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# Dynamical Decoupling of a $^{43}Ca^+$ Memory Qubit

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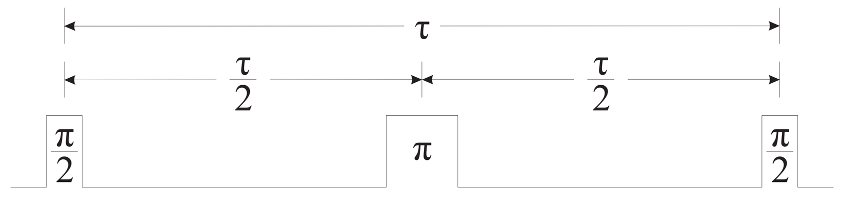
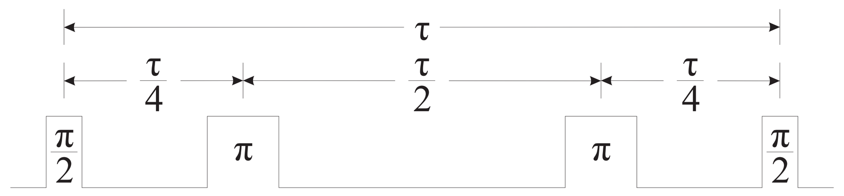
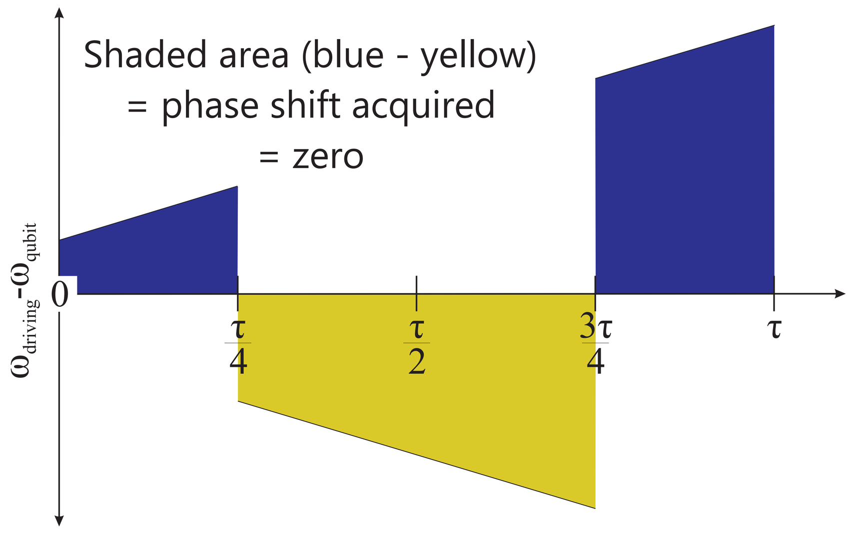
## Generalised Spin-Echo to Protect Against Changing Magnetic Field

The Hahn spin-echo is a well-known method to improve the coherence of a Ramsey experiment, if the frequency of the atom's free precession is slightly different to the driving radiation. A p-pulse in the middle of the gap can "unwind" the excess phase acquired from this offset, and restore the fringe contrast.




Any variation in the frequency error, such as a drifting magnetic field, will cause an uncorrected error. However, we see by inspection that *two* p-pulses can precisely cancel out the error if the frequency is varying linearly with time. They must be placed at times $t = \tau/4$ and $t = 3\tau/4$, where $\tau$ is the total Ramsey gap.




To generalise further, suppose the detuning $\delta(t)$ is an $(n-1)$th order polynomial with time: $\delta(t) = a_0 + a_1 t + a_2 t^2 + \ldots + a_{n-1} t^{n-1}$. Perfect, instantaneous $\pi$-pulses occur at times $\alpha_1\tau, \alpha_2\tau, \ldots, \alpha_n\tau$. The spurious accumulated phase $\phi_{err}$ is given by integrating the detuning with respect to time, so demanding that $\phi_{err}$ vanishes requires us to solve:

