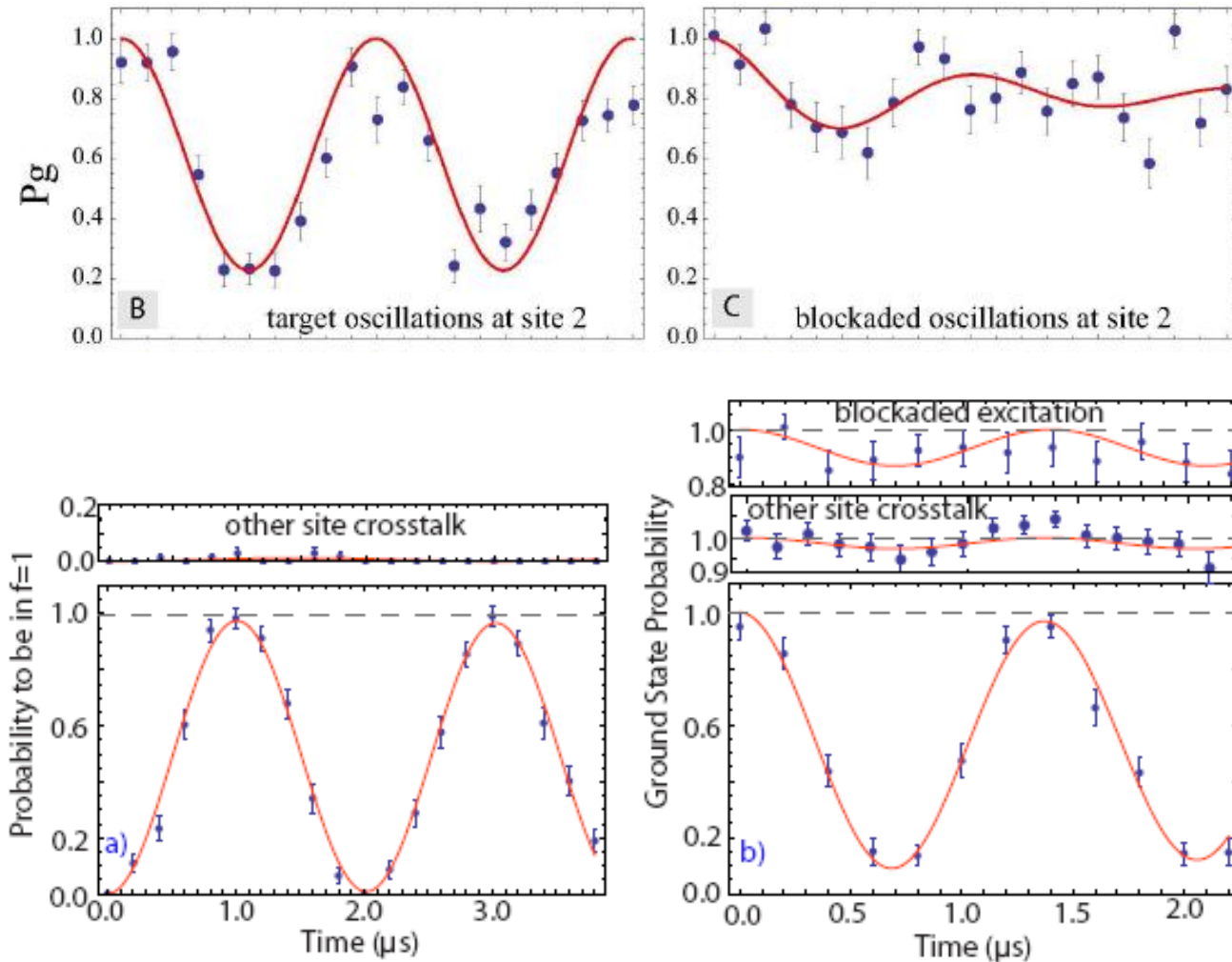


FIG. 2: (color online) a) Ground Rabi flopping on targeted