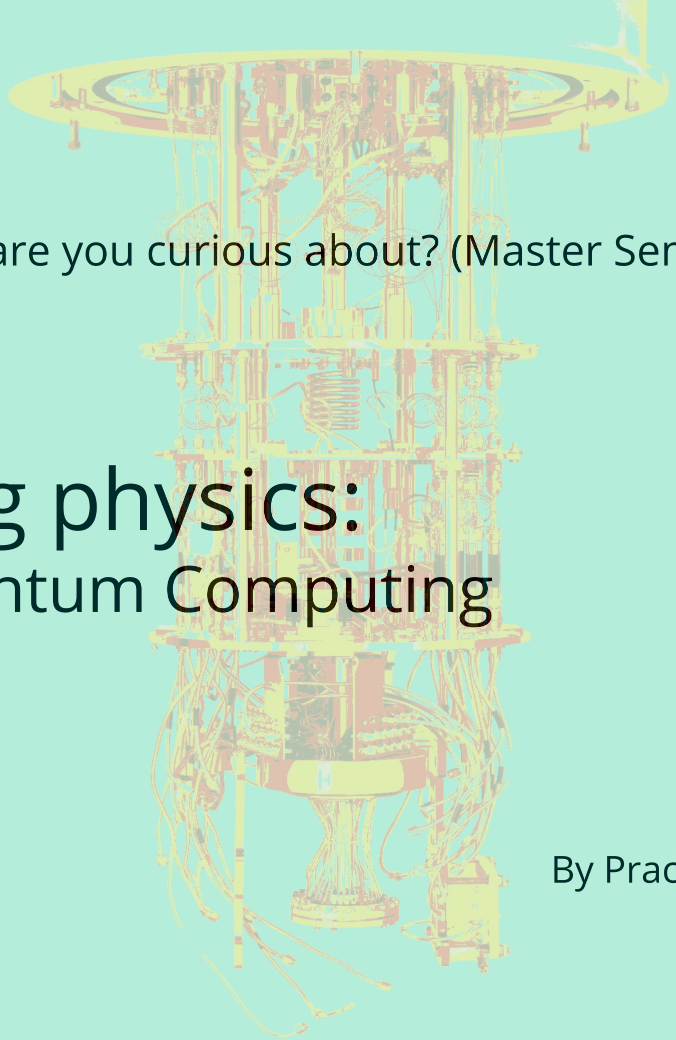
Your passion for (AMO) physics: What are you curious about? (Master Seminar)

The rise of Rydberg physics:
Atomic approach to Quantum Computing



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11.05.2021

Motivation

Classical bits versus Qubits

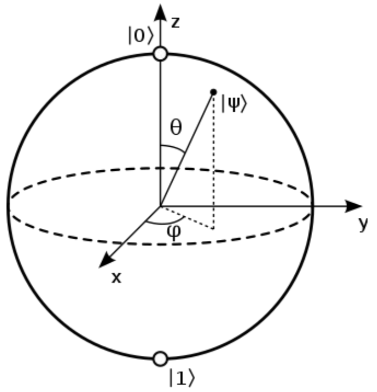
0 or 1

N classical bits can store a single data value out of 2^N possibilities.

$a_0 \,|0> + a_1 \,|1>$

N qubits can store 2^N different values simultaneously.

Quantum Superposition!



Bloch Sphere,
Source: Wikipedia

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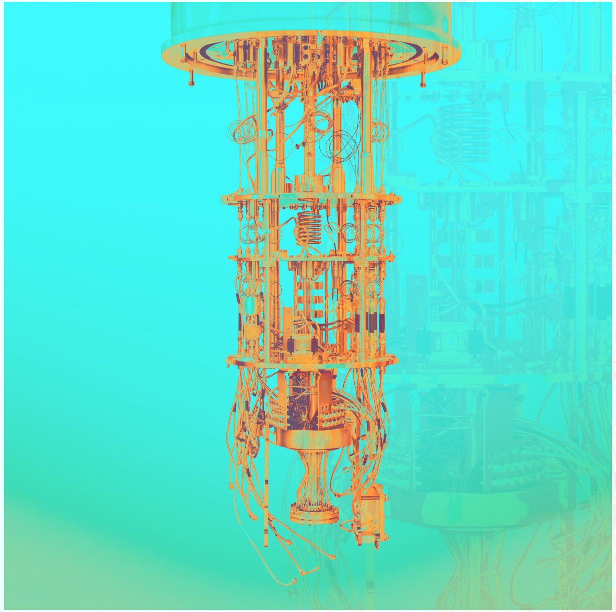
Recipe for quantum computing

