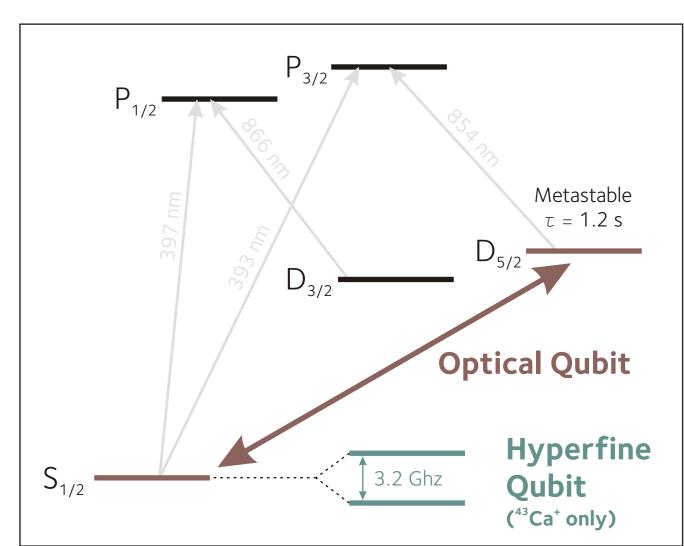


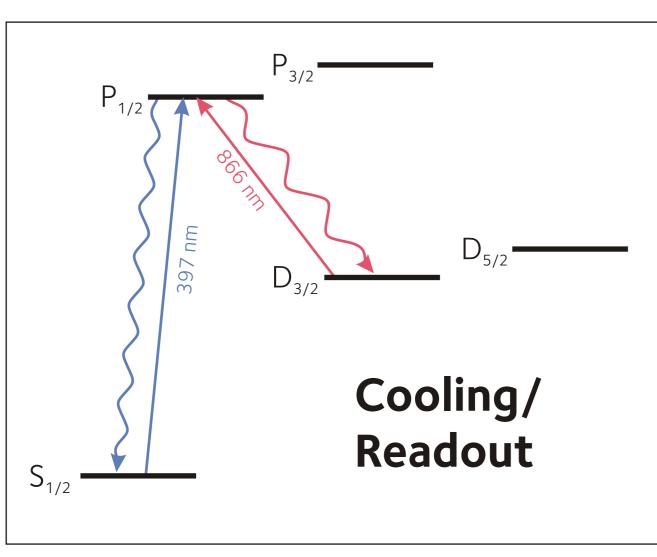
High-Fidelity Readout of Trapped-Ion Qubits

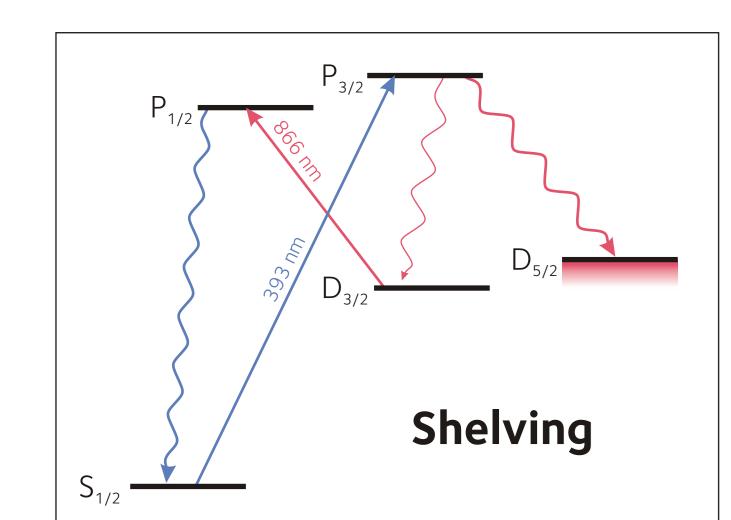
Ion Trap Quantum Computing Group - Department of Physics - University of Oxford

