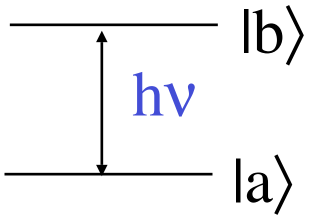
Clocks

How the NIST F-1 Cesium Fountain Clock Works



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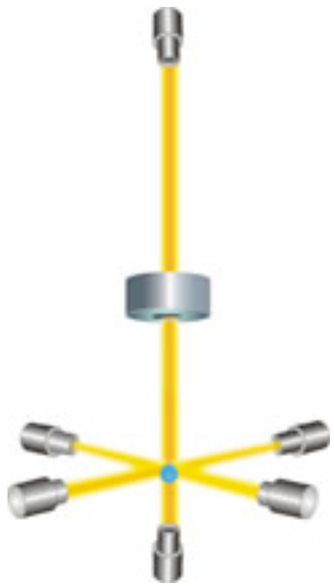
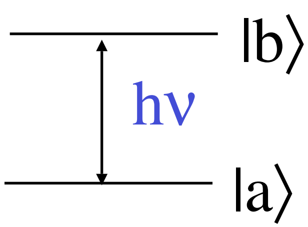


A gas of cesium atoms enters the clock's vacuum chamber. Six lasers slow the movement of the atoms, cool them to near absolute zero and force them into a spherical cloud at the intersection of the laser beams.



Clocks

How the NIST F-1 Cesium Fountain Clock Works

The ball is tossed upward by two lasers through a cavity filled with microwaves. All of the lasers are then turned off.

$$\psi = |a\rangle - i|b\rangle$$

$|b\rangle$

$h\nu$

$|a\rangle$

Clocks

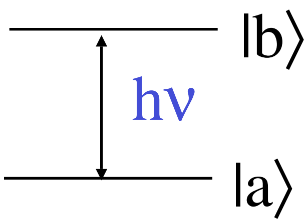
How the NIST F-1 Cesium Fountain Clock Works

Gravity pulls the ball of cesium atoms back through the microwave cavity.

$$\psi = |a\rangle - ie^{-i(E_b - h\nu)/\hbar}|b\rangle$$

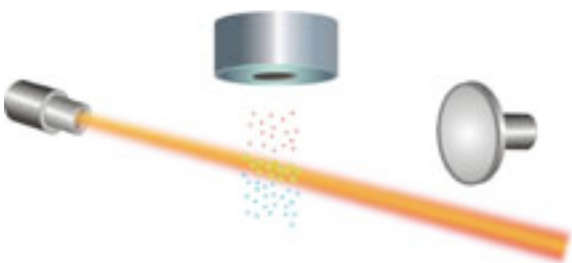
The microwaves partially alter the atomic states of the cesium atoms.

$$\psi = \left(1 - e^{-i(E_b - h\nu)t/\hbar}\right)|a\rangle - i\left(1 + e^{-i(E_b - h\nu)t/\hbar}\right)|b\rangle$$



Clocks

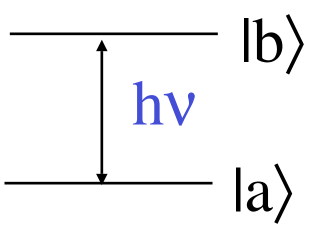
How the NIST F-1 Cesium Fountain Clock Works



Cesium atoms that were altered in the microwave cavity emit light when hit with a laser beam. This fluorescence is measured by a detector.

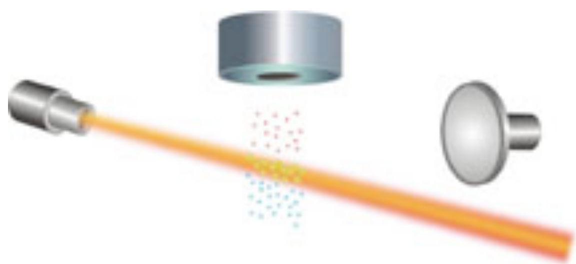
$$P_b = \left|\langle b|\psi\rangle\right|^2 = \frac{1}{2}+\frac{1}{2}\cos\left((E_b - h\nu)t/\hbar\right)$$

The entire process is repeated until the maximum fluorescence of the cesium atoms is determined.



Clocks

How the NIST F-1 Cesium Fountain Clock Works



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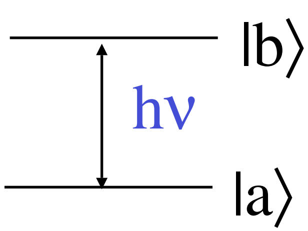


$$\frac{\delta\nu}{\nu} = 10^{-15}$$

Quantum Manipulation of Neutral Atoms Without Forces

Atom Trainers

Grad Students

Todd Johnson
Erich Urban
Thomas Henage
Larry Isenhower

Faculty

Mark Saffman
Thad Walker
Deniz Yavuz

University of Wisconsin-Madison

- Rydberg Blockade physics
- Experimental Realization of 2 qubit system
- Two-atom blockade observations
- Extensions to ensembles

Qubits-Quantum Information

——— $|b\rangle$

——— $|a\rangle$

$\alpha^2+\beta^2=1$

Classical bit can be in 0 or 1

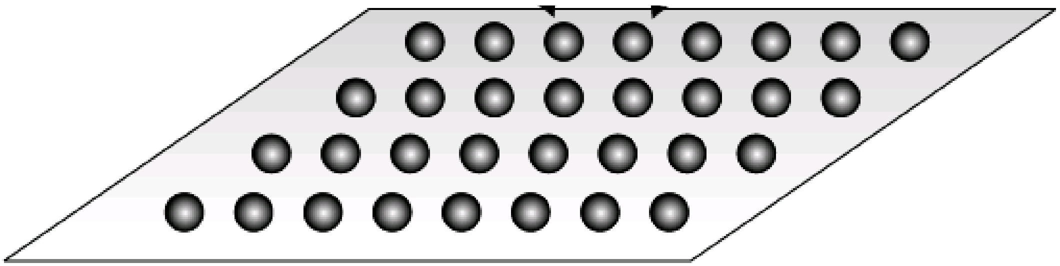
Qubit is in superposition of $|a\rangle, |b\rangle$

Entanglement: pairs of Qubits cannot be written in the form $|\psi_1\rangle|\psi_2\rangle$

Example: $|\Psi\rangle = |ab\rangle - |ba\rangle$

Superposition+Entanglement $\Rightarrow$ Quantum Info. Processing

Future Quantum Computer



Need to entangle a large number
of near atomic clock quality qubits
that are resolvable distances apart

Long-Range Forces Between Atoms

At optically resolvable (1 μm) distances, what is the dominant interatomic interaction?

Ground state Rb atoms

Highly excited (Rydberg) atoms, n=90

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Ground state Rb atoms $V(R) \sim \frac{\mu^2}{R^3} \sim 10^{-20}\,\mathrm{eV}$

Highly excited (Rydberg) atoms, n=90

Long-Range Forces Between Atoms

At optically resolvable (1 μm) distances, what is the dominant interatomic interaction?

Ground state Rb atoms $$V(R) \sim \frac{\mu^2}{R^3} \sim 10^{-20}\,\mathrm{eV}$$

Highly excited (Rydberg) atoms, n=90 $$V(R) \sim \frac{n^4 e^2 a^2}{R^3} \sim 10^{-4}\,\mathrm{eV}$$

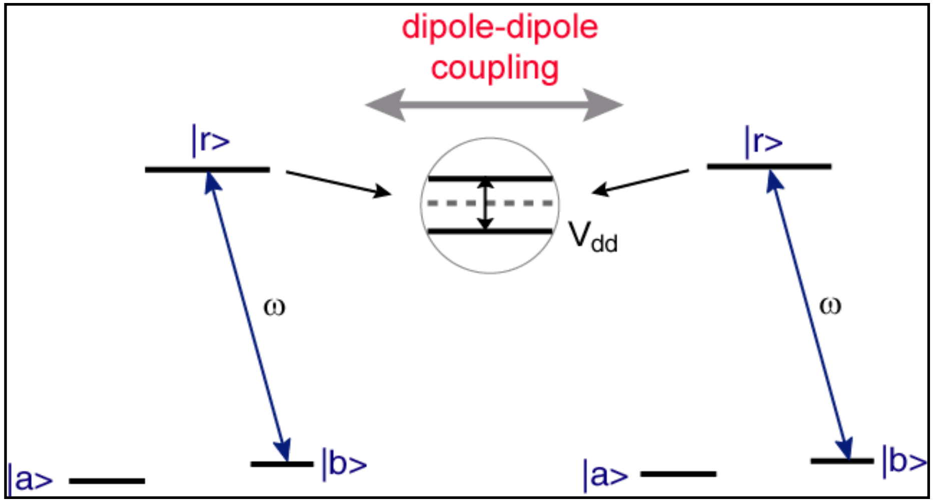
Requirements for Universal Quantum Computer

Atom Trainers

diVincenzo:

- state initialization
  - deterministic loading, optical pumping
- universal set of gates:
  - single qubit rotations via Raman
  - two-qubit gates via Rydberg
- qubit specific readout
  - addressable shelving
- decoherence rate << rate of coherent operations
  - clock transition
- scalable
  - diffractive & acousto-optics

Entanglement Using Dipole Blockade



n=50 Dipole-dipole shifts 10s MHz
at 10 micron separations

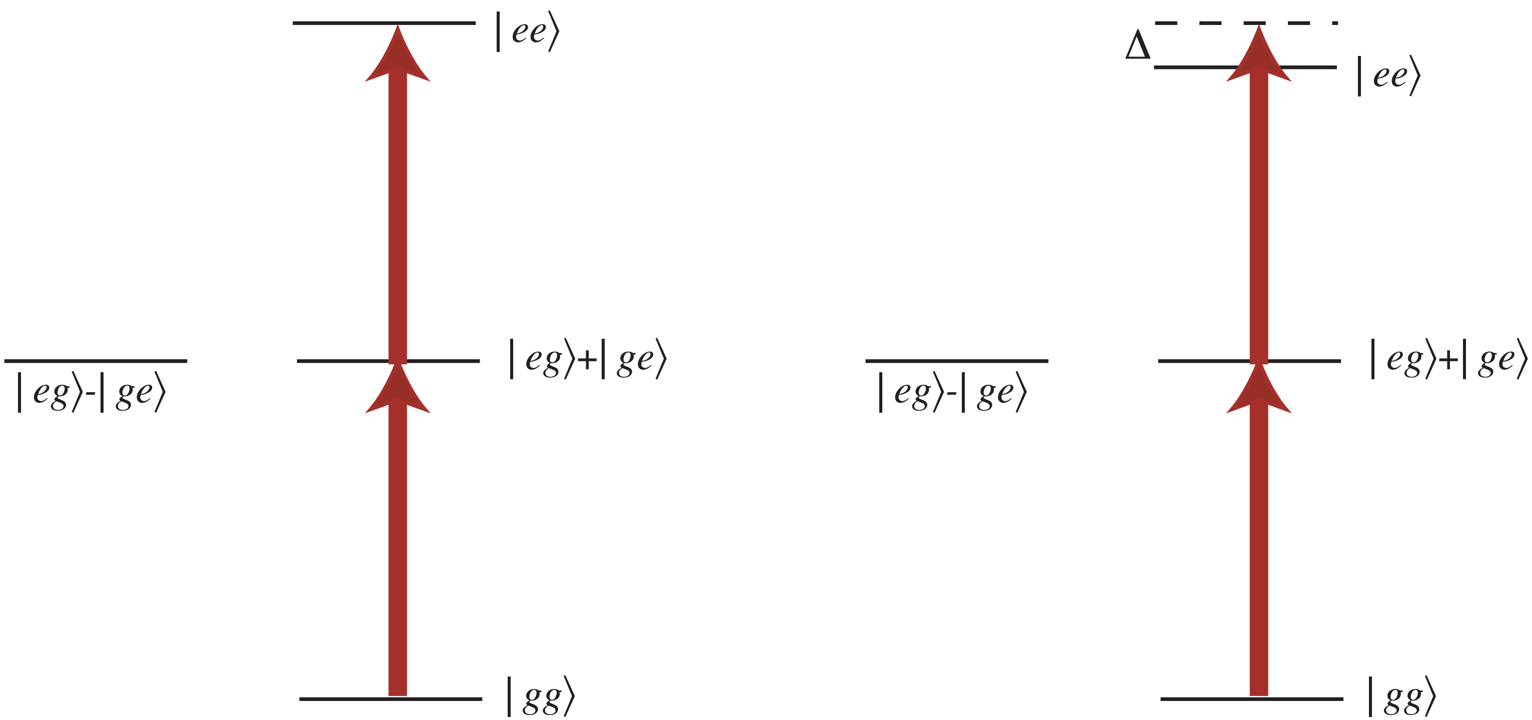
$$U \sim \frac{n^4}{R^3}$$

Jaksch...Lukin, et al. PRL 85, 2208 (2000):
Excitation of 2 nearby atoms energetically suppressed due to dipole-dipole shift

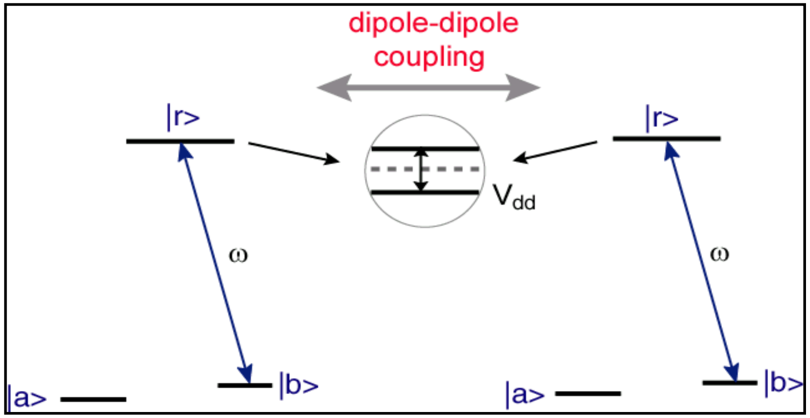
Two-atom blockade

No Interaction

With Dipole-Dipole Interaction



Dipole blockade phase gate



Rabi Flopping

"π-pulse":

$b \Rightarrow ir$

"2π-pulse":

$b \Rightarrow ir \Rightarrow -b$

Initial state	π control	2π data	π control
aa	aa	aa	aa
ab	ab	$-ab$	$-ab$
ba	$e^{i\pi/2}ra$	$e^{i\pi/2}ra$	$-ba$
bb	$e^{i\pi/2}rb$	$e^{i\pi/2}rb$	$-bb$

Controlled-NOT Gate

$$\boxed{\begin{array}{l} aa \Rightarrow aa \\ ab \Rightarrow ab \\ bb \Rightarrow ba \\ ba \Rightarrow bb \end{array}} = \text{C-Phase + Rabi Rotations}$$

CNOT+Rotations $\Rightarrow$ Arbitrary Quantum Manipulations

Features of Rydberg Blockade

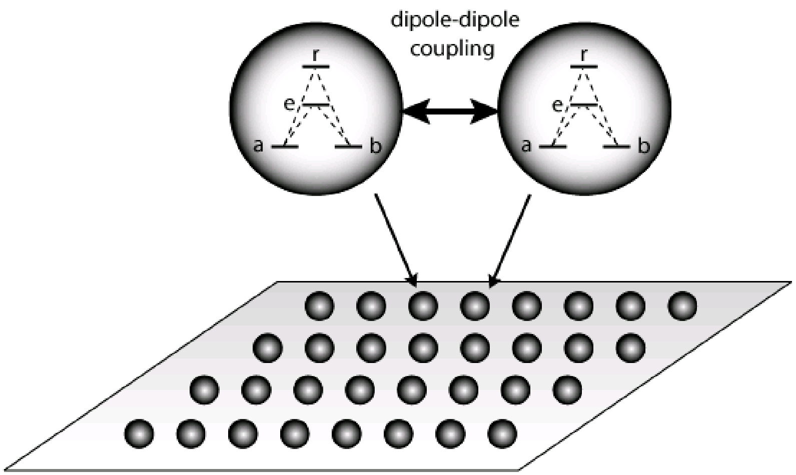
1) Blockade only involves internal degrees of freedom

2) Value of dipole-dipole interaction does not need to be precisely controlled

3) Strong blockade gives fast gates (MHz)

4) For good blockade, the atoms experience no atom-atom forces!

