Measurement-based cooling of a trapped ion

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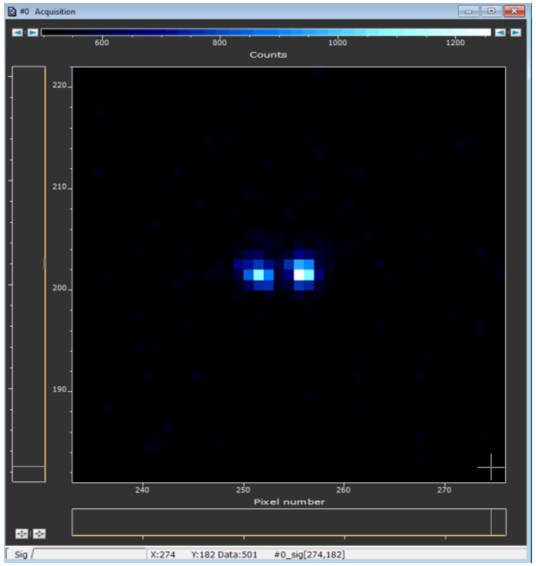
Quantum control of a trapped ion

- For many applications we need full control of the quantum state of a trapped ion, e.g.
  - Precision spectroscopy
  - Quantum information
  - Quantum optics
- This requires preparation of the *motional state* as well as the *electronic state* of the ion
- Doppler laser cooling will take us to an equivalent temperature of ~ l mK
  - This gives an average motional quantum number of typically $n \sim 20$
- Then *optical sideband cooling* will prepare the motion in $n = 0$



Two calcium ions with a separation of about 10 μm

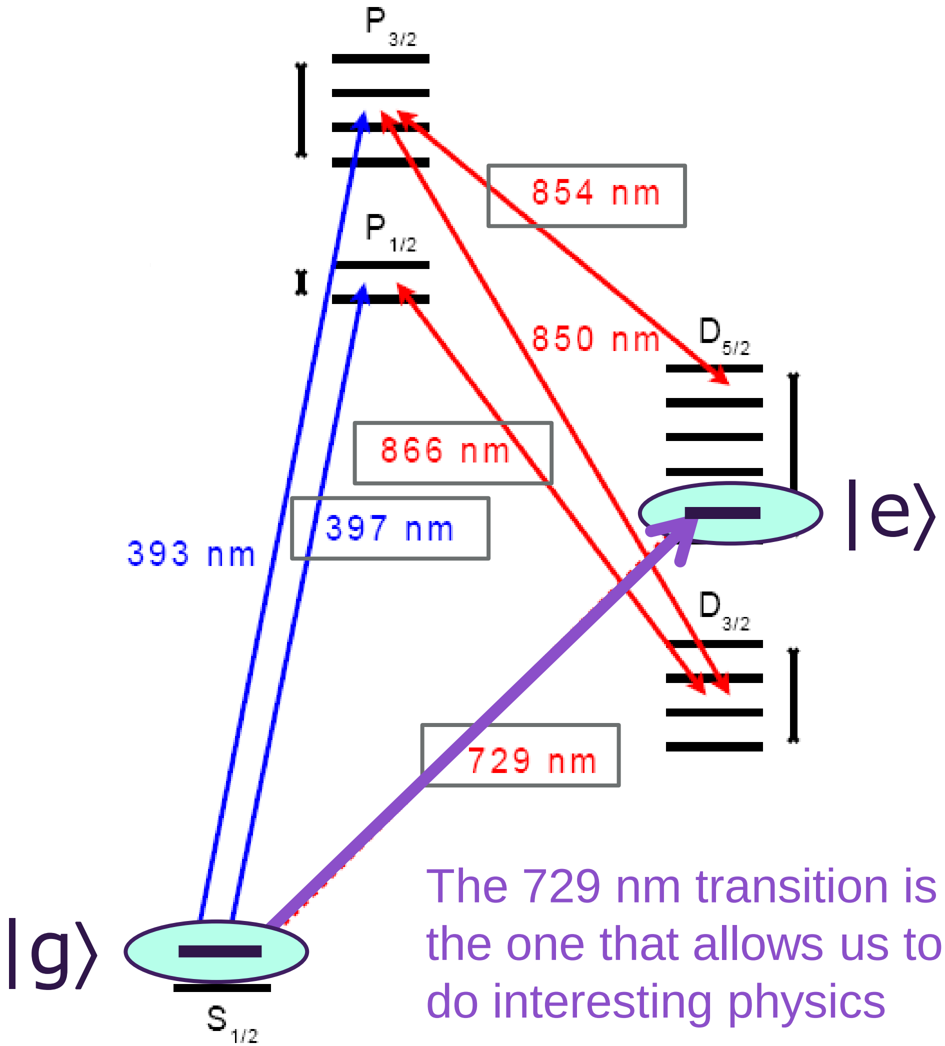
Laser cooling of Ca^+

397nm diode laser for Doppler Cooling

866nm diode laser for repumping

854nm laser diode for quenching/repumping

Ultra-stable 729nm diode laser for spectroscopy, sideband cooling, coherent control