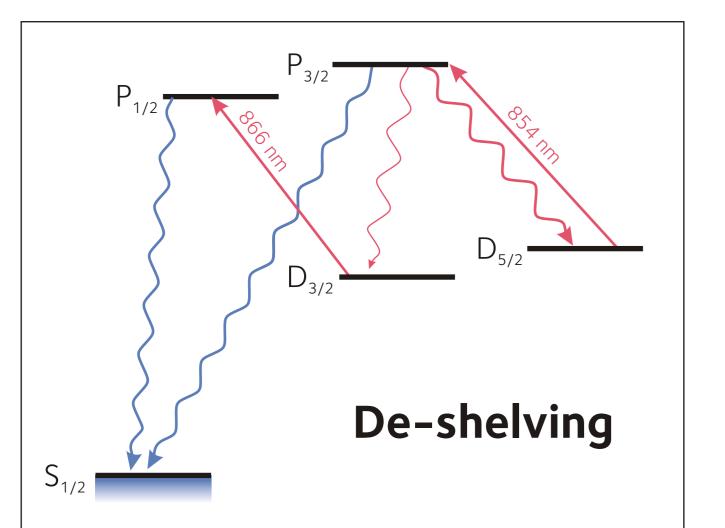
Qubits in ⁴⁰Ca⁺ and ⁴³Ca⁺

We report direct high-fidelity measurement of (i) an optical qubit $(4S_{1/2}, 3D_{5/2} \text{ levels of } ^{40}\text{Ca}^{+} \text{ ion)}$ and (ii) a hyperfine qubit $(S_{1/2} (F = 3, F = 4) \text{ sublevels of } {}^{43}\text{Ca}^{+} \text{ ion})$, where we first map the hyperfine qubit to the ${}^{43}\text{Ca}^{+} \text{ optical qubit}$. Readout is achieved by driving the $(S_{1/2} - P_{1/2} - D_{3/2})$ manifold and detecting the $P_{1/2} - S_{1/2}$ fluorescence. Absence of fluorescence indicates that the qubit was in the metastable $D_{5/2}$ state (lifetime 1168(7) ms).



