ECE 128: Trapped Ion Qubits

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1 Introduction

Computing using the underlying laws of quantum mechanics has received lots of attention over the past few decades, because it is believed that quantum computers are capable of performing computations in seconds that would take classical computers many years. Just as classical computing is built upon fundamental "bits" of information that can be altered, quantum computers rely on what we call "qubits". And like a classical computer, these qubits are two-state systems, which we often denote with $|0\rangle$ and $|1\rangle$. However, unlike classical computers, because we represent this information using a quantum-mechanical system, each qubit is capable of taking on super-positions of information represented by $\alpha |0\rangle + \beta |1\rangle$. Although the laws of quantum mechanics only allow us to measure the qubit and obtain $|0\rangle$ with probability α^2 or $|1\rangle$ with probability β^2, many algorithms find ways to cleverly have these qubits interact with each-other such that the user will measure some useful result with high probability.

There are many different competing fields of study for implementing qubits, but we will focus on just one such implementation, trapped ion qubits, and discuss their unique properties.

2 Physical Design and Mechanics

Before we jump into the implementation details, note that there are many different ways to trap, cool, and operate on ions. We will only cover the most common and simpler methods. A thorough survey of almost all methods is provided by [2]. All information in this section is provided by [2] [6] [9].

2.1 Trapping

By Earnshaw's theorem, it is not possible to trap a charged particle with static electric forces. As such, trapping ions will require an oscillating field. In the X and Y direction, a potential such as that in figure 2 is generated, and is rapidly rotated at a radio frequency. Although this causes an overall potential of zero, it does cause an oscillating force on any charged particle. This results in a kinetic energy gain proportional to the distance of the ion from the center of the trap. As such, the ion stays trapped in the center because it is the position of minimum energy. In the Z direction, typically two static electrodes are placed on both ends of the axis to confine the ions. Additionally, when more than one ion is in the trap, they will repel each-other and form a line along this Z axis. This is illustrated by figure 3.

2.2 Cooling

As with most quantum mechanical systems, trapped ions must be cooled such that there is not enough available energy for our states to be randomly changed. In the case of trapped ions, they must be cooled extremely to about a micro-Kelvin. Luckily, this is possible through laser-cooling methods.

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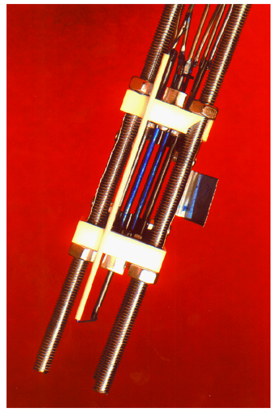

Figure 1: A real ion trap. The blue bars are the current-carrying conductors shown in figure 3, and the rest is structural support. (Source: [9])

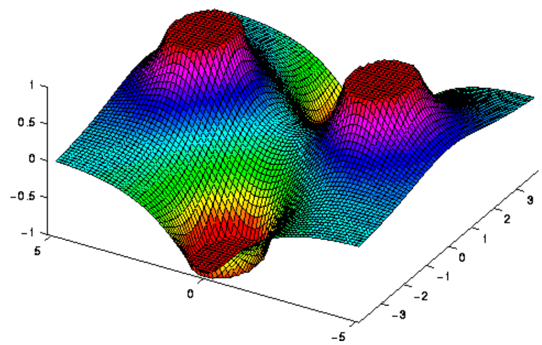

Figure 2: Potential generated by the ion trap. This saddle potential is rotated around it's center at a radio frequency. (Source: [9])

Typically, a method called Doppler Cooling is applied first. Doppler cooling relies on two principles: resonance and the Doppler effect. Because of the quantized energies of the ion, it will only interact with light at very specific frequencies, which we call resonant frequencies. And the Doppler effect is where the frequency of a wave is shifted upwards if you are moving towards it, and downward if you're moving away from it (just like you experience regularly with car sirens). As such, if we blast the ion with light that is just below one of it's resonant frequencies, it will only absorb the light if the ion is moving towards it. Because the photon and ion are moving at opposite directions at this moment in time, this will cause the ion to slow down and loose kinetic energy.

However, note that Doppler cooling has a fundamental limit, and it won't achieve the temperatures typically required. As such, a different method called Sideband Cooling must be applied at this point. This method utilizes the fact that the ion has quantized atomic and vibrational energies, and pulses the ion with specific photons that cause transitions to states with higher atomic energy, but lower vibrational energies. After a certain period of time the ion will spontaneously decay into a lower atomic energy state with vibrational energy equal to or lesser than the original state. Then the process can be repeated over and over again until the ion has low enough vibrational energy. This process is illustrated by figure 4.

2.3 Operations

Now that we have trapped and cooled the ions, they have well-defined quantized states which we can control precisely. Specifically, we will operate on the spin of each ion. Depending on the ion, there are a variety of different specific spin states we can choose to represent our binary system, but they all operate by shining carefully selected frequency lasers on specific ions for controlled amounts of time such that the spin state of the ion is affected in the desired manner.

