SAND21XX-XXXXR
LDRD PROJECT NUMBER: 224703
LDRD PROJECT TITLE: Three-Photon Optical Pumping for Trapped Ion Quantum Computing
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ABSTRACT:

In this report we describe the testing of a novel scheme for state preparation of trapped ions in a quantum computing setup. This technique optimally would allow for similar precision and speed of state preparation while allowing for individual addressability of single ions in a chain using technology already available in a trapped ion experiment. As quantum computing experiments become more complicated, mid-experiment measurements will become necessary to achieve algorithms such as quantum error correction. Any mid-experiment measurement then requires the measured qubit to be re-prepared to a known quantum state. Currently this involves the protected qubits to be moved a sizeable distance away from the qubit being re-prepared which can be costly in terms of experiment length as well as introducing errors. Theoretical calculations predict that a three-photon process would allow for state preparation without qubit movement with similar efficiencies to current state preparation methods.

INTRODUCTION AND EXECUTIVE SUMMARY OF RESULTS:

Quantum computing has the potential to provide significant advantage over classical computing, utilizing states that are not allowed with binary logic. State-of-the-art quantum computing systems are beginning to show supremacy over classical systems in particular metrics[1]. Trapped ion systems are a leading technology for quantum computing because they maintain long coherence times[2] and high gate fidelities[3], and have also demonstrated recent success in the commercial sector[4,5]. A limitation in any quantum architecture is the number of quantum bits (qubits) that can be maintained and fully controlled. We sought to demonstrate a novel scheme that would allow for quantum state preparation scalable up to as many as 32 qubits with currently available technology.

In a quantum computing experiment, a quantum state is prepared, manipulated, and measured. In an ideal quantum computer, each qubit would be fully accessible and controllable. Mid-experiment measurements must be performed without affecting the other qubits, and the measured qubit must be re-prepared to a known state before it can be used again. In a trapped ion quantum system, this is currently done by stopping the experiment, physically moving the ions, performing operations, and then moving the ions back. This delay caused by shuttling the ions can significantly increase the overall length of the experiment and may introduce new errors due to heating.

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Many current ion trapping experiments include technology that allows for individual addressing of the ions but only utilizes this for a laser to manipulate the quantum state once it has already been prepared. A three-photon optical pumping process would allow for individually addressed state preparation without requiring major changes to the experimental hardware.

We predicted that the three-photon optical pumping rate would be comparable to the current state preparation methods based on theoretical calculations, but it proved to unresolvable with our current methods. We increased the effective power in each part of the three-photon process and went out to long delays. Throughout the various searches for the three-photon process we saw optical pumping effects, putting the ion with a precision into a particular state. However, none of these demonstrated the appropriate sensitivity to the frequencies of the light applied, which is necessary to allow for individually addressed optical pumping. The nature of these other effects that appear as optical pumping limited the resolution and timescales of the experiments and remain an active area of interest. We do not believe the inability to resolve the three-photon effect was due to a lack of experimental hardware available.

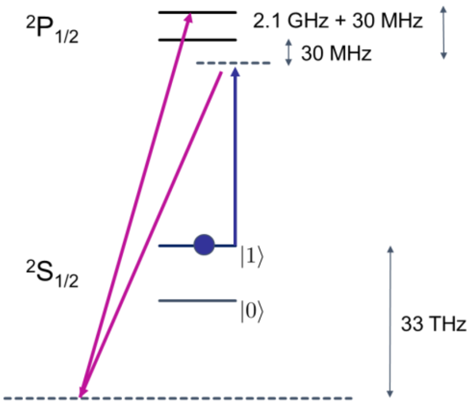

Figure 1: Schematic (not to scale) of the proposed three-photon optical pumping process utilizing the 369 nm and 355 nm lasers. The 369 nm light (blue) is detuning approximately 30 MHz from the $^2P_{1/2}$ $|F = 0\rangle$ state and an effective two-photon Raman process with the 355 nm light (pink) pumps the ion to the $^2P_{1/2}$ $|F = 1\rangle$ state.

The current 355 nm optical setup is designed to allow for 32 individually controlled beams each focused to less than a 1 μm beam waist with experimental hardware similar to that described here[6]. A three-photon process involving the 355 nm light will take advantage of this technology and is shown schematically in Figure 2. This would expand a similar level of control that currently allows for quantum operations to be performed on one ion with minimal crosstalk to a neighboring ion and allow for individually addressed state preparation. State preparation is currently done with the 369 nm light, which has a much larger beam waist, and is large enough to state prepare whole small chains of ions. In order to achieve the desired degree of individual addressability in the three-photon process, the 369 nm light must be sufficiently detuned to not affect the ion's state unless the 355 nm light is present as well. The 355 nm has demonstrated great success minimizing crosstalk between neighboring channels[6] and we believe that it would have similarly been able to minimize crosstalk for state preparation.

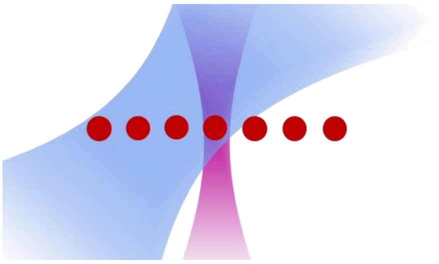

Figure 2: Schematic (not to scale) of the difference of the individual addressing capabilities of the 355 nm beams (shown in pink) relative to the 369 nm beam (shown in blue). A single 355 nm beam is shown, though each ion in the chain can be addressed by its own individually controlled focus.

As a part of this project, a major hardware upgrade was included that sought to decrease the amount of heating and noise on each ion and to increase ion trapping lifetimes. This included the exchange of an entirely new vacuum system with a new surface ion trap, previously shown to have much improved heating rates. Also as a part of this upgrade, a new filter board was added to the system as well as a new radio-frequency (RF) resonator. This upgrade was necessary for a related project that shared time on this apparatus. It unfortunately did limit the amount of time available to probe for the three-photon effect. The upgrade did however produce the intended improvement in the lifetime of an ion and initial indications still point towards a decreased heating rate.

DETAILED DESCRIPTION OF RESEARCH AND DEVELOPMENT AND METHODOLOGY:

State preparation requires an ion to be in a particular electronic state with near perfect probability. In our apparatus state preparation is traditionally done using a 369 nm laser with tuned sidebands to allow selection rules to pump the ion to a particular state. Light from a 369 nm Toptica DL Pro laser[7] is aligned through a free-space Qubiq electro-optic modulator (EOM)[8] which adds 2.105-GHz sidebands. While not used during the optical pumping step, this light also passes through a 14.7 GHz EOM to allow for cooling. After the EOMs, the 369 nm light is split into two paths each going through a double-passed acousto-optic modulator (AOM) for frequency control and then fiber coupled to the experiment. The two paths result in optical powers of approximately 0.5 μW and 5 μW for the narrow (approximately 8 μm beam waist) and wide (approximately 15 μm beam waist) focus sizes respectively, where both beams were used in our experimental pulse sequence. A majority of the scans performed used the narrow beam to provide 369 nm light for the three-photon process. The wide beam was then used for cooling and detection for most of the experiments. We did test driving the three-photon process with the wide beam as well.