Concept for Rydberg Atom Quantum Computer



0-0 clock transition for qubit

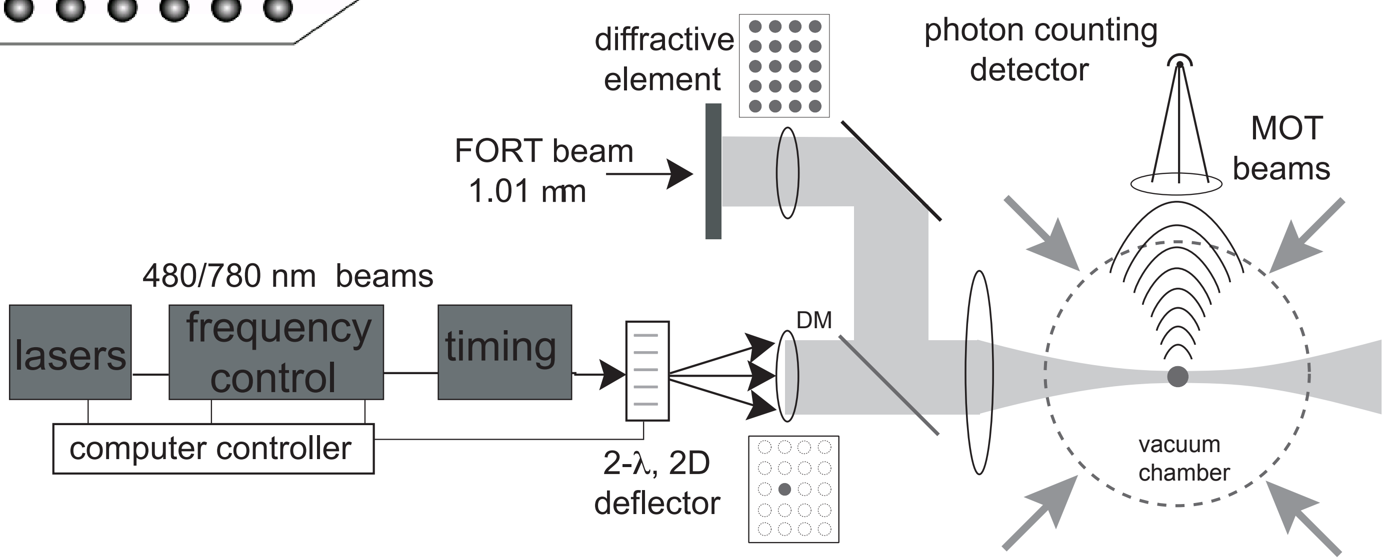
5-10 μm qubit spacing for addressability

Coherent 2-photon Rydberg Excitation

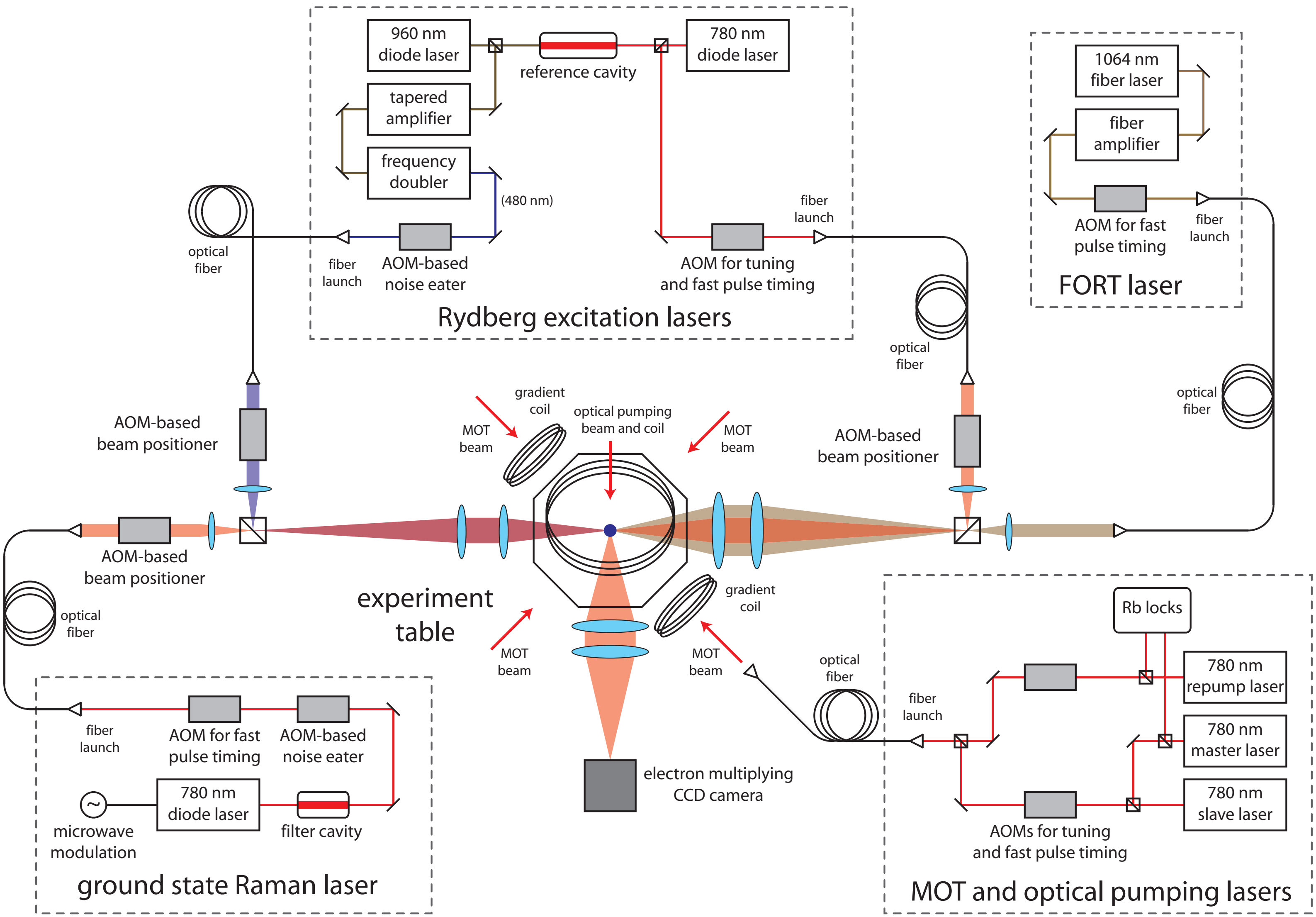
Entanglement via Rydberg blockade

Single qubit rotations via Stimulated Raman

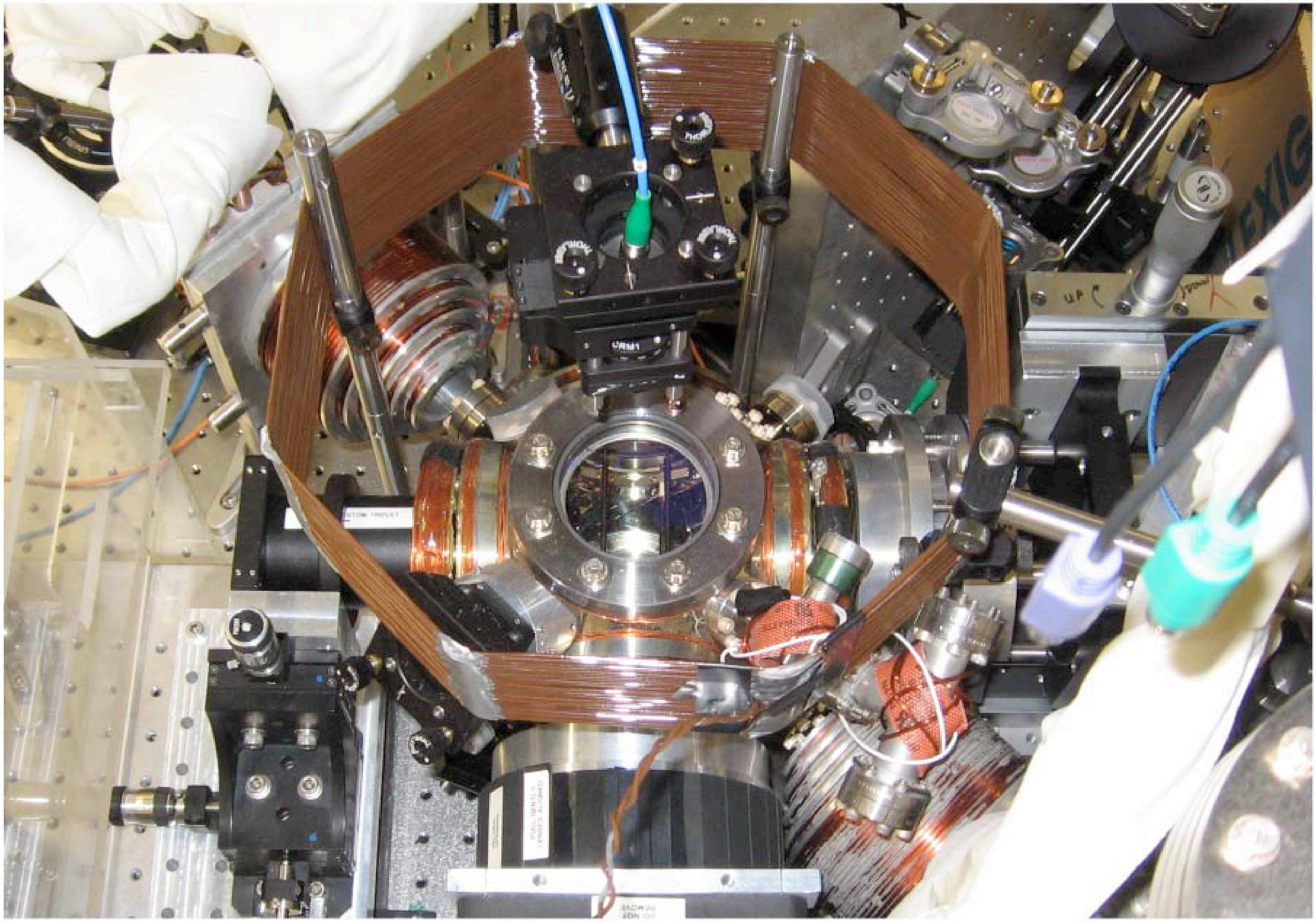
State measurement using shelving



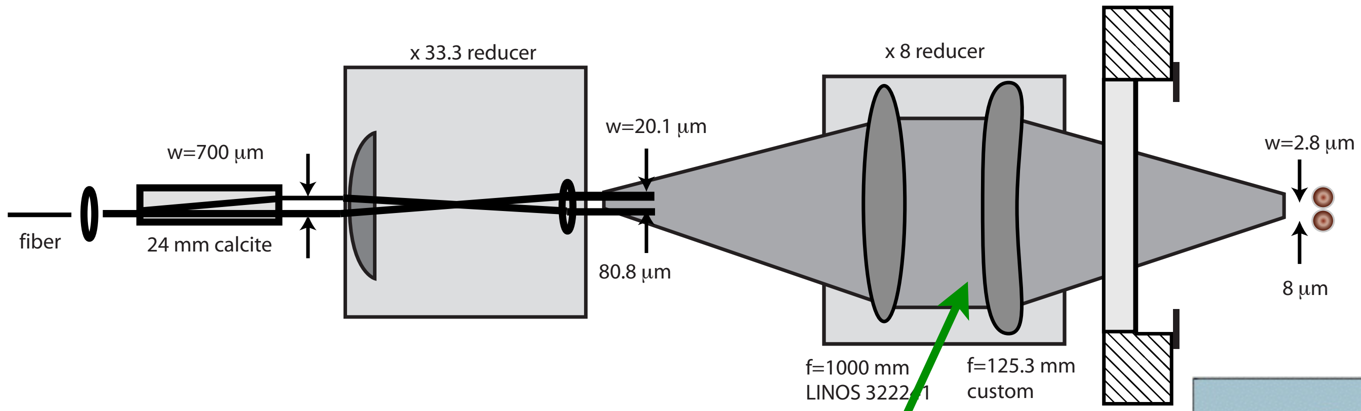
Setup in more detail



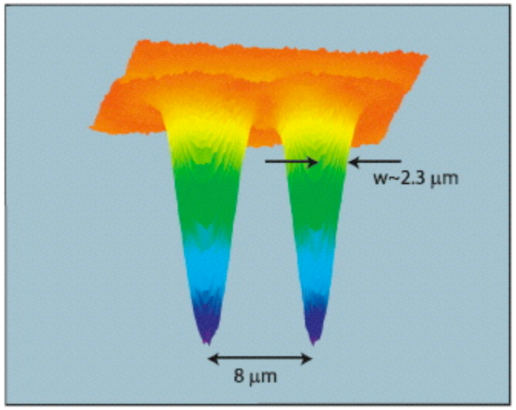
Chamber



FORT Optics



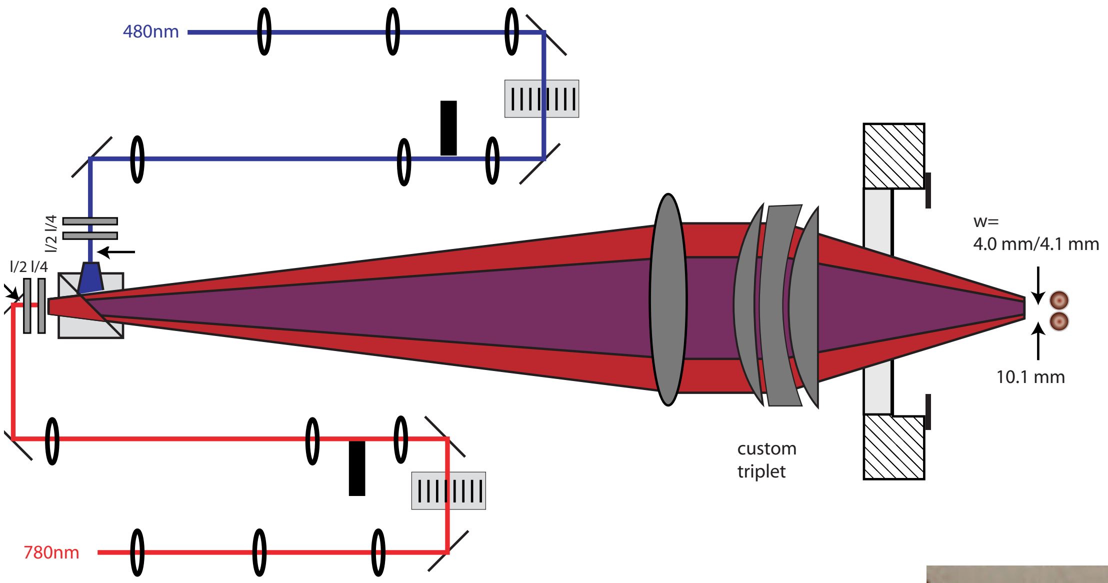
Custom 1.03/0.78 μm
achromatic triplet w/
window compensation



