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Quantum Uncollapse of a $^{40}Ca^+$ $D_{5/2}$ Qubit

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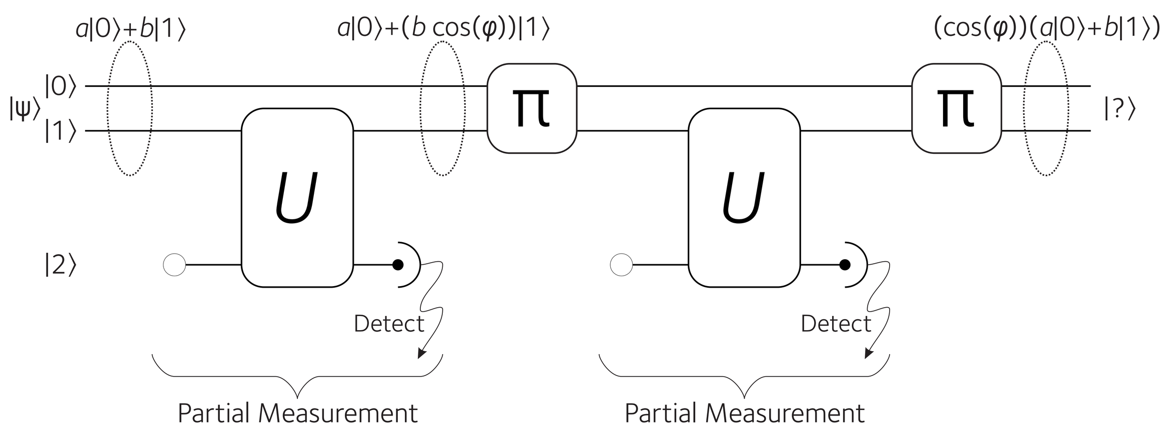
Introduction

We present and implement a method to restore the state of a single qubit, in principle perfectly, after it has partially collapsed. The method resembles the Hahn "Spin-Echo", but works on a wide class of relaxation processes in which the quantum state partially leaves the computational Hilbert space. It is not guaranteed to work every time, but successful events are heralded.

Here, we induce the partial collapse by weak optical pumping to an auxiliary state, followed by detection of population in that state. This can also be understood as a *weak measurement* of the qubit. We then undo the effect of that measurement by applying a spin-echo π-pulse and repeating the measurement. If the detector "clicks" in either partial measurement, though, the qubit state was irrevocably destroyed.

The procedure was first demonstrated in a solid state system [1]. Our data show that the fidelity after the "uncollapse" exceeds that which would be obtained by filtering the data by a simple error detection in our laboratory.

Theory



- Arbitrary $|\psi\rangle = a|0\rangle + b|1\rangle$ prepared in qubit states $|0\rangle$ and $|1\rangle$.
- Unitary rotation U couples qubit state $|1\rangle$ and auxiliary state $|2\rangle$.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & \sin\varphi \\ 0 & -\sin\varphi & \cos\varphi \end{pmatrix}$$

Where $\sin^2(\varphi) = p$ is the measurement strength

- $|2\rangle$ can be detected (e.g. by PMT). A "click" projects onto $|2\rangle$: qubit is lost. "No click" projects onto the qubit basis; the amplitude of state $|1\rangle$ has decreased.

$$|\psi_{\text{partial}}\rangle = \frac{a}{\sqrt{1-|b|^2 p}}|0\rangle + \frac{b\sqrt{1-p}}{\sqrt{1-|b|^2 p}}|1\rangle$$

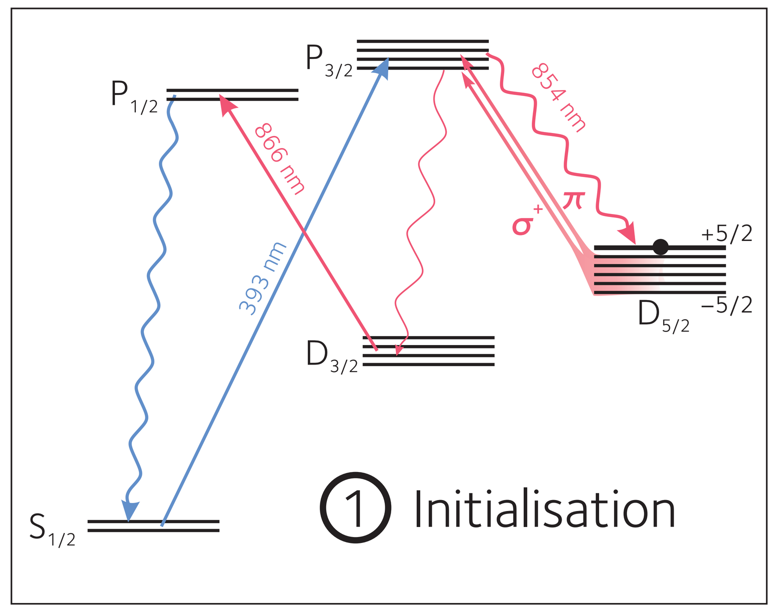
after normalisation.

