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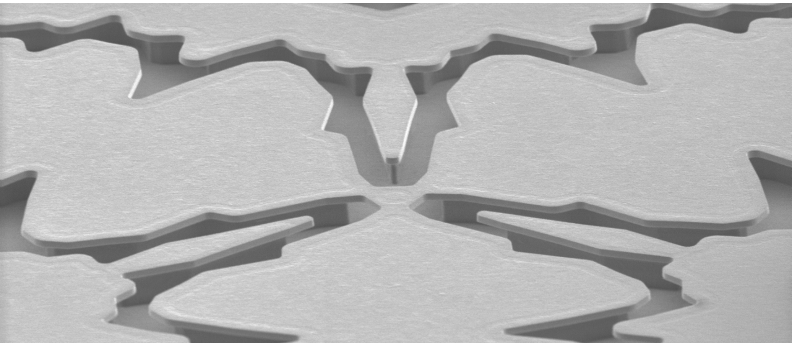

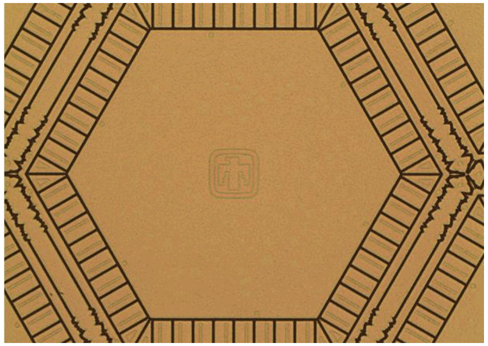

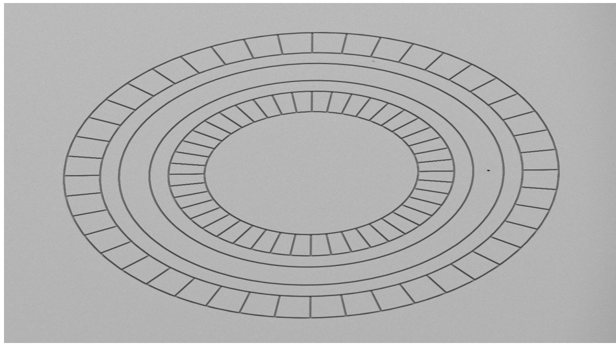

# Quantum information processing with trapped atoms

**Daniel Stick**

June 5, 2012

IARPA

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# Trapped ions

# Trapped neutral atoms

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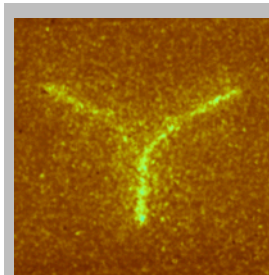

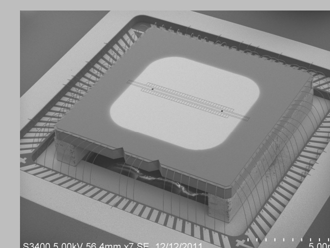


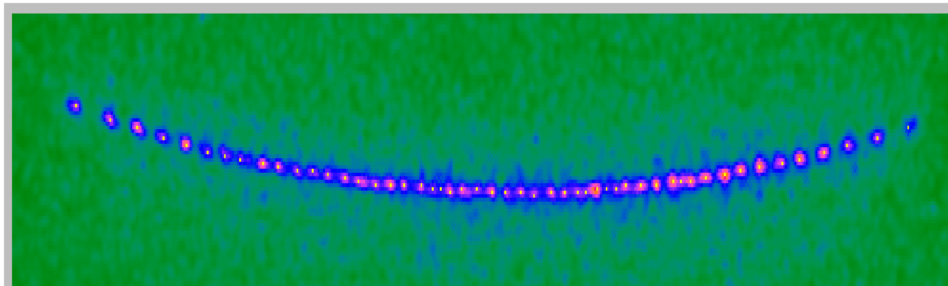

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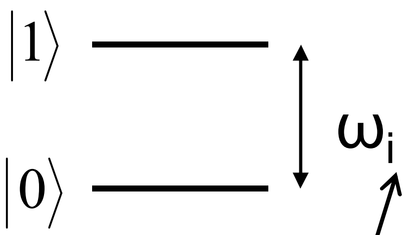
# Qubit

- Simplified “ideal” ion:
  - Hyperfine qubit
  - Spin ½ nucleus
  - Use magnetic field insensitive states (to 1st order)
  - Background Hamiltonian:

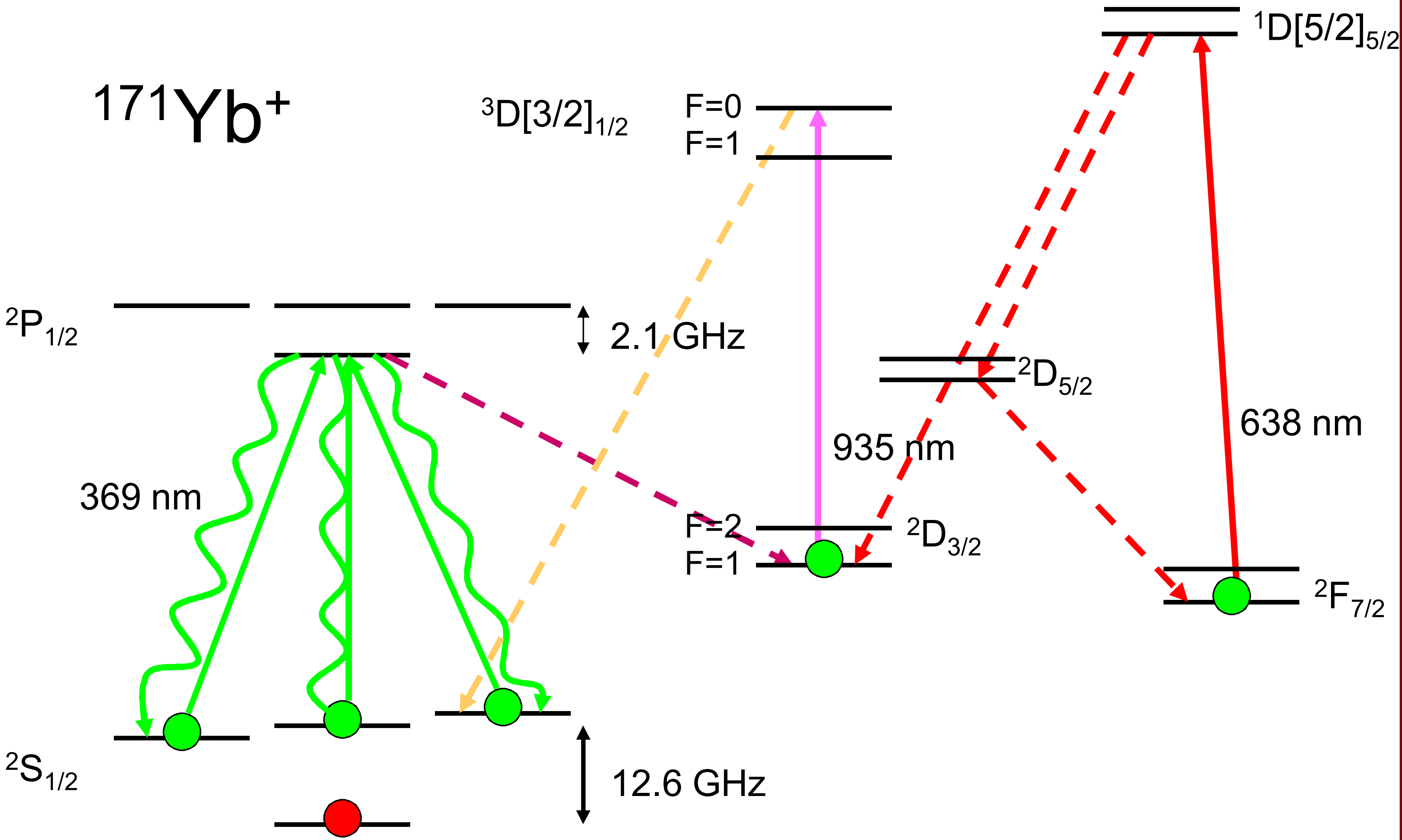



location index

$$H_{\text{background}} = \frac{1}{2}\hbar \sum_{i=1}^{N} \omega_i(t)(\sigma_z)_i$$

