How the NIST F-1 Cesium Fountain Clock Works

\[ |a\rangle \quad \text{hv} \quad |b\rangle \]
How the NIST F-1 Cesium Fountain Clock Works

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.
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.

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

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

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

The entire process is repeated until the maximum fluorescence of the cesium atoms is determined.
How the NIST F-1 Cesium Fountain Clock Works

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

\[ \frac{\delta \nu}{\nu} = 10^{-15} \]
Quantum Manipulation of Neutral Atoms
Without Forces

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  Todd Johnson
  Erich Urban
  Thomas Henage
  Larry Isenhower

Faculty
  Mark Saffman
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University of Wisconsin-Madison

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

NSF
Qubits - Quantum Information

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 → Quantum Info. Processing
Future Quantum Computer

Need to entangle a large number of near atomic clock quality qubits that are resolvable distances apart
At optically resolvable (1 \( \mu \text{m} \)) distances, what is the dominant interatomic interaction?

**Ground state Rb atoms**

**Highly excited (Rydberg) atoms, n=90**
At optically resolvable (1 μm) distances, what is the dominant interatomic interaction?

Ground state Rb atoms

\[ V(R) \sim \frac{\mu^2}{R^3} \sim 10^{-20} \text{ eV} \]

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

\[ V(R) \sim \frac{\mu^2}{R^3} \sim 10^{-20} \text{ eV} \]

Highly excited (Rydberg) atoms, \( n=90 \)

\[ V(R) \sim \frac{n^4 e^2 a^2}{R^3} \sim 10^{-4} \text{ eV} \]
Requirements for Universal Quantum Computer

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 $\ll$ rate of coherent operations
  clock transition

scalable
  diffractive & acousto-optics
Entanglement Using Dipole Blockade

\[ U \sim \frac{n^4}{R^3} \]

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

\[ |gg\rangle \rightarrow |ee\rangle \]

\[ |eg\rangle - |ge\rangle \]

With Dipole-Dipole Interaction

\[ \Delta |gg\rangle \rightarrow |ee\rangle \]

\[ |eg\rangle - |ge\rangle \rightarrow |eg\rangle + |ge\rangle \]
**Dipole blockade phase gate**

![Diagram of dipole blockade phase gate]

**Rabi Flopping**

"π-pulse":

\[ b \rightarrow ir \]

"2π-pulse":

\[ b \rightarrow ir \rightarrow -b \]

<table>
<thead>
<tr>
<th>Initial state</th>
<th>π control</th>
<th>2π data</th>
<th>π control</th>
</tr>
</thead>
<tbody>
<tr>
<td>( aa )</td>
<td>( aa )</td>
<td>( aa )</td>
<td>( aa )</td>
</tr>
<tr>
<td>( ab )</td>
<td>( ab )</td>
<td>( -ab )</td>
<td>( -ab )</td>
</tr>
<tr>
<td>( ba )</td>
<td>( e^{i\pi/2}ra )</td>
<td>( e^{i\pi/2}ra )</td>
<td>( -ba )</td>
</tr>
<tr>
<td>( bb )</td>
<td>( e^{i\pi/2}rb )</td>
<td>( e^{i\pi/2}rb )</td>
<td>( -bb )</td>
</tr>
</tbody>
</table>
Controlled-NOT Gate

\[
\begin{array}{l}
aa \Rightarrow aa \\
ab \Rightarrow ab \\
bb \Rightarrow ba \\
ba \Rightarrow bb
\end{array}
\]

= 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
During the loading phase of the experiment, the electron multiplying CCD camera measures the excited state atom fraction of
\[ f_{\text{exc}} = \frac{I}{2I_s} = 1 + \frac{I}{I_s} + (2\Gamma/\Delta)^2 \approx \frac{1}{6} \]

The experiment setup includes a 960 nm diode laser, a 780 nm diode laser, a tapered amplifier, and a frequency doubler. The 960 nm diode laser is connected to the reference cavity, while the 780 nm diode laser is used for tuning and fast pulse timing. AOM-based beam positioners are used to control the beam position. The experiment table includes a MOT beam and optical pumping coil. AOMs for tuning and fast pulse timing are used to control the laser frequency. The ground state Raman laser and microwave modulation are also part of the setup. The diagram illustrates the experimental setup in more detail.
Chamber

Figure 3.2 Photo of experimental setup around chamber and diagram highlighting key components.
FORT Optics

Custom 1.03/0.78 µm achromatic triplet w/ window compensation

2W/qubit

λ = 1.03 µm
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

Figure 3.3 Camera image showing resolution of two FORT sites separated by \( \sim 10 \, \mu\text{m} \).

Image composed by averaging about 150 single atom loading events.