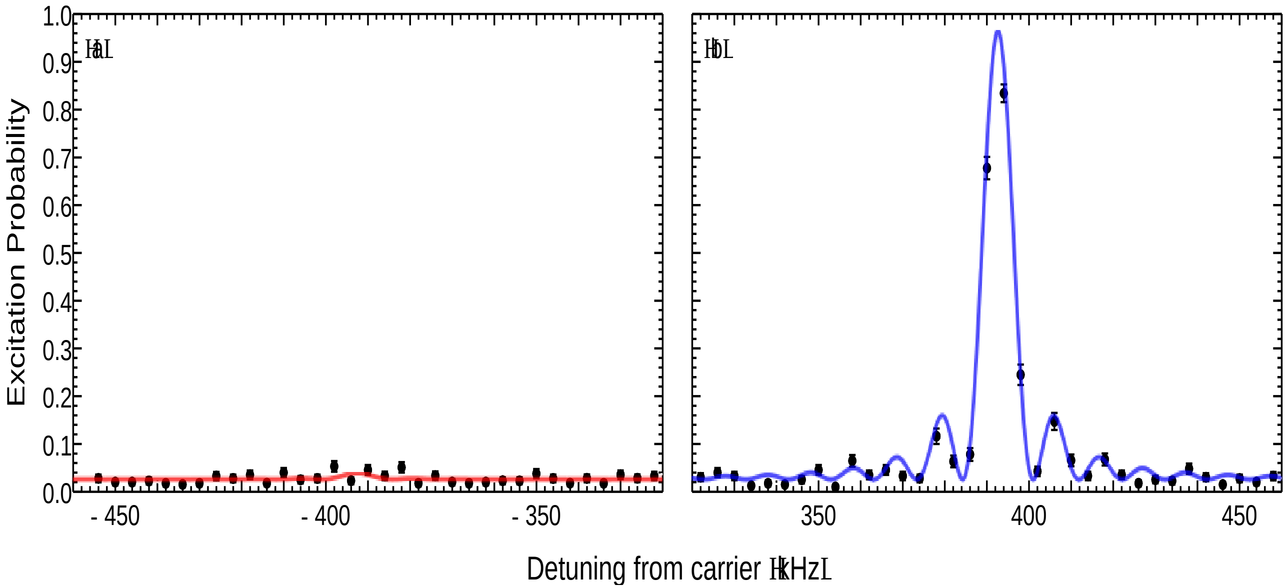
The 729 nm transition is the one that allows us to do interesting physics

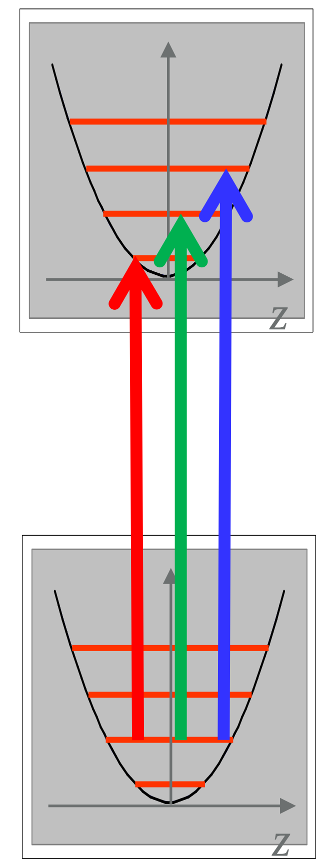
Sideband cooling of axial motion

A trapped ion is effectively a 2-level atom with a motional degree of freedom in a QM simple harmonic potential

