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Variable-strength measurement in a single ^{40}Ca$^+$ Qubit

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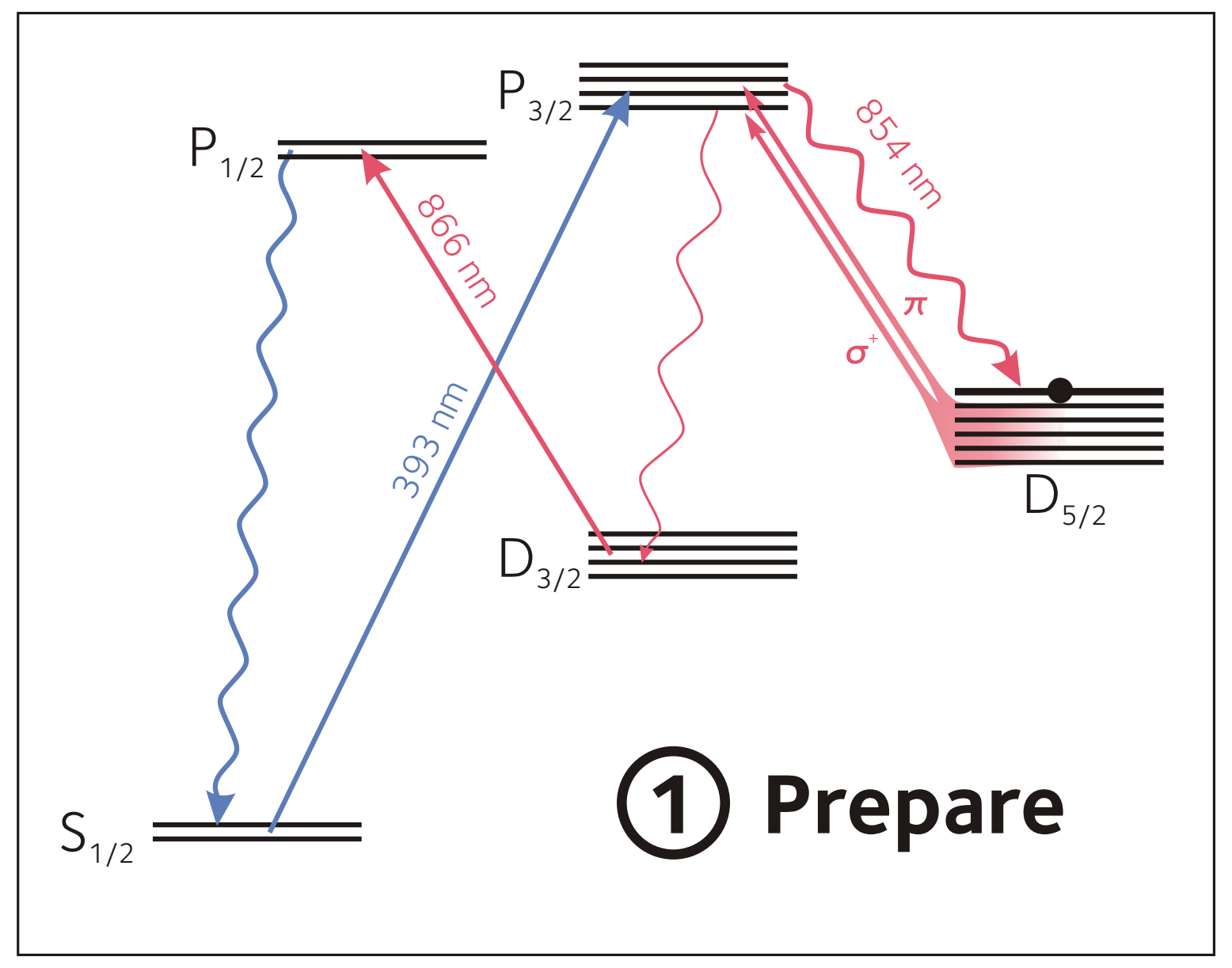
State Measurement and Wavefunction Collapse

