Single Trapped Barium Ion

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Abstract

I worked on several electronic aspects of the Barium Ion experiment. My main project was to design and build a circuit that would provide up to three amps of current to two light-emitting diodes. We hope that the addition of this circuit to the experiment will allow the experiment to run faster and enable data gathering.

Introduction

The single trapped ion is an interesting system for several reasons. For one, it is the simplest atomic system. There are no atom-atom interactions that need to be considered and accounted for. Secondly, barium is a good candidate because of its hydrogen-like properties. It has only one valence electron, which means that its energy levels are identical to hydrogen, except that the fine structure splittings are on the order of nanometers, much larger than those of hydrogen. Also, the fine structure splittings are optical. Finally, the lifetimes of barium's meta-stable states are especially long.

Using the trapped barium ion, we are able to probe many different areas of physics, aside from just atomic physics. There are implications in quantum computing, atomic clocks, precision spectroscopy, and parity violation.

My contribution to the experiment included constructing a current supply circuit to be incorporated into the setup. In the following sections, I will briefly explain the Barium Ion experiment, detail the circuit, and explain its role in the experiment.

Overview of Experiment

There are three basic steps that need to be implemented during every run of the Barium Ion experiment: trapping, cooling, and shelving.

Trapping

We first trap the ion using electric fields. We have a charged particle that we want to confine to some region. Laplace's equation dictates that static fields alone cannot confine a charged particle in all three dimensions. One solution to this problem is to use a large magnetic field. A second solution that we implement is to add an oscillating harmonic quadrupole field. The oscillating electric field creates a pseudo-potential, which is then able to confine the ion. A pseudo-potential is one that has no global minimum at any particular time, but when it changes in time (by rotation or flipping), it is capable of containing a particle.

There are different classes and geometries of traps that can be used, including ring and endcap models, a plane and hole trap, and a needle-like endcap trap. We use a wire ring trap, because there is great optical access to the ion, and the wire trap is cleanable.

Cooling

The second step is to cool the ion. We are able to cool the ion down to a temperature of about 100 μK, which is constrained by the Doppler limit. An explanation of laser cooling is pretty simple. All atoms have a resonant frequency, and only light of that frequency will be absorbed by the atom. More precisely, there is a range of frequencies that can be absorbed, the range depending on the temperature of the atom. If we send light in that is red-detuned, meaning that it has a lower frequency than the atom's resonant frequency, it is less likely to be absorbed by the atom, unless the atom is moving towards the laser light, in which case the frequency appears to be the atom's resonant frequency due to the Doppler Effect. In this case, the atom absorbs the light, goes into an excited state, and some time later spontaneously emits the light in a random direction, giving the atom a small kick in the opposite direction. The direction of the kick is different than the laser's direction, so the atom has been slowed down in the direction of the laser beam. Using six lasers, coming from orthogonal directions, would then effectively cool the atom.

In our setup, we don't use six lasers, but instead we use only one cooling laser. The ring trap creates a potential that always brings the ion back into the laser light, so it is can be cooled.

Shelving

The third step is shelving. Using the method of shelving we can control which state the ion is in and also determine how many ions have been trapped. We use a 493 nm laser to cool the ion (as detailed above), and also to excite the ion into the $6P_{1/2}$ state (see Fig. 1). When the ion spontaneously emits a photon, it can go into either the ground state or the meta-stable $5D_{3/2}$ state. We use a red, 650 nm laser to pump the ion out of the meta-stable state and back into the $6P_{1/2}$ state. From there, the ion relaxes to the ground state, emitting a photon of wavelength 493 nm, which is detected by the photomultiplier tube (PMT). This cycling of the ion is the Absorption/Emission Cycle, and the ion goes through the cycle a million times a second.

As previously stated, it is by detection of blue light at 493 nm by the PMT that we know we have at least one ion in the trap. In order to determine how many ions we have trapped and which state they are in, we play a game with the ion. As the ion goes through the Absorption/Emission Cycle, it sometimes emits blue light. The PMT signal will be high because there are a lot of blue photons being emitted. Then if we send in blue light at 455 nm, we can excite the ion into the $6P_{3/2}$ state. From this state, 90% of the time, the ion will relax back into the ground state, but 10% of the time, the ion will go into the meta-stable $5D_{3/2}$ state. When the ion reaches the meta-stable state, the ion is stuck, or what we call shelved. When the ion is shelved, it no longer can emit 493 nm light (it is isolated from the Absorption/Emission Cycle), and so we don't detect any blue light. The PMT signal goes low.

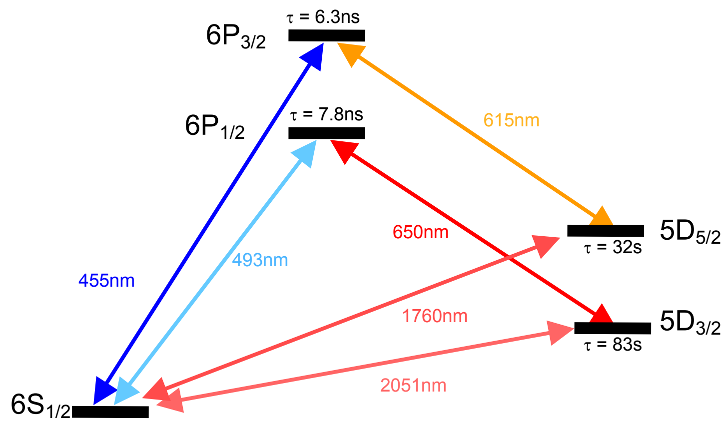

Fig. 1: Energy levels of the Barium ion.