$$
\begin{aligned}
0 &= \phi_{err} \\
&= \int_0^{\alpha_1} \delta(t)\,\mathrm{d}t - \int_{\alpha_1}^{\alpha_2} \delta(t)\,\mathrm{d}t + \cdots + (-1)^n \int_{\alpha_n}^{1} \delta(t)\,\mathrm{d}t \\
&= \left[a_0 t + \frac{a_1}{2}t^2 + \cdots + \frac{a_{n-1}}{n}t^n\right]_0^{\alpha_1} - \left[a_0 t + \frac{a_1}{2}t^2 + \cdots + \frac{a_{n-1}}{n}t^n\right]_{\alpha_1}^{\alpha_2} + \cdots \\
&\quad + (-1)^n \left[a_0 t + \frac{a_1}{2}t^2 + \cdots + \frac{a_{n-1}}{n}t^n\right]_{\alpha_n}^{1} \\
&= \sum_{j=0}^{n-1} \frac{a_j}{j+1}\left((-1)^n - 2\sum_{i=1}^{n}(-1)^i \alpha_i^j\right)
\end{aligned}
$$

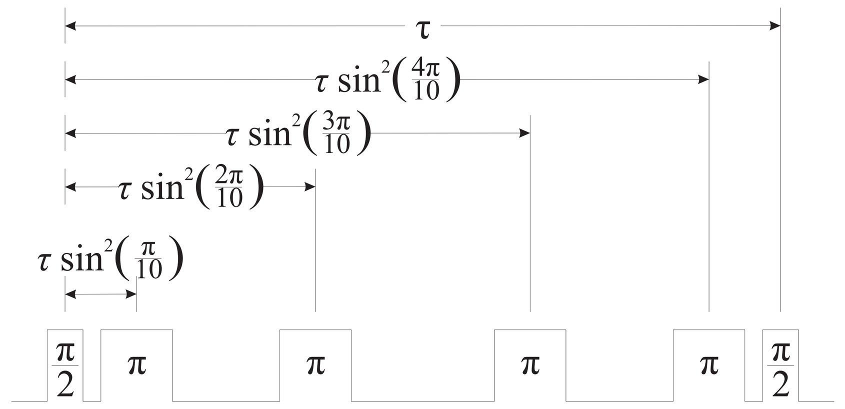
This equation must be independently true for each polynomial coefficient $a_i$, because they can take any (real) value. So we obtain a set of simultaneous equations:

$$(-1)^n - 2\sum_{i=1}^{n}(-1)^i \alpha_i^j = 0 \quad \forall j = 1, 2, \ldots, n.$$

These simultaneous equations are solved when the pulse times $\alpha_i$ take the values:

$$\alpha_i = \sin^2\!\left(\frac{\pi}{2}\frac{i}{n+1}\right)$$

This pulse sequence is illustrated below for $n = 4$.