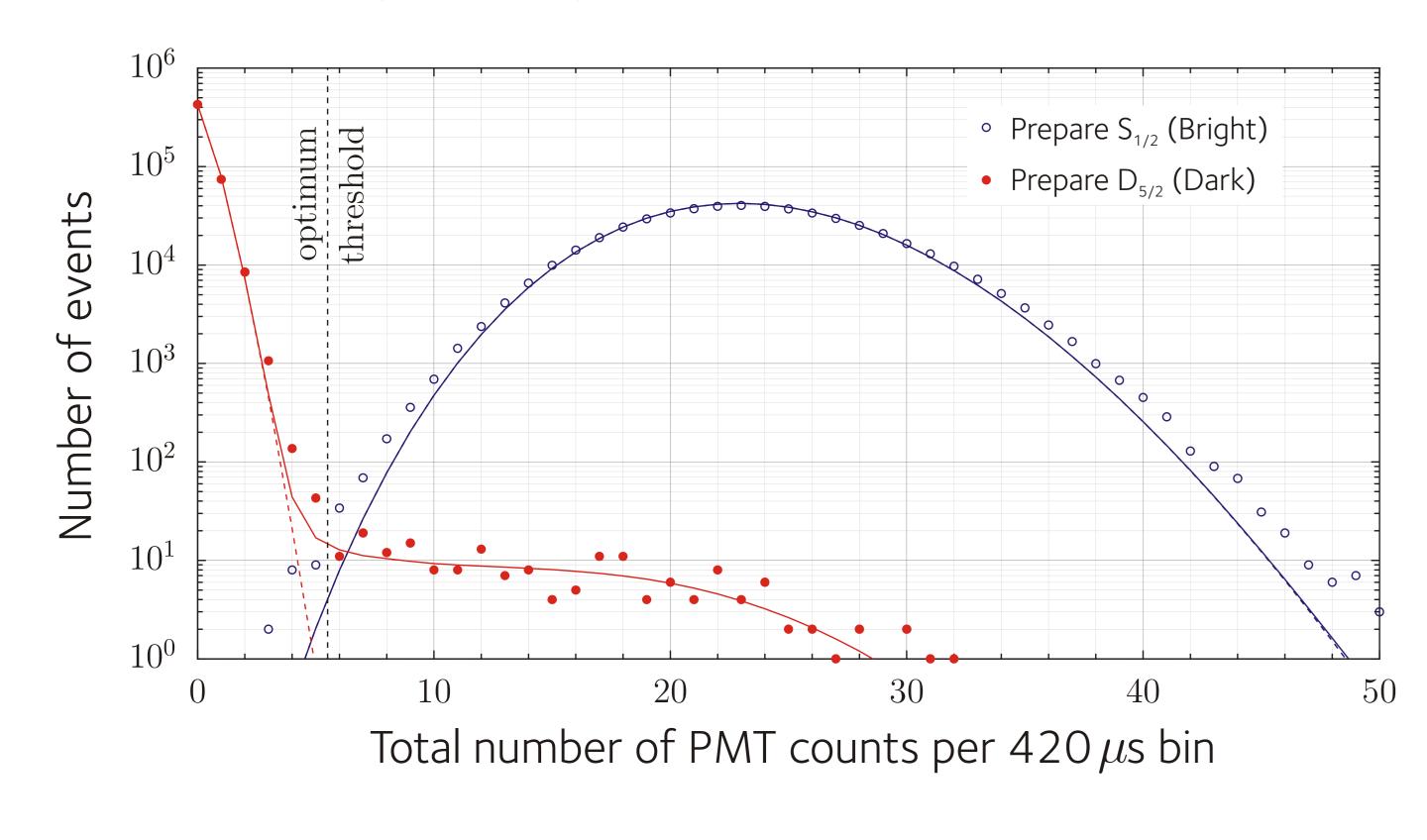






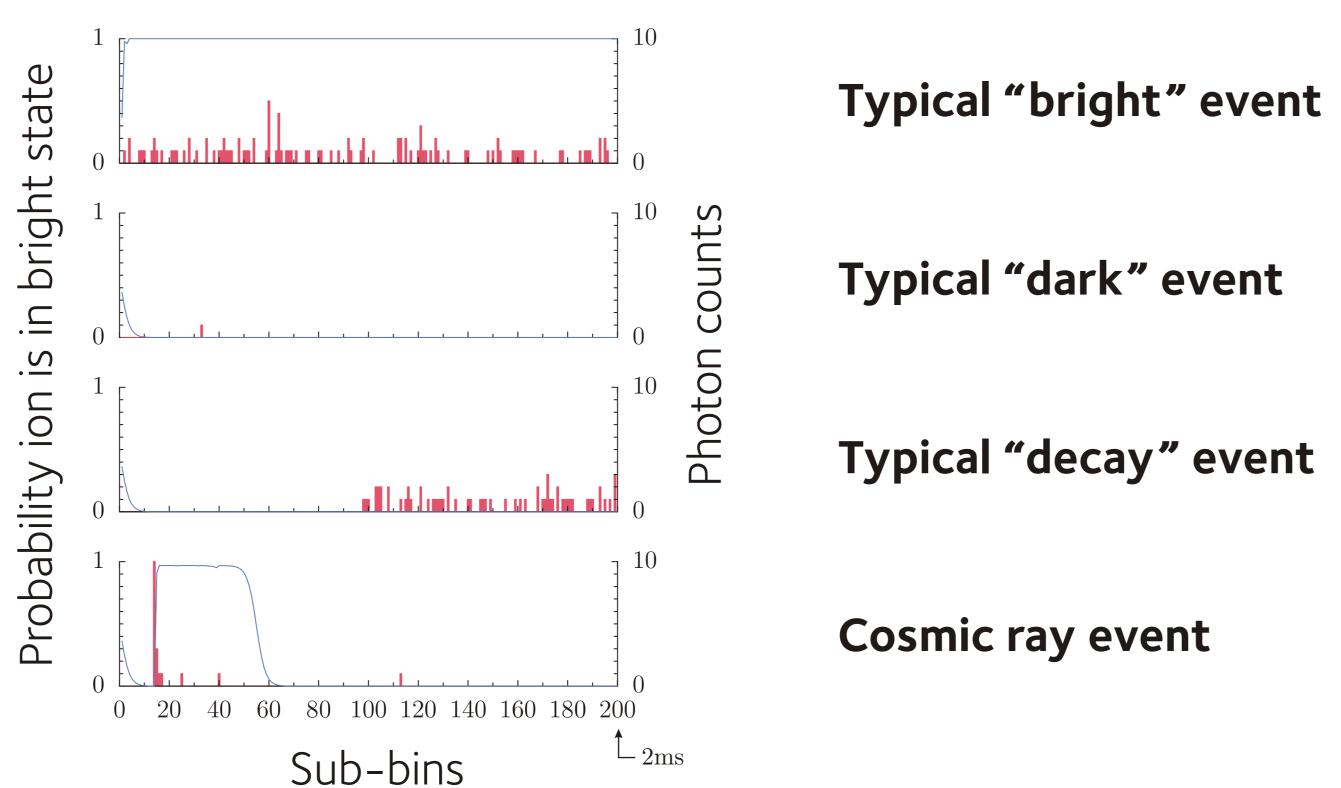
Threshold Photon Counting

Mean photon-count rates for fluorescence (R_B) and background (R_D) were $R_B = 55\,800\,\mathrm{s}^{-1}$ and $R_D = 442\,\mathrm{s}^{-1}$ (including the PMT) dark count 8.2 s⁻¹). Histograms of the number of counts observed after bright and dark state preparations are shown, along with Poisson distributions of the same mean (dashed). The 'dark' histogram shows a highly non-Poissonian tail due to the finite probability that the ion will decay from the metastable $D_{5/2}$ state and appear bright. Both histograms are also affected by cosmic ray events. Theory curves which take these effects into account are shown as solid lines (we neglect time correlations caused by cosmic rays). Here the total detection time $t_b = 420 \,\mu s$; this choice, with a threshold at 5.5 counts, optimizes the discrimination between the bright and dark histograms. The discrimination error is $1.8(1) \times 10^{-4}$ based on $\sim 10^{6}$ trials.