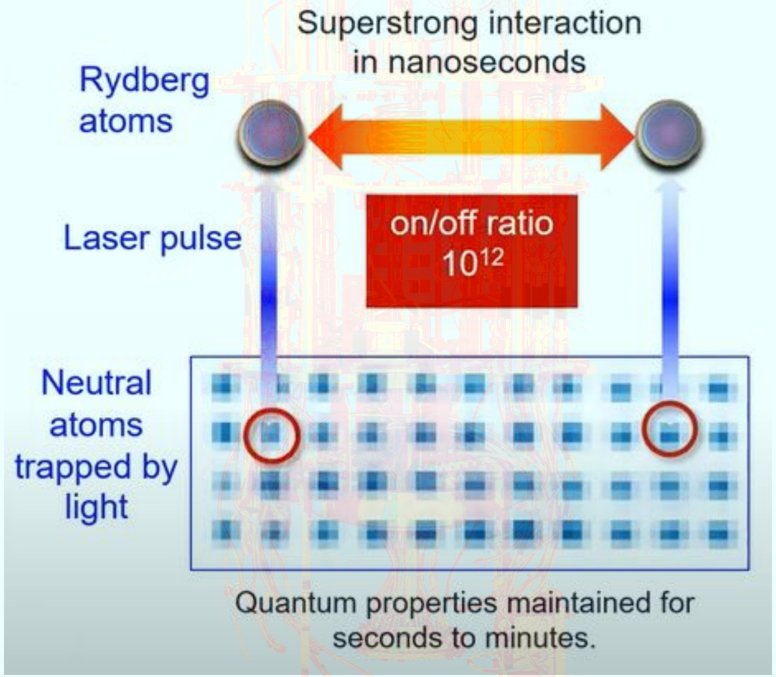


Quantum Computer
Source: MIT Technology Review

Sprinkle a handful of atoms – rubidium is a popular ingredient – into a vacuum chamber. Treat with laser beams to cool the atoms to mere fractions of a degree above absolute zero. Then add a couple of photons and hey presto – you've created one of the basic building blocks of a quantum computer.

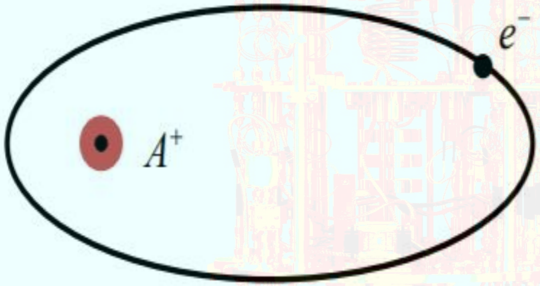
"that's the basic idea", says Mark Saffman, an atomic physicist at the University of Wisconsin–Madison in the US

The atomic advantage



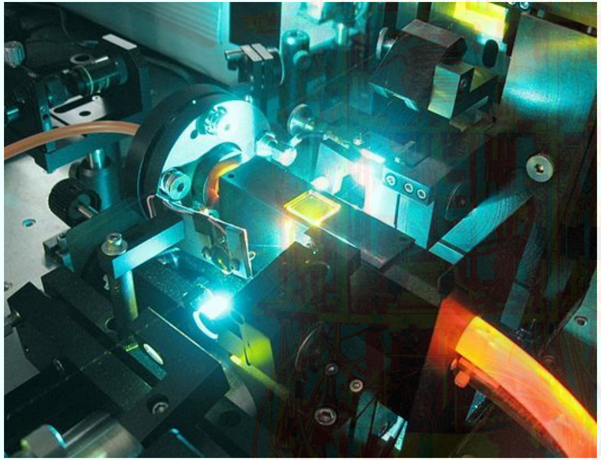
- Computation with qubits relies on full control and strong coupling
- Atomic approach has the potential for providing exquisite isolation and very strong control in a single system

Rydberg Atom



- It is an excited atom with one or more electrons that have a very high principal quantum number, n
- The radius of an atomic orbit scales as n^2 (the n = 137 state of hydrogen has an atomic radius ~1 μm) and the geometric cross-section as n^4

Methods of production



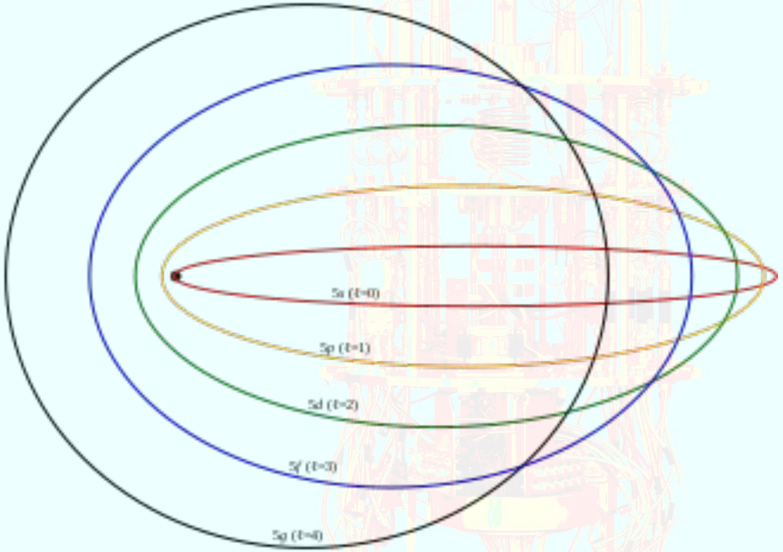
Dye laser
Source: Wikipedia

Electron impact excitation : $e^- + A \to A^* + e^-.$

Charge exchange excitation : $A^+ + B \to A^* + B^+.$

Optical excitation : $A + \gamma \to A^*.$

Quantum mechanical details



Semiclassical orbits for *n*=5 with all allowed values of orbital angular momentum. The black spot denotes the position of the atomic nucleus. Source: Wikipedia

