Quantum Physics

2025

The Theory/Framework Of *Almost* Everything *Today*

But Most Likely NOT of Tomorrow

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Course Overview

Course Structure And Goals

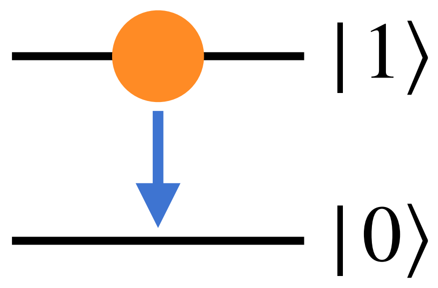
- **Part 1** : Mathematical Concepts And Tools.
- **Part 2** : Classical Physics.
- **Part 3** : Quantum Physics.

- Learn the language of quantum physics.
- Enhance the knowledge of classical physics.
- Develop modern quantum thinking.

We will focus on this one today.

Qubits

Physical Systems

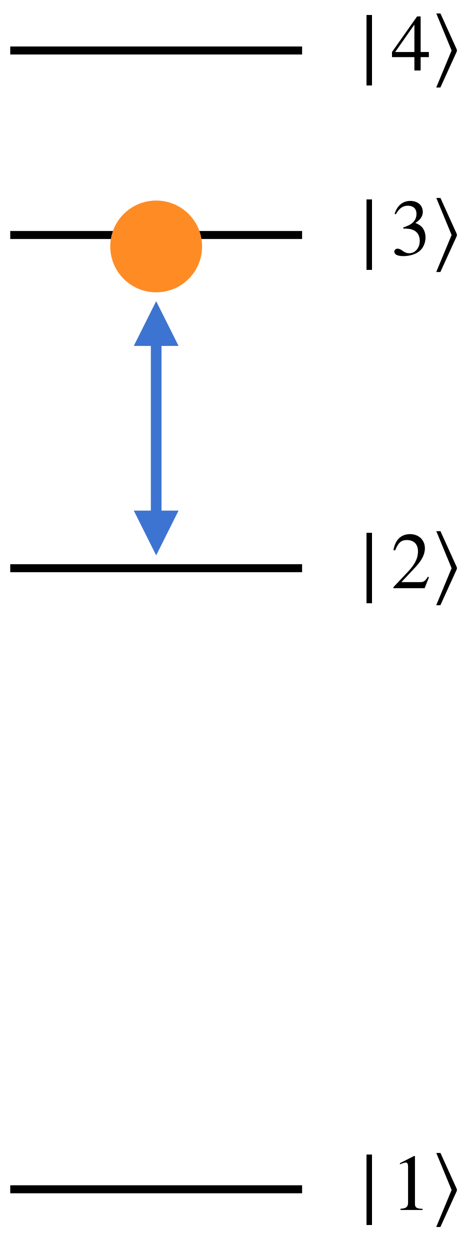


- Qubit, like an oscillator, is a general term
- Many physical systems can act as qubits
- Thus, there are logical and physical levels

Qubits

Atom as Qubit

$$\hbar\omega = E_{23}$$



$$E_n = -\frac{E_{ion}}{n^2}$$

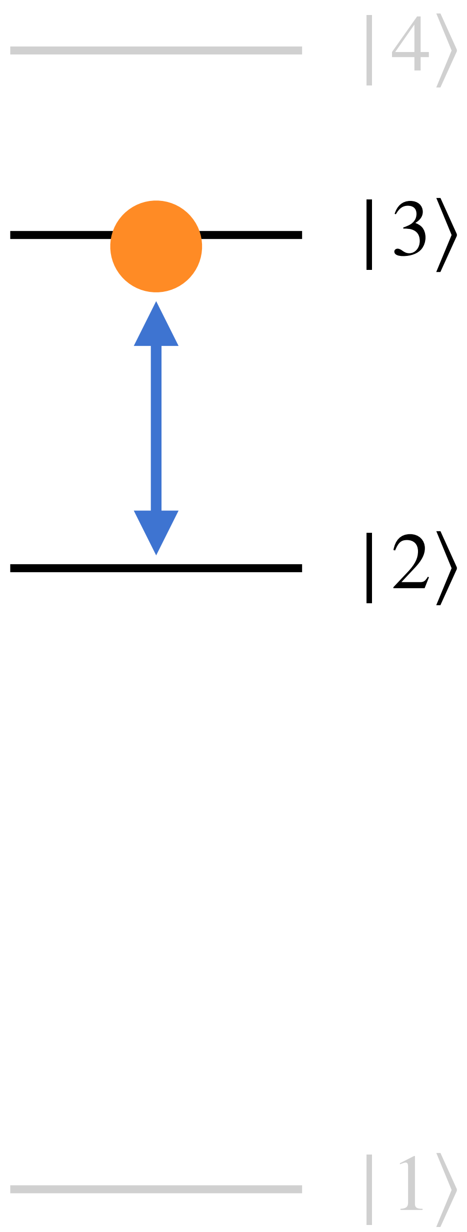
- Hydrogen (or any other) atom interacting with electromagnetic field of certain frequency that matches specific energy levels.

Hydrogen atom energy levels.