Time-resolved Photon Counting

Decay from the metastable $D_{5/2}$ state limits the fidelity of threshold photon counting. Beyond the optimum detection time, the increased likelihood of a decay outweighs the increased ability to discriminate between 'bright' and 'dark' counting statistics. We can do better by taking advantage of the arrival-time information of the photons. Using this, we can hope to identify some of the events where decay from $D_{5/2}$ or cosmic rays occur during detection. We may detect total photon counts above the threshold, but if these are clustered near the end of the bin or in a short spike this suggests a decay event or a cosmic ray event (respectively) rather than a bright ion.



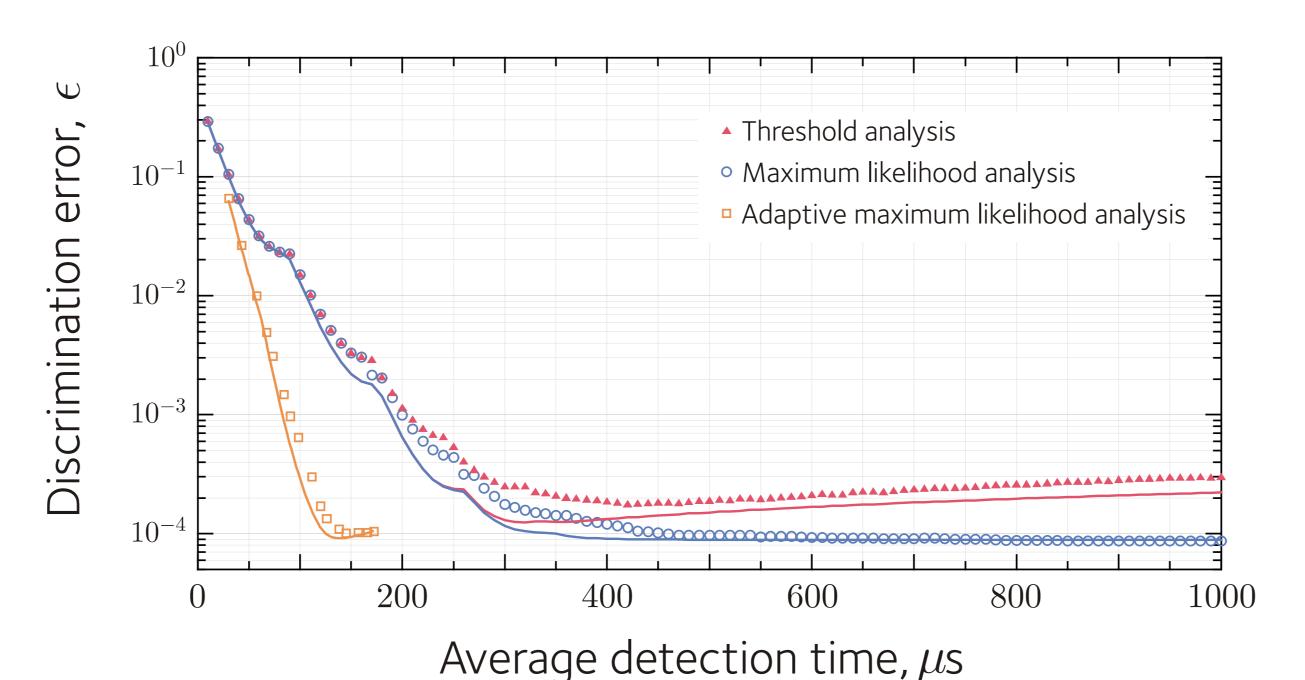
We achieve 99.9913(11)% average readout fidelity using the maximum likelihood method.

