This note records the hardware implementation of trapped-ion quantum computers. Specifically, let's use IonQ as an example.

1. Introduction

The basic idea is to use the two states of an outer electron as $|0\rangle$ and $|1\rangle$ of the qubit. The charged ions are confined by time-varying electric field.

Ytterbium-171 (Yb-171) is commonly used for quantum computing. Its electron configuration is $[Xe]4f^{14}6s^2$. After removing one of its electrons, it becomes a positively charged ion. Also, only one of the outer electron remains, which makes it well-suited to act as a qubit.

The $|0\rangle$ and $|1\rangle$ of the qubit are the hyperfine states of the electron. The electron has $1/2$ spin, and the Yb-171 nuclei also has $1/2$ spin. Therefore, due to spin-spin interaction, the electron $S_{1/2}$ states split into $F = 0$ singlet and a $F = 1$ triplet. (F is the total angular momentum, including electron spin, orbital angular momentum, and nucleus spin). In IonQ, $|F = 0,\ m = 0\rangle$ is used as $|0\rangle$ of the qubit, while $|F = 1, m = 0\rangle$ is used as $|1\rangle$.

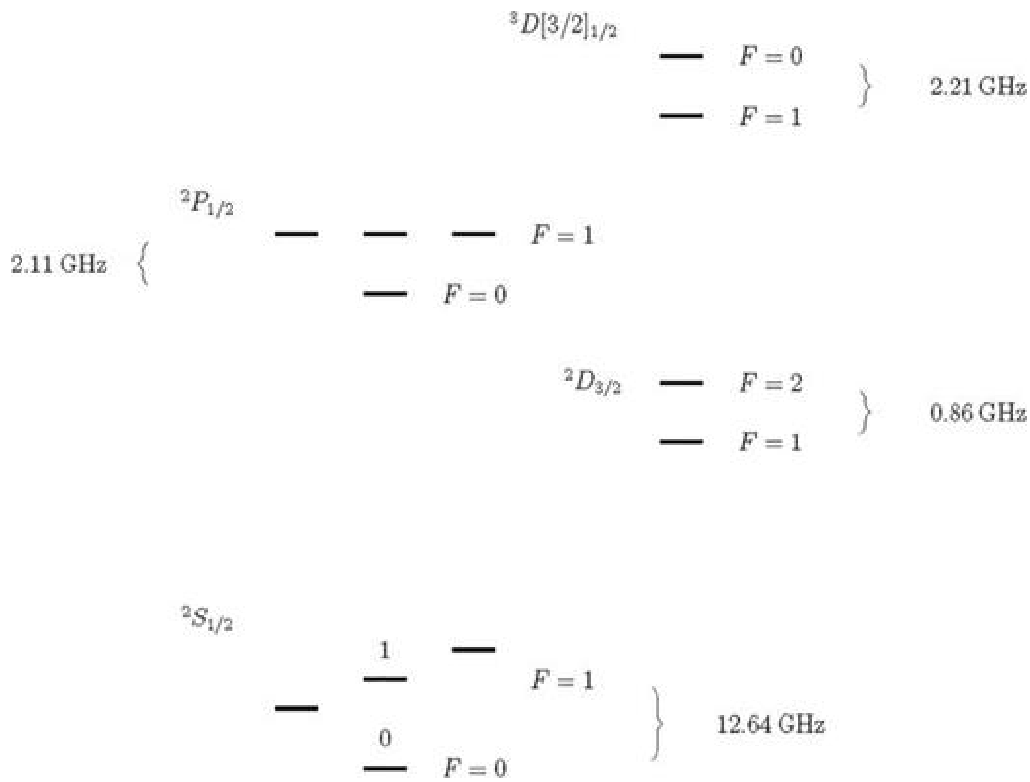


Figure 1: Structure of Yb-171 ion. The energy splitting in the $F = 1$ triplet is probably due to external magnetic field. Picture from https://pubs.aip.org/avs/aqs/article/3/4/044101/123715/Ytterbium-ion-trap-quantum-computing-The-current.

2. Ion trapping

Using laser, people can strip one electron off the Yb atom and turn it into a positively charged ion. Then, using electric field, it can be confined.

It can be shown that static electric potential cannot confine an atom. However, the average effect of a time-varying potential may be a trap. See TODO for an illustration.