Qubits

Atom as Qubit

$$\hbar\omega = E_{23}$$



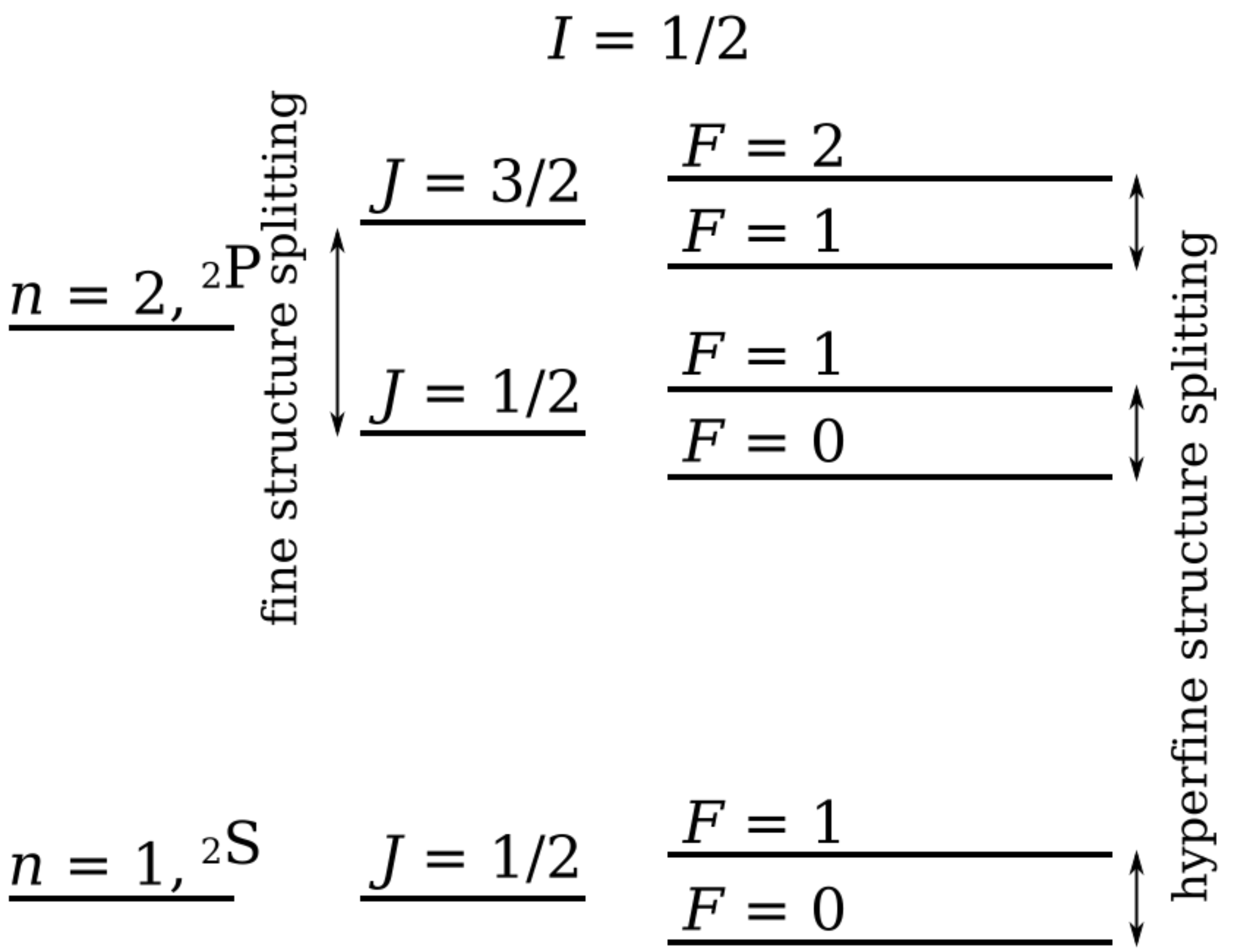
- Hydrogen (or any other) atom interacting with electromagnetic field of certain frequency that matches specific energy levels.
- Not very convenient. Not often used.