- π-pulse/NOT gate exchanges $|0\rangle$ and $|1\rangle$. Second partial measurement identical to the first; if no click, the amplitude of $|1\rangle$ decreases.
- If *neither* measurement gave a click, the qubit is restored to $|\psi\rangle$ after final π-pulse (with reduced amplitude).
- Probability of success $1-p$.

- First partial measurement alone could be used for error detection, omitting the second stage; expected fidelity of filtered ensemble is $F \approx 1-|a|^2|b|^2p^2/8$ for $p \ll 1$. Full uncollapse process ideally gives $F = 1$ for all $0 \leqslant p < 1$.

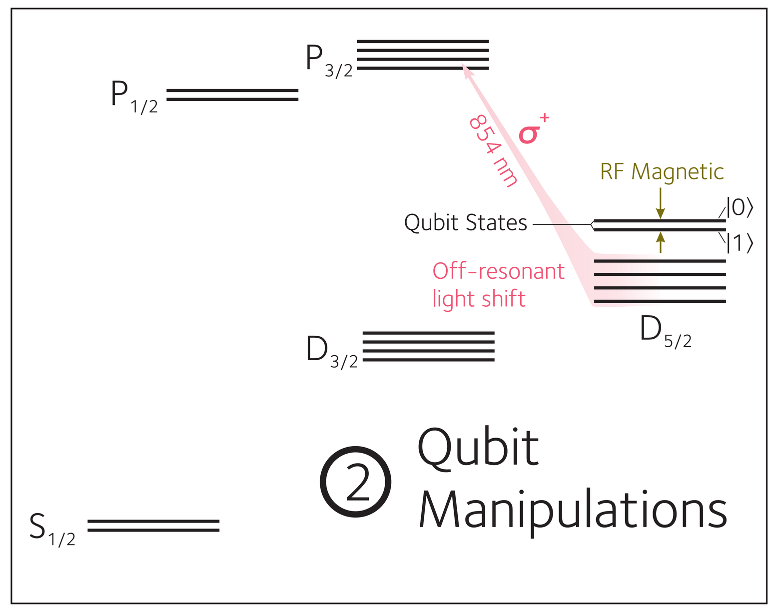
[1] "Reversal of the Weak Measurement of a Quantum State in a Superconducting Phase Qubit". N. Katz, M. Neeley, M. Ansmann, R. C. Bialczak M. Hofheinz, E. Lucero, A. O'Connell, H. Wang, A. N. Cleland, J. M. Martinis, and A. N. Korotkov. Phys. Rev. Lett. **101**, 200401 (2008)

