Physical implementations of quantum computing

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Overview

Introduction

- DiVincenzo Criteria
- Characterising coherence times

Survey of possible qubits and implementations

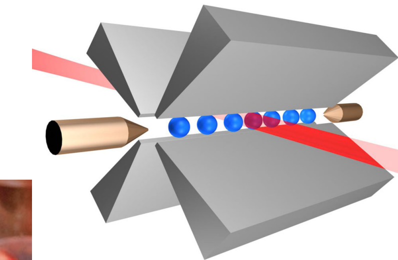
- Neutral atoms
- Trapped ions

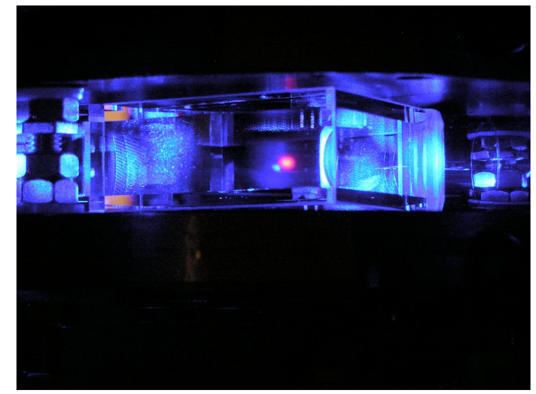
- Colour centres (e.g., NV-centers in diamond)
- Quantum dots
- Superconducting qubits (charge, phase, flux)

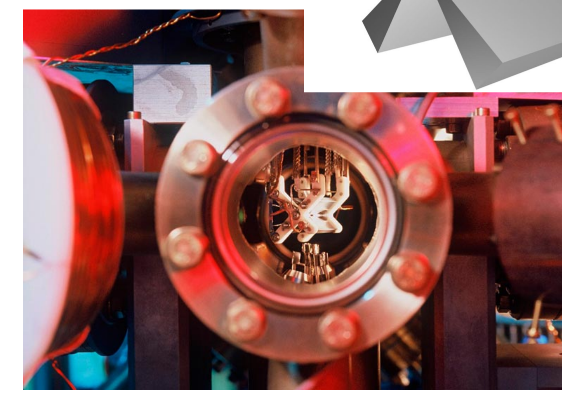
- NMR
- Optical qubits

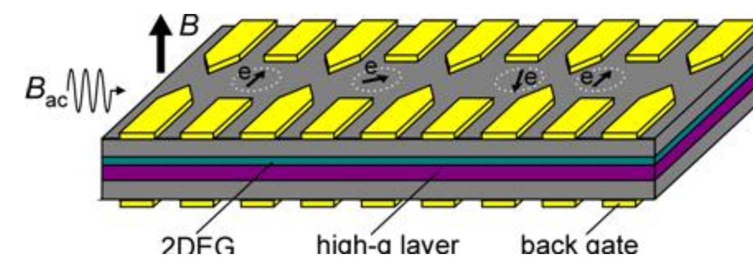
- Topological qubits

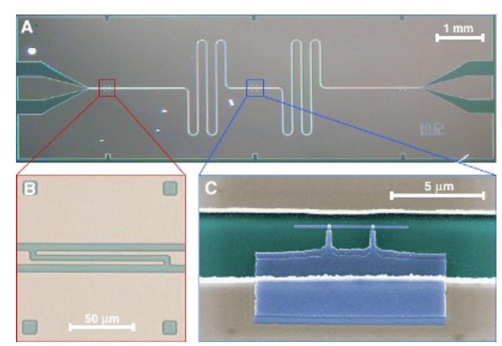
Summary and comparison

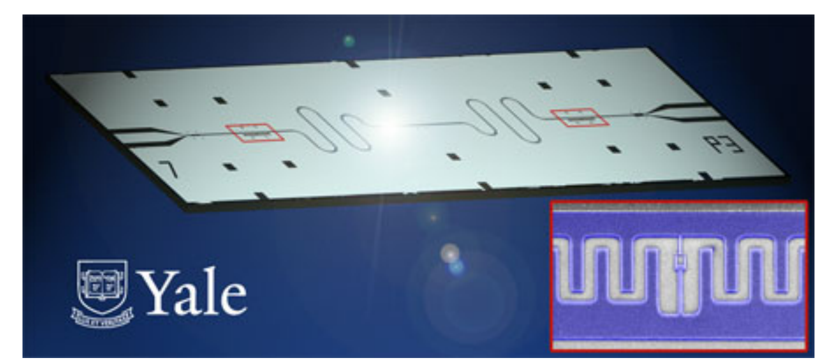


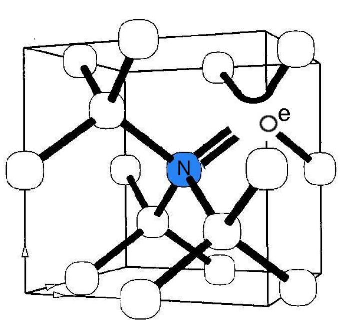


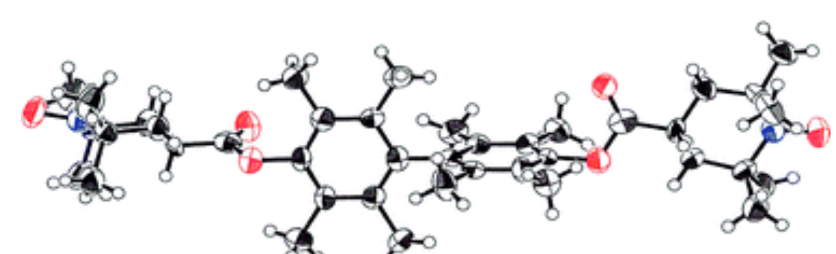








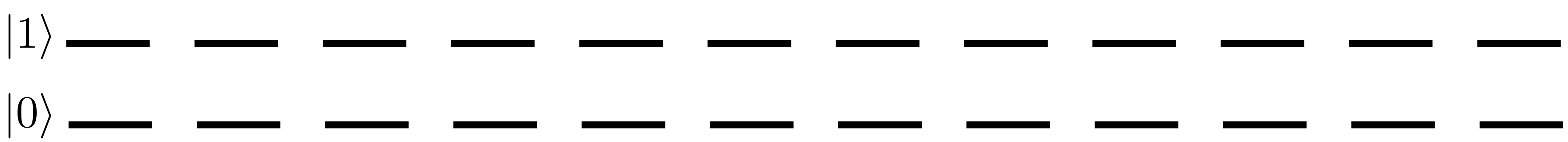




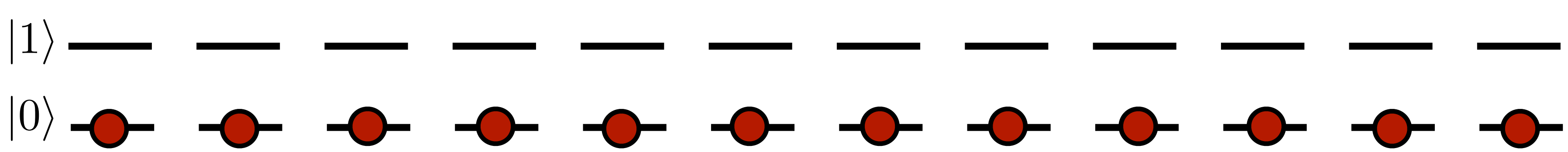
DiVincenzo Criteria:

Requirements for the implementation of quantum computation

1. A scalable physical system with well characterized qubits

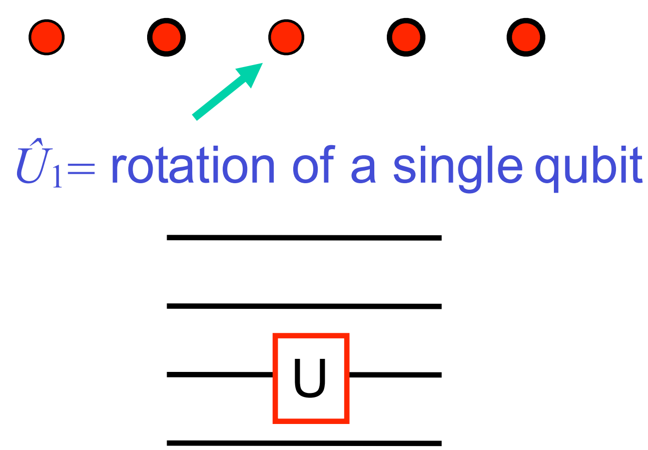


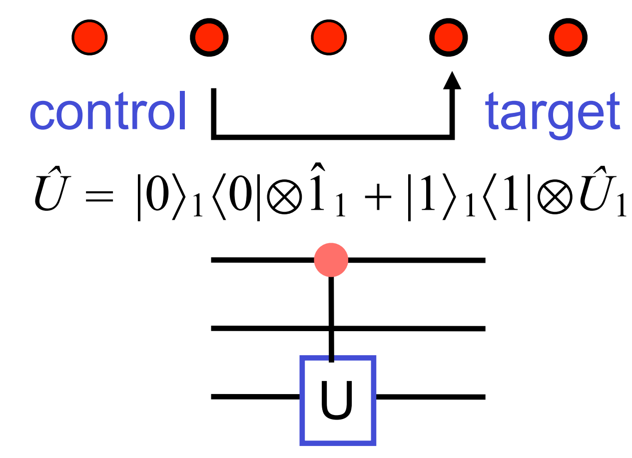
2. The ability to initialize the state of the qubits to a simple fiducial state, such as $|000...\rangle$



3. Long relevant decoherence times, much longer than the gate operation time
   (see next section)

4. A “universal” set of quantum gates
   (single qubit rotations
   + C-Not / C-Phase / ....)



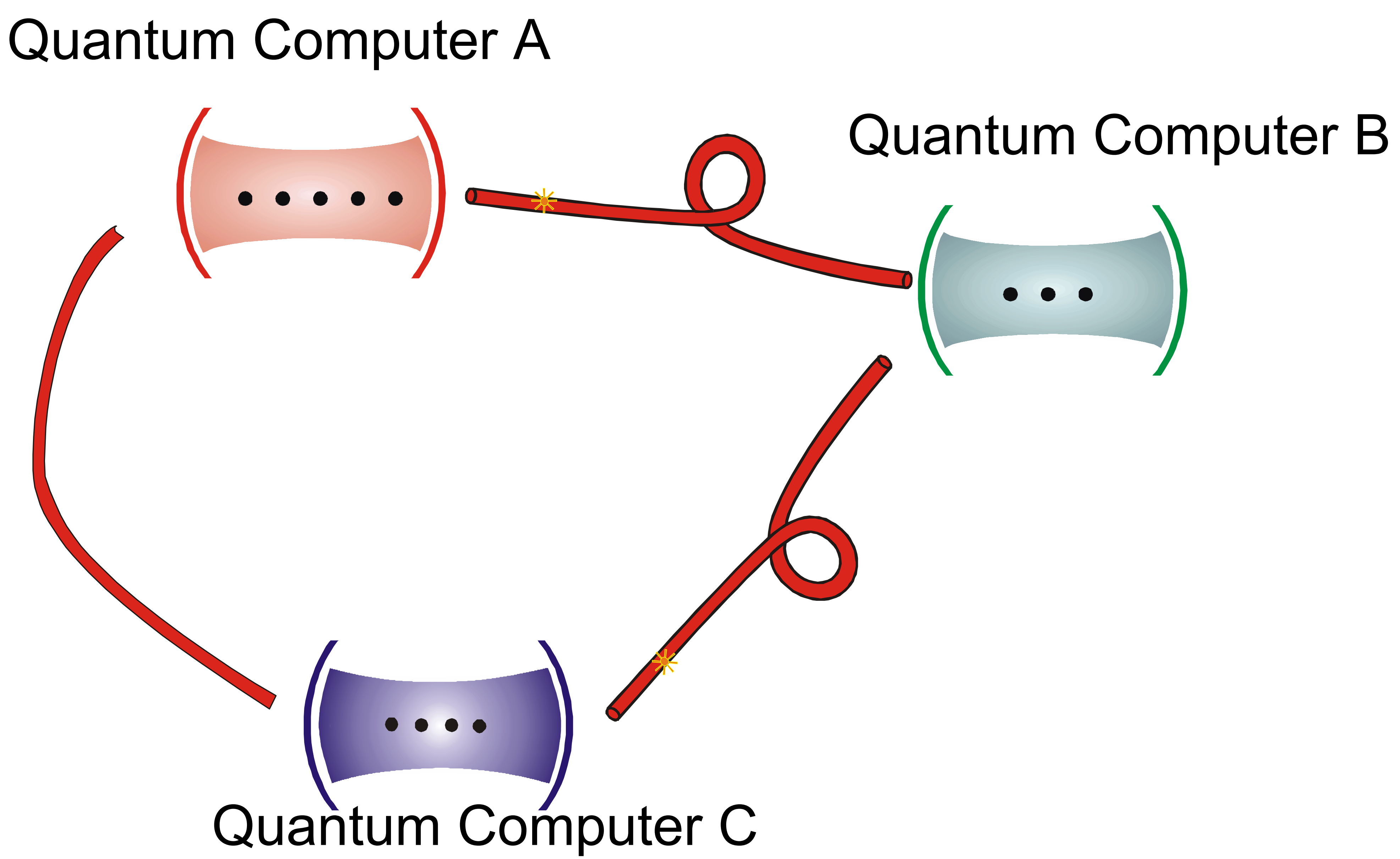


5. A qubit-specific measurement capability

D. P. DiVincenzo “The Physical Implementation of Quantum Computation”, Fortschritte der Physik **48**, p. 771 (2000)
arXiv:quant-ph/0002077