To perform single-photon optical pumping, or what is typically used in a trapped ion experiment to achieve state preparation, the 2.105 GHz EOM is turned on. If the ion is in the ${}^2S_{1/2}$ $|F = 1\rangle$ (where F is the total angular momentum quantum number), this light will pump the ion to the ${}^2P_{1/2}$ $|F = 1\rangle$ state where it will have a 1/3 chance of decaying to the ${}^2S_{1/2}$ $|F = 0\rangle$ state[9]. If the ion is in the ${}^2S_{1/2}$ $|F = 0\rangle$ the 369 nm light is sufficiently detuned that it will not pump the ion.

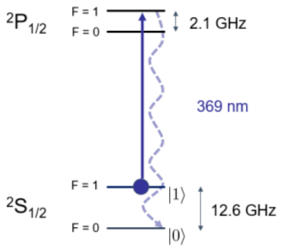

Figure 3: Schematic (not to scale) showing the single-photon optical pumping process. The 369 nm light passes through a 2.105 GHz EOM that allows the ion to be pumped from the ${}^2S_{1/2}$ $|F = 1\rangle$ to the ${}^2P_{1/2}$ $|F = 1\rangle$ state

This cycle can be repeated until the ion is prepared to its exact state. This single-photon optical pumping process is efficient (10 μs for an experiment that runs for 10's of ms) and precise (near perfect preparation)[9]. Even when using the narrow focused 369 nm laser, a standard ion chain spacing (~ 5 μm between ions) is such that the light addressed to one ion will affect the state of the neighboring ions. Even a single stray 369 nm photon can negatively impact the state of a neighboring ion. It has been measured that 10s of μm of spatial separation is not sufficient to protect an ion in a particular state from this optical pumping beam.

The quantum state of the ion is defined in the ${}^2S_{1/2}$ manifold by the $|F = 0\rangle$ and $|F = 1\rangle$ states. We can control population between these states with radiation that spans the 12.6 GHz microwave difference. To allow for individual addressability along a chain of ions, we use a pulsed laser to drive a Raman transition to span this transition. Figure 4 shows typical oscillations produced by the 355 nm light, shown both in the counterpropagating and copropagating geometries. In addition to the 355 nm light that is individually focused, there is also a beam path that is larger and addresses all the ions in a chain. The copropagating geometry mentioned here uses this globally addressed beam path. Knowing that the three-photon transition could prove difficult to resolve, we maximized the performance of the 355 nm system with regular calibrations, trying to minimize the Rabi oscillation π-time, thereby maximizing the effective intensity at the ion. We used both the copropagating and counterpropagating geometries during our experiments and set up waveplates to allow full polarization control of the 355 nm laser.

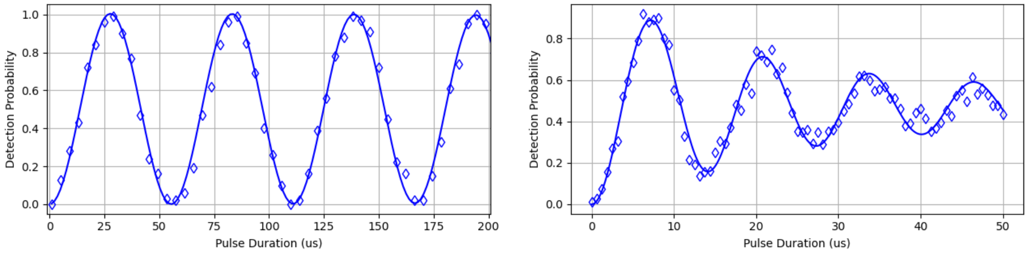

Figure 4: Typical global copropagating (left) and counterpropagating (right) Rabi flopping with the 355 nm laser. A Raman process with the 355 nm light drives the ion from the $|\mathrm{F}=0\rangle$ to the $|\mathrm{F}=1\rangle$ state in the $^2\mathrm{S}_{1/2}$ manifold. Detection probability references the experimental average of finding the ion in the $|\mathrm{F}=1\rangle$ or “bright” state.

The cavity length of the 355 nm pulsed laser is not actively stabilized and because of this there will be instabilities of the frequencies relevant to the Raman process due to the “breathing” of the frequency comb. To correct for this, the laser is locked similar to [10], and described more fully in [6], to correct for frequency errors due to these cavity length variations. The frequency difference between the Raman beams is controlled to lock the closest integer harmonic that provides the correct energy for the transition. We take advantage of recent technology where the required signals to control the Raman transition are generated with a Radio Frequency System on a Chip (RFSoC)[6].

Because of this locking scheme, rather than targeting the integer harmonic that spans the 12.6 GHz transition, a software change is sufficient to lock the laser to a different harmonic which could be set to span a different transition. We typically lock to the 106th harmonic when trying to span the 12.6 GHz transition and the 18th harmonic when trying to span the 2.1 GHz. It is important to note that even if locked to a different harmonic, scanning in frequency space should still resolve the transition as we change the relevant 355 nm AOMs. The location of the effect would just be unstable as the 355 nm laser cavity drifts. The locking scheme would become increasingly important for a three-photon process to be applied mid-experiment but was not a limiting factor during the search to resolve the process.

The 355 nm beam path includes a 32-channel AOM that allows for light to be controlled via 32 individual foci, each with independent frequency control. A typical, though not fully optimized, scan demonstrating the capabilities of this system in shown in Figure 5. A single ion is physically moved through five 355 nm beams. As the ion moved through a beam, it is driven into the $|F = 1\rangle$ or “bright” state. For the duration of this project, we focused on maximizing as much 355 nm light to the ion. This included not only using tones from an individually addressed beam discussed here, but also using tones on a 355 nm beam that is focused to globally address a chain of ions.