2W/qubit

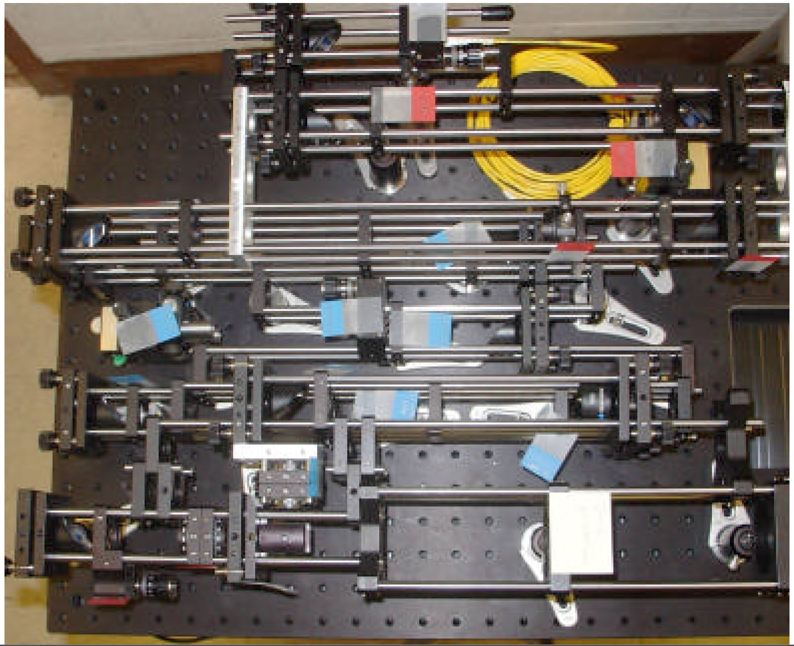
$\lambda = 1.03\ \mu m$

Logic Beam Optics



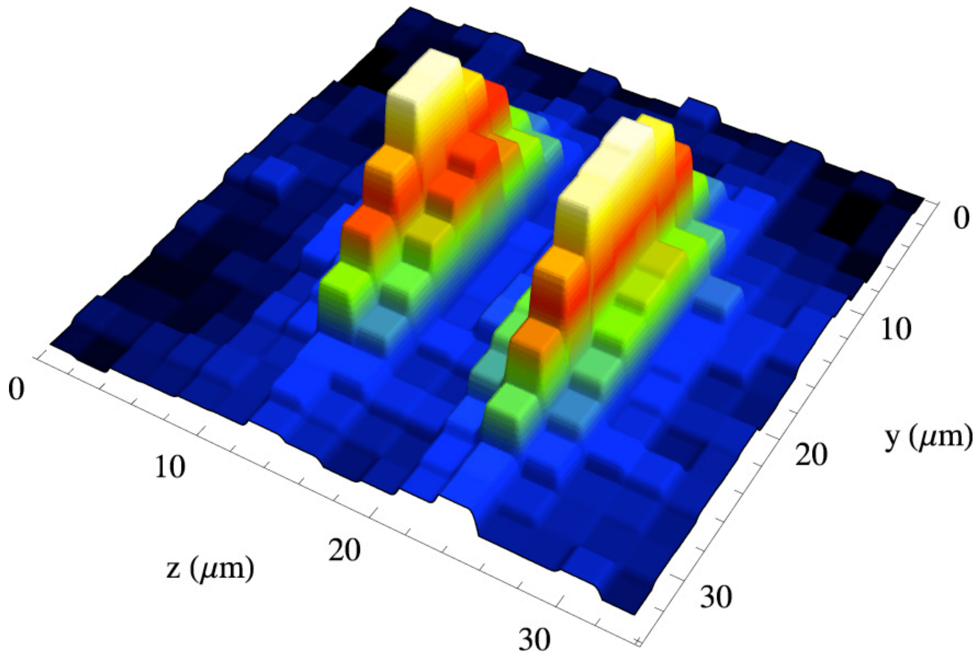
Shift A/O frequency to address individual qubits

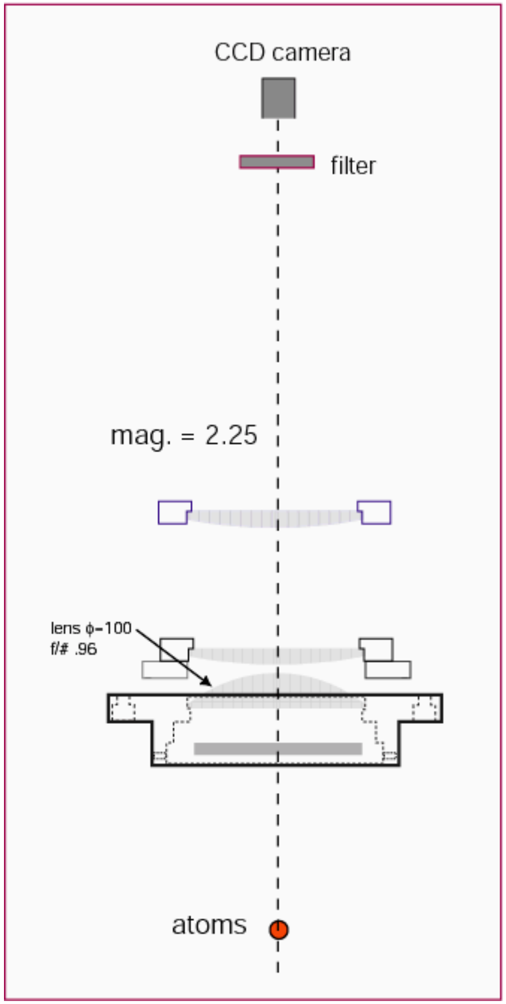
Use +/- 1 order A/O for red/blue, drive w/ same VCO, compensate magnifications to get commensurate red/blue motion