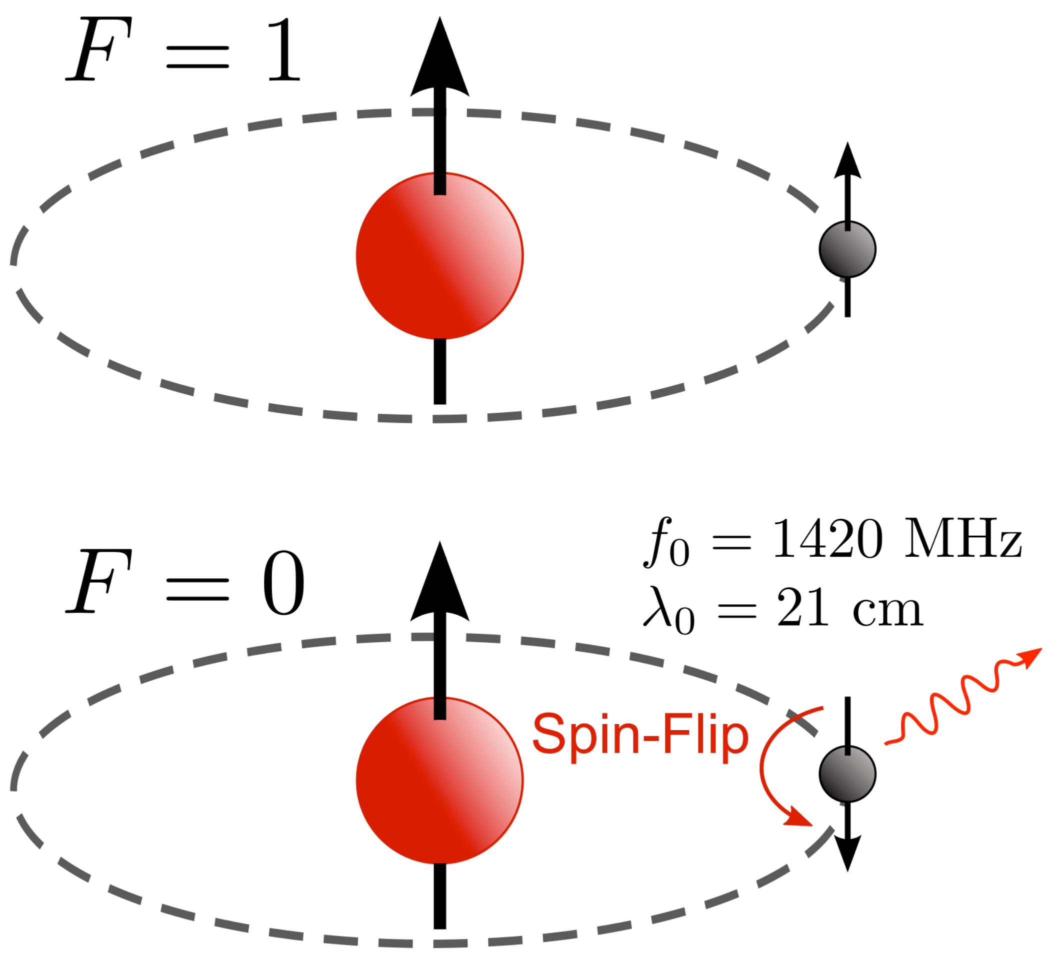
$$E_n = -\frac{E_{ion}}{n^2}$$

Hydrogen atom energy levels.

Qubits

Atom as Qubit: Find and Hyperfine Structure





- Spins of electrons and nuclei, as well as non-spherical shape of the nucleus result in intricate energy levels.
- There is *fine structure* and *hyperfine structure*.
- Atomic states from "normal" (optical), fine, and hyperfine levels can be used for qubits.

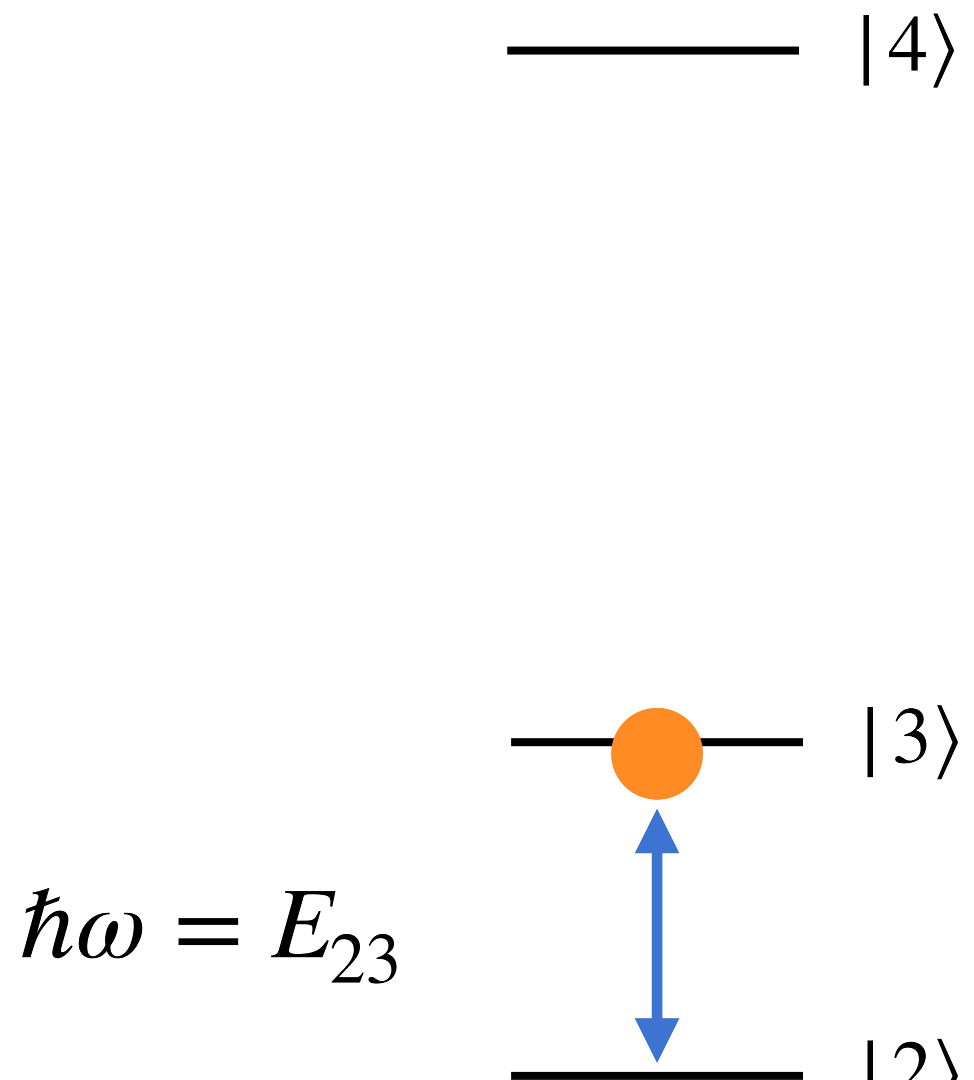
$$\boxed{E_n = -\frac{E_{ion}}{n^2}}$$

Too simple

Atomic energy levels are far from simple!

