L4 Quantum information and computing (QIC) 2020-21

Lecture 11: Part II: Building a quantum computer

October 27, 2021

Aims of Lecture 11: To introduce the atomic structure associated with **Rydberg atom quantum computers**. We shall focus on Rb, Cs, and Sr atoms in particular. This lecture is a roadmap for what follows.

Introduction:

The first half of the course was about the concept of quantum computing. The second half will be able the practicalities of how to build a quantum computer. In Lecture 1 we mentioned five possible qubit candidates—superconductors, semiconductors, photons, ions and atoms. Rather than trying to cover all five, we shall focus on only one. Each has various advantages and disadvantages, and it would be reasonable to claim that superconductors and ions are current leading in terms of commercial systems. However, we chose atoms because, firstly, the atom platform is completely based on lasers and links to the first part of the modules, and second, atoms offer arguably the most promising route to 1000 qubit systems with all-to-all connectivity.

In terms of choice of atom, Rubidium (Rb), Caesium (Cs) and Strontium (Sr) atom computers are the leading candidates.[1] We shall focus on Cs. Everything we say is also applicable to Rb, just the nuclear spin and transition wavelengths are different.

Once we have decided on how to build a Cs atom quantum computer our focus turns to how to fulfill each of the DiVincenzo criteria (DV1–5) for this example. But first we need to review the atoms structure of the Cs atom.

Cs atomic level structure The energy levels of Cs-133 are shown in Fig. 1. The ground states and the first excited state is 6s and 6p, respectively. Due to the electron and nuclear spin, each state is split into multiple fine (for orbital angular momentum $\ell > 0$) and hyperfine states. In Cs which has a nuclear spin ($I = 7/2$), the ground state is split into a $F = 3$ and $F = 4$ level. Each of these consists of $2F + 1$ magnetic sub-levels, labelled m_F. The $(F = 3, m_F = 0)$ to $(F = 4, m_F = 0)$ transition is used in **atomic clocks** and the definition of the **second** and hence the definition of the speed of light. As all the ground state hyperfine levels are stable we can select a pair of states to form the computational basis. In Fig. 1 we have chosen $|0\rangle \equiv |(F = 3, m_F = 3)\rangle$ to $|1\rangle \equiv |(F = 4, m_F = 4)\rangle$.

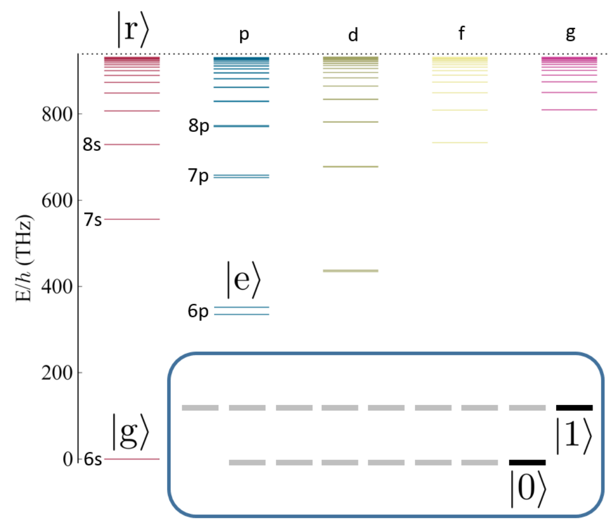

Figure 1: The energy level of the Cs atom. The magnetic sub-levels within the ground state are shown inset. A Cs atom quantum computer uses hyperfine ground states, $|0\rangle$ and $|1\rangle$ for the computational basis, an excited state $|e\rangle$ for initialisation, single-qubit rotations and read-out, and a highly-excited Rydberg state $|r\rangle$ for two-qubit gates.

Initialisation (DV1 The next few lectures will discuss how to prepare an array of qubits in state $|0\rangle$ or $|1\rangle$. The first step is to prepare an array of atoms with spacing of a few microns. An example is shown in Fig. 2. This allows each atom to be separately addressed using lasers, but still close enough to enable the implementation of multi-qubit gates.

The preparation of the array involves laser cooling and trapping (Lectures **12-14**) and optical pumping (Lecture **15**). To perform these tasks we need to make use of the excited state 6p. This state is split by the fine structure

[1] Pasqal is building a Rb QC in France, see details in Quantum 4, 327 (2020). M2 laser and Strathclyde University are building Cs QCs in the UK, and Atom Computing a Sr QC in the US.

