Entanglement and high-fidelity readout of calcium ion qubits

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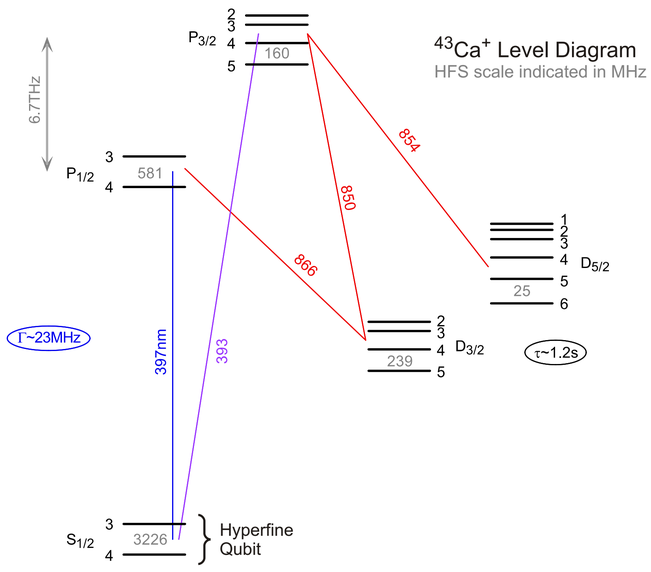
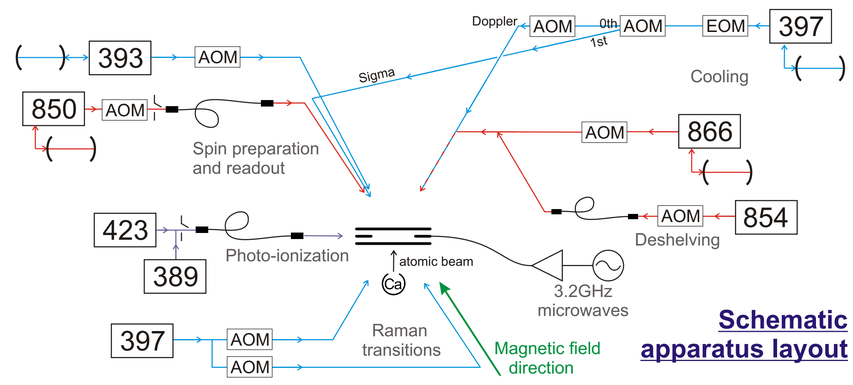
Research supported by:
DTO
E.U. (CONQUEST/SCALA)
EPSRC (QIP IRC)
Royal Society

$^{40}Ca^+$ and $^{43}Ca^+$ qubits

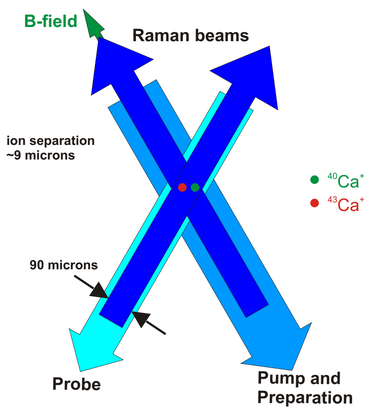
We use $^{43}Ca^+$ and $^{40}Ca^+$ trapped-ion qubits:
- ground $S_{1/2}$ level offers stable qubits (spin-qubit in $^{40}Ca^+$, hyperfine qubits in $^{43}Ca^+$)
- D levels allow high-fidelity readout ~99.9% by electron shelving technique



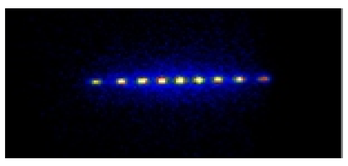
Experimental details



Cooling Laser Beams



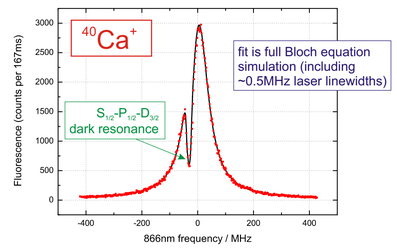
Ion loading



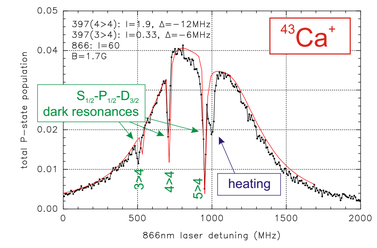
Above: pure crystals of $^{43}Ca^+$ can be loaded from a natural abundance (0.14%) source by isotope-selective photo-ionization.