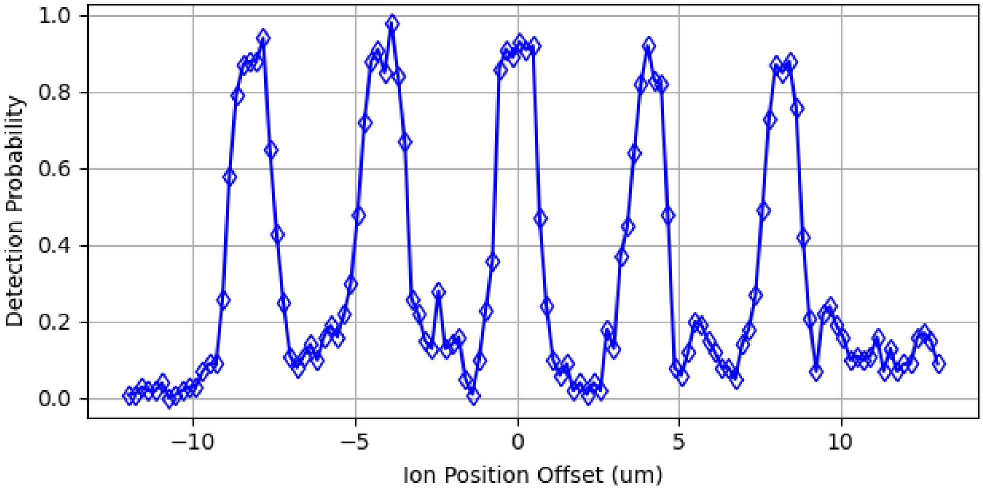

Figure 5: A sample scan of the individual addressing capabilities of the 355 nm imaging system. An ion is physically moved through 5 beams with the 355 nm light in a counterpropagating geometry driving the ion to the $|F = 1\rangle$ or “bright” state with a Raman transition.

Had the three-photon process been resolved, there are additional capabilities with the RFSoC setup that would allow for further minimization of crosstalk and could improve the individual addressability of three-photon effect[6].

RESULTS AND DISCUSSION:

Our novel optical pumping technique drives a three-photon transition between the $^2S_{1/2}\ |F = 1\rangle$ and $^2P_{1/2}\ |F = 1\rangle$ states, labeled $|1\rangle$ and $|b\rangle$ in Figure 6, with energies $E_{|1\rangle}$ and $E_{|b\rangle}$, respectively. All transitions between different Zeeman levels of these states are dipole-allowed except for $m_F = m_F' = 0$; therefore, by avoiding the polarization that only drives $\Delta m_F = 0$ Zeeman transitions, we can ignore the slight polarization dependence of the pumping process. This process involves three laser tones, where the i-th tone has frequency ω_i and detuning Δ_i from a one-photon transition with Rabi rate Ω_i, and the tones all add up to resonantly drive the three-photon transition: $\Delta = \omega_1 + \omega_2 + \omega_3 - (E_{|1\rangle} - E_{|b\rangle}) \approx 0$. For this transition be dominant, the three tones need to be far off resonance from all one-photon and two-photon transitions by satisfying $\Omega_i \ll \Delta_i$ and $\Omega_i^*\Omega_j /2\Delta_i \approx \Omega_i^*\ \Omega_j/2\Delta_j \ll \Delta_{ij}$, where Δ_i and Δ_{ij} are the one-photon and two-photon detunings, respectively.

We estimate the Rabi rate of the three-photon transition using third-order, time-dependent perturbation theory,

$$\Omega = \sum_{\mathrm{i}\neq\mathrm{j}\neq\mathrm{k}} \Omega_{\mathrm{ijk}}$$

$$\Omega_{\mathrm{ijk}} = \frac{\Omega_{\mathrm{i}}^{*}\Omega_{\mathrm{j}}\Omega_{\mathrm{k}}^{*}}{4(\omega_{\mathrm{j}}\text{-}\omega_{\mathrm{k}})\Delta_{\mathrm{k}}} \qquad (1)$$

where we have neglected terms that contain the sum $\omega_j + \omega_k$ in their denominator. To achieve optical pumping into the $^2S_{1/2}\,|F = 0\rangle$, labeled $|0\rangle$ in Figure 6, Ω needs to be large enough to produce a non-negligible probability for the ion to be in $|b\rangle$, from which the ion spontaneously emits a fourth photon and decays into $|0\rangle$ at the rate Γ = 19.6 MHz. We use the steady-state solution of the optical Bloch equations to find the probability for the ion to be in $|b\rangle$ at long times and multiply this probability by Γ to estimate the optical pumping rate,

$$\mathrm{R} = \frac{\Omega^2\Gamma}{\Gamma^2+4\Delta^2+2\Omega^2} \qquad (2)$$

where we have assumed a unity branching ratio for the spontaneous decay process.

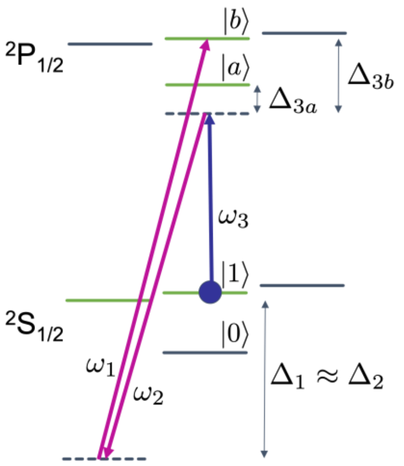

Figure 6: Level diagram and the dominate pathway for the three-photon optical transition. The blue arrow represents the global tone ω_3 from the 369 nm laser with single-photon detunings Δ_{3a} and Δ_{3b}. The purple arrows represent the individually focused tones ω_1 and ω_2 from the 355 nm laser, with single-photon detunings Δ_1 and Δ_2, respectively. The green levels are examples of states coupled by these three tones for a certain choice of polarizations.

Figure 6 shows how we implement the three-photon optical pumping process. A global 369 nm laser produces the tone ω_3 with the single-photon detunings Δ_{3a}= 30 MHz from the $|0\rangle$ - to -$|a\rangle$ transition and Δ_{3b} = 2.1 GHz from the $|1\rangle$ - to -$|b\rangle$ transition. Then an individually-focused

355 nm laser bridges the frequency gap Δ_{3b} for only one ion by producing the tones ω_1 and ω_2 split by $\omega_1 - \omega_2 = \Delta_{3b}$. These tones have the single-photon detunings $\Delta_1 \approx \Delta_2 \approx 33$ THz from the $^2S_{1/2}\,|F = 1\rangle$ to $^2P_{1/2}\,|F = 1\rangle$ transition and combine with ω_3 to resonantly drive the three-photon transition.