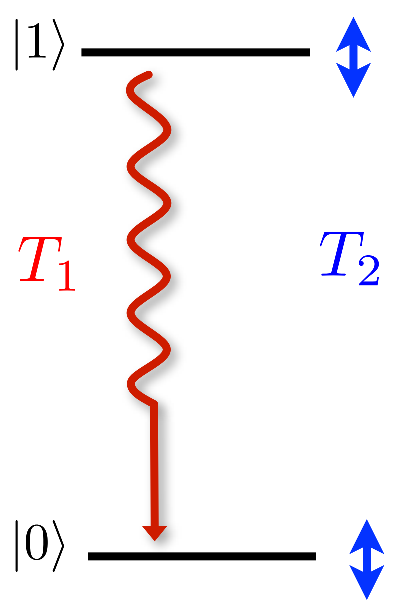
Desiderata for quantum communication

6. The ability to interconvert stationary and flying qubits
7. The ability faithfully to transmit flying qubits between specified locations



Characterising coherence times

- Coherence times for qubits are characterized by the timescales:
  (1) for a change in the probability of occupation of either qubit state; and
  (2) for a randomisation of the phase in superposition states



State $\quad |\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

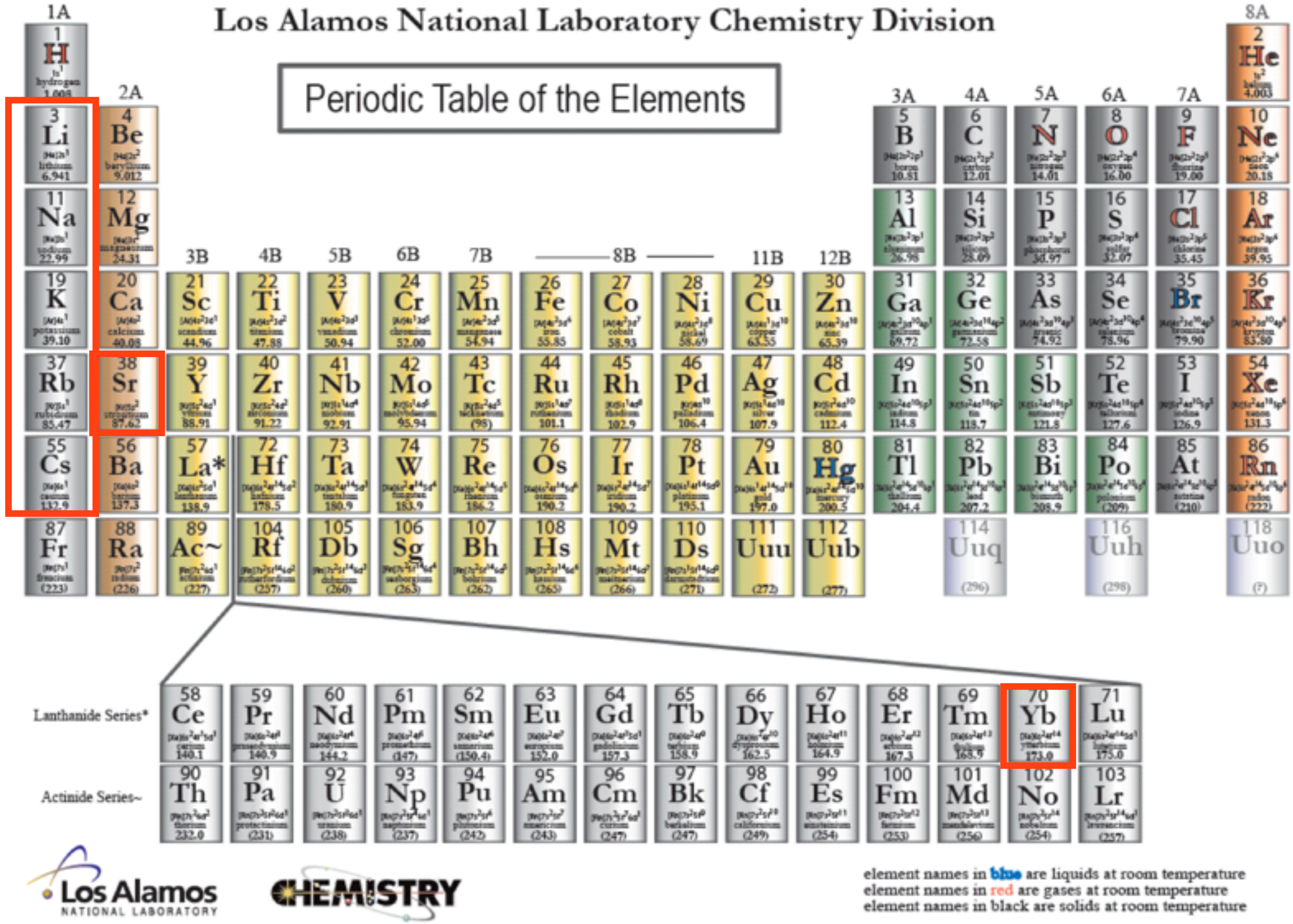
Density matrix

$$\rho = |\psi\rangle\langle\psi| \to \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \beta\alpha^* & |\beta^2| \end{pmatrix}$$

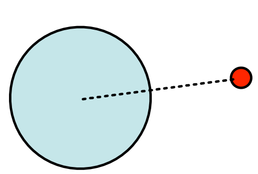
- Timescale T_1 characterises changes in $|\alpha|^2$ and $|\beta|^2$
- Timescale T_2 characterises decay of $\alpha\beta^*$, $\beta\alpha^*$ (loss of purity)
- Typically, $T_2 < T_1$

- For ensemble measurements (e.g., repeated measurements with fluctuating parameters or multiple qubits in inhomogeneous environments), the system may appear to decohere, due to averaging on a timescale $T_2^* < T_2$
- This can often be corrected, e.g., by spin-echo experiments that remove the averaging over the fluctuating parameter

Neutral atoms



Rb:



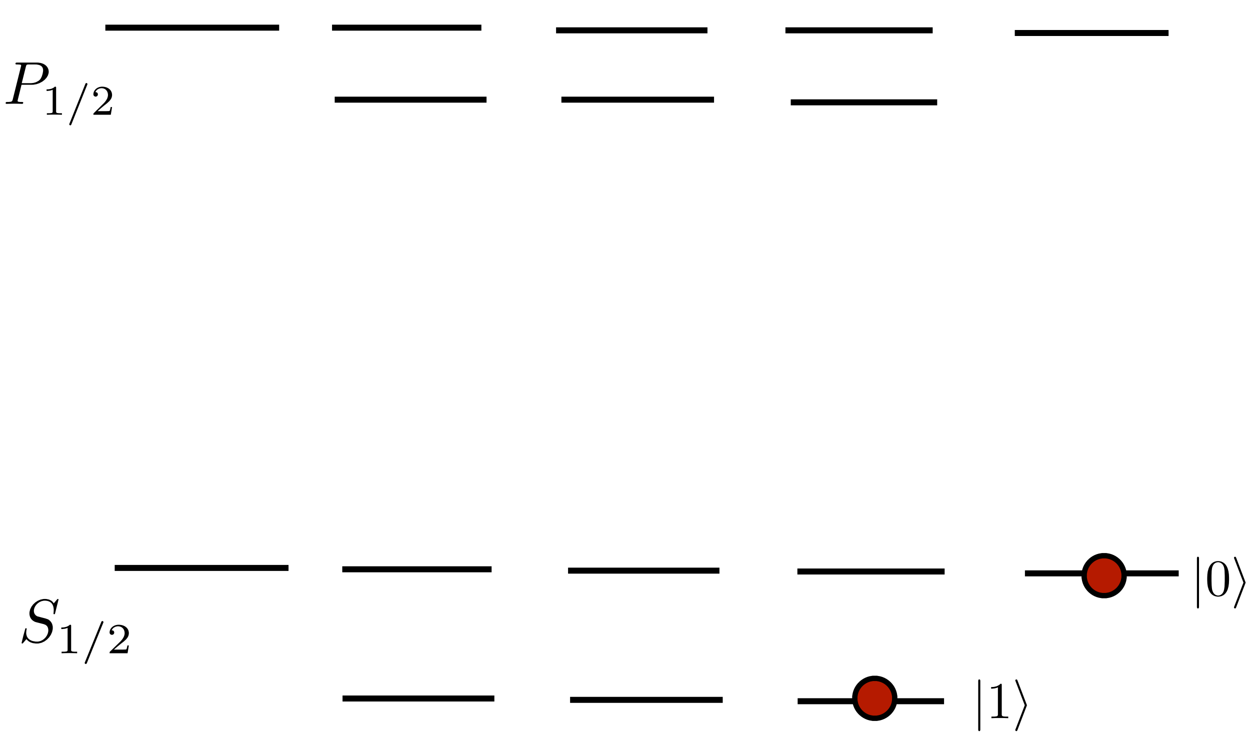
Electron outside closed shell

Quantum numbers: $n, l, m_l,$
$m_l = -l, \ldots l$

$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6$ core

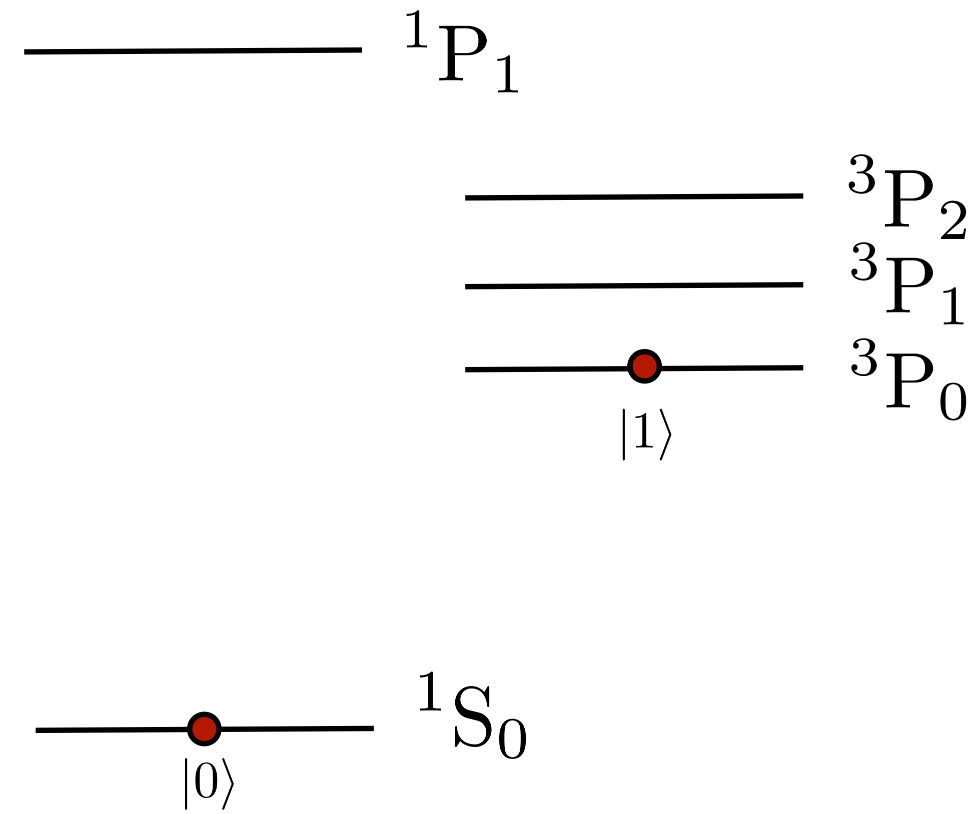
Alkali atoms

- e.g., Rb, Li, K, Cs,....
- Qubits encoded on long-lived hyperfine states

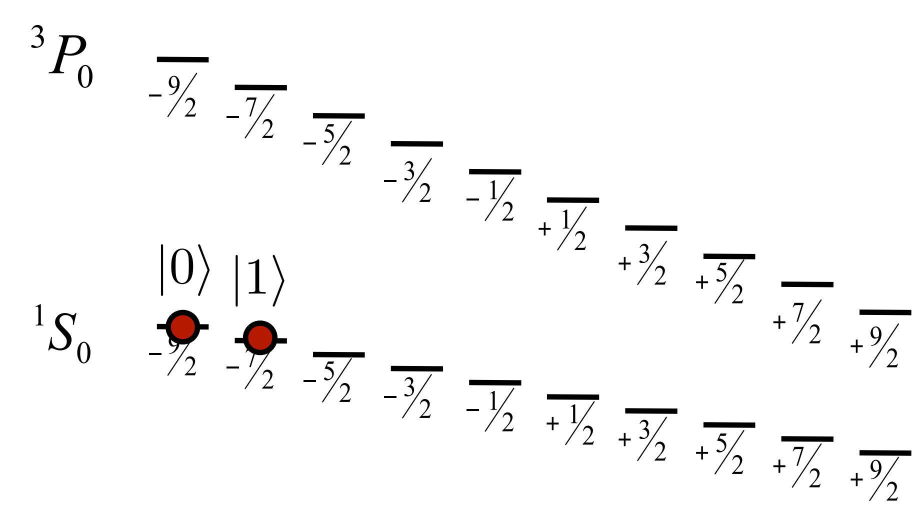


Alkaline earth (-like) atoms

- e.g., Sr, Yb,....
- Metastable electronic states



- or nuclear spin states



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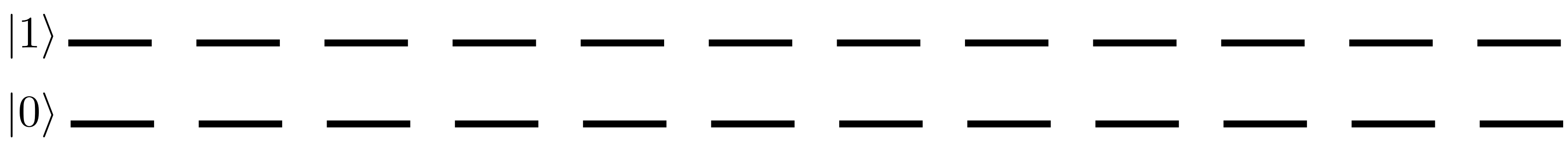

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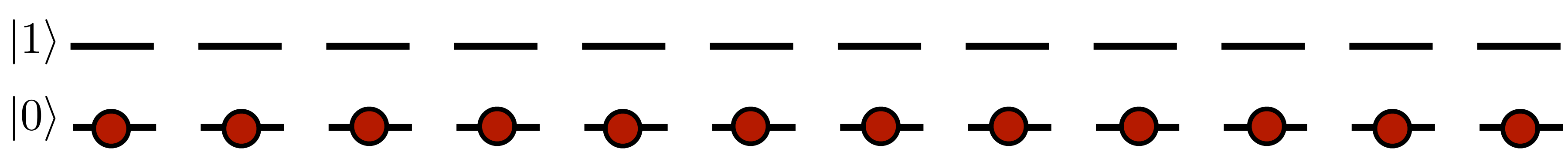

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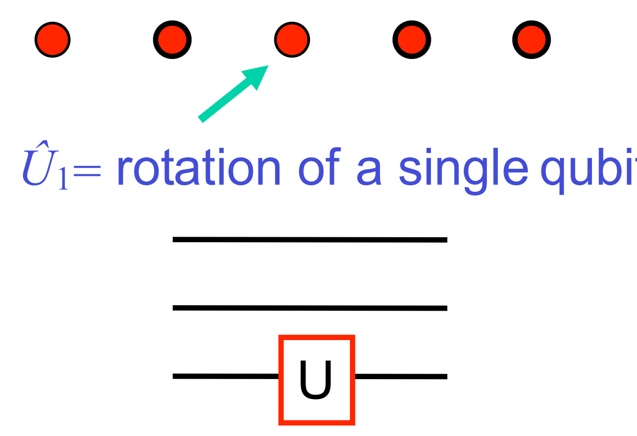

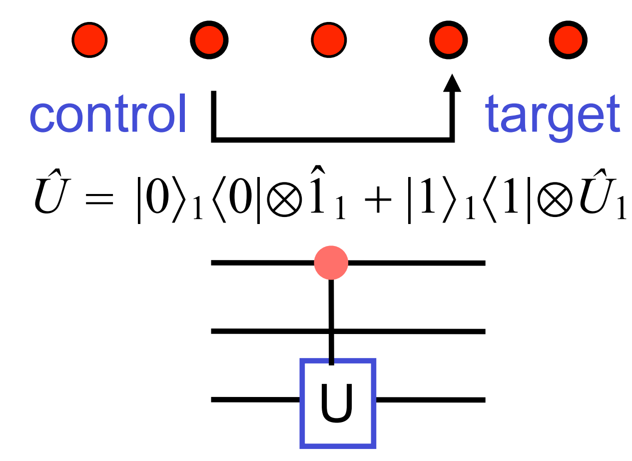

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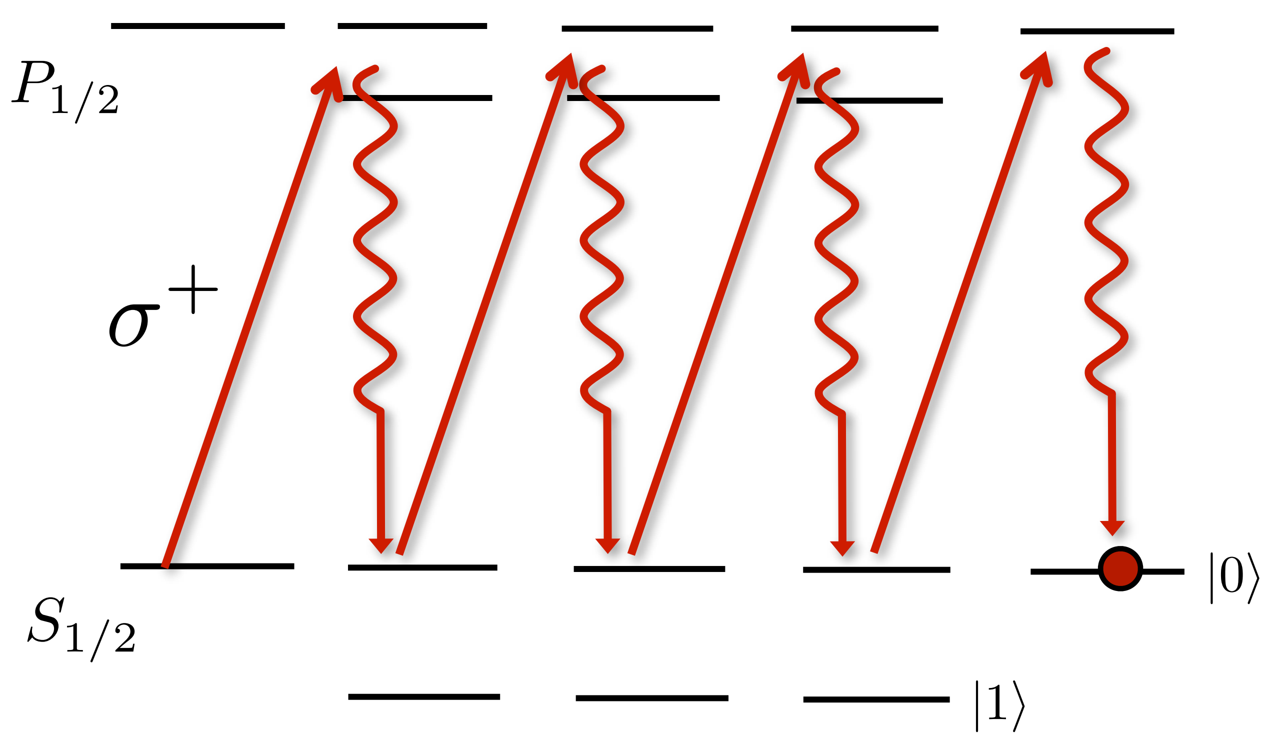
Initialisation

- Optical pumping

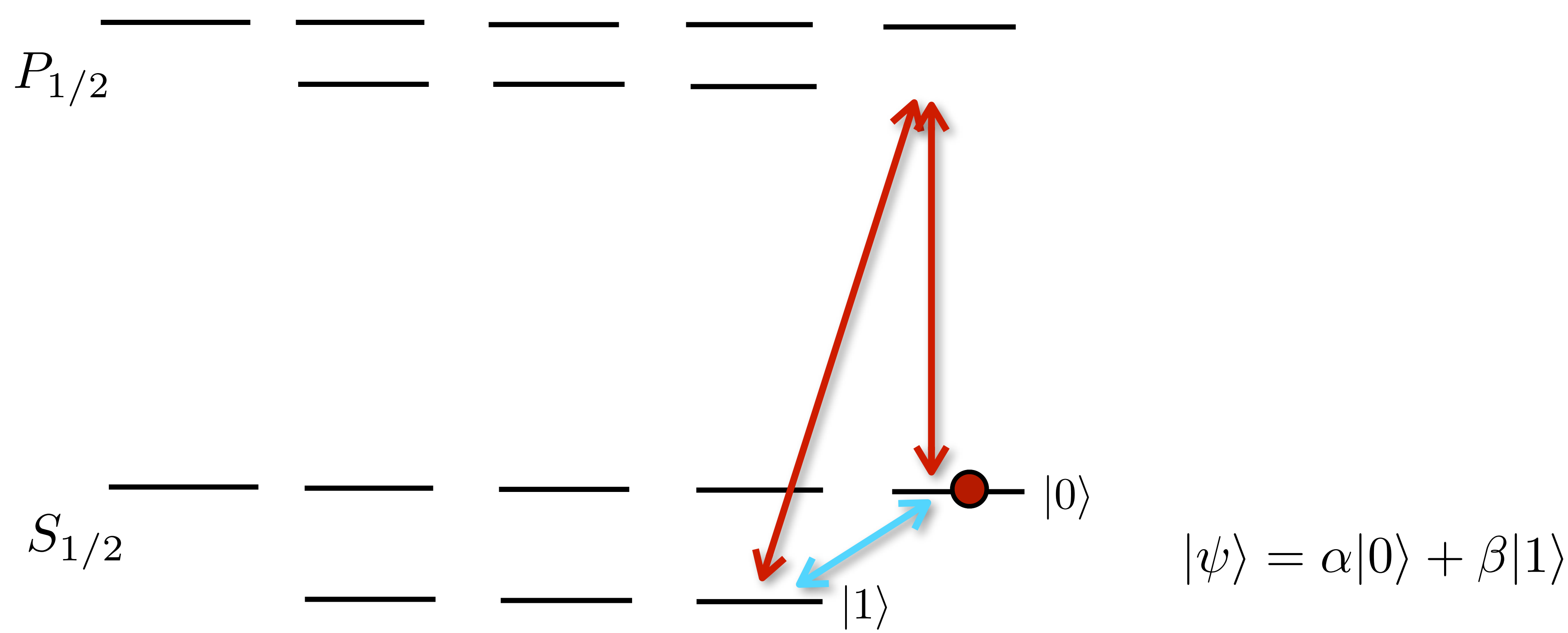


Decoherence times

- T_1 is very long (e.g., generated by blackbody radiation, $T_1 > 100$s)
- T_2 is limited, e.g., by inhomogeneous magnetic field fluctuations (measured scales ~100ms - 20s)