Atom Detection

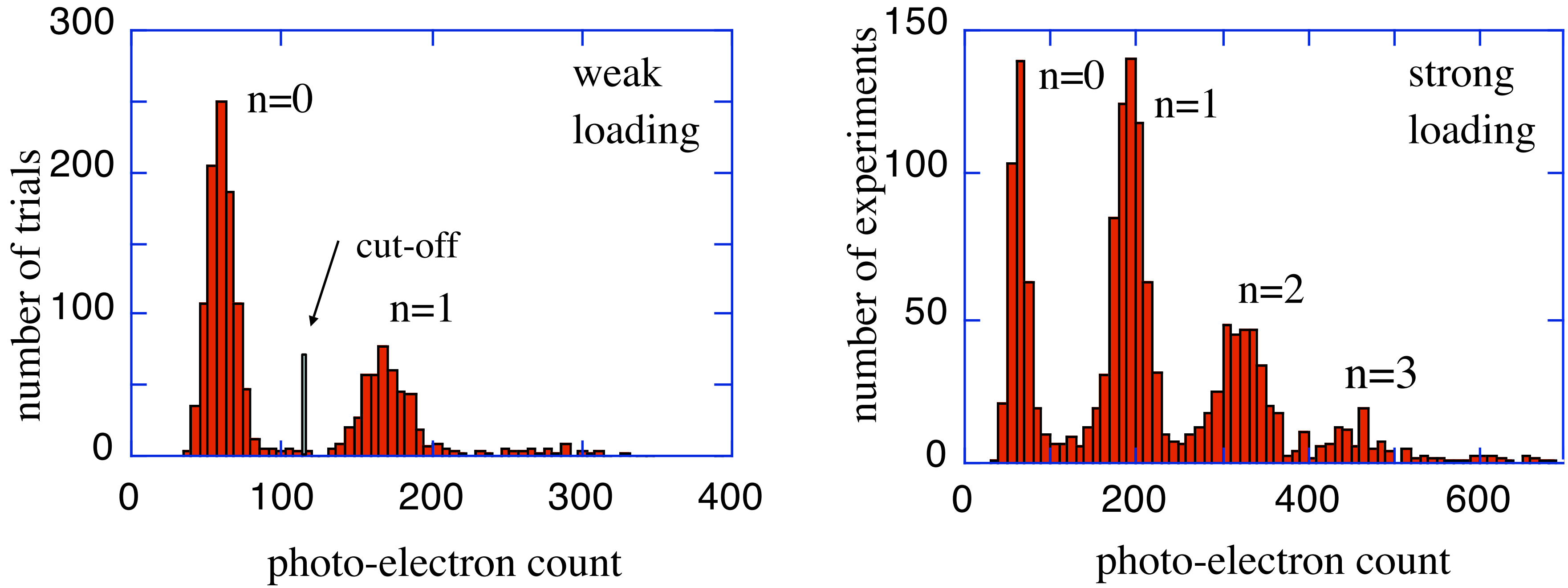
Andor iXon e-multiplying CCD





Single-Atom Detection

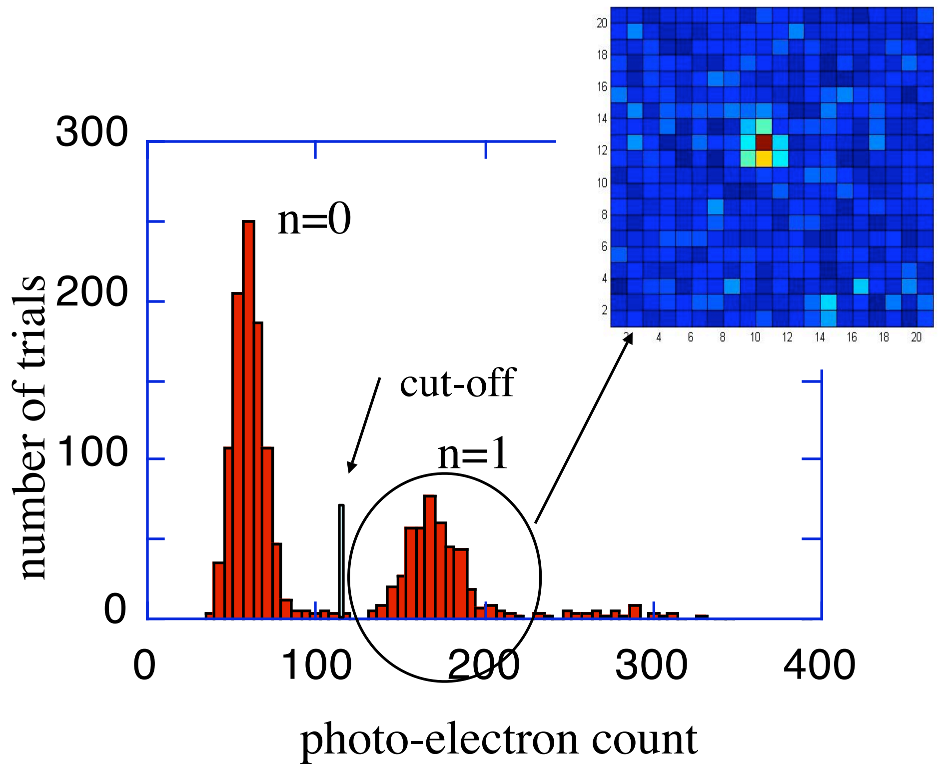
Switch FORT on/off @ 500 kHz

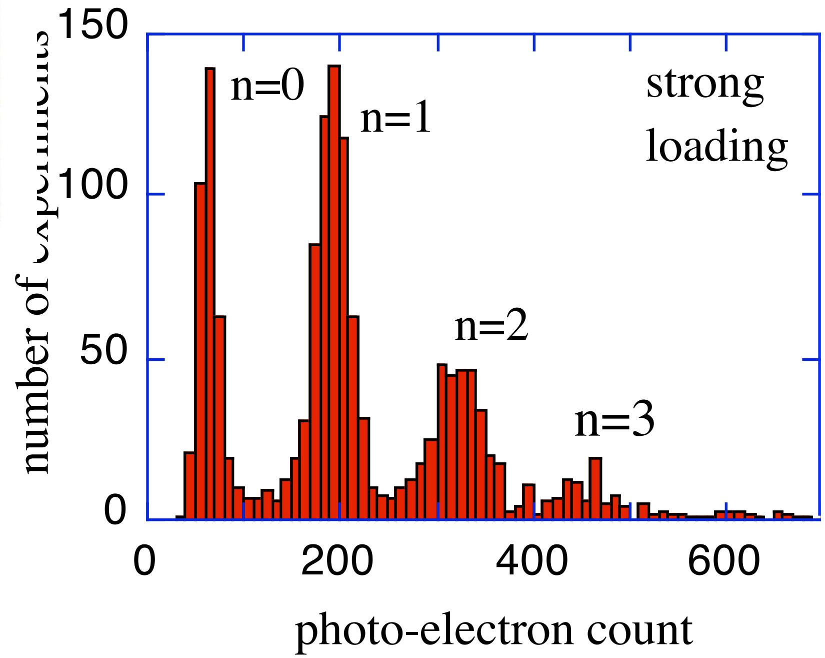


97% fidelity

Single-Atom Detection

Switch FORT on/off @ 500 kHz

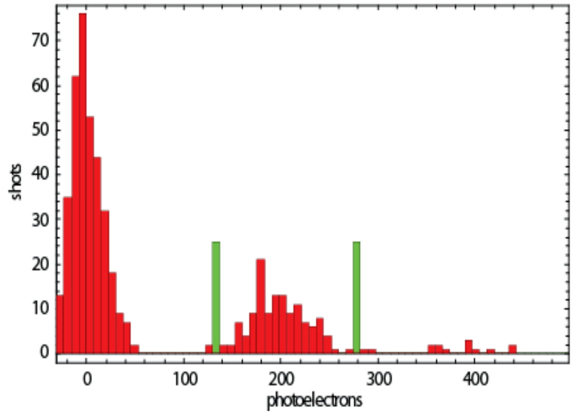




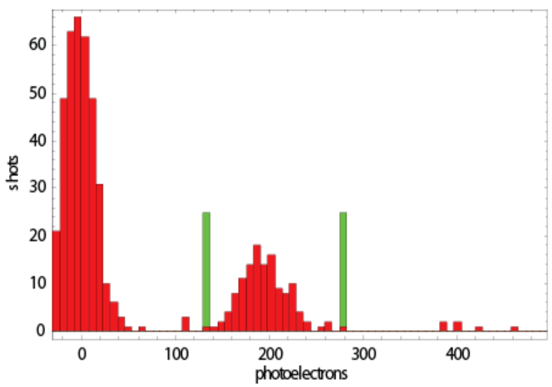
97% fidelity

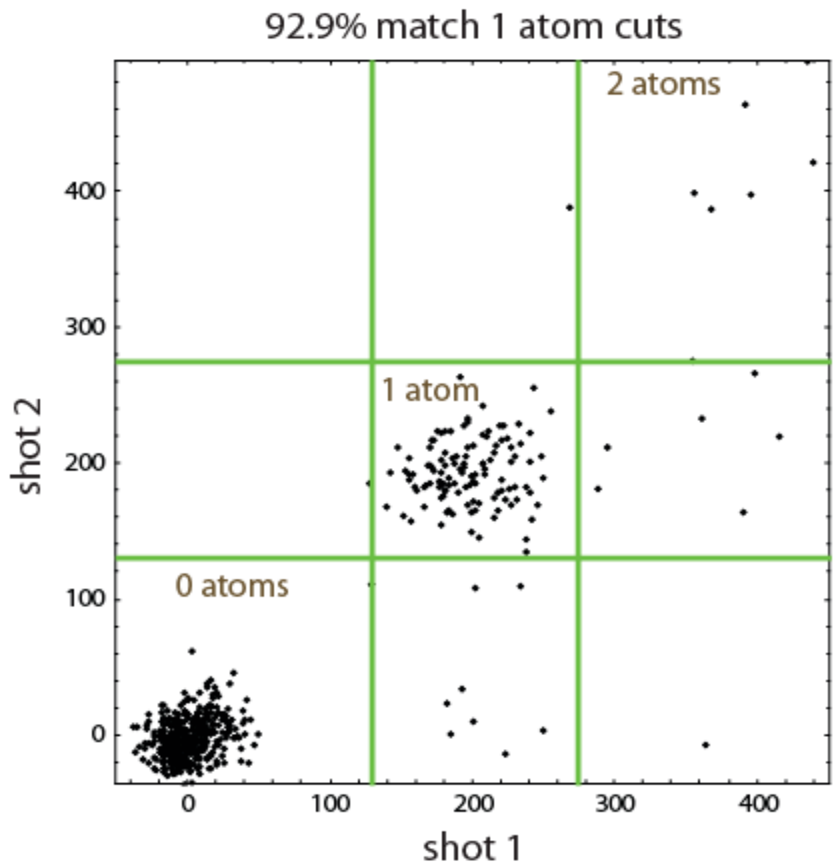
Single-atom preparation

1st shot



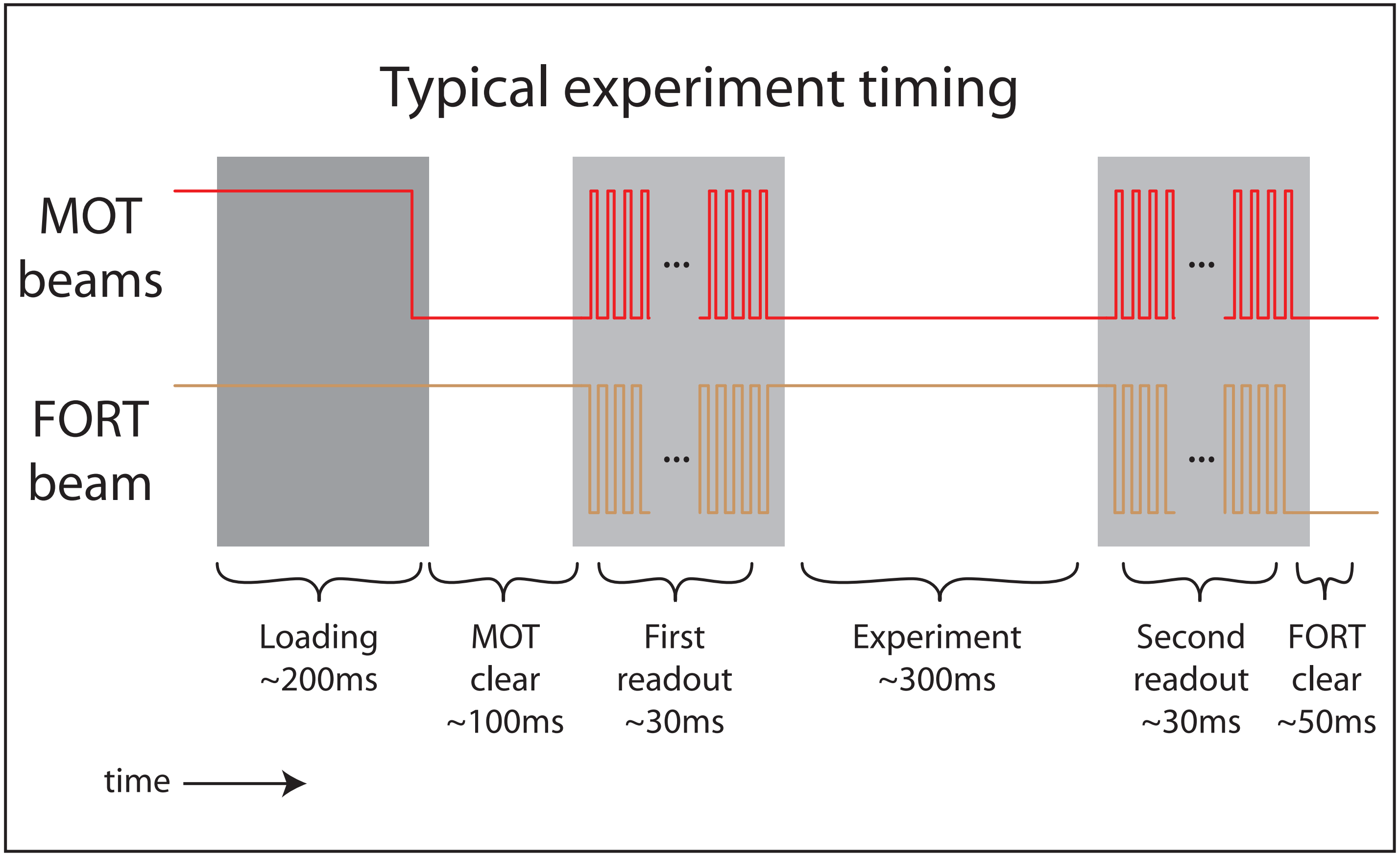
2nd shot



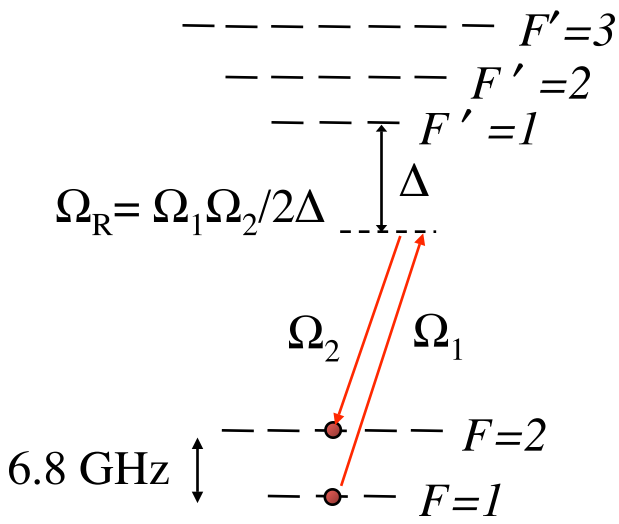


Typically 80% retention of 1 atom
from shot 1 to shot 2

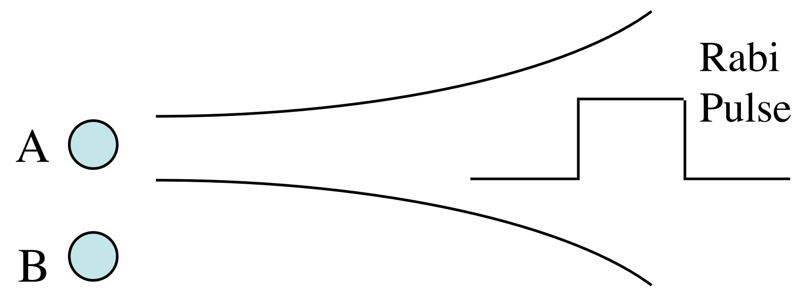
Generic Timing Sequence



Single-qubit Rotations



$\Delta = -50$ GHz

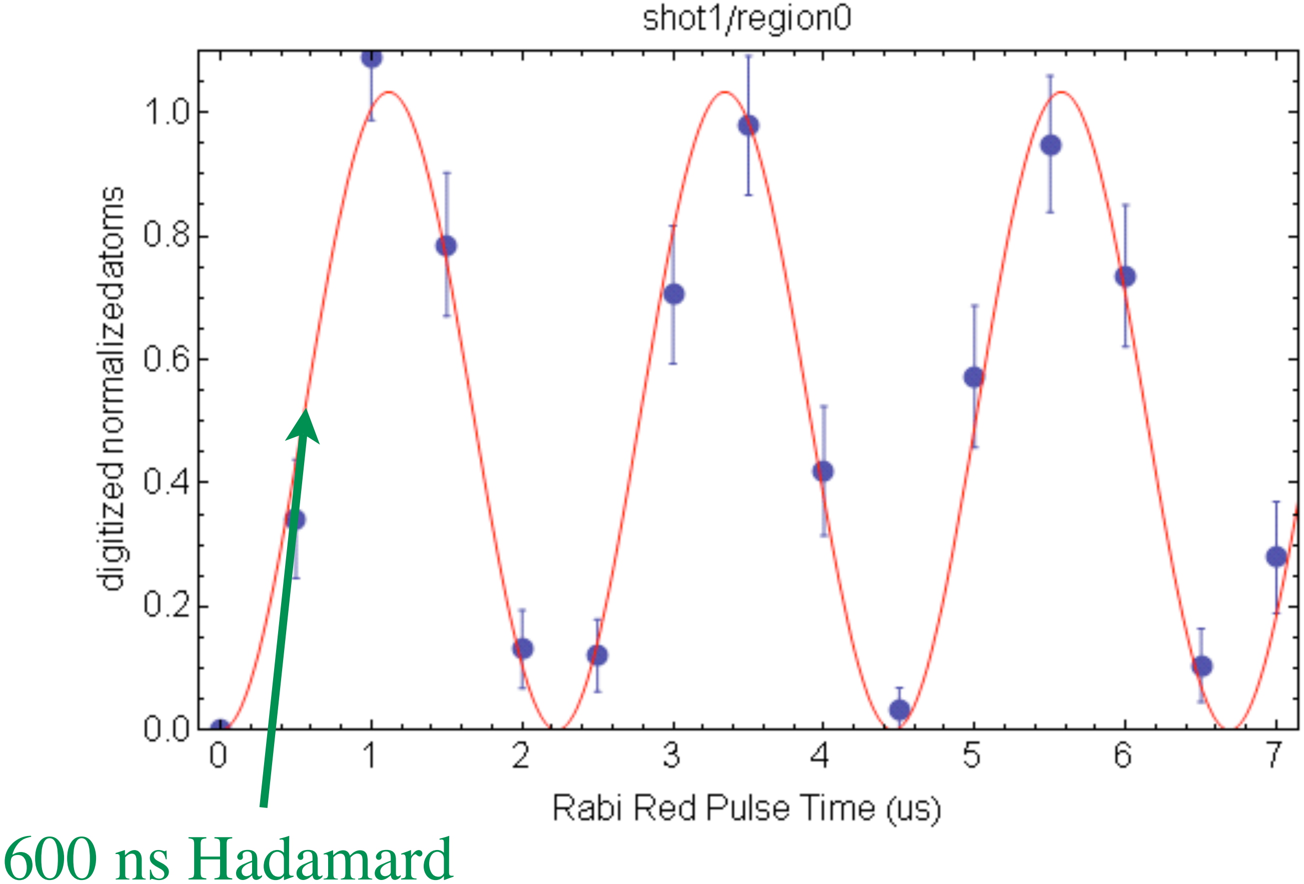


10 G bias field added to lift Zeeman degeneracy

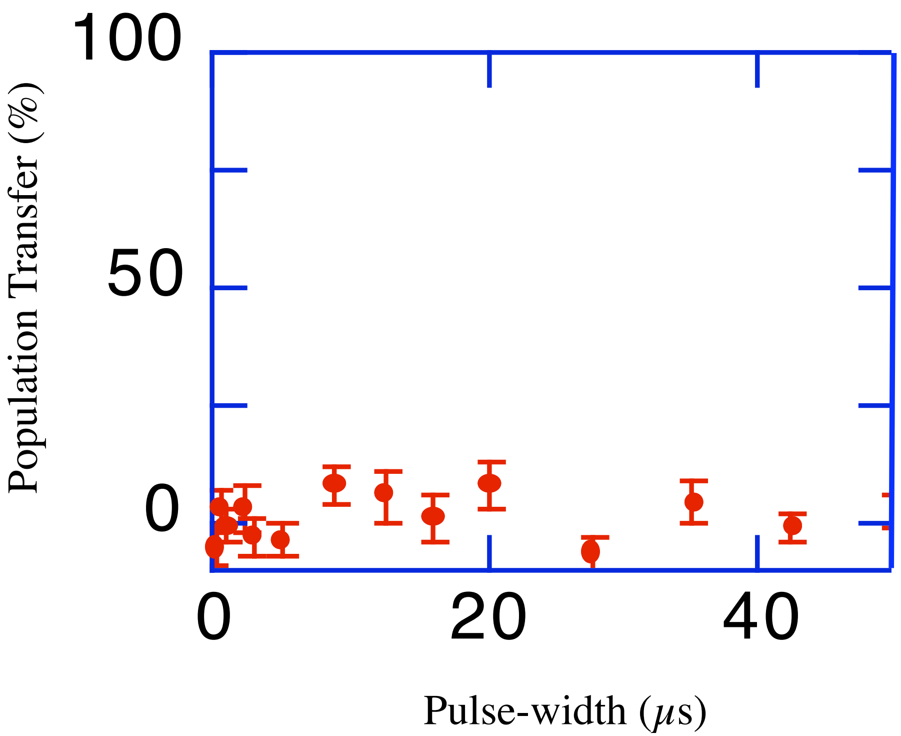
Light generated by μ-wave modulation of diode at 3.4 GHz, low-finesse filter cavity passes ± 1 orders.

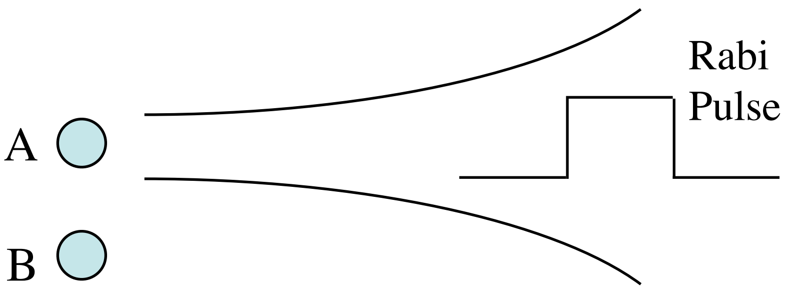
Rabi Rotations

PRL 96, 063001 (2006)