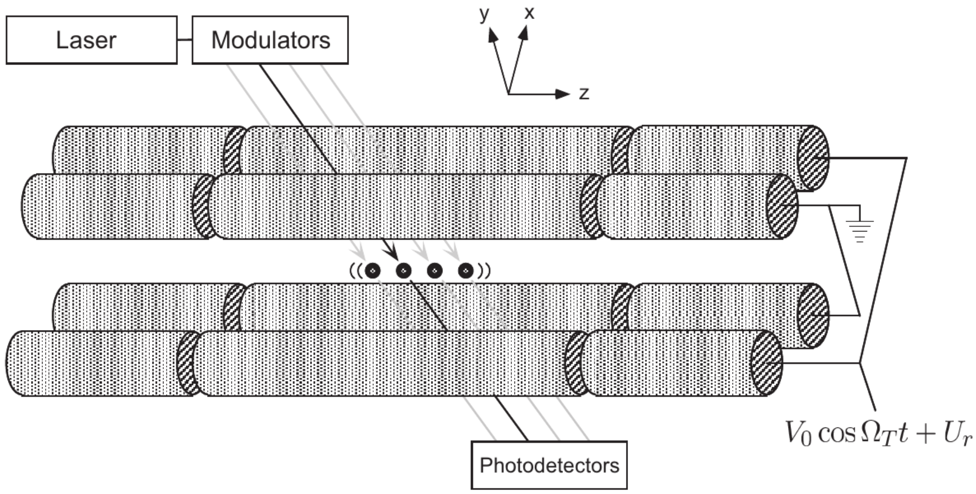


Figure 2: Original design of ion trap. There are 4 cylindrical electrodes. Two are grounded. The other two have time-varying potential. Picture from Nielson and Chuang's book.

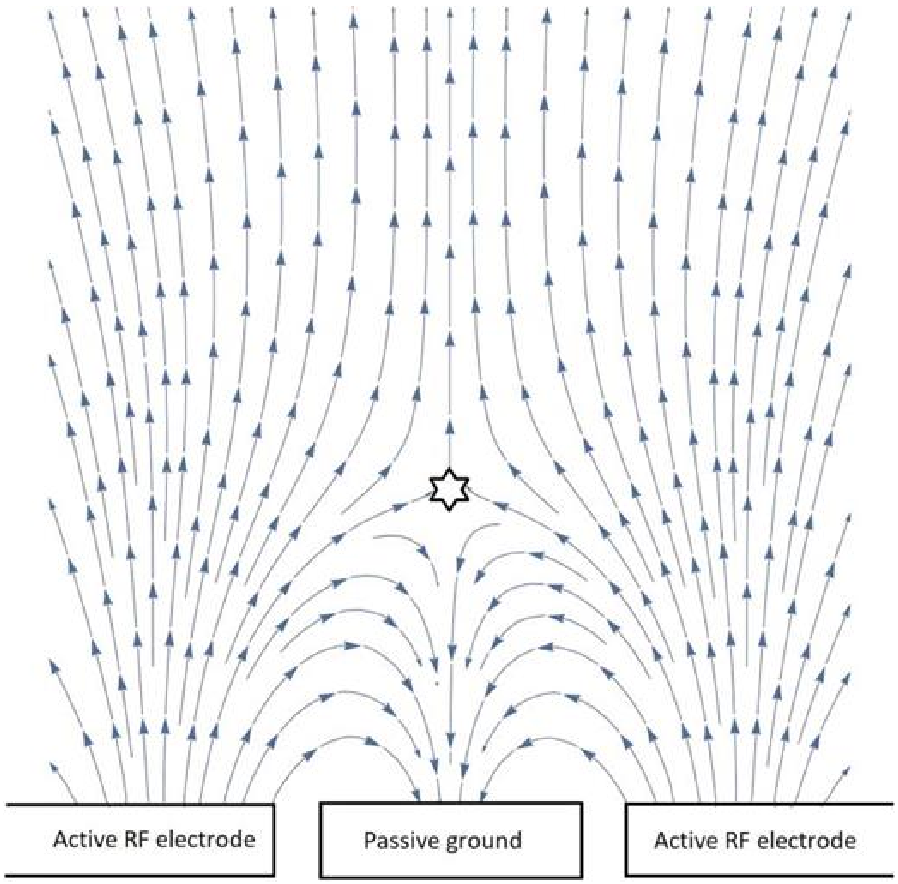


Figure 3: Modern design of the ion trap. The electrodes are integrated on a 2D surface. One advantage of this design is that people already have mature techniques of fabricating things on a silicon surface. Picture from https://pubs.aip.org/avs/aqs/article/3/4/044101/123715/Ytterbium-ion-trap-quantum-computing-The-current

3. Cooling

The ions need to be cooled to a very low temperature. To achieve this, Doppler cooling and resolved sideband cooling is used.