A timing diagram for a typical experiment is shown in Fig. 3.4. FORT loading begins by turning on the FORT and MOT beams simultaneously for \( \sim 200 \) ms. The MOT beams are switched off for \( \sim 100 \) ms, allowing the MOT cloud to fall out of the beam paths to avoid subsequent recapture of the cooled atoms. The MOT magnetic field coils are left on at all times, with residual magnetic fields at the FORT site measured at the \( \sim 200 \) mG level using Raman spectroscopy of the Zeeman splitting of hyperfine ground states \( |5\text{s}\,1/2, F = 1, 2\rangle \).

Readout of the FORT occupation is accomplished by switching the FORT beam on and off at rates of 0.5 to 2 MHz with a 50% duty cycle, while probing with the MOT lasers. Later experiments also switched the MOT lasers at the same rate (and out of phase with the FORT) with a 30% to 40% duty cycle to guarantee no overlap time between the MOT and FORT light. Scattered photons are collected by the optics.
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

Typically 80% retention of 1 atom from shot 1 to shot 2
and focused on the CCD camera to create images of the atoms in the FORT, with typical exposure times of 30 ms.

Figure 3.4

The camera image is processed by summing the pixels in a region of interest around the FORT position, subtracting an average background count value, and converting the integrated count signal to a photoelectron number. The result of 500 load/readout trials is shown in Fig. 3.5(a). The quantized nature of the integrated photoelectron signal is due to the presence or absence of atoms.

We describe the fit function used in Fig. 3.5(b) with Poisson distributions over atom and photoelectron numbers. With discrete shot noise limited events of average value \( \mu \) we expect a distribution

\[
 f_p(m) = \mu m e^{-\mu} m!
\]

[3.1]

where \( f_p(m) \) is the fraction of events with discrete value \( m \).

In the limit that \( \mu > 10 \), the Poisson distribution can be well approximated by a Gaussian distribution

\[
 g(m) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\left(\frac{(m - \mu)^2}{2\sigma^2}\right)}
\]

[3.2]

with mean offset \( \mu \) and standard deviation \( \sigma = \sqrt{\mu} \).
Single-qubit Rotations

\[ \Delta = -50 \text{ GHz} \]

\[ \Omega_R = \frac{\Omega_1 \Omega_2}{2\Delta} \]

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

10 G bias field added to lift Zeeman degeneracy.
Rabi Rotations

PRL 96, 063001 (2006)

600 ns Hadamard
Cross-talk

![Graph showing population transfer vs. pulse-width (µs).]

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

\[ T = 100 \mu s \]

\[ T = 300 \mu s \]

\[ T = 1 \text{ ms} \]

\[ T = 3 \text{ ms} \]

\[ \delta \omega/2\pi \text{ (kHz)} \]

\[ \Omega_2 \]

\[ \Omega_1 \]

\[ F = 2 \]

\[ F = 1 \]
Coherence time measurement

$T_2 = 870 \, \mu s$

$T_2 = \frac{1}{\pi \times 400} = 795 \, \mu s$

Figure of Merit

$$\frac{T_2}{t(\pi/2)} = 5000$$
Coherent Rydberg Excitation

Single atom Rydberg excitation

**Excitation scheme**

- 28d$5/2$, $F=2$
- $\gamma_r = 0.06$ MHz
- $\gamma_{\text{ion}} = 0.35$ MHz

- $\gamma_2$
- $\gamma_\text{ion}$
- $\gamma_r$

- $\text{P}=10$ mW, 480 nm
- $\text{P}=2 \mu$W, 780 nm

- 5p$3/2$
- 5s$1/2$, $F=2$
- 3.6 GHz

- $\text{time} \rightarrow$
- $\sim 8 \mu$s
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

|0⟩ | 1⟩ | r⟩
|---|---|---
|0⟩ | control | target
|1⟩ | control | target
|r⟩ | control | target

- **Step 1**
- **Step 2**
- **Step 3**

Figure 3.3 Camera image showing resolution of two FORT sites separated by ∼ 10 µm. Image composed by averaging about 100 images with a duty cycle of 20% for the MOT and FORT light. Scattered photons are collected by the optics.

Later experiments confirm the separation length along the y axis. Alignment of the Rydberg beams to one site (typically one) can be parameterized by a single step. The separation is measured to be parameterized by a single step.

Alignment of the Rydberg beams to one site (typically one) can be parameterized by a single step. The separation is measured to be parameterized by a single step.
Figure of Merit for Rydberg Blockade


Primary errors
Excitation of 2 or more atoms
AC-Stark shift of effective 2-level system
Blockade Shift

Prob of double excitation after $\pi$-pulse

\[ P_2 = \frac{\Omega^2}{2B^2} \]

Average over atom pairs $ij$, potentials $\varphi$

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

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

\[ P_2(55^\circ) = 0 \]

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

|n,p> atom 1  atom 2
|n,s>
|n-1,p>

No ext. field req’d

\[ V_{dd} \sim \frac{P_{ns,np} P_{ns,n-1,p}}{r^3} \]

\[ E_{95s} = \frac{E_{94p} + E_{95p}}{2} = 160 \text{ MHz} \]

Isotropic! (not \( \kappa \))
\[ |n,p> \text{ atom 1} \quad \text{atom 2} \]

\[ |n,s> \]

\[ |n-1,p> \]