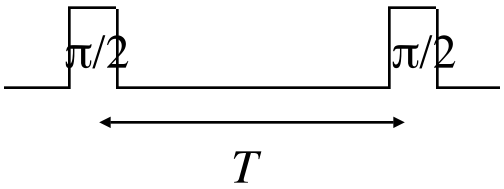
Cross-talk

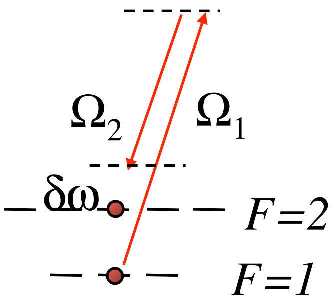


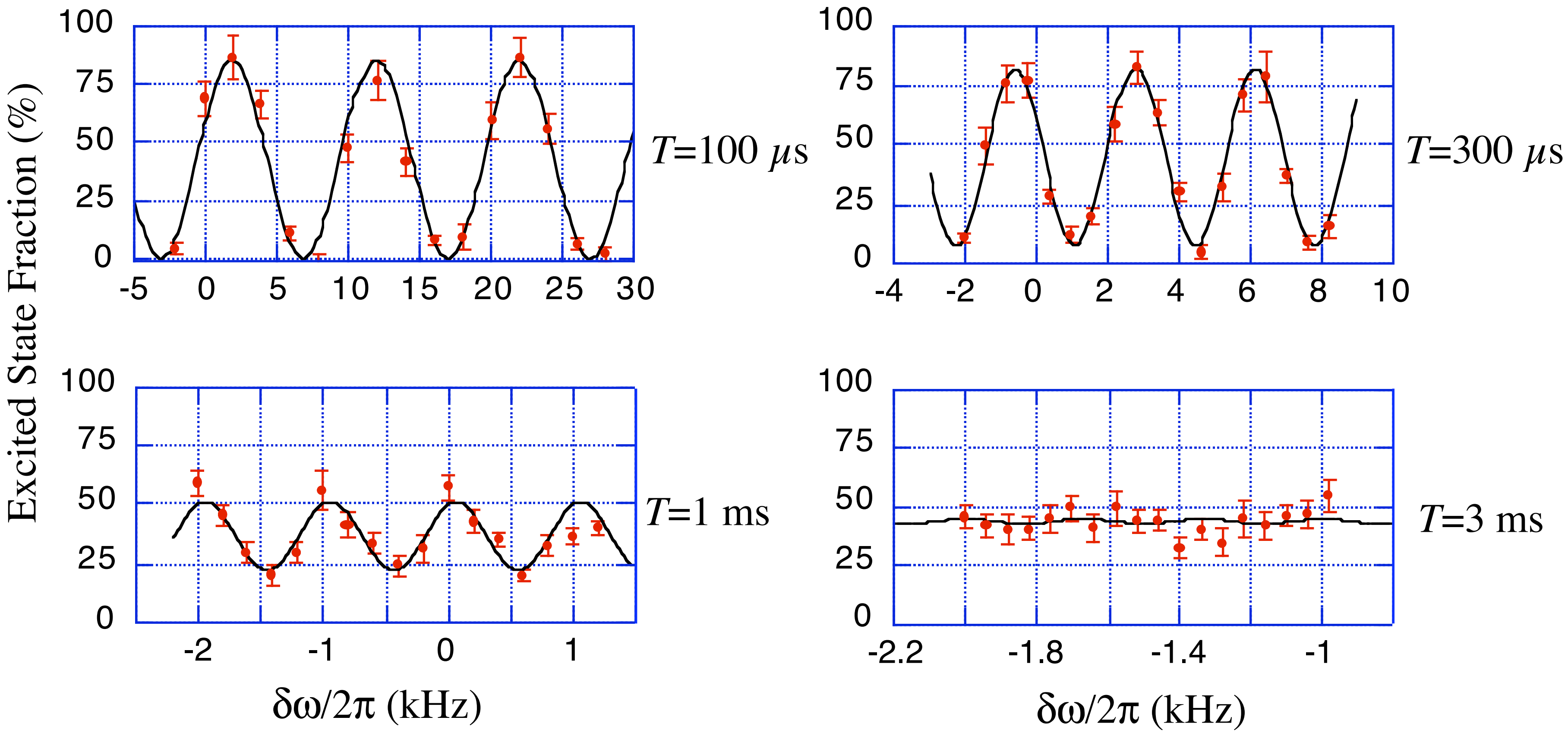


Cross-talk $< 10^{-3}$

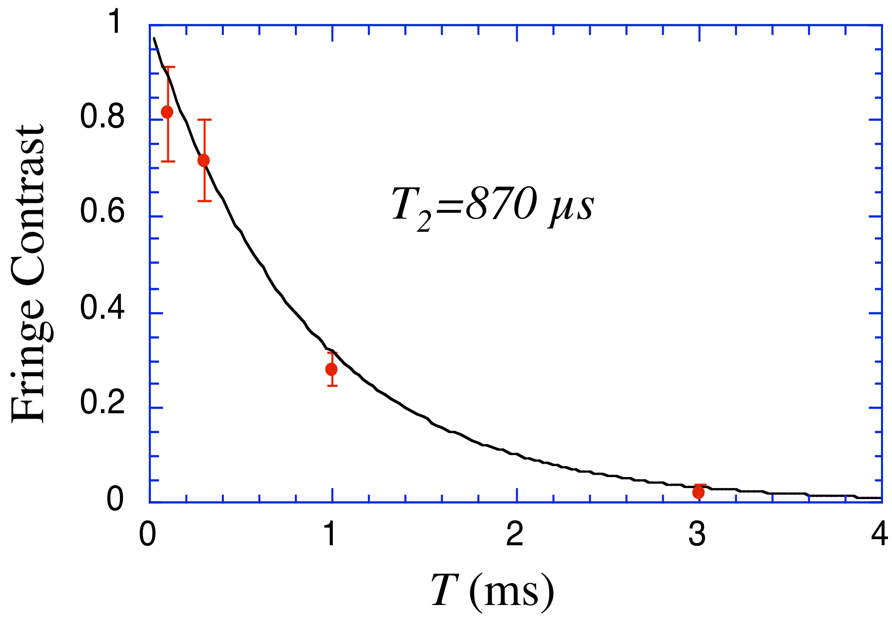
Ramsey Oscillations

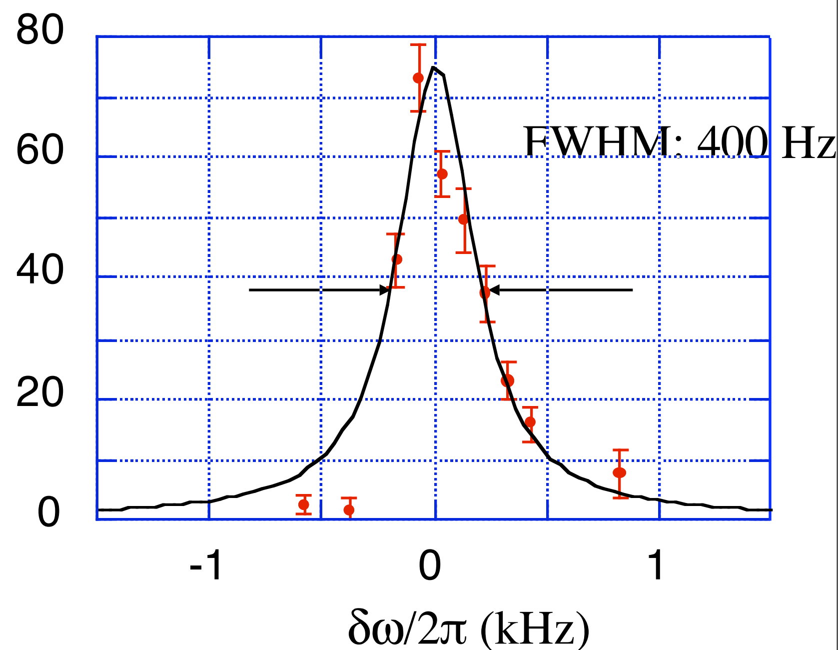






Coherence time measurement

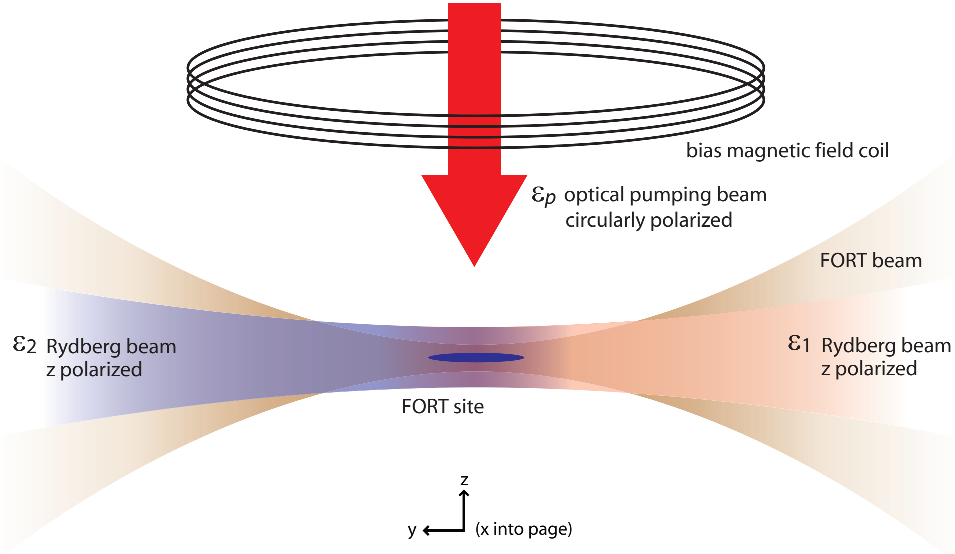




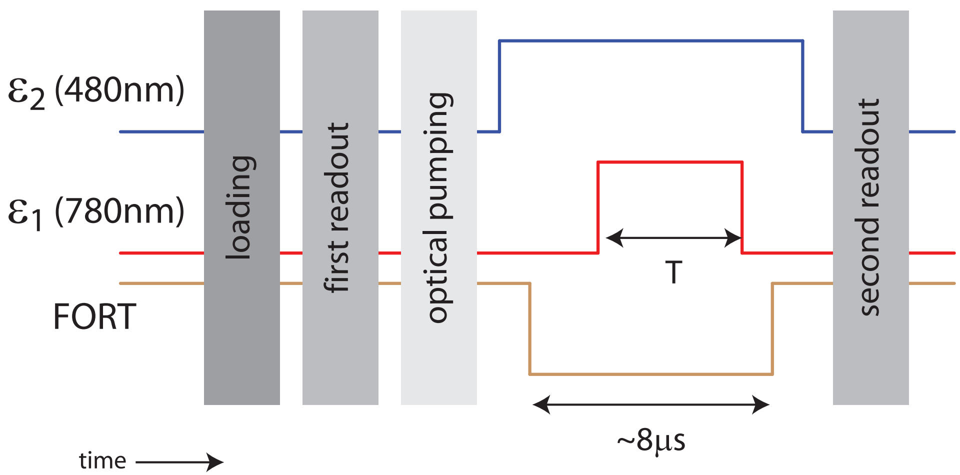
$T_2 = 1/(\pi\ 400) = 795\ \mu s$

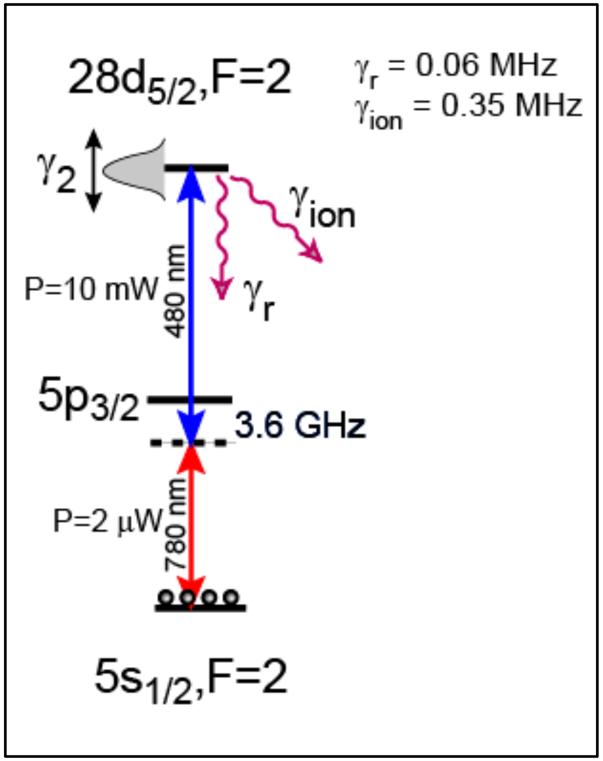
Figure of Merit $\dfrac{T_2}{t(\pi/2)} = 5000$

Coherent Rydberg Excitation



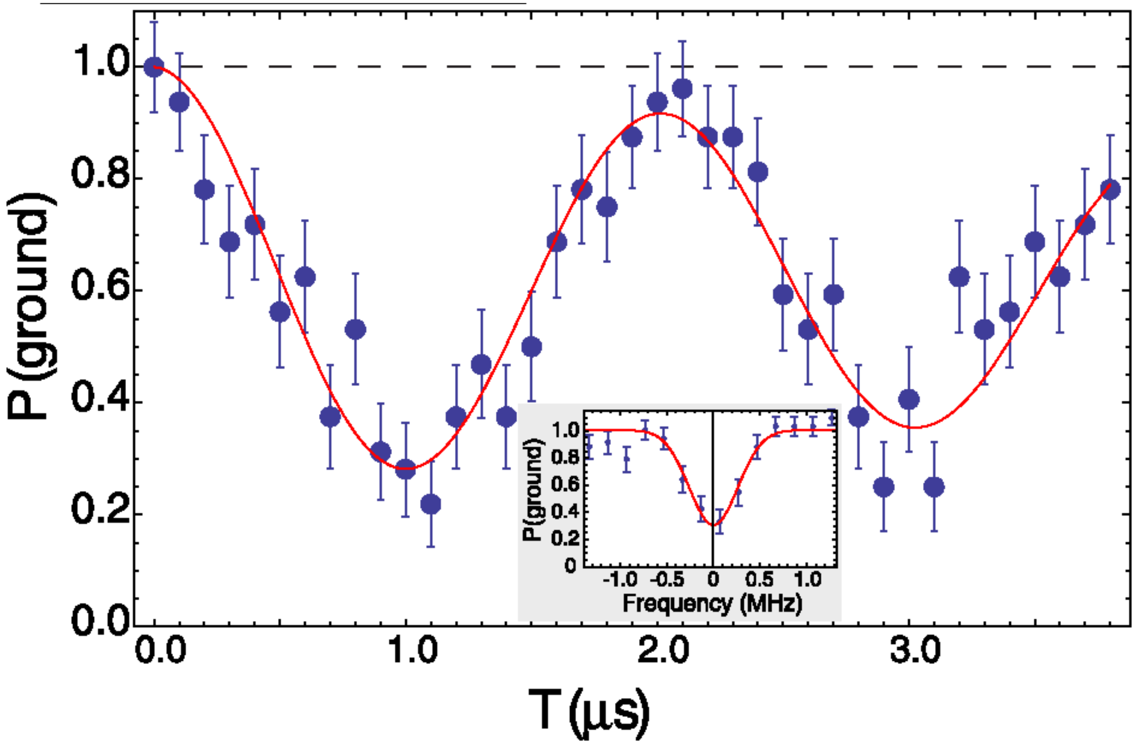
Single atom Rydberg excitation





Excitation scheme

Single Atom Rydberg Rabi Flopping

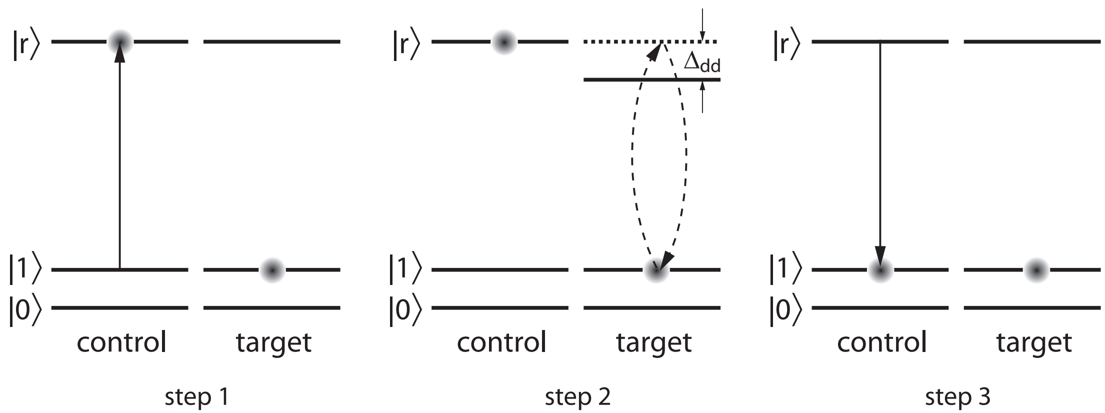


fit: Rabi frequency 490 kHz (550 kHz expected)
T2=8.1 µs
vis=0.76

Visibility: Doppler Broadening

PRL 100, 113003 (2008)

Next Step: Two Atoms in Nearby Traps



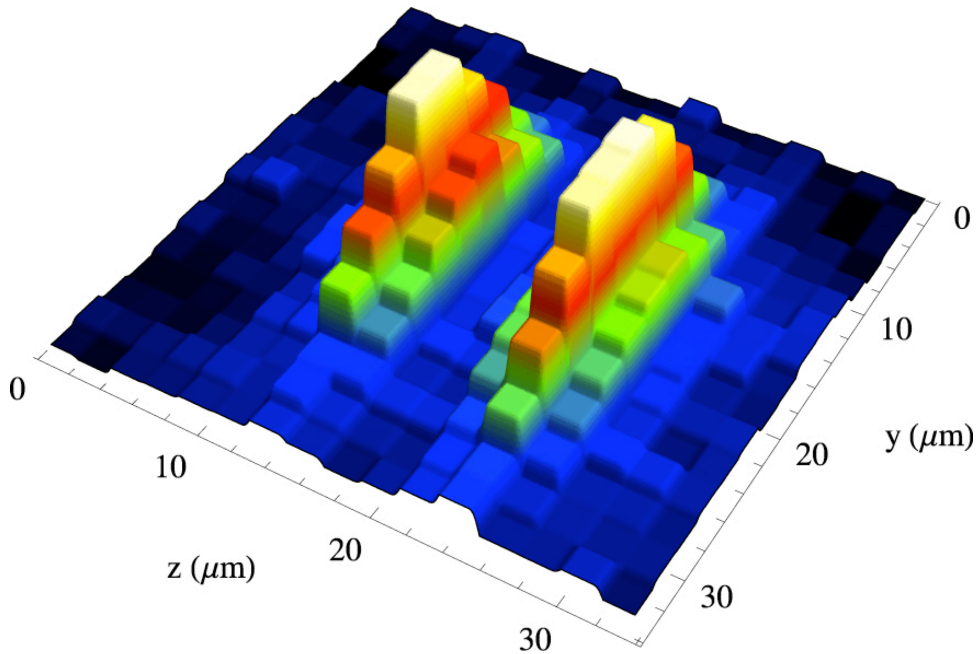
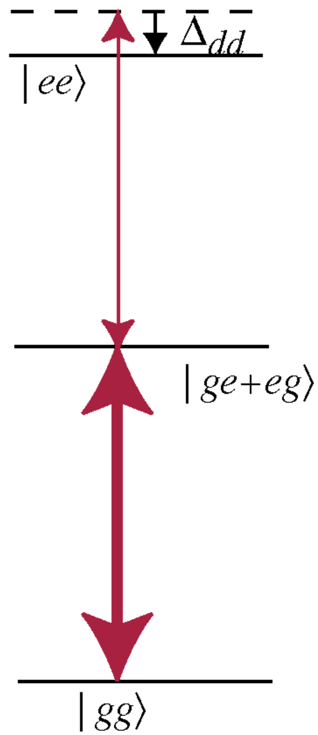