Red sideband

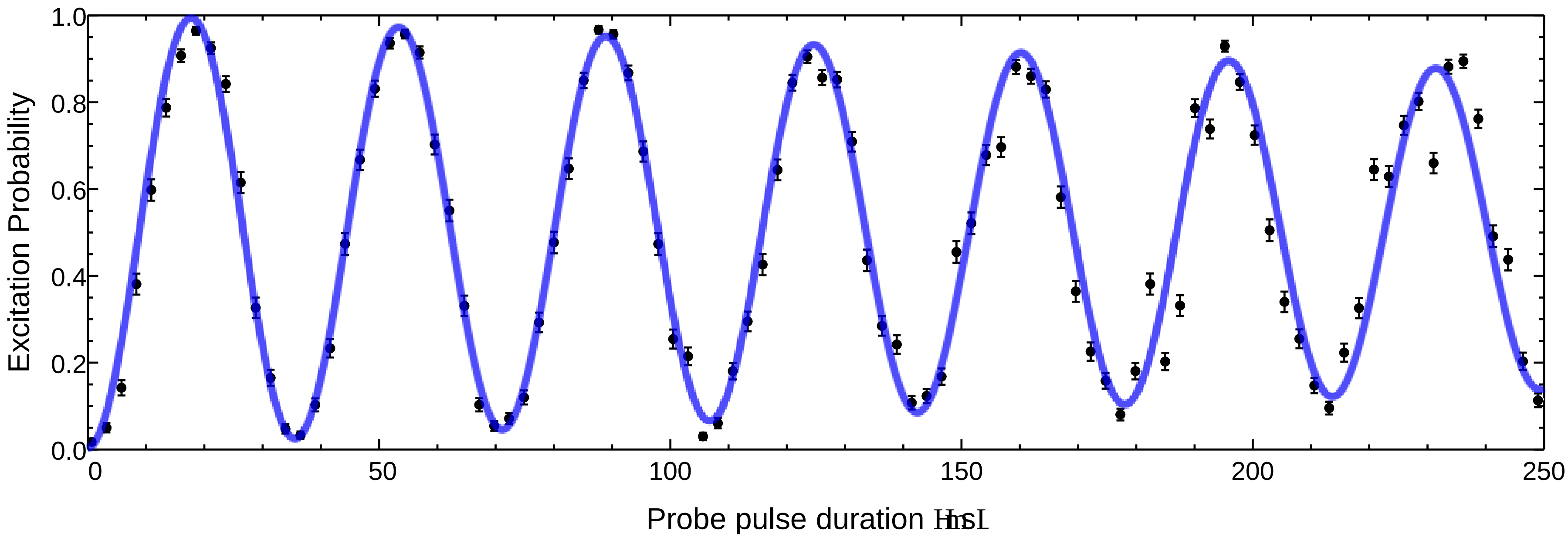
Blue sideband





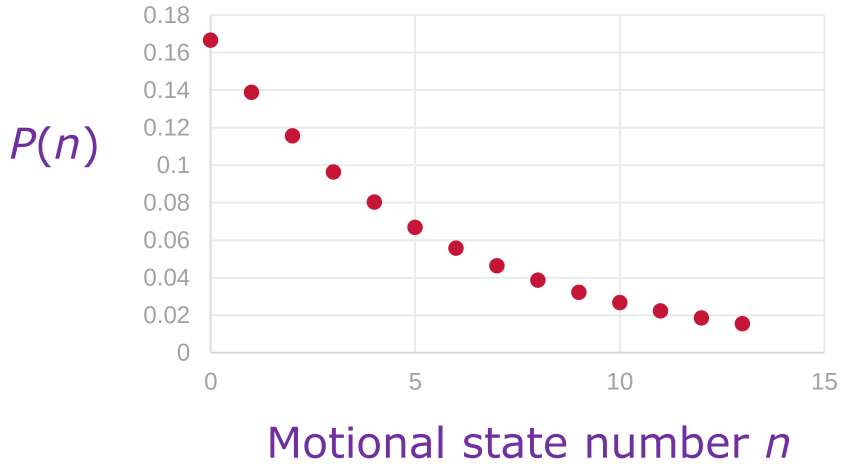
Absence of red sideband indicates that ion is in the ground vibrational state.

Rabi oscillations



- Rabi oscillations are the coherent oscillation of the wavefunction between the |g⟩ and |e⟩ electronic states
- We can see Rabi oscillations for ground-state cooled ions on the carrier transition
  - This shows that we can perform coherent manipulations of our system
- The coherence time is ~0.8 ms

Measurement-based cooling

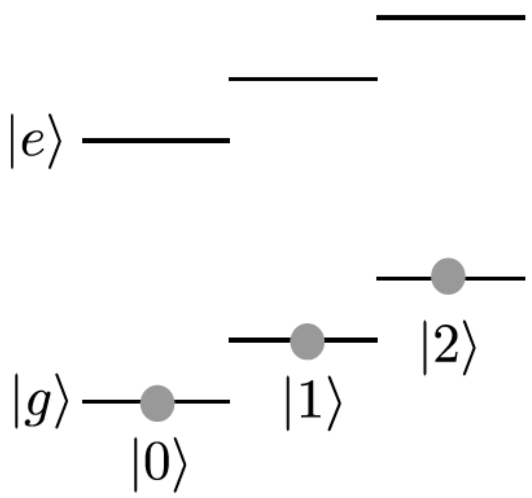


This is the distribution for a mean excitation number of 5

- After Doppler cooling of an ion, the mean motional excitation number is typically 10 − 20
- Sideband cooling actively pumps the system into n=0 by exciting the red sideband of the qubit transition
- An alternative to sideband cooling would be to select the occasions when the system happens to be in n=0
  - This is the principle of *measurement-based cooling*

