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High-Fidelity Single-Shot Readout of Trapped-Ion Qubits and Qunybbles

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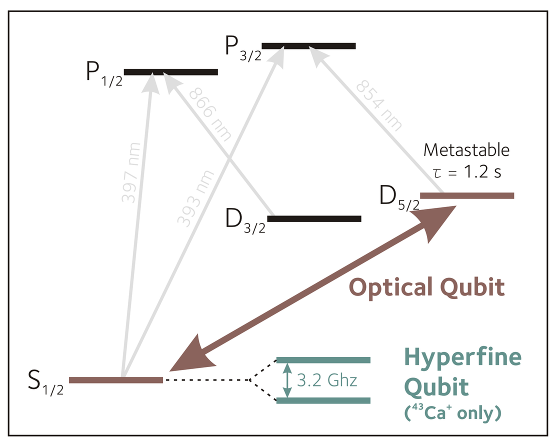
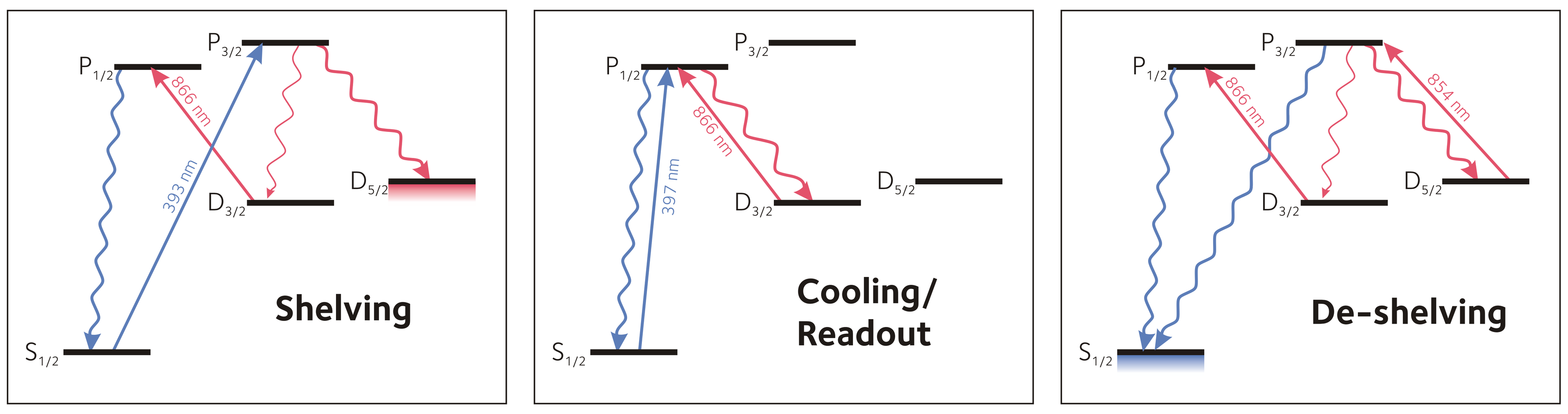
Qubits in $^{40}Ca^+$ and $^{43}Ca^+$