Figure of Merit for Rydberg Blockade

Phys. Rev. A **77**, 032723 (2008)



Primary errors

Excitation of 2 or more atoms

AC-Stark shift of effective 2-level system

Blockade Shift

Prob of double excitation after π-pulse

$$P_2 = \frac{\Omega^2}{2B^2}$$

Average over atom pairs ij, potentials φ

$$\frac{1}{B^2} = \left\langle \frac{1}{V_{dd}^2} \right\rangle$$

Properties of Blockade Shift

Weighted very strongly toward large R

Small R behavior of potential curves hardly matters

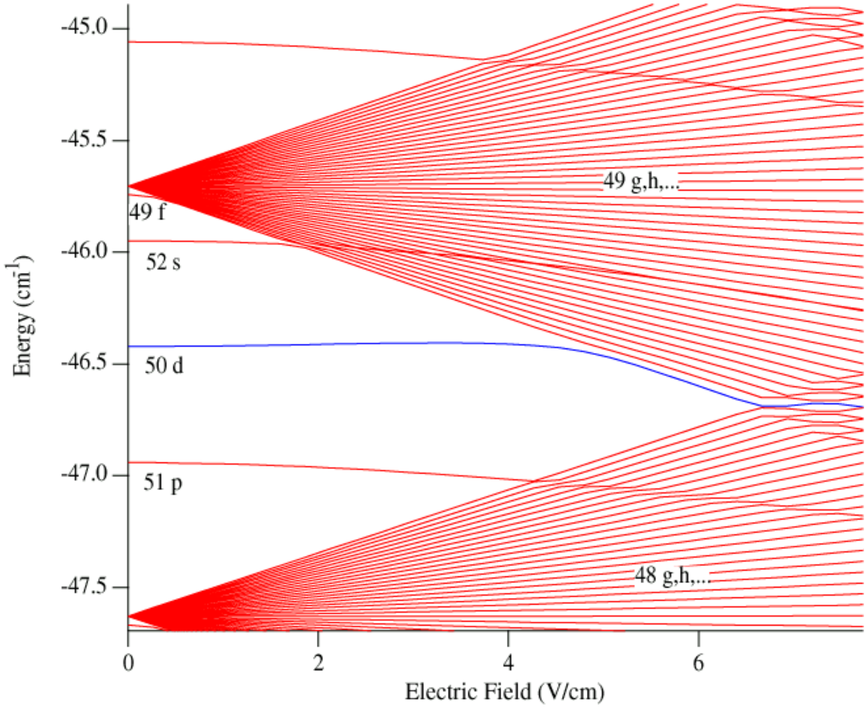
One or more weak potential curves can completely dominate over a large number of strong ones

$$\frac{1}{B^2} = \left\langle \frac{1}{V_{dd}^2} \right\rangle$$

Classical Dipole-Dipole Coupling

$$V = \frac{e^2 n^4 a_0^2}{R^3} P_2(\theta)$$

$P_2(55^\circ) = 0$
can be avoided in
high aspect ratio
traps
PRA 71, 021401R(2005)



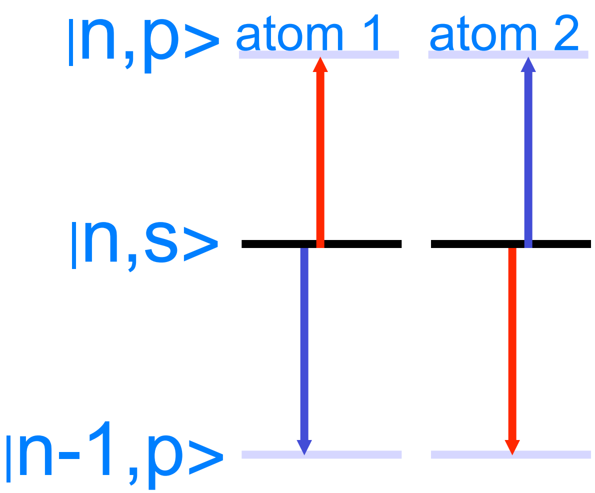
Stringent stability req.s

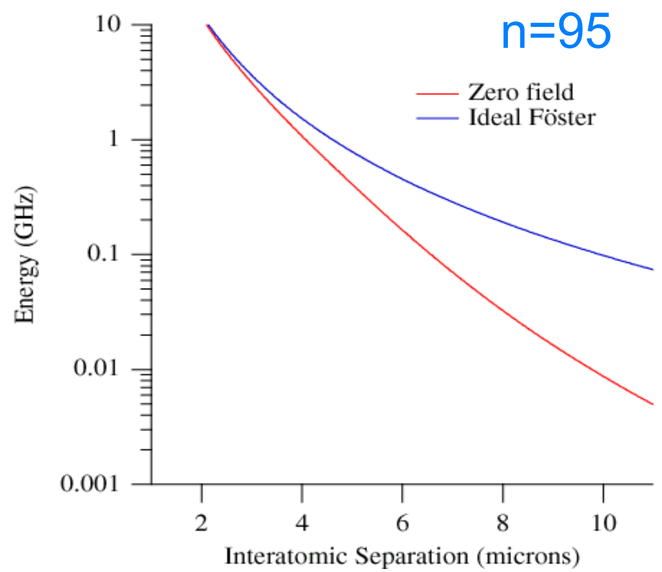
1 MHz Rabi flopping w/ 1% error

$$n = 50 \rightarrow 2 \text{ GHz/(V/cm)}$$

$$\rightarrow 10 \text{ kHz/}(5\ \mu\text{V/cm})$$

Förster Process





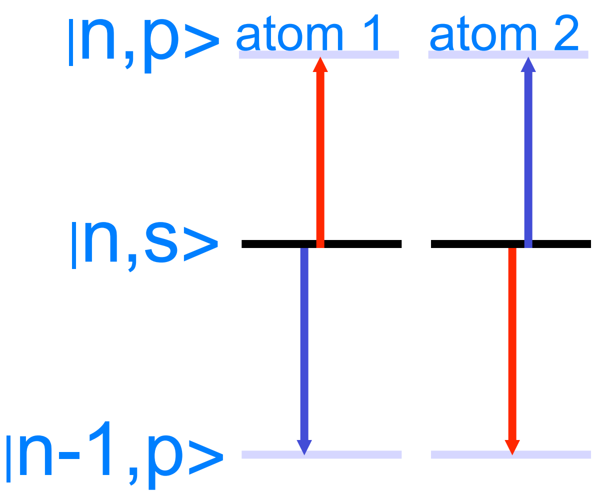
No ext. field req'd

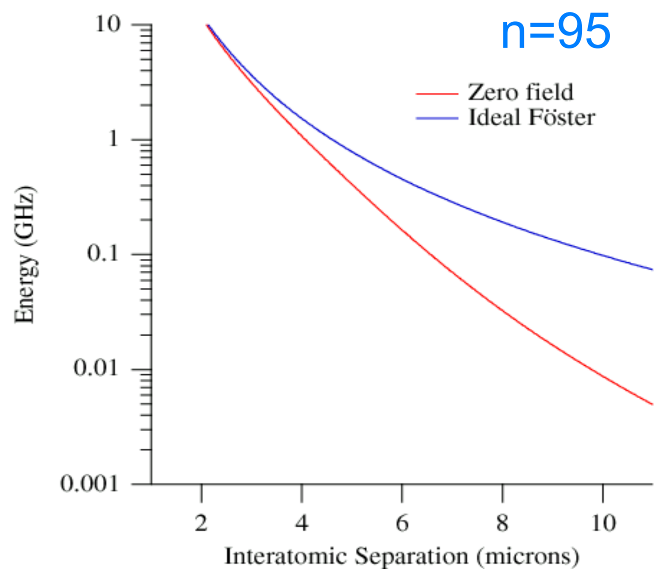
$$E_{95s} - \frac{E_{94p} + E_{95p}}{2} = 160\,MHz$$

$$V_{dd} \sim \frac{p_{ns,np}\, p_{ns,n-1p}}{r^3}$$

Isotropic! (not κ)

Förster Process





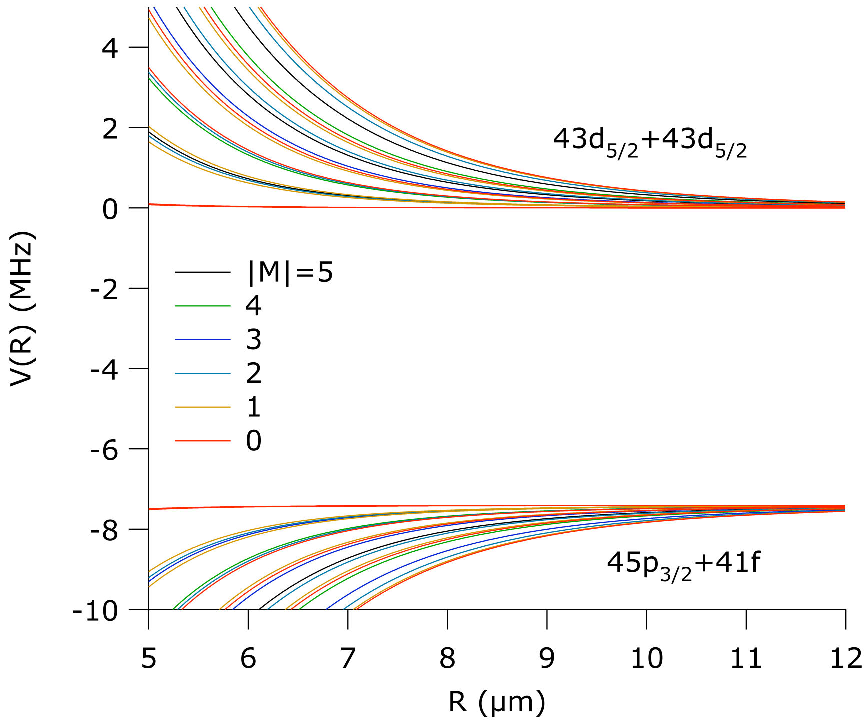
No ext. field req'd

$$E_{95s} - \frac{E_{94p} + E_{95p}}{2} = 160\,MHz$$

$$V_{dd} \sim \frac{\left(p_{ns,np}\,p_{ns,n-1p}\right)^2}{r^6 \Delta E}$$

Real life $\Delta E \neq 0$

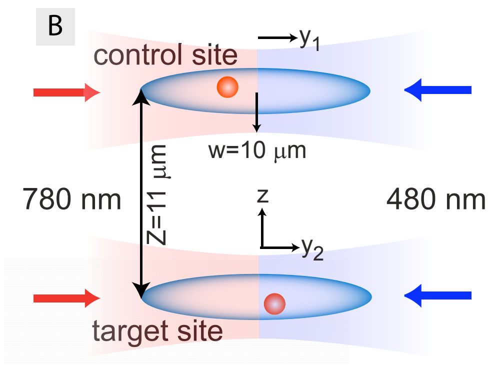
Rb 43d+43d->41p+45f

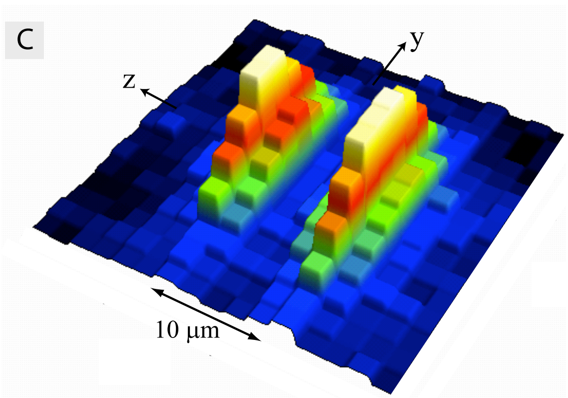


B=30 kHz for 10 μm cloud

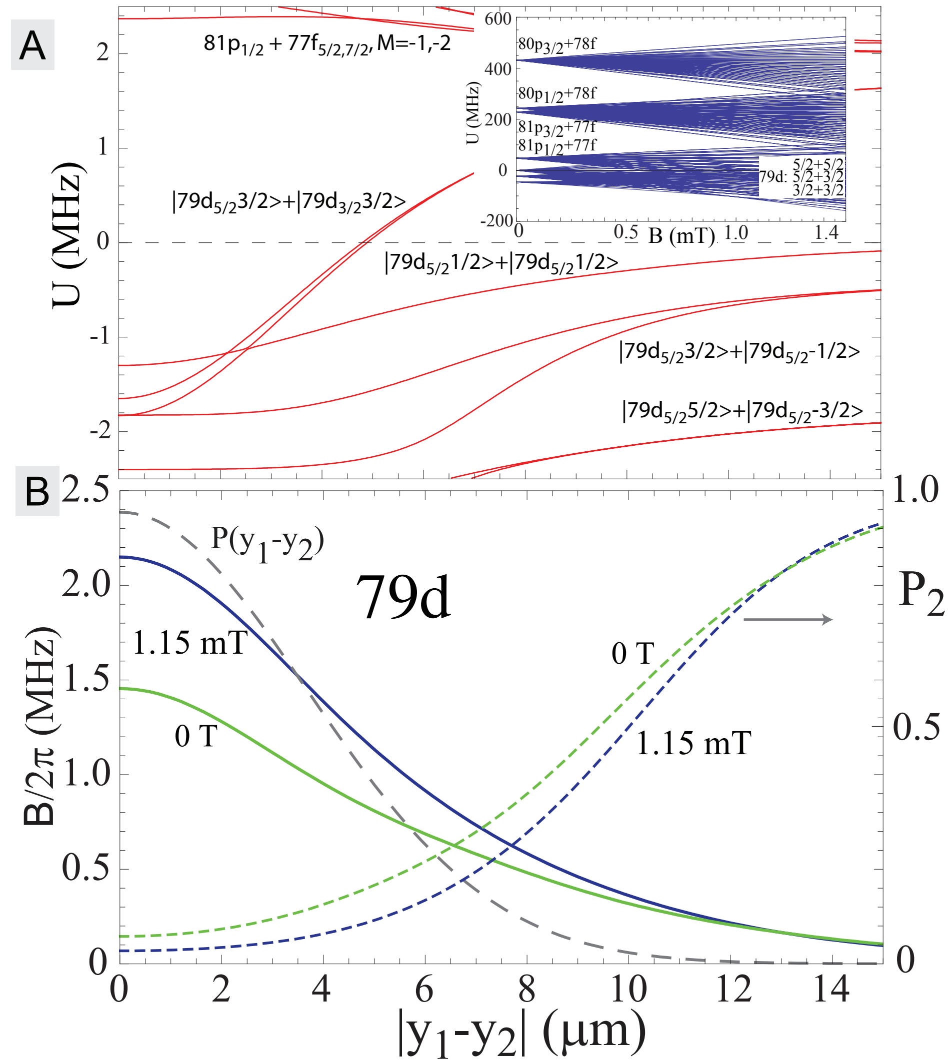
$$|\psi_0\rangle = \frac{1}{\sqrt{107}}|(50d0)(50d0)\} + 2\sqrt{\frac{2}{107}}|(50d1)(50d-1)\} + 7\sqrt{\frac{2}{107}}|(50d2)(50d-2)\}$$