- In Hydrogen, the binding energy is

  $E_B = - Ry/ n^2$

- For Rydberg atoms,

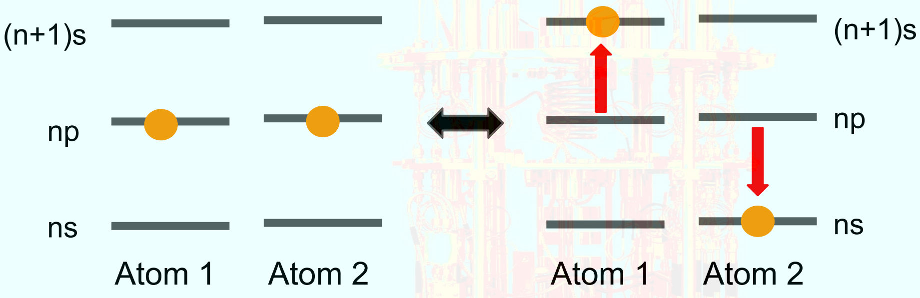
  $E_B = - Ry/ (n - \boldsymbol{\delta}_l)^2$

Properties

Quantity	n dependence	^{87}Rb @ 60D
Binding energy	n^{-2}	$3.96\,\mathrm{meV}$
Ionizing field	n^{-4}	$\sim 44\,\mathrm{V/cm}$
Orbital radius	n^{2}	$5156\,a_0$
Radiative lifetime	n^{3}	$215\,\mu\mathrm{s}$
Polarizability	n^{7}	$191\,\mathrm{MHz}\,/\,(\mathrm{V/cm})^2$

- The binding energy is very small.
- The radiative lifetime is very long.
- The dipole matrix elements are big.
- They are very sensitive to electric fields

Typical scenario for two atoms



$|1\rangle = |np\,,np\rangle$

$|2\rangle = |ns\,,(n+1)s\rangle$

$H = E_1|1\rangle\langle 1| + E_2|2\rangle\langle 2| + V(R)\,(|1\rangle\langle 2| + |2\rangle\langle 1|)$

Diagonalize H:

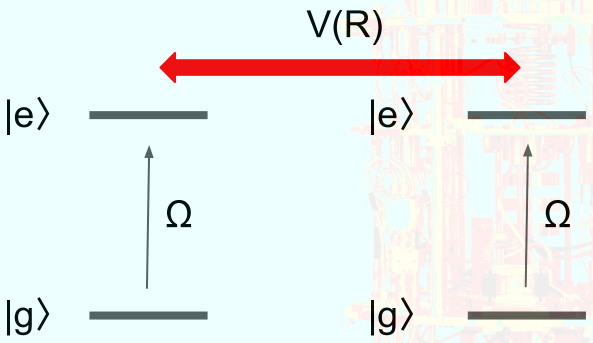
$H = \lambda_+|+\rangle\langle +| + \lambda_-|-\rangle\langle -|$

$\lambda\pm = \Delta/2 \mp \mathrm{sqrt}\,(\Delta^2/4 + V(R)^2)$ $\qquad [\Delta = E_2 - E_1]$