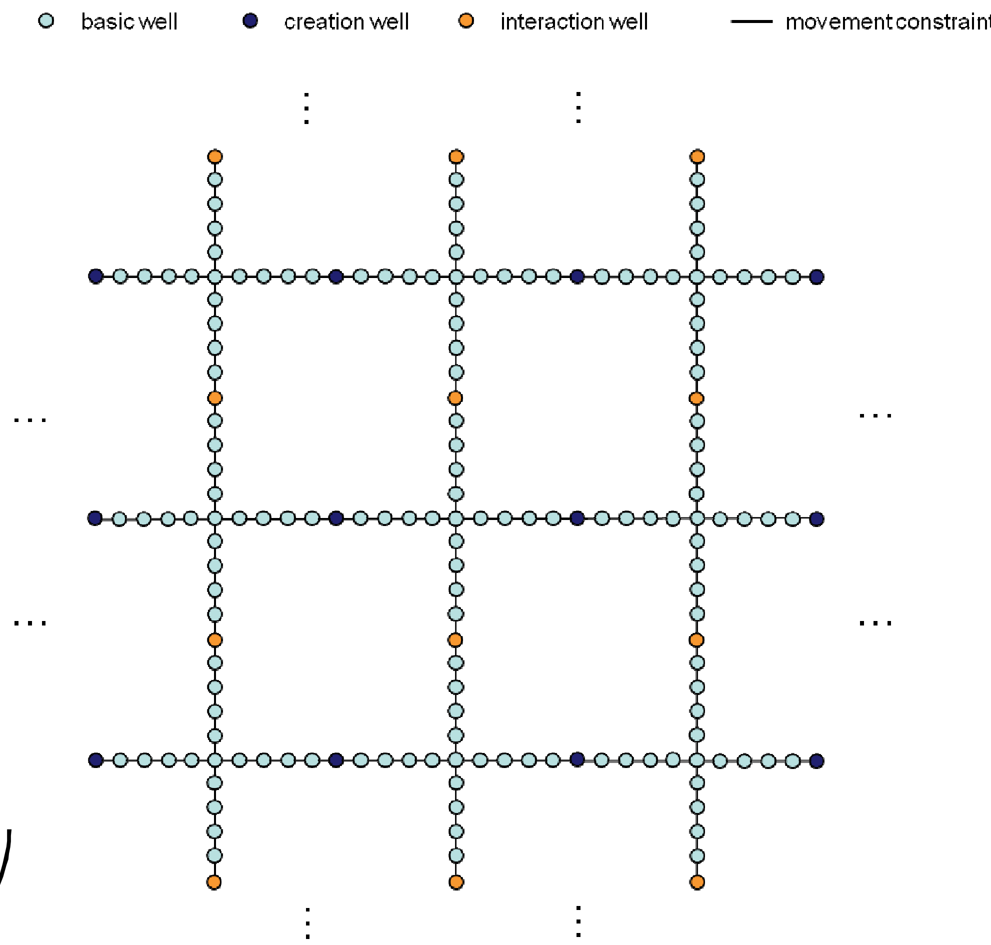
$$\langle \omega_i(t) \rangle / 2\pi = \omega_0 / 2\pi = 1 \text{ GHz} \qquad \epsilon_i(t) = \omega_i(t) - \omega_0$$

# A Real Qubit

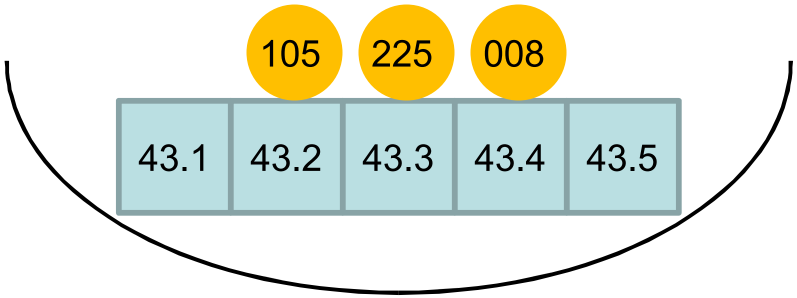

171Yb+
3D[3/2]1/2
F=0
F=1
1D[5/2]5/2
2P1/2
2.1 GHz
2D5/2
369 nm
935 nm
638 nm
F=2
F=1
2D3/2
2F7/2
2S1/2
12.6 GHz

# Topology

- Rectangular unit cell, infinite graph in 2D plane
- All wells can store up to 5 ions

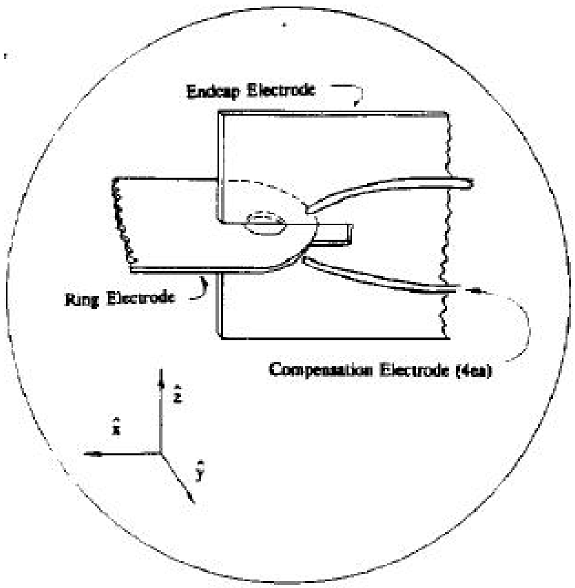


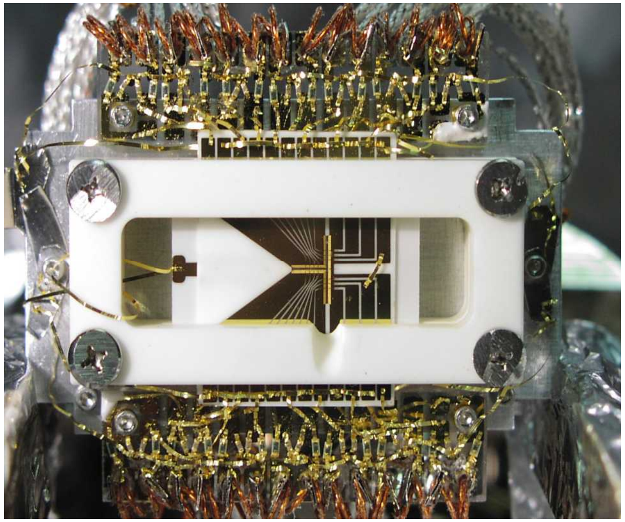

Example:

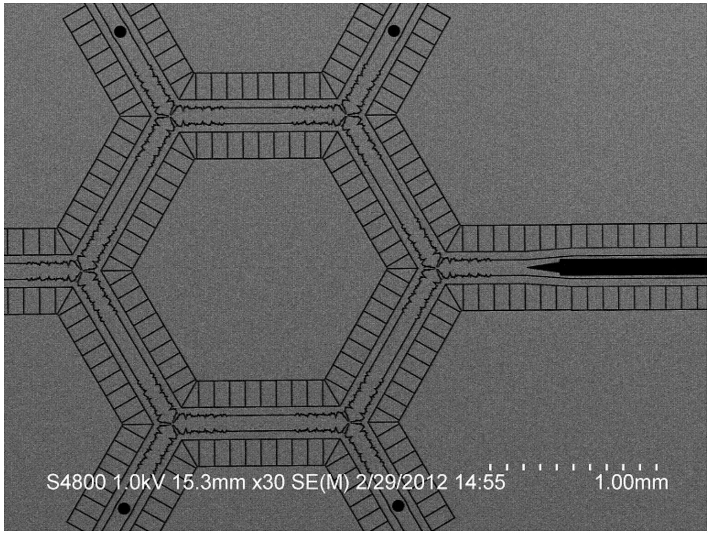


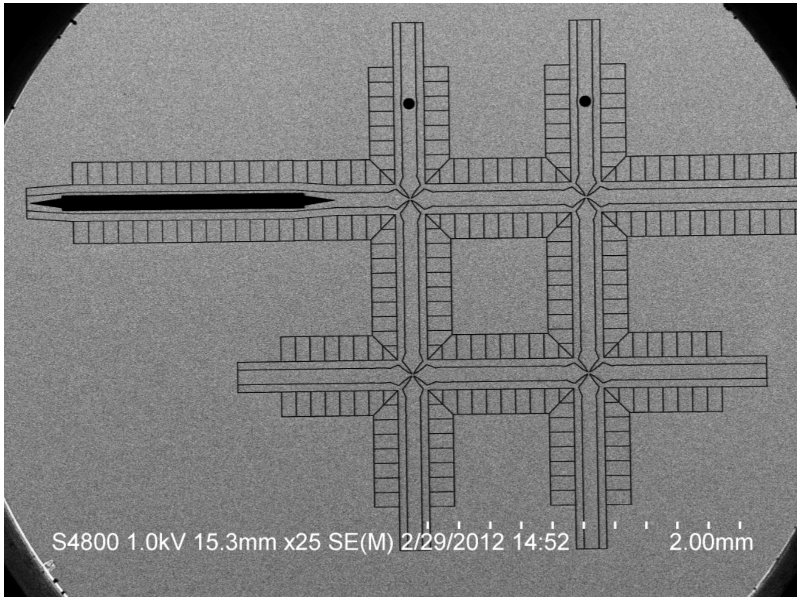

well 43

# Evolution of topology



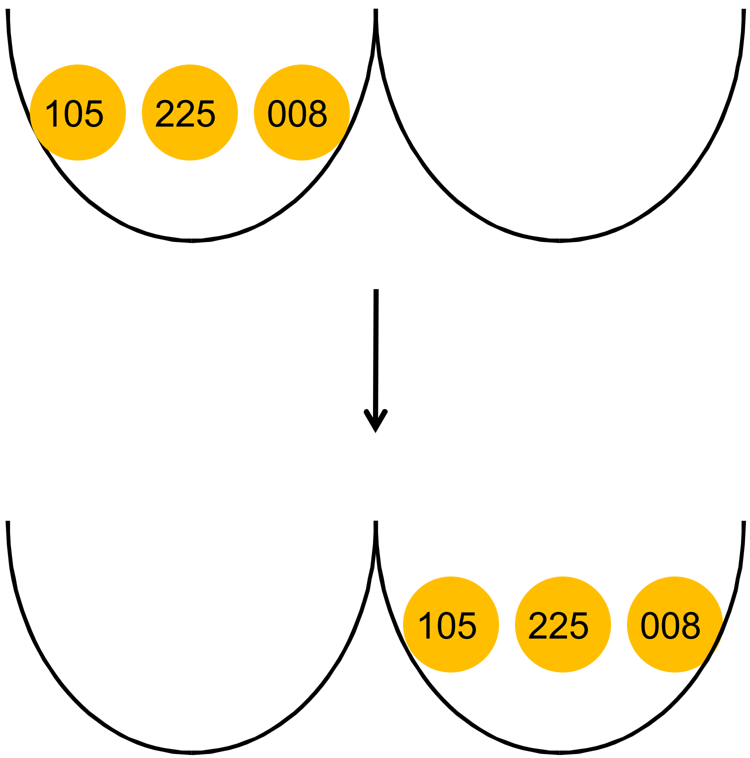





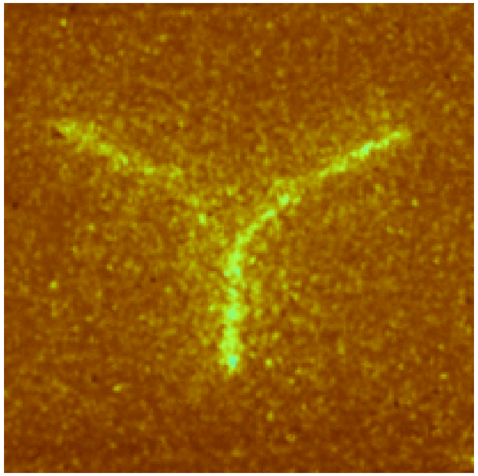



# Instructions

- CREATE: load an ion at a creation well; created ion is described by mixed state $\frac{1}{2}I$
- MOVE: shuttle all ions in a well to a neighboring well
  - adjacency
  - speed
  - order preserved



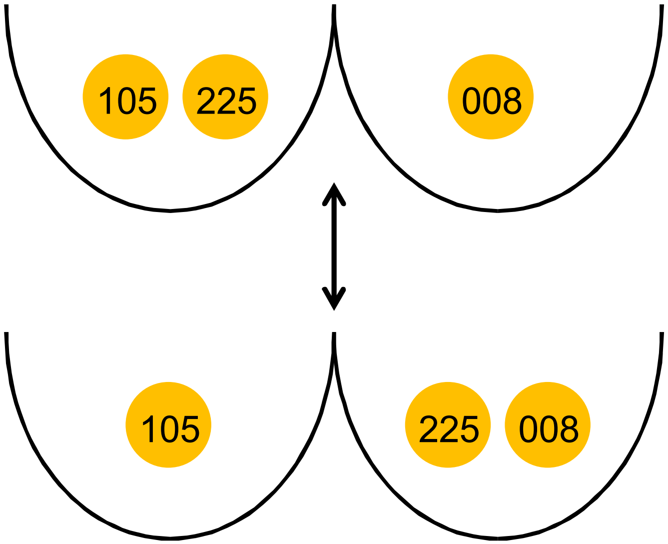
# Instructions

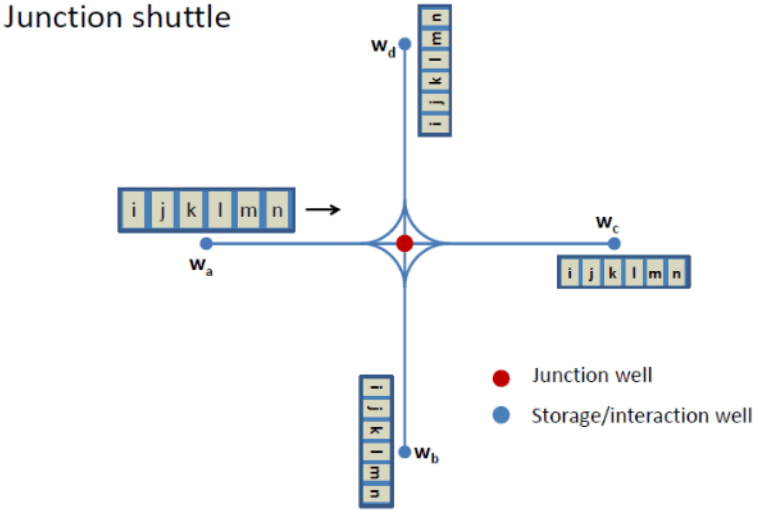


# Instructions

- SPLITCOMBINE: move all or a fraction of the ions in one well into a neighboring well, which may or may not already have ions
  - speed, adjacency, order
  - neither well can have > 5 ions at any time