Single-qubit gates

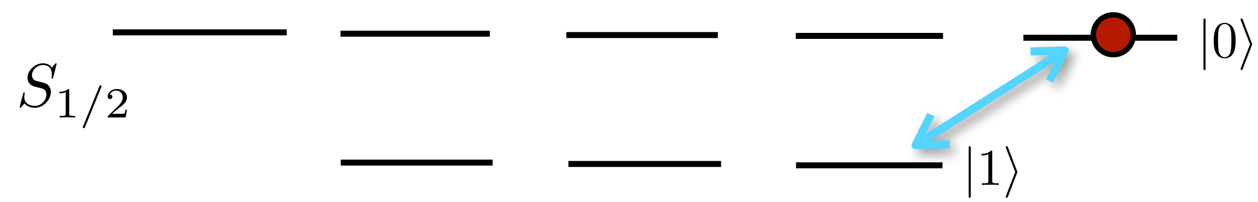
- Raman transitions or radio frequency / microwave fields



- In appropriate parameter regimes, resonant laser coupling will generate the equations of motion (Schrödinger equation)

$$i\frac{d}{dt}\begin{pmatrix}\alpha\\ \beta\end{pmatrix} = \begin{pmatrix}0 & -\frac{1}{2}\Omega(t)\\ -\frac{1}{2}\Omega(t) & 0\end{pmatrix}\begin{pmatrix}\alpha\\ \beta\end{pmatrix}$$

where we make a Rotating wave approximation, and write the qubit states in the rotating frame. This treatment is excellent (good to within a factor of $\sim 10^{-8}$ in typical experiments). We have also chosen the phase of Ω so that it is real at the location of the qubit.



$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$i\frac{d}{dt}\begin{pmatrix}\alpha\\ \beta\end{pmatrix} = \begin{pmatrix}0 & -\frac{1}{2}\Omega(t)\\ -\frac{1}{2}\Omega(t) & 0\end{pmatrix}\begin{pmatrix}\alpha\\ \beta\end{pmatrix}$$

- Introducing $\tau = \int_0^t \Omega(t)dt$ as a new time variable we can solve this equation exactly:

$$\begin{pmatrix}\alpha(t)\\ \beta(t)\end{pmatrix} = U_t\begin{pmatrix}\alpha(0)\\ \beta(0)\end{pmatrix}$$

$$U_t = \begin{pmatrix}\cos\frac{1}{2}\tau & -i\sin\frac{1}{2}\tau\\ -i\sin\frac{1}{2}\tau & \cos\frac{1}{2}\tau\end{pmatrix}$$

- In particular a so-called π-pulse $\int_{-\infty}^{+\infty}\Omega(t)dt = \pi$ inverts the TLS,

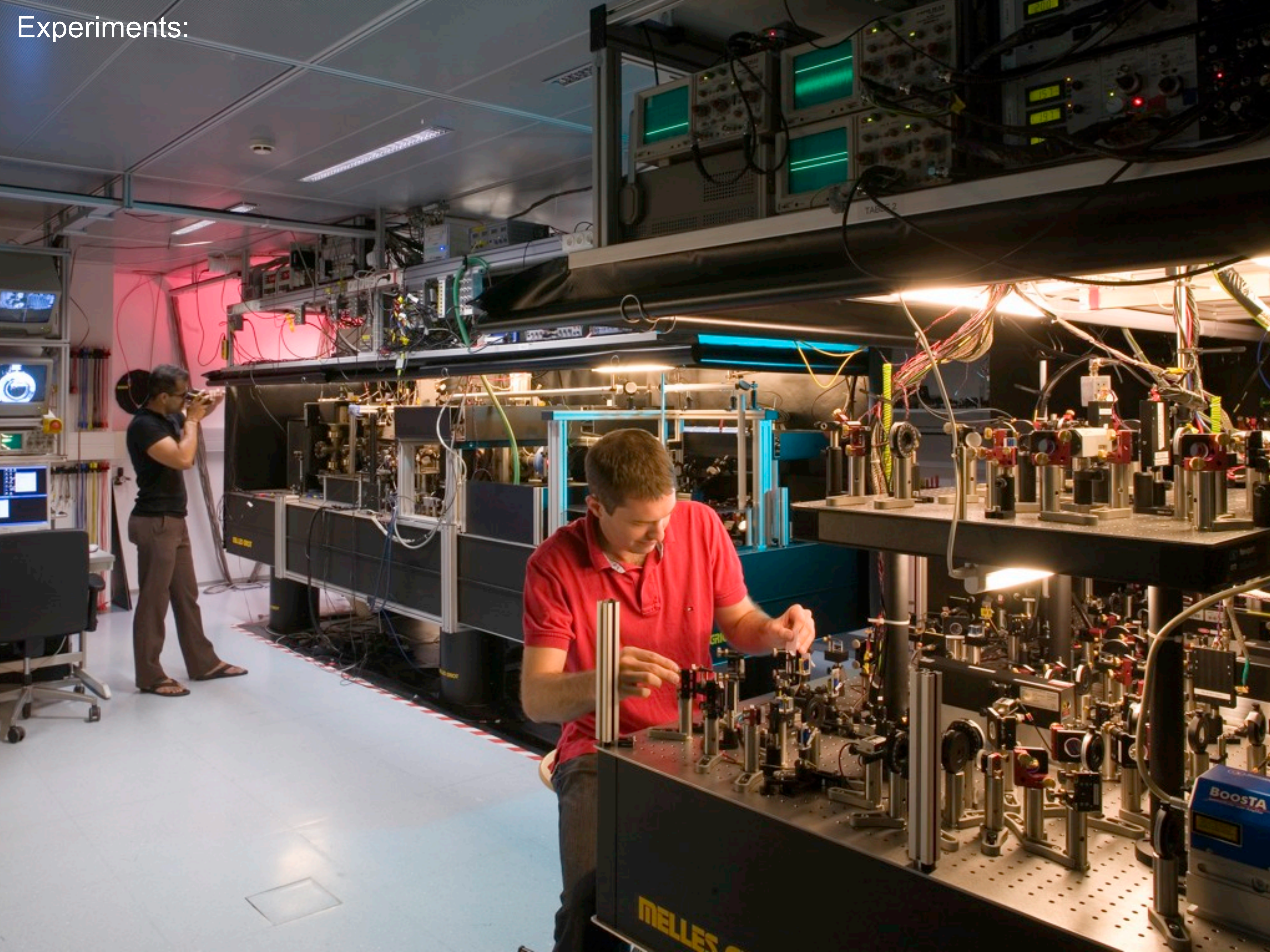
$$U_{t=\pi/\Omega} = \begin{pmatrix}0 & -i\\ -i & 0\end{pmatrix} \qquad \left[\begin{array}{ccc}|g\rangle & \to & -i|e\rangle\\ |e\rangle & \to & -i|g\rangle\end{array}\right]$$

and a 2π pulse returns the atom to its ground state,

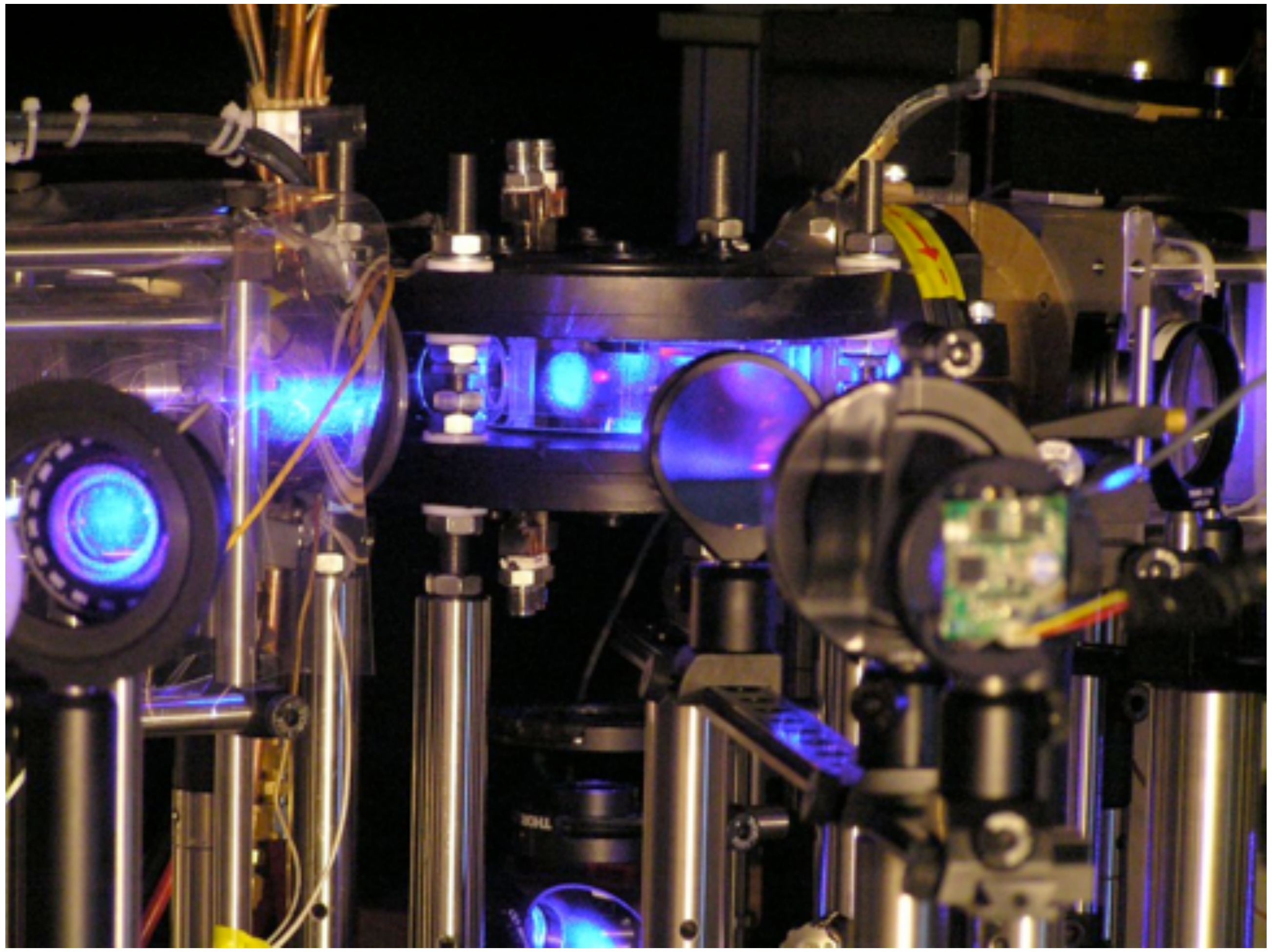
$$U_{t=2\pi/\Omega} = \begin{pmatrix}-1 & 0\\ 0 & -1\end{pmatrix} \qquad \left[\begin{array}{ccc}|g\rangle & \to & -|g\rangle\\ |e\rangle & \to & -|e\rangle\end{array}\right]$$