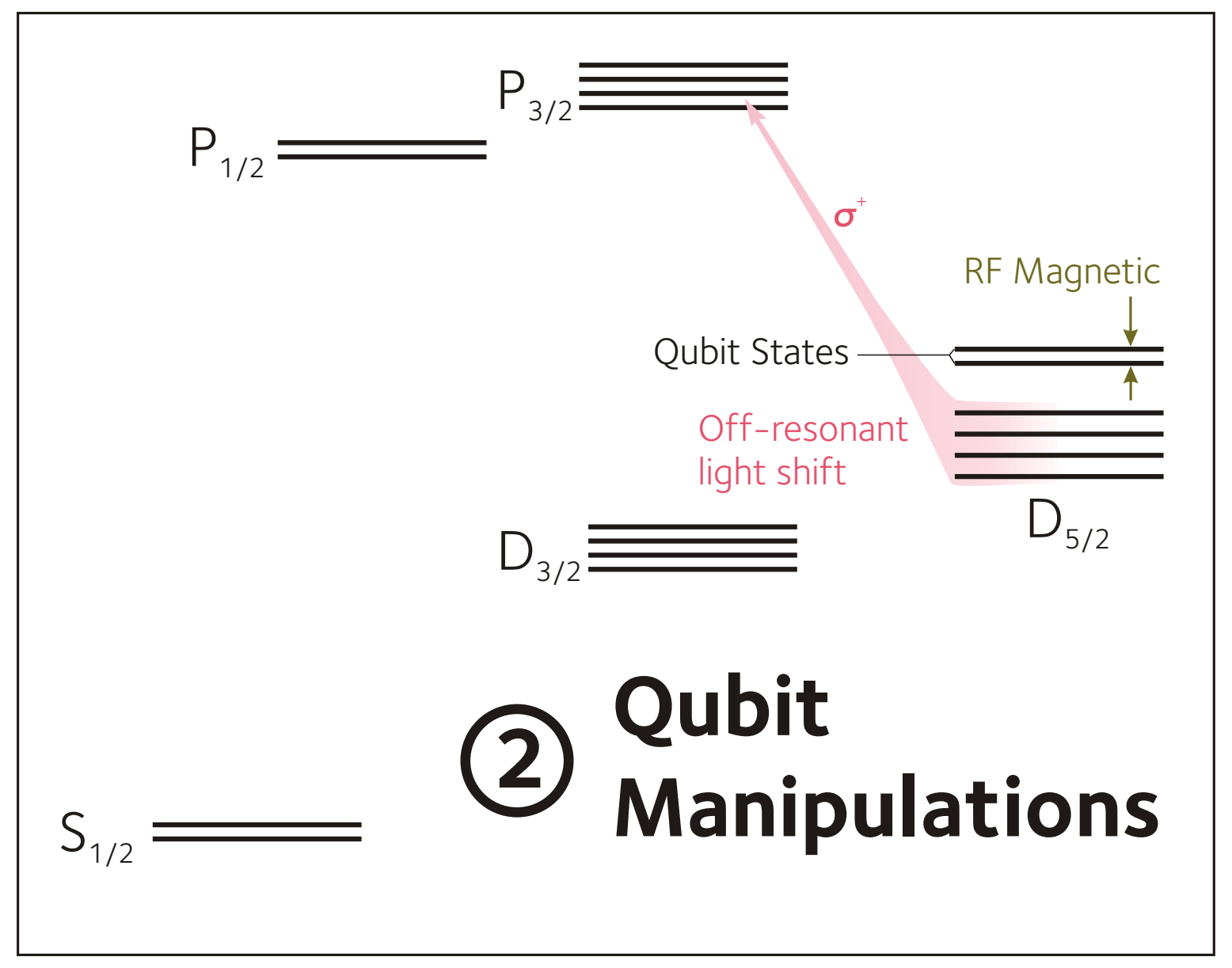
The description of quantum mechanical measurement as resulting in a "wavefunction collapse," whereby a system is irreversibly projected into an eigenstate of a measurement operator, is simply a special case of a much richer theory of the interaction of a quantum system with a measuring device. In particular, a generalized measurement need not be irreversible in the sense that it is possible to fully restore an unknown and arbitrary quantum state even after a measurement has been made on it. A non-projective measurement need not destroy all information about the initial superposition wavefunction; it can leave the system's wavefunction "partially collapsed." Since this process involves non-unitary evolution, it will not be possible to restore or "uncollapse" the wavefunction by coherent control alone. However, another well-chosen measurement process with a "lucky" result can map the partially-collapsed wavefunction back to its initial state.

We describe an experimental procedure to partially collapse and restore the wavefunction of a quantum bit stored in two magnetic sub-levels of a ^{40}Ca$^+$ trapped-ion qubit. We prepare the qubit in a coherent superposition of the $D_{5/2}$ $m = +5/2$ and $m = +3/2$ states, and perform a weak measurement which detects the $m = +3/2$ state with probability p, but does not detect the $m = +5/2$ state. If no detection event occurs, we partially collapse the superposition (this becomes a projective measurement if we perform a "strong" measurement with $p = 1$). We extract some classical information about the system even if no detection even occurs because of the asymmetry in the detection probability. We then coherently swap the amplitudes of the states in the partially-collapsed qubit with a π-pulse, then perform the same measurement. If we again have no detection event, the classical information we extract undoes the asymmetry from our first measurement, and we restore the qubit to its initial state (up to a π rotation)[1]. This occurs with an overall probability 1-p (for two null results) regardless of the qubit's initial state. If we get a detection event in either measurement, we fully collapse the system.