3.1. Doppler Cooling

Use laser with a frequency slightly smaller than the transition frequency of the Yb ion. As the ion moves towards the laser, the laser will be blueshifted, making it more likely to be absorbed. As the ion absorb the photon, it receives a kick opposite to the direction of its velocity. Later, the ion will release a photon in a random direction. Long story short, in average, this whole process (receiving and then releasing a photon) will slow down the movement of the ions.

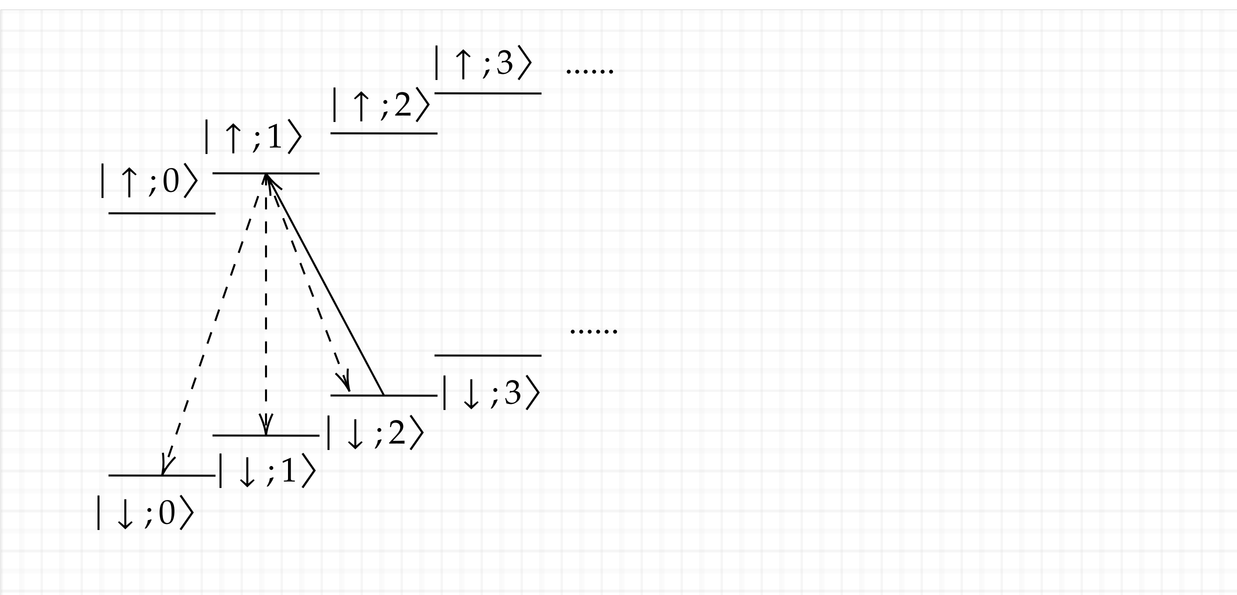
3.2. Resolved sideband cooling

While ions are confined in the traps, they still vibrate. The vibration of the ions can be treated as quantum harmonic oscillators (phonons). Let's use quantum number n to denote the photon state, where n range from 0 to ∞.

Phonon describes the vibrational motional degrees of freedom of the ions. In the mean time, we also need to pay attention to the internal degrees of freedom of the ion, namely the electron state. As mentioned in previous sections, we use the electron state as the qubit state. While we used the notation $|0\rangle$ and $|1\rangle$ in the previous sections, let's use the notation $|\downarrow\rangle$ and $|\uparrow\rangle$ to avoid confusion with the phonon state.

A quantum state can be characterized by something like $|\downarrow;0\rangle$ or $|\uparrow;2\rangle$. Take $|\uparrow;2\rangle$ for example; it means the electron is in the $|\uparrow\rangle$ state while the phonon is in the $n=2$ state.

Let's use $|\downarrow;2\rangle$ to illustrate the process of sideband cooling. By tuning the laser, we can stimulate the transition from $|\downarrow;2\rangle$ to $|\uparrow;1\rangle$. Then, $|\uparrow;1\rangle$ may decay into $|\downarrow;0\rangle$, $|\downarrow;1\rangle$, or $|\downarrow;2\rangle$. In the first two cases, the system goes to a lower phonon state; thus, cooling is achieved.