Qubits

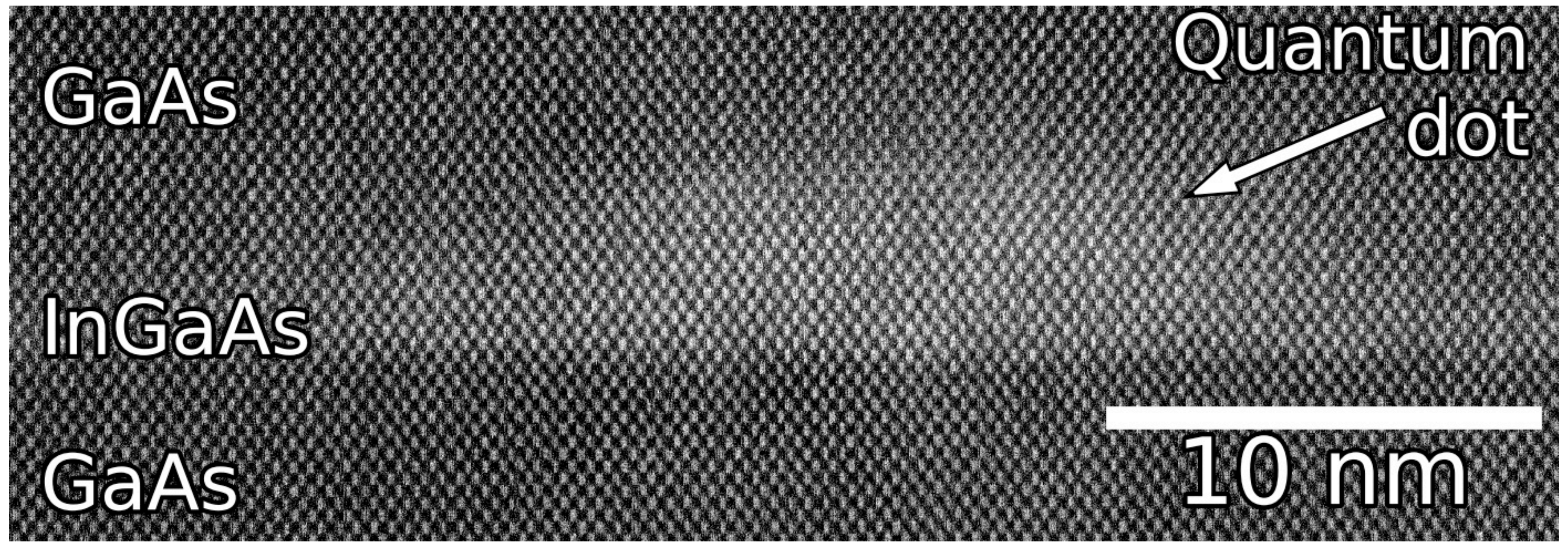
Atom-like Structures as Qubit



$$E_n = -E_1 n^2$$

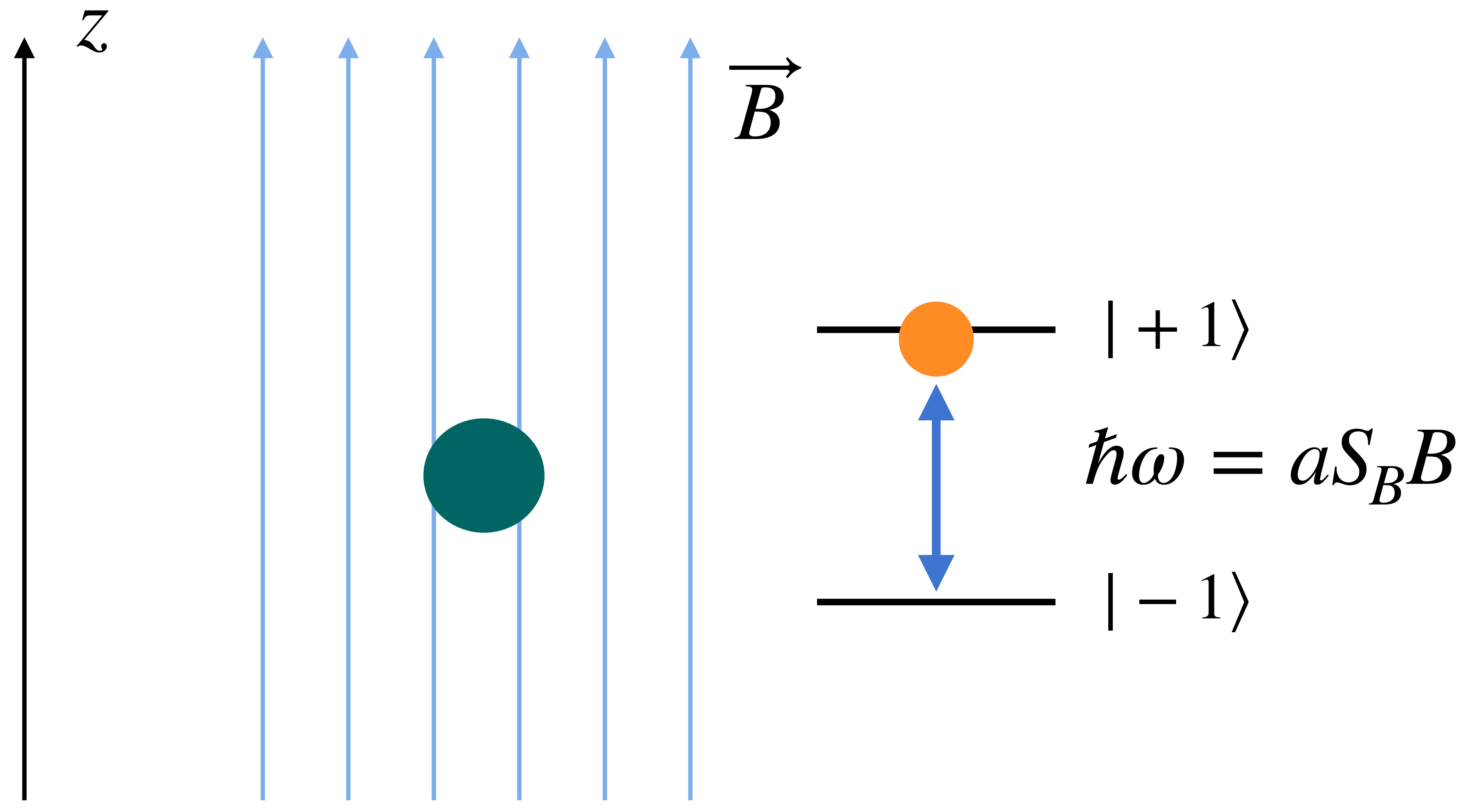
- When electrons are trapped in a small volume of a material (e.g. semiconductor like silicon) we get *quantum dot*.
- Quantum dots are, effectively, artificial atoms.