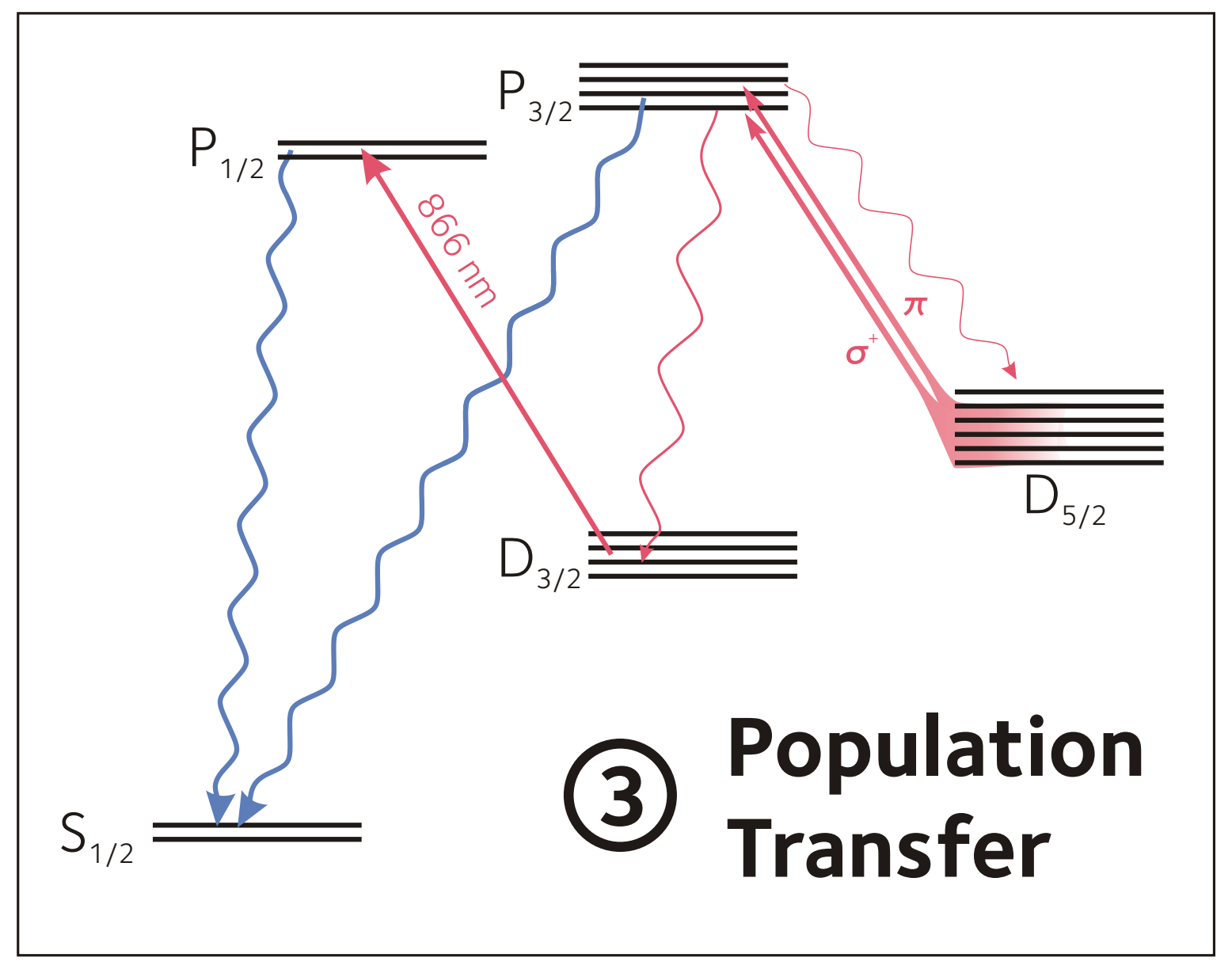
^{40}Ca$^+$ $D_{5/2}$ Qubit Operations



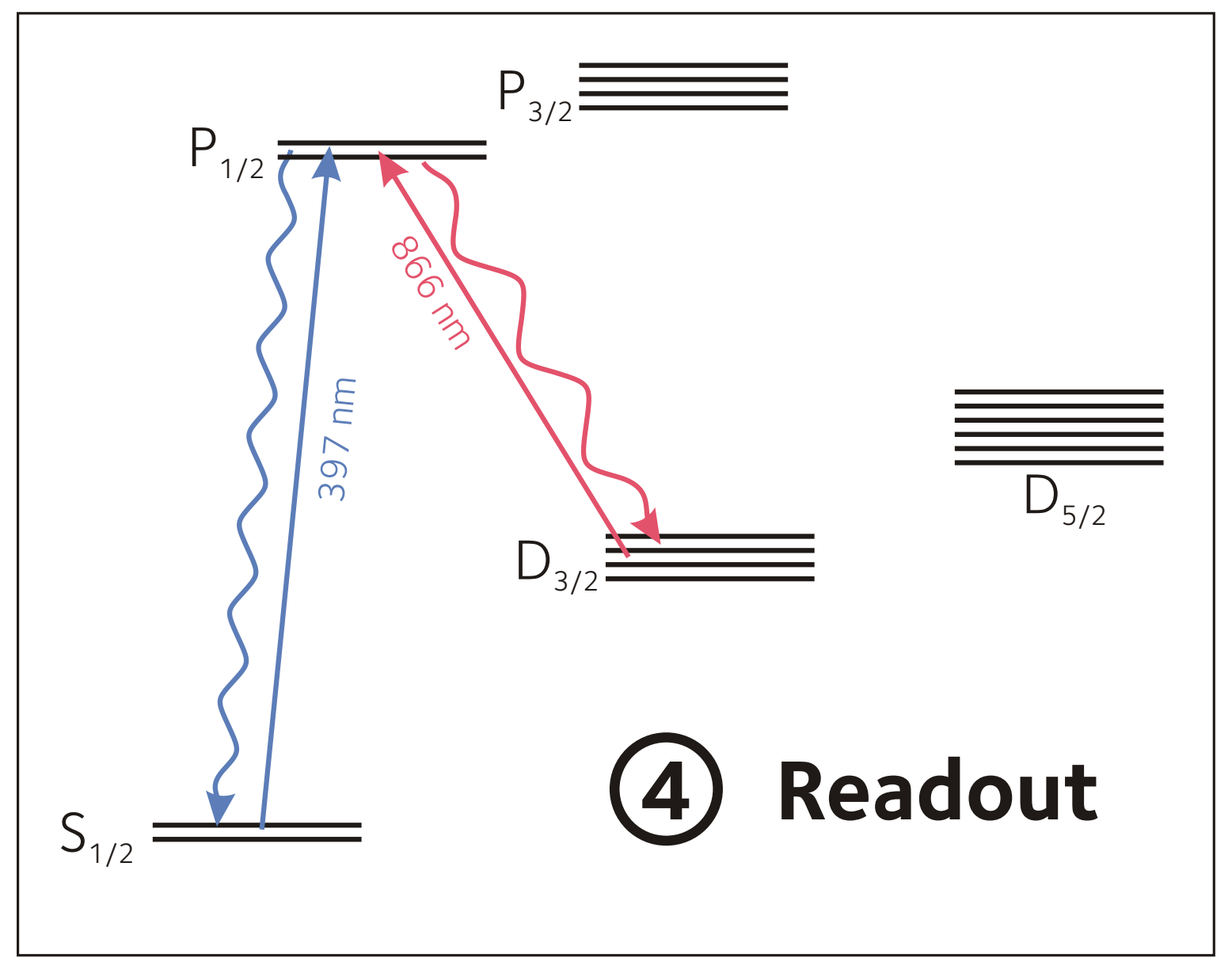
① **Prepare**



② **Qubit Manipulations**



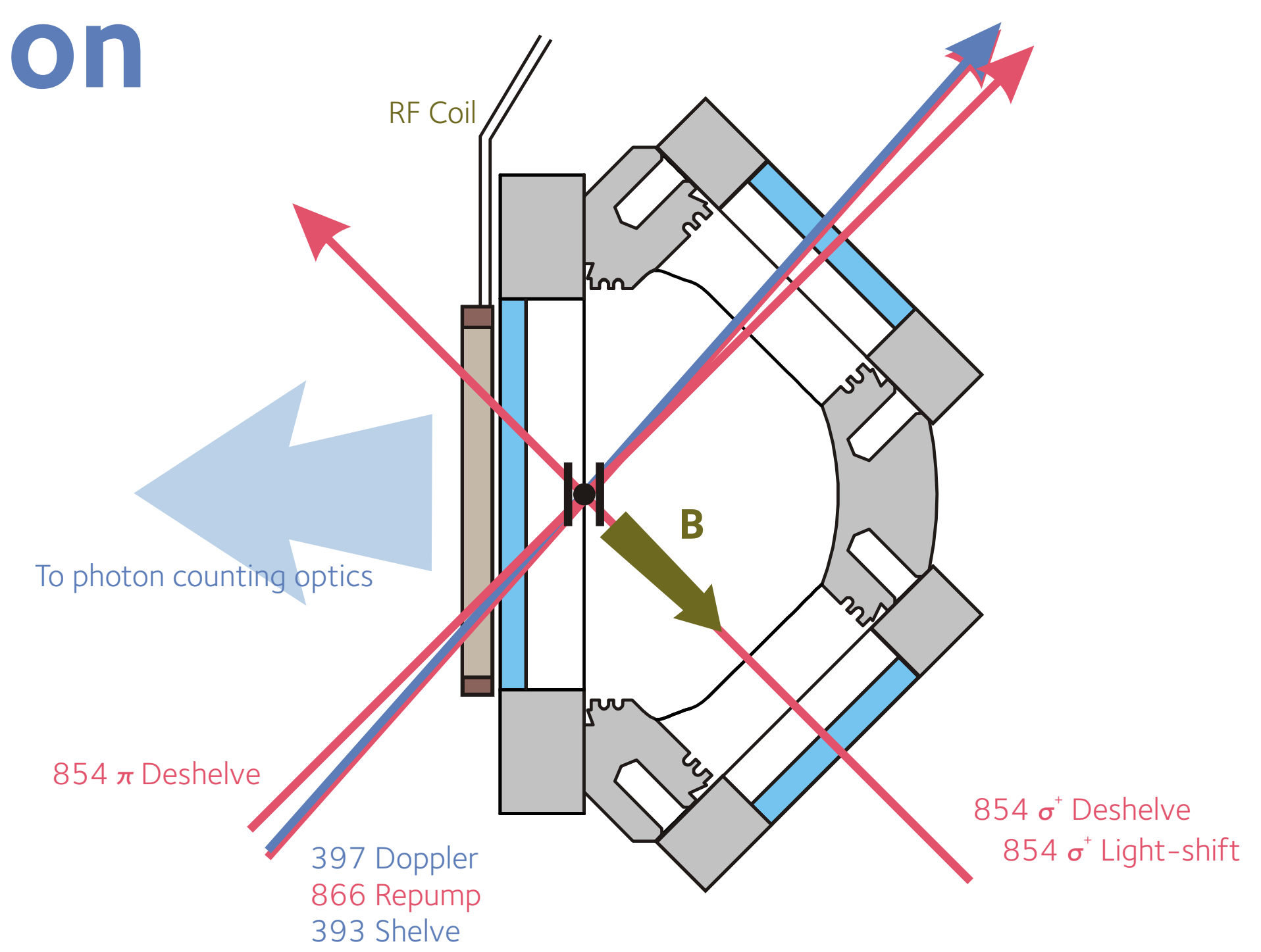
③ **Population Transfer**



④ **Readout**

State Preparation

Laser light at 393 nm excites the ion from its ground state to the $P_{3/2}$ state where it decays with a 5.3% branching ratio to the $D_{5/2}$ state. This metastable state has a lifetime of 1168 ms. We apply laser light at 854 nm, polarized to σ+ and π to optically pump to the $m = +5/2$ level which forms our initial state.



