An Investigation into the Fundamentals of Quantum Mechanics Using Quantum Computing Simulations

A capstone project by

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April 21, 2014

Abstract

The aim of the capstone project is to analyze how quantum mechanical principles are utilized through quantum computing. The project first tried to understand the basics of quantum mechanics through study of textbooks and through independent research. This was necessary to understand how the principles would work in quantum computing. The basic functioning of quantum computers was then explored and compared to conventional computers. Once that analogous nature was made apparent, the focus was switched to look at quantum computer simulations. This avenue was chosen because actually realizing quantum computing is a task that would take more than a year to complete and would be very expensive. Simulation provides great grounds to understand how something works. The simulation qsims was chosen to analyze and the goal of the project was then to understand the physics behind the simulation. The simulation qsims is a representation of the quantum NOT gate. The physical layout for how a quantum computer operates was then researched as well as the physics behind what the simulation was doing. qsims is based on the hyperfine splitting of Cesium-133 in an addressable optical lattice and the transition between these levels in the optical lattice make it possible to represent the flipping of an atom's state as a NOT gate operation. With the knowledge gained from researching the principles of quantum mechanics, the physical layout of a quantum computer and the physics behind how a quantum computer functions, the simulation qsims is aptly understood and explained.

Introduction

Since their inception, computers have continually been improving. This has primarily taken place through advances in size and speed. A computer that used to fill an entire room now

fits in a pocket ("Timeline of Computer History: Computers Entry," n.d.). Since the transistor, a fundamental building block of the computer, was first invented in 1947 at Bell Laboratories it has decreased in size and as of February 2014, the fastest transistor operated at 798 GHz ("1947 – Invention of the Point-Contact Transistor," n.d.; Robinson, 2014, para. 1). This means that the transistor can have 798 billion operations in a single second (Lander, n.d.). Yet, even with so much progress, there are fundamental limits to how fast and how small computers can get. Because a transistor is a physical, electronic object, it takes time to operate and takes up physical space. If a computer could use certain principles of quantum mechanics in the right way, then the computer would not bound by these limitations. A computer that achieves this is called a quantum computer. This quantum computer is essentially an extremely small and extremely fast conventional computer, yet because it utilizes the physics of quantum mechanics it is not bound to the fundamental limits that a computer operating under the rules of classical physics is bound to. Quantum computers today are still very difficult and expensive to create, but operations of a quantum computer can be studied through simulations, which are much more easily obtainable. The goal of this capstone is to take a simulation of a basic function of a quantum computer and understand how it operates and the physics behind it.

In the conventional, non-quantum computer, information is represented in bits that are stored in memory locations. A bit has a binary state, meaning that it can be in a state of either 0 or 1 (Nielsen & Chuang, 2010, Quantum bits section, para. 3). A logic gate manipulates the bits to convert them from one form to another (Nielsen & Chuang, 2010, Single qubit section, para. 1). Physically, a gate is a transistor or a combination of several resistors arranged in different ways. One example is the inverter, or NOT gate, which is shown in Figure 1(Booyabazooka, 2006).

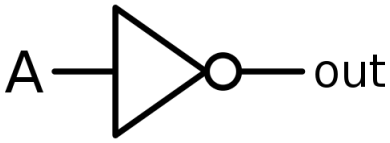

Figure 1 – Traditional Symbol of the NOT Gate

The NOT gate is a single bit gate because it only manipulates a single bit, or in other words, only one state of a bit goes in and only one comes out. The function of the NOT gate is that it flips the state to the other possible state of the bit, which is shown in Table 1 (Logic gate, 2014, Symbols section, under the Truth table column and NOT type row). If the input is the state 0, then the output will be not 0, or 1 (Nielsen & Chuang, 2010, Single qubit section, para. 1). Likewise, if the input is 1, then the output will be not 1, or 0 (Nielsen & Chuang, 2010, Single qubit section, para. 1). Circuits are compilations of multiple gates with wires connecting them and from these circuits the entire mainframe of a computer can be created (Nielsen & Chuang, 2010, Single qubit section, para. 1).

INPUT	OUTPUT
A	NOT A
0	1
1	0

Table 1 -Truth Table of the NOT Gate

The basic structure of a quantum computer is analogous to a conventional computer (Nielsen & Chuang, 2010, Quantum computation section, para. 1). Quantum bits, or qubits, represent information in the same way as conventional bits do (Nielsen & Chuang, 2010, Quantum bits section, para. 1). The difference with a quantum computer is that the states of the qubit are represented by the physical states of an atom. So if an atom were in its ground state, it would represent the 0 state and if the atom were excited into a higher energy state, then it would represent the 1 state. These qubits have the notation of |0> and |1> (Nielsen & Chuang, 2010, Quantum bits section, para. 3). The most interesting and the most useful thing about qubits is that they can be in states other than |0> or |1>, which are linear combinations of states, often called superpositions (Nielsen & Chuang, 2010, Quantum bits section, para. 3). This is where the advantage of quantum computing lies because with this superposition of states, both |0> and |1> can be simultaneously realized. This means that if certain combinations of qubits represented

outcomes to a particular problem that had many solutions, then all the solutions would be simultaneously realized as well. This would be exponentially faster than the conventional method of finding each possible outcome separately. Using this quantum mechanical principle is unique to quantum computing and sets it apart from the conventional computer.