- Note: shuttling through a junction is required to change order



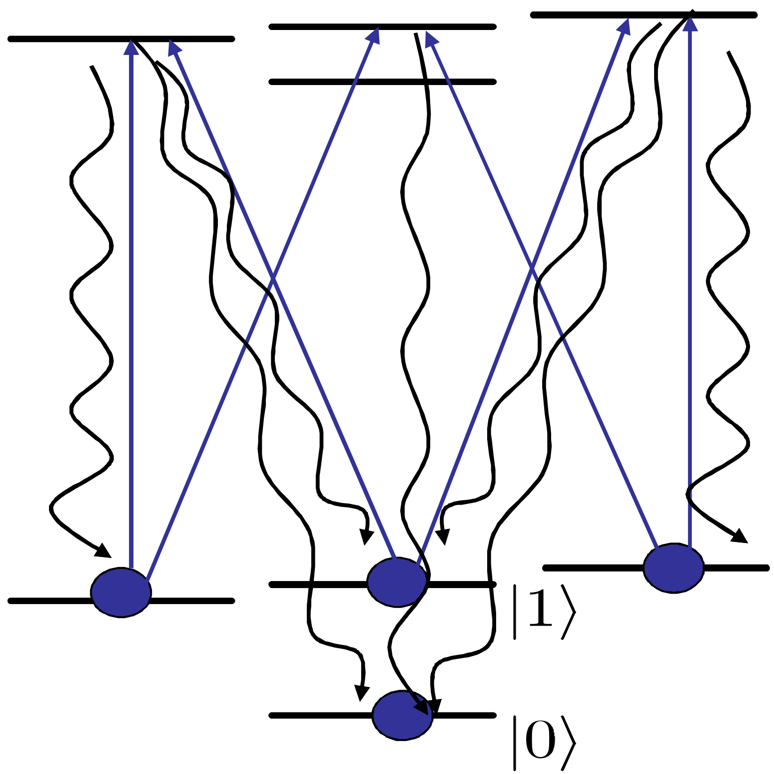
# Instructions

- SETZ: initialize the ion

$$\rho_{init} = \begin{bmatrix} 1-\epsilon_{init} & 0 \\ 0 & \epsilon_{init} \end{bmatrix}$$

$$\epsilon_{init} = 10^{-5}$$

State initialization



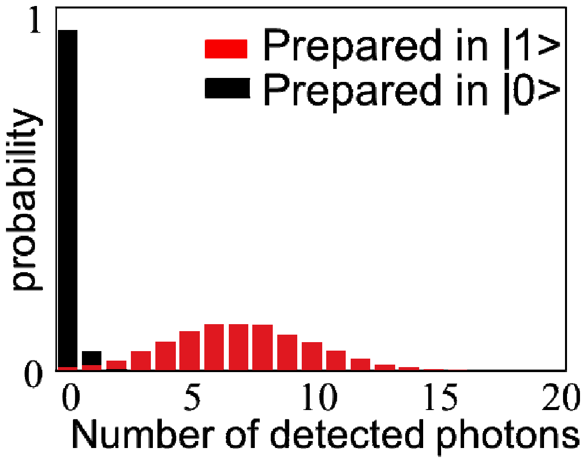
# Instructions

- MEASUREZ: measure the state of the ion

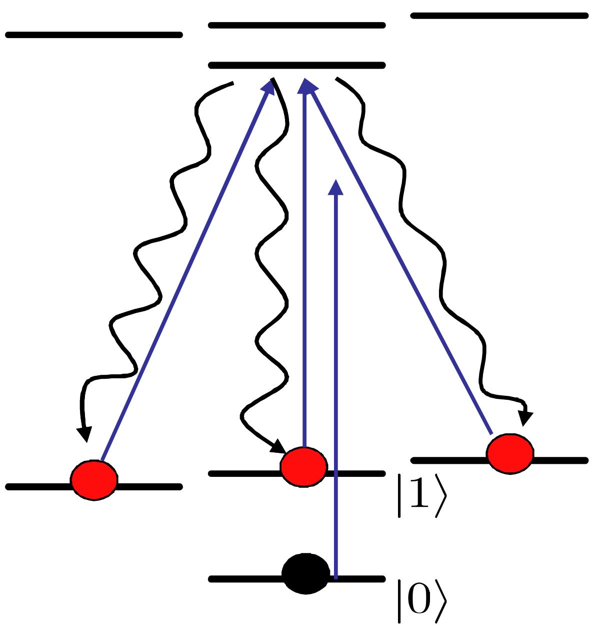
$$a|0\rangle + b|1\rangle$$

$$p(|0\rangle) = 1 - \epsilon|a|^2 - (1-\epsilon)|b|^2$$

$$p(|1\rangle) = \epsilon|a|^2 + (1-\epsilon)|b|^2$$




State detection




$\epsilon$ is the probability of a bit flip error in the measurement. $\epsilon = 10^{-4}$

# Instructions

$$\theta_{xy} = 2\int_0^T \Omega'_{xy}(t)\,dt$$

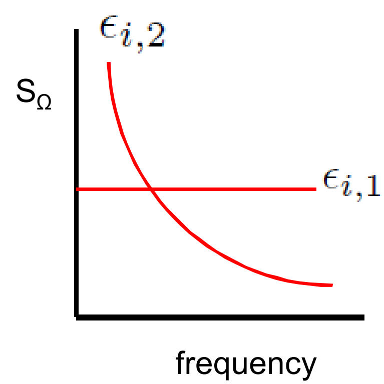
- ROTXY:

$$R_{xy}(\theta_{xy},\phi_{xy}) = cos(\theta_{xy}/2)I + i\sin(\theta_{xy}/2)\cos(\phi_{xy})\sigma_x + i\sin(\theta_{xy}/2)\sin(\phi_{xy})\sigma_y$$

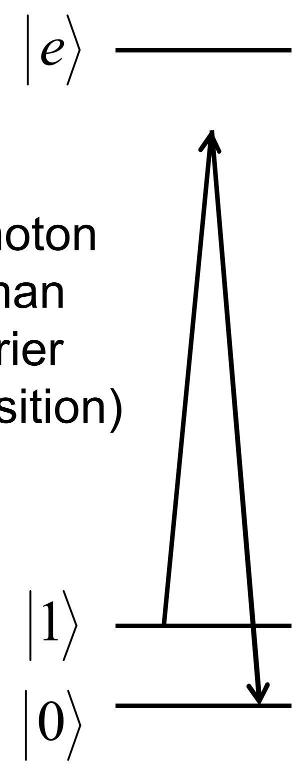
$$H_{xy} = \frac{\hbar}{2}\Omega'_{xy}(t)\begin{bmatrix} 0 & e^{i\phi_{xy}} \\ e^{-i\phi_{xy}} & 0 \end{bmatrix}$$

- errors:

$$\Omega'(t) = \Omega(t) + \epsilon_{i,1}(t) + \epsilon_{i,2}(t)$$




2 photon Raman (carrier transition)



