The Ion Trap Architecture

Atul Singh Arora
Indian Institute of Science, Education and Research, Mohali

Prerequisites

Basic knowledge of physical concepts. A rough idea about qubits will be helpful; infact knowing that they reside in the space spanned by the states of any two level quantum system is sufficient.

Confining the ions

If you've read Griffiths with any love, you would know that Earnshaw's theorem prohibits creation of a minima using electrostatic potential. (now don't ask which Griffiths) Thus you can't trap ions conventionally.

1. Production of ions: It involves heating calcium in high vacuum, then firing of high speed electrons on its vapour. Consequently some resulting ions fall inside the trap and get stuck.

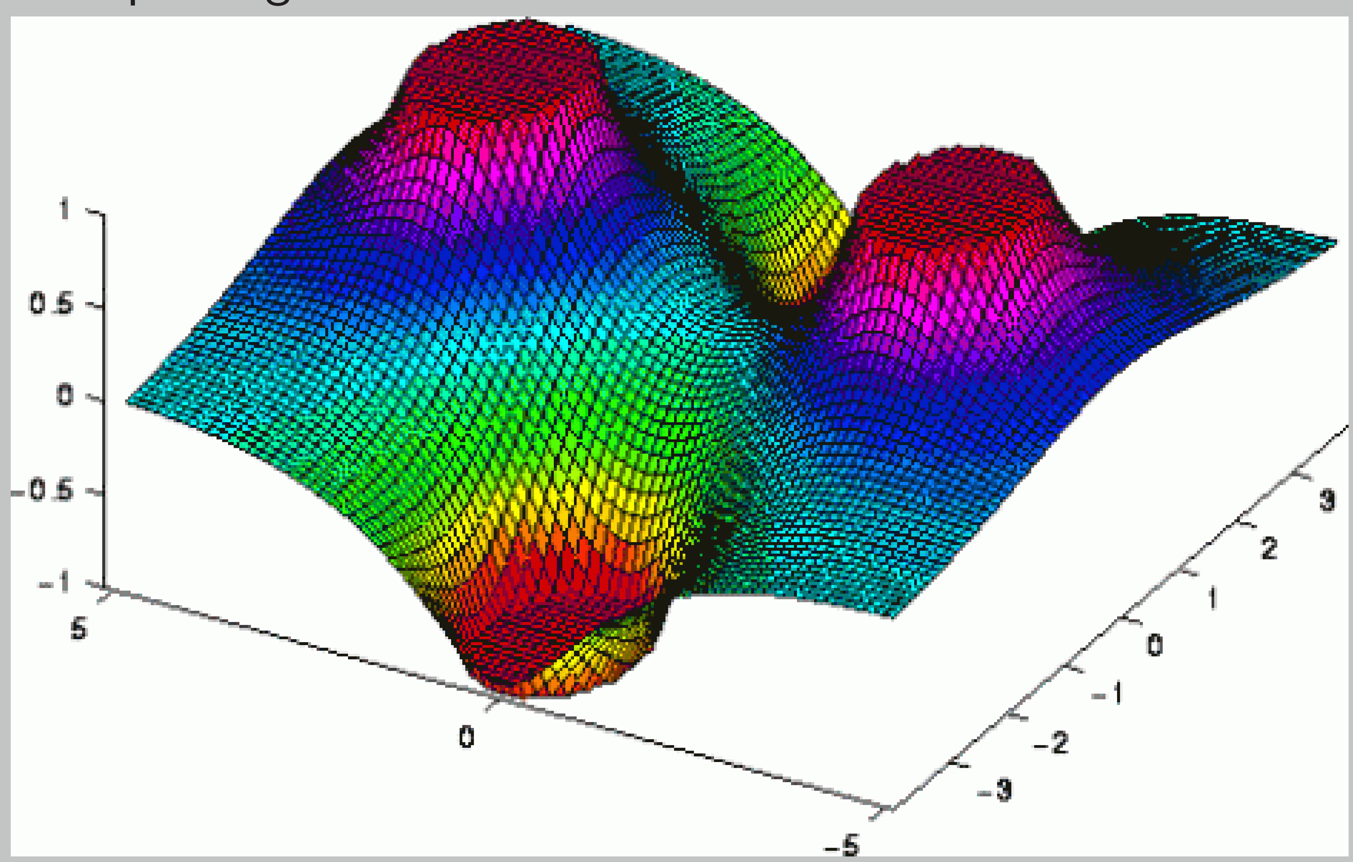

Figure 1: Potential in space [1]

2. Trap structure: The idea is simple. Since you can't create a potential minima anywhere inside the boundary, you can't trap an ion. But you see the saddle point. (In the figure, the X and Y axis represent physical space and Z is the potential.) You change the potential rapidly so that the 'U' minima oscillates between being along the X and Y axis (say). (The flat circular part is the electrode's surface) This way, on an average, the saddle point sees zero average potential. If the ion was anywhere other than this point, it'll experiences oscillating forces. This effectively results in confinement of the atom. Q1. How does an oscillating force ensure confinement? Q2. What frequencies are most effective and why? Q3. How do you know only 1 ion is trapped?
The next immediate question is what restricts the ion in the spatial Z axis. Well, we just pin the ion using a positive potential (by putting two electrodes along the said axis.)