Although this method is the definite advantage of quantum computing, the basic functions of a quantum computer must be understood. The focus of this project is on such a basic function. The simulation being analyzed, called *qsims: Quantum Simulation Software* or just qsims, is a simulation of a quantum NOT gate (Travis Beals, n.d.). The project analyzes the physical setup that a quantum gate, such as that simulated by qsims, would take place in as well as the general physics behind what the simulation displays.

Methods

The methods undertaken in this project were divided up into different sections, with each section involving a different purpose. There were three major sections in this project and they each built on each other. The first was research of the fundamentals of quantum mechanics, the second was research of quantum computers, and the third and final section was research of the specific simulation. The final component cannot come about without the support of the first two.

The first section was necessary to form a strong foundation to build on. At the start of this project I had only taken a course on modern physics and not one on quantum mechanics. With this almost complete lack of knowledge about the principles of quantum mechanics, it was necessary to undertake the time and effort to study and research these principles, because only then could the full implications of quantum computing be realized. As such, the method that I took was to spend 3 dedicated hours a week studying the *Introduction of the Quantum Theory* by

David Park (1992). On average I was able to cover somewhere between 6 and 10 pages per week. The goal was not to rush and just get through the material, but to take the time to understand what was going on. Detailed notes were taken and questions that needed clarification were noted. I would then take these questions to my advisor, Dr. Edward Brash, and we would talk through them. It was useful to get the personal time trying to understand the material combined with the live time asking questions with Dr. Brash. This provided for a dynamic learning environment to make sure I understood the material. During the second semester of this project, I enrolled in a quantum mechanics course and took it alongside doing research for this project. The class covered all the points I needed to know for this project in a more rigorous fashion than personal study and thus was a great addition and aided in my understanding of the physics portion of the project.

The second section of studying quantum computers took place throughout the project in small portions. This mostly consisted of researching quantum computers online to gain a better idea of what they were and general knowledge that would fill in the gaps of my understanding. Through searches on the topic, I would find news articles and related scientific articles and read them. When I came across things I did not understand, I would research them. I also did receive some feedback from Dr. Brash to refine some of the final points that I had made to correct some erroneous ideas I had of the physics behind it all. It should be noted that this section could not take place with great effectiveness until some of the key principles of the first section were found. The third section followed suit and built upon the two previous sections.

The third section had to do with choosing a simulation, installing it, running it and then evaluating what it did and the physics behind it. There are several simulations of quantum systems available for free online and after Dr. Brash did a quick look at some of the ones

available, *qsims: Quantum Simulation Software* was decided upon. qsims was developed by Travis Beals (n.d.) as a tool for studying quantum computing and is available as Free Software from http://qsims.sourceforge.net/index.html. Once a program was chosen, the next task was to install it. Because I was not familiar with the process of installing programs manually, this took some time to complete. Before the actual installation, specific dependencies, which for this were just libraries and packages, had to be installed as well (Beals, n.d., Installation section, Dependencies subsection). After going through the process and with some advice from Dr. Brash on a program that would help me install these dependencies, it was successfully installed.

Next was to create a simulation and this was done through a tutorial section that was provided on the website (Beals, n.d., Tutorial section). Running the program was even more difficult because first, I am not familiar with Mac terminal prompts, and secondly the code had not been developed since 2005, so many of the commands that were used in the tutorial were outdated (Beals, n.d.). Thus I kept running into issues and had to do a good deal of research about the programs that were supposed to execute the commands and what analogous new commands were needed to get the same results as were intended at first. I was finally able to figure it out along with some guidance from Dr. Brash. The idea was not to be purely computational with a great deal of involved programming for this project, but to focus on the physics of the simulation. The simulation I had created through the tutorial provided was a simple simulation in the realm of quantum computing, yet it still involved complicated physical principles and was a worthy candidate to focus on. Thus it was decided that this would be the single simulation that the project would utilize.

After the simulation was successfully completed, the physics behind it was analyzed. The outcome of the simulation was very simple and not very clear as to the internal workings of the

program. The tutorial gave a brief overview of what was happening and from this the research was conducted (Beals, n.d., Tutorial section, Simulation details subsection). I spent time looking up terms in textbooks and articles online as well as general definitions. Dr. Brash was also a very great resource to help me understand the physics behind it. Much of what he taught me provided the right insight into how the simulation worked and he pointed me in the right direction to find out the details myself. From this research, the general function of the simulation was understood, which was the goal of the project. Also, since the simulation was freely available online, no money was needed for this project.

Layout and Theory

It is useful to understand what the physical layout of a quantum computer might be in order to understand how the principles of quantum mechanics could be applied in such an environment. qsims is based on a specific type of quantum computer setup that traps atoms in an addressable optical lattice (Beals, n.d., Tutorial section, para. 1). Now an addressable optical lattice is a *lattice* structure that is created by interfering lasers, hence *optical*, where each atom that is trapped is able to be individually manipulated or *addressed*. For the setup, one possible way of creating the lattice is by four rotating laser beams that are refracted through a lens and interfere with one another (Direct quantum simulation, n.d., Figure 1 caption). A CO_2 laser, with a wavelength of 10.6 μm, can be used and this will create a lattice with a spacing of 5.3 μm between each atom