The PMT signal will stay low for about 32 seconds, the lifetime of the $5D_{3/2}$ state. After some time, the atom will spontaneously decay down to the ground state through an electric quadrupole interaction. This transition is a forbidden transition, because the angular momentum of the ion decreased by two. It is forbidden only by an electric dipole transition, but allowed by a quadrupole transition. Quadrupole transitions have a lower probability of occurring, which is why the lifetime of the meta-stable states are so much longer. As each shelved ion decays to the ground state, and reenters the Absorption/Emission Cycle, it begins to emit blue light again, and the PMT signal steps up. The number of steps in the PMT signal shows us how many ions we have trapped.

The 455 nm and 515 nm light are essential in determining the state of the ion. There aren't any lasers made cheaply at these wavelengths, so we use Light Emitting Diodes (LED) instead. They are relatively easy to use, except that they are a difficult load to deal with. The main challenge of my research was to design a circuit that would supply up to three amps of current to the LEDs, as well as to a cooler and fan for each.

Circuit/Circuit Analysis

Circuit

We designed a circuit that would supply three amps of current to the LEDs as well as to each of their coolers. The circuit (Fig. 2) is relatively simple to understand. The current at the LED is the same as the current after the 0.1 Ω power resistor. By measuring the voltage across the resistor, we can quickly determine the current going to the LED, using Ohm's Law. We insert a voltmeter across the measuring resistor so that we can continually monitor the current going to the LED.

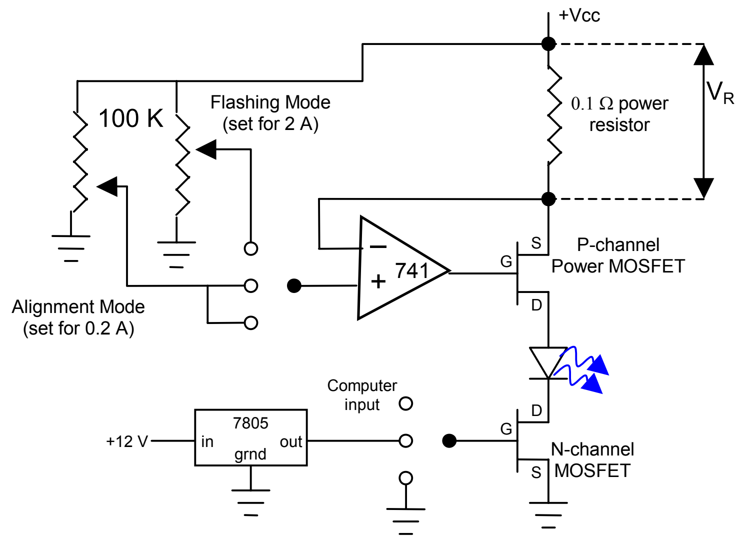

Fig. 2: Current supply circuit for the light-emitting diodes.

Circuit Analysis

We remember the two golden rules of op amps: 1) Current never flows through an op amp, and 2) the output will do whatever is necessary to keep the voltage at each input equal. We program a voltage at the non-inverting input using a potentiometer. That voltage will then equal the voltage at the inverting input and also at the point below the power resistor. Remember that the voltage at this point determines the current flowing down to the LED, so we are able to adjust the amount of current going to the LED by adjusting the voltage on the non-inverting input of the op amp.

We use two MOSFETs as switches. We use FETs (Field Effect Transistors) because they conduct with a voltage on the gate, rather than with a small current going to the base, as with ordinary transistors. Using FETs, we don't draw any current away from the LED. The top MOSFET is always conducting, because there is always a voltage coming from the output of the op amp. The second MOSFET is the flasher. This second MOSFET turns the circuit on and off. When the gate is grounded, the MOSFET does not conduct, and no current flows. If we put five volts on the gate, the MOSFET conducts and the LED lights. We also included an option for using a computer input to control the voltage going to the gate.

We have designed the circuit to run in two modes: Alignment Mode and Flashing Mode. In Alignment Mode, the LED remains on, but at a lower current so it is easier to adjust and align the light. In Flashing Mode, the computer is used to control when the light goes on and off, and the current is set to about 2 to 2.5 V.

Conclusion

It is our hope that once the circuit is constructed, it will allow for up to three amps of current to be supplied to the LEDs. It is important that we supply more current, because the more current that runs through the LEDs, the brighter they will be. As mentioned above, the shelving transition happens only 10% of the time. If we can make the LEDs brighter, we can drive this transition faster, and hence shelve the ion quicker. This will make the entire experiment run much faster, since right now, the shelving is the slowest part of each data run.

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