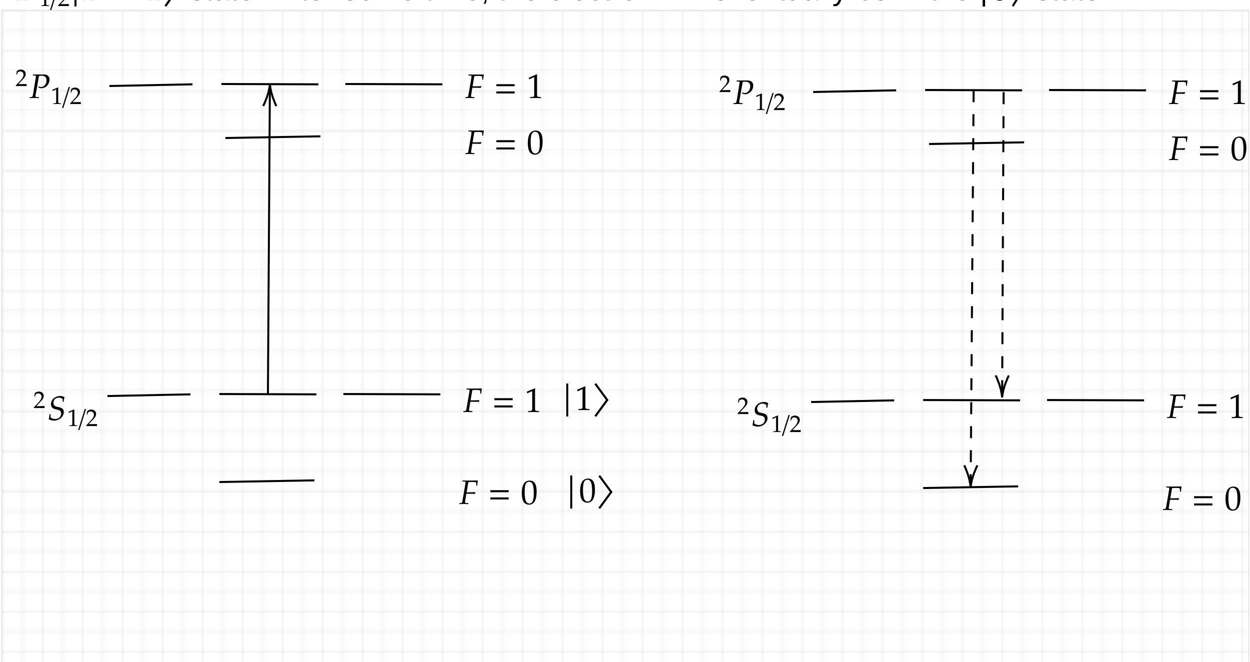


This is the process described by Nielson and Chuang's book. I have not yet confirmed whether this is the exact implementation used by IonQ or Honeywell.

4. Initialization

The purpose of initialization is to prepare the qubit in the $|0\rangle$ state. To do this, optical pumping is used.

A simplified version of optical pumping is shown as follows. Using a laser to stimulate the transition from $|1\rangle$ to ${}^2P_{1/2}|F=1\rangle$. Only $|1\rangle$ will be excited, not $|0\rangle$. Once it is in ${}^2P_{1/2}|F=1\rangle$, it has a certain probability of decaying into the $|0\rangle$ state. It may also decay into $|1\rangle$ state[1]; however, when this happens, the laser can excite $|1\rangle$ again into ${}^2P_{1/2}|F=1\rangle$ state. After some time, the electron will eventually be in the $|0\rangle$ state.