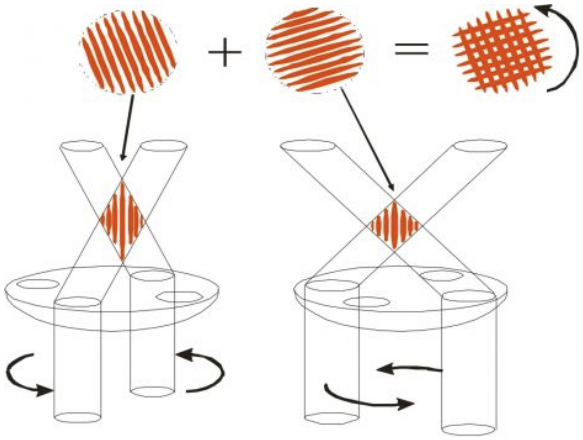

Figure 2: 2D Rotating Lattice

(Beals, 2005, Creating the lattice slide). In Figure 2, the four beams are split into two for clarity and as is shown, the resulting interference pattern from the two sets of beams is a lattice formation (Direct quantum simulation, n.d., Figure 1 caption). The rotation of the beams simulates the effect of an applied magnetic field, which will prove useful later on (Direct quantum simulation, n.d., A rotating optical lattice section, para. 2). This is one method to successfully form an addressable optical lattice, but the most important thing to realize is that each crossing point of the interference pattern of the lattice is a physical location where a neutral atom is trapped. In each of these locations a potential well forms and altogether this periodic potential has the shape of an egg-box, as shown in Figure 3 (Addressable optical lattices, n.d., para. 1). Each one of these wells, were the interference patterns intersect, is where an individual atom resides and in quantum computing this serves as a memory location for information through qubits.

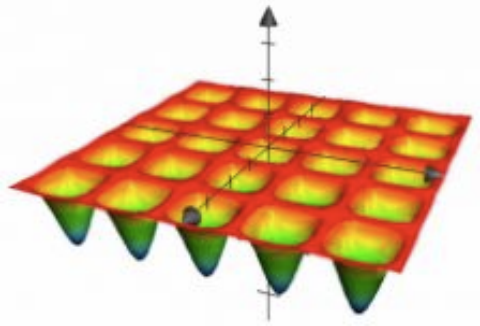

Figure 3: 2D Periodic Potential

Once the lattice is formed, the atoms have to be loaded into the lattice, their states changed, and their locations shifted to have a proper setup for a quantum computer to function. The first step is to load the atoms from a magneto-optic trap (MOT) (Beals, 2005, Initialization & preparation (I) slide). A MOT is a device that optically cools and traps neutral atoms and renders atoms with slow velocities, low kinetic energies, greatly reduced collisional perturbation, and long interaction time with the ability to store a high density of and a large number of atoms (Kowalski et al., 2010, pp. 115). All of these characteristics allow for highly precise experiments to take place (Kowalski et al., 2010, pp. 115). The MOT utilizes three pairs of lasers to laser cool the atoms, which will be explained shortly, and to trap them in an optical molasses, which will also be explained shortly

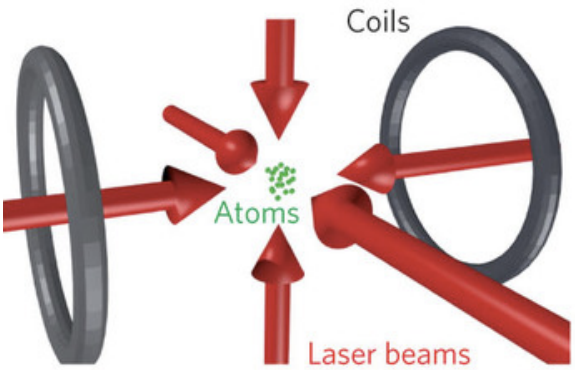

Figure 4: Magneto-Optical Trapping Schematic

(Kowalski et al., 2010, pp. 116-117). See Figure 4 for a schematic of the MOT (Estève, 2014). After loading the atoms into the lattice, several atoms are left in each lattice site where the potential well was created (Beals, 2005, Initialization & preparation (I) slide).

The atoms within the lattice are then laser cooled (Beals, 2005, Initialization & preparation (I) slide). Laser cooling occurs when a laser is shone upon an atom that is moving, and because of the law of the conservation of momentum, when the atom absorbs photon from the laser the photon's momentum is transferred to the atom (Kowalski et al., 2010, pp. 116). After the absorption there is a spontaneous emission from the atom, but the recoil of the atom in this emission is in random directions and as such, there is no total change in the momentum on the average (Kowalski et al., 2010, pp. 116). See Figure 5 for a schematic of this effect (Kowalski et al., 2010, pp. 116). Altogether, the change in the atom's momentum is based only on the absorption of the photon and the resulting force is directed along the laser beam path (Kowalski et al., 2010, pp. 116-117). An atom moving in the direction opposite the laser beam would be de-accelerated at a very efficient rate (Kowalski et al., 2010, pp. 117). The idea behind the atoms *cooling* comes from the kinetic theory of gases, where the average energy is directly proportional to both the velocity and the temperature of the molecules by the equation

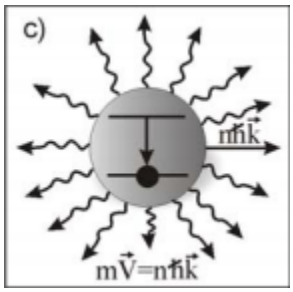

Figure 5: Recoil Momentum based on the Spontaneous Emission Average

$$KE_{avg} = \overline{\left[\frac{1}{2}mv^2\right]} = \frac{3}{2}kT$$

where v, the velocity, is also directly proportional to T, the temperature (Nave, n.d.b, Kinetic temperature section). As such, as the atom's momentum changes and its velocity decreases, so does its temperature. Thus, the atom is *cooled*. Only after a few microseconds during the cooling, half the sites have one atom and half have no atom (Beals, 2005, Initialization & preparation (I) slide). These filled sites are scattered throughout the lattice, with a mix of empty sites in between.