Experimental Implementation



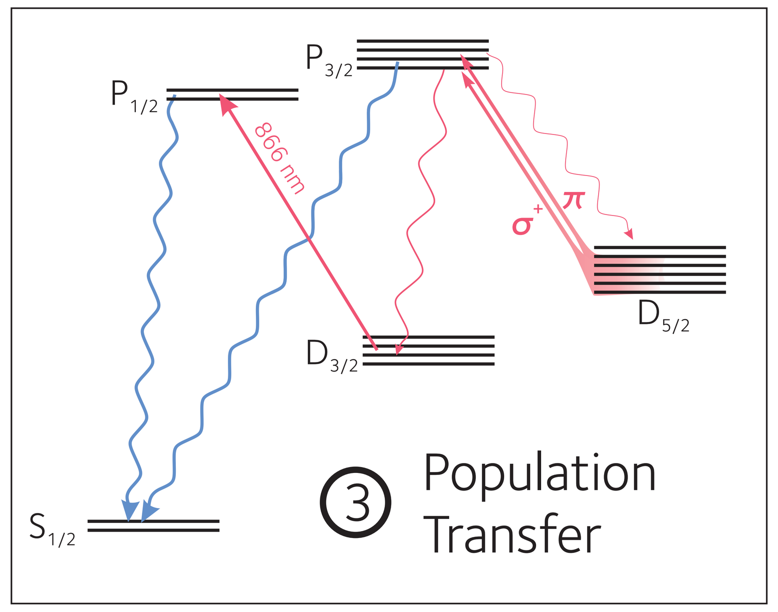
1 Initialisation

- $D_{5/2}$ is a metastable (lifetime 1.17s) "shelf" level.
  - $|0\rangle = D_{5/2,\,m=+5/2}$
  - $|1\rangle = D_{5/2,\,m=+3/2}$
  - $|2\rangle$ = Doppler cooling manifold ($S_{1/2}$, $P_{1/2}$, $D_{3/2}$)
- $|0\rangle$ prepared by optical pumping.



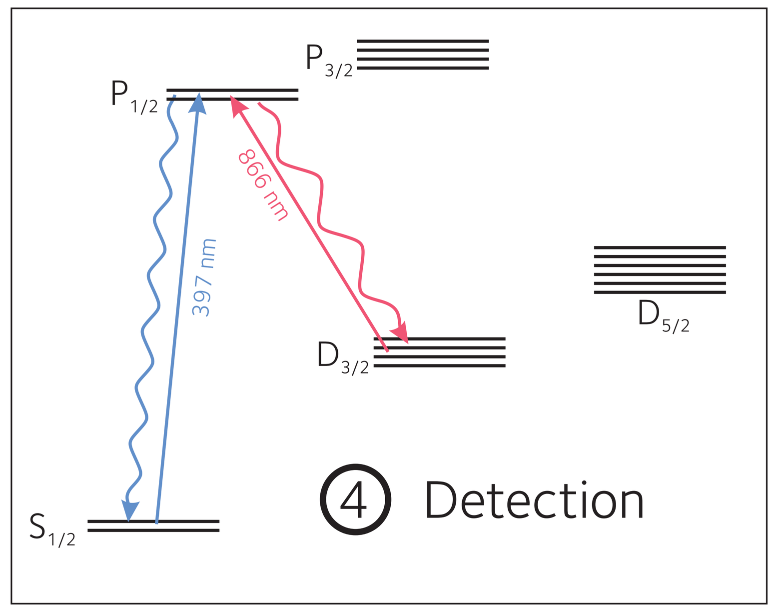
2 Qubit Manipulations

- Zeeman substates split by 2.7 MHz at 1.6 gauss.
- Intense $\sigma+$ laser, 10 GHz detuned from 854 nm transition, applied to further separate substates. Qubit states ($m = +5/2$ and $+3/2$) are untouched, and are now a 2-level system.
- Qubit manipulated with RF field.



3 Population Transfer

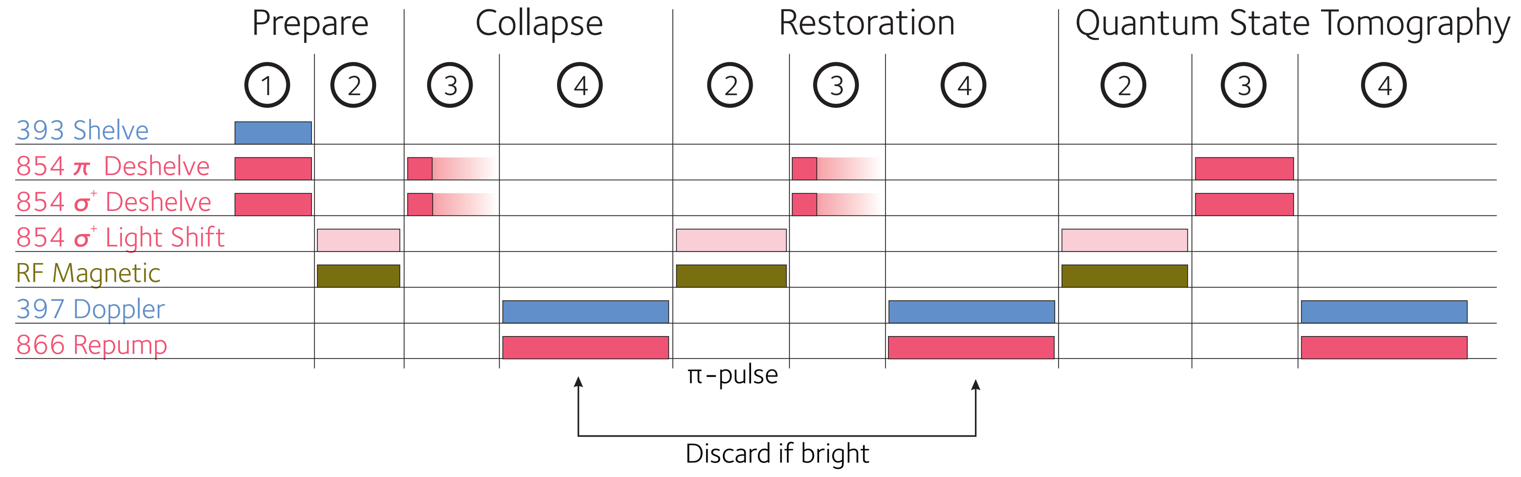
- Combines U with possible collapse into $|2\rangle$.
- A weak resonant 854 nm beam, polarised $\sigma+$ and π, couples to $|1\rangle$ but not $|0\rangle$.
- Pulse time set so probability of transferring $|1\rangle$ to $P_{3/2}$ is p.
- 95% chance that $P_{3/2}$ decays to $S_{1/2}$ or $D_{3/2}$.
- 5.3% chance of decay back to $D_{5/2}$: unwanted but well understood source of error.