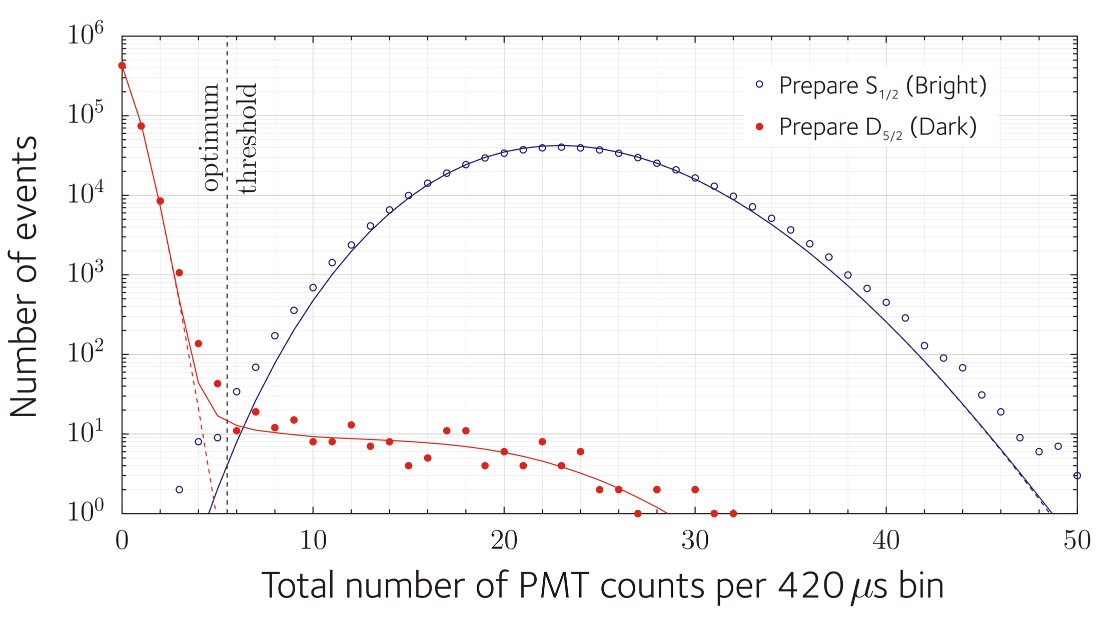
We report direct high-fidelity single-shot measurement of (i) an optical qubit ($4S_{1/2}$, $3D_{5/2}$ levels of $^{40}Ca^+$ ion) and (ii) a hyperfine qubit ($S_{1/2}$ ($F = 3$, $F = 4$) sublevels of $^{43}Ca^+$ ion), where we first map the hyperfine qubit to the $^{43}Ca^+$ optical qubit. Readout is 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). For the optical qubit, we give results for single-qubit readout using a photomultiplier and multi-qubit readout using an EMCCD camera.





Threshold Photon Counting

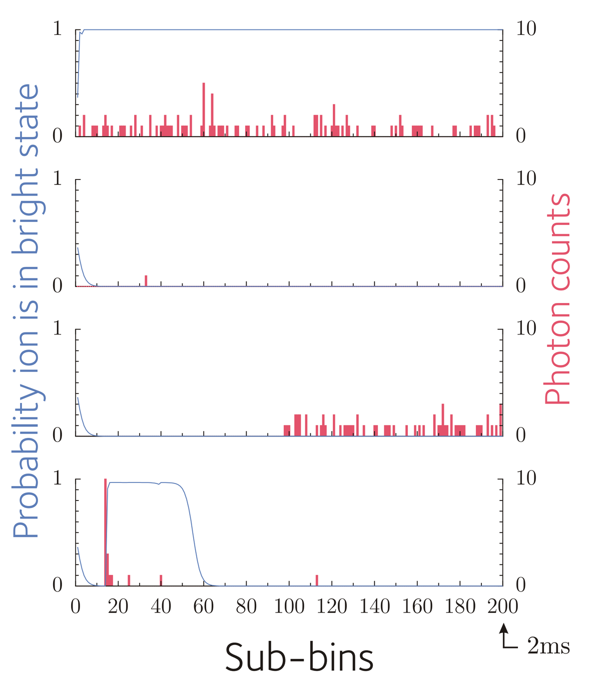
When photon counting with a photomultiplier tube (PMT), the mean photon-count rates for fluorescence (R_B) and background (R_D) were $R_B = 55\,800\ s^{-1}$ and $R_D = 442\ s^{-1}$ (including the PMT dark count $8.2\ s^{-1}$). Histograms of the number of counts observed after bright and dark state preparations 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 $t_b = 420$ μs; 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. We split our counting bin up into shorter sub-bins. Using this extra information, 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.