Magnetic Field/Fine Structure Mixing



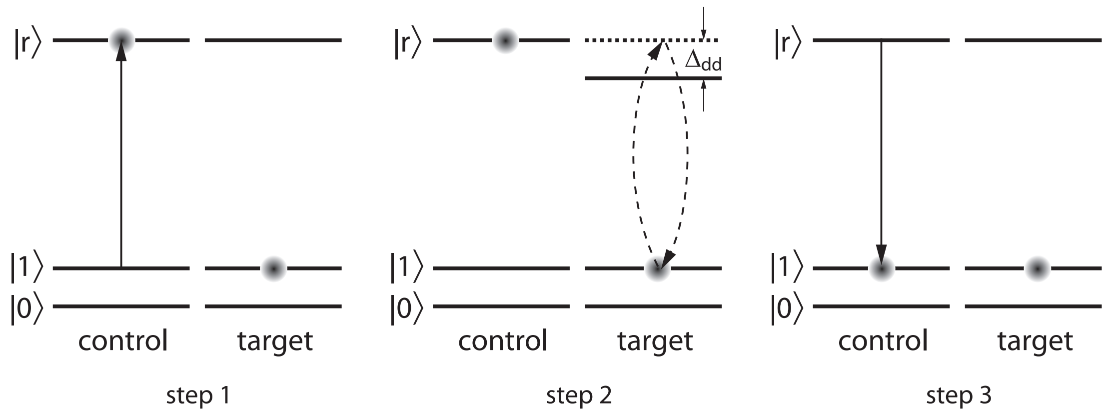


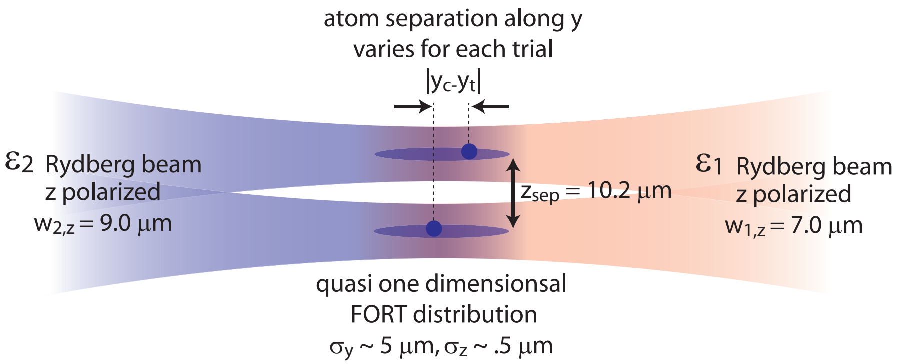
B=1.3 MHz



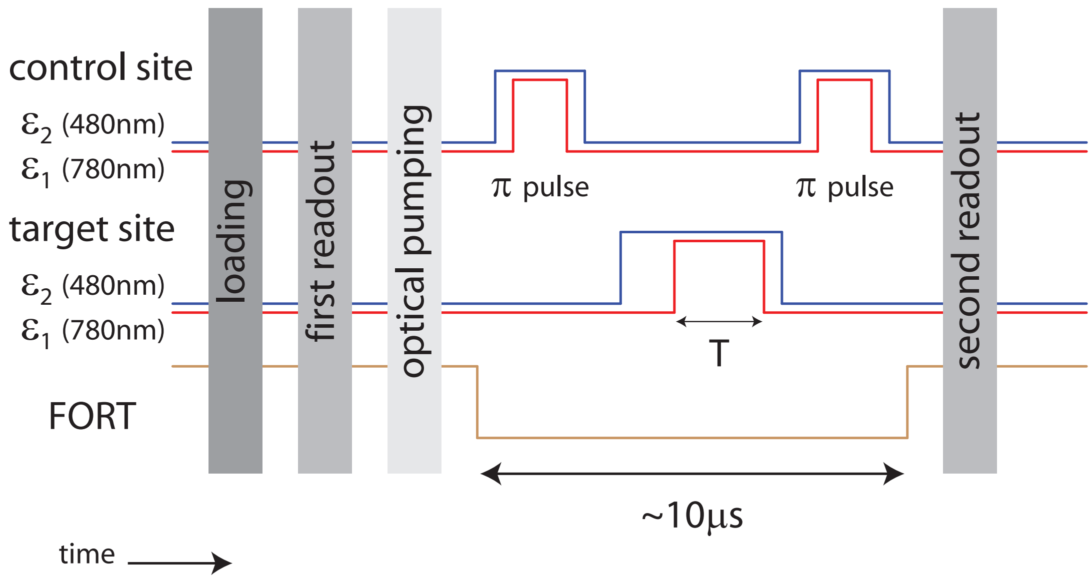
Fine-structure mixing by V_{dd} gets rid of Förster zero states.

Blockade Experiment

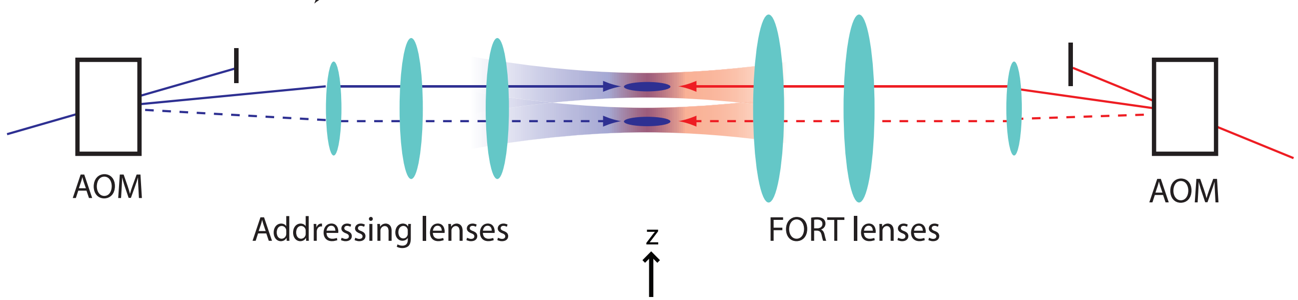




Timing

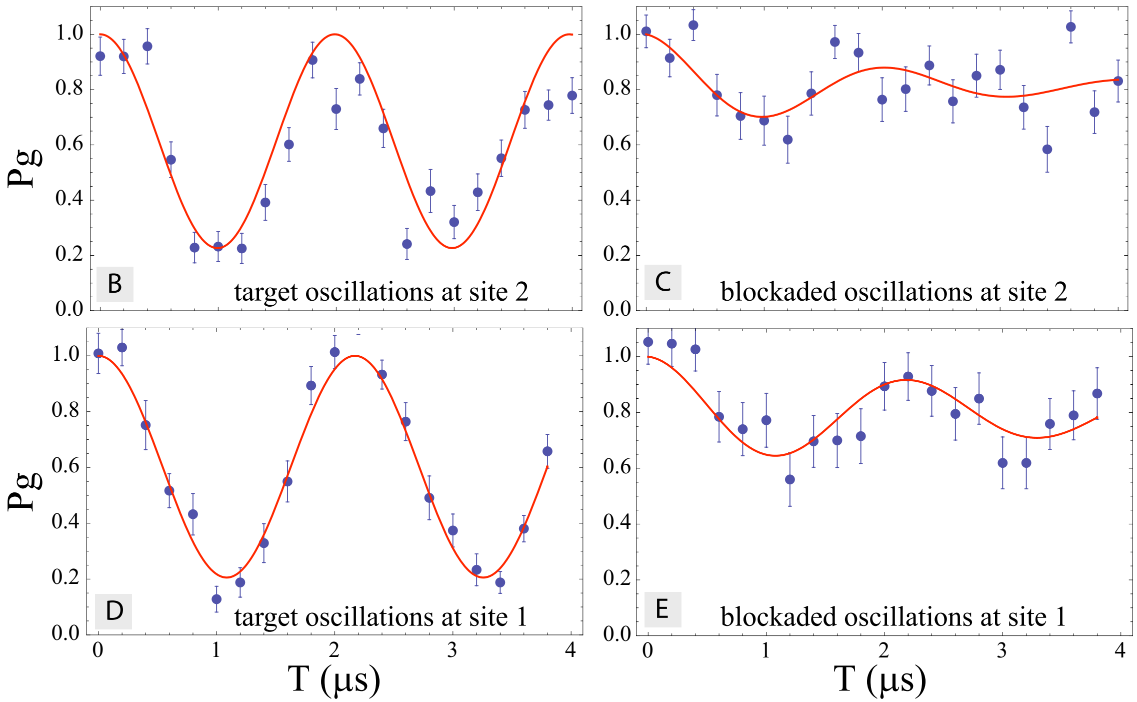


control site
$\mathcal{E}_2$ (480nm)
$\mathcal{E}_1$ (780nm)
target site
$\mathcal{E}_2$ (480nm)
$\mathcal{E}_1$ (780nm)
FORT
loading
first readout
optical pumping
π pulse
π pulse
T
second readout
~10μs
time



AOM
Addressing lenses
z
FORT lenses
AOM

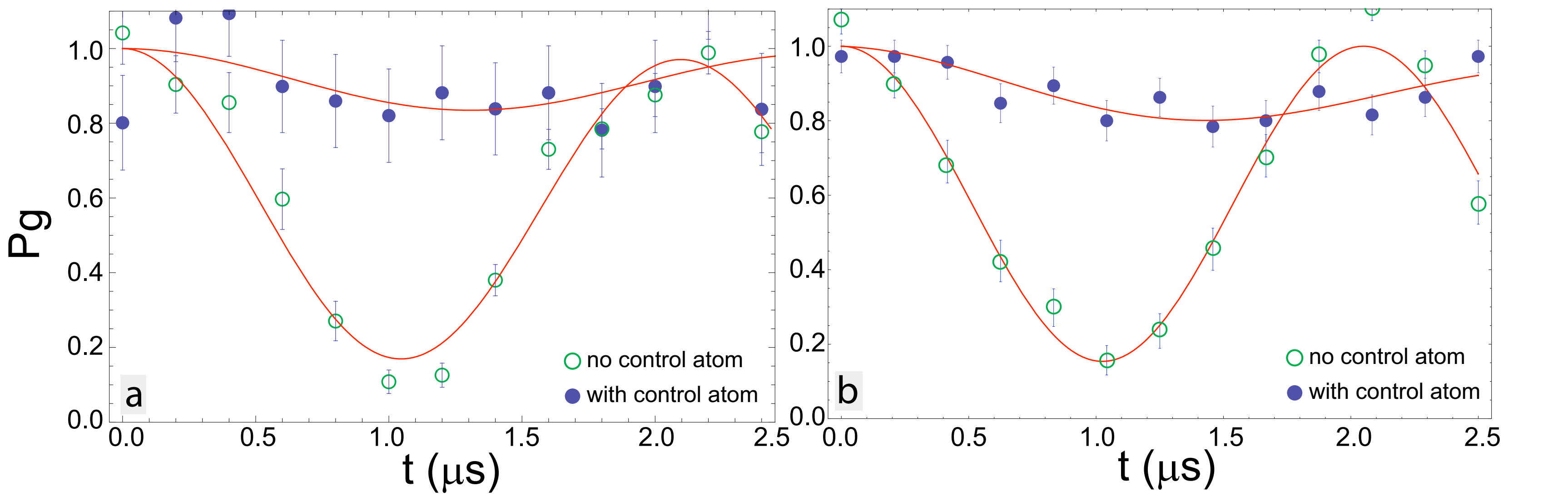
Blockade Results-79d



Expected residual oscillations (Doppler, finite blockade shift)
0.1--additional errors from atom loss on 1st readout, imperfect optical pumping, and imperfect photoionization

Blockade Results-90d

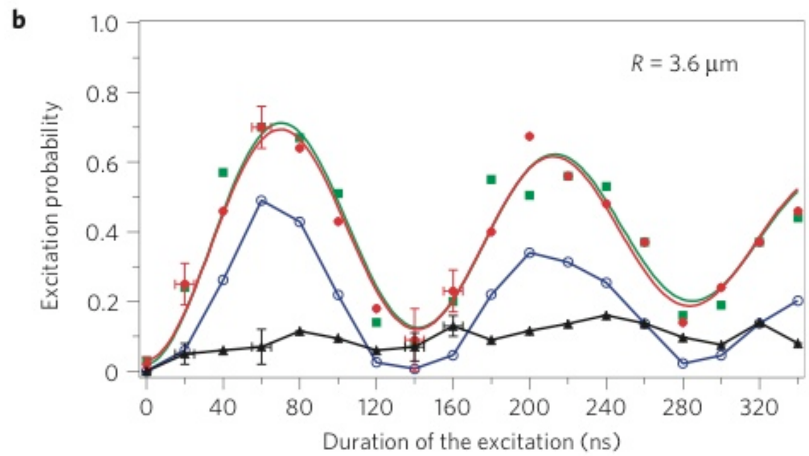
Nature Physics 5, 110 (2009)



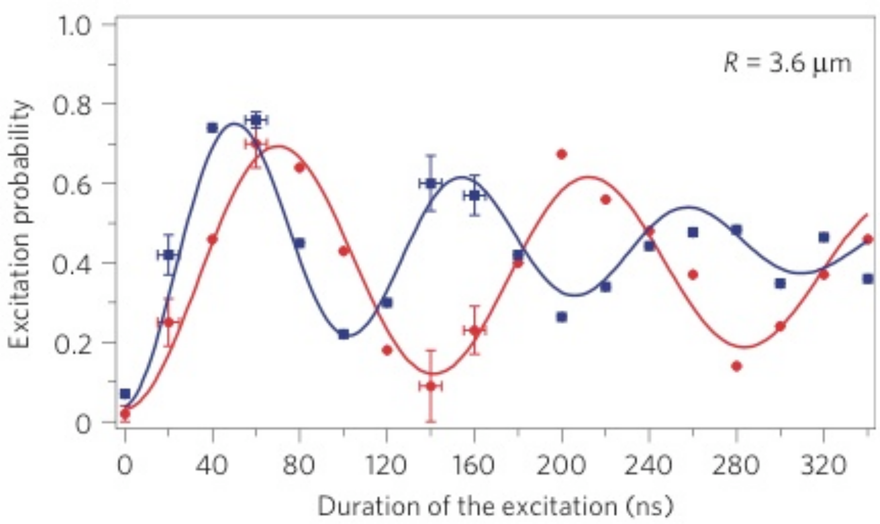
Demonstrates coherent control of the evolution of one atom based on the quantum state of a single additional atom 11 microns away.

