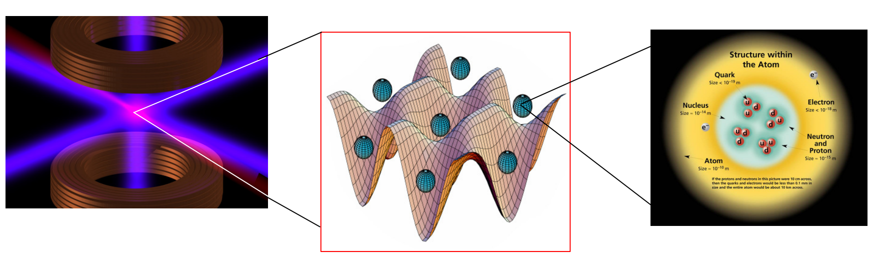
The DiVincenzo criteria

Quantum Information Processing
with
Neutral Atoms

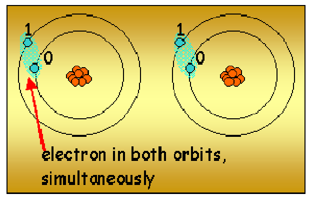
Quantum computing with neutral atoms



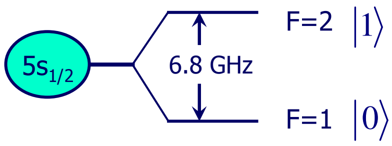
1. A scalable physical system with well characterized qubits: memory

(a) Internal atomic state qubits:

ground hyperfine states of neutral trapped atoms
well characterized
Very long lived!



M_F=-2,-1,0,1,2



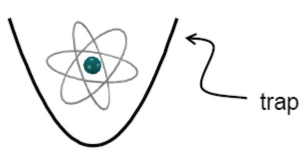
^{87}Rb: Nuclear spin I=3/2

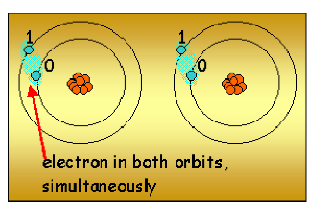
M_F=-1,0,1

1. A scalable physical system with well characterized qubits: memory

(a)Internal atomic state qubits
(b) Motional qubits

single trapped atom:

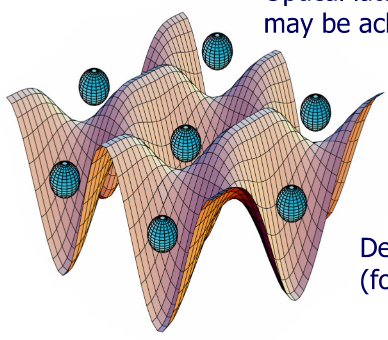




Advantages: very long decoherence times!
Internal states are well understood: atomic spectroscopy & atomic clocks.

1. A scalable physical system with well characterized qubits

Optical lattices: loading of one atom per site may be achieved using Mott insulator transition.



Scalability: the properties of optical lattice system do not change in the principal way when the size of the system is increased.

Designer lattices may be created (for example with every third site loaded).

Advantages: inherent scalability and parallelism.
Potential problems: individual addressing.

2: Initialization

Internal state preparation: putting atoms in the ground hyperfine state

Very well understood (optical pumping technique is in use since 1950)

Very reliable (>0.9999 population may be achieved)

Motional states may be cooled to motional ground states (>95%)

Loading with one atom per site: Mott insulator transition and other schemes.

Zero's may be supplied during the computation (providing individual or array addressing).

3: A universal set of quantum gates

1. Single-qubit rotations: well understood and had been carried out in atomic spectroscopy since 1940's.

2. Two-qubit gates: none currently implemented (conditional logic was demonstrated)

Proposed interactions for two-qubit gates:

(a) Electric-dipole interactions between atoms
(b) Ground-state elastic collisions
(c) Magnetic dipole interactions

Only one gate proposal does not involve moving atoms (Rydberg gate).

Advantages: possible parallel operations
Disadvantages: decoherence issues during gate operations

Rydberg gate scheme

Gate operations are mediated by excitation of Rydberg states
Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)

Why Rydberg gate?

