A More Efficient Way to De-shelve $^{137}Ba^+$

Andrea Katz
Trinity University
UW REU 2010

Abstract:

In order to increase the efficiency and reliability of de-shelving barium ions, an infrared laser beam was doubled in frequency to create a 614 nm beam, which was sent to the ion trap. Part of the infrared beam was double-passed through an acousto-optic modulator and sent to a Fabry-Perot cavity, whose output we used to stabilize the frequency of the laser.

Introduction to Quantum Computing:

Traditional computing employs the bit in logic operations. Bits are binary systems and can have values of either 0 or 1. Quantum computing improves upon this by using the qubit, which is a quantum mechanical system that may exist in any linear combination of two levels such that its wavefunction $|\varphi>$ is

$$|\varphi>= \alpha|0> + \beta|1>, \tag{1}$$

where α and β are constants. This gives quantum computers several advantages over traditional computers. For example, Shor's algorithm shows that a quantum computer could quickly factor a number too large to be handled by today's computers, which would allow us to break RSA encrypted codes.[1] A quantum computer could also search extensive databases quickly and handle large amounts of information.

A good way to physically implement a qubit is to use two energy levels in a trapped ion as the two qubit states. In order to trap the ion, we use a Paul trap, which suspends an ion by using an oscillating quadrupole field. A good way to visualize an ion in a Paul trap is to imagine a ball sitting on a spinning saddle, as shown in Figure 1.[2] The ball starts to roll down the sloping portion of the saddle, but before it gets very far, the saddle has rotated so that the ball is moving up hill and must change directions. If we rotate this saddle-shaped potential very rapidly, the ion stays in the center, feels only the time-averaged effect of zero slope, and has very little motion.[2] We can also laser cool the ion to remove some of its energy. After these two steps, we have a trapped ion on which we can perform qubit operations.

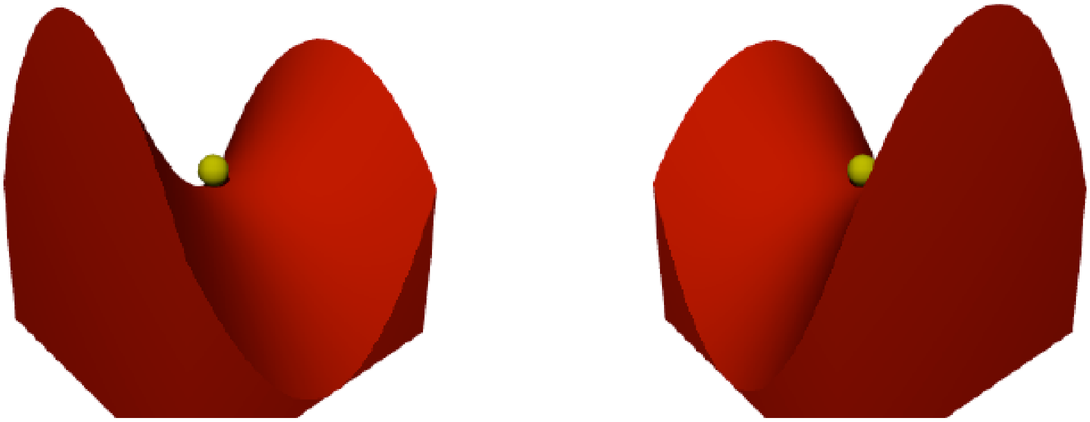

Figure 1. A good way to visualize an ion in a Paul trap is a ball in the center of a rotating saddle shape.

Barium as a Qubit:

In the Trapped Ion Quantum Computing lab at UW, we use the hyperfine levels in the ground state of $^{137}Ba^+$ as the two states of the qubit. A simplified energy level diagram for Ba^+ is shown in Figure 2. The only hyperfine splitting shown is that of the ground state, though the other levels are also split.[3]