Each term $\mathbf{\Omega}_{ijk}$ in equation (1) corresponds to a different pathway of three-photon transitions, and we find that the term,

$$\Omega_{123a} \approx \frac{\Omega_1^* \Omega_j \Omega_{3a}^*}{4\Delta_1\Delta_{3a}} \tag{3}$$

dominates over the other terms for our choice of tone frequencies, where we have made the approximation $\omega_2 - \omega_3 \approx \Delta_1$, and we note that $\omega_{3a} = \omega_3$. The arrows in Figure 6 represent this pathway, and equation (2) gives its corresponding optical pumping rate on resonance,

$$R_{123a} = \frac{\Omega_{123a}^2 \Gamma}{\Gamma^2 + 2\Omega_{123a}^2} \tag{4}$$

To estimate this rate, we parameterize $\mathbf{\Omega}_{3b}$ by the saturation parameter, s_{3b}, of the $|1\rangle$ - to - $|b\rangle$ transition on resonance,

$$\Omega_{3b}^2 = \frac{s_{3b}\Gamma^2}{2}, \tag{5}$$

We also assume $\mathbf{\Omega}_1 = \mathbf{\Omega}_2$ and parameterize these Rabi rates by the π-time, τ_π, of a single-qubit Raman transition on resonance,

$$\Omega_1^2 = \frac{2\pi\Delta_1}{2}, \tag{6}$$

Assuming $s_{3b} = 1$ and $\tau_\pi = 1\mu$s, we have $\mathbf{\Omega} \approx \mathbf{\Omega}_{123a} = 116$ kHz and $R \approx R_{123a} = 1.36$ kHz for our choice of tone frequencies. In order for the three-photon optical pumping rate to be the dominant process, all off-resonant, single-photon pumping rates must be significantly smaller than R. For example, the global 369 nm tone ω_3 off-resonantly drives the $|1\rangle$ - to - $|b\rangle$ transition and pumps the ions into $|0\rangle$ at the rate,

$$R_{3b} = \frac{\Omega_3^2 \Gamma}{\Gamma^2 + 4\Delta_{3b}^2 + 2\Omega_3^2}\,. \tag{7}$$

Although Δ_{3a} is much smaller than Δ_{3b}, scattering off the $^2P_{1/2}\,|F = 0\rangle$ state, labeled $|a\rangle$ in Figure 6, does not cause the ions to decay into $|0\rangle$ because this transition is dipole forbidden, and we only require a large ratio of R_{123b} to R_{3b} to observe the three-photon pumping process, even though R_{123b} benefits from the small value of Δ_{3a} in the denominator of $\mathbf{\Omega}_{123a}$ in equation (1). This ratio is,

$$\frac{R_{123b}}{R_{3b}} = \frac{\Omega_{123b}^2}{\Omega_3^2}\frac{\Gamma^2 + 4\Delta_{3b}^2 + 2\Omega_3^2}{\Gamma^2 + 2\Omega_{123b}^2}\,, \tag{8}$$

$$\approx \frac{\Omega_1^2\Omega_2^2}{16\Delta_1^2\Delta_{3a}^2}\left(1 + 4\Delta_{3b}^2/\Gamma^2\right). \tag{9}$$

where we have made the approximations $\mathbf{\Omega}_{123b} \ll \Gamma$ and $\mathbf{\Omega}_3 \ll \Delta_{3b}$. For our choice of laser parameters, we have $R/R_{3b} \approx R_{123b}/R_{3b} = 6.59$. We can see that increasing Δ_{3b} would enhance this ratio but simultaneously reduce R. Interestingly, decreasing Δ_{3a} provides a dramatic increase in both R and the ratio of R/R_{3b}. Decreasing Δ_{3b} to zero would invalidate the third-order perturbation theory and drive a "1+2-photon" optical pumping process instead. In this process, a resonant drive of the $|1\rangle$ - to - $|a\rangle$ transition by ω_3 populates $|a\rangle$, from which ω_1 and ω_2 drive a two-photon Raman transition between $|a\rangle$ and $|b\rangle$. Although all of the ions would be disturbed by ω_3, only the individually addressed ion would be pumped into $|0\rangle$.

Experimentally, we have performed extensive spectroscopy within this project, including upgrades to both the hardware and software components of the apparatus. We have focused on increasing the expected signal through maximization of the available power and going to long delays. A majority of the spectroscopy scans performed were similar to what is shown in Figure 7. In this set of scans, we cool the ion with a 369 nm beam, we apply a probe pulse with the different 369 nm beam detuned for the three-photon process at the same time with the 355 nm light, and then we detect using the original cooling beam. In the absence of the three-photon effect we expect that the ion will be mostly bright after cooling and thus be close to a probability of bright detection of 100%. In a different set of scans, we modified our experiment to include the previously defined single-photon optical pumping step and then use a microwave pulse to put the ion in the bright state with higher fidelity. The microwave pulse was controlled by a DDS channel on electronics separate than the RFSoC to ensure that it would not affect the subsequent pulses designed to search for the three-photon process. Performing this step did not have a significant impact on the signal-to-noise and added additional complication and was therefore not included in later scans.

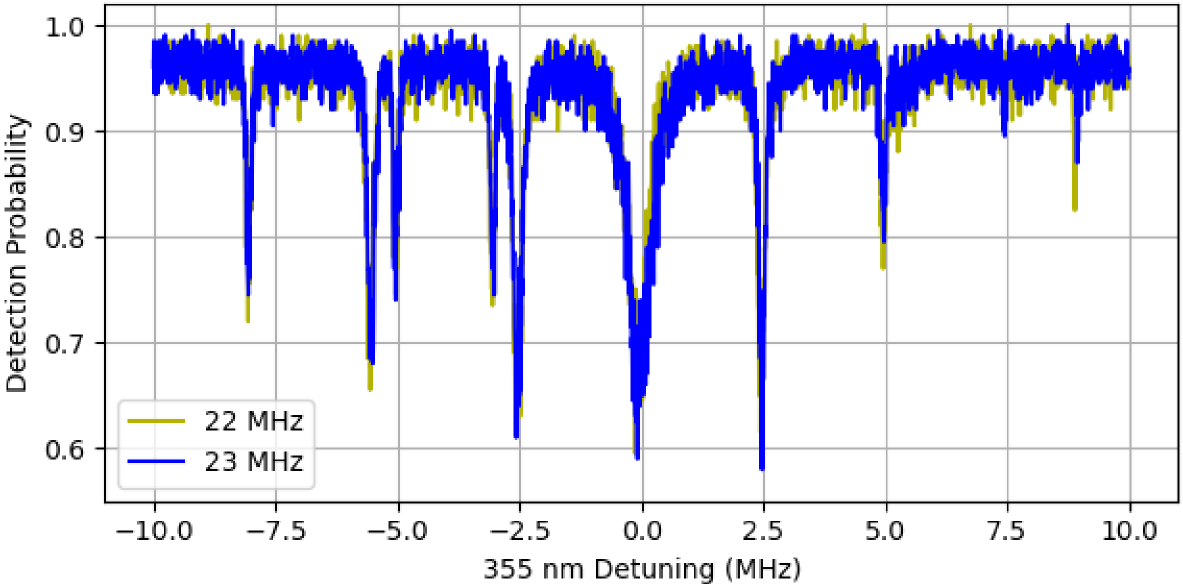

Figure 7: A sample set of experiments scanning the frequency of one of the two 355 nm AOMs. Changing one of the two 355 nm frequencies scans through known Raman transitions which appear as downwards spikes in the scan. Any feature that depends on the three-photon process will change with the detuning of 369 nm laser, shown in the legend.