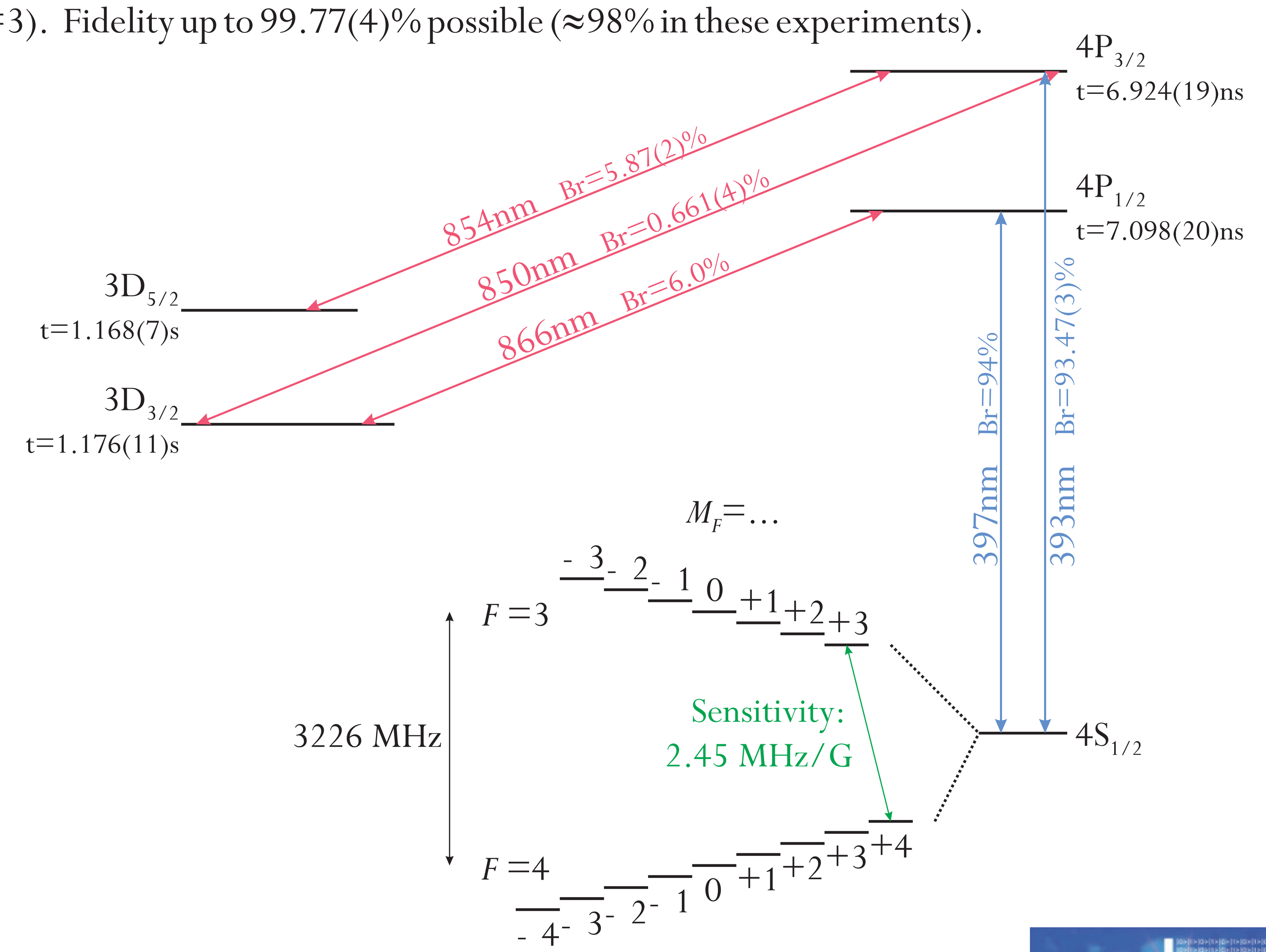



### An *n* pulse sequence precisely cancels out the spurious accumulated phase when the detuning is an (*n*-1)th order polynomial in time.

This sequence is called Uhrig Dynamical Decoupling (UDD). Previously discovered in a solid-state context, by considering a spin-echo sequence as a frequency domain filter. See: "Exact results on dynamical decoupling by p pulses in quantum information processes", Götz S Uhrig, New Journal of Physics **10** (2008) 083024. Biercuk *et al.* have implemented UDD on an ensemble of ions in a Penning trap: "Experimental Uhrig dynamical decoupling using trapped ions", Michael J Biercuk *et al.*, Physical Review A **79** (2009) 062324.