We achieve 99.99% fidelity in 145μ s average detection time using the adaptive maximum likelihood method.

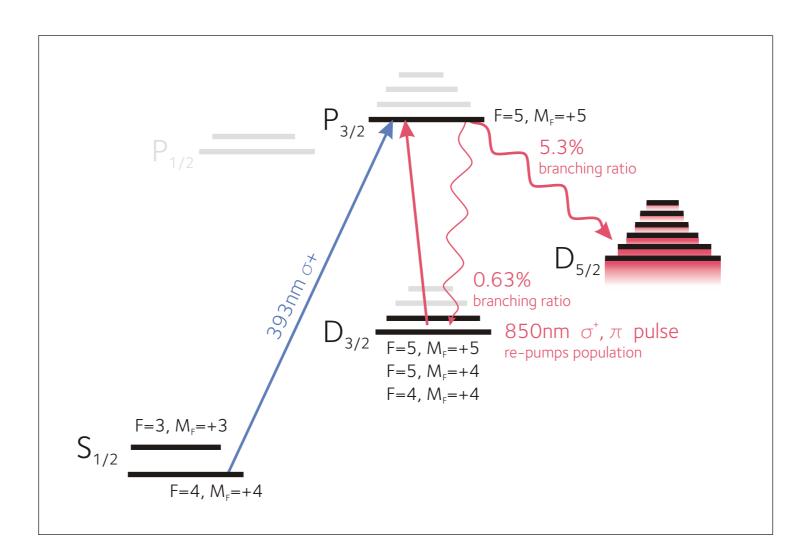
Threshold Compare *total photon counts* for the entire bin to the threshold value. Above threshold is 'bright' and below

Maximum Using photon arrival time information, calculate the likelihood p_{R} that the given set of sub-bins $\{n_{i}\}$ could **likelihood** have been generated by a 'bright' ion and compare this with the likelihood p_D that the set of sub-bins $\{n_i\}$ arose from an ion which was 'dark' at the beginning of the detection period. We infer the ion was in which ever state was more likely.

Adaptive Calculate p_B and p_D at the end of each sub-bin, and calculate the *estimated* error probability using Bayes' **maximum** Theorem. Terminate detection when the error falls below some chosen error cutoff, or after a certain **likelihood** maximum bin time, whichever comes first.