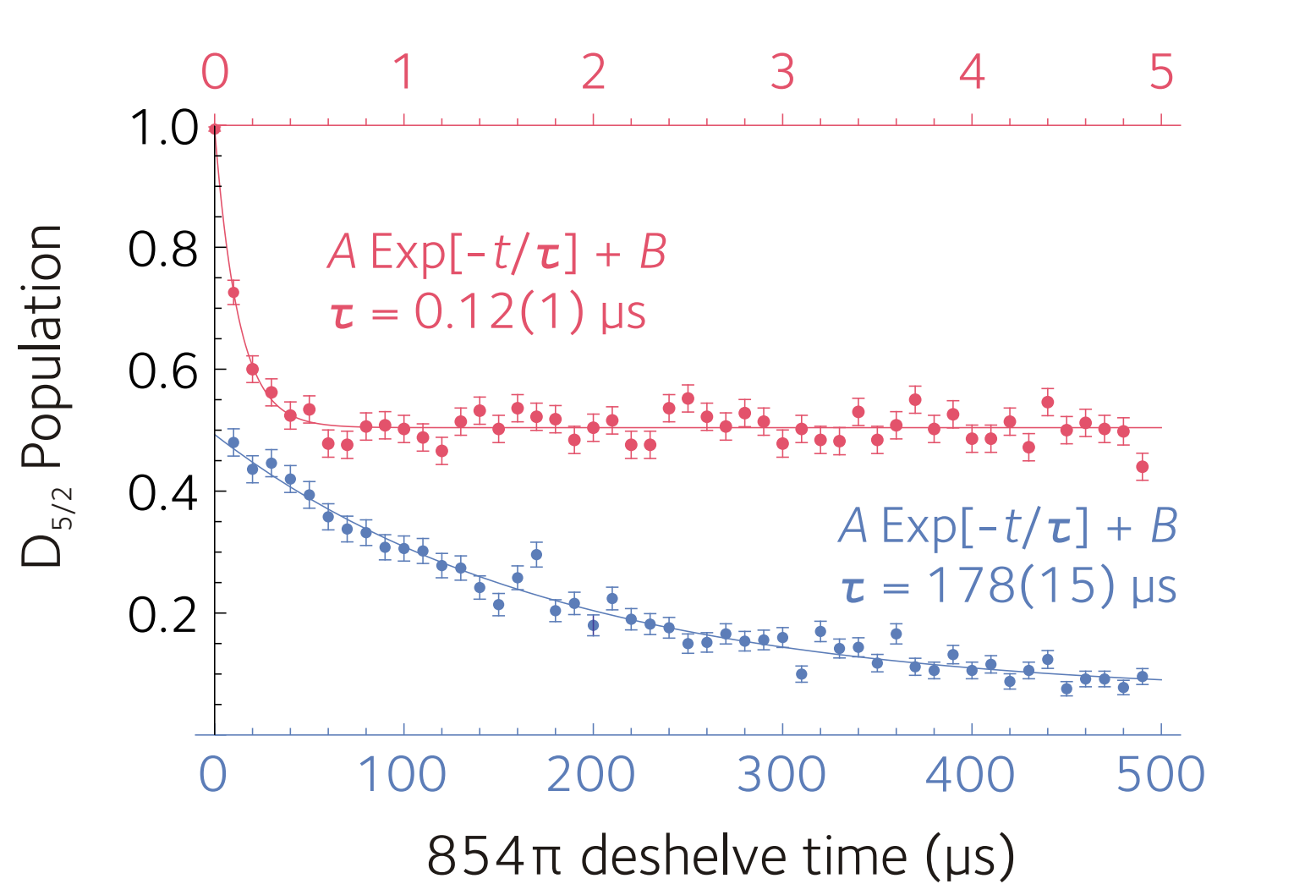
Qubit Manipulations

The m-states in the $D_{5/2}$ manifold are split by the Zeeman effect by ~2.7 MHz, which we drive with a small coil mounted near the front window of the vacuum system. An intense laser near 854 nm is applied red-detuned by ~10 GHz to create a differentiating light shift which lifts the degeneracy in the magnetic level splitting. It is polarized σ+ to leave the qubit states ($m = +5/2$ and $m = +3/2$) unshifted. This reduces the $j = 5/2$ manifold to an effective two-level system, so long as the magnetic dipole Rabi frequency is small compared with the light shift.

Population Transfer

Lasers polarized to σ^+ and π, and resonant with the $D_{5/2}$ - $P_{3/2}$ transition near 854 nm couple to the $m = +3/2$ state but not the $m = +5/2$. This allows us to selectively deshelve one qubit level. By varying the length and/or intensity of the pulse, we can vary the proportion of the $m = +3/2$ amplitude that we deshelve. Population excited to the $P_{3/2}$ level quickly decays radiatively, predominately to the ground state (94% branching). Population which