L4 Module: **Atoms, Laser and Qubits**, **Quantum information and computing (QIC)** 2022-23

Lecture 0: Overview of the Course

June 19, 2023

Course overview:

The aim of the course is to understand **the physics of quantum computing**, and to give a specific example of **how to build a quantum computer**. These two topics map onto roughly two halves of the course:

- **Part I** on **theoretical concepts** and
- **Part II** on the **Rydberg atom quantum computer**.

Lecture Summary:

Each **'Lecture'** consists of the live event or video presentated and annotated using Caroline plus a set of text Notes (2+ page pdf). The Notes contain all the essential material.

1. 1.1 **Qubits**: What are they?
   1.2 **Quantum advantage**.
2. 2.1 The **diVincenzo criteria**; (DVC1–5)
   2.2 The **Bloch sphere**.
3. 3.1 The **density matrix**
   3.2 The **Pauli matrices**.
4. 4.1 **Rotation operators**
   4.2 The **Rabi solution**.
5. 5.1 **$\pi/2$, π and 2π pulses** (DV2).
   5.2 The **Hadamard gate** (DVC2.1).
6. 6.1 **Decoherence**: (DVC4) What can go wrong?
   6.2 The **optical Bloch equations**.
7. 7.1 **Measurement**: Read-out (DVC3)
   7.2 **Quantum interference**. (DVC2)
8. 8.1 **Bell states**.
   8.2 **Entanglement**.
9. 9.1 **Two-qubit gates**. (DVC2)
   9.2 **Quantum circuits**.
10. 10.1 **Quantum circuit model of decoherence**. (DVC2–4)
    10.2 **Summary of Part I**.
11. 11.1 **Part II: Introduction**. (DVC1–5)
    11.2 **Atomic level structure**.
12. 12.1 **Qubit initialisation**: Qubit arrays (DVC1)
    12.2 **Light forces**
    12.3 **The light shift**
13. 13.1 **Qubit initialisation** Qubit arrays (DVC1)
    13.2 **Optical tweezers** (DVC1)
    13.2 **Qubit position** (DVC4)
14. 14.1 **Qubit initialisation** State preparation (DVC1)
    14.2 **Laser cooling** (DVC1)
    14.3 **Optical pumping** (DVC1)
15. 15.1 **Single-qubit gates** (DVC2.1)
    15.2 **Stimulated-Raman transitions** (DVC2.1)
    15.3 **Read out** (DV3)
16. 16.1 **Two-qubit gates** (DVC2.2)
    16.2 **Rydberg atoms** (DVC2.2)
17. 17.1 **Interactions and entanglement** (DVC2.2)
    17.2 **Rydberg blockade** (DVC2.2)
18. 18.1 **Rydberg CNOT gate** (DVC2.2)
    18.2 **Summary of Part II**

Quantum quotes:

1. *Before Maxwell people thought of physical reality [...] as material points [...]. After Maxwell they thought of physical reality as represented by continuous fields, not mechanically explicable [...] This change in the conception of reality is the most profound and the most fruitful that physics has experienced since Newton.* A. Einstein, *Maxwell's Influence on the Development of the Conception of Physical Reality*, Written for the centenary of Maxwell's birth (1931).

2. *all things physical are information-theoretic in origin and this is a participatory universe.* John Archibald Wheeler, *Information, Physics, Quantum: The Search for Links*, Proc. 3rd Int. Symp. Foundations of Quantum Mechanics, Tokyo, 1989, pp. 354-368.

3. *Although my primary realist convictions remain firm, [...] experimental results gathered over the last 30 years [...] have forced me to question the presumption that the wavefunction represents the real physical states of real physical things. I've developed some real doubts.*. Jim Baggott writing in Physics World Dec. 2 2020.

4. *The wave function [or state vector] is NOT a description of the quantum object, it is a prescription for what to expect when we make a measurement on that object.* Phillip Ball, *Quantum mechanics is not weird*, Qiskit Seminar, 12th February 2021.

5. *In mathematics you don't understand things. You just get used to them.*. John von Neumann. Attributed to Neumann by Felix Smith, see Gary Zukav, *The Dancing Wu Li Masters: An Overview of the New Physics* (1979).

6. *I think I can safely say that nobody understands quantum mechanics.* Richard Feynman, The Messenger Lectures, Cornell, 1964. Full lecture: 7:55.

7. *The difficulty really is psychological [. . .] the perpetual torment that results from you saying to yourself, 'But how can it be like that?' [. . .] Just relax and enjoy. I'm going to tell what Nature behaves like. [. . .] Don't keep saying to yourself [. . .], but how can it be like that? Because you'll get down a drain, you'll get down into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.* Full lecture: 7:08–8:40.

8. *Quantum is THE enduring mystery of the Universe.* Ivan Deutsch, quantum physicist at the Univ. of New Mexico. 2020.

9. *To be AND not to be.* Not William Shakespeare.

Tech quotes:

1. *If I had a magic wand that could make one thing true to help solve climate, I'm making a fully fault-tolerant parallel massive quantum computer because it is the equivalent of, if I had one wish for a genie, I'm wishing for infinite wishes.* Mark Cupta, 2022. Quantum computing could be a critical climate solution.

2. *I think there is a world market for maybe five computers.* Thomas B Watson, president of IBM, 1943

3. *no exponential is forever... But we can delay "forever".* Gordon Moore on keeping the tech revolution going. Slide 29 in No exponential is forever at the International Solid State Circuits Conference 50th anniversary, 2003.

4. *we won't experience 100 years of progress in the 21st century — it will be more like 20,000 years of progress*, The Law of Accelerating Returns, Ray Kurzweil.

Background reading: Everything you need to know is in these Notes. The links and references provide additional background reading. For the first part of the course we shall refer to Nielsen and Chang, *Quantum Computation and Quantum Information*, (10th Anniversary Ed. 2010). The atomic physics underpinning the second part is covered in Foot, *Atomic Physics* (OUP 2005).

Summary:

What do you need to do?

1. Find all the material on Ultra.

2. Check that you can follow up on any references in the Notes.

3. Ask the Lecturer about anything that is not clear.