Hyperfine State-selective Population Transfer

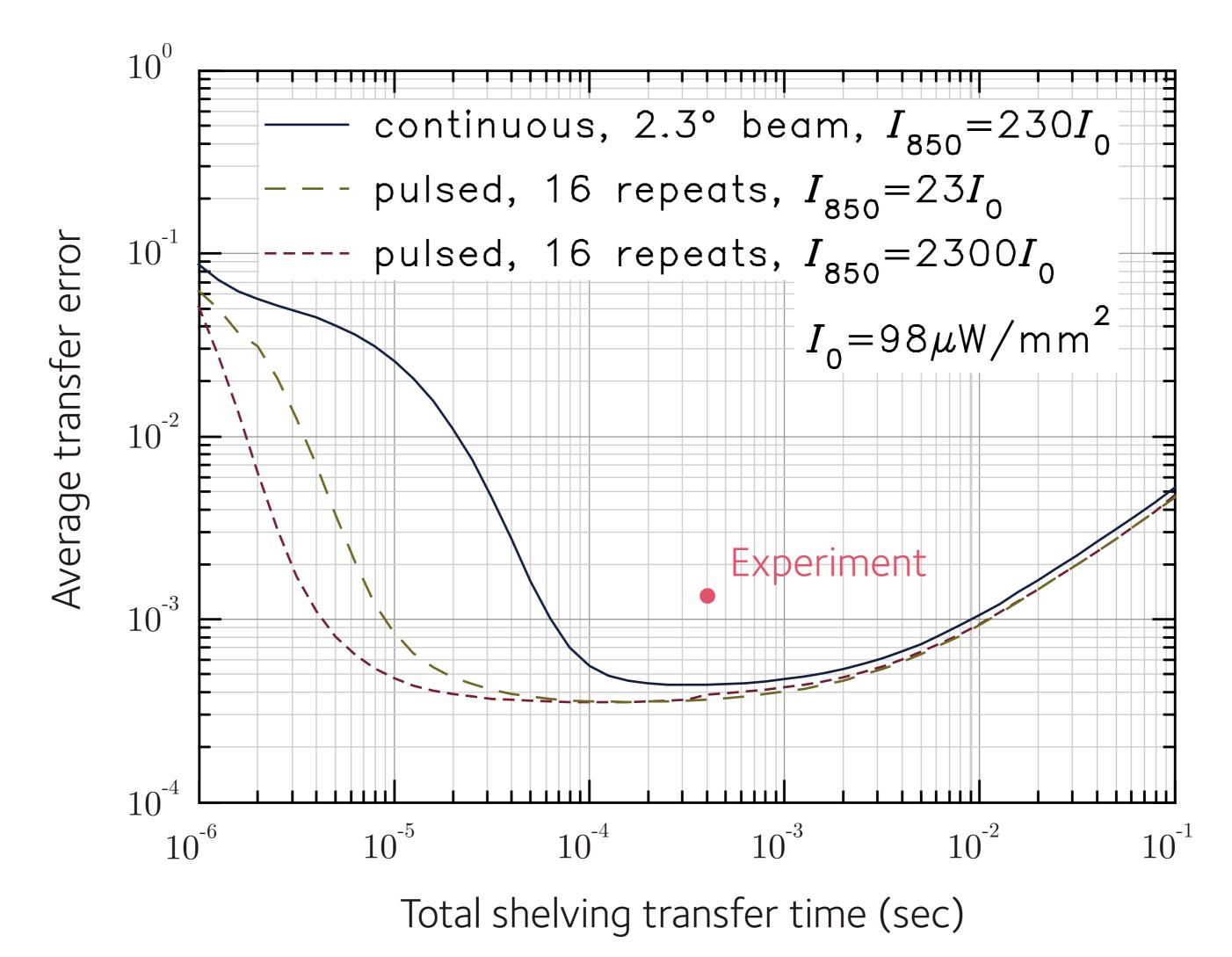


Hyperfine qubit readout by state-selective shelving. A single pulse of 393nm laser on F = 4 to F = 5 (no 850nm laser needed) would give ~95% accuracy, but we want to achieve 99.9%. Introducing well-chosen 850nm re-pumping pulses allows this.

Idealized case uses separate σ^{\dagger} and π 850nm beams for re-pumping. Otherwise ion could enter a $P_{3/2}$ F=4state, fall to the other qubit state ($S_{1/2} F = 3$) and fail to be shelved. Current experiment has 850σ beam with small admixture (at 2.3° to B-field): turns out to be very nearly as good! Model predicts 99.96% average transfer fidelity to $D_{5/2}$.