1D-quantum dot levels



Qubits

Electron Spin-Based Systems



- Due to electron's charge and spin, it possesses magnetic moment — acts like a little magnet.
- Magnetic moment interacts with external magnetic fields.

$$\hbar\omega = aS_B B$$

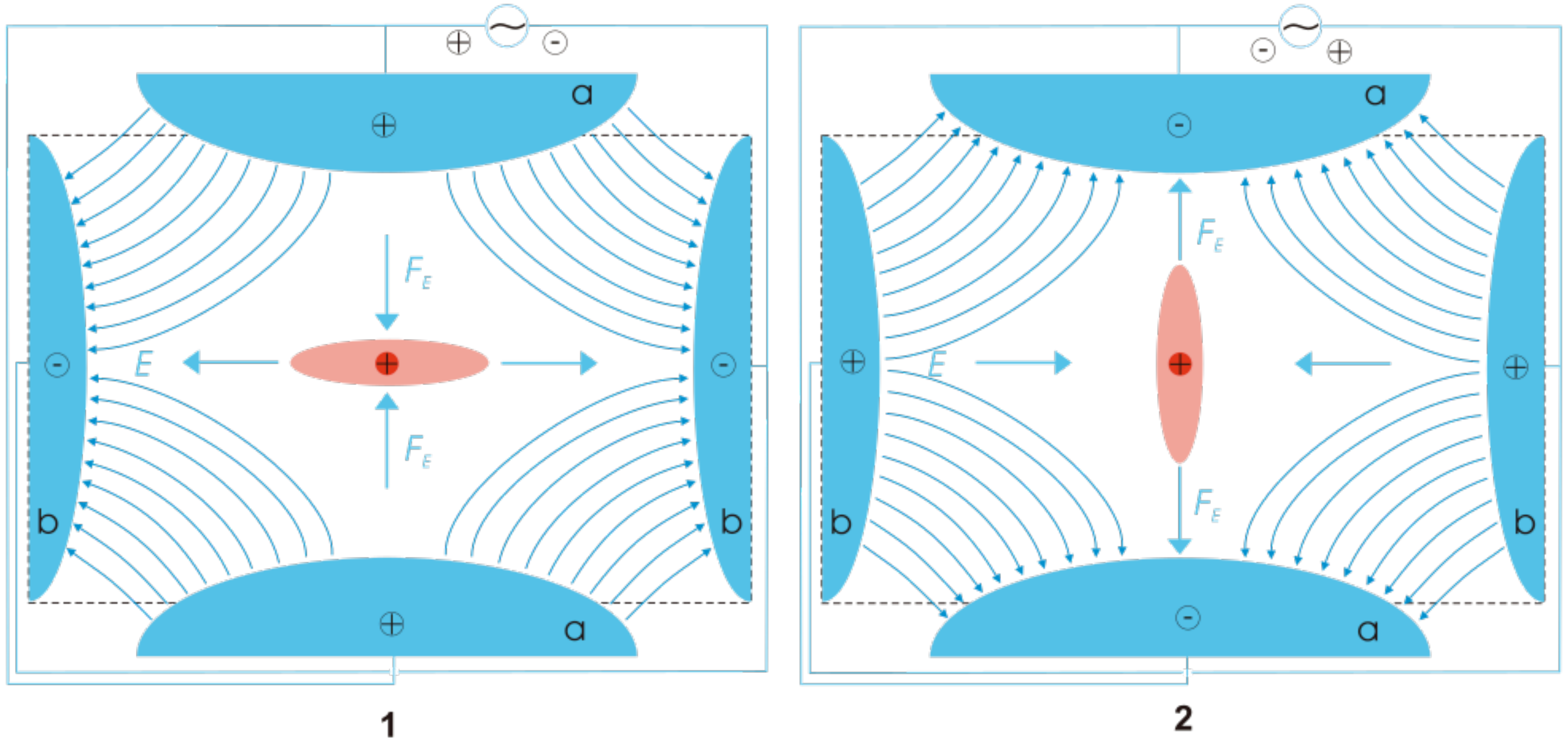
Magnetic field strength

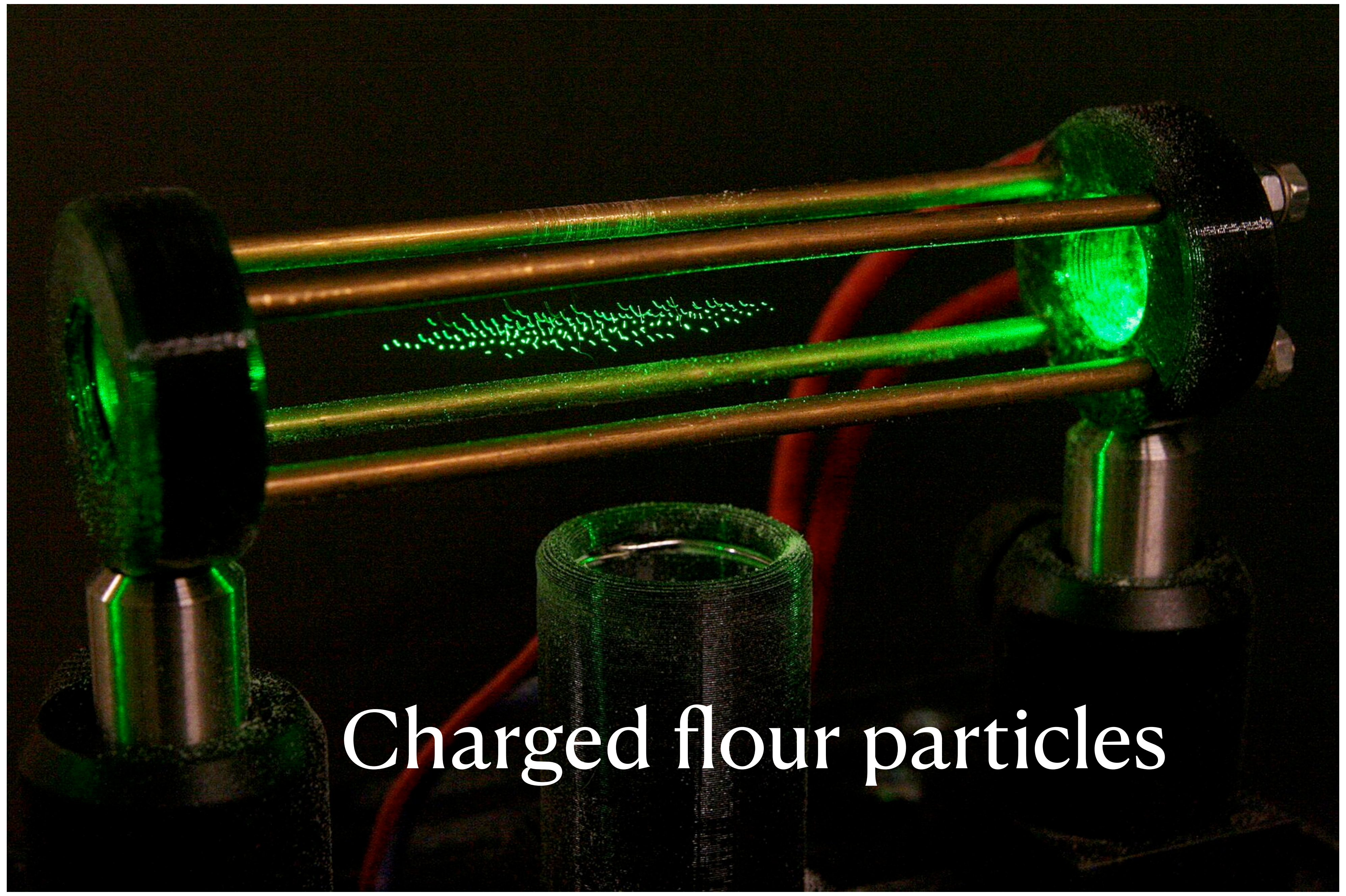
Spin "projection" on B

Spin is called "intrinsic angular momentum."