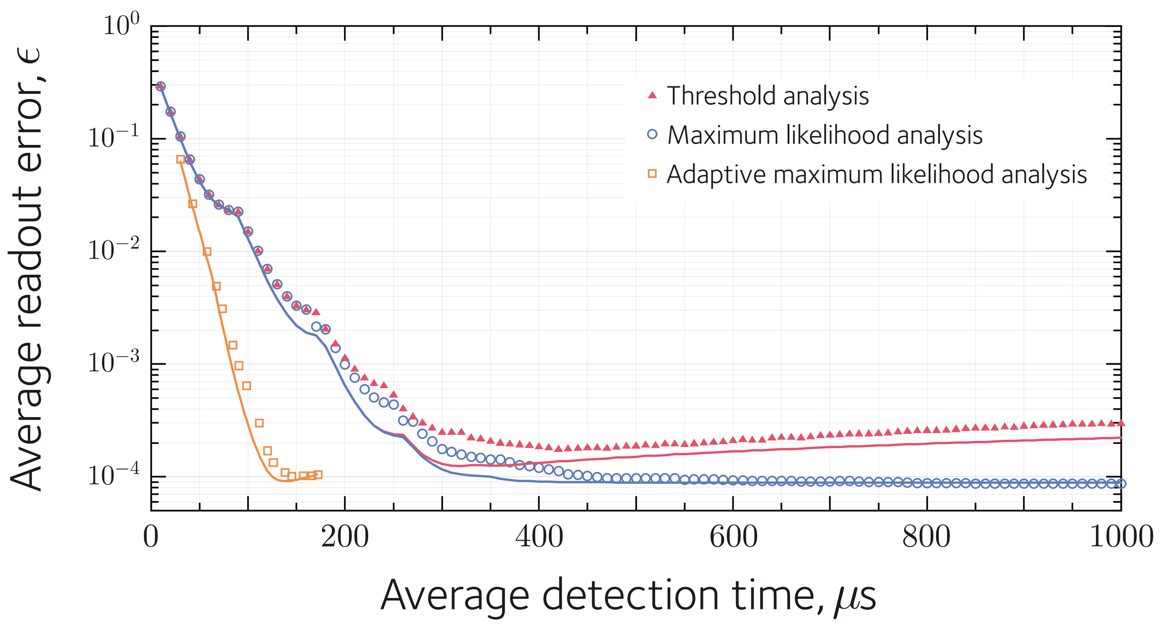
We achieve **99.9913(11)%** average readout fidelity using the maximum likelihood method.

We achieve 99.99% fidelity in **145** μs 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 threshold is 'dark.'

Maximum likelihood Using photon *arrival time* information, calculate the likelihood p_B that the given set of sub-bins $\{n_i\}$ could 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 maximum likelihood Calculate p_B and p_D at the end of each sub-bin, and calculate the *estimated* error probability using Bayes' Theorem. Terminate detection when the error falls below some chosen error cutoff, or after a certain maximum bin time, whichever comes first.

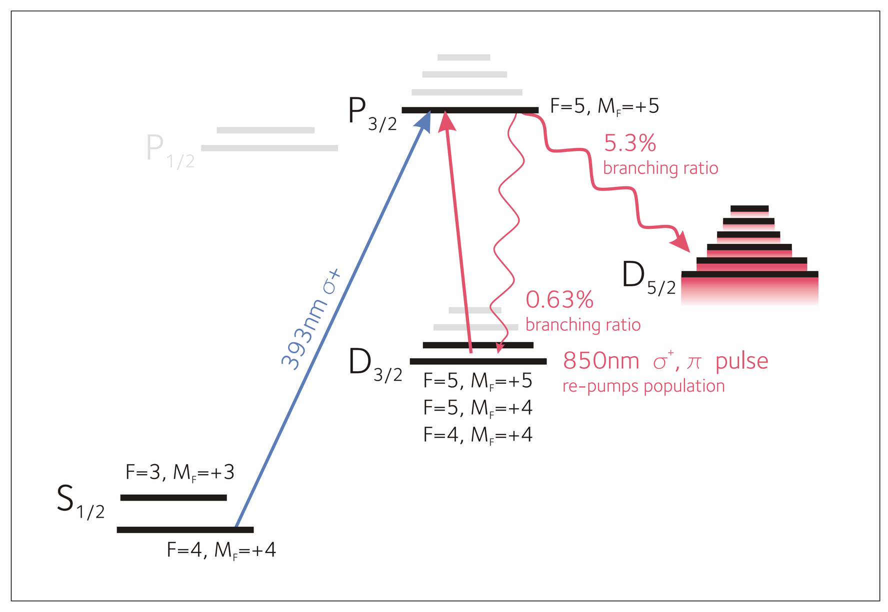


The Maximum likelihood method does not require a precise choice of parameters (threshold and detection time) which must be determined from control data; we only need to know the independently measured rates R_B and R_D, and to choose a sufficiently long detection time.