Laser cooling the atoms causes them to be in optical molasses. Optical molasses results from the same setup as a MOT with three pairs of orthogonal laser beams that are counter propagating, or not spreading out, and intersect in a vacuum chamber with a vapor of the element being used (Kowalski et al., 2010, pp. 117). Figure 6 shows the formation of optical molasses (Lilius, 1997). The term *optical molasses* refers to the viscous damping, or confinement, scheme that slows down atoms a great degree and causes them to become very cold, down to ~240 μK (Chu, Hollberg, Bjorkholm, Cable, & Ashkin, 1985, pp. 48-49). Optical molasses is not a trap like the MOT, but confines atoms to a small region for a short amount of time and allows for greater cooling of the atoms than other cooling techniques (Chu et al., 1985, pp. 48). This is achieved through the laser beams, which are tuned to below the resonance of the atoms, creating a viscous region with an inhibiting force that acts on the atom, but the atom is still free to move around in the region and eventually diffuses out of the region (Kowalski et al., 2010, pp. 115). One interesting note is that because of the density of the cloud of atoms in optical molasses, which can reach 10^6 atoms/cm^3, it is clearly visible to the naked eye (Chu et al., 1985,

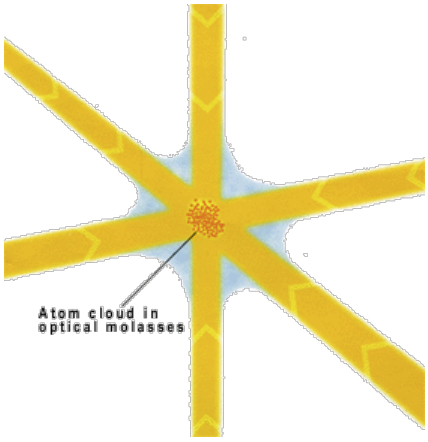

Figure 6: Optical Molasses

pp. 49). Thus by using a high numerical aperture lens, the lattice can be imaged so that the locations of each individual atom can be realized (Beals, 2005, Initialization & preparation (I) slide).

The final cooling step is to use 3D Raman sideband cooling to get the atoms into their vibrational ground states (Beals, 2005, Initialization & preparation (I) slide). 3D Raman sideband cooling goes beyond optical molasses, because although optical molasses is fast, easy to use, efficient and versatile, at high densities the re-absorption of scattered photons causes heat and radiation pressure that pushes atoms out of the optical molasses (Kerman, Vuletic, Chin, & Chu, 2000, pp. 439). Through the process of 3D Raman sideband cooling, a far-detuned optical lattice induces transitions in the energy states of atoms, called degenerate Raman transitions, which shifts the energy states down and thus cools the atoms (Kerman et al., 2000, pp. 440). Fast optical pumping assists in the cooling process until the final cooling stage where a weak optical pump is used (Kerman et al., 2000, pp. 440). This method cools the atoms very quickly into their vibrational ground state and prevents re-absorption heating; Kerman et al. were able to do the whole process in 10 μs and ended with temperatures as low as 290 nK, which is three orders of magnitude colder that achieved by optical molasses (Kerman et al., 2000, pp. 439-440).

Once the atoms are cooled to their vibrational ground state in each lattice site, the atoms in the lattice must be rearranged to form a smaller, but perfectly filled lattice (Beals, 2005, Initialization & preparation (I) slide). This compacting of the lattice is necessary for large-scale quantum computing (Vala et al., 2005, pp. 032324-1). The compacting takes place through a multi-

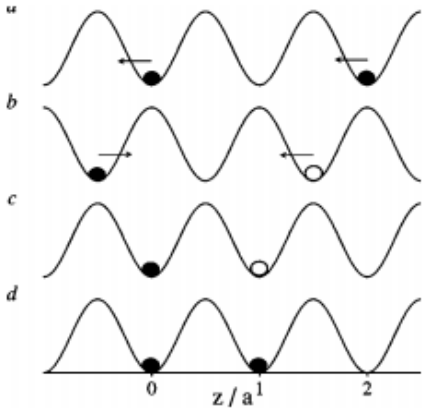

Figure 7: Compacting Scheme

step process. Following Figure 7, the first row (a) takes place when the angle of the polarization of the laser beam is rotated and at the end of the rotation, (b) the states of the atoms are selectively flipped, which is denoted by the unfilled white circle (Vala et al., 2005, pp. 032324-3). Next, (c) the angle of the polarization is rotated back to its original value and the atom whose state was flipped shifted to the next vacant lattice site and then finally, (d) the atom with the flipped state again has its state flipped back to its original state (Vala et al., 2005, pp. 032324-3). Thus the atoms shifted to fill empty spaces within the lattice. The atoms within the lattice can also be shifted by row with more than one atoms being shifted at once to fill possible empty sites, this can be seen in Figure 8 (Vala et al., 2005, pp. 032324-7). These methods can theoretically be used to compact 8000 lattice sites in a single cycle that would take less than a single second (Vala et al., 2005, pp. 032324-9). After the compacting scheme takes place, the lattice can be optically cooled and imaged and the scheme can be performed again until all the sites are perfectly filled (Vala et al., 2005, pp. 032324-9).