$\lambda_1 \sim 1/R^3 \quad \Delta << V(R)$ Forster resonance

$\sim 1/R^6 \quad \Delta >> V(R)$ Van der waals

Rydberg Blockade



|e> = Rydberg state

$$H = H_1 + H_2 + H_{12}$$

$$H_1 = \hbar\Omega_1 \left(A_{eg}^{(1)} + A_{ge}^{(1)}\right) \otimes 1_2$$

Laser-driving of atom1

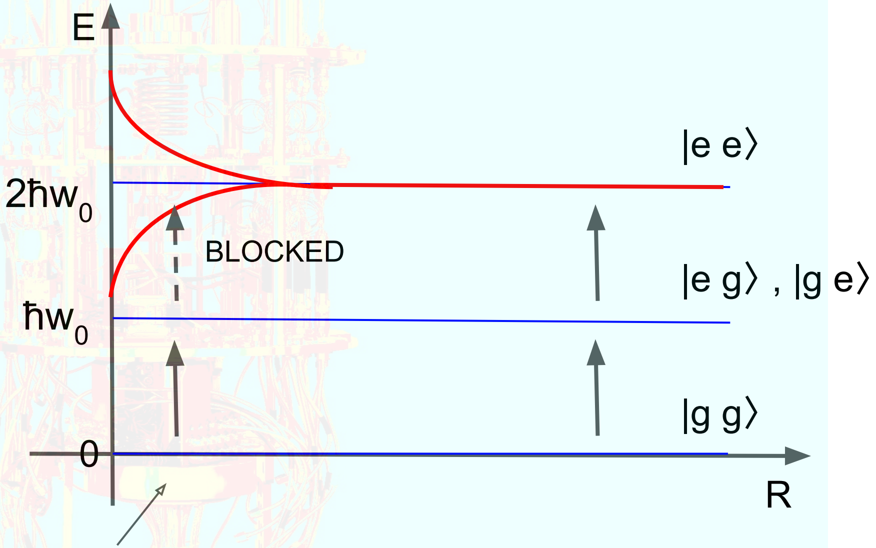
$$H_2 = \hbar\Omega_2 \left(A_{eg}^{(2)} + A_{ge}^{(2)}\right) \otimes 1_1$$

Laser-driving of atom 2

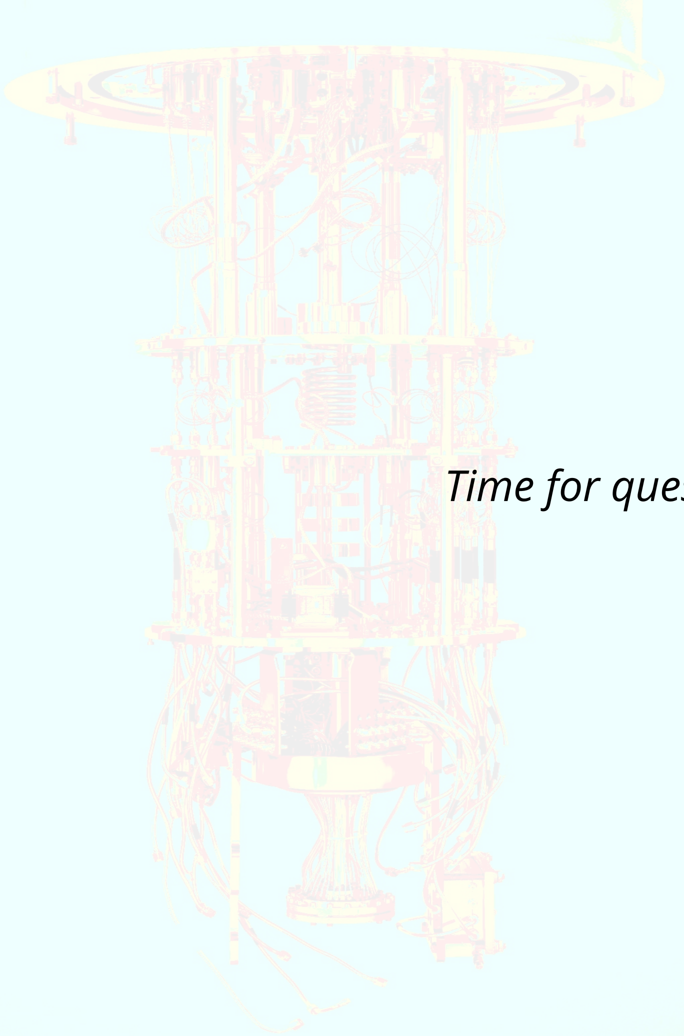
$$H_{12} = \hbar V(R)\, A_{ee}^{(1)} \otimes A_{ee}^{(2)}$$

Rydberg-Rydberg interaction of both atoms excited

Energy Diagram

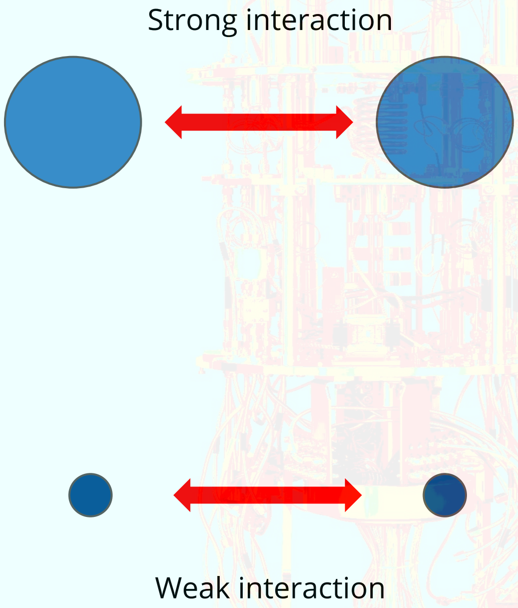


At this distance, |e e⟩ is strongly shifted because of V(R)