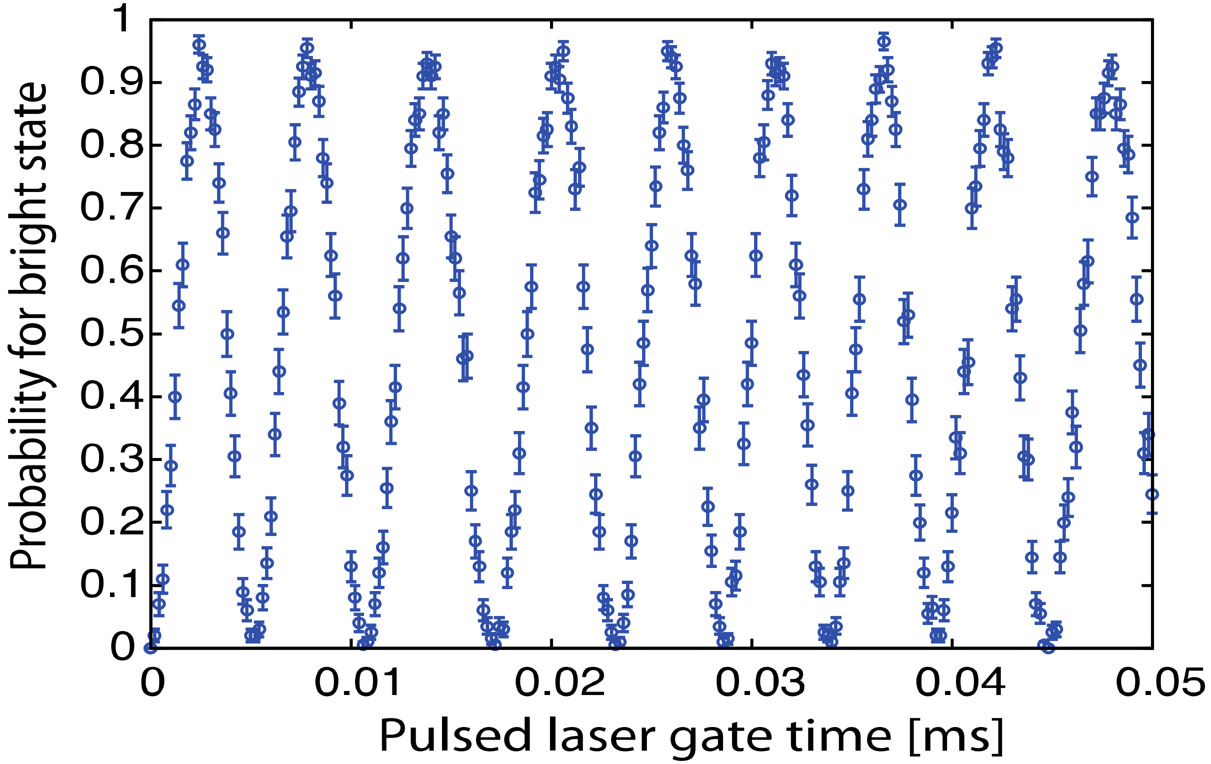

- constraints:

$$0 \le \Omega(t) \le 1.5\times10^6 \text{ radians/s}$$

$$0 \le |d\Omega(t)/dt| \le 6\times10^{13} \text{ radians/s}^2$$

# Instructions

Pulsed laser Rabi oscillation




π time: 3 μs

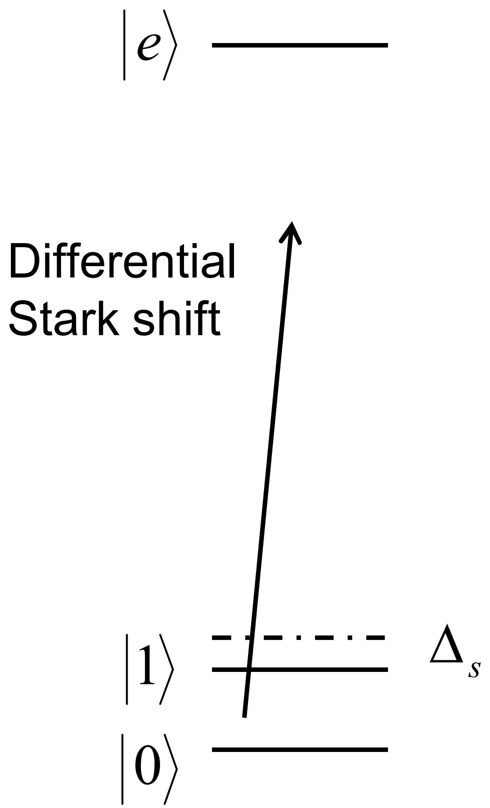
courtesy of Duke University

# Instructions

- ROTZ: $R_z(\theta) = e^{i\,(\theta/2)\,\sigma_z}$

$$\theta = 2\int_0^T \Omega'(t)\,dt$$

$$H = \frac{\hbar}{2}\Omega_s(t)\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$




- errors:

$$\Omega'(t) = \Omega(t) + \epsilon_{i,1}(t) + \epsilon_{i,2}(t)$$

- constraints:

$$0 \le \Omega(t) \le 1.5 \times 10^6 \text{ radians/s}$$

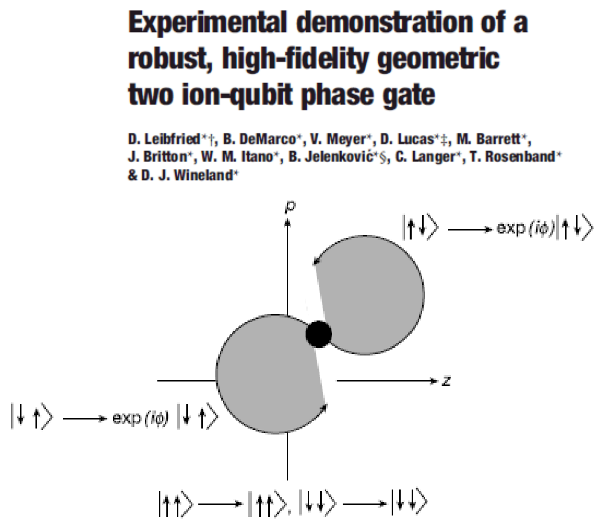
$$0 \le |d\Omega(t)/dt| \le 6 \times 10^{13} \text{ radians/s}^2$$

# Instructions

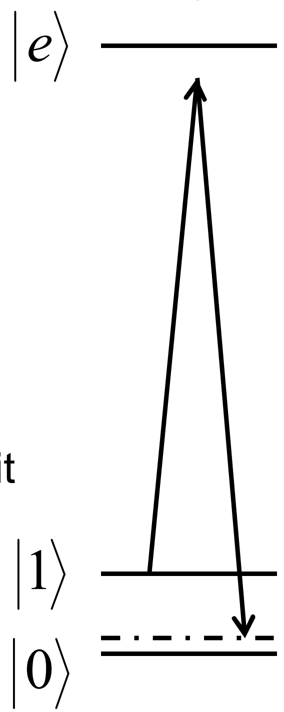
- GEOPHASE

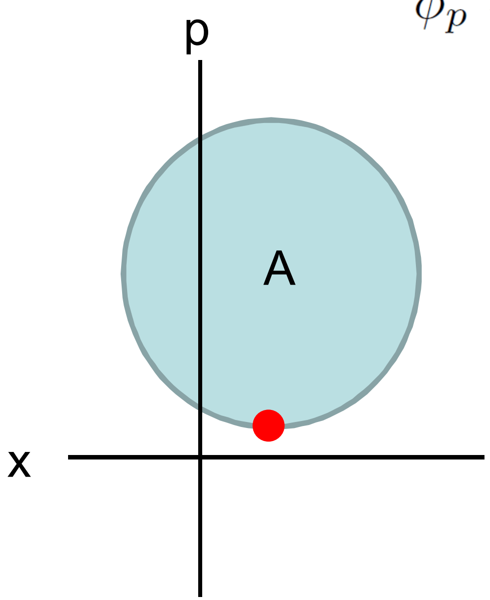
$$U_p = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\phi_p} & 0 & 0 \\ 0 & 0 & e^{i\phi_p} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\phi_p = \int_0^T \Omega'_p(t)\, dt$$




2 photon Raman (detuned from motional mode)