4 Detection

- Resonant 397 nm and 866 nm beams applied.
  - If ion is in $S_{1/2}$ or $D_{3/2}$, it fluoresces. Scattered photons detected with PMT.
  - If ion remains in $D_{5/2}$, no fluorescence seen.
- Fluorescence collected for 300 μs, for a bright count of ~10 photons. Simple threshold method distinguished bright/dark with 99% fidelity.
- CPMG Dynamical Decoupling used during partial measurement fluorescence periods, to protect against dephasing.

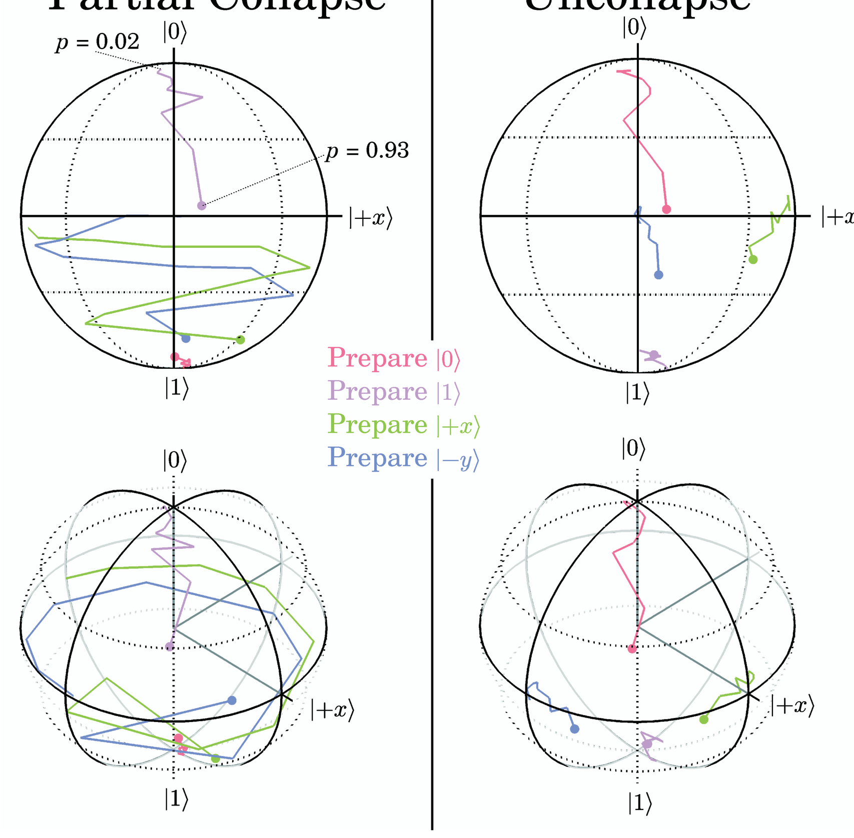
Sequence



- The sequence above is repeated many (5000-12500) times with constant settings.
- If either partial measurement was bright, the qubit was destroyed and we exclude it from the ensemble.
- Those occasions when both partial measurements were dark comprise an ensemble of qubits that should have been restored to the initial state $|\psi\rangle$, by the end of the Restoration step. Do complete Quantum State Tomography on this ensemble, as follows:
  - Either apply $\pi/2$ qubit rotation about x- or y-axis, or do no RF pulse; this rotates qubit into $\hat{Y}$, $\hat{X}$ or $\hat{Z}$ basis.
  - Perform a full-strength projective measurement.
  - Combining the results from all qubits in the pre-selected ensemble allows the state to be deduced.
- Four initial states $|\psi\rangle$ were used: $|0\rangle$, $|1\rangle$, $|+x\rangle = (|0\rangle+|1\rangle)/\sqrt{2}$ and $|-y\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}$. Performing State Tomography starting from each of these states allows Quantum Process Tomography (QPT).