A separate scheme to resolve the three-photon process involved going to a smaller detuning controlled by the 369 nm double-pass AOM as shown by the schematic in Figure 8. The small detuning from the existing single-photon optical pumping process would not be effective when applied to a chain of ions because neighboring ions would begin to pump dark. However, this process was theoretically calculated to be at least twice as efficient as the originally proposed three-photon process. Resolving the effect in a different regime would develop understanding over how to approach maximizing the signal at larger detunings (which then would allow for individual addressing). When the single-photon optical pumping process is appropriately calibrated with the 2.105 GHz EOM it is a very efficient process, producing a nearly perfect state preparation in less than 10 µs. Even going to 30 MHz of detuning with the AOM, the single-photon optical pumping was roughly equivalent as shown in Figure 9. Compared to such an efficient process, it would be extremely difficult to resolve the three-photon process before the ion was pumped dark. We also explored if we could gain additional detuning by changing the frequency of the 2.105 GHz EOM and found that it had a very limited range.

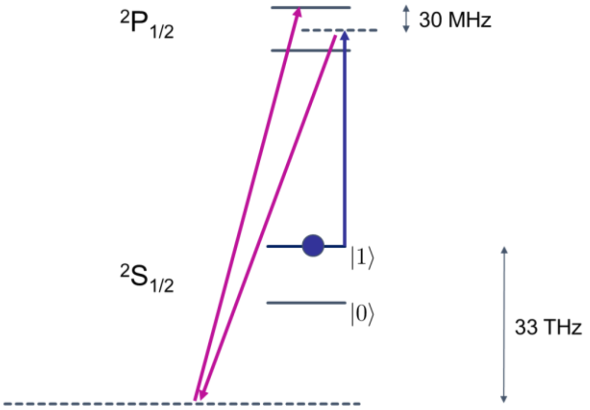

Figure 8: Schematic of three-photon optical pumping with small detuning. This three-photon process with the 2.105 GHz EOM turned on should produce a stronger pumping rate compared to the process described in Figure 1.

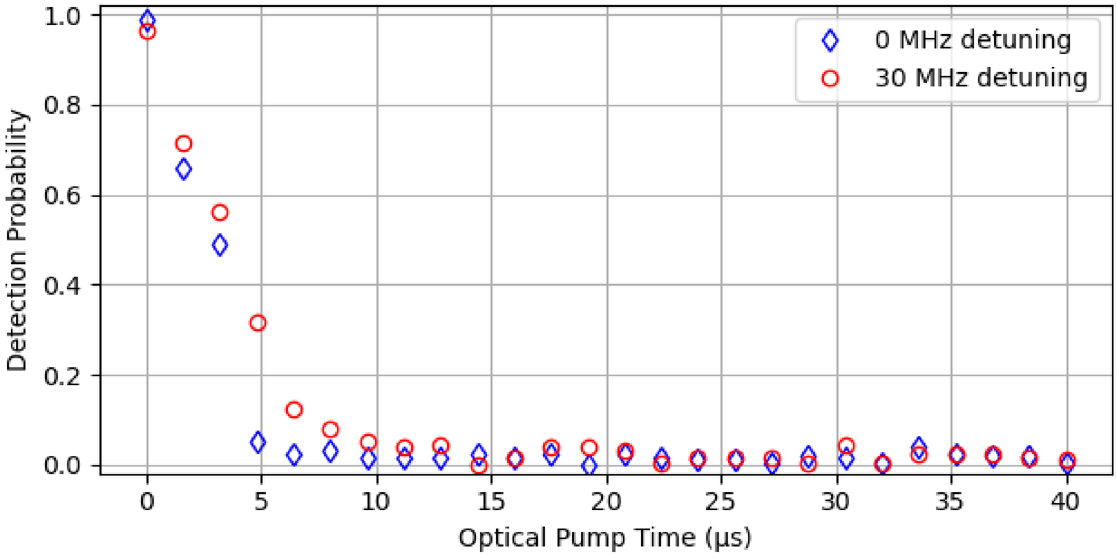

Figure 9: Single-photon optical pumping with the 2.105 GHz EOM turned on. Modifying the detuning of the 369 nm AOM does not have a sufficient effect to allow for the resolution of a slower optical pumping process.

At larger detunings it is important that we maximize the 369 nm power to resolve the three-photon process. Figure 10 shows that with this higher power and at moderate probe times, we see the ion nearly completely pumped dark. We monitor the throughput 369 nm power with a photodiode on the far side of the experimental chamber. Included in Figure 10 are different probe pulse times and 369 nm photodiode voltages. At 0.39 V this corresponds to approximately 3.0 μW of power. We normally operate this experiment with the same beam at 0.05 V which corresponds to approximately to 0.4 μW of power. At the higher power, we noticed that the fluorescence scattered from the ion during idle time (between experiments) not only saturated but had started to slightly decrease. Furthermore, we see the expected two-photon features broaden and shift during our three-photon optical pumping scans.

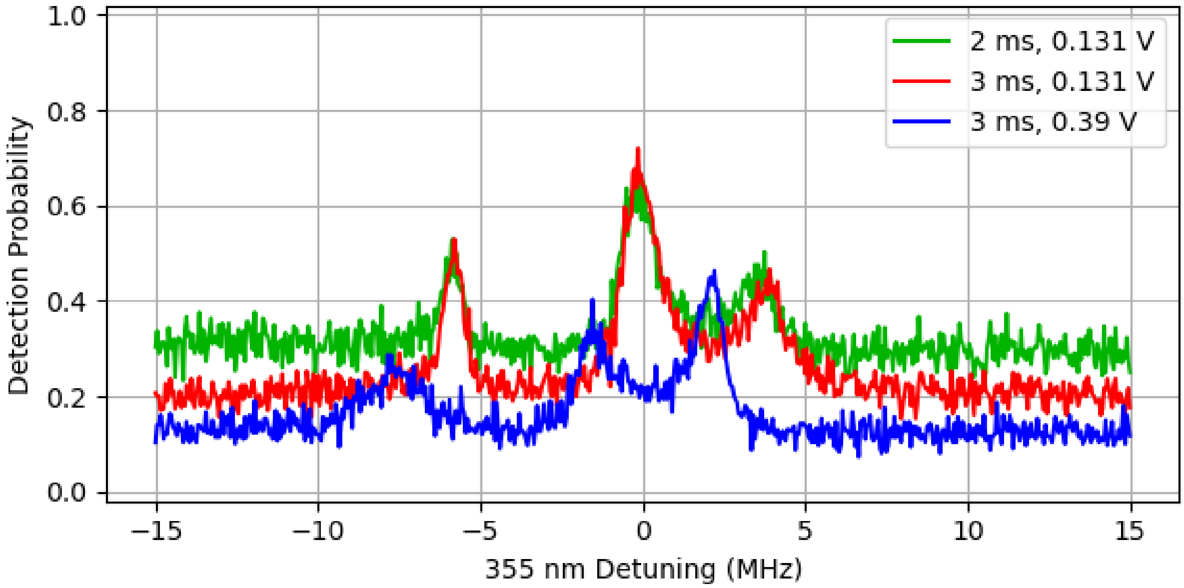

Figure 10: Spectroscopy scans looking for a three-photon process at higher 369 nm power. There is sufficient 369 nm power to optically pump the even with the 2.105 GHz EOM fully turned off and we observe broadening and shifts peaks due to the known two-photon Raman transitions.