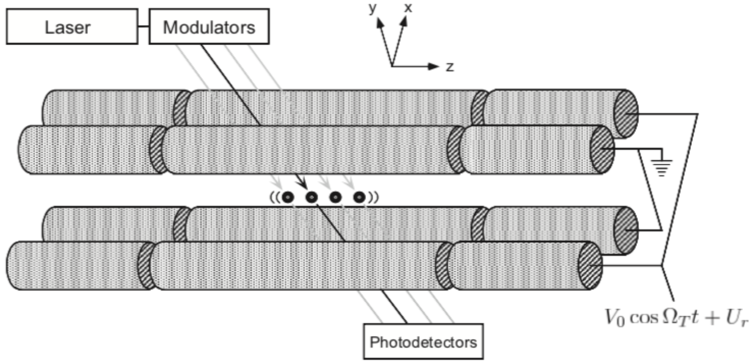

Figure 3: Diagram of the trap structure. A potential is oscillated via current from the rods, and static electrodes are placed on either end of the Z axis. The ions then become aligned in a line along the Z axis. (Source: [6])

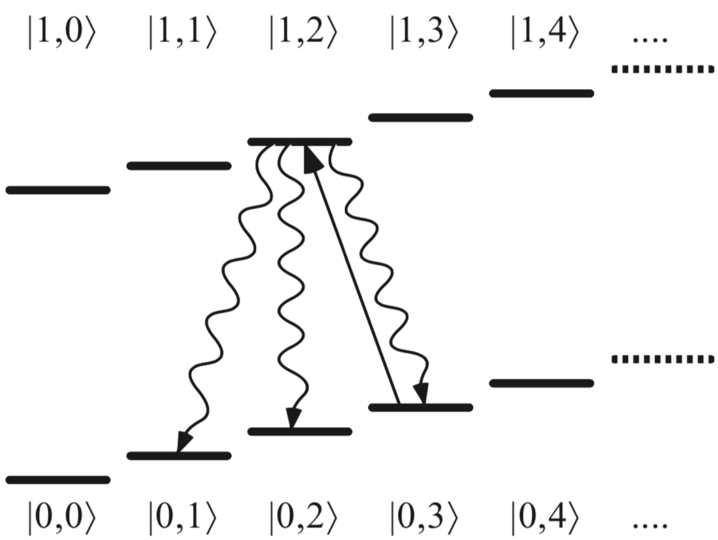

Figure 4: Illustration of the energy transitions of sideband cooling. The energy state is represented by $|n, m\rangle$, where n is the electronic energy of the ion and m is the phonon (vibrational) energy of the ion. The ion is excited such that it will gain electronic but loose vibrational energy. It will then decay from the excited electronic state into a state with vibrational energy equal to or lesser than the original state. This process is repeated until the ion is in a near-zero state. (Source: [6])

However, in order to do useful computation, there must be a mechanism for these ions to share information selectively. For this, we use the shared vibrational state of the system. Note that each ion is vibrating, and in the Z-axis, their vibrations affect how strongly they repel each other ion in the trap. Just like spin, this energy is also quantized, where each step of energy is referred to as a "phonon". As such, the complete system can be described by the individual spin states of each ion, and the shared "phonon" state of the entire string of ions. Furthermore, we can modify the energy of each ion in relation to spin via Zeeman splitting, which lowers the energy in one spin direction and raises it in the other. As such, just as we did before with the single ions, we can choose our laser frequencies such that an ion will only raise the phonon state of the system if it's in a specific spin state. We can then operate on another ion in a way such that it will only be affected if the system is in an excited phonon state, and finally we'll apply a third pulse to reverse the effect on the initial ion and return the whole system to a relaxed phonon state. As such, this provides a mechanism for altering the state of a single ion dependent upon the state of another ion.

2.4 Measurement

Measurement of each ion's spin state is similarly done through this concept of resonance. A frequency of laser is chosen such that if the ion is in one state, it won't interact with the laser, but if it is in the other, it will interact and start repeatedly emitting photons. These photons are detected and used to determine the state of the ion. (This isn't a perfect process, so some statistics must be run on the measured results.)

3 Tradeoffs and Research

The DiVincenzo criteria are five commonly used criteria for evaluating different implementations of qubits [3]. These criteria include (1) a system containing well-defined two-level systems isolated from the external environment, (2) the ability to initalize the system into a well-defined and deterministic initial state, (3) system decoherence times much longer than the time of a single operation, (4) a set of universal operations that can be applied to each qubit or pairs of qubits, and (5) the ability to read out the qubit state with high accuracy. We will touch upon some of these points in relation to trapped ions here.

3.1 Pros

Firstly, trapped ions have very long coherence times. This means that they are capable of maintaining their internal quantum state for long periods of time, before the system is corrupted by random noise from outside forces. Often this allows for roughly 10^6 operations to be applied before the system falls apart, whereas other types of qubits only get around 1000 [2].

Additionally, generally operations and measurements can be performed with very high "fidelity". In practice fidelity has a precise mathematical definition, but at a high level it essentially means the "closeness" of a quantum operation to the theoretically perfect operation. For single-qubit operations, fidelities of up to 99.9999% have been achieved [4], and for two-qubit operations 99.9% has been achieved [1]. Similar levels have been achieved for measurement operations. Essentially the bottom line is that trapped ions allow us to implement qubit operations that are very precise and introduce very little noise.

3.2 Cons

However, the overall time of trapped ion operations can be slow. The fastest-implemented gates are in the micro-time scale [8], whereas other qubit technologies can implement gates in the nano-time scale [2]. This could be problematic for general speed and supremacy in general, as this means that currently classical computers and other qubits are capable of performing operations roughly 1000 times faster than trapped ions.

Furthermore, as more and more ions enter a trap, their shared vibrational state becomes more complex and much harder to control. So far only a few hundred ions have been demonstrated to be trapped with any sort of meaningful control [7]. This is roughly on par with the numbers seen for other qubit implementations, but never the less raising this capacity will be key if trapped ions are to become the front-runner technology for qubits.

4 Conclusion

Although trapped ions still have a ways to go before becoming viable for large scale quantum computations, they are a promising technology that many researchers are excited about. (Including researchers at UCLA [5].) Irregardless of whether trapped ions end up being the "winning" qubit technology, it is exciting to see computational devices being implemented using the fundamental nature of quantum mechanics.

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