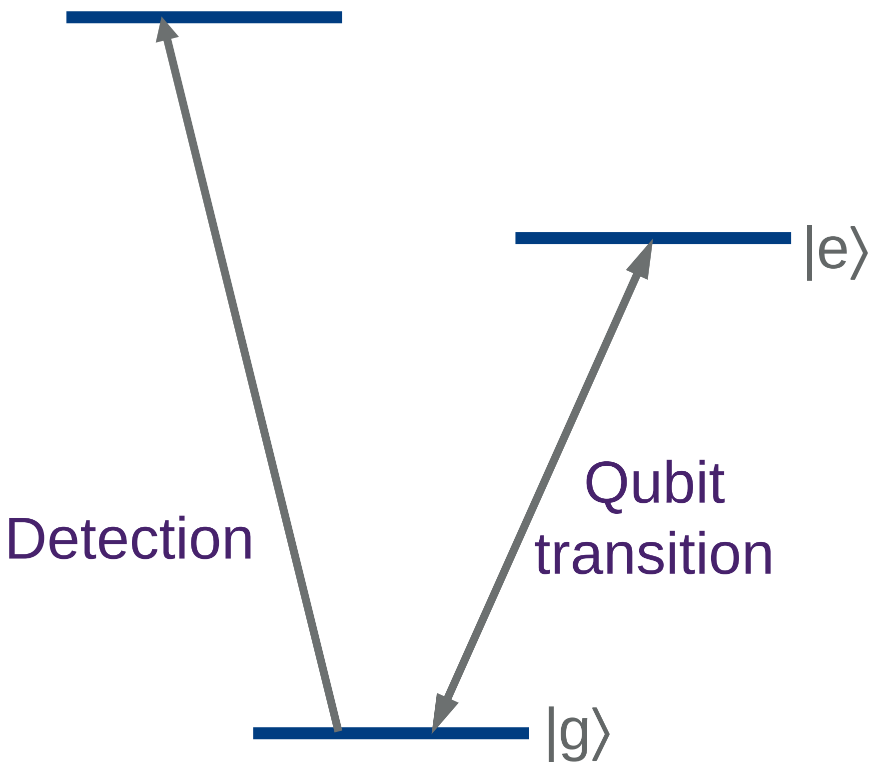
Making a measurement

- After Doppler cooling the system is in the qubit state |g⟩ and a mixture of motional states
- We want to determine whether *n*=0 but the only measurement we can make tells us whether the qubit state is |e⟩ or |g⟩
    - This does not tell us the motional state

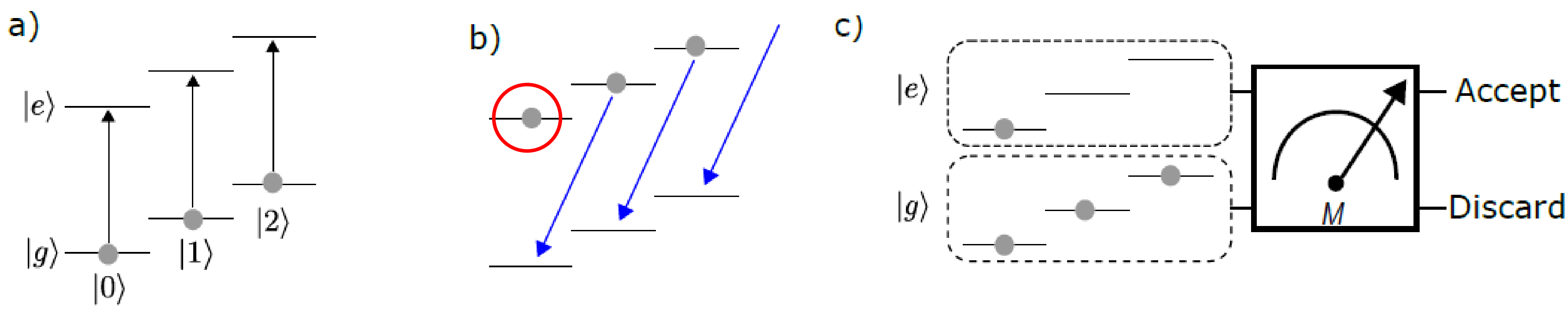


Determining the qubit state

- Turn on Doppler cooling lasers
- If we see fluorescence, we know the qubit state is |g⟩
  - **BUT** the motional state changes after spontaneous decay
- If we see no fluorescence, we know the qubit state is |e⟩
  - The motional state is unchanged
- We can use a sideband transition to associate *n*=0 only with the qubit state |e⟩