French results

Grangier, Pillet, Nature Physics 5, 115 (2009)

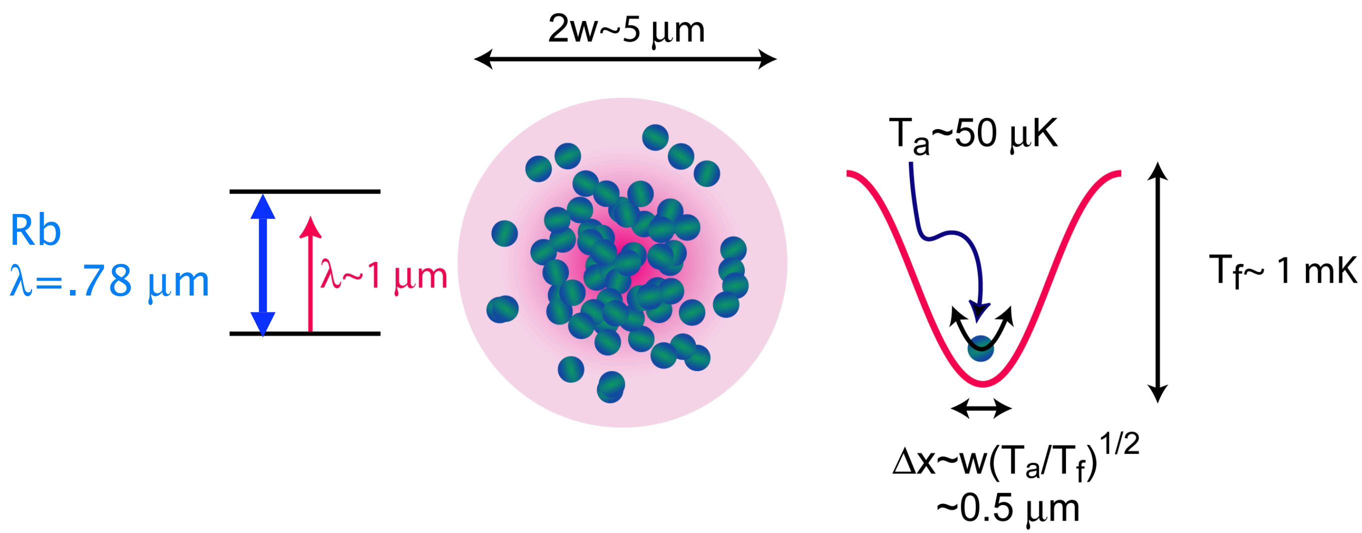


Blockade



Sqrt(2) enhancement

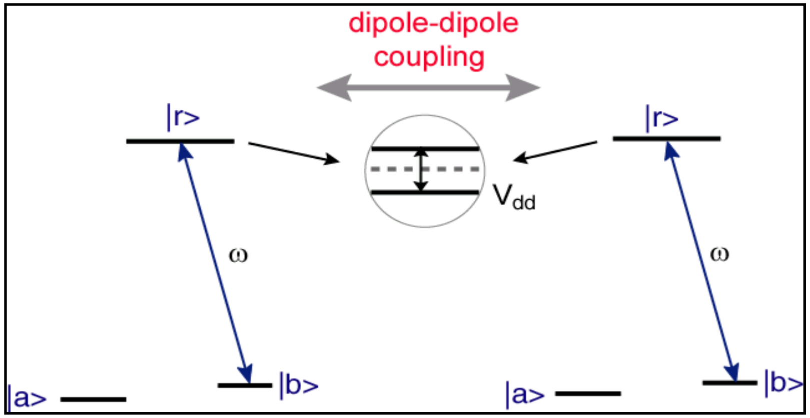
Mesoscopic Dipole Blockade



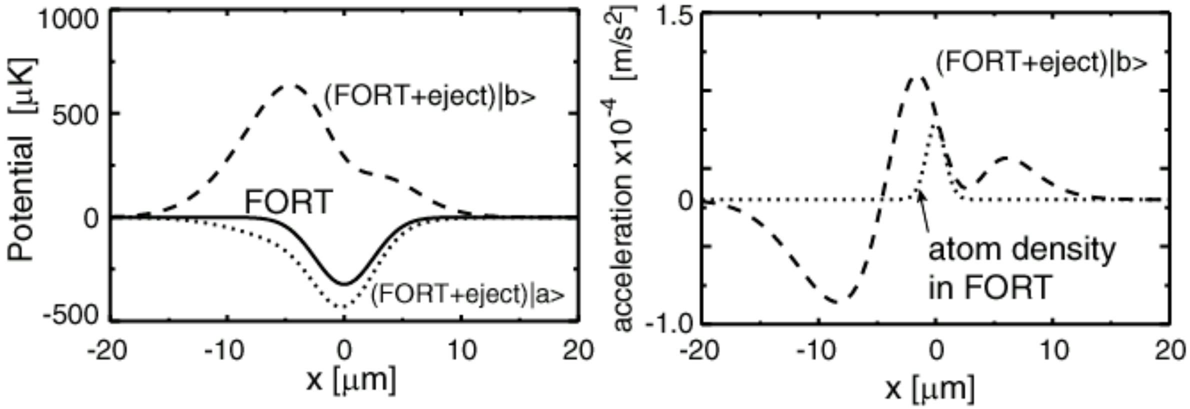
Lukin...PRL **87**, 037901 (2001). : Multi-atom excitation strongly suppressed in mesoscopic cloud

Single Atom Source

Protocol for single atom loading:

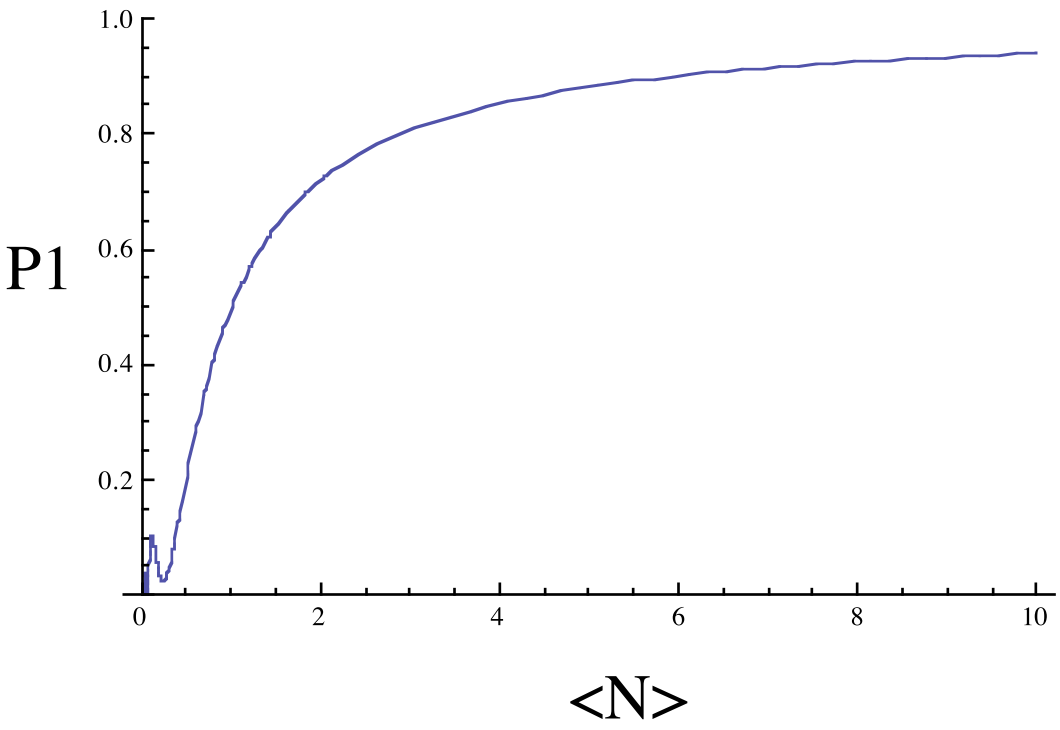


- trap N atoms into FORT
- pump all N atoms to |b> $\quad |\psi\rangle \sim |b_1....b_N\rangle$
- transfer "1" atom to |a> $\quad |\psi\rangle \sim \frac{1}{\sqrt{N}} \sum_j |b_1..a_j..b_N\rangle$
- eject (N-1) atoms in |b>



PRA 66, 065403 (2002)

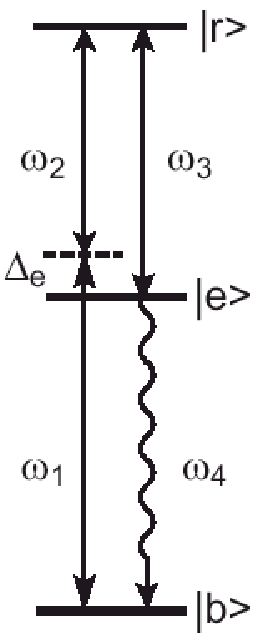
Single-atom Loading Fidelity



Assumes no initial N measurement

With an initial N measurement, in principle no bounds on the fidelity

Single Photon Source



Drive b–e–r–e sequence
via dipole-blockade

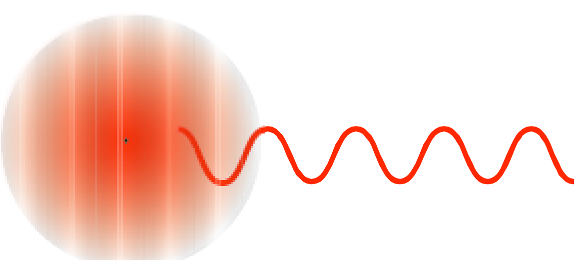
Get entangled state

$$\Psi = \frac{1}{\sqrt{N}} \sum_j e^{i\phi_j} \left| 0 \ldots e_j \ldots \right\rangle$$

$$\phi_j = (k_1 + k_2 - k_3) \cdot r_j$$

Single-photon emitted

but, spatially-varying phase imprinted
on atoms



PRA 66, 065403 (2002)

Phased Array Single-Photon Source

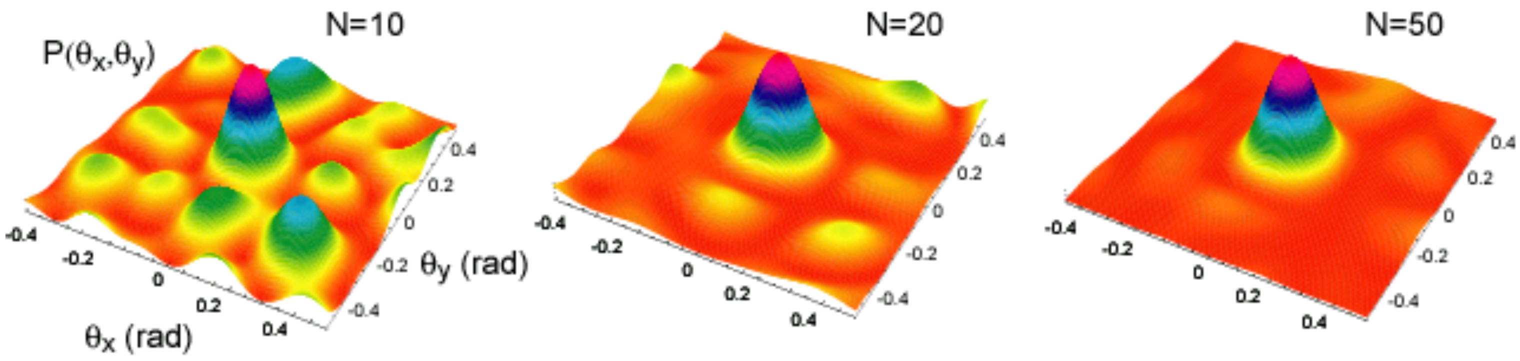
Prob of emission in direction ***k***

$$\left|\langle 0|a^{+}e^{-ik\cdot r}|\Psi\rangle\right|^{2} \sim \left|\sum_{j} e^{-ik\cdot r}e^{i\phi_{j}}\right|^{2}$$

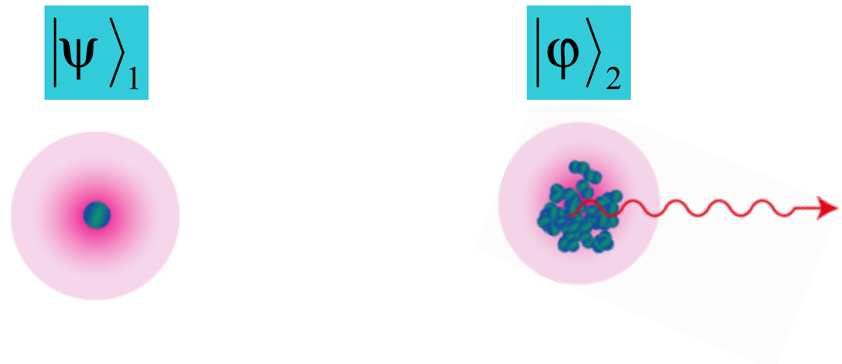
Phase-matched when

$$\mathbf{k} = (\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3)$$

N-fold enhancement in phase-matched direction



Single Qubit to Directed Photon



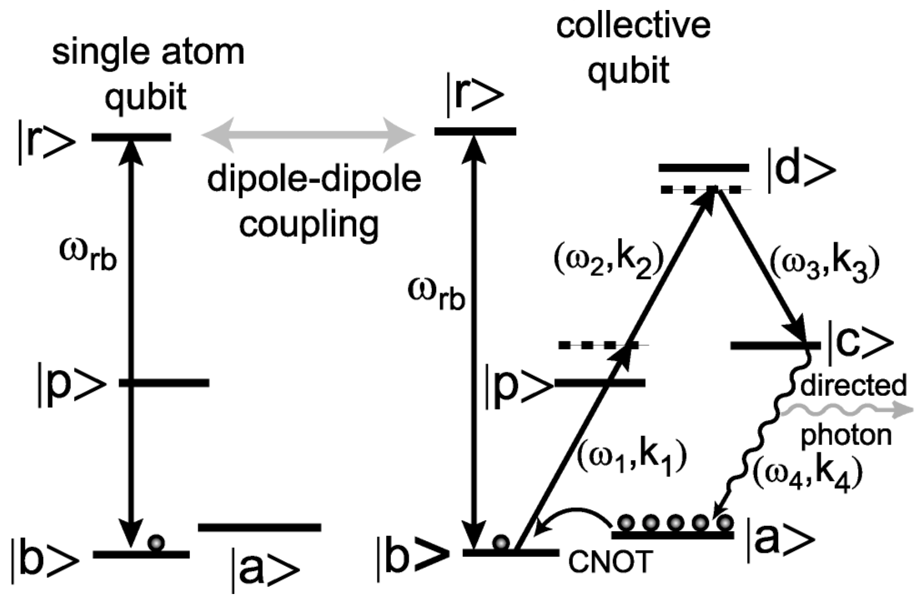
initialize

$$|\varphi\rangle_2 \rightarrow |\bar{a}\rangle_2$$

entangle

$$|\psi\rangle_1 |\bar{a}\rangle_2 \rightarrow |\bar{a} \oplus \psi\rangle_2$$

$$|\bar{b}\rangle_2 \rightarrow |\bar{c}\rangle_2 \rightarrow |\bar{a}\rangle_2 |1\rangle_{k_4}$$



PRA 72, 022347 (2005)

Cross Entanglement

- Single atom qubits are optimal for computation – but couple weakly to a single photon
- N atom ensembles couple strongly to single photons, but have shorter coherence time
- Cross entanglement combines the advantages

computation qubit

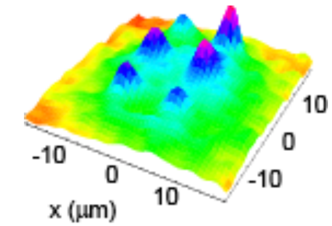
communication qubit

Potential for fast readout, quantum state transmission...

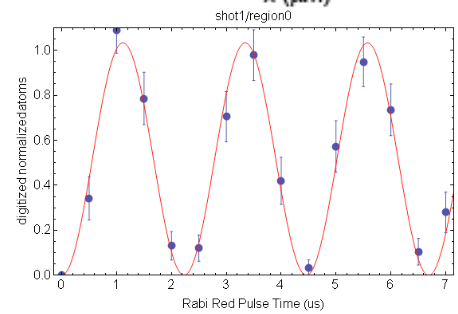
PRA 72, 022347 (2005)

Summary

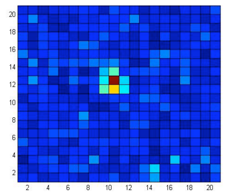
•2-D array of addressable FORTs w/Rydberg entanglement promising approach to quantum computation



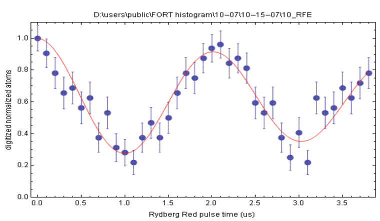
•MHz single qubit rotations demonstrated, long coherence times



•Efficient single-atom detection and preparation



•Coherent Rydberg Rabi flopping



•Demonstrated blockade between 2 atom separated by 11 μm