At full 369 nm power, with the 2.105 GHz EOM and the 355 nm light off, we see a single-photon optical pump times on the order of a few ms, as shown in Figure 11. Based on our calculations that this frequency independent optical pumping effect may be due to off-resonant coupling to the $^2P_{1/2}$ $|F = 1\rangle$ state, we should have more than a sufficient amount of 369 nm light to observe a three-photon process. It is possible that an additional pathway may be contributing to this pumping and this remains an active area of interest to investigate.

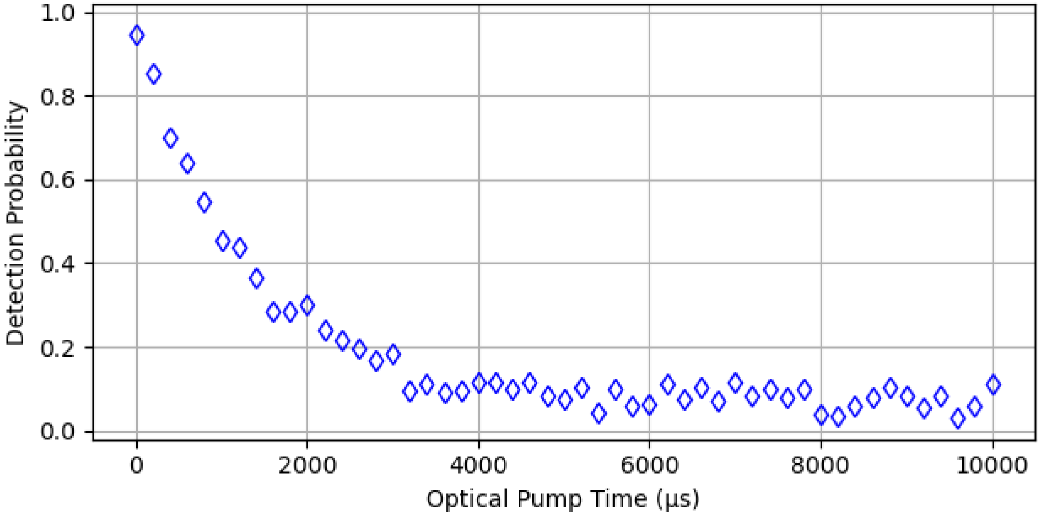

Figure 11: With the 369 nm laser power maximized and the 355 nm laser off, we see that a single-photon optical pumping effect appears to be dominant in as little as 2 ms. This is a significant limitation for the observation of the possibly slower three-photon process.

Based on the observations at higher 369 nm power, especially as it appeared enough to broaden and shift the known two-photon peaks, we moved to operate with moderate probe times of around 1 to 2 ms so as not to be dominated by frequency independent optical pumping. Because of trapped ion's long coherence times we expect experiments to be able to last for many ms. In Figure 12, the observation of one and two-photon processes provide a measure of how we could best explore the parameter space. This corresponds to roughly 20% of the 369 nm power compared to the experiment performed in Figure 10. We expect to see the structure that depends on the 355 nm AOM frequency. Regardless of which harmonic we are locked to, we expect to see a carrier oscillation around 0 MHz AOM detuning as it drives the 12.6 GHz transition putting ion population either from a primarily dark state bright or a primarily bright state dark. We explored a wide range of 369 nm detunings and corresponding 355 nm detunings. As shown with Figure 7, we were unable to resolve a feature that shows the correct frequency dependence, indicative of a three-photon process. Even at more moderate 369 nm powers, we still see a frequency-independent effect that begins to obscure our search as the ion is pumped dark.

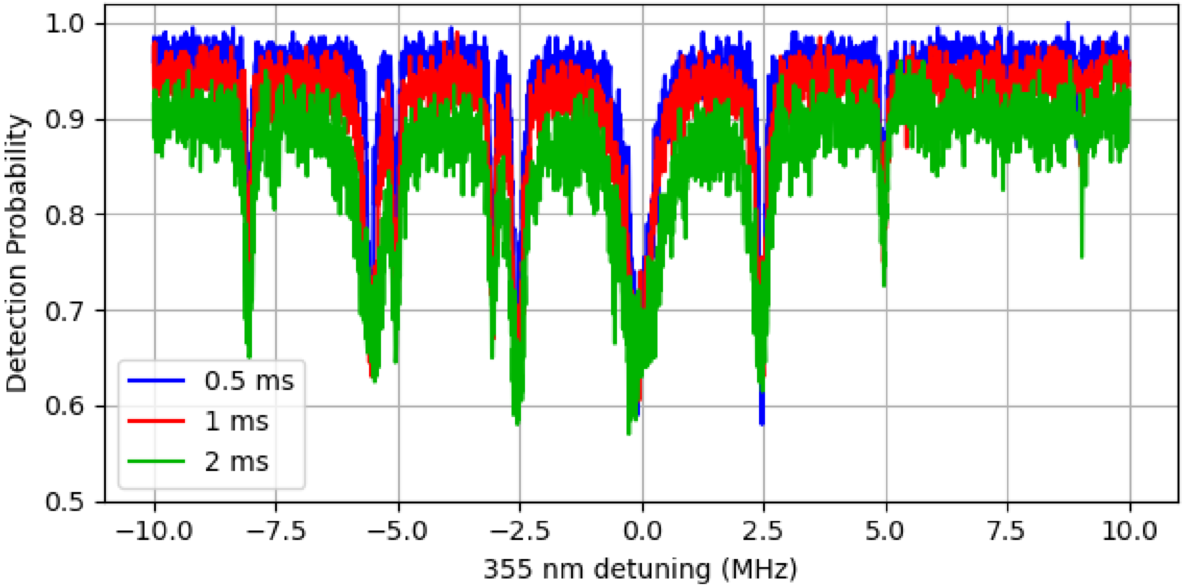

Figure 12: Spectroscopy scan showing the expected two-photon processes driven by the 355 nm laser with increasing single-photon optical pumping as the probe time is increased.

ANTICIPATED OUTCOMES AND IMPACTS:

Throughout this project we have worked extensively with members of other trapped ion teams at Sandia, including the Quantum Scientific Computing Open User Testbed (QSCOUT), LogiQ, Malpais, as well as others. Information has been shared about the methodology and attempts at resolving the three-photon process and suggestions and brainstorming were returned about why were unable to resolve the process. Our focus on this effort has provided a helpful influence on these programs who have considered a similar approach or have already dedicated resources to attempting this process. We suggest that ion chain shuttling protocols be a more effective focus for these projects as it is lower risk means of performing mid-experiment measurements.