decays back to the $D_{5/2}$ (5.3% branching) contributes to errors in the experiment. A laser at 866 nm repumps any population which decays to the $D_{3/2}$ (0.63% branching).

Time scan of 854π deshelve, random m-state preparation



Polarization purity allows us to clear out $m = +3/2$ population >1000 times faster than we deshelve $m = +5/2$ population.

Readout

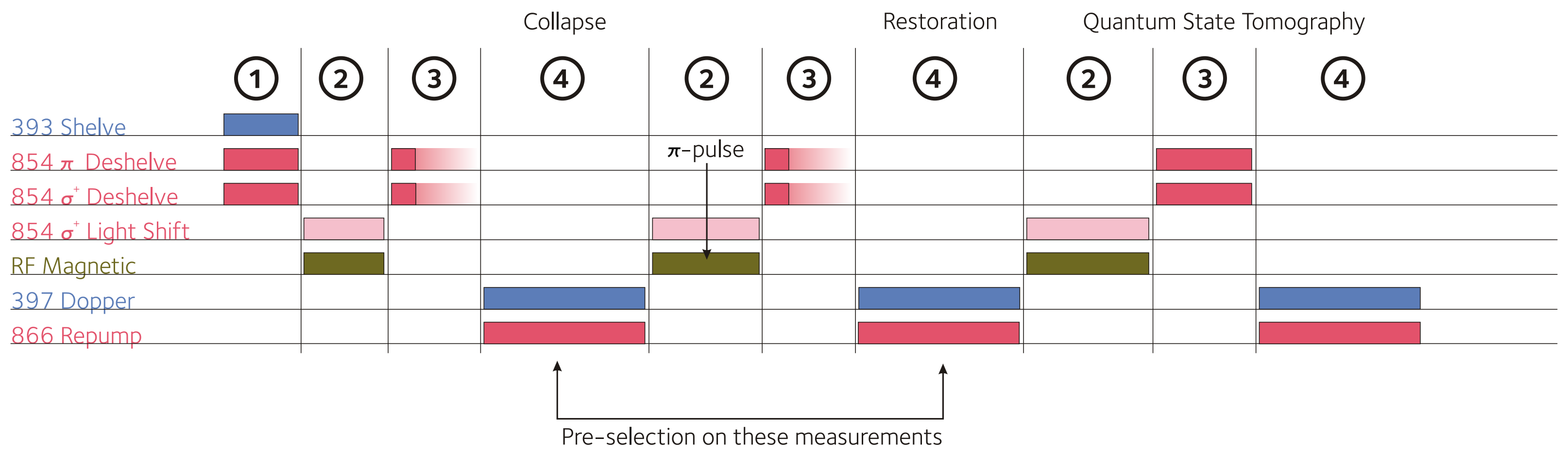
A laser resonant to the $S_{1/2}$ - $P_{1/2}$ transition at 397 nm will cause an ion in the ground state to fluoresce. A "repump" laser resonant with the $P_{1/2}$ - $D_{3/2}$ transition at 866 nm prevents optical pumping due to the 6% branching on the decay from the $P_{1/2}$ excited state. An ion in the $D_{5/2}$ metastable state will not fluoresce and remains essentially undisturbed by these laser pulses. By counting scattered photons we can discriminate between these states and read out the ion. Using a simple threshold method with a fixed readout time we can obtain 99% average fidelity, and by using a time-resolved maximum likelihood method we have previously demonstrated 99.99% average fidelity [2].