Selecting the motional ground state



Thermal distribution in |g⟩ after Doppler cooling

Excite all the population into |e⟩ with a pulse on the carrier transition

Use a pulse on the blue sideband to bring the population back into |g⟩

But if the ion is in the motional ground state *n*=0, it remains in |e⟩

Detect qubit state using the Doppler cooling lasers

If fluorescence is seen (qubit state is |g⟩), discard data point and start again

If no fluorescence seen (qubit state is |e⟩), ion is in motional ground state and experiment can proceed

Absence of fluorescence heralds the system being in the motional ground state

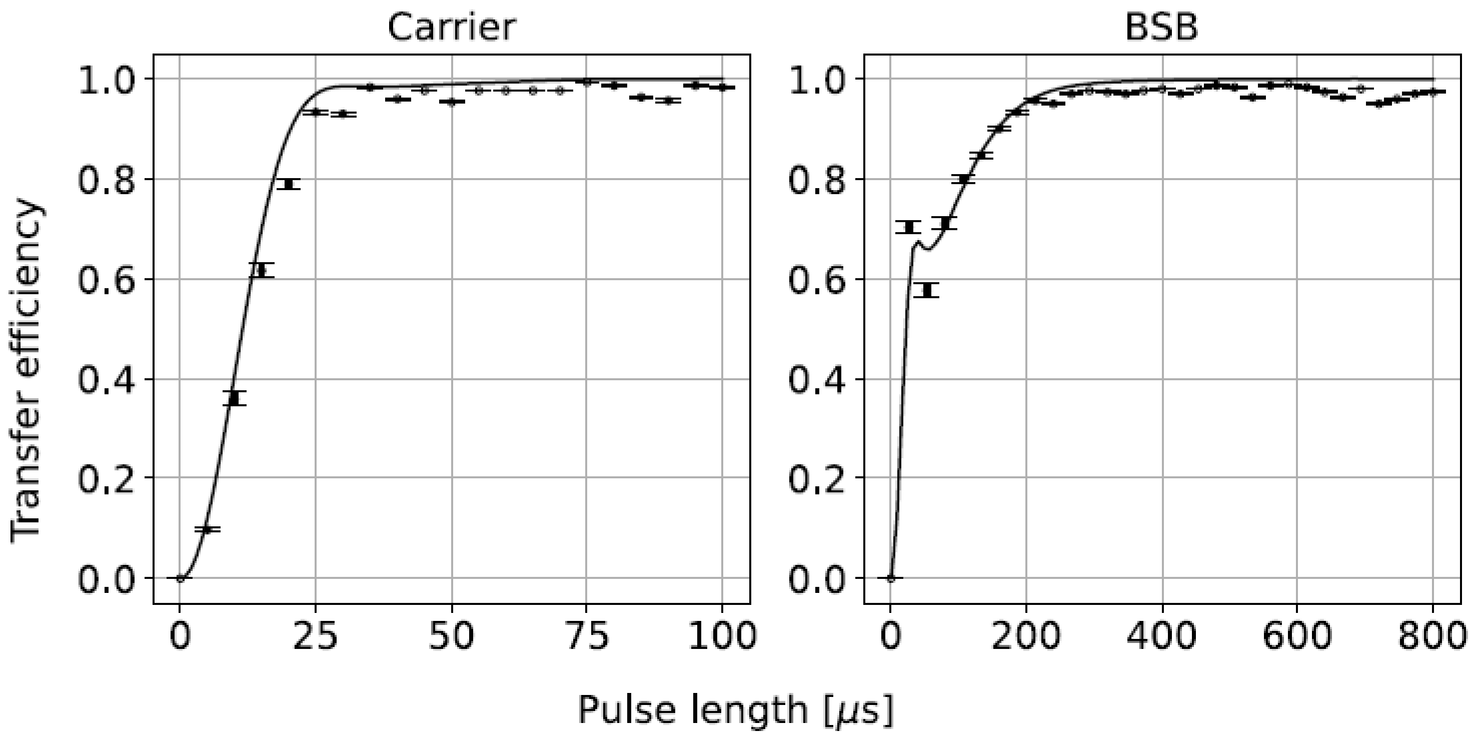
Rapid Adiabatic Passage

- The experiment requires us to transfer population between $|e\rangle$ and $|g\rangle$ on the carrier and the sideband transitions with high fidelity, independent of the value of *n*.
- Since the Rabi frequencies depend on *n*, we can't just use conventional Rabi oscillations to give a π-pulse
- Rapid Adiabatic Passage can work with high fidelity for all *n* as the transfer efficiency is largely independent of the Rabi frequency
  - The laser frequency is swept through the resonance smoothly over a range δ_0 in a time *T*, with a $\sin^2$ intensity envelope

$$\delta(t) = \frac{\delta_0}{T}\left(t - \frac{T}{2}\right),$$

$$\Omega(t) = \Omega_{\mathrm{peak}} \sin^2\left(\frac{\pi t}{T}\right), \quad 0 \le t \le T$$