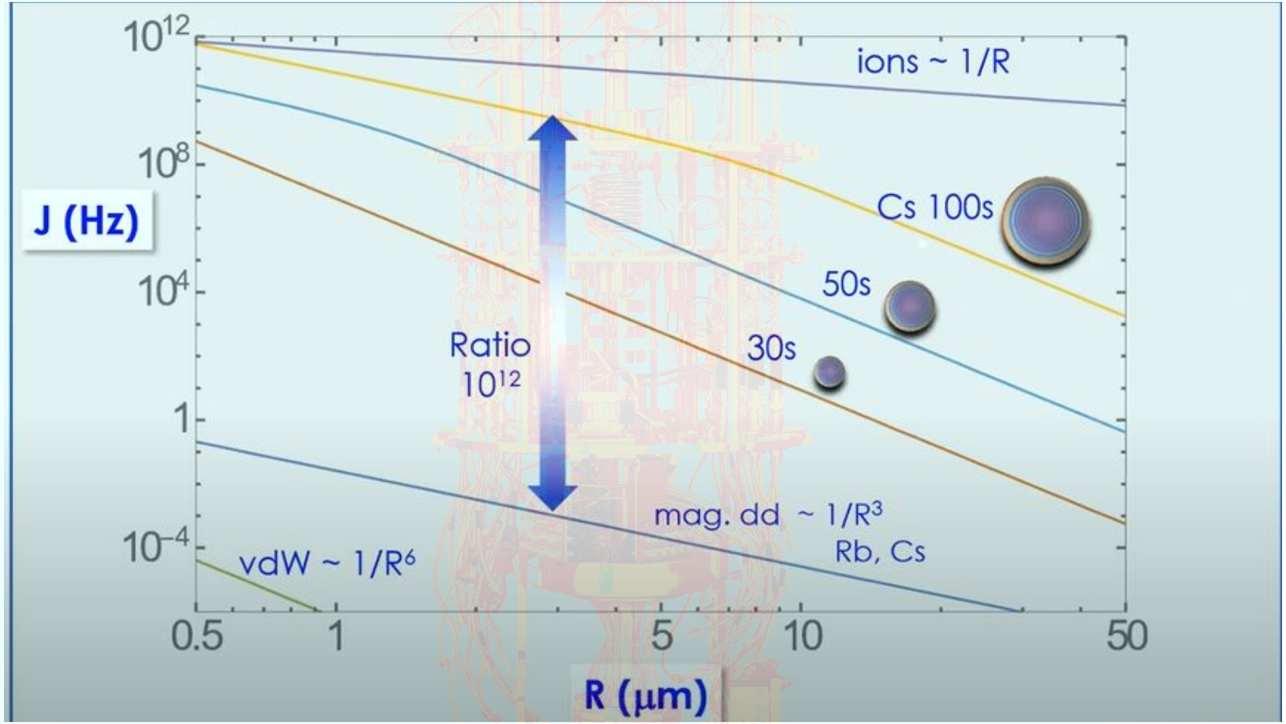
Time for questions

Atomic approach to quantum computing



- A qubit is a two-state (or two-level) quantum-mechanical system. Here, an atom.
- To perform logic, we need to turn on the interaction between the atoms and we do that by going up to rydberg states.

Interaction strength



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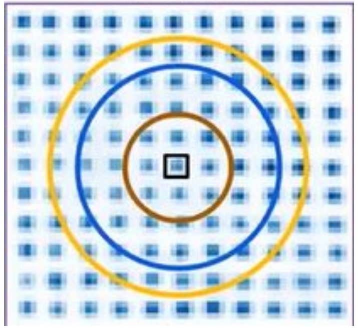
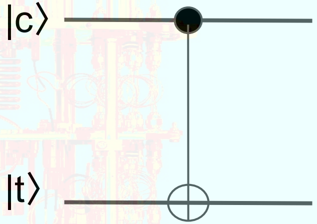
fully connected
~60 qubits