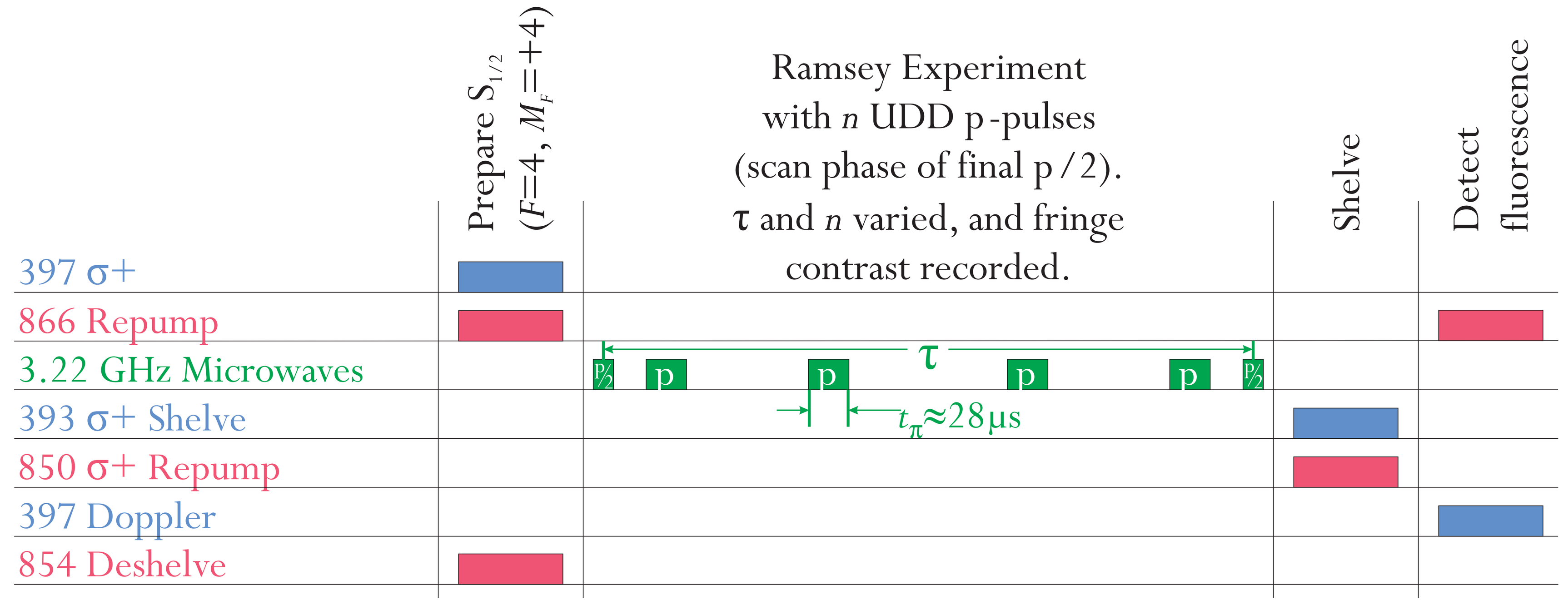
## $^{43}Ca^+$ Hyperfine Qubit

- Qubit stored in $S_{1/2}$ hyperfine-split level: $(F=3, M_F=+3)$ and $(F=4, M_F=+4)$ states.
- Sensitive to magnetic field: 2.45 MHz/gauss. 3.226 GHz at zero field. Work at 2.4 G. Rabi frequency up to 18 kHz ($t_\pi \approx 28$µs).
- Doppler cooling, and observation of fluorescence, at 397 nm. Repump at 866 nm.
- Readout: use 393 nm to shelve ion in $D_{5/2}$, with 850 nm to repump from $D_{3/2}$. Frequency selective - shelve only from $S_{1/2}(F=4)$. Then apply 397 nm + 866 nm and observe fluorescence only if ion was in $S_{1/2}(F=3)$. Fidelity up to 99.77(4)% possible (≈98% in these experiments).




## Experimental Results

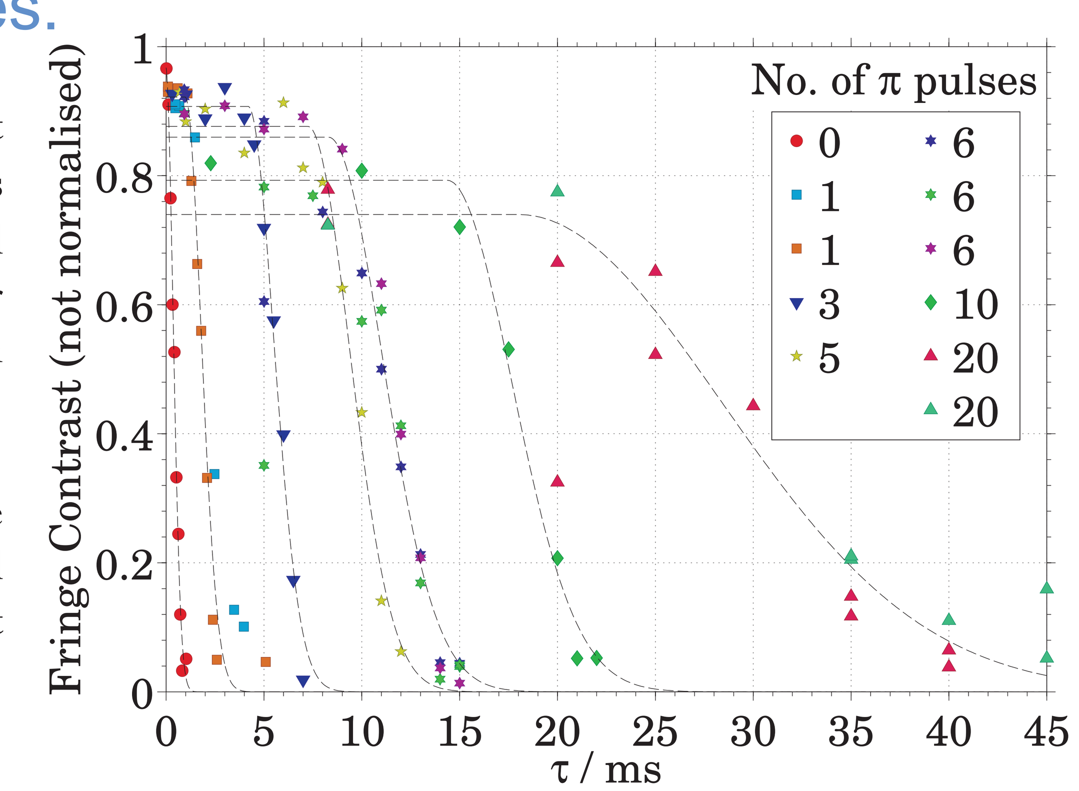
We have implemented Dynamical Decoupling using the $^{43}Ca^+$ hyperfine qubit.