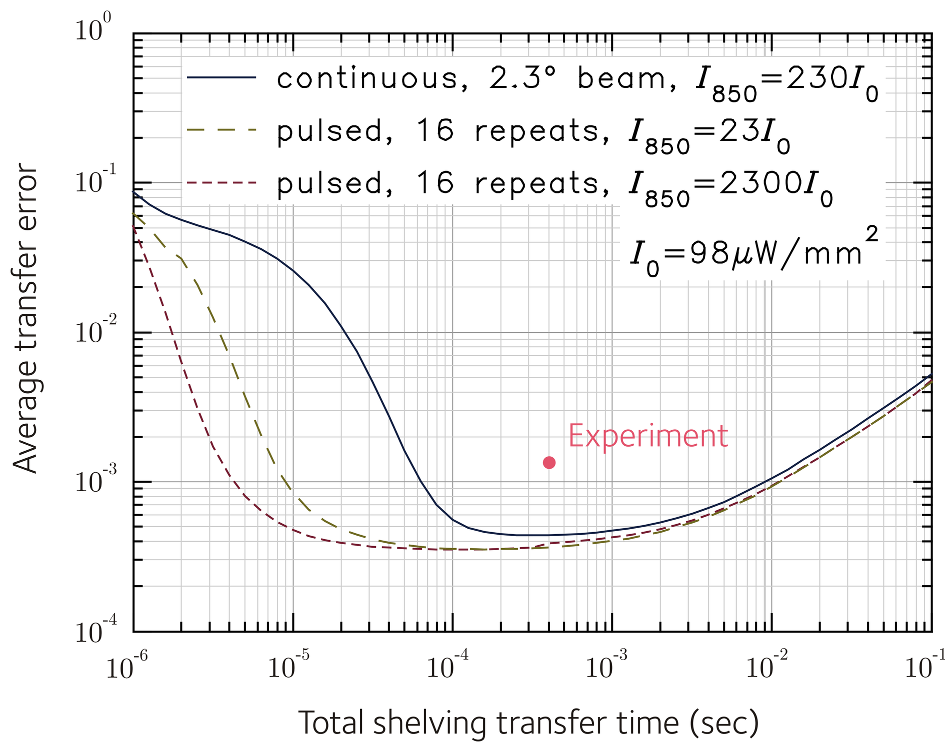
Hyperfine State-selective Population Transfer

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^+ and π 850nm beams for re-pumping. Otherwise ion could enter a $P_{3/2}$ $F=4$ state, 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 $1.0(2)\times10^{-3}$, implies transfer fidelity was **99.87(4)%**.

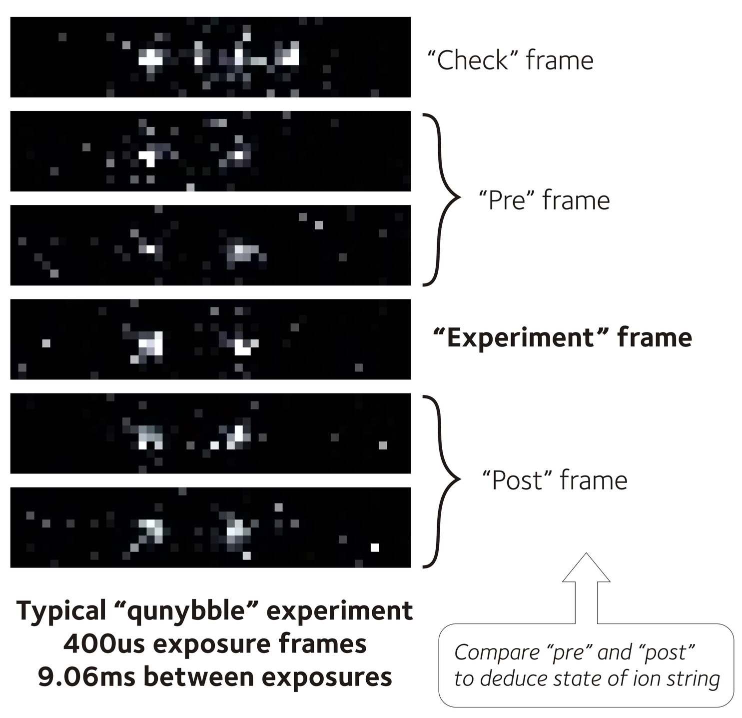


The shelving transfer process was modeled by rate equations applied to the entire 144-state (4S, 4P, 3D) manifold. We find the optimum method is a repeated sequence of three laser pulses (393 nm σ^+, 850 nm σ^+, 850 nm π), to minimise optical pumping to $S_{1/2}$ $F = 3$. The main limitation is off-resonant (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 plot, left). 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(σ^+, π, σ^-) = (0.9992, 0.0008, 2×10^{-7}) × 230(70) I_0, where I_0= 98 μW/mm^2. The transfer was accomplished with a single simultaneous 393 nm + 850 nm pulse, with duration the predicted optimum value: 400 μs.