CNOT gate and entanglement

Input	Output
00	00
01	01
10	11
11	10



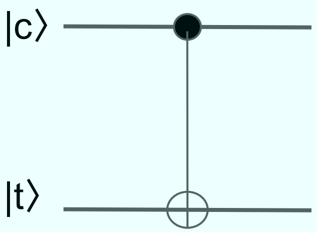
CNOT gate

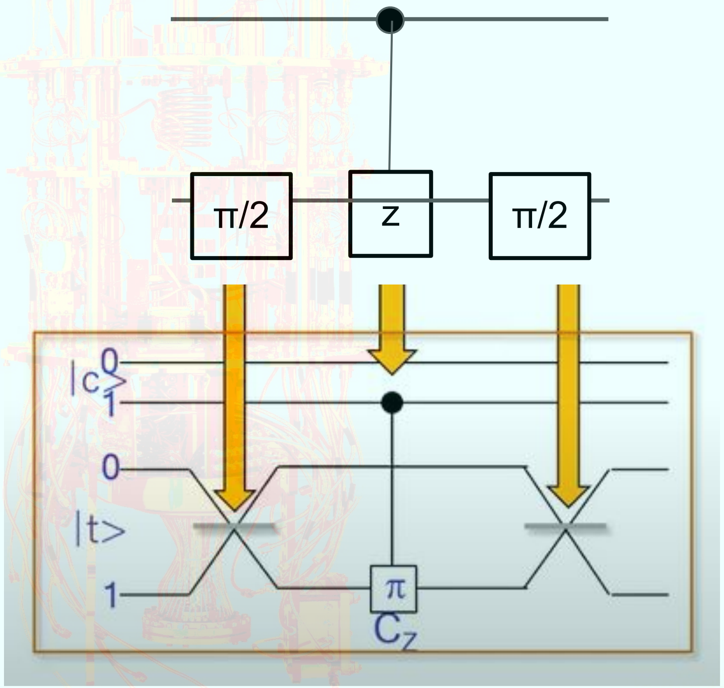
$$\begin{array}{cc} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} & \begin{array}{c} 00 \\ 01 \\ 10 \\ 11 \end{array} \end{array}$$

Preparing entanglement:

$$00 \xrightarrow[\text{Rotate 1st qubit}]{} (0+1)0 = 00 + 10 \xrightarrow[\text{CNOT}]{} 00 + 11$$

From C_Z to CNOT



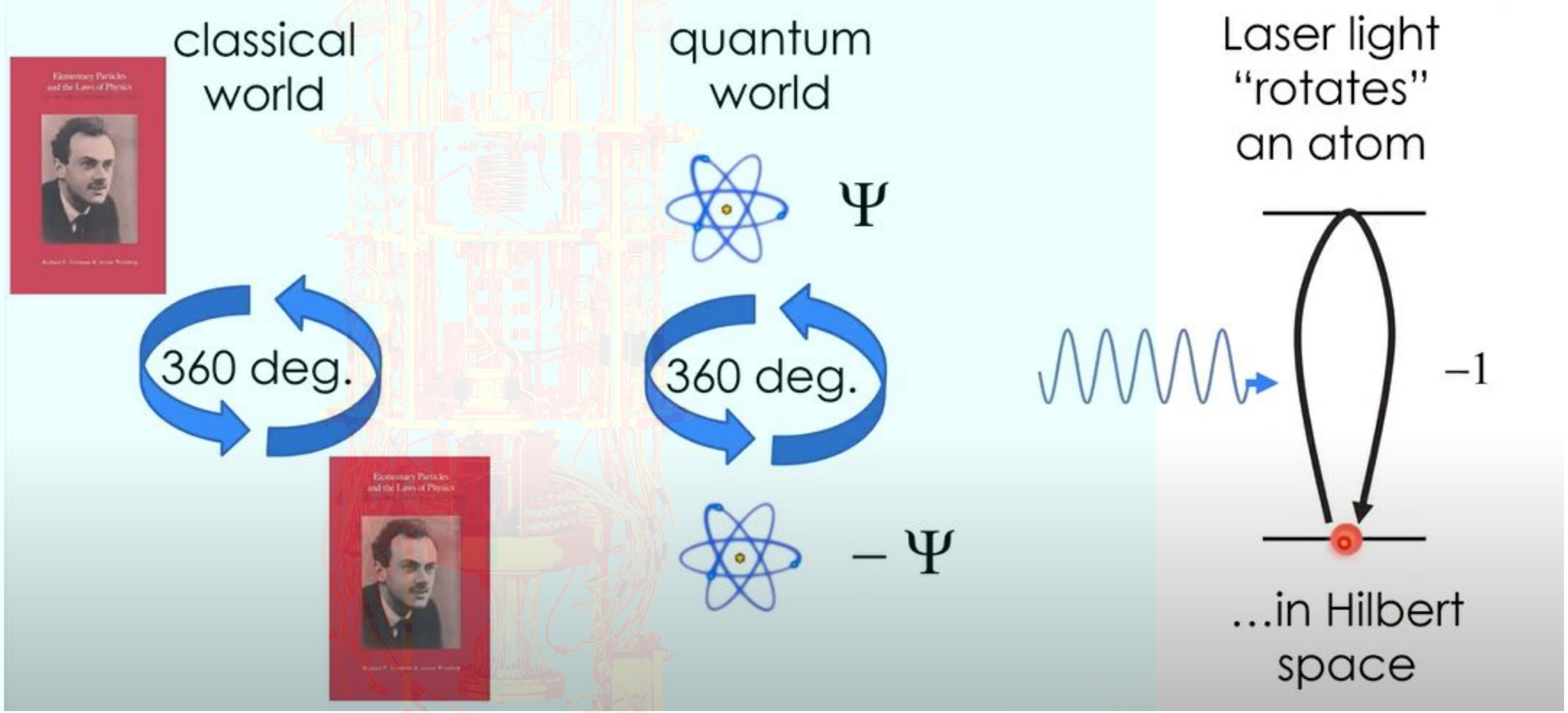


$$\begin{array}{c|c} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} & \begin{array}{c} \mathbf{00} \\ \mathbf{01} \\ \mathbf{10} \\ \mathbf{11} \end{array} \end{array}$$