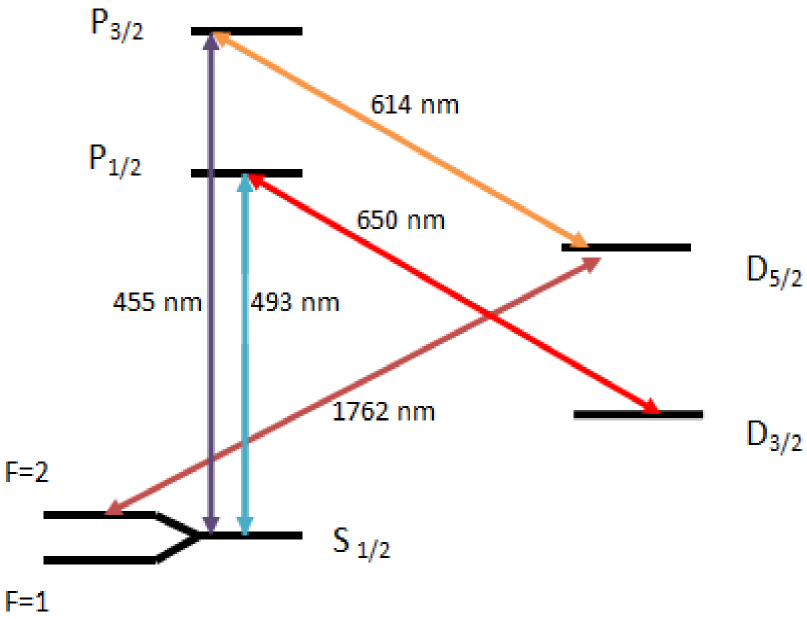

Figure 2. Relevant energy levels for barium ions and their transition wavelengths.

It is easy to test whether or not the ion is in one of the two hyperfine ground states by hitting it with a 493 nm laser beam and driving the transition to the $P_{1/2}$ state. From here, the electron will either fall back down to its ground state, at which point the ion emits a 493 nm photon and can be seen to fluoresce, or it will fall down to the $D_{3/2}$ state. This state has a lifetime of around 80 seconds, but in order detect the ion's fluorescence, we need the electron to transition repeatedly and continuously from $P_{1/2}$ to ground, so we must use a 650 nm laser to "re-pump" the ion into the $P_{1/2}$ state. Therefore, if we turn on the blue and red lasers and the ion is seen to fluoresce, we know that the ion is in one of the hyperfine ground states. In order to determine which of these states it is in, we hit the ion with a 1762 nm beam. If the ion is in the higher energy hyperfine state, a transition will occur to $D_{5/2}$ and no fluorescence will be observed when we turn on the blue and red lasers. If the ion is in the lower energy hyperfine state, the infrared beam will not cause a transition, and fluorescence will be observed with the blue and red lasers.

The "shelved" state, $D_{5/2}$, has an average lifetime of 32 s. The rest of the experiment runs on the order of microseconds, so we would like to speed up the de-shelving process. One way to do this is to hit the shelved ion with an orange beam at 614 nm, driving the transition to $P_{3/2}$, from which it quickly decays back to the ground state. Before we began this project, de-shelving was accomplished using the 1762 nm laser, but the process was inefficient and did not always work. Using an orange laser beam is expected to speed up the de-shelving process and be more reliable.

Producing an Orange Beam:

Using an orange laser beam to de-shelve the ion is complicated by the fact that diode lasers do not exist at 614 nm. To create an orange beam, a 1228 nm infrared beam was sent through a PPLN crystal waveguide, which doubled the frequency. A schematic of the setup is shown in Figure 3.