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

\[ \Delta E \neq 0 \]

\[ E_{95s} = \frac{E_{94p} + E_{95p}}{2} = 160 \text{ MHz} \]

Förster Process

No ext. field req’d
$B = 30 \text{ kHz for 10 } \mu\text{m cloud}$

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

$$+ 7 \sqrt{\frac{2}{107}} |(50d2)(50d - 2)\rangle$$
Magnetic Field/Fine Structure Mixing

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

The figure illustrates the process of implementing a blockade experiment in quantum systems. The process is divided into three steps:

**Step 1:**
- Control state $|0\rangle$
- Target state $|1\rangle$

**Step 2:**
- Apply a phase shift $\Delta_{dd}$
- Control state $|0\rangle$
- Target state $|1\rangle$

**Step 3:**
- Control state $|0\rangle$
- Target state $|1\rangle$

For each trial, the atom separation along the $y$ axis is measured, typically $0.5 \mu m$, and varies.

The Rydberg beams are oriented and parameterized by a single separation length along the $y$ axis. Alignment of the Rydberg beams to one site (typically $5.4 \mu m$) is necessary for successful blockade.

The beams are described as $|0\rangle$, $|1\rangle$, and $|r\rangle$ with corresponding controls and targets.

**Beam Parameters:**
- $\epsilon_2$: Rydberg beam with $z$ polarized, $w_{2,z} = 9.0 \mu m$
- $\epsilon_1$: Rydberg beam with $z$ polarized, $w_{1,z} = 7.0 \mu m$

**Distribution Parameters:**
- Quasi one-dimensional FORT distribution
- $\sigma_y \sim 5 \mu m$, $\sigma_z \sim 0.5 \mu m$
- $z_{sep} = 10.2 \mu m$
Figure 5.4

Timing

<table>
<thead>
<tr>
<th>control site</th>
<th>first readout</th>
<th>optical pumping</th>
<th>second readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_2$ (480nm)</td>
<td>$\varepsilon_1$ (780nm)</td>
<td>$\pi$ pulse</td>
<td>$\pi$ pulse</td>
</tr>
<tr>
<td>$\varepsilon_2$ (480nm)</td>
<td>$\varepsilon_1$ (780nm)</td>
<td>$\pi$ pulse</td>
<td>$\pi$ pulse</td>
</tr>
</tbody>
</table>

FORT

~10µs

Target site

FORT timing parameters:

- Loading
- First readout
- Optical pumping
- Second readout

$T$
**Blockade Results-79d**

**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) blockaded oscillations on site 2 when the π pulses are applied to site 1. Panels D) and E) show the same as B) and C) but with the roles of sites 1 and 2 reversed.

In order to explain these observations we must account quantitatively for the strength of the Rydberg interactions. 87Rb atoms excited to the 79d5/2 state experience a Förster interaction \( (27) \) that is dominated by the near degeneracy of the energy of two 79d atoms with the energy of a two atom state \( n_p n_f \). The interaction is strongest for channels with \( n_p = 80, n_f = 78 \) and \( n_p = 81, n_f = 77 \). The situation is complicated by the fact that the \( B_0 = 1.15 \) mT bias magnetic field that is used for optical pumping remains on during the Rydberg interaction giving Zeeman shifts and coupling of different fine structure states. This leads to mixing of the 79d5/2 and 79d3/2 fine structure manifolds which have a zero field separation of only about 23 MHz.

Expected residual oscillations (Doppler, finite blockade shift)

0.1--additional errors from atom loss on 1st readout, imperfect optical pumping, and imperfect photoionization
Demonstrates coherent control of the evolution of one atom based on the quantum state of a single additional atom 11 microns away.
French results


Blockade

$\sqrt{2}$ enhancement
Mesoscopic Dipole Blockade

Lukin...PRL 87, 037901 (2001).: Multi-atom excitation strongly suppressed in mesoscopic cloud
Protocol for single atom loading:

- trap \( N \) atoms into FORT
- pump all \( N \) atoms to \( |b\rangle \)
- transfer “1” atom to \( |a\rangle \)
- eject \( (N-1) \) atoms in \( |b\rangle \)

\[
\psi \sim \frac{1}{\sqrt{N}} \sum_j |b_1...a_j...b_N\rangle
\]

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

\[ \Psi = \frac{1}{\sqrt{N}} \sum_j e^{i\phi_j} |0...e_j...\rangle \]

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

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

$$k = (k_1 + k_2 - k_3)$$

N-fold enhancement in phase-matched direction
**Single Qubit to Directed Photon**

- **initialize**
  \[ |\psi\rangle_1 \rightarrow a_2 \]

- **entangle**
  \[ |\psi\rangle_1 |a\rangle_2 \rightarrow |a + \psi\rangle_2 \]

\[ |b\rangle_2 \rightarrow |c\rangle_2 \rightarrow |a\rangle_2 |1\rangle_{k_4} \]

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

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