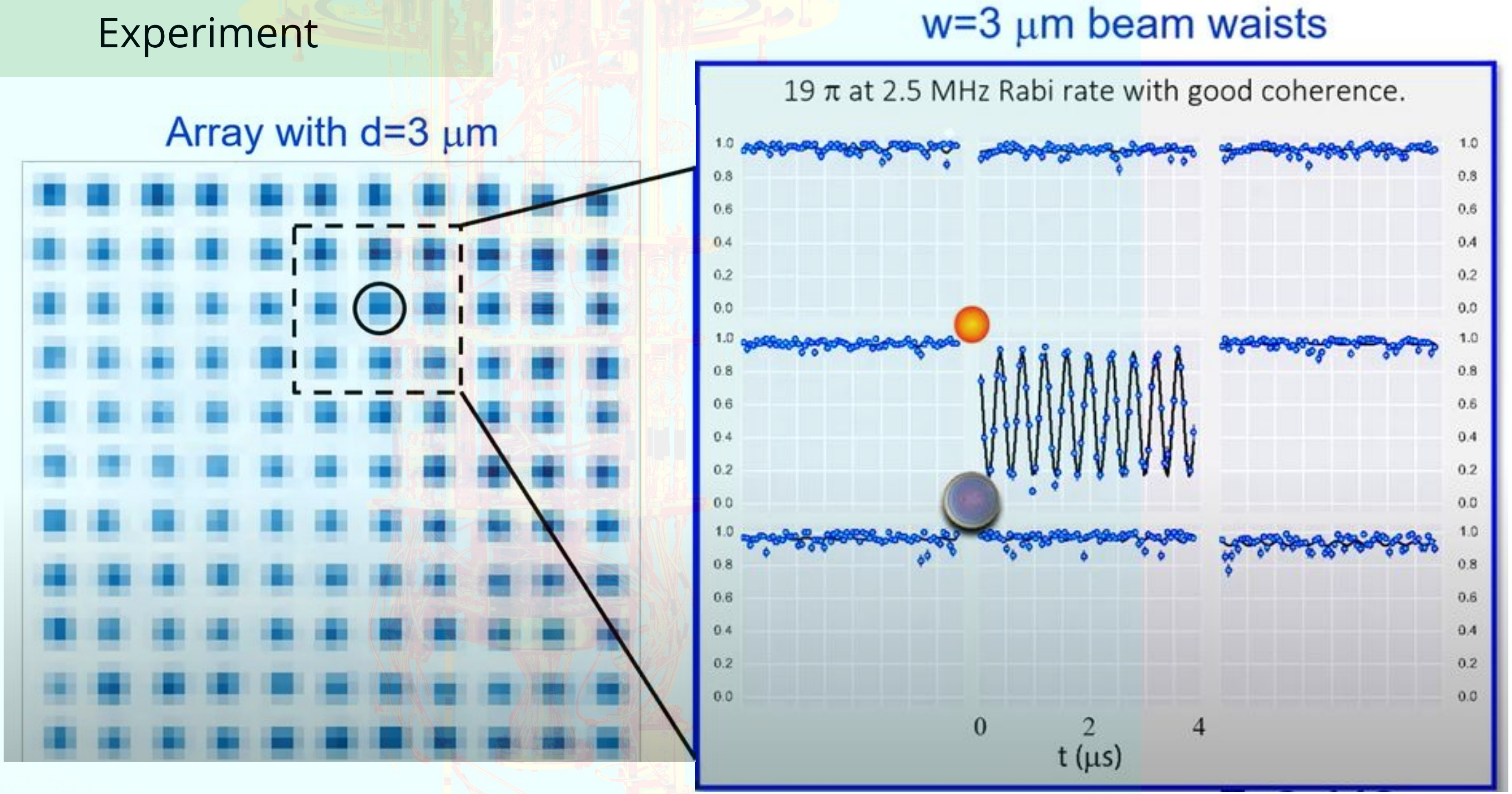
‘Mach - Zehnder in Hilbert space’

- The CNOT gate can be realised with a controlled phase C_Z plus Hadamards
- How do we get a π phase?