Qubits

Trapped-Ions



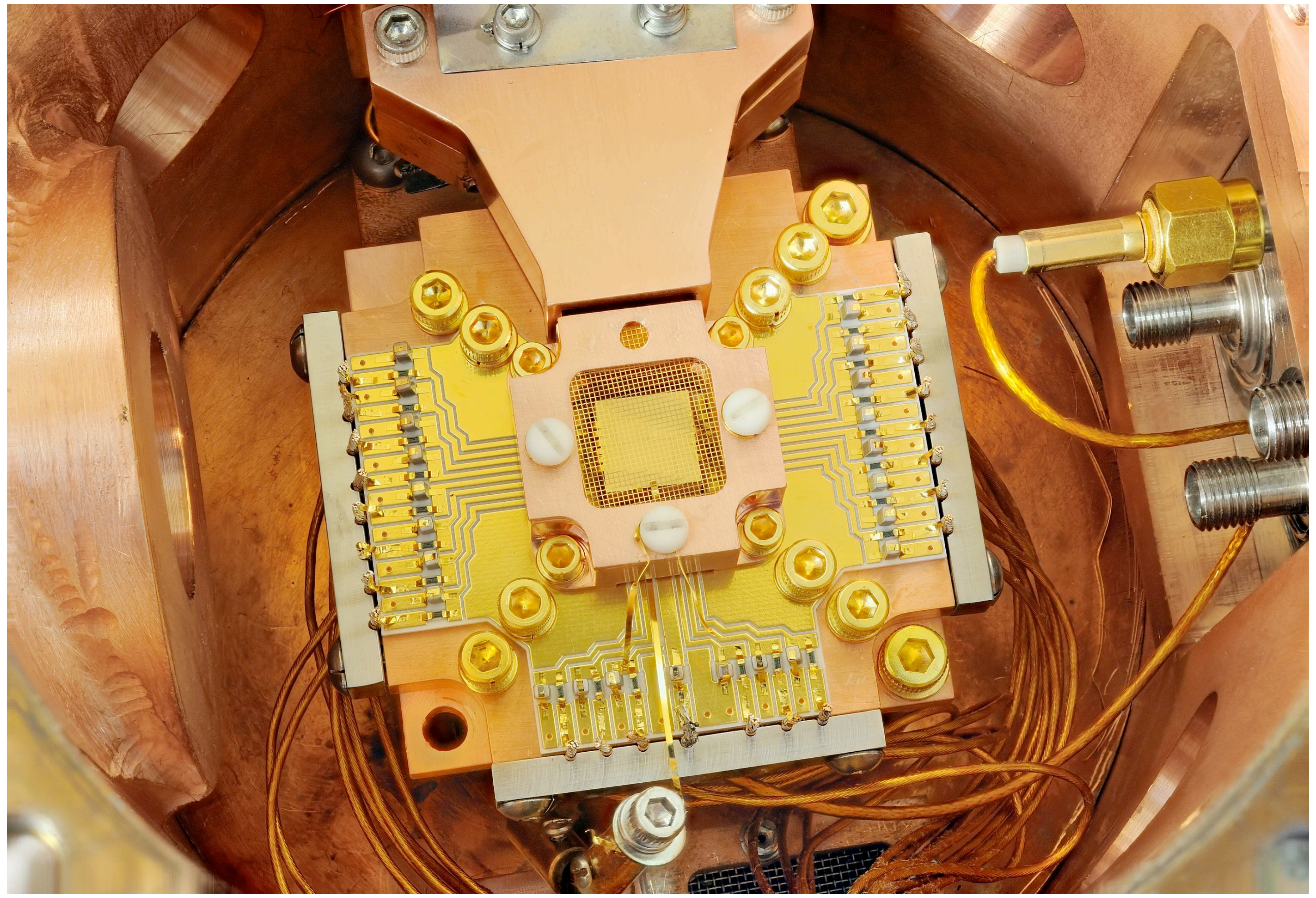


- 4-electrod (quadrupole) configuration creates a *slowly changing (~1GHz) electric* field that keeps ion in a trap.
- Electron's magnetic moment interacts with electromagnetic waves.