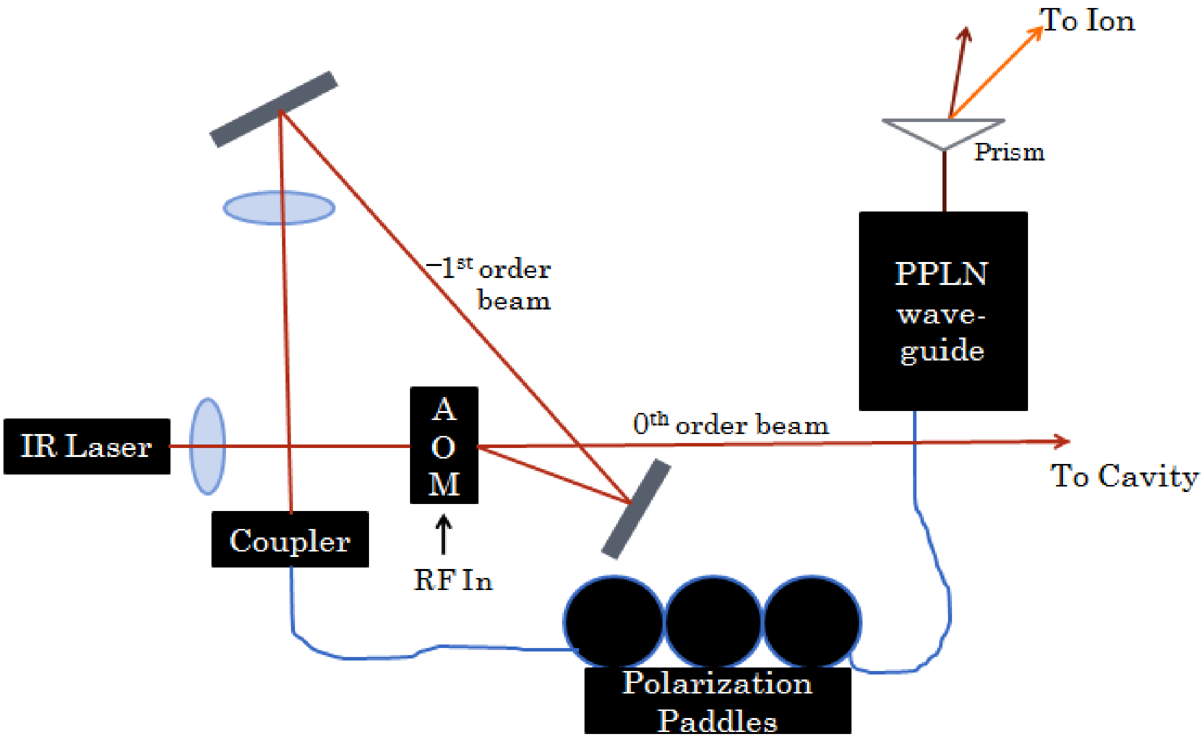

Figure 3. A schematic diagram of the frequency doubling setup.

Upon leaving the laser, the infrared beam first passed through an acousto-optic modulator. An AOM works by sending an ultrasonic sound wave through a crystal. The incoming light wave interacts with the sound wave, and part of the light is diffracted, with its frequency increased or decreased by the frequency of the sound wave.[4] The minus first order (diffracted) beam was picked off with a mirror and sent to the frequency doubler. This setup is advantageous because the AOM can be turned on and off instantly, with nearly 100% extinction of the diffracted beam. This prevents accidental de-shelving and possible qubit readout errors while leaving the zeroth order beam in place to use for laser stabilization.

Two mirrors were used to steer the diffracted beam into a single mode fiber. In order to avoid absorption losses, silver-coated mirrors were used, and the 40 cm lens that focused the light into the fiber for better coupling was specially coated for infrared light. The fiber went through three polarization paddles before entering the PPLN waveguide, which generated 614 nm light.

PPLN:

PPLN (periodically poled lithium niobate) is a non-linear crystal with a periodic reversal of domain orientation. Nonlinear crystals can be used for second harmonic generation, in which two photons from an incoming laser beam are combined to make a photon with twice the frequency.[5] The ability of nonlinear crystals to efficiently produce frequency-doubled light is due to their χ^2 properties, which mean that the intensity of the doubled frequency beam is proportional to the square of the intensity of the input beam. Because a small gain in the intensity of the infrared light results in a large gain in the intensity of the orange beam, a PPLN waveguide was used instead of a normal PPLN crystal. The infrared beam has a smaller cross-sectional area in a waveguide than in a block of crystal, so its intensity is higher and more orange light is generated. In order to take fully utilize the waveguide's frequency doubling advantage, the polarization of the incoming light must be aligned with the axis of the waveguide. This was accomplished with three polarization paddles set along the length of the fiber leading up to the PPLN. When the polarization is set correctly, using a PPLN waveguide instead of a normal PPLN crystal increases the efficiency of SHG by a factor of 100.

The advantage of using PPLN for SHG over other nonlinear crystals is that it allows for phase matching, in which the doubled wave interferes partially constructively with the incoming wave. This results in a stronger beam of frequency-doubled photons, as shown in Figure 4[5]. Phase matching is achieved by changing the poling period of the PPLN, since photons generated in each domain orientation will be 180° out of phase with those generated in the orientation before, so by picking the appropriate period, we can ensure that newly generated orange light interferes partially constructively with previously generated orange light and with the continuing infrared beam. We can change the poling period by adjusting the temperature of the crystal.