Ion Control

1. Let's say that it is obvious we need the kinetic energy of the ions to be much smaller than that it picks up upon interaction with a laser (or upon emitting a single photon). This number turns up to be about 32 K Hertz (Energy/Plank's constant). The corresponding temperature to have thermal energy lower than this, turns out to be a few micro kelvins!
This is a serious challenge.
2. How do you circumvent this? Laser cooling. Oxymoron you might say but the following little thought is illuminating. If you hit an atom with light with opposite momentum, the atom slows down as the light is bounced back. So if you could get the ions to absorb light preferentially going opposite in direction to their momentum, you've found a ground-breaking method of cooling!
And yes, somebody thought of that too. You use something you're already familiar with, resonance and Doppler.
   - 2.1 Resonance: This is the (in)famous phenomenon where an innocent and mild vibration can cause an otherwise stable system to have almost devastating effects, given the frequency is just right. A similar effect is observed with atoms and with remarkable sensitivity to the precision of the frequency. Light is absorbed by the atom only when the frequency is just right.
   - 2.2 Doppler: This is as you're well aware, the principle behind the sound effect you get when a car zooms past. We exploit this and set the frequency of the laser just below the resonant frequency. This does it then.

   NOTE: This is not at all this simple. Q1. If the photon is absorbed, it must be emitted giving the atom a push again! What's wrong? Q2. What about line broadening etc.?

Lets Get Quantum Computing!

1. Ions as qubits: Every ion is one qubit. (In these experiments, we deal with 3-4 qubits.) To process information on these qubits, we need to be able to
   - 1.1 Initialize each qubit individually: This is done by shining light on it since they're physically separated enough and as the laser light can be focussed to distances much smaller than that between adjacent ions.
   - 1.2 Perform C-NOT between any pair of qubits (this is explained below)
2. Ions as tiny magnets: The ion can be thought of as a tiny magnet. We can code point up to be state zero and pointing down to be state one. So far it is the same as classical information storage. However, quantum mechanically, the magnet can 'point in other directions'. This is perhaps best understood as some sort of angle the magnet is at with the z-axis (the direction of an external magnetic field). However this is not a conventional angle. When you make a measurement, you'll get state zero or one with probabilities proportional to the projection along the relavent axis. (Its very handwaving but gets the idea across. Do not extend this picture too much without proper formalism) This is then as though the atom is in a superposition of zero and one states and you get one of them upon measurement.
This is exploited for information processing. How we probe the ion (qubit) is by using light. Its interaction with the ion can be understood as
   - 2.1 Classically; it changes the orientation of magnet as light has (is?) electromagnetic fields. The magnet has again, a frequency dependent response and the twist magnitude can be controlled by the duration of the pulse.
   - 2.2 Quantum(ly?); the laser mixes the zero and one states. The frequency and duration can be used to calculate precisely the mix created, enabling us to create the desired superpositions.
3. The computer; ion string: Lets quickly review what C-NOT does. You flip the target iff the control is one. So, in our setup, the problem is to flip the state of ion B, iff ion A is in (say) state one (magnet pointing down). Note that we can't quite use the magnetic field of the ions themselves for, one they're too small and two, ion A and B may not be adjacent. Seems like a deal breaker. But these people (the real scientists) are clever. What they do goes something like this
   - 3.1 A laser light is shone on ion A such that its absorbed only in state one.
     - 3.1.1 An ion with magnet down (state one), resonates at a slightly different frequency compared to one with magnet up. Thus it is possible.
     - 3.1.2 The ion is given a little more energy (higher frequency). Why, well because the ions are able to rattle to and fro about their position in the trap. However this is in a plane perpendicular to the line of ions (the string). A vibration in this plane is transmitted to all the ions, because of their charge, viz. interaction by coulombic forces. Now as we are dealing with single ions, it so happens that this whole string vibration is also quantized! Thus we give this exact energy extra in the laser beam.
   - 3.2 With the entire string vibrating, conditioned by if ion A is in state one, we shine a light on ion B with a little less energy. If the string is already vibrating, this would be sufficient to interact with B. This causes ion B to flip its state iff ion A is in state one.
   - 3.3 Finally, a beam of light is shone on ion A again to kill the vibration of the string.

Conclusion

And that's how its done! Ladies and Gentlemen, we have the ion trap quantum computer architecture.
Ofcourse, we've made far too many assumptions but the rough idea should be clear now. In the accompanying report, we address some of the remarks/questions you might have (such as whaat!, how do you do that? etc.)

References

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