A focus of the original proposed project was to explore the expansion of individual addressability within the recent technological advancements. We believe that using the 355 nm imaging setup as well as the locking and frequency control remain a way this can be done. Any optical process that involves the 355 nm should be one that could be individually addressed in a chain of ions. We felt that the optical pumping process was the simplest part of the experimental process that could demonstrate this individual addressability expansion, but the correctly tuned process could also access either sideband cooling or individually addressed detection. These steps together would allow for a complete quantum error correction circuit to be performed without shuttling and would be an appropriates scope for a full laboratory directed research and development (LDRD) project or would be interest to other quantum computing calls as well as the projects already mentioned. If a separate optical process can be demonstrated, this technology could readily explore these types of quantum engineering advancements.

Given the work already performed calculating the expecting three-photon pathways and their respective pumping rates we remain optimistic that this work could lead to a theoretical publication with minimal additional support. With the experimental results recorded in this project we may be able to narrow the parameter space for a future search even if it requires additional resources not available on a standard ion trapping experiment or what was available during the course of this project.

CONCLUSION:

In conclusion, we were unable to demonstrate the three-photon effect despite seeing expected single-photon and two-photon processes. Because of this, we were unable to explore how this process could be applied to achieve individually addressed state preparation. Theoretical calculations show that a three-photon process should be resolvable with our current laser powers and detunings. We believe that other processes may affecting the electronic state of the ion, obscuring the three-photon process, and consider this an area of on-going interest, though one that remains high risk. In order to fully resolve the three-photon process, we also may need to advance past what is currently available in state-of-the-art ion trapping experiments.

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ADDENDUM:

LDRD
LABORATORY DIRECTED
RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

Three-Photon Optical Pumping for Quantum Computing, LDRD 224703

Craig Hogle (PI, 5225), Megan Ivory, Daniel Lobser, Brandon Ruzic, Christopher DeRose (PM, 5225)

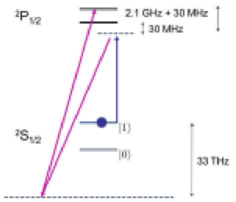
We sought to demonstrate a new form of quantum state preparation.

Current quantum computers are able to perform high fidelity operations but are often limited by the number of qubits which can be fully controlled. We tested a new scheme that would have allowed for full individually addressed state preparation using existing technology.

Based on theoretical calculations, we performed spectroscopy looking for signatures of a three photon process that would allow for state preparation. This experimental information motivated developing an explanation of what parameters are required to observe this effect. While we were unsuccessful in observing a three-photon signature, we gain valuable understanding of what pathways may be limiting this effect.

The three-photon process

We predicted the three photon optical pumping rate would be comparable to the current state preparation methods. It ended up being unresolvable with our current methods.



- A major hardware upgrade of the experimental system was performed installing a new surface ion trap for ongoing use
- The experimental/theoretical collaboration produced new ideas and other three photon processes were explored
- With greater understanding of the expected three-photon process we seek to aid other groups who may look for similar processes

We did not achieve evidence of the three-photon process, and therefore were unable to push it towards individually addressed applications. We believe we have narrowed towards experimental requirements that may be able to see this in the future, even if this is beyond a typical experimental setup.

Among the lessons learned was to how to better account for the uncertainty of hardware failures. It is important to allow for as many contingencies as possible.

Results and understanding have been continuously shared with other ion trapping projects here at Sandia. This process may see future applications as ion trapping continues to improve and develop.

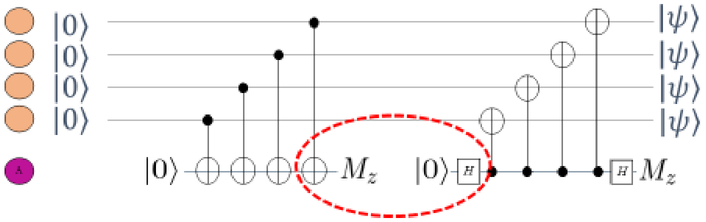
Two project staff are early career scientists and project staff included a promotion to principal and a staff member promoted from a postdoctoral appointee. This was the PI's first experience in that role.

Background: Quantum Computing Motivation

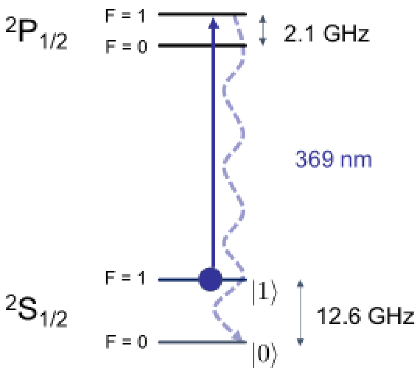
Quantum computing has the potential to provide significant advantage over classical computing, taking advantage of states that are not allowed with binary logic. The information in a single quantum state requires a significant number of bits in a classical computer. A main limitation is often the number of **quantum bits (qubits)** that can be maintained and controlled.

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

In a quantum circuit, a quantum state is **prepared**, manipulated and measured. Mid-experiment measurements must be performed without affecting the other qubits. Currently this is done by stopping the circuit, physically moving the qubits, performing operations and then moving the qubits back.



Background: Current limitations for State Preparation



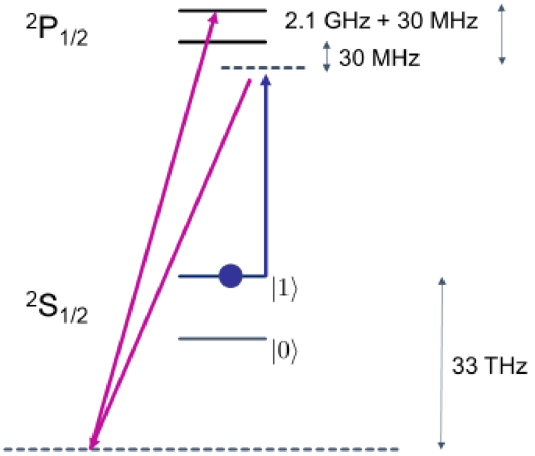
State preparation requires forcing an ion to be in a **particular electronic state** with near perfect probability.

To perform state preparation, a 369 nm laser is tuned to use selection rules to pump the ion to a single state. This cycle can be repeated until the ion is prepared to its exact state.

This single photon **optical pumping process is efficient** (10 µs for an experiment that runs for 10's of ms) **and precise** (near perfect preparation)[1], however it affects all ions and even a single crosstalk photon can negatively impact the state of a neighboring ion.

[1] Olmschenk, S., et al. Phys. Rev. A 76, 052314

A New Scheme for Three-Photon Optical Pumping



We sought to demonstrate a novel scheme for optical pumping that will utilize the **individual addressability of the 355 nm laser** system in combination **with a detuned global 369 nm laser**.