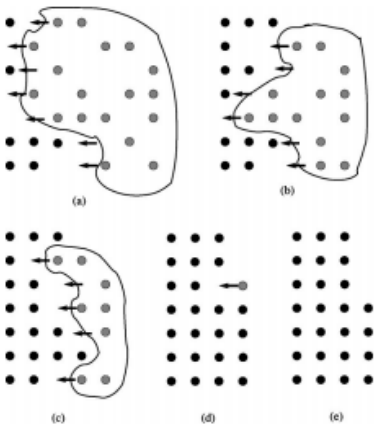

Figure 8: Row Compacting Process

Thus with the atoms in the addressable optical lattice cooled to their vibrational ground state and compacted to create a perfectly filled lattice, the initial physical layout is completely set up for a quantum computer.

The simulation qsims is based on the Alkali atom Cesium-133 in an addressable optical lattice (Beals, n.d., Tutorial section). Cesium-133 being the stable isotope of the Cesium atom, it is so stable and has so well defined energy levels that it is used to define the second (Leap seconds, n.d.). Figure 9 shows the electron configuration of Cs and highlights the single outer shell containing one electron (Nave, n.d.a, Cesium atomic clock section).

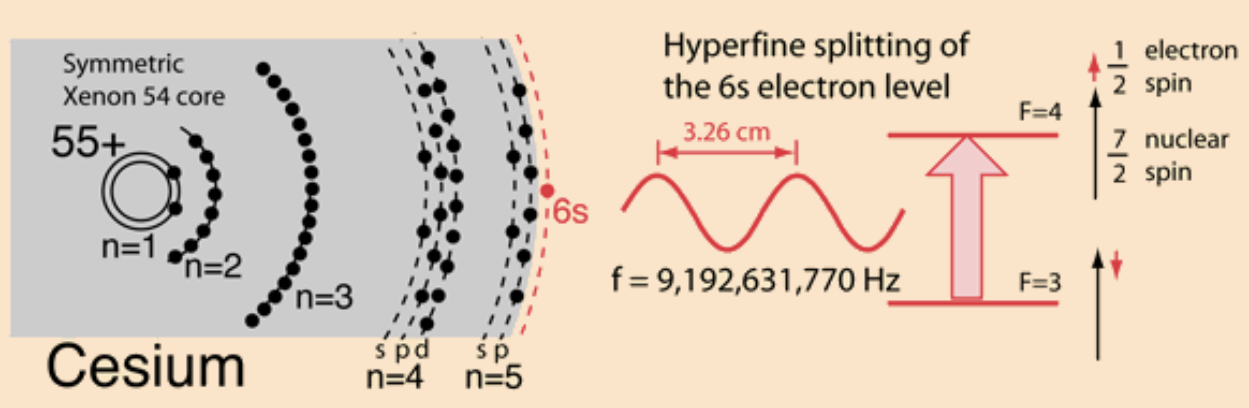

Figure 9: Hyperfine Splitting of Cesium

The figure also shows the frequency that goes into the transition between the hyperfine states of Cs and also shows what electron spin and what nuclear spin Cs has (Nave, n.d.a, Cesium atomic clock section). This transition will be important later on.

To understand the hyperfine splitting of ^{133}Cs, it is useful to understand a simpler model, namely that of hydrogen. Figure 10 depicts a simplified version of the hydrogen atom (Hünniger, 2008). The electron rotates about the nucleus, and the electron has an orbital angular momentum, *L*, while the nucleus also has a nuclear spin, *I*, intrinsically. The $\vec{J} = \vec{L} + \vec{S}$ orbital angular momentum and the nuclear spin interact with each other and are given by the relation of the dot product of the two vectors, *I* • *L*. Along with the electron's orbital angular momentum, it also possesses a spin, or intrinsic, angular momentum, *S*, and it too interacts with the nuclear spin of the nucleus and is given by a similar relation, *I* • *S*. The total angular momentum, *J*, is given by the linear combination:

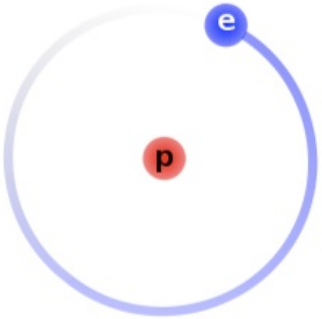

Figure 10: Hydrogen Atom

The hyperfine sublevel denoted by F is given by the interaction of J and I.