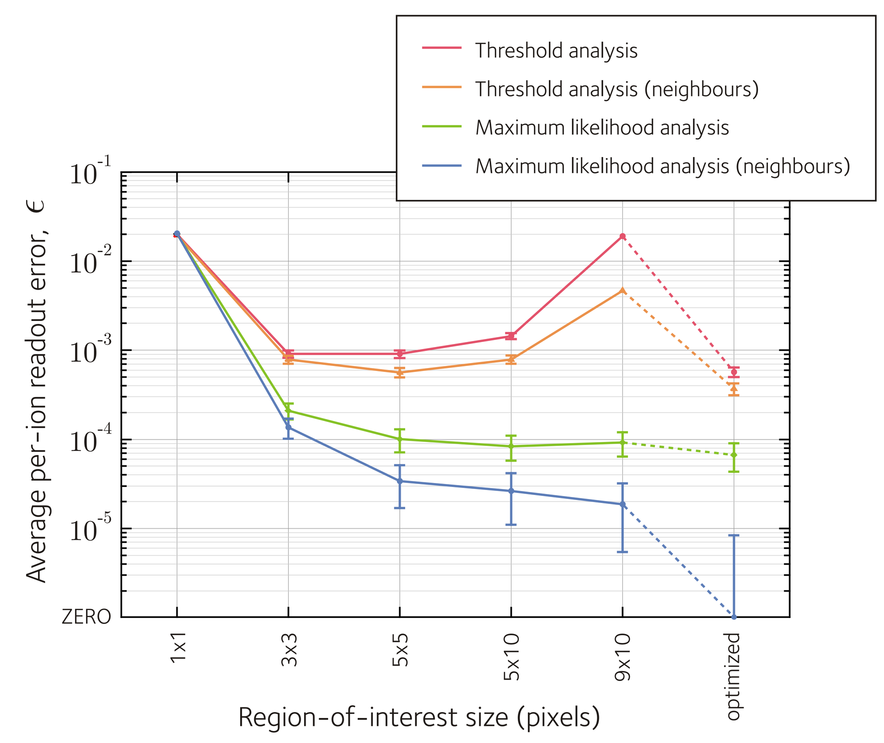
Multi-qubit readout using an EMCCD

In addition, we present a demonstration of the high-fidelity readout of a four-qubit "qunybble" using an Electron-Multiplying CCD camera. We first investigate the readout of a single $^{40}Ca^+$ ion using the camera, achieving a fidelity of 99.991(3)% for a single 400μs exposure and a similar fidelity for a time-resolved analysis using six 200μs exposure sub-frames. In the case of the camera, time-resolved detection does not give an improved fidelity because of the increased readout noise associated with taking multiple exposures.

Secondly, we investigate the simultaneous readout of a string of four ions separated by ~18μm. Here, cross-talk between neighbouring ion images (present at the ~2% level) might be expected to significantly reduce the readout fidelity. In an experiment designed to measure the cross-talk error without the effect of decay from the $3D_{5/2}$ state (but with the same 400μs exposure time), we find an average fidelity of 99.94(1)% per ion using a simple threshold to discriminate between ion states. We then show that by using a spatial maximum-likelihood analysis which takes into account the states of neighbouring ions, we are able to compensate for the cross-talk and achieve >99.999% readout fidelity (<1 error in 118853 trials). Together, these experiments imply a fidelity of 99.990(3)% for simultaneous qubit readout in an ion string.



Typical "qunybble" experiment
400us exposure frames
9.06ms between exposures



Threshold Compare *total summed counts* for all pixels in the region of interest to the threshold value. Above threshold is 'bright' and below threshold is 'dark.'

Spatial Maximum likelihood Using counts from *individual pixels*, calculate the likelihood p_B that the given set of pixels $\{n_i\}$ could have been generated by a 'bright' ion and compare this with the likelihood p_D that the set of pixels $\{n_i\}$ arose from an ion which was 'dark'. We infer the ion was in which ever state was more likely.

...using states of neighbours The optimal threshold or probability distributions to use for the above methods depend on the states of the neighbouring ions. Therefore, once an initial guess at the state of the ion string has been made, repeat the analysis for each ion using the more optimal thresholds or probability distributions.

We achieve **99.991(3)%** readout fidelity for a single ion with the EMCCD.

For a qunybble, using a spatial maximum likelihood method taking into account neighbouring ions, we achieve a discrimination fidelity of **>99.999%**, implying a fidelity of **99.990(3)%** for simultaneous qubit readout in an ion string.

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