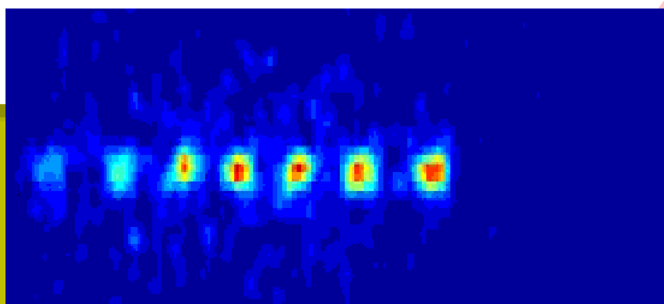


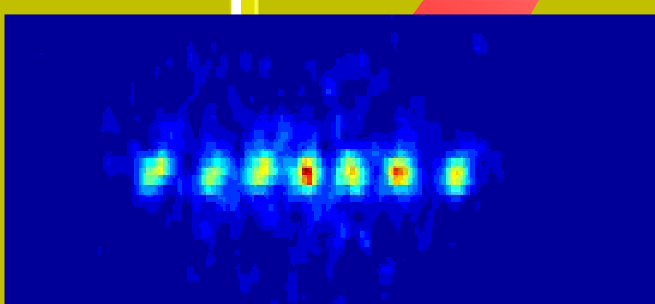




Errors

- Area A (proportional to $\phi_p$)
  - laser intensity
  - only one in PMD, similar to single qubit rotation
- Under/over rotation
  - Pulse timing, frequency fluctuations
- Size of phase space
  - Ion heating

# Two qubit gate





ternal states of these ions entangled

Thanks: R. Blatt, Univ. Innsbruck

**Cirac and Zoller, Phys. Rev. Lett. 74, 4091 (1995)**

# Future

- Future additions/changes to ion PMD
  - More “realistic” noise amplitudes
  - Change frequency range of 1/f noise to allow for more quantum control
  - Leakage (ion loss)
  - Impact of heating on 2 qubit gate
    - Time for sympathetic cooling
    - Decrease in fidelity
  - Clock noise (jitter, phase noise)

Trapped ions

# Trapped neutral atoms

Grant Biedermann

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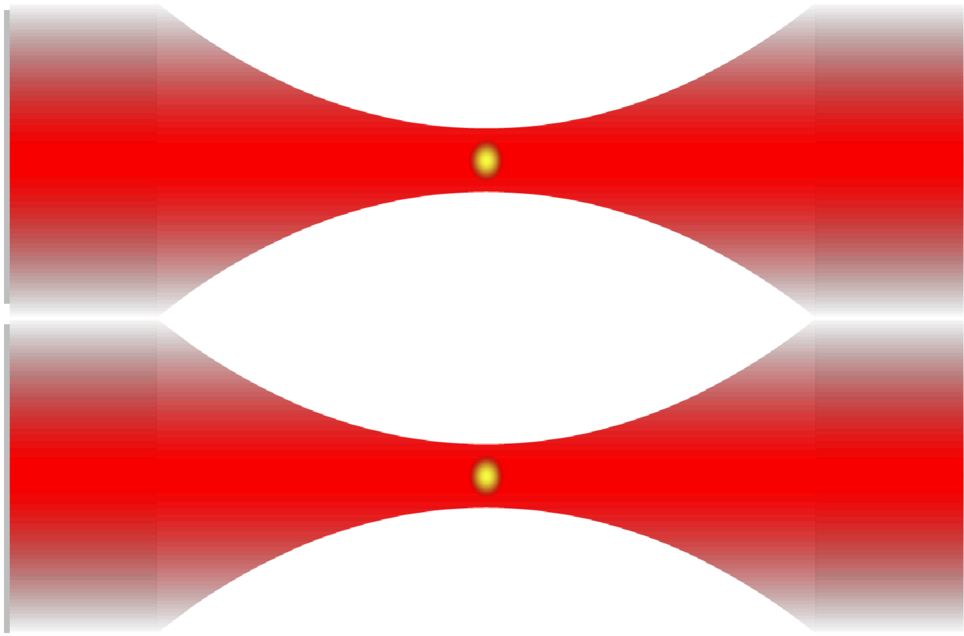

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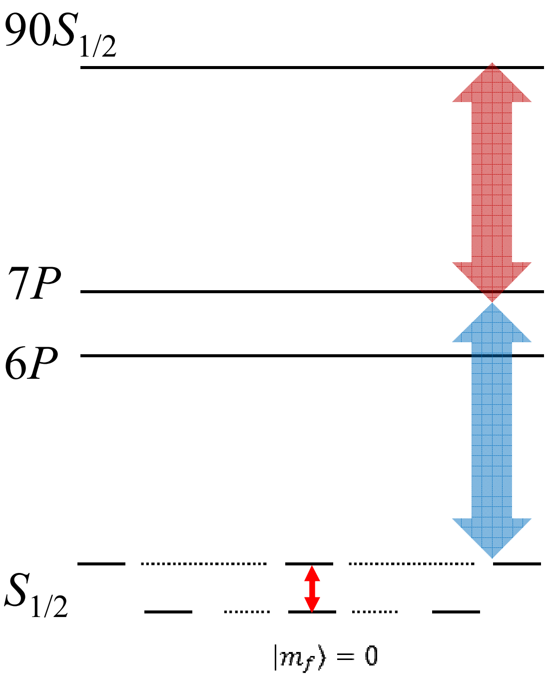
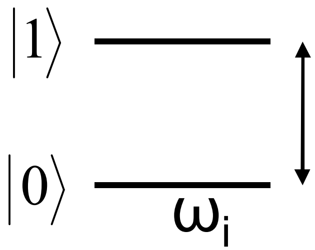
# Qubit

- Simplified "ideal" neutral atom:
  - Hyperfine qubit
  - Use magnetic field insensitive states
  - Ground states space of atom identical to qubit space-(cannot decay outside qubit sub-space)