[1] **Reversal of the Weak Measurement of a Quantum State in a Superconducting Phase Qubit**
N. Katz, M. Neeley, M. Ansmann, R. C. Bialczak M. Hofheinz, E. Lucero, A. O'Connell, H. Wang, A. N. Cleland, J. M. Martinis, and A. N. Korotkov, Phys. Rev. Lett. **101**, 200401 (2008)

[2] **High-Fidelity Readout of Trapped-Ion Qubits**
A. H. Myerson, D. J. Szwer, S. C. Webster, D. T. C. Allcock, M. J. Curtis, G. Imreh, J. A. Sherman, D. N. Stacey, A. M. Steane, and D. M. Lucas, Phys. Rev. Lett. **100**, 200502 (2008)

Partial Collapse and Restoration

An experimental pulse sequence is illustrated schematically below: We prepare the ion in the $m = +5/2$ state of the $D_{5/2}$ manifold, then create an initial test state, ψ, with a pulse from our RF coil. We then selectively transfer a portion, p, of the $m = +3/2$ population to the ground state with a deshelve pulse. The length and intensity of this pulse determines p. We then measure whether the ion is in the ground state, which it will be with probability p times the $m = +3/2$ population in ψ. A null result partially collapses the superposition toward the $m = +5/2$ eigenstate.



To restore the initial state ψ, we perform a π-pulse with the RF coil, swapping the $m = +5/2$ and $+3/2$ amplitudes, and then measure again with a deshelve pulse of strength p and a readout pulse. If we obtain another null result, then the ion is restored to the initial state but with the amplitudes of the $m = +5/2$ and $+3/2$ states reversed. We could restore the exact initial state ψ with another π-pulse, but we may just as easily work with the rotated state and take this into account in our analysis. We verify the final state by quantum state tomography, which consists of performing repeated "strong" measurements on the qubit in different bases. This amounts to subjecting the qubit to a final rotation, a strong deshelve pulse, and a readout.

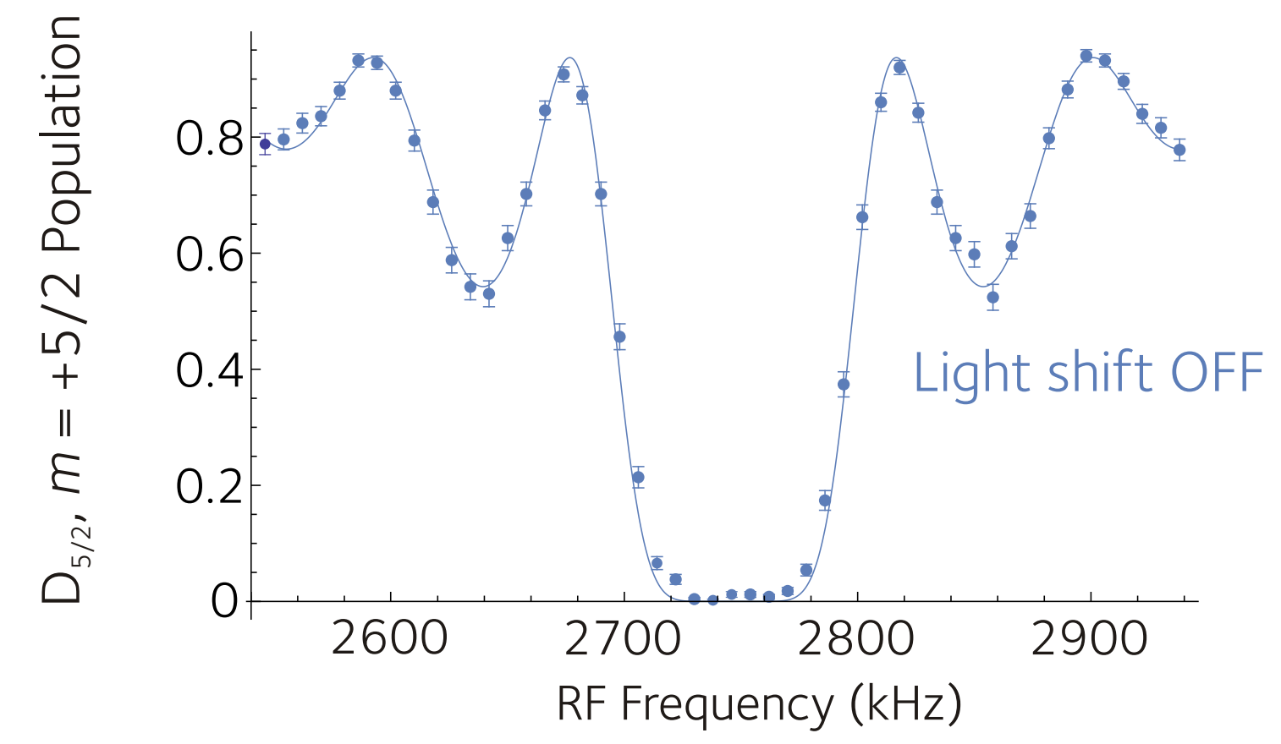
The qubit is only restored to its initial state in the case when the two p-strength measurements return null results, so we select from our data an ensemble of experimental runs where the first two measurements returned null. In this "pre-selected" ensemble, the results from the tomography experiments give the final state to finite precision (limited by statistics and any errors introduced in the rotations and measurement), which we compare with the initial state to determine the fidelity of our uncollapse procedure.