$$\vec{F} = \vec{I} + \vec{J}$$

Now spectroscopic notation is commonly used in atomic physics to name states of atoms (Branson, 2013). The general form is $N^{2S+1}L_J$, where N is the principle quantum number, S again is the spin angular momentum, L again is the orbital angular momentum, but is written as S, P, D, F, … for when L= 0, 1, 2, 3, …, to represent the different electron shells of the atom and J is again the total angular momentum (Branson, 2013). For ^{133}Cs the spectroscopic notation is given as $6\ ^2S_{1/2}$ and as such,

$$N = 6,\ S = \frac{1}{2},\ L = 0,\ J = \frac{1}{2}$$

(Beals, n.d., Tutorial section, Simulation details subsection). Following the previous equation given for total angular momentum:

$$\vec{J} = 0 + \frac{1}{2} = \frac{1}{2}$$

It was notated previously that I = 7/2 for ^{133}Cs and this is based on the nuclear shell model, which functions similarly to the electron shell model. Using this information, it can be determined that:

$$\vec{F} = \frac{7}{2} \pm \frac{1}{2} = 3,\ 4$$

The plus or minus comes in because the hyperfine sublevel F is concerned with the projection of the electron spin, and since the electron has a spin up and spin down, the hyperfine level is split into two different values. Namely F = 3 and F = 4. Figure 11 depicts the fine and hyperfine structure

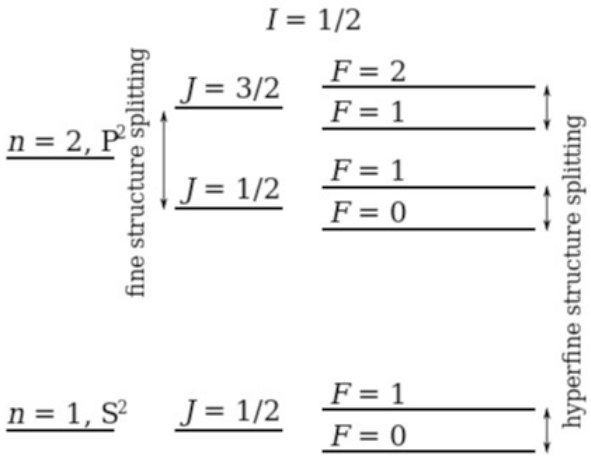

Figure 11: Fine and Hyperfine Structure of a Hydrogen Atom

of a hydrogen atom (Edudobey, 2010). It can be clearly seen that at the principle quantum number of $N = 2$, there is a fine splitting in the fine structure into two different total angular momentum values. Likewise, when the nuclear spin is taken into account with the total angular momentum, there is a hyperfine splitting that takes place in the hyperfine structure.

Although this is fascinating, it does not stop there. Once a magnetic field is applied to the hyperfine structure, there is another splitting in the projected values of the hyperfine sublevels.

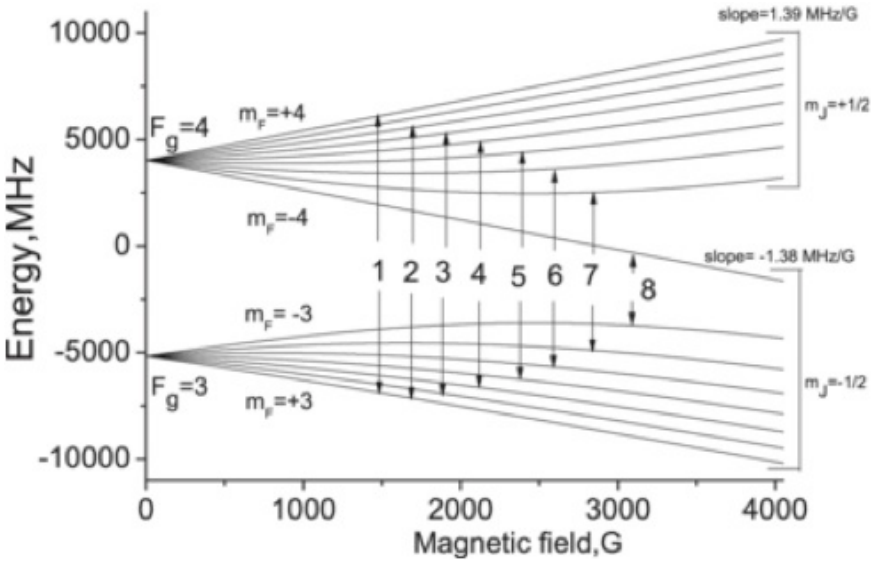

Figure 12: Theoretical Magnetic Field Dependence of the Hyperfine Structure of ^{133}Cs

Figure 12 shows the effect of an applied magnetic field on the hyperfine sublevels of ^{133}Cs (Slavov, 2014, pp. 5). There is yet another splitting and the energy levels can be seen to diverge with the strength of the magnetic field. The projections follow the rule:

$$m_F = -F,...,0,...,F$$

Thus

$$F = 3,\ m_F = -3,...,0,...,3 \quad \& \quad F = 4,\ m_F = -4,...,0,...,4$$

Notice how there are seven values for $F = 3$ and nine values for $F = 4$ and how in Figure 12 for $F = 3$ there are seven lines that split representing m_F going from +3 to -3 and for $F = 4$, there are

nine lines that split representing m_F going from -4 to 4. The numbered lines that go between the states are narrow band N-type resonances and they essentially restrict which transitions are possible between the m_F levels (Slavov, 2014, pp. 5). Two important ones to note are transitions number 5 which transitions between $F = 3$, $m_F = 0$ to $F = 4$, $m_F = 1$ and number 4 which transitions between $F = 3$, $m_F = 1$ to $F = 4$, $m_F = 0$. Understanding the hyperfine structure, hyperfine splitting and the allowed transitions prove especially necessary to understand the functioning of the simulation qsims.