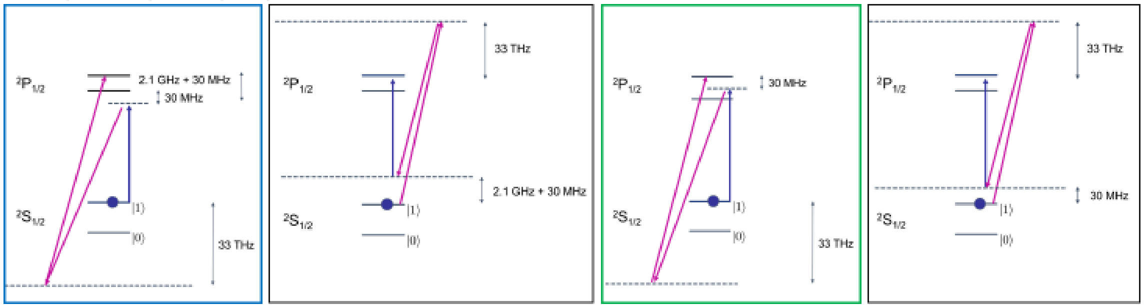
The 369 nm light, which will affect the entire chain of ions, must be sufficiently **detuned from resonance** to not destroy the neighboring ions.

We will measure **1) optical pumping rate** and **2) neighboring ion state population** as a function of global laser detuning to prove this technique can be advantageous to current optical pumping method.

Theoretical estimates of other three photon processes

Theoretical calculations were advanced throughout the scope of the project. The lasers are applied simultaneously so there is not an order to the three photon process, nor control of what other states may contribute.

Other possible pathways explored:

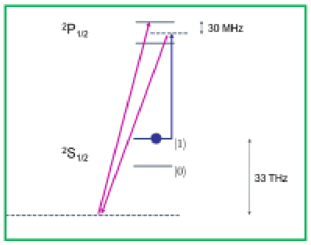


This clarified the pumping pathways which contribute and allowed for brainstorming for other detunings. Calculations continued to support that this should be observable experimentally.

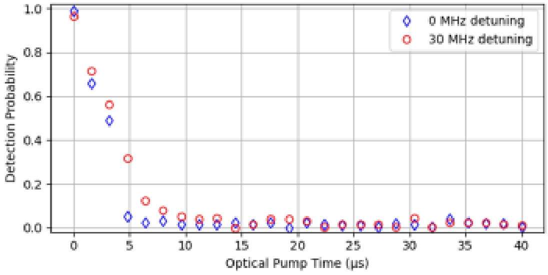
Small Detunings Are Single-Photon Dominated

- Small detunings proved insufficient and were dominated by the typical single photon optical pumping process.
- We discovered the 2.1 GHz electro-optic modulator (EOM) would not provide a continuous shift over the bandwidth.
- Small detunings would have been insufficient to use with a chain of ions

Proposed 3 Photon Scheme: Expected timescale ~100 us

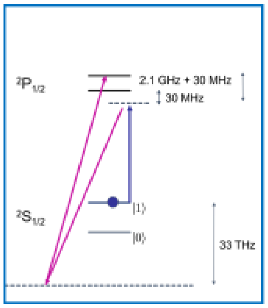


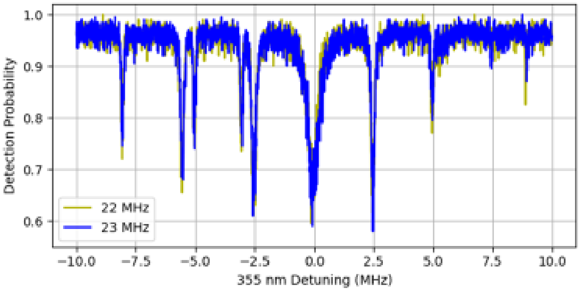
Previously observed 1 Photon Scheme: Timescale ~10 us



Spectroscopy Results

We have performed extensive spectroscopy within this project, including upgrades to both the hardware and software components of the apparatus. We have focused on increasing the expected signal through maximization of the available power and going to long delays.





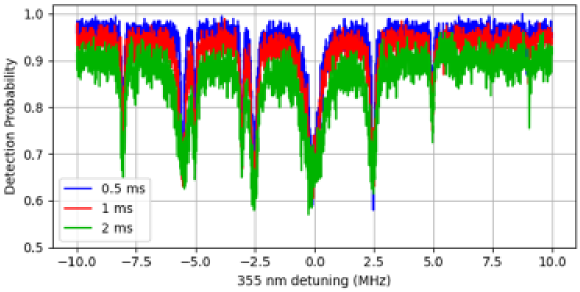
Optimizations performed:

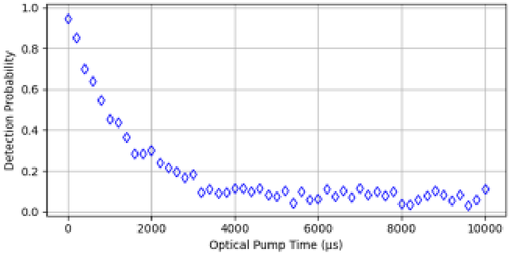
355 nm detuning
369 nm detuning
2.1 GHz settings
Initial state preparation
369 intensity
Pulse probe time
Relative detuning 355/369
355 beam geometry
Signal-to-noise limitations
Scan resolution

We have performed extensive spectroscopy within this project, including upgrades to both the hardware and software components of the apparatus. We have focused on increasing the expected signal through maximization of the available power and going to long delays.

Spectroscopy Results

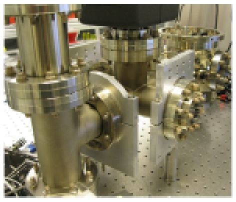
The observation of expected one and two photon processes provide a measure of how we could best explore the parameter space. We had expected a need to maximize the power of the 369 nm laser. With this optimization we observed a process similar to the single photon optical pumping but on longer time scales. When this effect is compared to the known optical pumping rates we suspect that there are other pathways limiting the resolution of the three-photon effect.

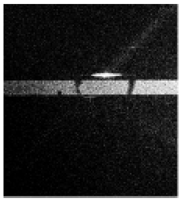




Lessons Learned

- If possible, allow for contingencies for any change in experimental hardware.
- This project provided excellent collaboration with our theoretical calculations.





Project Legacy

- We have exhausted the available avenues looking for a three photon process and have shared this information with other ion trapping groups at Sandia (LogiQ, QSCOUT, Malpais, …). This will hopefully help direct their efforts towards more risk adverse techniques for state preparation such as shuttling chains of ions.
- The work performed will set the stage for a manuscript for a theory paper. We remain optimistic that may yet produce a publication.
- Two members of the project team are early career; two members received promotions within the scope of the project (postdoc to staff, senior to principal); first time PI of a project