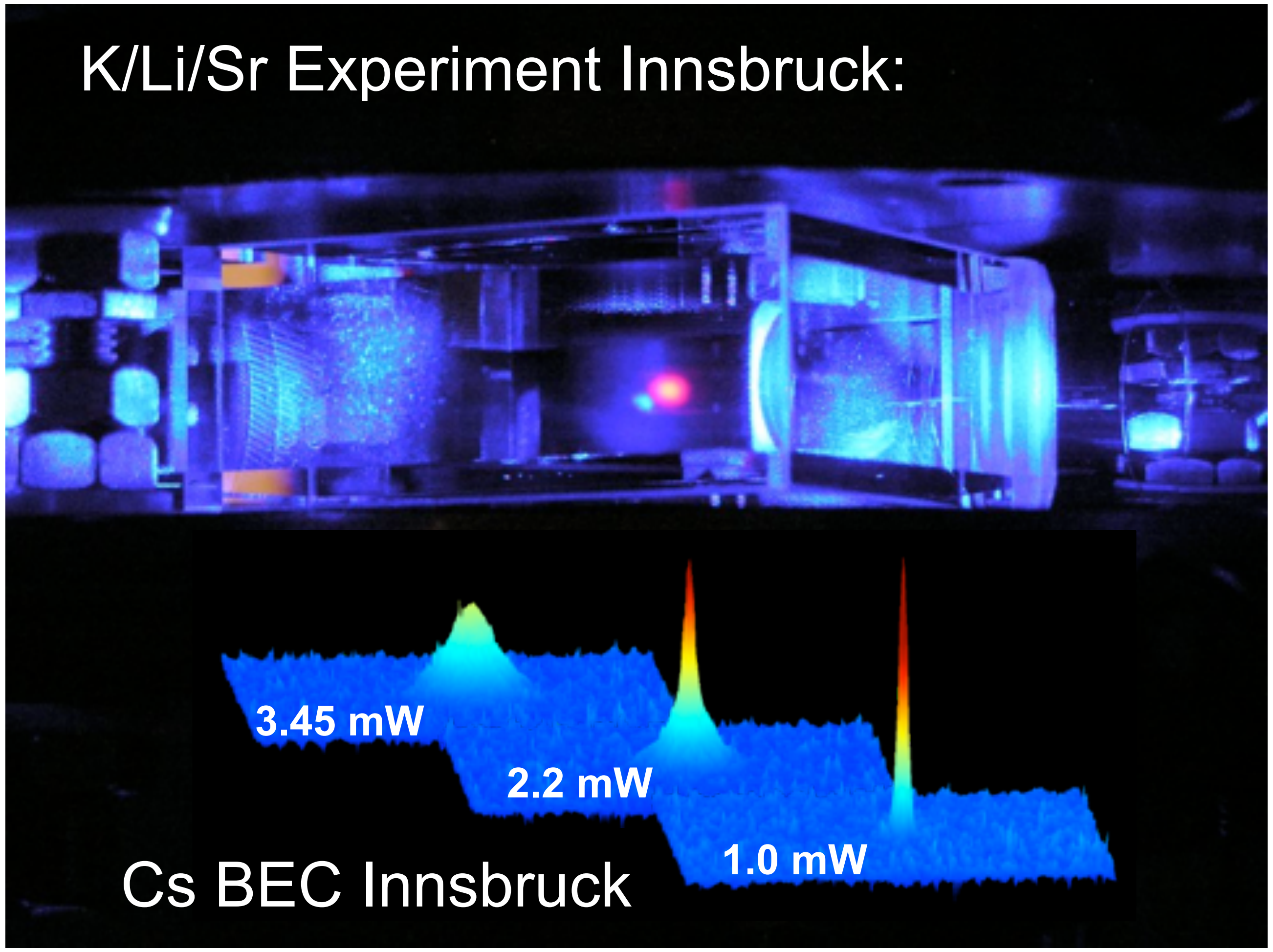
but with a negative sign for the amplitudes (rotation of a spin-1/2 by 2π changes the sign).

Experiments:

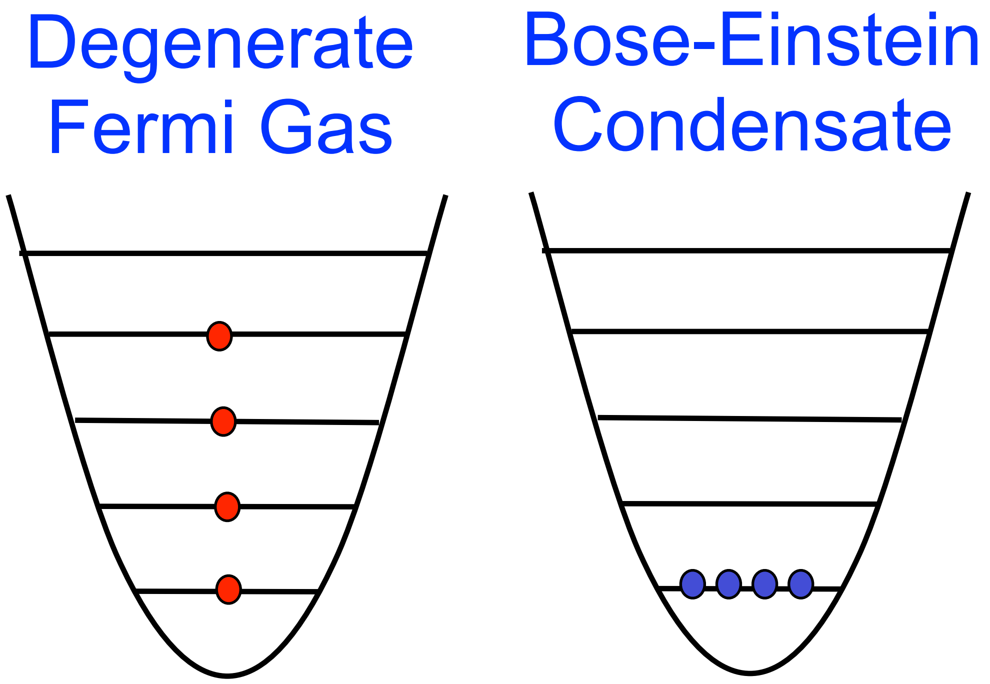


Degenerate Bose/Fermi Gases in the laboratory:

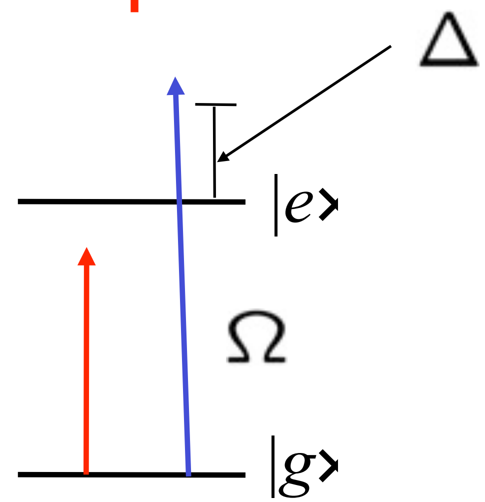


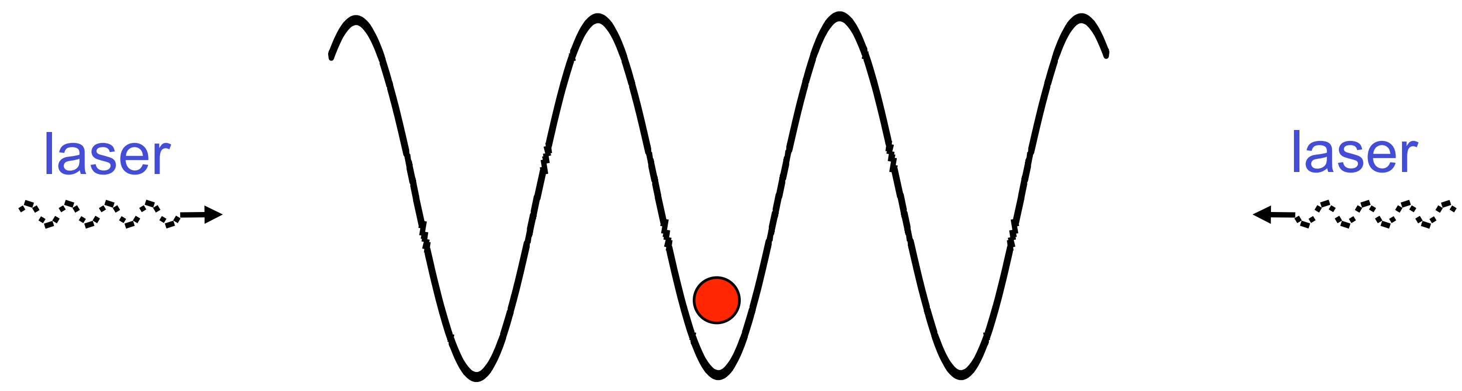


- Features:
  - Control via magnetic field / laser light
  - Microscopically well understood systems

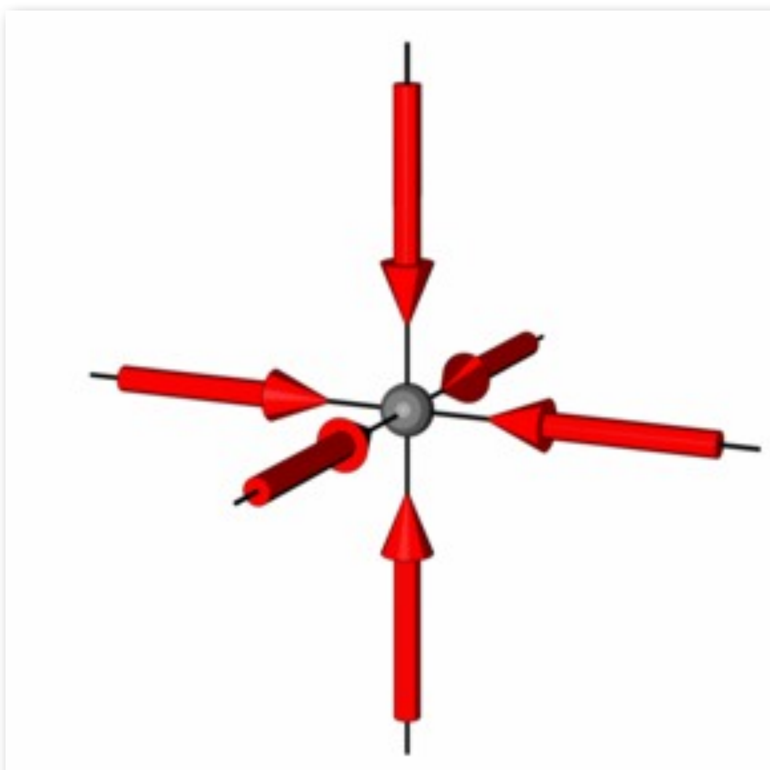


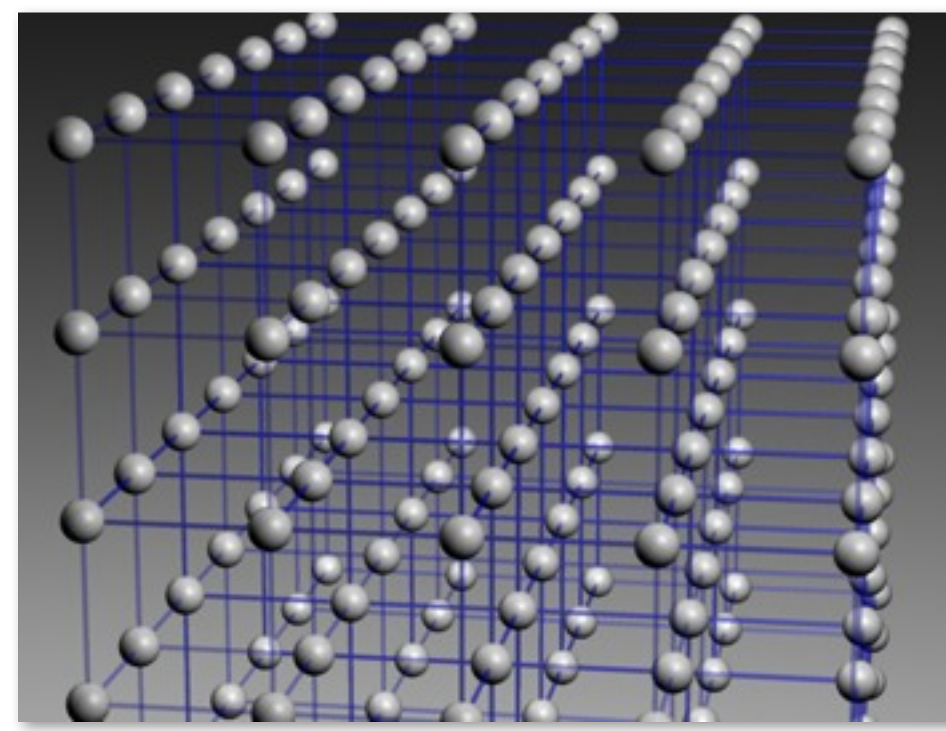
Dipole traps and optical lattices:





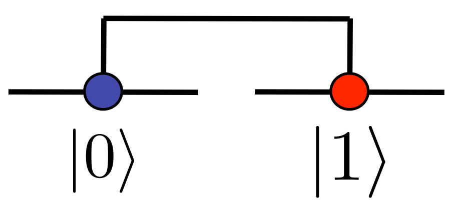
$$V(x) = \alpha(\omega) I = V_0 \sin^2(kx)$$

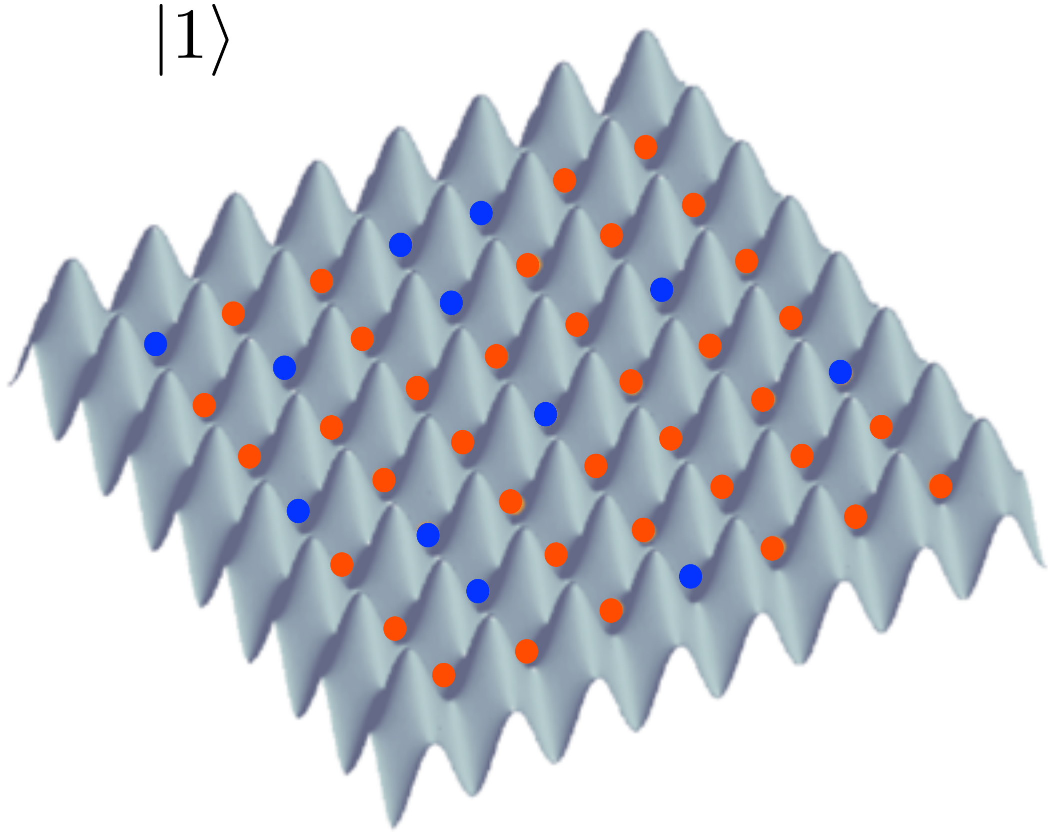




- Dipole traps for single atoms can be used to trap individual atoms for quantum computing purposes
- Optical lattices allow preparation of a whole register at once, in contrast, e.g., to trapped ions.

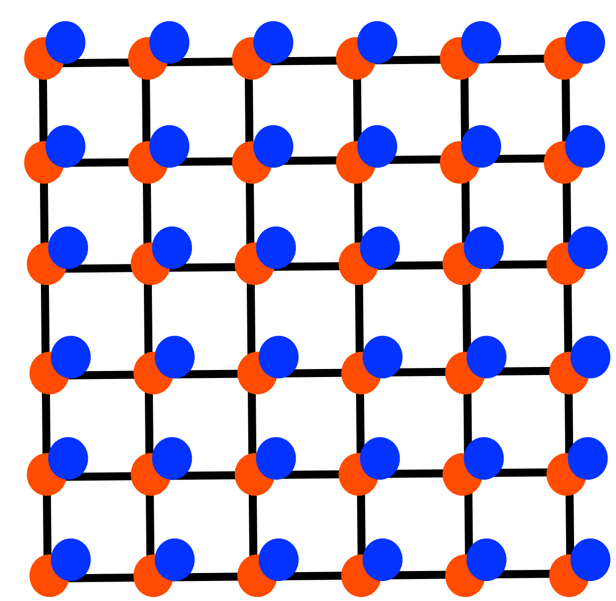
Quantum Register





Requirements:

- Long lived storage of qubits
- Addressing of individual qubits
- Single and two-qubit gate operations



- Array of singly occupied sites
- Qubits encoded in long-lived internal states (alkali atoms - electronic states, e.g., hyperfine)
- Entanglement via Rydberg gates or via controlled collisions in a spin-dependent lattice

Rydberg Blockade Gates:

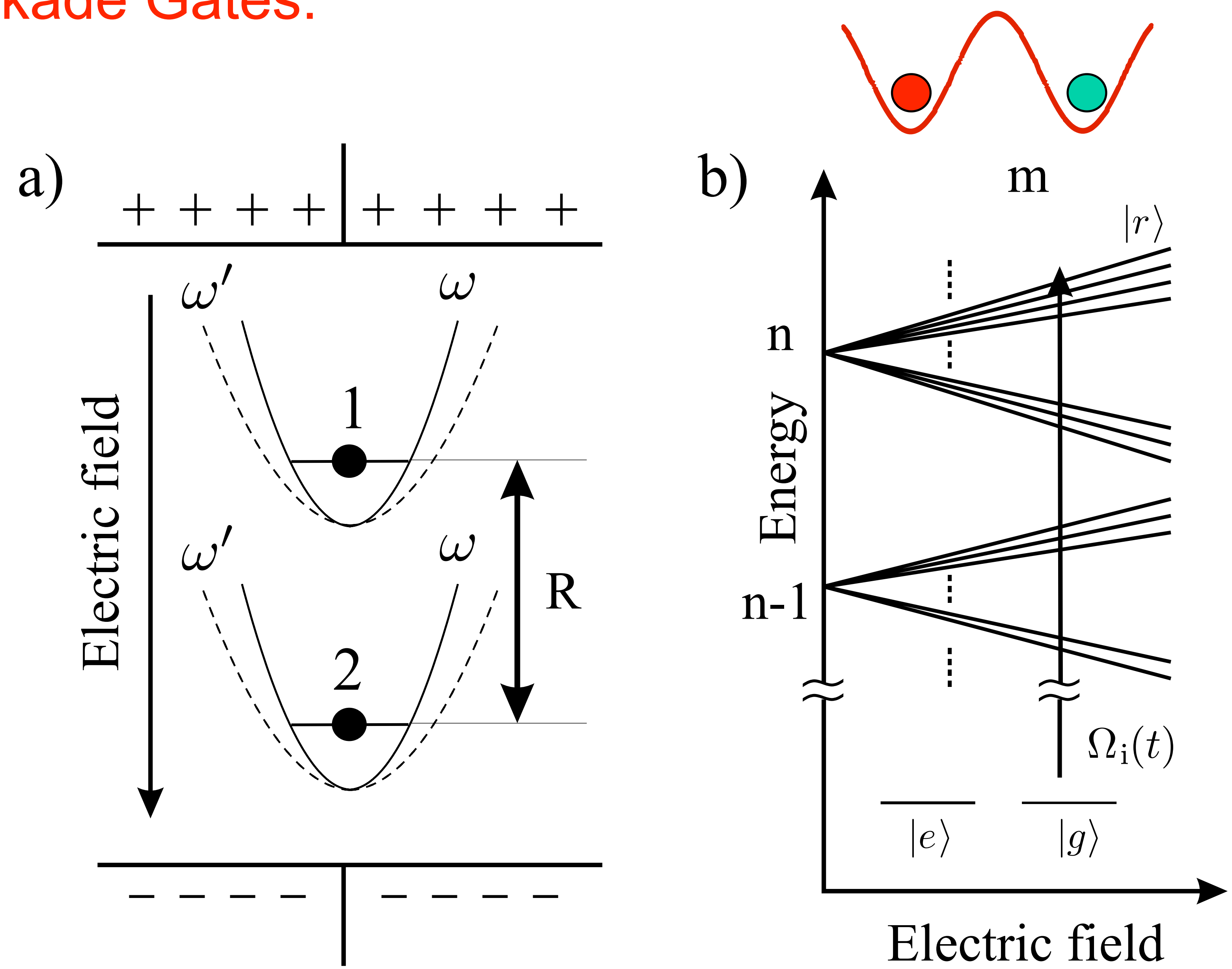
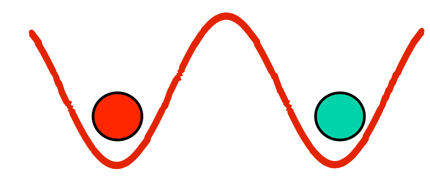


FIG. 1. (a) Setup: A constant electric field along the z direction is applied to alkali atoms trapped in microtraps. (b) Level scheme: Two ground states $|g\rangle$ and $|e\rangle$ (qubits), and laser excitation to the Rydberg state $|g\rangle \rightarrow |r\rangle$.

- Excitation of atoms to Rydberg states (highly excited electronic states), with long-range interactions

Jaksch, Cirac, Zoller, Rolston, Coté, Lukin, PRL 2000

Rydberg Blockade Gates:



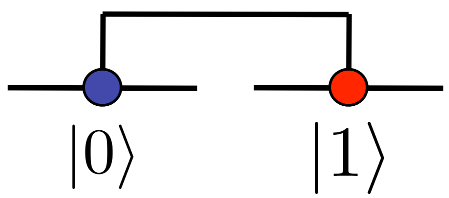
- Excitation of atom 1 ($\pi-$pulse $g \leftrightarrow r$)
- Excitation and deexcitation of atom 2 ($2\pi-$pulse $g \leftrightarrow r$)
- Deexcitation of atom 1 ($\pi-$pulse $g \leftrightarrow r$)

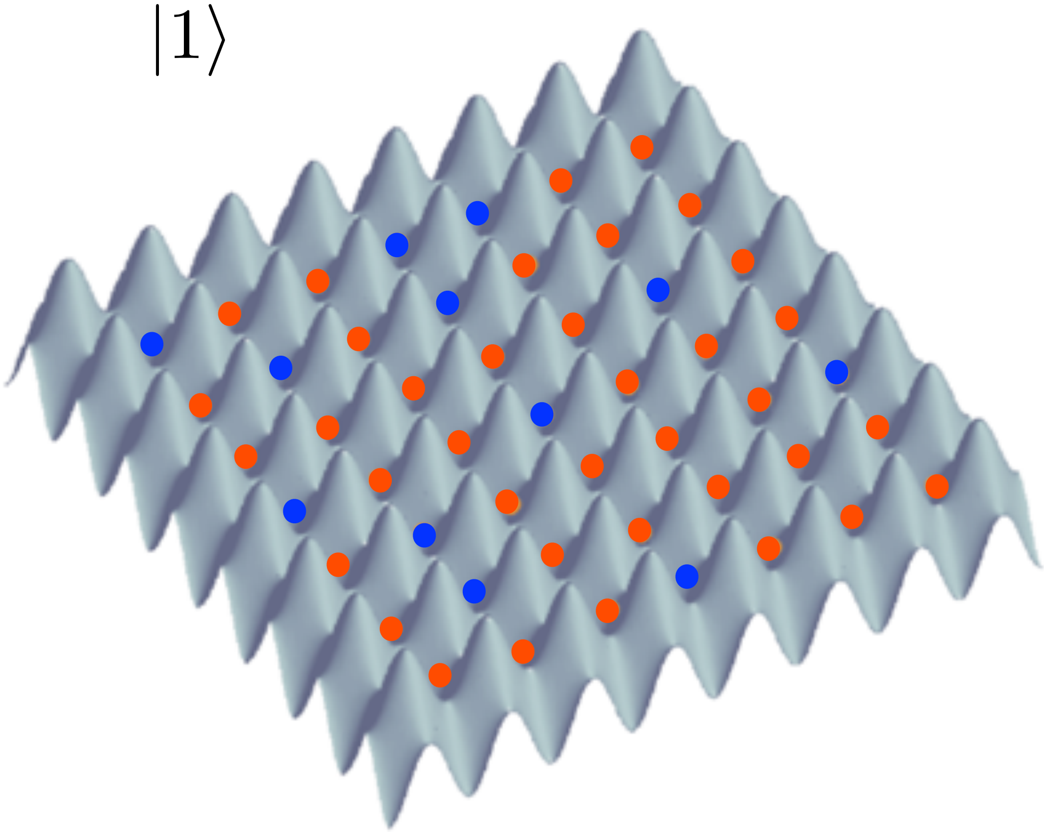
Initial	Step 1	Step 2	Step 3
$\|ee\rangle$	$\|ee\rangle$	$\|ee\rangle$	$\|ee\rangle$
$\|ge\rangle$	$-i\|re\rangle$	$-i\|re\rangle$	$-\|ge\rangle$
$\|eg\rangle$	$\|eg\rangle$	$-\|eg\rangle$	$-\|eg\rangle$
$\|gg\rangle$	$-i\|rg\rangle$	$-i\|rg\rangle$ (not $\|rr\rangle$)	$-\|gg\rangle$