Results

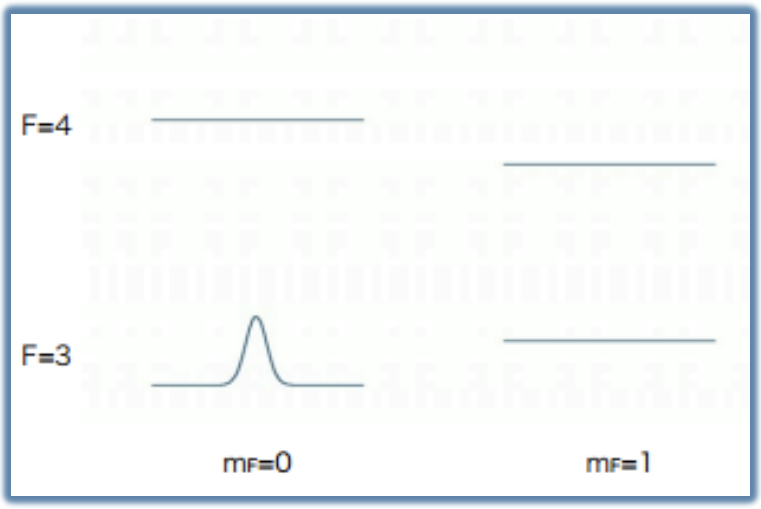

Figure 13: Layout of qsims with Labeled Axis

Figure 13 is an image of the beginning state of qsims with a labeled axis (Beals, 2005, Single qubit gates (3) slide). It can be seen that the four levels represent the energy states $F = 3$, $m_F = 0, 1$ and $F = 4$, $m_F = 0, 1$ and follow the arrangement of the corresponding paths of the hyperfine splitting in a magnetic field, as shown in Figure 12. In the actual simulation, the labels are not present and the only things visible are the lines. It can be seen in the $F = 3$, $m_F = 0$ level that there is a Gaussian-like wave present. This represents the probability density distribution of

finding the state of the atom in that particular atom. So at the present moment, all the probability lies in the first $F = 3$, $m_F = 0$ level. Because qsims is simulating a quantum NOT gate, the idea is to flip between the states of the hyperfine structure of ^{133}Cs, specifically between $F = 3$, $m_F = 0$ to $F = 4$, $m_F = 0$. This would essentially be flipping a single atom from its ground energy state to an excited state. Yet this transition is difficult to do, and several transitions to allowable, but temporary levels are required to make the final transition between the ground and excited states.

In the physical layout of the quantum computer setup, as outlined previously, the addressable optical lattice is completely compacted with atoms, in the case of qsims they will be ^{133}Cs atoms, and they are cooled to their vibrational ground state. Now in order to perform an actual quantum NOT gate on this system, a single site is picked within the lattice and a focused addressing beam, with wavelength ~880 nm, shifts $m_F \neq 0$ levels at the site while keeping $m_F = 0$ levels and atoms undisturbed (Beals, 2005, Single qubit gates (2) slide). A microwave pulse is then used to flip the atom's state from $F = 3$, $m_F = 0$ to the temporary state of $F = 4$, $m_F = 1$, which is transition number 5 in Figure 12 (Beals, 2005, Single qubit gates (2) slide). Another microwave pulse is used to flip between the temporary state $F = 4$, $m_F = 1$ to another temporary state $F = 3$, $m_F = 1$ (Beals, 2005, Single qubit gates (2) slide). A final microwave pulse flips the atom from the temporary state of $F = 3$, $m_F = 1$ to the final state of $F = 4$, $m_F = 0$, which is

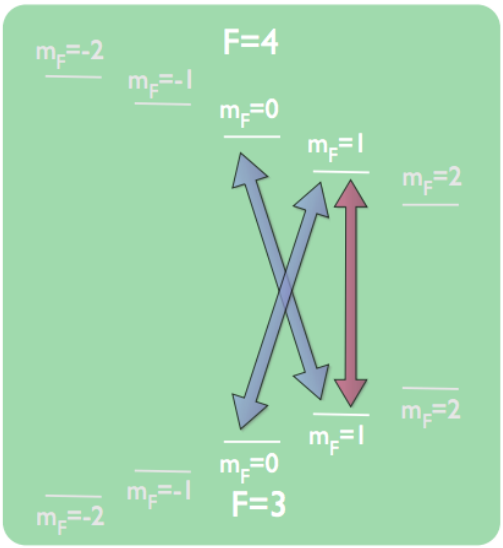

Figure 14: Transitions of the Hyperfine Sublevels that make up the NOT Gate

transition number 4 in Figure 12 (Beals, 2005, Single qubit gates (2) slide). Once this is complete the atom has successfully undergone through a NOT gate operation. Figure 14 depicts this whole process (Beals, 2005, Single qubit gates (2) slide).

Figure 15 depicts some pictures of the final outcome of the qsims simulation, which comes out as a short .mov file (Beals, 2005, Simulation: bad single qubit slide). The transitions of the probability density distribution of finding the atom in that particular state are clearly visible.