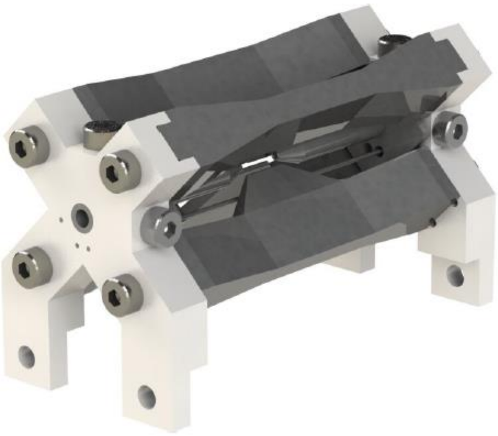
Rapid Adiabatic Passage

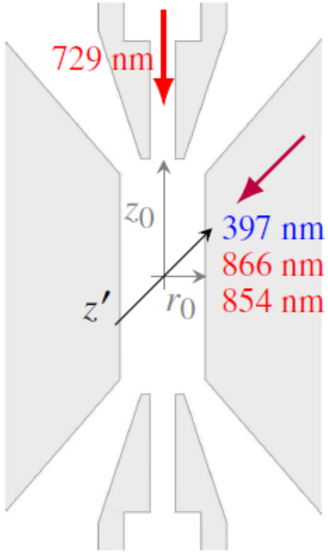


- The transfer efficiency saturates at about 95% on both the carrier (*left*) and the sideband (*right*)

Experimental setup

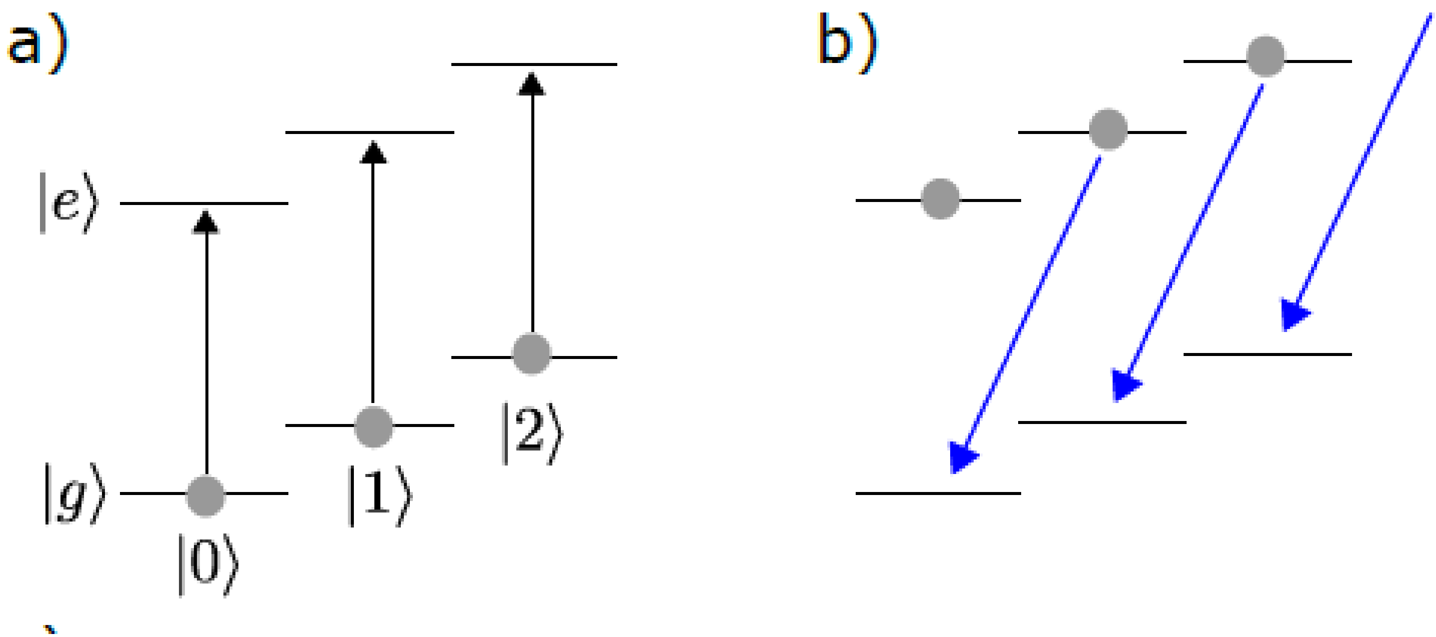
- Ca^+ ions in an RF blade trap
- Axial trap frequency is at ~ 1 MHz
- Laser cooling at 397 nm and 866 nm
- Qubit transition is the $^2S_{1/2}(m_j=1/2)$ to $^2D_{5/2}(m_j=1/2)$ optical transition at 729 nm
- 729 nm laser beam is parallel to the trap axis