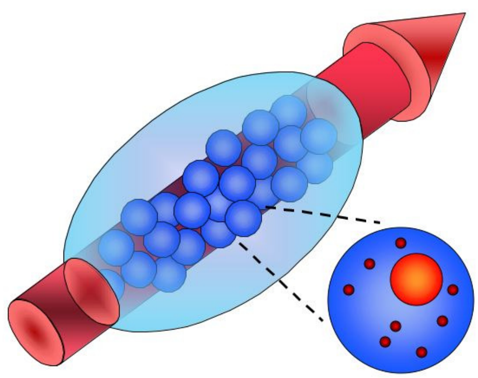
Rydberg gate scheme

Gate operations are mediated by excitation of Rydberg states
Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)

Do not need to move atoms!

FAST!

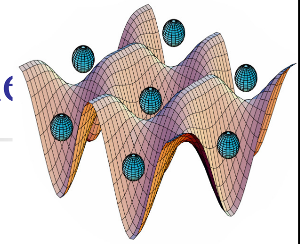
Local blockade of Rydberg excitations



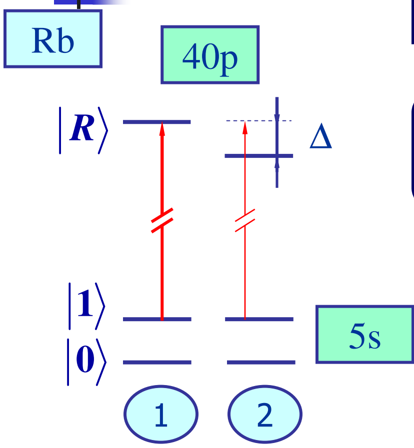
Excitations to Rydberg states are suppressed due to a dipole-dipole interaction or van der Waals interaction

http://www.physics.uconn.edu/~rcote/

Rydberg gate scheme



FAST!

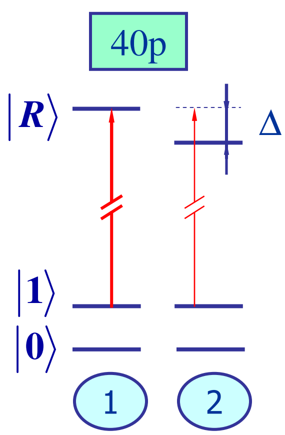


Apply a series of laser pulses to realize the following logic gate:

$$
\begin{aligned}
|00\rangle &\rightarrow |00\rangle \\
|10\rangle &\rightarrow |01\rangle \\
|01\rangle &\rightarrow |10\rangle \\
|11\rangle &\rightarrow -|11\rangle
\end{aligned}
$$

Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)

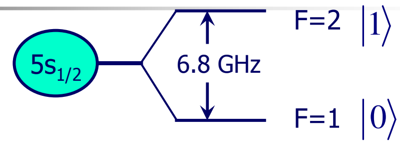
Rydberg gate scheme



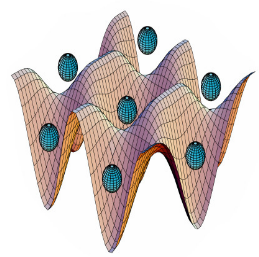
$$
\begin{array}{ccccccc}
 & \pi[1] & & 2\pi[2] & & \pi[1] & \\
|00\rangle & \rightarrow & |00\rangle & \rightarrow & |00\rangle & \rightarrow & |00\rangle \\
|01\rangle & \rightarrow & |01\rangle & \rightarrow & -|01\rangle & \rightarrow & -|01\rangle \\
|10\rangle & \rightarrow & |R0\rangle & \rightarrow & |R0\rangle & \rightarrow & -|10\rangle \\
|11\rangle & \rightarrow & |R1\rangle & \rightarrow & |R1\rangle & \rightarrow & -|11\rangle
\end{array}
$$

4. Long relevant decoherence times

Memory: long-lived states.



Fundamental decoherence mechanism for optically trapped qubits: photon scattering.



Decoherence during gate operations: a serious issue.

5: Reading out a result

"Quantum jump" method via cycling transitions.
Advantages: standard atomic physics technique, well understood and reliable.