Experiment achieves 99.77(3)% net readout fidelity. Correcting for finite "optical qubit" error [see left], in this case 9.6x10⁻⁴, implies transfer fidelity was **99.87(4)**%.

The shelving transfer process was modeled by rate equations applied to the entire 144-state (4S, 4P, 3D) manifold. We find the optimum method is a repeated sequence of three laser pulses (393 nm σ^+ , 850 nm σ^+ , 850 nm π), to minimise optical pumping to $S_{1/2}$ F = 3. The main limitation is off-resonant (by 3.1 GHz) excitation of $S_{1/2}$ F = 3 to $P_{3/2}$ F = 4. Continuous excitation allows similar fidelity if the 850 nm π component is weak (though with slower shelving; see below). In the experiment, we used a single circularly polarized 850 nm beam travelling at a small angle (2.3°) the quantization axis, giving polarization intensities $I(\sigma^+, \pi, \sigma^-) = (0.9992, 0.0008, 2 \times 10^{-7}) \times 230(70) I_0$, where $I_0 = 98 \,\mu\text{W/mm}^2$. The transfer was accomplished with a single simultaneous $393 \, \text{nm} + 850 \, \text{nm}$ pulse, with duration the predicted optimum value: $400 \, \mu \text{s}$.

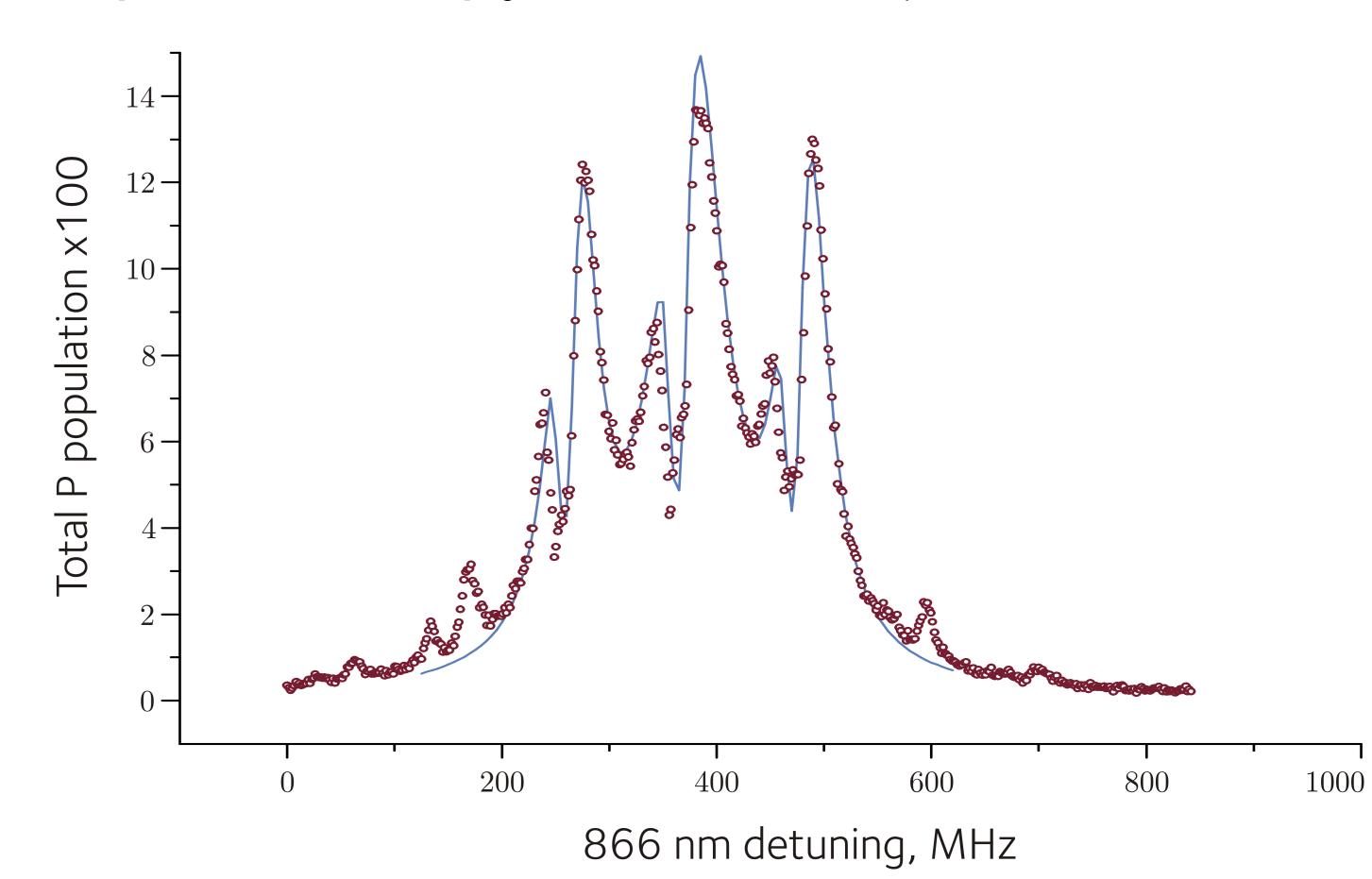


High-Fidelity Readout of Trapped-Ion Qubits

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), DOI:10.1103/PhysRevLett.100.200502

Optical Bloch Equations with Multiply Connected States

A theoretical framework allowing us to understand the behaviour of atoms or ions subject to laser fields including coherent effects is essential for devising and implementing information processing schemes. The standard approach is to use the optical Bloch equations. For some simple laser combinations the optical Bloch equations reduce to a set of linear differential equations with constant coefficients, so that they can be solved relatively easily even for a large number of states However, this is not always the case. Consider for example a laser at 866 nm used to repump 43 Ca $^{+}$ from 3d 2 D_{3/2} to 4p 2 P_{1/2}. Because of the hyperfine structure, this process is inefficient with only a single laser frequency; however, if two are used there will in general be some transitions driven by both. The coherence of the states involved then contains contributions oscillating at two different frequencies and the simplicity of the Bloch formalism is lost. We have shown that