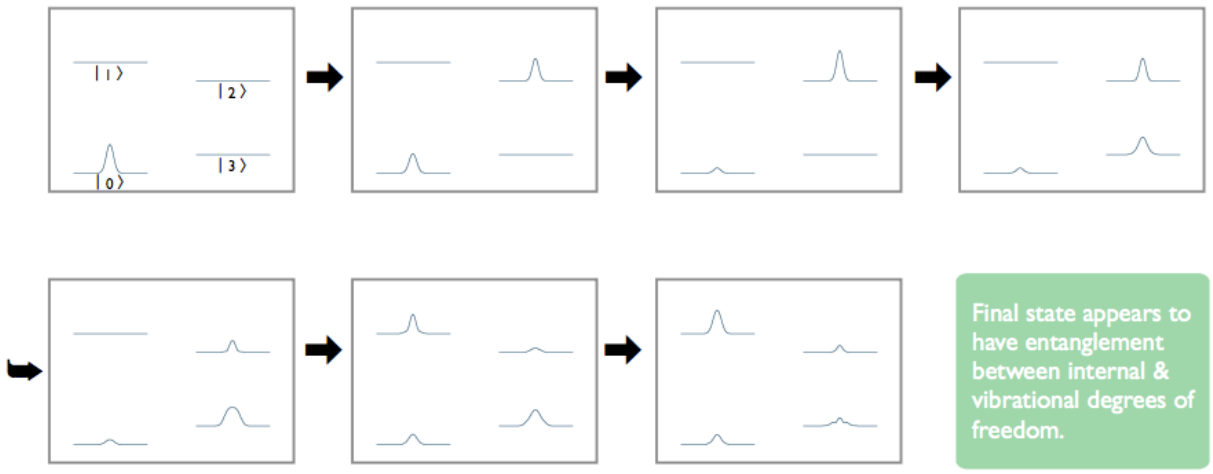

Figure 15: Pictures Depicting the Outcome of qsims, which is the NOT gate operation

Discussion and Conclusions

The outcome of this project was an understanding behind how the simulation qsims functions and thus how a quantum NOT gate could simulated as well as an understanding of the layout procedures for setting up a quantum computer and carrying of the NOT gate operation. The end achievement was an acquisition of knowledge. Now, admittedly, I do not understand all of the details behind how it all functions and I believe some of it is truly over my head as an undergraduate with limited experience in the field of quantum information science and quantum mechanics for that matter. As such, a great deal of the technical details had to be hand-waved or

simplified to a level where I could understand them and communicate them to others. An example of this is Raman sideband cooling: I know that it cools atoms and gets them to their vibrational ground state, but I do not know the physics behind degenerate Raman transitions. As such, some of the deeper issues of how the simulation functions or how it is setup is lost upon me. Such is the difficulty of a project with this nature. I do not believe that this should disqualify the project though, because the acquisition of such knowledge is valuable, even if all the details are not understood.

Another very valid point is one that Dr. Anton Riedl gave through his notes on my final capstone presentation that I gave before some of faculty of the PCSE department. Dr. Riedl pointed out that my project seemed to be focused on understanding the theory behind how quantum works, which is true. He noted that this topic did not seem appropriate as an *applied* physics major. I do agree that this project does not support the applied portion of the degree in physics that I am currently seeking. I believe that at first the idea of the project was to have something more tangible and testable, but because of lack of progress during the second semester of the project, I was not able to get as far as I would have liked. I still believe that I have a valid outcome that works, but it is not completely appropriate or satisfactory in regards to the stated purpose of my degree.

Yet there might be some light in this all. The information that I found was very valuable and would prove a great foundation for someone else to build upon in the future. If some of the necessary equipment could be obtained, such as a CO_2 laser and a vacuum chamber, then it might actually be possible to form the basics of a quantum computing set up. This is a big statement and more than likely would need a team of people with many resources to successfully accomplish, but the scalability of this project is feasible. It is not like a nuclear lab where there is

so much involved and requires a big laboratory for an accelerator. Quantum computing can be developed on a much smaller scale and can be used for a multitude of research. Some interesting questions that could be researched include: why is it so difficult to sustain a significant number of qubits with the current academic procedures and how might this be overcome? On a more theoretical side, one could look at how quantum computers affect security and how quantum encryption comes into play. Continuing on with quantum computing development, one could explore how more involved logic gates might function in a quantum computer and some of the difficulties associated with that.

There are many different paths that could be taken from this basic start at examining quantum computers. That is why I believe that this project is still a valid undertaking, because the information gained is a viable springboard to explore more complicated and interesting questions involving quantum computing and even some of the principles of quantum mechanics itself, which was the original hope of this project. Looking back on this project, it would have been more effective if I had kept the rigorous time commitment to the project that I had during the first semester so that everything would have been more spaced out and not last minute. I might have been able to get further and gain some tangible, testable results. Yet, even though my more theoretical project might not have been completely suited for the program I am in at CNU, I do believe it has been a valuable experience and one that has been worthwhile.

I would like to thank Dr. David Gore for keeping me on track with where I needed to be on this project and asking the difficult questions to point out the gaps in my understanding. I would also like to thank my advisor, Dr. Edward Brash, who through many a stop at his office and over emails, lead me all the way through this project and allowed me come to a decent conclusion. Thank you.

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