r_0=1mm

Rapid Adiabatic Pulse sequence - reminder



- First pulse (carrier) brings all the population from |g⟩ to |e⟩
- Second pulse (sideband) brings the population back down to |g⟩ except for *n*=0

Experimental procedure

Laser cooling

↓

State preparation

↓

RAP on carrier

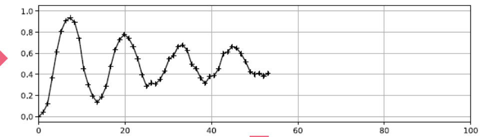
↓

RAP on sideband

↓

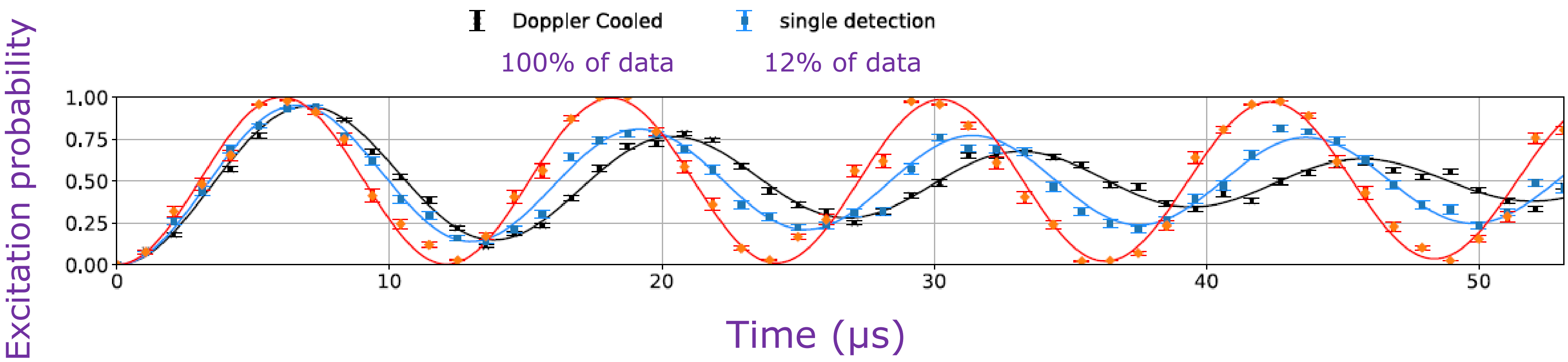
State detection – see fluorescence?

- YES → Ignore data → Start again
- NO → Rabi pulse (t) → State detection →



→ Start again

Demonstration of ground state selection



- Rabi oscillations on the carrier transition as a function of time
- Black curve: Rabi oscillations after Doppler cooling with no selection
- Blue curve: Rabi oscillations with one stage of post-selection (12%)
  - Reduced decay rate indicates that most of population is in the ground motional state
  - Selection process is not perfect due to experimental imperfections
  - Some population with *n*>0 remains in |e⟩

Experimental procedure – two cycles

Laser cooling

State preparation

RAP on carrier

RAP on sideband

State detection – see fluorescence?

YES

Ignore data

Start again

NO

RAP on sideband

State detection – see fluorescence?