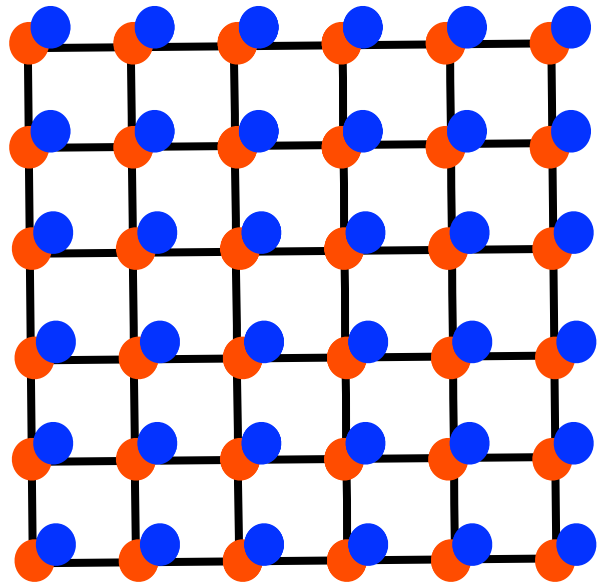
$|ee\rangle$

Jaksch, Cirac, Zoller, Rolston, Coté, Lukin, PRL 85, 2208 (2000)
E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, and M. Saffman, Nature Phys. 5, 110 (2009).
A. Gäetan, Y. Miroshnychenko, T. Wilk, A. Chotia, M. Viteau, D. Comparat, P. Pillet, A. Browaeys, and P. Grangier, Nature Phys. 5, 115 (2009).

Gates by controlled collisions





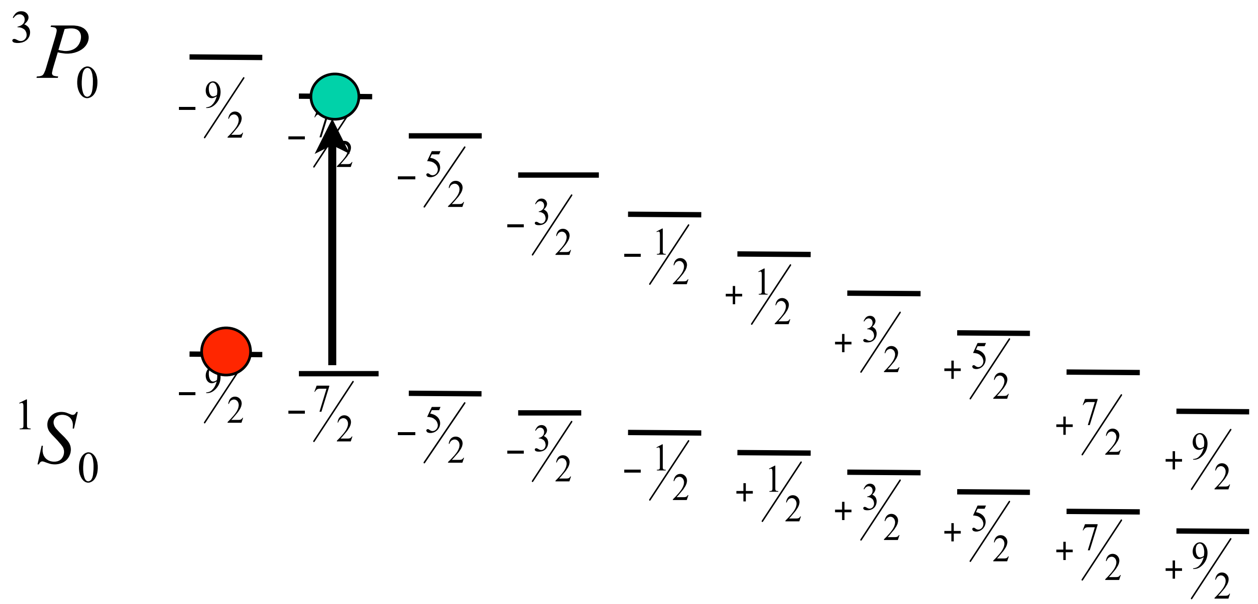


- State - dependent lattice: particles move only if they are in state 0
- If two particles are present on the same site, their energy shifts by U due to collisions. This leads to a phase accumulation $e^{-iUT/\hbar}$

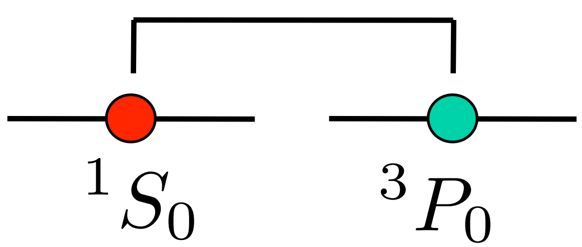
Initial	Final
$\|00\rangle$	$\|00\rangle$
$\|01\rangle$	$e^{-iUT/\hbar}\|01\rangle$
$\|10\rangle$	$\|10\rangle$
$\|11\rangle$	$\|11\rangle$

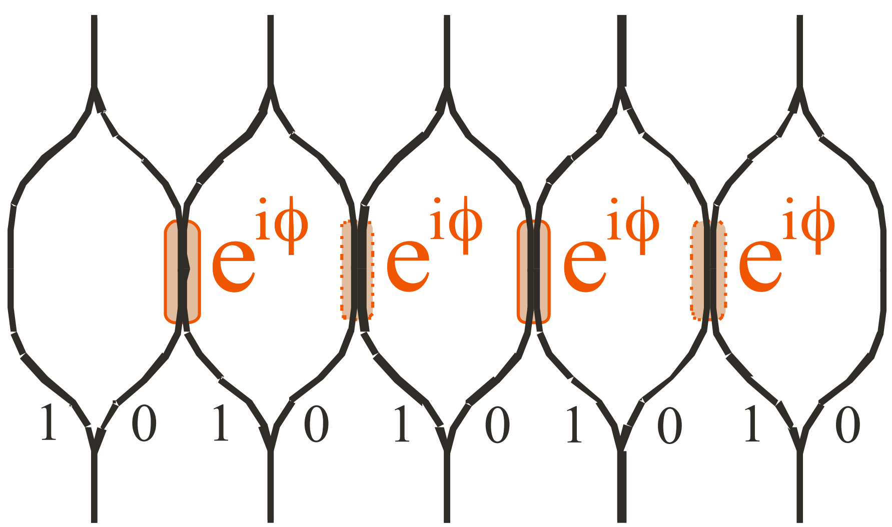
D. Jaksch, H.-J. Briegel,J. I. Cirac, C. W. Gardiner, and P. Zoller, PRL 82, 1975 ('99)

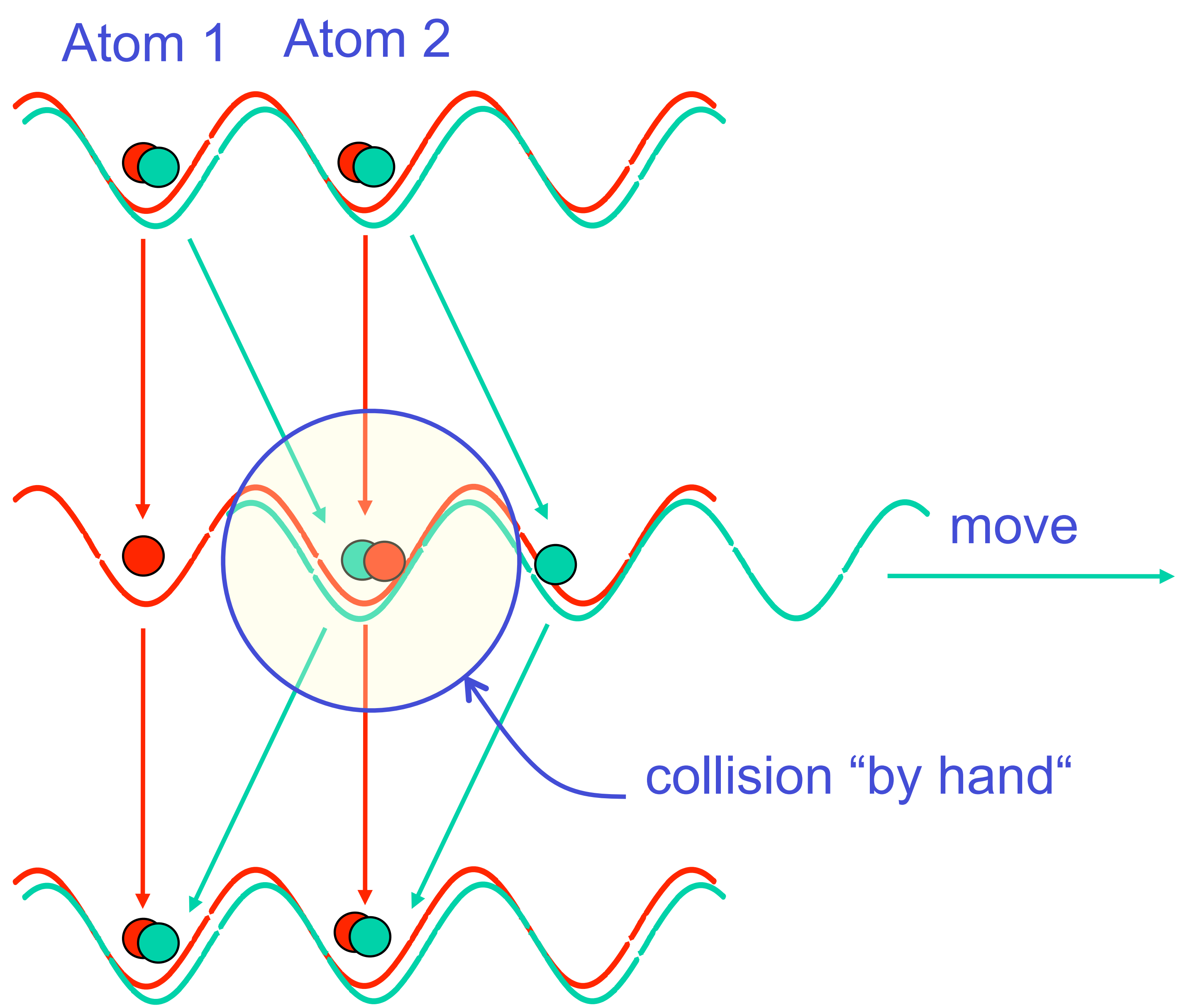
Collisional Gates (simple example):



- Gate: controlled collisions
  D. Jaksch et al., PRL 82, 1975 ('99)
- Operation performed in parallel for whole system
- Simple preparation of a cluster state
- Ideal setup for measurement-based quantum computing.