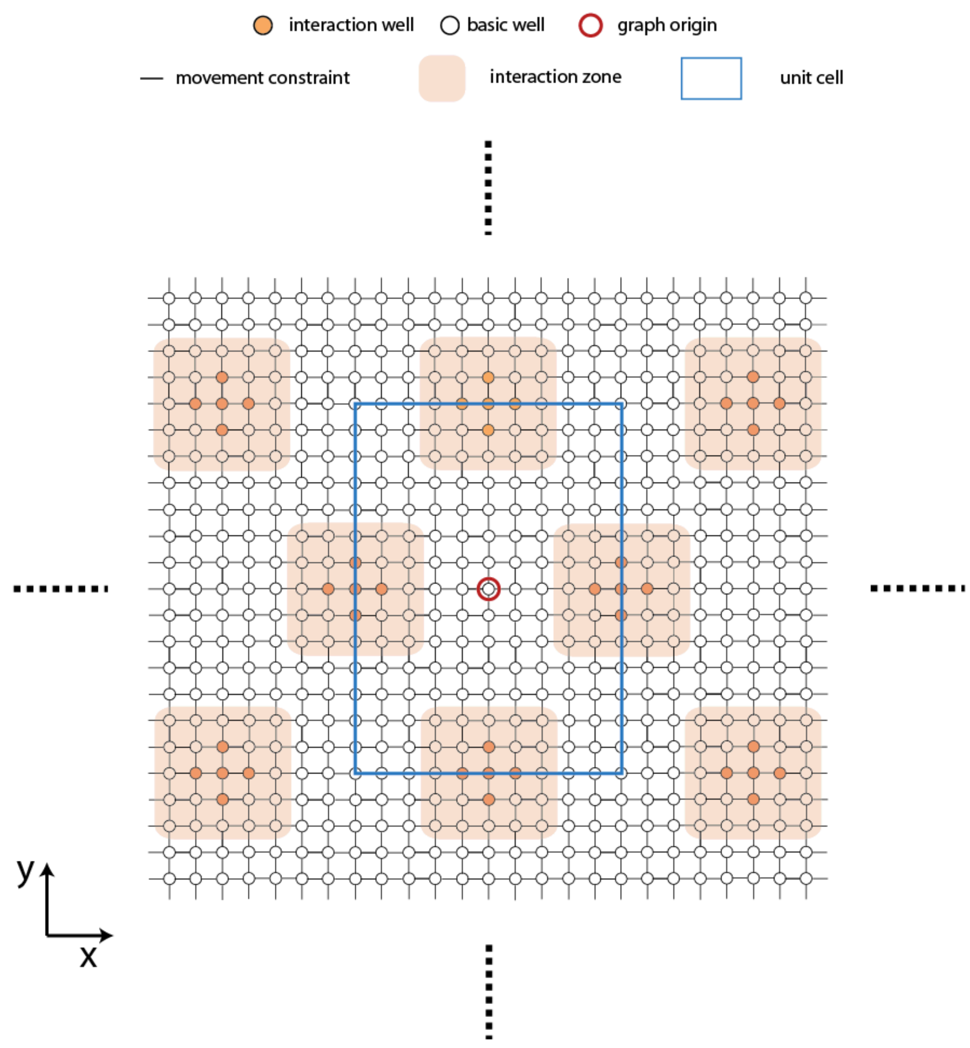
Cs Energy Structure



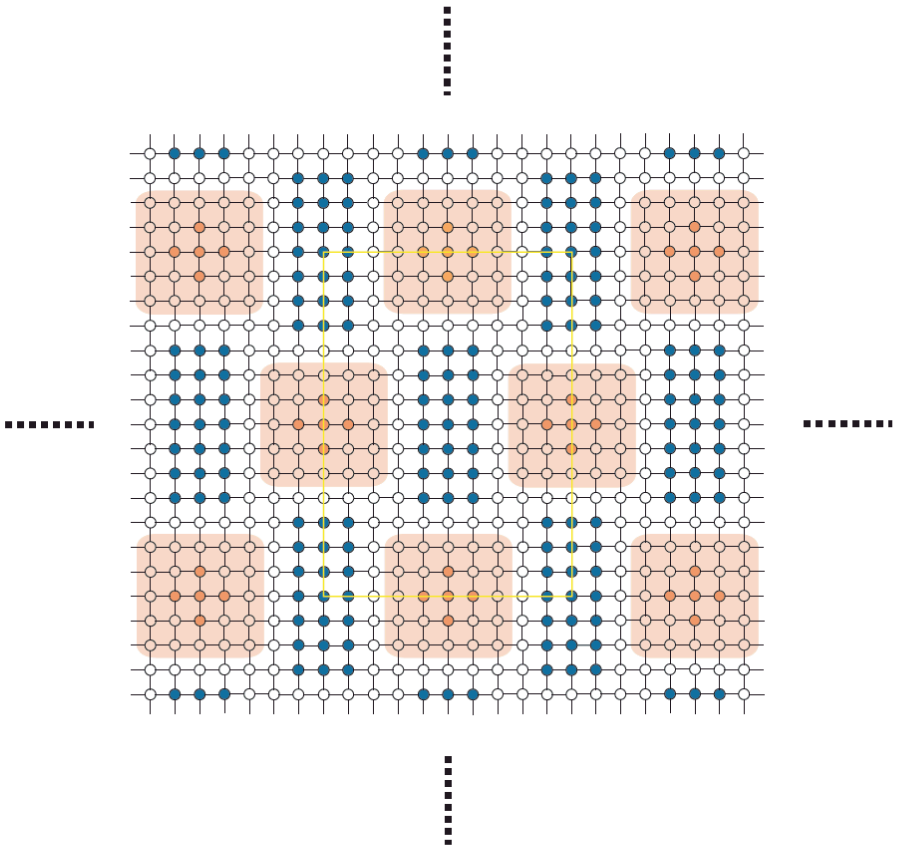
# *Neutral atoms* Topology

- Infinite graph in 2D plane, origin indicated
- Two types of wells
  - Interaction: performs any instruction
  - Basic: supports only move and create
- Wells can store 1 atom
- Interaction zone size defined by Raman laser size
- Distance between interaction zones defined by dipole-dipole interaction of Rydberg states



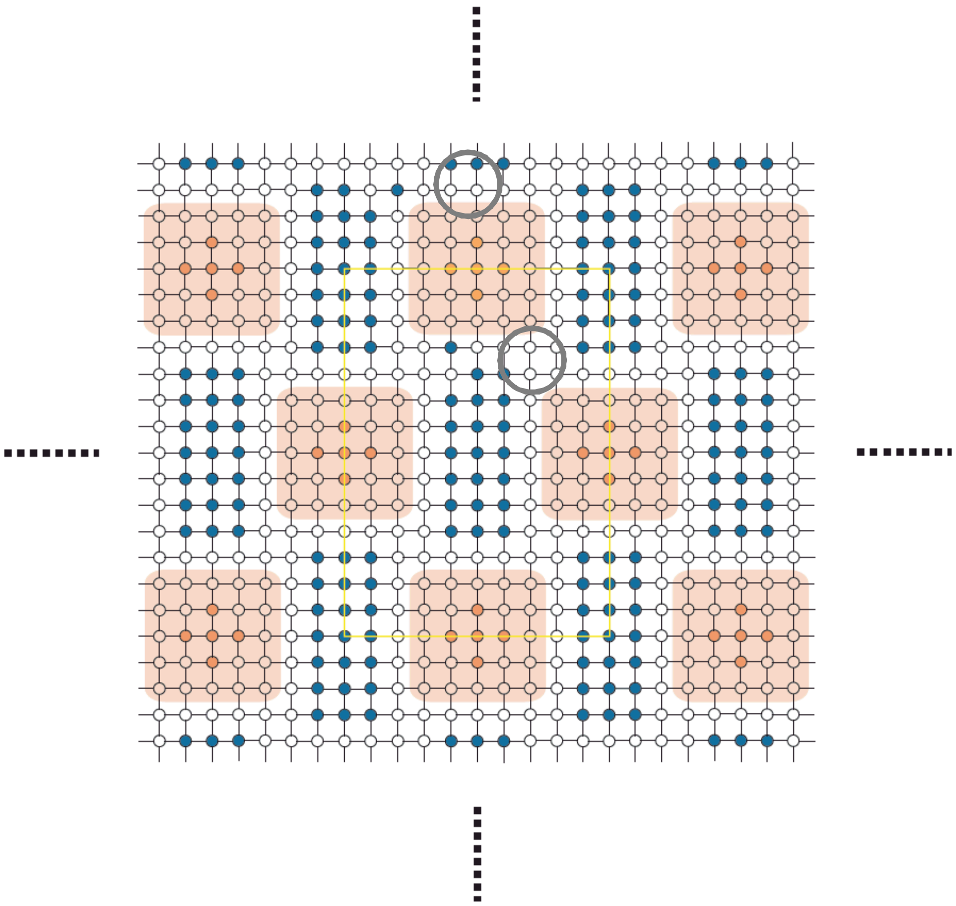
# Instructions

- CREATE:
  - There is a single loading event at the beginning of the computation.
  - Makes atom/qubits physically present
  - Takes 10 seconds
  - Can load atoms anywhere
  - Mott-insulator technique.
  - Example layout shown by blue wells in figure
  - Atom state is described by mixed state ½$I$