provided the times of interest in the problem are long compared with that set by the difference in the laser frequencies the equations revert to the simple form. The theory has so far been applied to the system of 40 Ca+, with the 866nm laser having two sidebands. The fluorescence spectrum is well-reproduced, as shown below, and a programme to treat ⁴³Ca⁺ is now under way.



Comparison between experiment and theory for a single cold ion of ${}^{40}\text{Ca}^+$. The transition $4\text{S}_{1/2}$ — $4\text{P}_{1/2}$ at 397 nm was excited by a single laser with fixed frequency, while a laser with sidebands acted as a repumper on the $3D_{3/2}$ – $4P_{1/2}$ transition at 866 nm. The fluorescence was measured as a function of the repumper carrier frequency, allowing the total P level population to be determined. Only the carrier and the two strongest sidebands (at the carrier frequency ± 106 MHz) were taken into account in the theoretical profile, though in fact small features due to the higher order sidebands are visible in the wings of the experimental data.

Optical Bloch Equations with Multiply Connected States

D. N. Stacey, D. M. Lucas, D. T. C. Allcock, D. J. Szwer, and S. C. Webster, J. Phys. B, **41**, 085502 (2008), DOI: 10.1088/0953-4075/41/8/085502

Current Experiments

High fidelity readout using a CCD camera

We are currently working on high-fidelity measurements of multiple ions in a string using an electron multiplying CCD camera, which enables measurements to be made with spatial resolution. Preliminary data: fidelity of 99.913(9)% per ion with the camera, using a single 400 µs detection bin with threshold discrimination (based on 28688 experiments with a string of four ions prepared in random configurations of bright and dark states).

⁴⁰Ca⁺ – ⁴³Ca⁺ phase gate

We are attempting to perform a phase gate between a mixed crystal of the two different isotopes of calcium discussed on this poster, having previously implemented a similar gate between two ⁴⁰Ca⁺ ions. One advantage of using two isotopes is that they can be spectrally distinguished, and we have implemented individual readout of the two ions. This will allow a full tomography of the gate operation to be performed, something we were not able to do for the 40 Ca $^{+}$ 40 Ca $^{+}$ gate, due to a lack of individual addressing and readout.