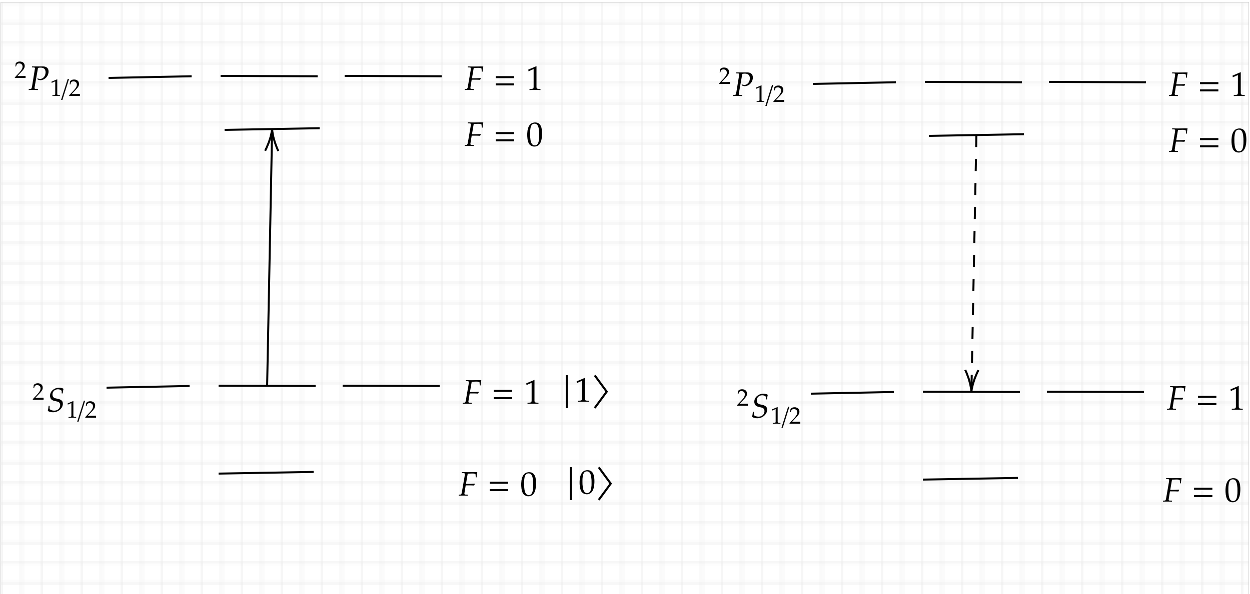


5. Measurement

After some computation, the final step is to measure the state that the qubits are in. To do this, we use the laser at a certain frequency to pump the $|1\rangle$ to ${}^2P_{1/2}|F=0\rangle$ state. Then, ${}^2P_{1/2}|F=0\rangle$ will decay, emitting a photon. Moreover, due to symmetry, the decay from ${}^2P_{1/2}|F=0\rangle$ to $|0\rangle$ is highly suppressed. When ${}^2P_{1/2}|F=0\rangle$ decays into $|1\rangle$, the $|1\rangle$ state

[1] It may also decay to the metastable state ${}^2D_{3/2}$. However, people can use laser at another frequency to excite ${}^2D_{3/2}$ to ${}^3D[3/2]_{1/2}$, which can quickly decay into $|1\rangle$.

can be excited by the laser again into ${}^2P_{1/2}|F=0\rangle$, which will decay into $|1\rangle$ again[2]. This is called the "cyclic transition." As the state goes from ${}^2P_{1/2}|F=0\rangle$ and $|1\rangle$ again and again, it will emit many photons. On the other hand, $|0\rangle$ will almost not emit photons.



That is to say, during the final measurement, the $|1\rangle$ qubit will glow, while the $|0\rangle$ qubit will not glow. One can use this to read the state.

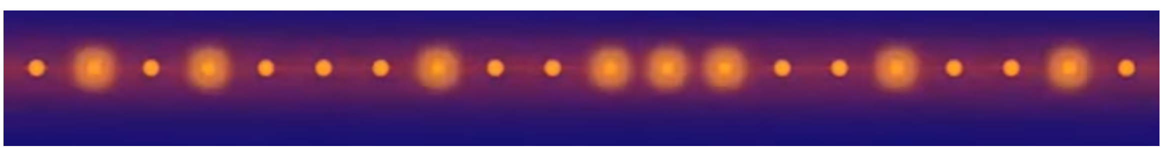


Figure 4: Measurement of the state.

6. Implementation of gates

TODO

7. Resources

- Chapter 7 of *Quantum Computing and Quantum Information* by Nielson and Chuang. More specifically, section 7.6 is about ion-trap computer.

[2] To be more exact, it may also decay into ${}^2D_{3/2}$. It can be pumped into ${}^3D[3/2]_{1/2}|F=0\rangle$, which can decay into $|1\rangle$.

- Video from IonQ: https://ionq.com/resources/anthology/lecture-series-introduction-to-quantum-computers
- A good review: https://pubs.aip.org/avs/aqs/article/3/4/044101/123715/Ytterbium-ion-trap-quantum-computing-The-current
- A paper from IonQ: https://www.nature.com/articles/s41467-019-13534-2