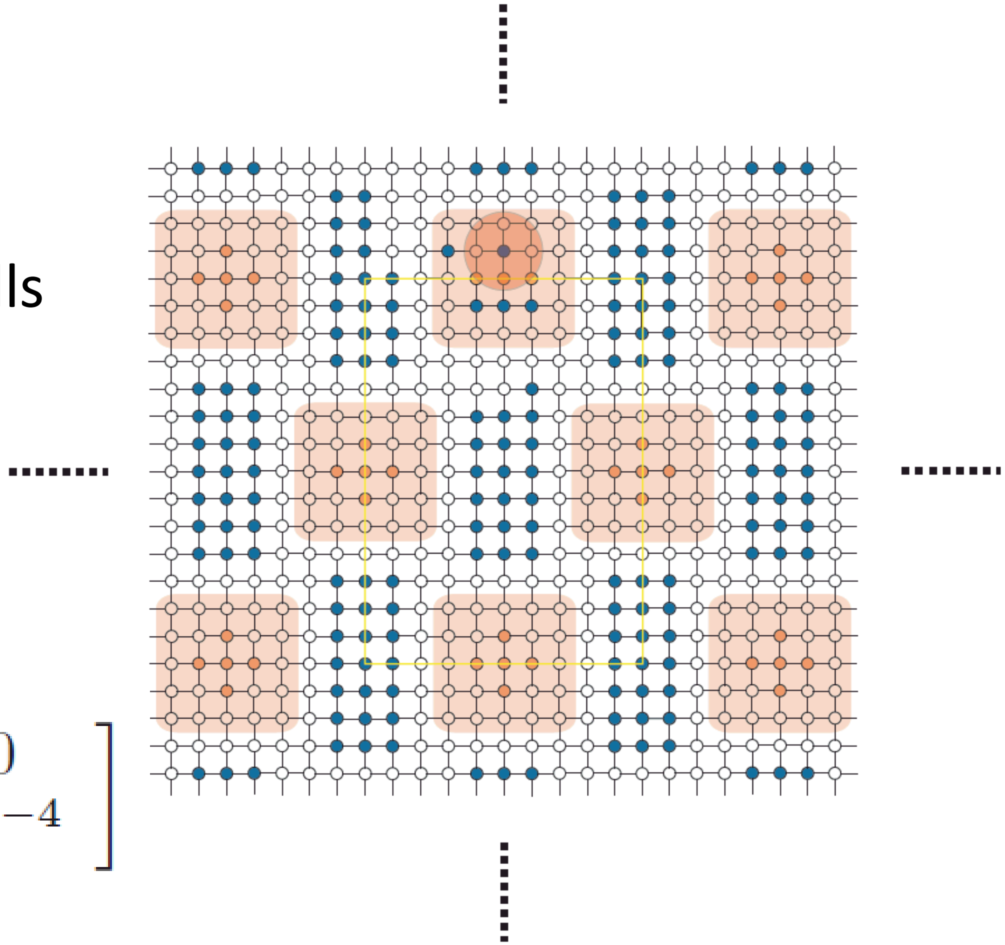
# Instructions

- MOVE: shuttle atom in a well to a neighboring well
  - adjacency
  - Speed—50 μs per well
  - Can occur simultaneously at all sites
  - Atoms cannot move past one another



# Instructions

- SETZ:
  - initialize the atom
  - Adjacent ‘square’ of wells must be unoccupied
  - Atom must be at an interaction well



$$\rho_{init} = \begin{bmatrix} 1 - 10^{-4} & 0 \\ 0 & 10^{-4} \end{bmatrix}$$

# Instructions

- MEASUREZ:
  - measure the state of the atom
  - Same rules apply from SETZ

$$a|0\rangle + b|1\rangle$$

$$p(|0\rangle) = 1 - \epsilon|a|^2 - (1-\epsilon)|b|^2$$

$$p(|1\rangle) = \epsilon|a|^2 + (1-\epsilon)|b|^2$$

$\epsilon$ is the probability of a bit flip error in the measurement. $\epsilon = 10^{-4}$

# Instructions

- ROT:
  - Usage

$$R(\theta,\phi) = cos(\theta/2)I + i\sin(\theta/2)\cos(\phi)\sigma_x + i\sin(\theta/2)\sin(\phi)\sigma_y$$

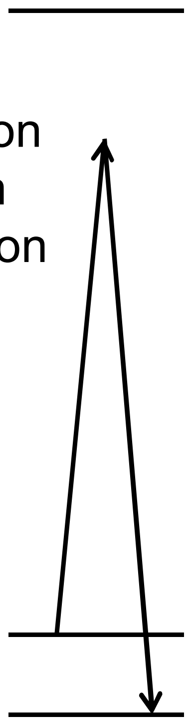
$$\theta = 2\int_0^T \Omega'(t)\,dt$$

$$H = \Omega(t)(1 \pm \Gamma_\omega)(S_+ e^{i\phi} + S_- e^{-i\phi})$$

  - Constraints:
    - topology identical to SETZ
    - $2\pi \times 10^6 \leq \Omega \leq 20\pi \times 10^6$ radians/s or $\Omega = 0$ radians/s.
  - Errors: shot-to-fluctuation in Rabi frequency

$$\langle \Gamma_\omega(t)\Gamma_\omega(t')\rangle = 4/\pi \times 10^{-4}$$

2-photon Raman transition



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*Neutral atoms*

# Instructions

- CPHASE:
  - 2-qubit controlled phase gate
  - Rydberg mediated
  - Only the two participating atoms may reside in interaction zone

Quantum information with Rydberg atoms

M. Saffman and T. G. Walker

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K. Mølmer

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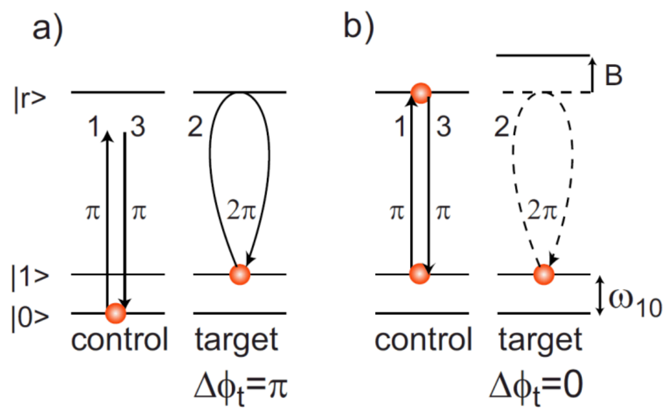
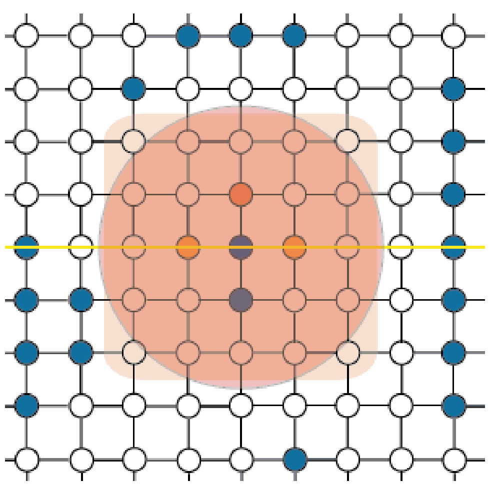
(Published 18 August 2010)



# Instructions

- CPHASE (cont.):
  - Hamiltonian

$$H_{\text{eff}} = \hbar\Omega_R \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

    - Where $\Omega_R = 18\pi \times 10^6$ radians/s.
    - Rabi frequency is not adjustable beyond on/off switching
  - Error
    - Arises from spontaneous decay from Rydberg level
    - Neglect rotation error as it leads to spontaneous decay
    - Model as amplitude damping according to Lindblad equation

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + \gamma\left(\sigma_-^{(1)}\rho\sigma_+^{(1)} - \frac{1}{2}\sigma_+^{(1)}\sigma_-^{(1)}\rho - \frac{1}{2}\rho\sigma_+^{(1)}\sigma_-^{(1)}\right) + \gamma\left(\sigma_-^{(2)}\rho\sigma_+^{(2)} - \frac{1}{2}\sigma_+^{(2)}\sigma_-^{(2)}\rho - \frac{1}{2}\rho\sigma_+^{(2)}\sigma_-^{(2)}\right)$$

Here $\gamma = 10^{-4}$