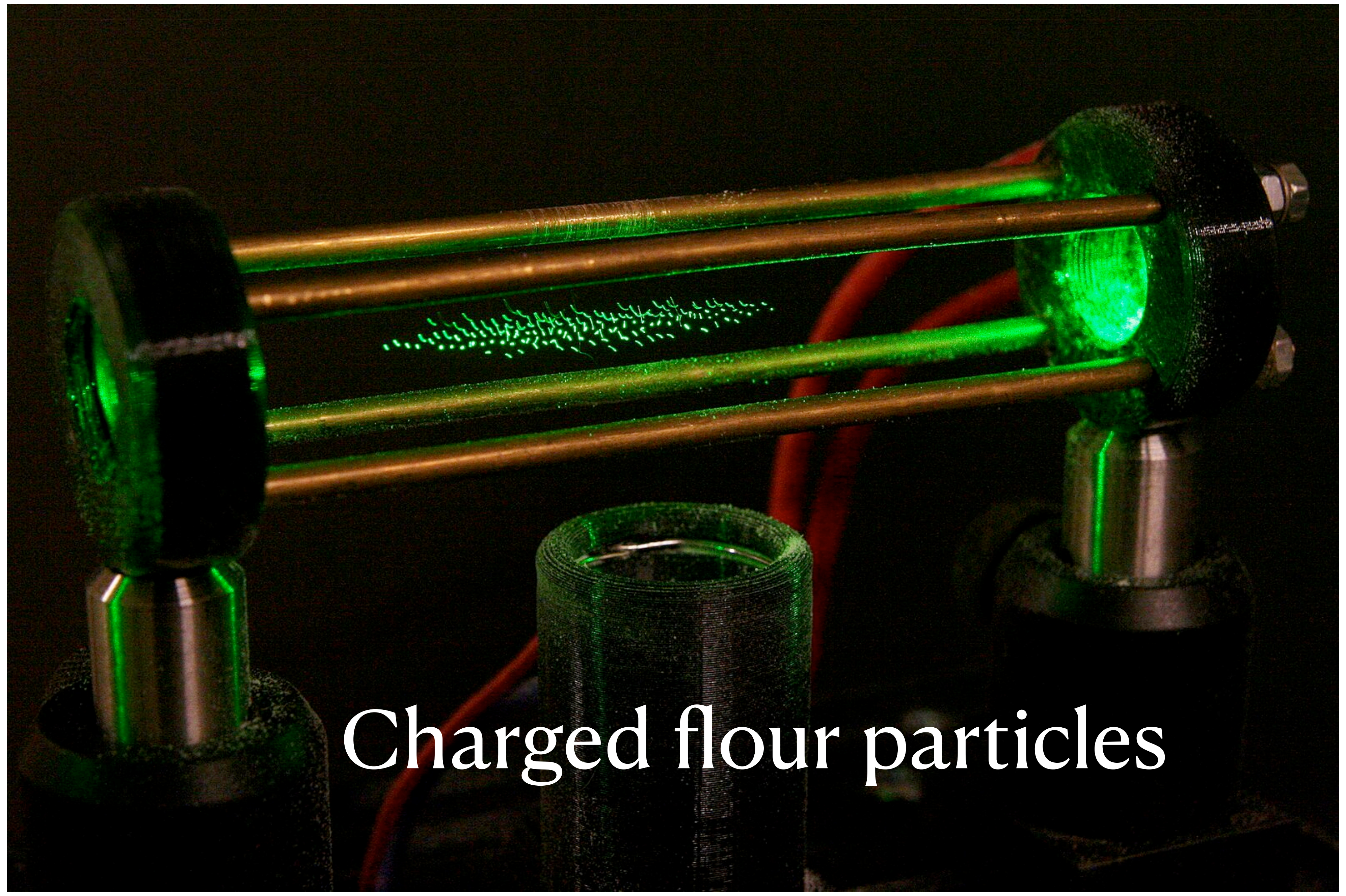
- Ytterbium atom is ionized — Y^+

Qubits

Trapped-Ions



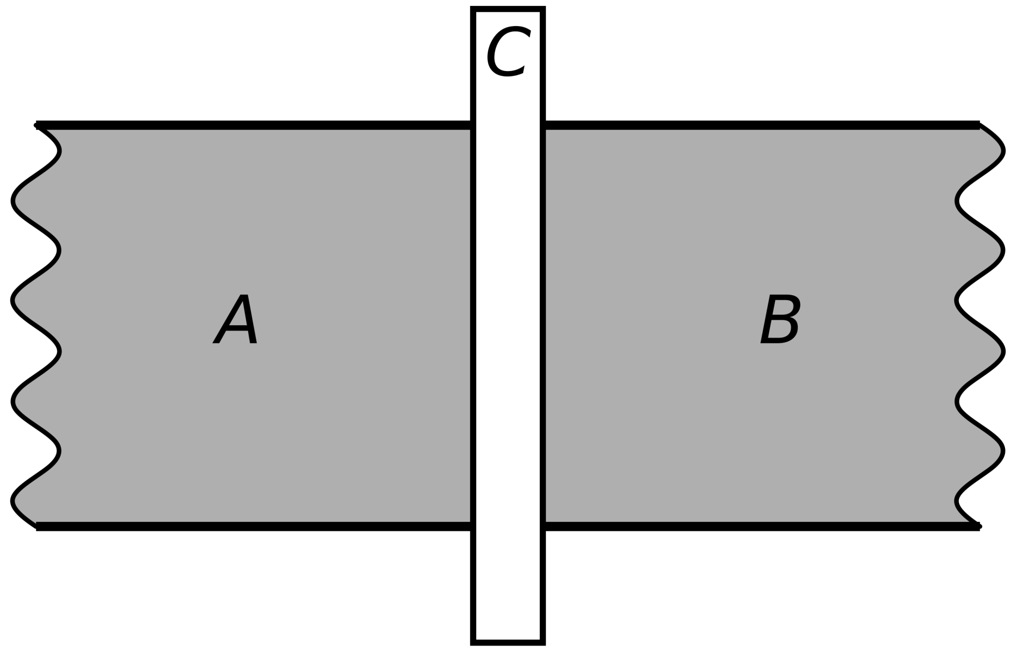
- Many more electrons may be used to make better traps.
- Traps can be made very small.



- Ytterbium atom is ionized — Y^+

Qubits

Superconducting State



- Superconductivity is a quantum phenomenon when many electrons act as a single quantum system (*correlated behavior*).
- Acting “together” electrons avoid “collisions” with the atoms of the material and “flow” without resistance.
- Happens at low temperatures.
- Sandwich of SC-INS-SC form a junction, which acts as a quantum systems with states.

Qubits

In States of EMF

- Polarization
- Field “accuracy” (squeezed states)
- Number states (Fock states)

- Need to review quantum oscillator.

Homework Problems

Interacting Qubits

1. Watch videos:
    1. https://youtu.be/wjTelKoHqUk
    2. https://youtu.be/aV1wL5jsfRU
2. Review harmonic oscillator quantization and related problems.

Quantum Theory

In a Nutshell

II. POSTULATES FOR QUANTUM MECHANICS

In this paper, all state vectors are supposed to be normalized, and mixed states are represented by density operators, i.e., positive operators with unit trace. Let A be an observable with a nondegenerate purely discrete spectrum. Let $\phi_1, \phi_2, \ldots$ be a complete orthonormal sequence of eigenvectors of A and $a_1, a_2, \ldots$ the corresponding eigenvalues; by assumption, all different from each other.

According to the standard formulation of quantum mechanics, on the result of a measurement of the observable A the following postulates are posed:

(A1) *If the system is in the state ψ at the time of measurement, the eigenvalue a_n is obtained as the outcome of measurement with the probability $|\langle\phi_n|\psi\rangle|^2$.*

(A2) *If the outcome of measurement is the eigenvalue a_n, the system is left in the corresponding eigenstate ϕ_n at the time just after measurement.*

The postulate (A1) is called the *statistical formula*, and (A2) the *measurement axiom*. The state change $\psi \mapsto \phi_n$ described by the measurement axiom is called the *state reduction*.

You will understand this paragraph in the end of the course.