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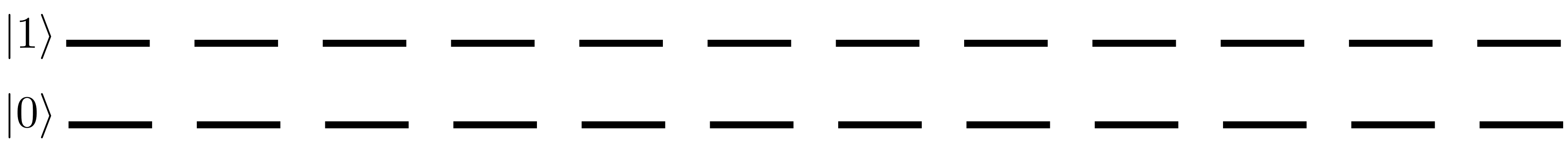

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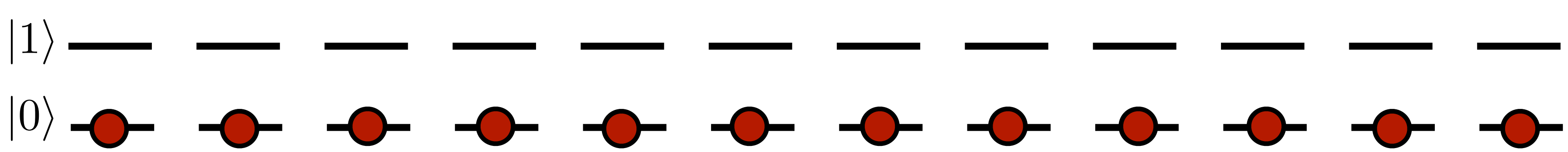

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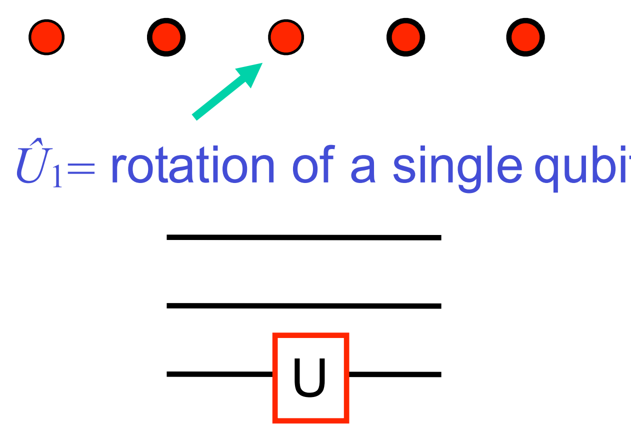

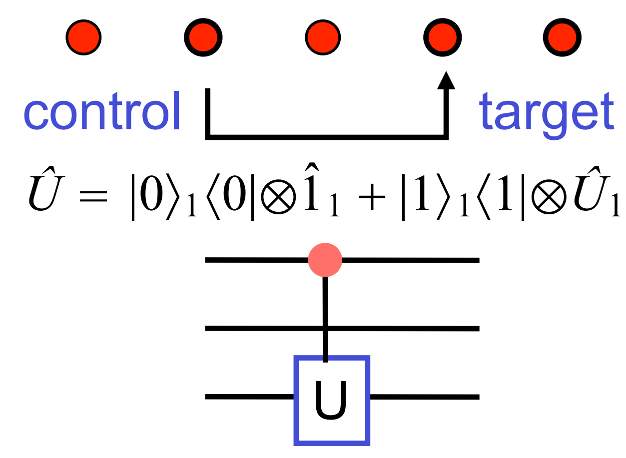

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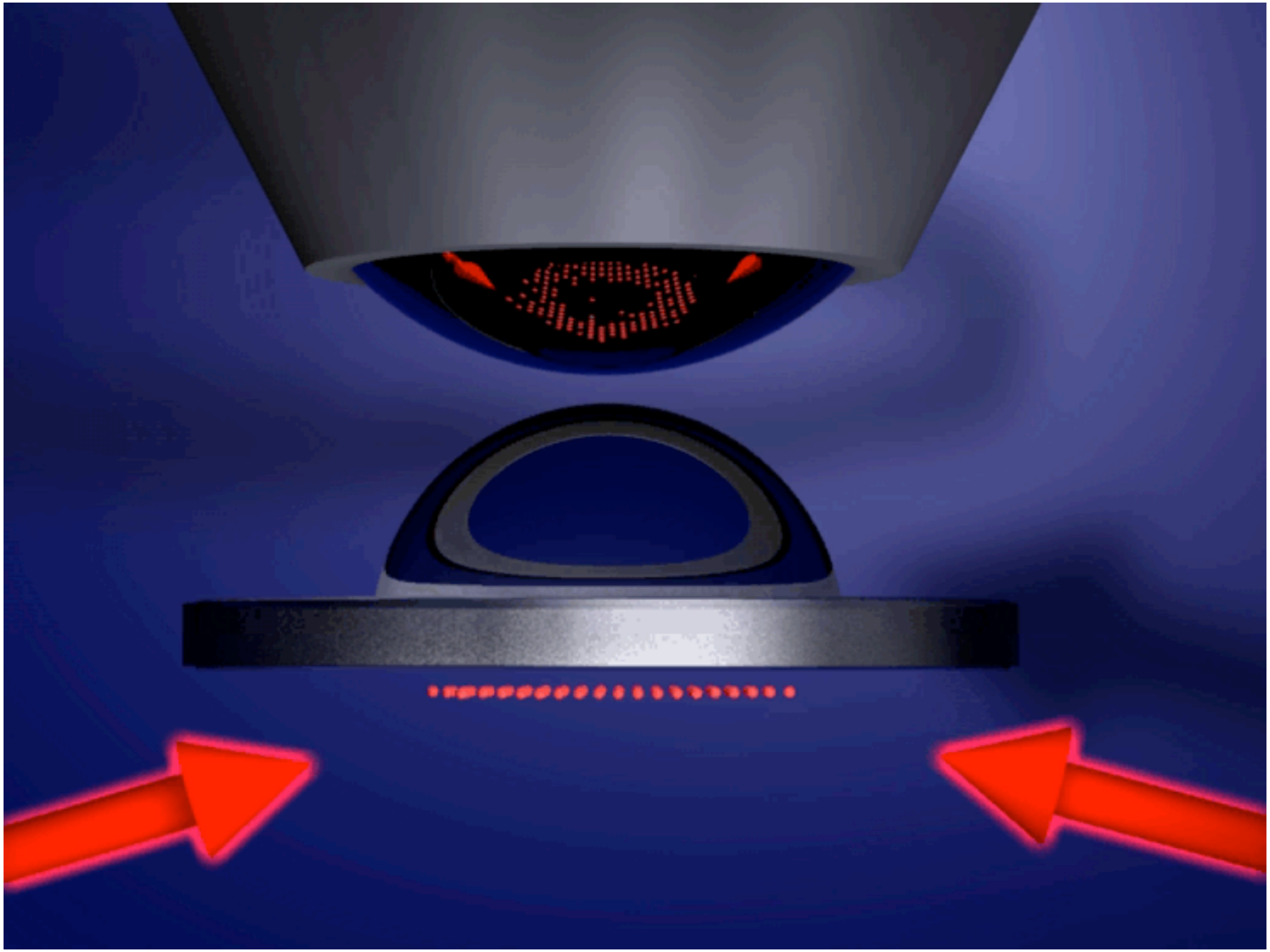
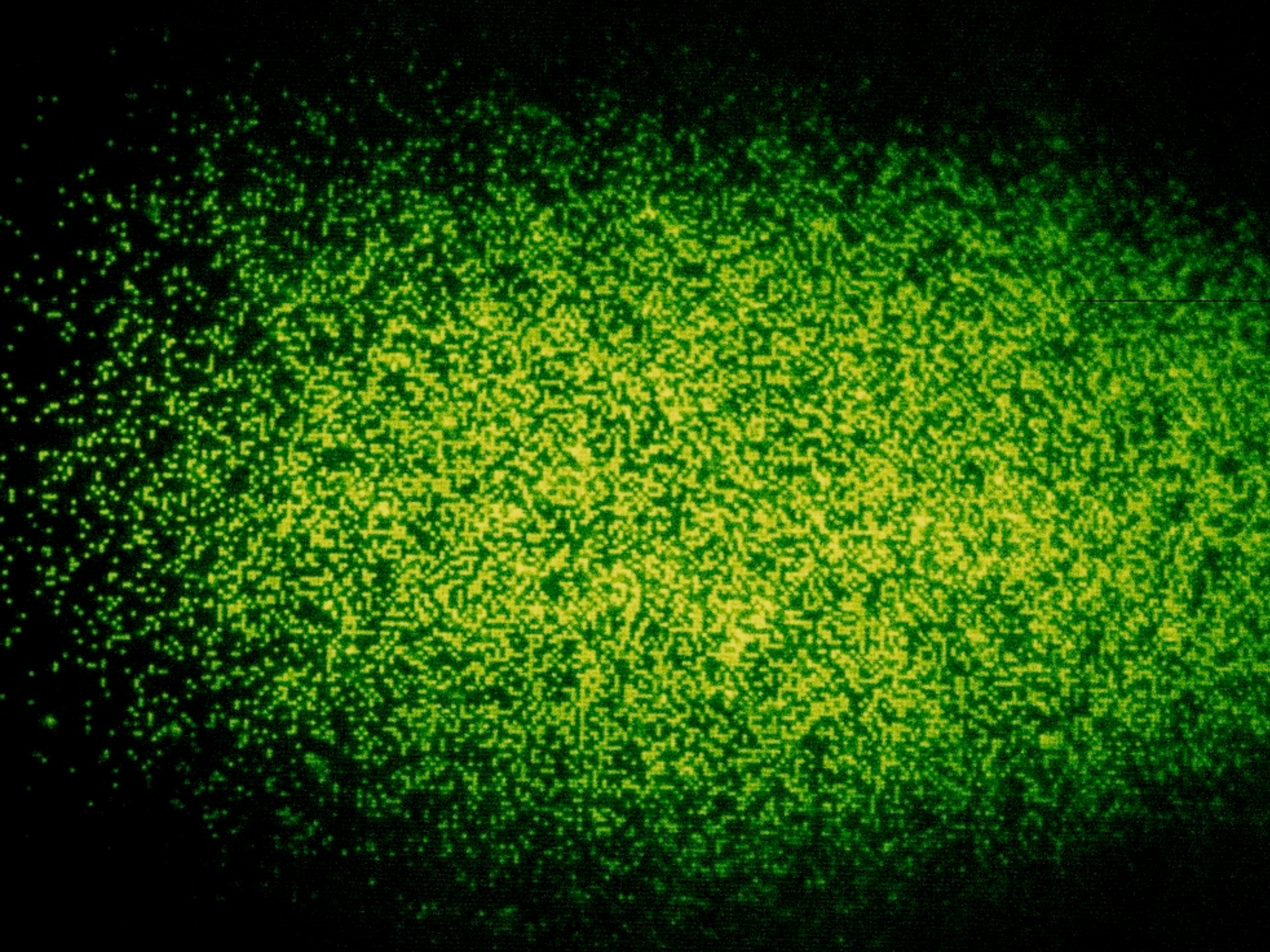
New Possibility: In-situ measurement of atoms, correlation functions:

- Experiments: Harvard, Chicago, Munich, Oxford, Toronto,.....
- e.g., Markus Greiner's "Microscope" at Harvard:





New Possibility: In-situ measurement of atoms, correlation functions:

- Experiments: Harvard, Chicago, Munich, Oxford, Toronto,.....
- "Quantum Gas Microscopes" at Harvard / Garching:

W. S. Bakr, A. Peng, M. E. Tai, R. Ma, J. Simon, J. I. Gillen, S. Foelling, L. Pollet, and M. Greiner, Science 329, 547-550 (2010).

C. Weitenberg, M. Endres, J. F. Sherson, M. Cheneau, P. Schauß, T. Fukuhara, I. Bloch, and S. Kuhr, Nature 471, 319-324 (2011).