Progress

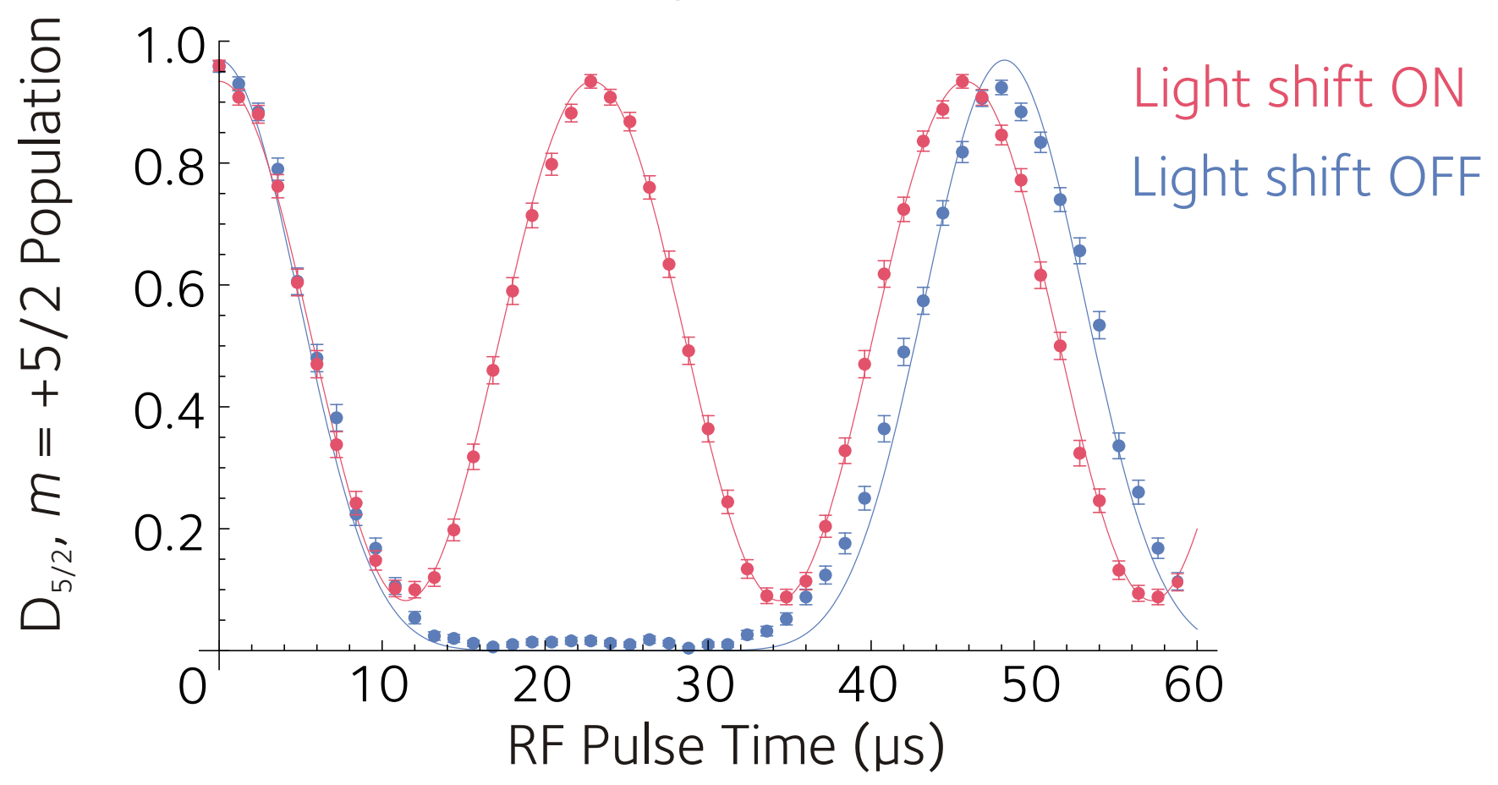
This experiment is currently underway in our lab in Oxford. We have demonstrated polarization purity of >1000:1, and state preparation at the 95% level.

Our RF coil drives spin-flips in the $D_{5/2}$ with Rabi frequencies from ~20 - 160 kHz in the un-lightshifted manifold. We fit these experiments by modelling the effect of the coil as a real rotation of the electron spin (in the rotating reference frame defined by the RF frequency). This allows a closed form solution to be found even in the case of off-resonant driving.

Frequency scan of 12.3 μs RF pulse, 37.4(5) kHz Rabi



Time scan of RF pulse, on resonance



With the application of the light-shift laser, we have shown coherent driving between the $m = +5/2$ and $+3/2$ states.

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