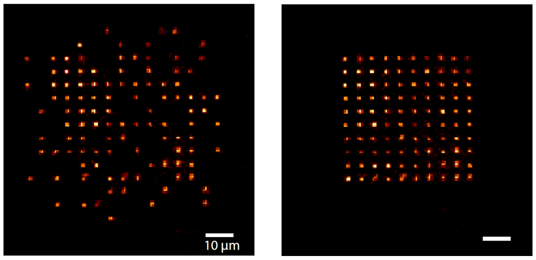

Figure 2: An atom array used for quantum computing. The left-hand image shows the array before sorting. From arXiv:2011.06827.

interaction into $6p_{1/2}$ and $6p_{3/2}$. For laser cooling, optical pumping and read-out we will use $|e\rangle \equiv 6p_{3/2}$. The $6p_{3/2}$ is also split by the hyperfine interaction. Particularly special are the 'swing' states $6p_{3/2}(F = 5, m_F = \pm 5)$ as they only has one decay channel. The transitions $6s_{1/2}(F = 4, m_F = \pm 4) \rightarrow 6p_{3/2}(F = 5, m_F = \pm 5)$ are known as **closed**.

Read-out (DV3) The closed transitions,

$$6s_{1/2}(F = 4, m_F = \pm 4) \rightarrow 6p_{3/2}(F = 5, m_F = \pm 5) \ ,$$

are particularly useful for read-out as we can scatter many photons off a single atom and collect the scattered light without it falling into another state, see Fig. 3. For our choice of qubit states, read-out consists of tuning the laser to $6s_{1/2}(F = 4, m_F = 4) \rightarrow 6p_{3/2}(F = 5, m_F = 5)$. If the atom scatters (lights up) it is in state $|1\rangle$, if it remains dark it must be in $|0\rangle$ (or something bad has happened).

Single-qubit gates (DV2) The excited state, $|e\rangle \equiv 6p_{3/2}$, is also indirectly involved when we perform single-qubit rotations. We could drive the transition $|0\rangle \rightarrow |0\rangle$ directly using microwaves at 9.2 GHz. However, as the microwave wavelength is much larger than the spacing between the atoms (of order microns) it is not straightforward to address only one atom at a time. Instead, for single-site addressing (even in 3D) we can use two lasers beams to drive the two-photon stimulated-Raman transition $6s_{1/2}(F = 3, m_F = 3) \rightarrow 6p_{3/2} \rightarrow 6s_{1/2}(F = 4, m_F = 4)$. We shall discuss this in Lecture **16**.

Two-qubit gates (DV2)

Finally, in order to create entanglement and two-qubit gates, we need a way to make the atoms interact. Atoms always interact via van der Waals type interactions but for ground state and low-lying excited state this is extremely small. However, for highly-excited (Rydberg) states (Lecture **17**) with principle quantum numbers $n > 50$, the interaction is sufficiently large to implement gates. So the final state necessary to realise an atom quantum computer is a highly-excited Rydberg state, labelled |r in Fig. 2. We shall discuss the implementation of a CNOT gate in Lecture **18**. A schematic of all the levels involved for two-qubit is shown in Fig. 3

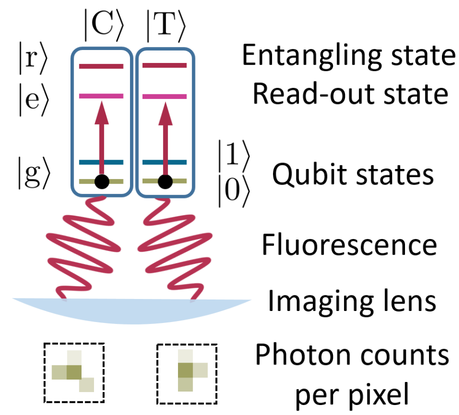

Figure 3: The level scheme for implementing two-qubit gates using alkali-metal atoms such as Rb and Cs.

Scalability (DV5) Rydberg atom quantum computers have the advantage of offering easy scaling to 3D using optical tweezers, see Fig. 4. The other advantages are that it is relative each to implement next-nearest and next-next nearest neighbour inteactions, plus also multi-qubit gates.

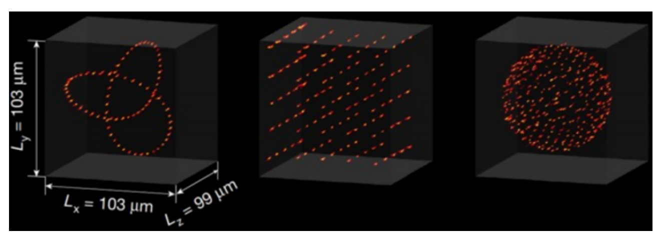

Figure 4: 3D arrays of qubits. From Quantum **4**, 327 (2020)

Summary:

What do you need to be able to do?

1. Be able to explain why Rb, Cs and Sr make good choices for quantum computing.
2. Be able to explain what states are chosen for the computational basis and why.
3. Have an overview of other energy levels that are important in the initialisation (DVC1) and gate operation (DVC2) for a Rydberg atom quantum computer.