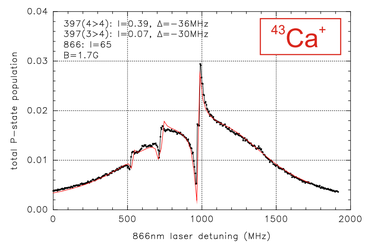
Simulations

We have developed full Bloch equation treatments for the $S_{1/2}$-$P_{1/2}$-$D_{3/2}$ system in both $^{40}Ca^+$ and $^{43}Ca^+$ and find quantitative agreement with experiment. A rate equations approach is much less successful. Knowledge of the theoretical profile is essential to optimise conditions and to detect heating. For $^{43}Ca^+$, even the simplest SPD level system involves 64 states, giving 4096 independent variables in the Bloch equations, but sparse matrix techniques make the problem tractable.



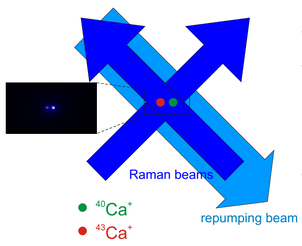
For $^{43}Ca^+$, it appears difficult to find experimental parameters which give fluorescence rates more than ~30% that of $^{40}Ca^+$. Efficient repumping from $D_{3/2}$ requires large 866nm laser power; however, this gives rise to significant heating effects due to dark resonances which at high power are very broad.



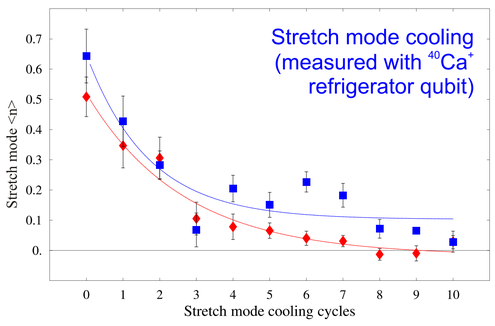


Coherence of an actively-cooled qubit

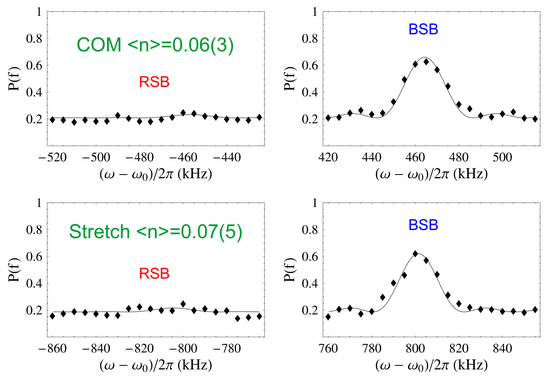
We measure the coherence of a "logic" qubit stored in the hyperfine clock states of $^{43}Ca^+$ *while* it is being actively cooled by a $^{40}Ca^+$ "refrigerator" ion in the same trap. The $^{40}Ca^+$ ion cools the $^{43}Ca^+$ ion sympathetically, through the Coulomb interaction. We cool the stretch motion of the ion-pair using pulsed Raman sideband cooling. Some decoherence of the logic qubit is expected due to photon scattering by the Raman laser and by the $^{40}Ca^+$-resonant repumping beam applied between Raman pulses. We show that the Raman pulses are the dominant source of decoherence, which may in principle be eliminated with a higher-power far-detuned laser [Ozeri *et al.*, PRL 2005]. The repumping beam is calculated to give <0.1% decoherence per cooling cycle; it gives a measured qubit phase shift of 37mrad per cooling cycle.

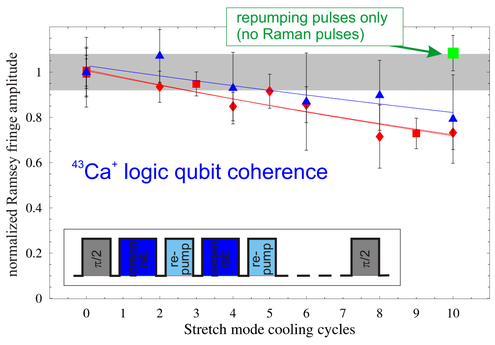


- cooling beams illuminate both ions
- isotope shifts ~1GHz between $^{40}Ca^+$ and $^{43}Ca^+$ 397nm transitions allow qubit coherence to be maintained while $^{40}Ca^+$ is actively cooled
- $^{43}Ca^+$ qubit coherence measured by microwave Ramsey experiment



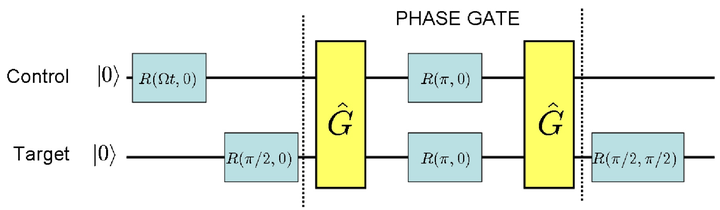
$^{40}Ca^+$ / $^{43}Ca^+$ Sympathetic Cooling results