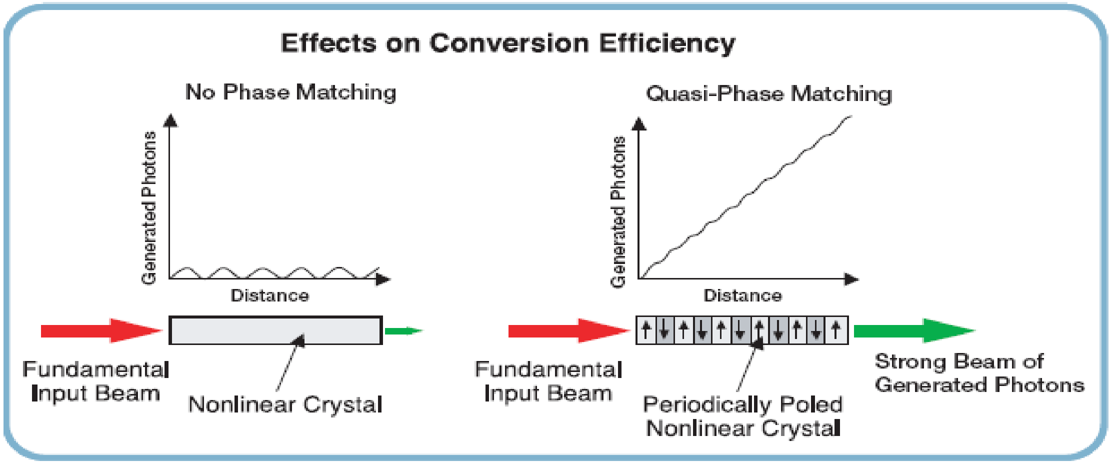

Figure 4. PPLN crystals allow for phase matching, which make them more efficient at SHG than other nonlinear crystals.

After optimizing the temperature of the PPLN, infrared polarization, and infrared beam alignment, the resulting orange beam had 5 μW of power, about 1% of the original power of the infrared laser. We suspect that the losses are due to attenuation in the fiber and difficulty in coupling.

Aligning the orange beam:

When the orange beam left the PPLN waveguide, we had to couple it into another single mode fiber to get the light to the room containing the ion trap, resulting in more loss of power. In order to get the orange beam to the ion trap, we used a dichroic mirror that transmits blue light and reflects orange to combine it with the 493 nm beam, which was already aligned to reach the ion. The power of the orange beam by the time it reaches the ion is about 1.5 µW. We have not attempted to de-shelve an ion with the orange beam yet, though we believe that 1.5 µW is enough power for fast de-shelving.

Laser Stabilization:

Even after careful alignment of the orange beam, we were not ready to use it to de-shelve barium ions. De-shelving requires that the orange beam be at the exact transition frequency, and since the laser's frequency can drift, it was important to stabilize it. To enable us to do this, the zeroth order infrared beam was double-passed through a second AOM before entering a Fabry-Perot cavity.

The cavity we used is a hollow tube with a curved piece of glass on either end. It has a free spectral range of about 300 MHz and a finesse of around 10. The only frequencies that are resonant in a Fabry-Perot cavity and thus transmit through the other side are those in which an integer number of wavelengths fit within the cavity. If we scan the laser through a range of frequencies and look at the light output from the cavity, we see a series of transmission peaks.

After the double-passed AOM, only 3 µW of infrared light entered the cavity. This small amount of input light meant that the output from the cavity was very faint, so in order to increase our signal-to-noise ratio and improve detection, we used the double-passed AOM to put a slight frequency modulation on the light entering the cavity. Then, we could use a lock-in amplifier to pick up the transmitted signal. Using a wavemeter, we determined which resonant frequency was closest to our desired frequency and we adjusted the laser to get maximum transmission at that peak. To prevent the frequency from wandering, we send the output of the lock-in amplifier to a lock box. The lock-in amplifier outputs a value that is either positive or negative depending on whether the laser's wavelength is red or blue of the peak transmission wavelength. At the peak wavelength, the lock-in amplifier's output is zero. The lock box feeds back to the laser, adjusting the piezo voltage to ensure that the lock-in amplifier's output remains at zero and that the transmission is the highest possible value. This keeps the laser at the desired frequency.

Future Steps:

Due to time constraints and work on the ion trap, the laser stabilization process was unfinished at the time of writing. We hope to finish work on the feedback system and stabilize the laser at the appropriate wavelength. Then, we will attempt to use it to de-shelve barium ions. If there is not enough orange light to de-shelve the ions, changes will have to be made to increase coupling into optical fibers and reduce absorption losses.

References:

1. Hayward, Matthew. Quantum Computing and Shor's Algorithm. http://alumni.imsa.edu/~matth/quant/299/paper/
2. Dietrich, Matthew. Barium Ions for Quantum Computation. http://depts.washington.edu/qcomp/pdfs/matt_thesis.pdf
3. "Initialization and Detection of $^{137}Ba^{+}$ Hyperfine Qubit." http://depts.washington.edu/qcomp/detection.html
4. "Acousto-optic Modulators." Encyclopedia of Laser Physics and Technology. http://www.rp-photonics.com/acousto_optic_modulators.html
5. "Periodically Poled Lithium Niobate (PPLN)- Tutorial." http://www.thorlabs.com/catalogPages/693.pdf