YES

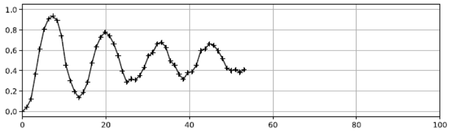
Ignore data

Start again

NO

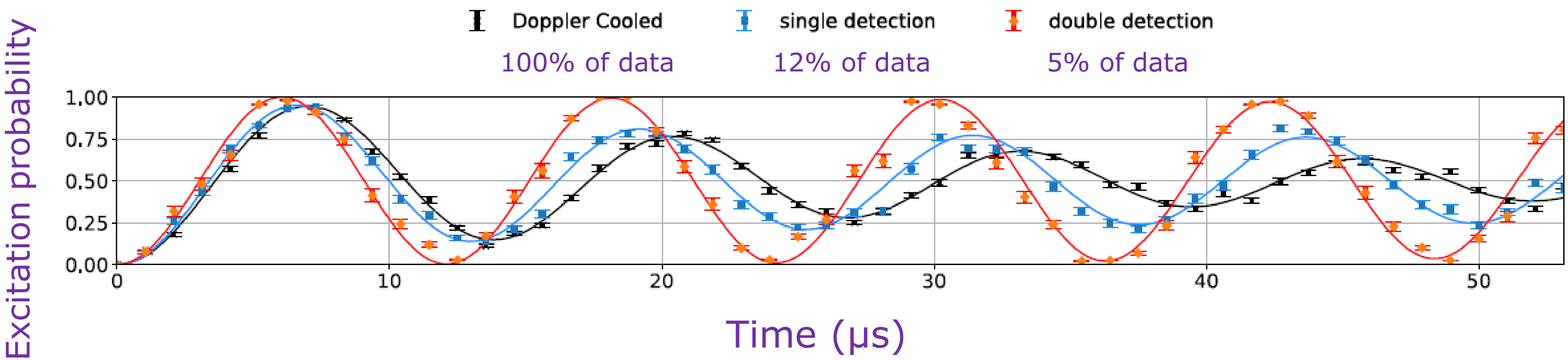
Rabi pulse (t)

State detection



Start again

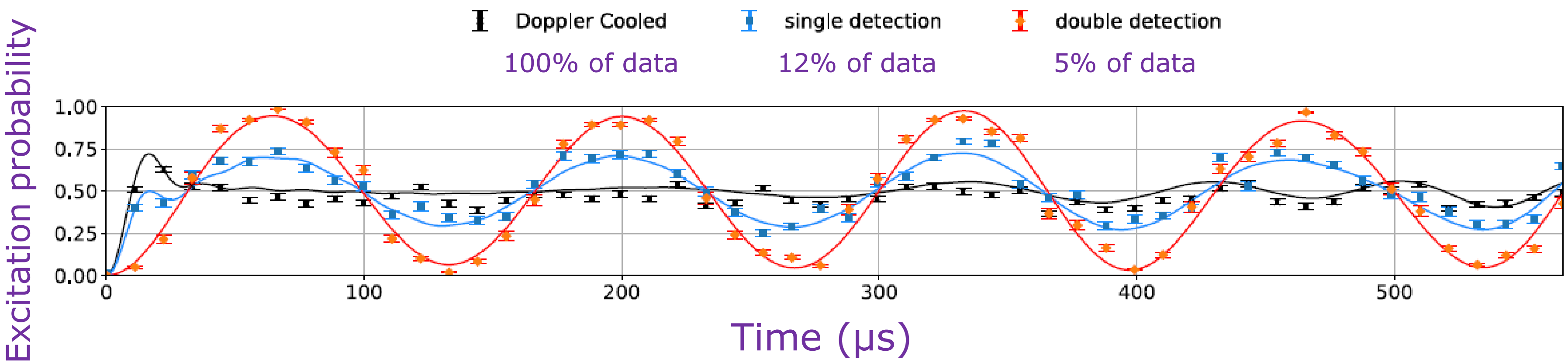
Demonstration of ground state selection



- Rabi oscillations on the carrier transition as a function of time
- Black curve: Rabi oscillations after Doppler cooling with no selection
- Blue curve: Rabi oscillations with one stage of post-selection (12%)
- Orange curve: Rabi oscillations with two stages of post-selection (5%)
  - High visibility oscillations indicate near perfect preparation of ground motional state
- We have effectively prepared the system in the ground state

Lee, Chungsun *et al*, *Physical Review A* **107** 033107 (2023)

Demonstration of ground state selection



- Rabi oscillations on the sideband transition as a function of time
- Black curve: Rabi oscillations after Doppler cooling with no selection
  - Rapid decay due to strong dependence of Rabi frequency on *n*
- Blue curve: Rabi oscillations with one stage of post-selection (12%)
  - Reduced decay rate indicates that most of population is in the ground motional state
  - The rest of the population is spread over many motional states
- Orange curve: Rabi oscillations with two stages of post-selection (5%)
  - High visibility oscillations indicate near perfect preparation of ground motional state

Lee, Chungsun *et al*, *Physical Review A* **107** 033107 (2023)

Theoretical model

- Assume that the failure probability of the RAP is ε
- The probability of being in *n*=0 after selection is then

$$p(n = 0|e) = \frac{1}{1 + 2\epsilon\bar{n}}$$

- The experimental probability p_0 of being in *n*=0 after Doppler cooling is ~5%
  - After one cycle of selection it rises to ~49%
  - After two cycles of selection it rises to ~96%
- This is successfully modelled with ε = 0.05

Conclusion

- We have demonstrated measurement-based cooling of a single trapped ion
- After two stages of selection we know that the system is in the *n*=0 state 95% of the time
- This enables us to carry out coherent operations on the ion
- This method could be applied to other systems where sideband cooling is not feasible

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