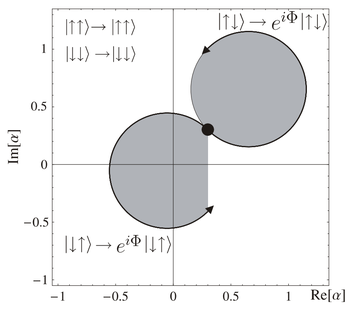




Mixed-species logic gate

- idea: perform phase gate between a Ca40 and a Ca43 ion
- allows individual addressing of two ions in same trap by frequency addressing
- useful to be able to perform SWAPs between different ion species

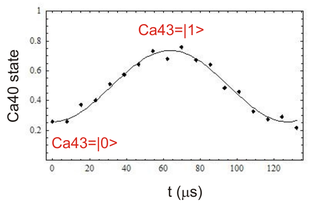




Phase space evolution of stretch-mode (out-of-phase mode) for two ions during application of phase gate
[Leibfried et al. 2003]

- unequal forces and unequal Lamb-Dicke factors for each isotope
- cannot cancel single beam differential light shifts for both ions
- solution: use "double-pulse" method with spin-echo sequence to flip spins between two gate pulses

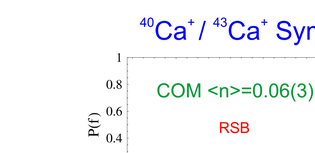
$$\begin{aligned} f_s^{(4\uparrow)} &= -0.05F_s(\uparrow\downarrow) \\ f_s^{(4\downarrow)} &= 1.01F_s(\uparrow\downarrow) \\ f_s^{(3\uparrow)} &= -0.85F_s(\uparrow\downarrow) \\ f_s^{(3\downarrow)} &= 0.21F_s(\uparrow\downarrow) \end{aligned}$$



- preliminary data shows conditional effect ("target" Ca40 ion flips as "control" Ca43 ion rotated)
- contrast only ~50%: entanglement not yet demonstrated

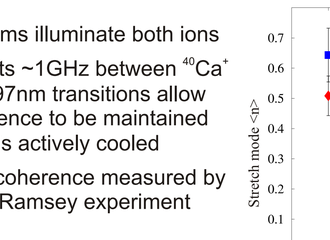
Readout: $^{40}Ca^+$ optical qubit

Detector Limitations: Cosmic Ray background



- non-Poissonian dark counts of photomultiplier limit discrimination fidelity of ion fluorescence
- source is probably cosmic rays, followed by luminescence in PMT
- difficult to "gate out" due to long ~1ms timescale of luminescence; but other detectors (e.g. CCD) less susceptible?

Ion/background Discrimination



- fluorescence signal/background ratio depends on scattered laser light and saturation of Doppler-cooling transition
- calculate expected ion/background discrimination error using Poisson distributions with cosmic ray "tail"

- compare with experiments (above) in which 866nm repumper is turned on (for signal) and off (for background)
- cosmic ray effect introduces error at ~10^{-4} level in this apparatus

Optical qubit readout

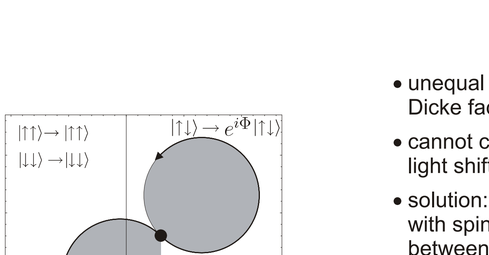
- for readout of ($S_{1/2}$,$D_{5/2}$) "optical qubit", also need to include effect of finite $D_{5/2}$ lifetime (ion can decay during PMT bin)

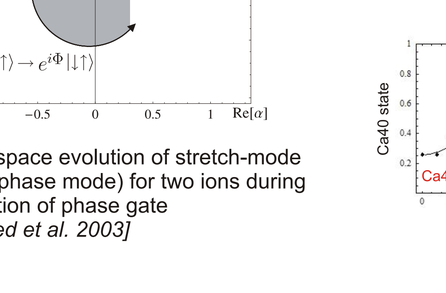
- theory (above) predicts minimum error attainable ≈3.0x10^{-4} in 0.6ms bin
- experiment (below) gives readout error of 3.5(3)x10^{-4} in 0.5ms