- QPT is performed both without and with the Restoration step above, fully characterising the effects of the partial collapse/measurement *and* the attempted uncollapse.
- For both partial- and uncollapse, a variety of partial measurement strengths p (0.02 to 0.93) were tested.

Results

Partial Collapse | Uncollapse



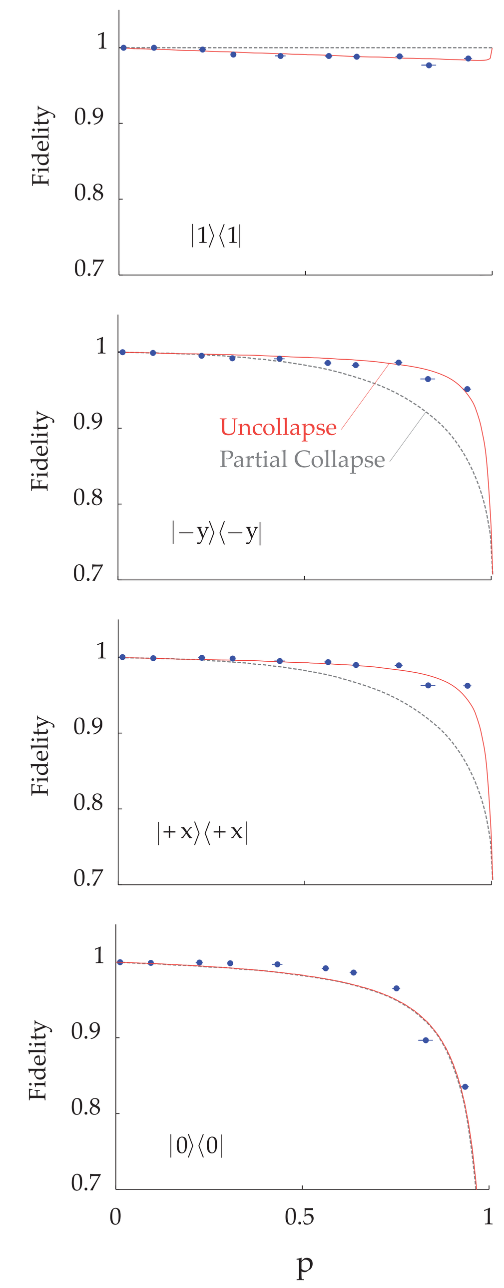
Uncollapse achieves identity operation with *Process* Fidelity above **0.65** for p up to **0.94**

- **Left:** State Tomography results plotted on Bloch sphere.
  - Colours distinguish different initial states.
  - "Trails" show how final states vary with p; filled circles mark highest p.
- Two artefacts to ignore:
  - In partial collapse, $|+x\rangle$ and $|-y\rangle$ trails trace a spiral, due to light shift of deshelve beam.
  - All trails move towards $|1\rangle$, due to 5.3% decay back to $D_{5/2}$.
- Desired effect of Restoration step: $|+x\rangle$ and $|-y\rangle$ trails stay much nearer the equator in Uncollapse results.

- **Right:** Find the fidelity of the restored states ρ_o compared to the (measured) initial states ρ_i.

$$F = \text{trace}\left(\sqrt{\sqrt{\rho_i}\,\rho_o\,\sqrt{\rho_i}}\right)$$

- Plot fidelity vs. p for each initial state.
- Excellent match to theory (with no free parameters) when decay back to $D_{5/2}$ is included (red line).
- Clear improvement over partial measurement with filtering only (grey dotted line).



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