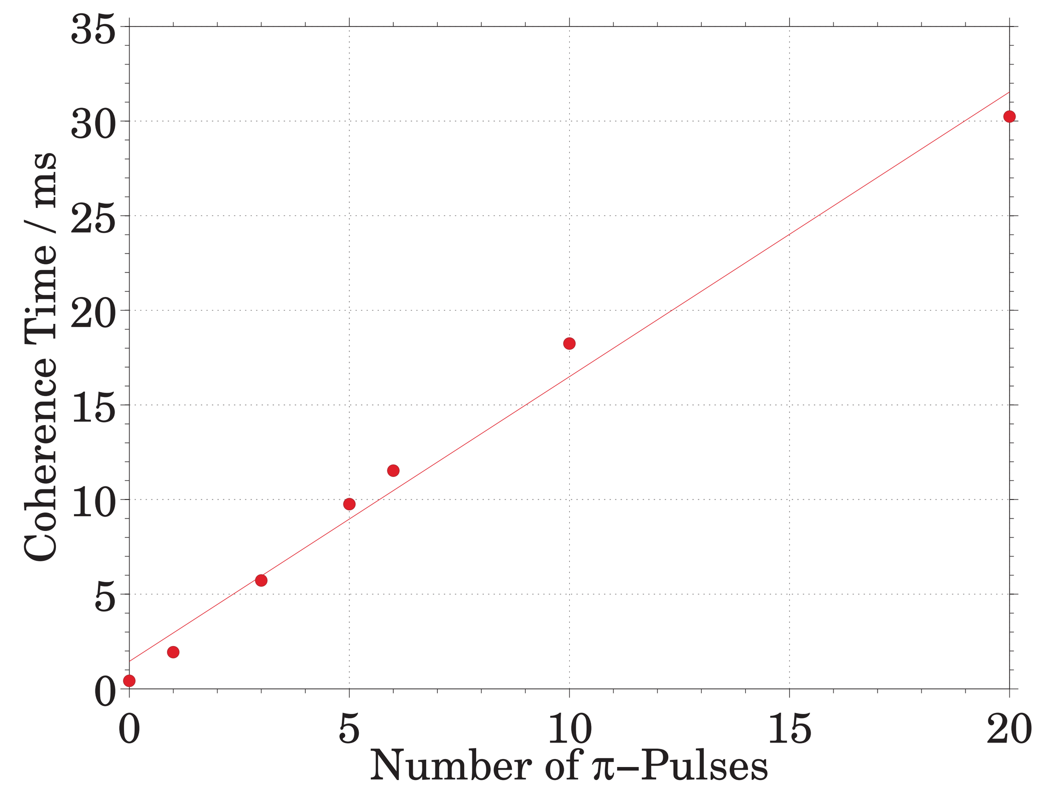



### Coherence time increased from 0.45 ms (no π-pulses) to ≈28 ms with 20 π-pulses.

Plot the Ramsey fringe contrast against the total time $\tau$. The different symbols denote the number of $\pi$-pulses used for that sequence; different colours for the same symbol indicate data from different days.

Black dashed lines are fits to guide the eye. Consisting of a flat line followed by a half-Gaussian, they do not represent any physical model.




For each of the above fits, the time at which the curve reached half its initial value is a measure of the coherence time. These times are plotted against the number of pulses, and fitted with a straight line.

UDD could also be performed using the magnetic-field insensitive $M_F=0$ "clock" states. Previously, we used a single spin-echo pulse on such a qubit and observed negligible (d1%) decoherence in 1 s. Dynamical decoupling could extend this even further. See: "A long-lived memory qubit on a low-decoherence quantum bus", David M Lucas *et al.*, arXiv:0710.4421 [quant-ph].

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