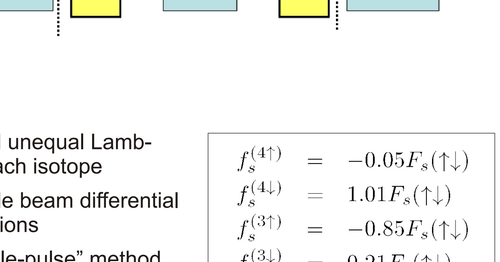
- modest increase in net detection efficiency from 0.1% to 0.5% would reduce error to 0.6x10^{-4} in 120μs

Readout: $^{43}Ca^+$ hyperfine qubit

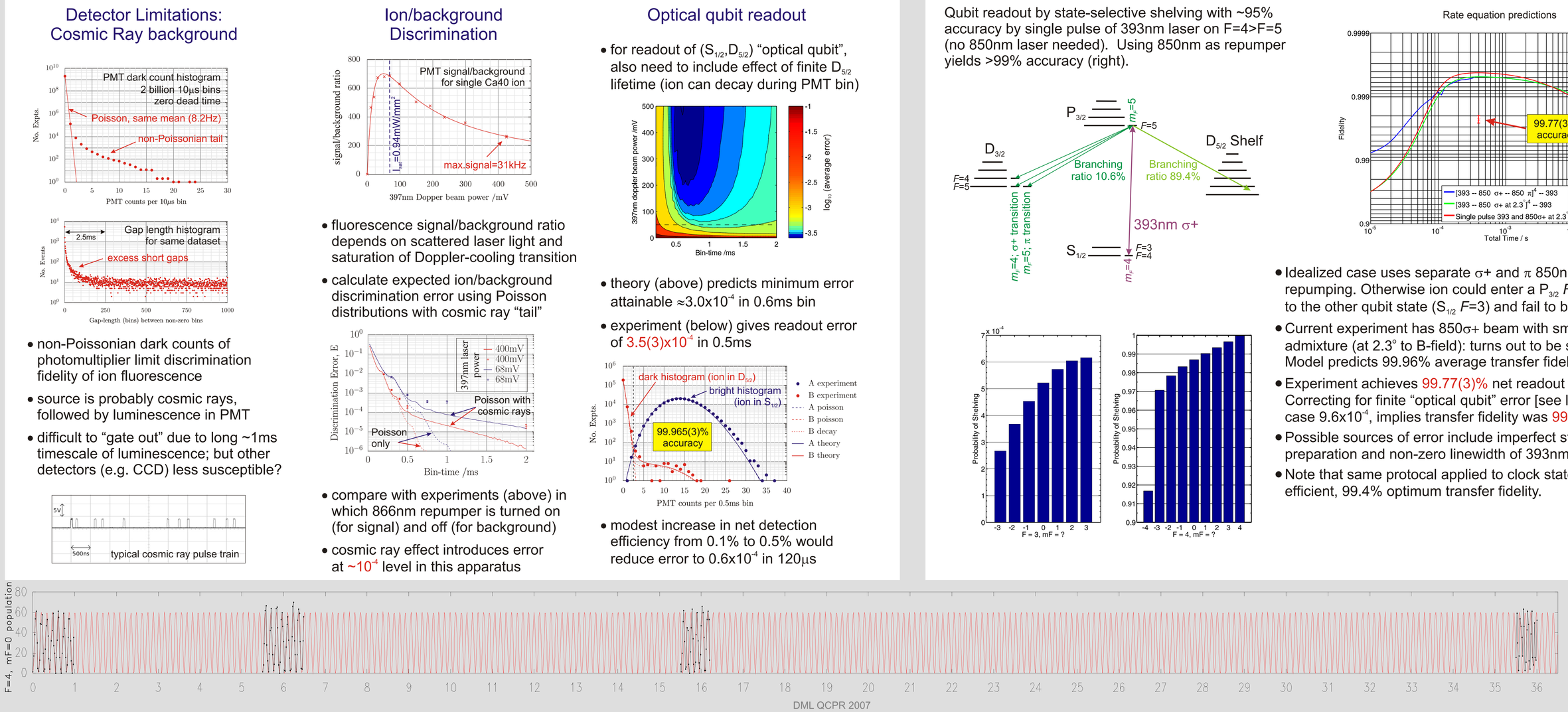
Qubit readout by state-selective shelving with ~95% accuracy by single pulse of 393nm laser on F=4>F=5 (no 850nm laser needed). Using 850nm as repumper yields >99% accuracy (right).







- Idealized case uses separate σ+ and π 850nm beams for repumping. 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 π admixture (at 2.3° to B-field): turns out to be slightly better! 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(3)%.
- Possible sources of error include imperfect state preparation and non-zero linewidth of 393nm laser.
- Note that same protocal applied to clock state qubits is less efficient, 99.4% optimum transfer fidelity.



Rabi-flopping on field-independent $^{43}Ca^+$ qubit. (~270 flops)