Quantum Magic



Experiment



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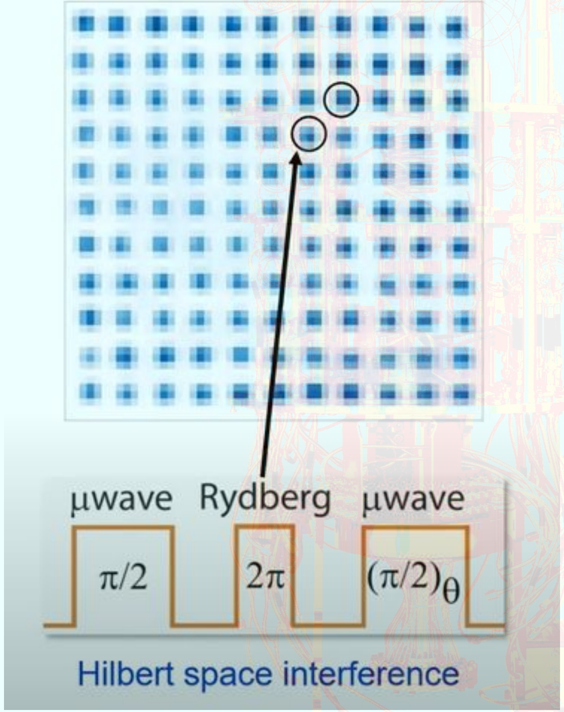
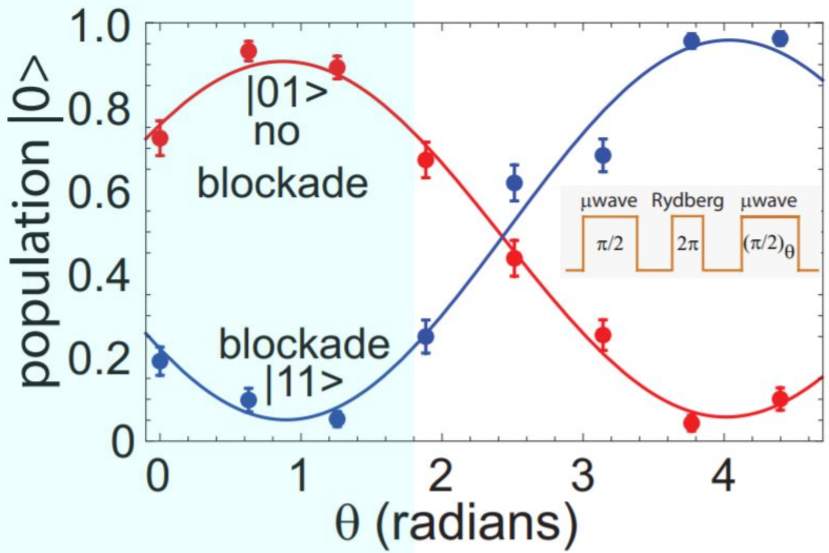
Conditional dynamics from blockade





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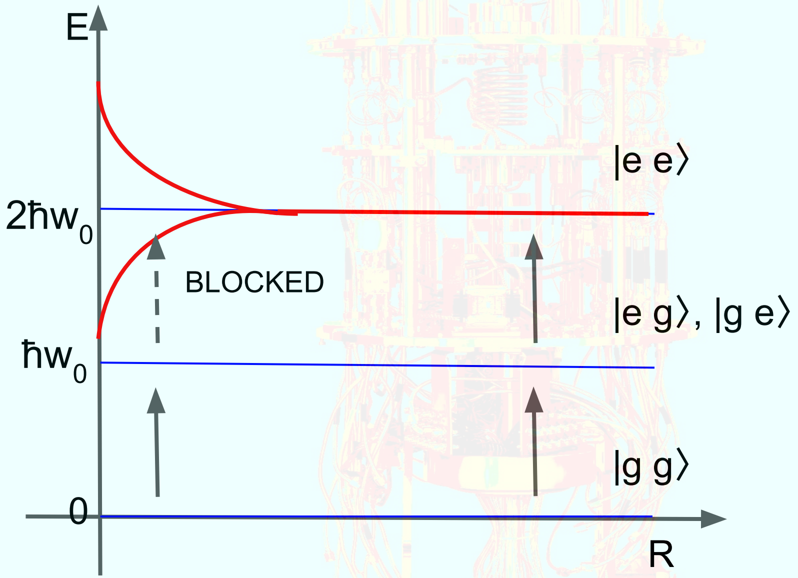
Summary



Energy diagram showing blockade

- Rydberg atoms have properties different than ordinary atoms.
- This makes them a good option for use in quantum computation.
- Computation with qubits relies on full control and strong coupling
- Rydberg blockade provides a way to do this.
- The CNOT gate can be implemented with getting a pi phase shift using rydberg transitions

Outlook

- The goal is to push for higher-fidelity manipulation of these logic gates to increase the quality of their output and provide internal error corrections.
- One can imagine a hybrid system, whereby Rydberg atoms and photon interactions are both involved in the information processing
- Rydberg atoms have other uses too. For example, by choosing a Rydberg ensemble at a specific resonant frequency – say terahertz, or microwave – it could act as a sophisticated sensor, producing an optical output when it picks up those fields.
- Photon–photon interactions forced by Rydberg blockades could even lead to exotic states of light that are considered crystalline or liquid, where the interactions hold the photons together in something that might look like a lightsaber.
- Rydberg interactions have also turned out to be important for creation of long range molecular dimers (Bendkowsky et al., 2009)
- Recent proposals(Weimer et al., 2010) to use Rydberg atoms for implementing multi-partite interaction operators point to broad possibilities for simulating quantum many-body physics

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